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# Effects of Steel Fibers Geometry on the Mechanical Properties of SIFCON Concrete

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**Abstract**

This research aims to shed light on the effect of steel fiber shape, length, diameter, and aspect ratio on the mechanical properties of slurry infiltration fiber reinforced concrete (SIFCON). This study comprised of casting and testing three groups of SIFCON specimens with 6% fiber volume fraction. The first group was reinforced with micro steel fiber, other reinforced by hook end steel fibers, while the last group of specimens reinforced by mixing two shape of steel fiber as hybrid fiber (3% micro steel fiber +3% hook end steel fiber). Silica fume was used as a partial replacement (10%) by weight of cement. 3.7% super plasticizer was used to make the slurry liquid enough to penetrate through the fiber network, while the w/c ratio kept constant at 0.33. It was found from the results achieved that the compressive strength, static modulus of elasticity, splitting tensile strength and toughness are extremely affected by the geometry of fibers because the network of fibers formed and their density depends on the size and shape of fibers. Where the values of micro steel fibers are far outweighing the values of hooked end fibers. It was also deduced from empiricism results that combining long and short fibers gives excellent results.

*Keywords:* SIFCON; Micro Steel Fibers; Hooked End Fiberd; Modulus of Elasticity; Splitting Tensile Strength; Toughness.

## 1. Introduction

Notwithstanding very high compressive strength values and several advantages of high or ultra-high performance concrete, these materials stay essentially a brittle composite material. The incorporation of adequate fiber increases the tensile strength with enhanced deformation ability and therefore offers ductility. In traditional fiber reinforced concrete, the volume of fiber is usually limited to 1-3%, owning to the difficulties of placing emerged from the effect of interlocking of high amount of fibers. To produce high-performance concrete with high fiber content and to avoid mixing and packing difficulties, a new type of concrete was produced by Lankard in 1979 called slurry infiltrated fiber concrete (SIFCON) [1-5]. It is a comparatively new material which varies from normal fiber reinforced concrete in respects of composition and fabrication. The production SIFCON include firstly sprinkling the fibers in the mold to its full capacity. Then the network of fiber is penetrated by cement based slurry. To ensure proper slurry infiltration of the fiber bed, vibration is often necessary [1, 6]. The quantity of fibers can be very large, varying from 5 to 20 % and is a function of several parameters, such as the shape, diameter, and aspect ratio of fibers; their orientation; the method used in packing; mold size; and the extent of vibration. SIFCON exhibits good strength and ductility compared to traditional FRC with a high volume fraction of steel fibers [7, 8]. Research into the mechanical properties of SIFCON has shown excellent properties of the material in respect of the strength (tension, compression and shear), ductility and energy absorption capacity [3, 9]. There are many types of steel fiber used to produce SIFCON as shown in Figure 1. Hooked end and

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crimped fibers are the most commonly used types. Also, straight and deformed fibers are used, but they are less popular. Smaller or shorter fibers can be packed more densely than longer fibers and with adequate vibration, higher volume of fiber can be obtained [10]. The fibers used in SIFCON must be loose (single or discreet) to infiltrate the fiber bed without clogging or honeycombing. Therefore, before placing them in the molds, the agglutinant fibers had to be separated and dissolved [1].

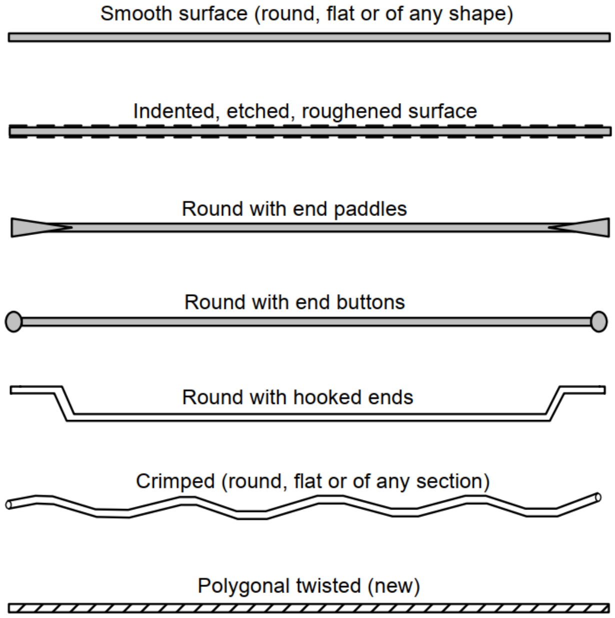


**Figure 1. Typical steel fiber profiles frequently used in SIFCON [11]**

Kim and Choi [12], investigate the compression and tensile characteristics of SIFCON. They used hooked end steel fibers in the mixture, with fraction of fiber ranging from 4 % to 10 %. The ratio of water to cement is held constant at 0.4. The silica fume was added 10 % by weight of cement. To improve the slurry's workability, 0.5% of water-reducing admixture has been added. The test outcomes showed that the compressive strength of SIFCON was approximately (1.59 to 2.68) times compared to the cement paste. Significant increase in ductility ant toughness of SIFCON was also observed with the increasing in volume of fibers.

Yoo et al [13], investigated the effect of fibers shape, length and aspect ratio on the flexural behavior of ultra-high performance fiber reinforced cement composites (UHP-FRCC) by using straight, hooked, and twisted steel fibers. For compressive strength test, cylindrical specimens were used with 200 mm height and 100 mm diameter. While for flexural tests, 100 × 100 $mm^2$ cross sectional prismatic beams have been fabricated. The result show that, at volume fraction of fibers higher than 1%, the hooked end fibers offered lower flexural strength and toughness then straight fibers. For straight fibers, in most cases small length fibers provided better flexural results in respects to higher flexural strength, deflection capacity, and toughness compared to small length fibers owing to their greater aspect ratio.

Yang et al [14], studied the effect of fibers length on compressive strength and toughness of reactive powder concrete (RPC). Three length of steel fibers have been used (6, 12 and 20) mm and aspect ratio of (37.5, 75 and 125) respectively. The test results show that the compressive strength of (RPC) was less effected by length of steel fibers. However, for RPC with 150 MPa and reinforced with long steel fibers had the highest compressive strength, peak strength and toughness due to the higher bonding between the fibers and the ultra high strength RPC matrix. While for RPC with 270 MPa compressive strength, the reinforcement using short steel fibers is more effective.

Ipek and Aksu [15] examined the fiber type effect on the flexure strength and toughness of slurry infiltrated fiber concrete (SIFCON). They blended two types of fiber (hooked end steel and polypropylene fibers) with ratios 1/1, 1/3 and 2/3. They found that this combinations of fibers leads to an increase in the number and volume of fibers and thus this combination led to the high flexural strength (44.02 MPa) and fracture toughness (221.03 Nm) values of SIFCON.

Hybrid fiber concrete is defined as a fiber concrete containing fibers of different geometry and/or made of different materials. For example, one could add 2 or 3 types of steel fibers with different size, or a combination of polymer fibers, carbon and steel fibers, so the principle is the same in all these attempts and thin fibers are used for microcrack amrest, and long thicker fibers are used for macrocrack bridging [16].

Kanagavel and Kalidass [17], studied the mechanical properties of hybrid fiber reinforced quaternary concrete. Quaternary blending cement concrete with fibers is researched in terms of compressive, flexural strength, split tensile strength, and impact resistance. Polypropylene, carbon and steel fibers have been utilized in this study with various volume fractions. The results showed that the use of steel-carbon and steel-carbon-polypropylene hybrid fiber reinforced concretes (SCPHFRC) demonstrate outstanding results for compressive strength, flexural strength and split tensile strength and compared to the control concrete but the workability decreases as the fiber content increases in hybrid-fiber reinforced concrete mixes.

The primary aim of this research is to study the effect of fibers shape, diameter, length and aspect ratio on SIFCON's mechanical properties such as compressive strength, modulus of elasticity, splitting tensile strength and toughness. In addition to highlighting the possibility of mixing tow shape of fibers as hybrid fibers in SIFCON concrete and how this mixing affects the interlocking of fibers and therefore on the aforementioned properties. Figure 2 show the methodology of research.

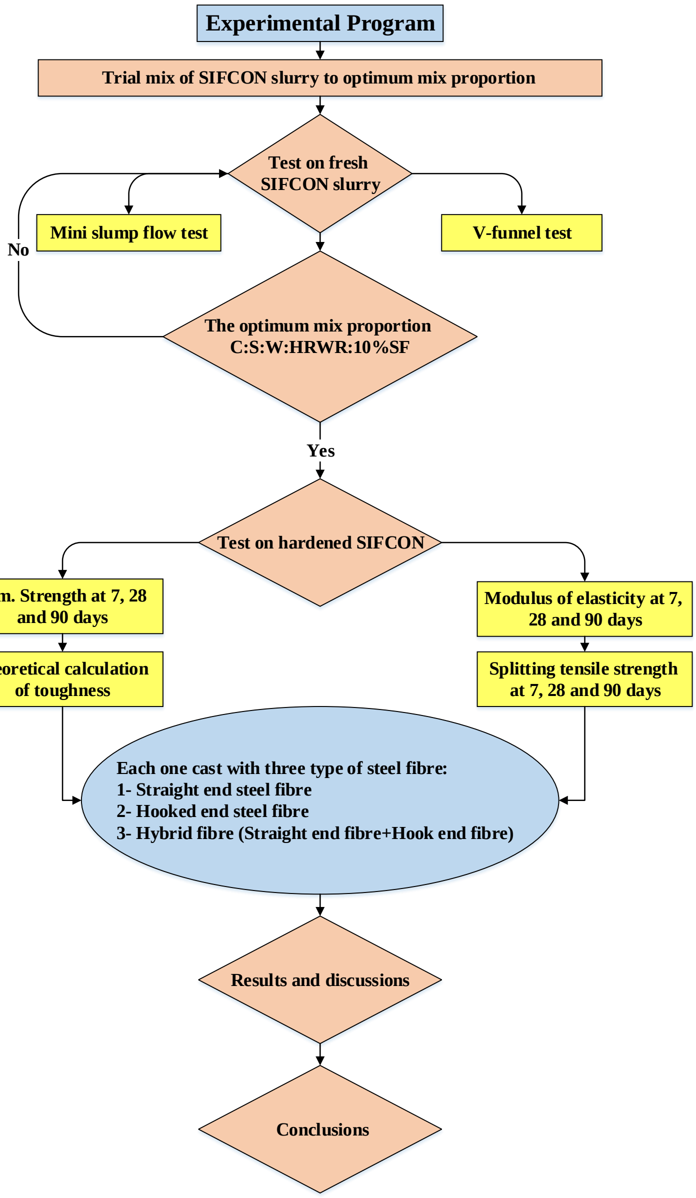


**Figure 2. Flowchart of the research plan**

# 2. Materials and Methods

## 2.1. Cement

The type of cement used in this study was ordinary Portland cement type I complied with (EN, 2011) [18].

## 2.2. Fine Aggregate

AL-Ukhaider natural sand was used in this investigation as fine aggregate and it is complying with the Iraqi requirements [19]. The size of sand is a significant requirement for sand used in in the slurry of SIFCON. It must be small enough to guarantee full permeation through the dense steel fibers without blocking. AL-Ukhaider natural sand was too coarse for use effectively in the production of SIFCON slurry. Therefore, only fine sand, which was sieved through (1.18 mm sieve) to segregate the coarser particles, was used in preparing SIFCON mortars. Figure 3 shows the grading curve of the natural sand in accordance with (IQS No.45/1984) [19].

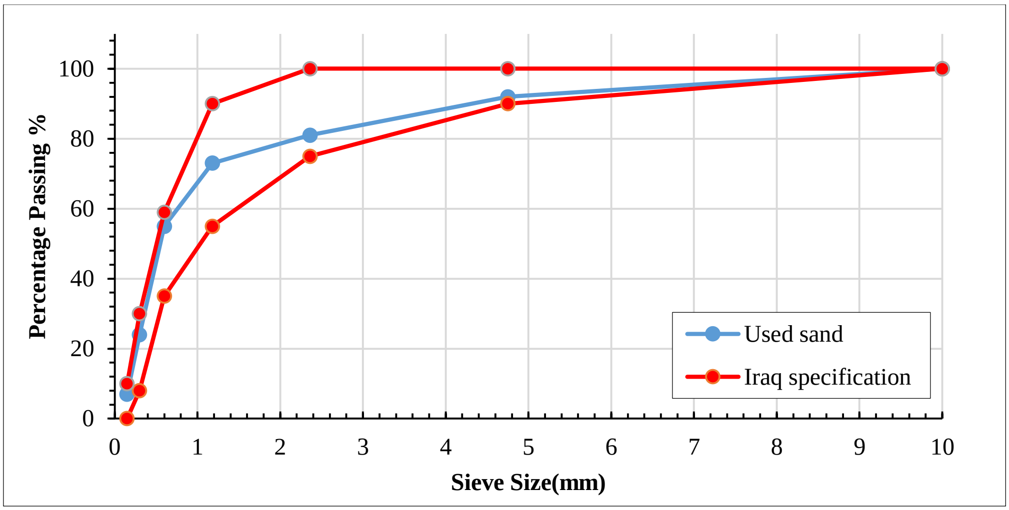


**Figure 3. Grading curves for fine aggregate**

## 2.3. Micro Silica Fume (SF)

The silica fume used in this investigation was commercially known as Mega Add MS (D) from chemical company (CONMIX), and it was utilized in this investigation as a partial replacement (10%) by weight of cement. It is improving the micro structure of the cement paste and makes it of more resistance to any type of external influence.

## 2.4. High-Range Water Reducing Admixture (HRWRA)

The high - performance and third generation super plasticizer water reducing admixture was used in this research for preparation of SIFCON slurry, known commercially as (Hyperplast PC200). It is imported from the company (DCP), and comply with the requirements of (ASTM C494/C494 M)[20].

## 2.5. Steel Fibers

In this work two shapes of steel fiber are used, which are various in diameter, shape, length and aspect ratio (l/d). The first shape was straight micro steel fiber with (13) mm length, (0.2) mm diameter and 65 aspect ratio. The second shape was hooked end steel fibers with length of (30 mm), diameter of (0.5) mm and 60 aspect ratio. Figure 4 display the micro steel fiber and hooked end steel fiber were used in this research.

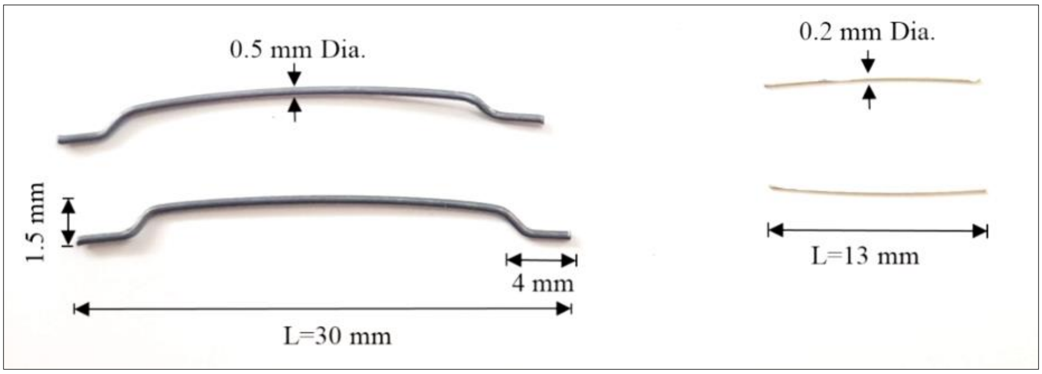


**Figure 4. Shape of fibers were used in this research**

## 2.6. Mix Proportion

Many trial slurry mixes have been prepared to achieve optimum fresh properties for SIFCON mortars by using mini slump flow and V - funnel time test, while at the same time achieving easy and to ensure complete penetration of prepared mortars through the steel fiber network, Figure 5 show an examples of lack of fluidity. Since there is no standard specification for SIFCON mix design yet, it has been based on previous research. Where the proportion of (sand: cement) by weight in most cases is equal to (1:1), so this value was adopted in this investigation. Also many investigators [21-

23] used cement content range from (800-1000) kg/m$^3$ and recommended to use w/b ratio less than 0.4 (by weight) for the production of SIFCON matrix. Therefor after many trails, the mix proportion used in this work are illustrated in Table 1. In this research 6% of steel fibers were used to reinforce the specimens. Once as micro steel fiber, other as hook end steel fiber and as mixed hybrid fiber (3% micro steel fiber +3% hook end steel fiber).

**Figure 5. An example of unsuccessful slurry penetration owing to absence of fluidity**

**Table 1. SIFCON optimal mixing proportions for 1 m$^3$**

| Constitutive Type | SIFCON |
|---|---|
| Cement (Kg/m$^3$) | 872.1 |
| Sand (Kg/m$^3$) | 969 |
| Silica Fume Kg/m$^3$ 10% rep. | 96.9 |
| Steel Fiber % | 6 |
| w/b or w/c ratio | 0.33 |
| SP (by wt. of binder)% | 3.7 |
| Mini-slump flow (mm) | 364 |
| V-funnel time (s) | 11 |

## 2.7. Procedure of Mixing and Casting

Sufficient mixing is necessary to achieve the needed performance and homogeneity of SIFCON slurry. Also the extending mixing time is important both to enable the HRWR to develop its complete potential and to obtain fully dispose of silica fume by break up any conglomerated particles. The mixing procedure adopted in this study is presented in Figure 6.

As shown in Figure 7, a multi-layer method is used to cast SIFCON samples. Each layer has a thickness of 10 cm. This technique involved initially placing and packing of fibers that were randomly oriented and sprinkling by hand in the mold up to a depth of 10 cm, followed by filling the mold up to this level with the slurry as shown in Figure 7A. In order to guarantee infiltration through the fiber, the slurry must be flowable enough. The fibers in the mold were then compacted using a steel rod with tapered head to prevent honeycombing or voids, see Figure 7B. This process was repeated (for each layer) where the entire mold was stuffed with the required fibers volume fraction. The samples have been covered after casting with nylon sheet to eliminate the risk of shrinkage cracks caused by evaporation of the mixing water and left in the laboratory for 24 hours as depicted in Figure 7C. Until the age of 7, 28 and 90, the specimens were immersed in tap water after marking it.

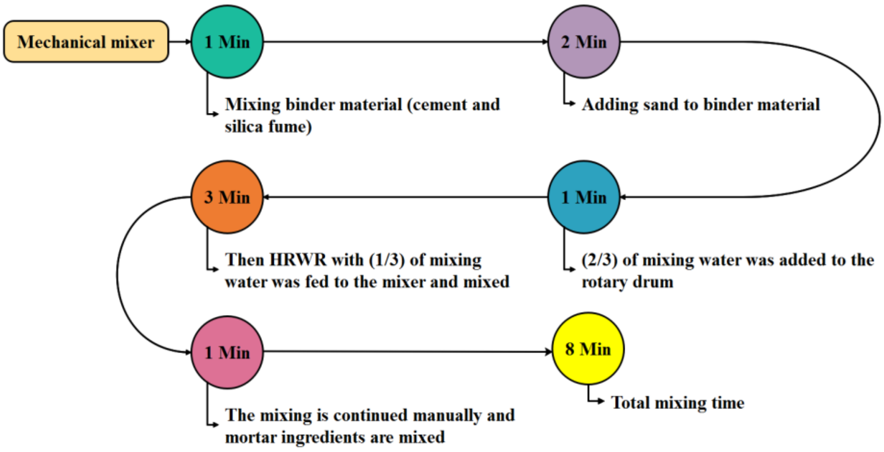


**Figure 6. SIFCON mixing time process**


**Figure 7. The procedure of casting SIFCON specimen**

## 2.8. Testing of Hardened SIFCON

### 2.8.1. Compressive Strength

In order to determine the compressive strength, three cubes (100 x 100 x 100 mm) were cast in the same manner as for each shape of fibers (micro steel fibers, hooked end steel fibers and hybrid fibers). The compressive strength test was determined by crushing three cubes at the age of 7, 28, 90 days using a (1900 kN) digital test device with a loading rate of 0.3 MPa / sec as shown in Figure 8.

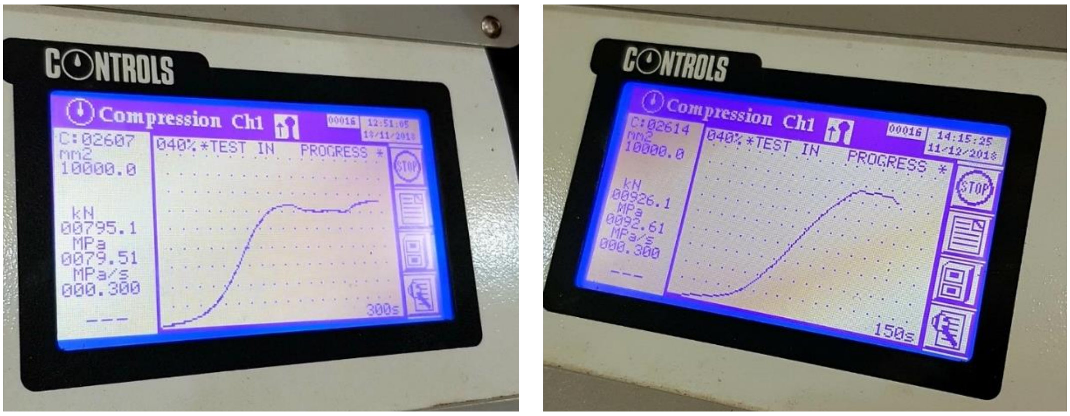


**Figure 8. An example of the loading chart on the specimen versus time**

### 2.8.2. Static Modulus of Elasticity

The static modulus of elasticity of concrete was performed on (100×200 mm) cylindrical specimens and according to ASTM C469 / C469M [24]. The top surface of cylinder was well finished and smoothed by using electric grinding machine to prevent any loss of strength.

### 2.8.3. Splitting Tensile Strength Test

Splitting tensile strength test was carried out using cylindrical specimens of 100×200 mm. The average result of three specimens was taken at 7, 28 and 90 days. The test was done according to ASTM C496 / C496M [25] by using a digital testing machine with a capacity of (1900 kN) and loading rate of (0.3 MPa / sec).

## 3. Results and Discussions

The result of compressive strength, elastic modulus and splitting tensile strength of SIFCON specimen are tabulated in Table 2.

**Table 2. Summary of compressive strength, elastic modulus and splitting tensile strength for SIFCON test values.**

| Shape of steel fibers | Compressive strength (MPa) | | | Static modulus of elasticity (GPa) | | | Splitting tensile strength (MPa) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 7 days | 28 days | 90 days | 7 days | 28 days | 90 days | 7 days | 28 days | 90 days |
| Micro steels fibers | 68.2 | 88 | 124.7 | 23.3 | 28.6 | 32.3 | 17.1 | 19.3 | 20.8 |
| Hybrid fibers | 61.6 | 71 | 113.6 | 21.7 | 26.8 | 30.6 | 15.3 | 17.2 | 18 |
| Hooked end fibers | 45.7 | 65.5 | 97 | 19.6 | 25.4 | 28.1 | 12.6 | ١4.1 | 14.7 |

### 3.1. Compressive Strength

Figure 9 show the effect of fiber shape (straight micro steel fiber, hooked end steel fiber, and hybrid fiber) on the compressive strength of SIFCON at different ages.

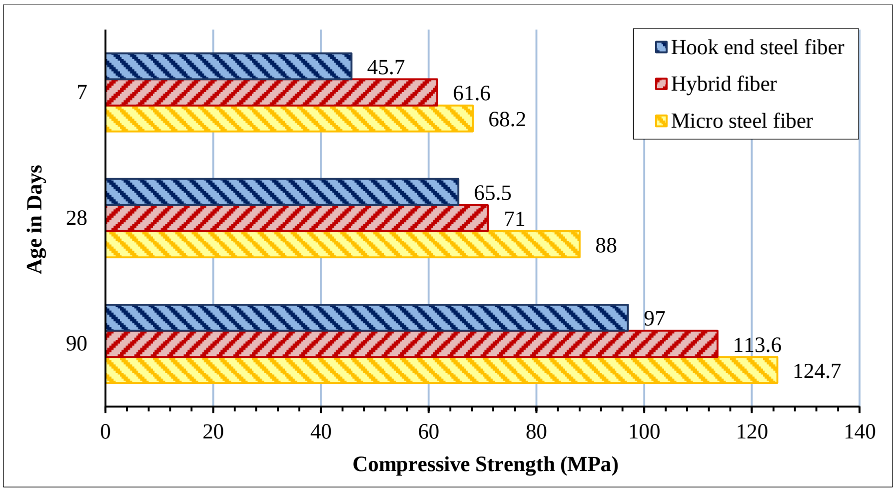


**Figure 9. Compressive strength of SIFCON for different shape of fibres**

It can be seen from the test results that specimens with micro steel fiber show significant increase in compressive strength comparing to hooked end and hybrid fiber specimens. The increasing ratios for all ages are (٤٩.23, 34.35, and 28.55%), for (7, 28, and 90 days) respectively. This is due to the higher aspect ratio of micro steel fiber as compared with other fibers, which causes increase in the strength of specimens [26]. Also, the short fiber are very thin and greatly increase the number of fibers used in the concrete, hence they are decreasing the cracks and delaying their coalescence in localized and large cracks this leads to increase the strength of concrete [27-29]. The uniform, dense and randomly distributed of micro steel fibers throughout the SIFCON matrix provide a better distribution of both internal and external stresses due to the development of a three-dimensional reinforcement network [30, 31]. It is clear that SIFCON specimens made with hybrid fibers were also show higher strength comparing to hooked fibers specimens, which is due to the combined effect of both (hooked ends and straight micro steel fibers) in bridging the micro cracks growth and produce higher bond between fibers and matrix, this consequently lead to higher strength of the SIFCON mixes. This is in agreement with Qian and Stroeven results [27], where they found that the addition of hybrid fibers created synergy in the concrete and leaded to significant improvements in fiber reinforced concrete. Figure 10 show the effect of fiber geometry on the crack pattern of SIFCON samples. A large number of cracks and spalling were observed in specimens reinforced by hooked end fibers due to the lower number of fibers per unit area compared to small fibers, where micro steel fibers provide a light number of fibers and more bone between fibers and slurry in specimens reinforced by micro and hybrid fibers. The compressive strength results of present research were compared with the results of several researchers for 6% volume fiber fraction and at 28 days as depicted in Figure 11. The researchers are sudaresana [32], Kim and Choi [12] and Ali and Riyadh [33].

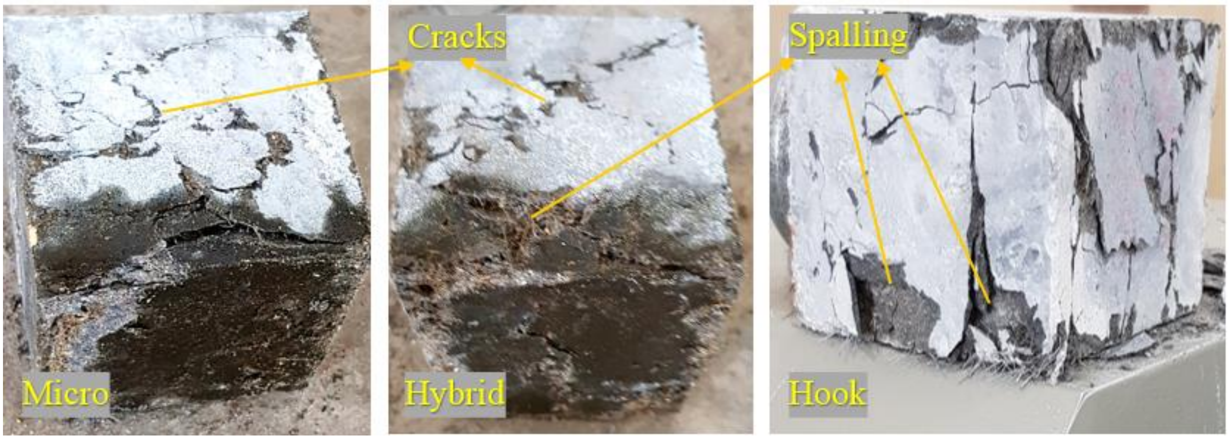


**Figure 10. Effect of fiber geometry on cracks pattern in SIFCON specimen**

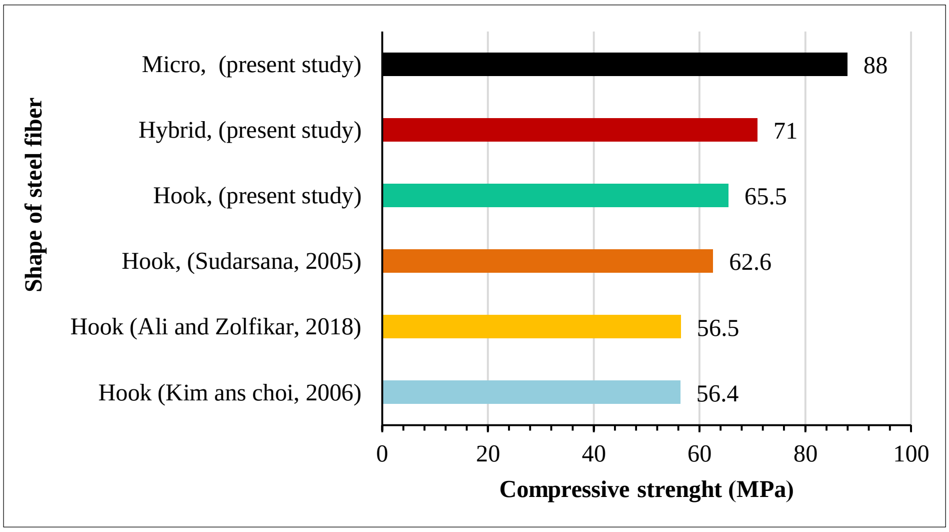


**Figure 11. Comparison of the compressive strength of SIFCON from the present study and other researchers at 28 days**

## 3.2. Static Modulus of Elasticity

The static modulus of elasticity (Ec) is one of the most significant characteristics of solid materials because it is describing the stiffness of material. The materials of concrete and their proportion is strongly influence on the elastic modulus. The increase in compressive strength resulting to an increase in the elastic modulus as the slope of the ascending branch of the stress strain curve has become steeper [34].

The test outcomes show that the modulus of elasticity is higher when using micro steel fibers than other type of fibers. Two things may be responsible for this behavior. First, since the modulus of elasticity is considered as a function of compressive strength and the compressive strength as mentioned above increased with increasing in aspect ratio of fiber, therefore, the modulus of elasticity was increase as aspect ratio of fibers increases [33, 35].

Second, micro fibers offer very large numbers of fibers per unit volume and their better fibre-to-fibre bond result in a stiffer composite at small strains. Since the the stiffer material will have higher elastic modulus, the micro fiber gave higher modulus of elasticity [36, 37]. For hooked end fiber, Bentur et al. [38] found that the present of hooked end provides a better restraint to shrinkage, thus reducing pre-loading shrinkage cracking which can lead to a reduction of the modulus of elasticity.

Research found that casting cylinders of SIFCON expose to phenomenon known as edge effects which may adversely effect on SIFCON properties. Its occur at the interface of SIFCON and the mould leaving voids in this area and the fiber density becomes low compared to the central region which characterized by high fibers density [6]. The microstructure around micro fibers is quite different than that of hooked end and hybrid fibers. Where it is characterized by a dense transition zone thus eliminating the edge effect in the packing of micro fiber, i.e. reduces the spaces between fibers [39], see Figure 12. Also, the micro steel fiber layers are much more interconnected (fiber to fiber bond) than other types of fibers. This lead to delay the dilation of concrete by serving as crack arresters, thus indirectly helping to confinement concrete under compression load and justifies the high performance of specimens reinforced with micro steel fiber.

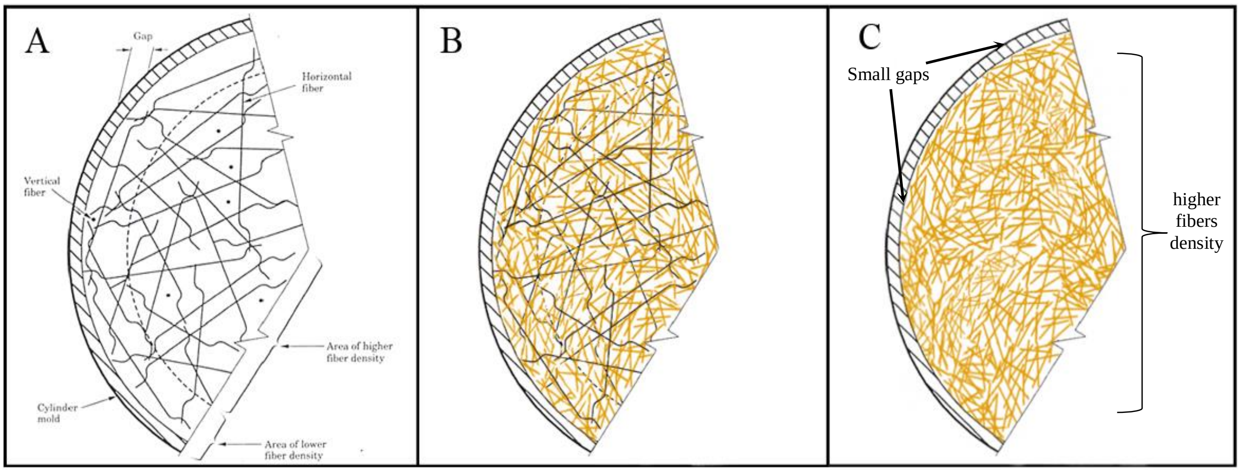


**Figure 12. Edge effect phenomenon and number of fibers per unit volume in SIFCON specimens reinforced with: (A) hooked end fibers [1], (B) hybrid fibers, (C) micro fibers**

### 3.3. Splitting Tensile Strength

The tensile strength administers the cracking behavior and affects other characteristics like durability and stiffness of SIFCON. It is found from the results that the SIFCON's splitting tensile strengths usually increases with age. However, under tensile load, the crack is easily propagated, making the tensile strength of the concrete much lower than the compressive strength. Increasing the strength with time is the consequence of the advancement of the hydration method of the matrix by completing its internal microstructure, which leads to extra strength added to the composite material, together with an increase in the bond strength between the fibers and the matrix [40]. The splitting tensile strength tests results of SIFCON, which illustrated in Table 2 show that the splitting tensile strengths for SIFCON specimen reinforced with micro steel fibers are slightly higher than the corresponding splitting tensile strength for specimens reinforced with hybrid and hooked end fibers. This increasing might be due to the effect of high aspect ratio of micro steel fiber compared with that of hooked fiber, which cause increase in the tensile strength of specimens. Also, this enhancement could be attributed to the fact that microcracks can be controlled by arresting and bridging mechanism of fibers. On the other hand, the using of micro steel fiber leads to an improved bond between fiber and matrix, hence improvement in mechanical properties of SIFCON [41]. The superiority of specimens reinforced with hybrid fiber also achieved duo to using a combination of long and short fibres as different lengths of fibres would control different scales of cracking [42]. Figure 13 shows a comparison between the results of the current study and the results of some researchers at the age of 28 days and for different shapes and volumes of fibers. The researchers are Ali and Riyadh [33], Elavarasi and Mohan [43] and Deepesh and Jayant [44].

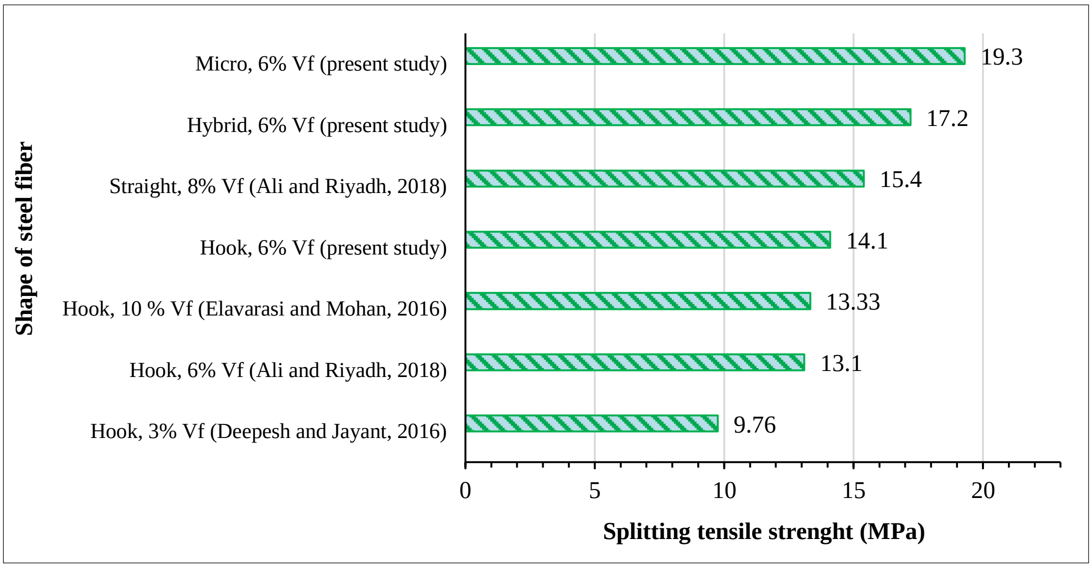


**Figure 13. Comparison between the results of the current study and the results of some researchers**

## 3.4. Toughness of SIFCON

Toughness is an amount of the capacity of material to absorb energy throughout the deformation. It could be predicted from the area under the stress strain or load deformation curves. A toughness index (TI) can be computed by expression suggested by [45] as follows:

$$TI = 1.421\ RI\ + 1.035 \quad (1)$$

Where RI = reinforcing index = Vf (l/d); Vf = volume fraction; l/d = aspect ratio of fiber.

Table 3 illustrates the toughness index (TI) for different shapes of fiber, and Figure 14 presents the toughness index versus reinforcing index of SIFCON specimens. According to the aspect ratio of fiber, as l/d increase, the toughness index increase. Where Nawy [46], Wang et al [47] and Sovják et al [48] mentioned that toughness is significantly improved as a function of the increasing of the aspect ratios of the fibers used. On the other hand, Homrich and Naaman [49] found that fiber length and aspect ratio affect the possible volume fraction of fibers that may be placed in molds, where a higher aspect ratio is reflected by a higher absolute number of fibers in the mixture which lead to more energy absorption and better crack control. Therefore, the toughness of SIFCON reinforced with micro steel fiber was higher than that of SIFCON with hooked end and hybrid fibers.

**Table 3. Toughness index of different shape of steel fiber**

| Shape of steel fibers | Aspect ratio (l/d) | Reinforcing index (RI) | Toughness index (TI) |
|---|---|---|---|
| Micro steel fibers | 65 | 3.9 | 6.57 |
| Hybrid Steel fibers | 62.5 | 3.732 | 6.33 |
| Hook end steel fibers | 60 | 3.6 | 6.15 |

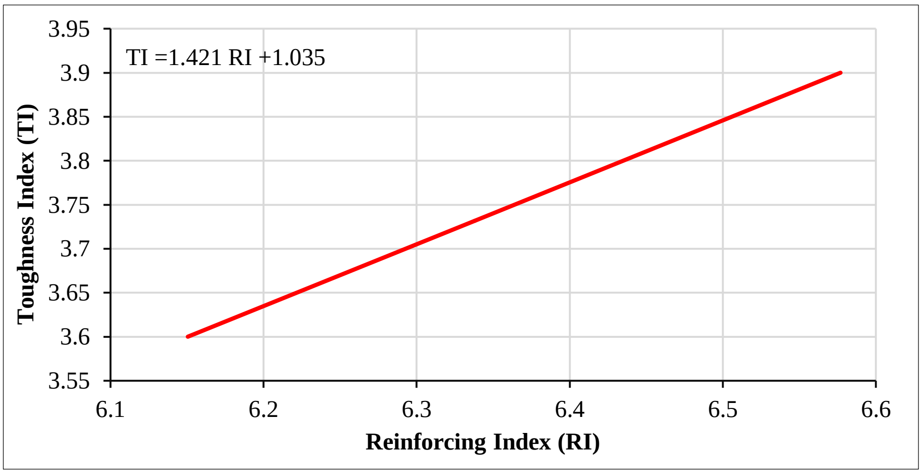


**Figure 14. Toughness index versus reinforcing index of SIFCON**

## 4. Conclusions

In this research, the effect of fibers shape, size, length, diameter and aspect ratio on the characteristics of SIFCON concrete has been investigated. Major results of this research can be summarized as follows:

- The experimental results clearly indicate that the compressive strength, modulus of elasticity, splitting tensile strength and toughness are significantly affected by fibers shape, where the values of micro steel fibers far outweigh the values of hooked end fibers.
- The shorter and smaller size of fibers, the greater the number of fibers in the unit area, resulting in a dense network of fibers with less space and less affected by the edge effect phenomenon and therefore better SIFCON characteristics.
- Substitution of micro fibers instead of hooked end fibers increased the compressive strength of the SIFCON remarkably by 28.5% at 90 days.
- It is found that the combination of two shapes of steel fibers as hybrid fibers yielded great outcomes and approached to that of micro steel fiber

## 5. Conflicts of Interest

The authors declare no conflict of interest.

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