Influence of Hooked-End Steel Fibers on Some Engineering Properties of SIFCON

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ABSTRACT

Slurry infiltrated fiber concrete (SIFCON) has been applied since 1979 in USA. Since it is not possible to use more than 2% of fiber in SFRC (steel fiber reinforced concrete) because of workability and mixing issues, SIFCON is applied to contain fiber amount as high as 12%.

Having higher mechanical properties in both strength and durability is an advantage of SIFCON in comparison with SFRC. In light of this advantage, this study has been carried out on fibers having length/aspect ratio of 80/60, 80/50, and 30/65 for approximate fiber amounts of 1%, 2%, 3% and 4% by the volume of concrete. Fiber orientation can also seriously affect properties of SIFCON where one can control the orientation easily. These properties are modulus of elasticity, flexural strength, stress strain behavior, absorbed energy, impact energy, and water permeability (depth of water penetration). Some of these parameters are studied in comparison with conventional concrete. At the end of this study results are analyzed to end up with optimum orientation and fiber type and volume fraction of fibers to reach admirable energy absorption capacity and durability.

Keywords: SIFCON, flexural strength, impact energy, water permeability.

ÖZ

Yüksek oranda çelik tel içeren çimento bulamacı (SIFCON) 1979 yılından beridir uygulamalarda kullanılmaktadır. Bunu ortaya çıkmasının esas sebebi ise normal çelik telli betonlarda kullanılabilecek lif oranının işlenebilirlik ve karıştırmadaki zorluklardan dolayı en çok %2 olmasındandır. SIFCON ile çelik tel oranı %12 seviyelerine kadar rahatlıkla çıkarılabilmektedir.

Mukavemet ve dayanıklılıktaki daha iyi sonuçlardan dolayı yüksek oranda çelik tel içeren çimento bulamacı (SIFCON) normal çelik telli betondan daha avantajlı duruma geçmektedir. Bundan dolayı, bu çalışmada boy/narinlik oranları 80/60, 80/50ve 30/65 olan çelik teller değişik karışım oranlarda kullanılarak (%1, %2, %3 ve %4) SIFCON üretilmiş ve hedeflenen özelliklerindeki değişimler bulunmuştur. Öte yandan çelik telin beton içerisindeki duruşu ve yönü SIFCON'un özelliklerini önemli ölçüde ekilediği bilinmektedir. Bu özellikler ise elastil modülü, çekme dayanımı, çekme şekil değiştirme davranışı, kırılma enerjisi ve su geçirgenliğidir. Yapılan çalışmada yukarıdaki özellikler kontrol betonu ile karşılaştırılmış ve optimum tel boyu/narinlik oranı ve karışım oranları bulunmuştur.

Anahtar Kelimeler: SIFCON, çekme dayanımı, kırımla enerjisi, su geçirimliliği.

To my dear Father and Mother

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I would like to express my greatest appreciation to my father, mother, sister who are the most valuable people for me on the earth. The love, support, strength, understanding, patience and guidance they have provided me throughout my life made me the person who I am.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing Materials
BS EN	British European Standard
FRC	Fiber Reinforced Concrete
LVDT	Linear Variable Differential Transformer
SFRC	Steel Fiber Reinforced Concrete
SIFCON	Slurry Infiltrated Fiber Concrete
W/C	Water to Cement ratio

LIST OF SYMBOLS

B	Bright fiber
C	Glued fiber
d	Diameter of fiber
I	Impact factor
l/d	Aspect ratio, length of fiber /diameter
L_f	Length of fiber
N	Low carbon fiber
R	Hooked end fiber
SP	Superplasticizer
V_f	Volume fraction
ΔL	Length difference
σ	Compressive strength

Chapter 1

INTRODUCTION

1.1 General

Slurry Infiltrated Fiber Concrete (SIFCON) is a type of high performance concrete in which discrete fibers are preplaced into molds either to a full capacity or desired volume fraction (V_f) rather than adding fibers to concrete mixer. It is possible to dispense fibers rather by hand or with fiber-dispensing units. Then liquid cement paste or slurry or mortar is poured on fibers to fill up the mold. During dispensing and filling molds, vibration can be held to avoid pores happen in concrete (Lankard,1985). In conventional Steel Fiber Reinfoced Concrete (SFRC) it is not easy to use fiber amounts above 1% by volume of concrete, while SIFCON method makes it possible to use fiber as high as 12%.

“Slurry Infiltrated Fiber Concrete (SIFCON) is a type of fiber reinforced concrete in which formwork molds are filled to capacity with randomly-oriented steel fibers, usually in the loose condition, and the resulting fiber network is infiltrated by cement based slurry. Infiltration is usually accomplished by gravity flow aided by light vibration or by pressure grouting” (ACI544.2R, 1987).

Typical uses of fibers in SFRC are “when it is used in structural applications, steel fiber reinforced concrete should only be used in a supplementary role to inhibit cracking, to improve resistance to impact or dynamic loading, and to resist material disintegration. In structural members where flexural tensile or axial tensile stresses will occur, such as in beams, columns, suspended slabs (i.e., not slabs on grade), the reinforcing steel must be capable of resisting the tensile stresses" (ACI544.2R, 1987).

SIFCON is advantegous in mechanical properties compared to SFRC. Differences between SFRC and SIFCON can be summerized as; higher volume fraction (V_f) of SIFCON, and absence of coarse aggregate in SIFCON. Furthermore SIFCON has got more cement and water content compred to SFRC.

Although SIFCON may seem to be expensive but it would be cost effective if we consider all structural elements and extra dead load made by larger elements. It is realized when SIFCON is viewed as a total interlated system. Application of SIFCON is quite easy and cost effective, expert labour is not needed and in fact, it has been shown that placing of the fibers and slurry can be automated in several applications. (Lankard, 1984 b)

1.2 Statement of the problem

There is not a study available on Influence of fibers especially hooked end steel fibers on properties of SIFCON such as absorbed energy, depth of water penetration and impact energy.

1.3 Works done

Applications of SIFCON has been widly used since 1980's such as explosive-resistant containers, security blast-resistance vaults, repair of structural components, bridge decks, airfield pavements and abrasive-resistance surfaces (Shah & Balaguru, 1992).Also, Various durability aspects of SIFCON has been investigated by Gilani (2007).

1.4 Objectives of this study

Objectives of this study are to demonstrate behavior of single class of concrete in flexural test by analyzing absorbed energy results obtained from third point loading and make comparative interpretations effect of parameters influencing this study such as fiber geometry (length, diameter, aspect ratio) and fiber amount. The behavior under flexural loading plays an important role in field applications. Energy impact test will be carried out on SIFCON to demonstrate effect of fibers on impact resistance. Also durability aspect of SIFCON will be analyzed based on results of water permeability test, to observe SIFCON's resistance in aggressive environment.

1.5 Guide to thesis

The following narrative covers the topics listed below:

In Chapter 1, an introduction for the thesis has been given, and previous studies consulted in the thesis described. The object and the scope of the thesis are stated.

In Chapter 2, the reader is given relevant information about a literature survey on SIFCON and its background.

In Chapter 3, material properties, mechanical properties of control concrete and apparatus and details on various tests conducted on SIFCON and control concrete are presented.

In Chapter 4, results gained from experimental studies are introduced, and compared.

In Chapter 5, conclusions and recommendation of this study will be provided.

Chapter 2

LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

In 1979, SIFCON was produced by Lankard Materials Laboratory, Columbos, Ohio, USA via large amount of steel fibers in steel fiber reinforced composites.

"Slurry Infiltrated Fiber Concrete (SIFCON) is a type of fiber reinforced concrete in which formwork molds are filled to capacity with randomly-oriented steel fibers, usually in the loose condition, and the resulting fiber network is infiltrated by cement based slurry. Infiltration is usually accomplished by gravity flow aided by light vibration, or by pressure grouting" (ACI544, 1987).

"Steel Fiber Reinforced Concrete (SFRC) is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete steel fibers" (ACI544, 1987).

The main difference between SIFCON and conventional SFRC are the following two items; first SIFCON contains larger volume fraction of fibers from 8 to 12 percentages but value up to 25 percentage have been reported. Another difference is higher strength and ductility due to fine particles in the matrix (Lee, 2003).

The fiber volume (V_f) depends upon the fiber type, i.e. length and diameter, and the vibration effort utilized to fill the form. Smaller or shorter fibers will pack denser than longer fibers, and higher fiber volumes can be achieved with increased vibration time.

2.2 Preparation

SIFCON can be considered as a preplaced fiber reinforced concrete comparable with prepared aggregate concrete. The first step to cast SIFCON is placing randomly distributed steel fibers in a mold or form. It can be placed by hand or commercial fiber dispensing units. Two parameters which specifically identify steel fibers are aspect ratio (l/d) and length. By the use of commercial steel fibers, SIFCONs from 5 to 18 percentage of fiber has been achieved (Lankard,1985).

First, steel fibers are placed in molds, as shown in Figure 1 and then slurry cement based mixture is poured on top of them with help of external vibration so that the infiltration of mortar gets complete to the steel fibers. Also fibers can be pressure-infiltrated from bottom of the molds (Lankard, 1985).

The condition of grain sizing of aggregate must be such that the minimum particles exceed the smallest opening in the packed fiber bed. If this condition does not happen the fiber will be clogged with aggregate particles and further infiltration will be impossible (Lankard, 1985). The curing procedure for SIFCON would be same as other concretes.

Figure 1 - Placement of fibers for SIFCON

2.3 Materials and mix properties

SIFCON is produced by mainly steel fibers and cement based slurry. The matrix can be from:

1. Only cement (slurry or cement),
2. Cement and sand (mortar),
3. Cement and other additives (mainly fly ash or silica fume).

For enhancing a good workability and complete infiltration of cement paste to steel fibers, superplasticizers can be used. This will be achieved without increasing the Water to cement (w/c) ratio. The effect of superplasticizers is significant on infiltration and cohesiveness of matrix.

2.3.1 Steel fibers

Many different types of fibers have been investigated for SIFCON (Lankard, 1985). To maximize the bond and mechanical anchorage of steel fibers and cement paste, fibers can be changed along their length by mechanical deformations or by roughing the surface. Hooked and crimped fibers are mostly used in case of SIFCON. Surface deformed and straight fibers are less common (Homrich, 1987 ; Balaguru, 1992. ; Mondragon, 1987 ; Reinhardt, 1989).

The steel fibers are defined short with aspect radio (l/d) of 20 to 100 with variety of cross sections. Four classes of steel fibers defined by ASTM (ASTMA820) are the following;

- Type I Cold-drawn wire.
- Type II Cut sheet.
- Type III Melt-extracted.
- Type IV Other fibres (Figure 2). (ACI544, 1987)

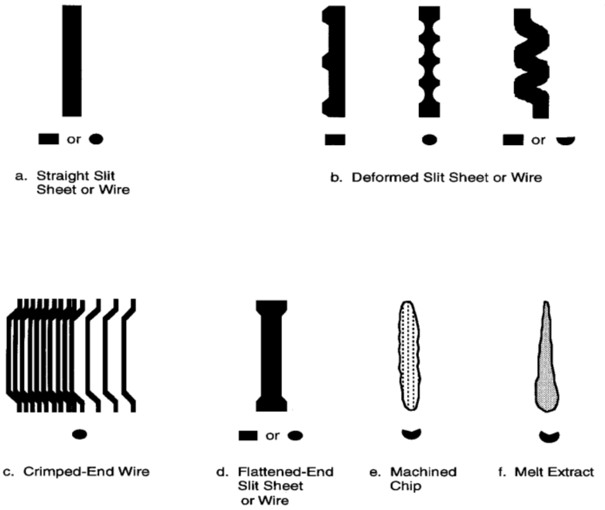


Figure 2 - Various steel fiber geometric

For SIFCON in most of the times cross section of fibers are circular, other types are rectangular, square or flat. Most common steel fibers are from 26 mm to 60 mm and diameter varies from 0.4 mm to 1 mm, and the common range of aspect ratio is 40 to 80 (Naaman, 2003).

2.3.2 Fiber properties

Important parameters for fibers are stiffness, fiber strength and ability of fibers to bond with concrete. Bonding of fibers with concrete is dependent to aspect ratio. Aspect ratio is the ratio of length to diameter of the fiber. Diameter may be equivalent diameter.

Equivalent diameter is the diameter of a circle with an area equal to the cross-sectional area of the fiber. For SFRC, equivalent fiber diameter, d, is calculated by equation 1: (Lankard, 1985)

$$d = f[\frac{D}{\text{SG}}]^{\frac{1}{2}}$$

[1]

Where:

f = 0.0120 for d in mm

f = 0.0005 for d in inches

D = fiber diameter

SG = fiber specific gravity

Normal range of aspect ratio is from 20 to 100 and length dimensions vary from 6.5 to 76 mm.

Steel fibers enhance high strength and modulus of elasticity. They can be protected by alkaline environment of cementitious materials from corrosion. The bond of fibers to concrete can be achieved by mechanical anchorage and surface roughness. Long term loading does not have negative effects on mechanical properties of SIFCON. In high factory refractory applications fibers can be helpful. The behavior of fiber in high temperature will be different due to amount of fibers (Lankard, 1985).

Minimum tensile strength and bending requirements and tolerance for length, diameter and aspect ratio are offered by ASTM (ASTMA820), minimum amount for tensile yield strength is 345 MPa. (Lankard, 1985)

2.4 Matrix of SIFCON

Practically, SIFCON does not contain coarse aggregate and the reason why SIFCON does not contain coarse aggregate is that coarse aggregates will not possibly pass through tiny spaces of fibers. The matrix contains cement, cement-sand, cement fly-ash, , cement silica fume, cement sand fly, cement sand fly ash, cement sand silica fume (Homrich, 1987 ; Balaguru, 1992. ; Naaman, 2003 ; Kosa &Naaman, 1991 ; Hamza 1992 ; Wood, 2000 ; Doğan, 1998). Fly ash and silica fume will improve shrinkage disadvantages of the matrix (Shah & Balaguru, 1992.). Also silica fume increases the strength and on the other hand, fly ash causes decrease in strength

(Mondragon, 1987). The results obtained showed that by increasing sand content, compressive strength could increase (Sonebi, 2005).

2.5 Mix proportions

Variables in SIFCON are fiber content and matrix composition. By placement technique, fiber geometry and fiber volume fraction is controlled. Suitable w/c ratio for SIFCON is 0.4 or less. If there is a need for more flowability, superplasticizers can be used to guarantee the infiltration of cement paste through fibers and avoiding honeycombs in concrete. Fine sand less than 0.5 mm is recommended to be used in SIFCON (Lankard, 1985 ; Homrich, 1987 ; Lankard,1984).

In the case of fly ash usage, it can be replaced by 20% of cement. When Silica fume is used recommended dosage is 10% of by weight of cement. Type I and Type III (ASTM) cements can be used (Shah & Balaguru, 1992.). Table 1 shows mix design from the literature by weight of cement.

Table 1 - Some SIFCON slurry mix designs from the literature (by weight of cement)

SIFCON Composition				
Cement(1)	Fine sand	water	Fly ash(2) or silica fume	SP
1	0.2	0.355	0.20	0.020
1	0.3	0.255	0.20	0.040
1	-	0.300	0.10	0.048
1	2.0	0.600	-	Not reported
1	-	0.360	-	0.030
1	-	0.500	-	-
1	1.0	0.600	0.20	Not reported
1	0.8	0.530	0.20	Not reported
1	0.6	0.450	0.20	Not reported
1	-	0.360	0.20	Not reported
1	1.0	0.400	-	0.013
1	1.0	0.320	-	0.035
1	1.0	0.480	0.20	0.020
1	-	0.360	0.20	0.030
1	-	0.325	0.25	0.040
1	1.5	0.400	0.20	0.010
1	1.0	0.320	0.20	0.020

1	-	0.360	0.20	0.030
1	-	0.325	0.25	0.040
1	1.5	0.400	0.20	0.020
1	1.0	0.320	0.20	0.020
1	0.5	0.240	0.20	0.030
1	1.0	0.450	-	0.032
1	0.9	0.500	0.30	0.024

(1) In all references, Type I Portland cement was used, except for references 6 and 11 where Type III was used.
(2) In all references Fly ash was used, except for reference 6 where silica fume is used.

2.6 Engineering and mechanical properties of SIFCON

2.6.1 Unit weight

Comparing to normal FRC and concrete, SIFCON has higher unit weight. As an example, slurry with unit weight of 1920 kg/m^3 will have more density from 2160 kg/m^3 to 3130 kg/m^3 by 5% to 20% by volume of steel fibers. Figure 3 shows that the increase of unit weight is directly affected by the amount of steel fibers (Lankard, 1984).

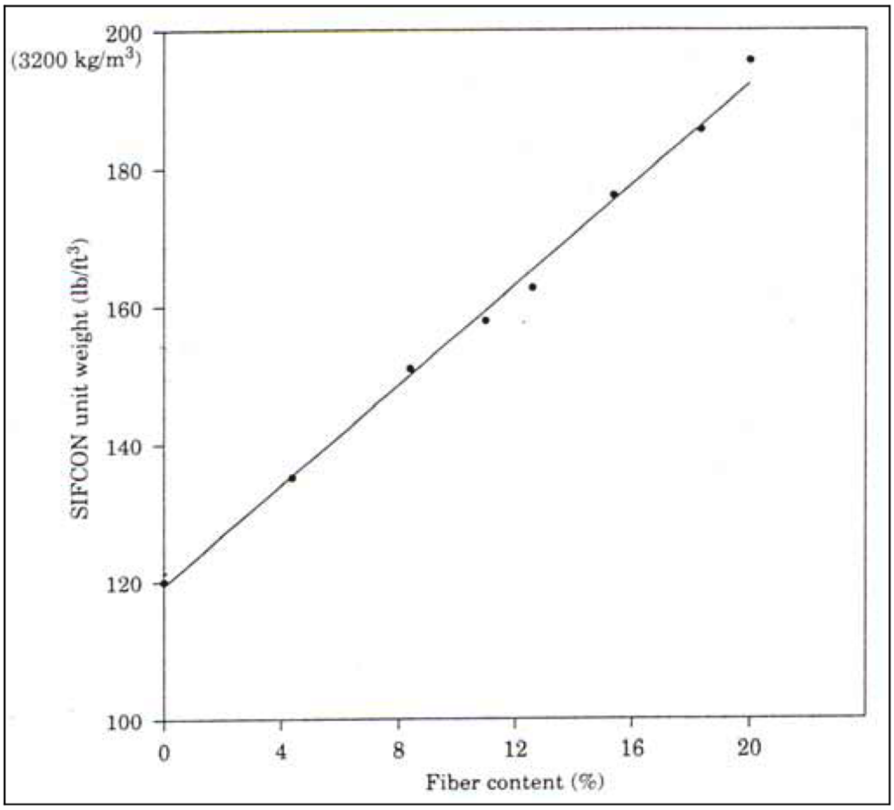


Figure 3 - Effect of fiber amount of unit weight

2.6.2 Behavior in compression

SIFCON has got high compressive strength characteristics. The highest compressive strength achieved for SIFCON is 210 MPa. Test has been done on cast and cored cylinder and variables were:

a) Fiber orientation effect (parallel and perpendicular to the loading axis)
b) Fiber geometry (hooked ends, crimped and deformed)
c) Matrix composition (plain cement matrix, matrix containing sand or fly ash, silica fume, or their combinations)

Results from these experiments are summarized by the following:

2.6.2.1 Compressive strength

Parameters influencing compressive strength are; mix design, matrix strength, fiber orientation, fiber volume fraction and fiber geometry. Tensile strength of fibers does not have any effect on compressive strength because fibers themselves don not break. Range of compressive strength obtained by different mix designs is shown in Table 2 and also it shows properties of steel fibers in experiment (Homrich, 1987).

Compressive strength depends on fiber orientation, content, type and dimensions.

Table 2 - Reported slurry mix designs and strength values

Mix Constituents	**Relative Weight of Constituents**	**W/C(1)**	**Strength Range (MPa)**
Type I cement	1.000	0.30	52 To 117
Fly ash	0.200		
Water	0.260		
SP	0.030		
Type I cement	1.000	0.35	41 To 86
Fly ash	0.200		
Silica slurry (2)	0.200		
Water	0.300		
SP	0.255		

Type I cement	1.000	0.30	41 To 86
Fly ash	0.200		
Silica slurry[(2)]	0.300		
Water	0.255		
SP	0.040		
Type I cement	1.000	0.26	69 To 121
Fly ash	0.250		
Water	0.325		
SP	0.040		

(1) W/C is water/cementations materials ratio including fly ash and silica.

(2) A slurry of approximately 50 % water and 50 % amorphous silica particles by weight.

Strength of SIFCON can be twice as that of plain concrete. Obviously increasing strength of matrix can increase strength of SIFCON. The effect of fiber geometries is less than matrix strength. When fibers are perpendicular to loading axis the compressive strength of SIFCON is higher (Gilani, 2007).

Figure 4 shows the effect of w/c ratio on compressive strength of SIFCON (Fritz & Reinhardt, 1989). Fibers of this study were 30 mm long with a diameter of 0.5 mm which made reinforcing index (V_f*l/d) equal to 700 and all mixes had 11.6% volume fraction.

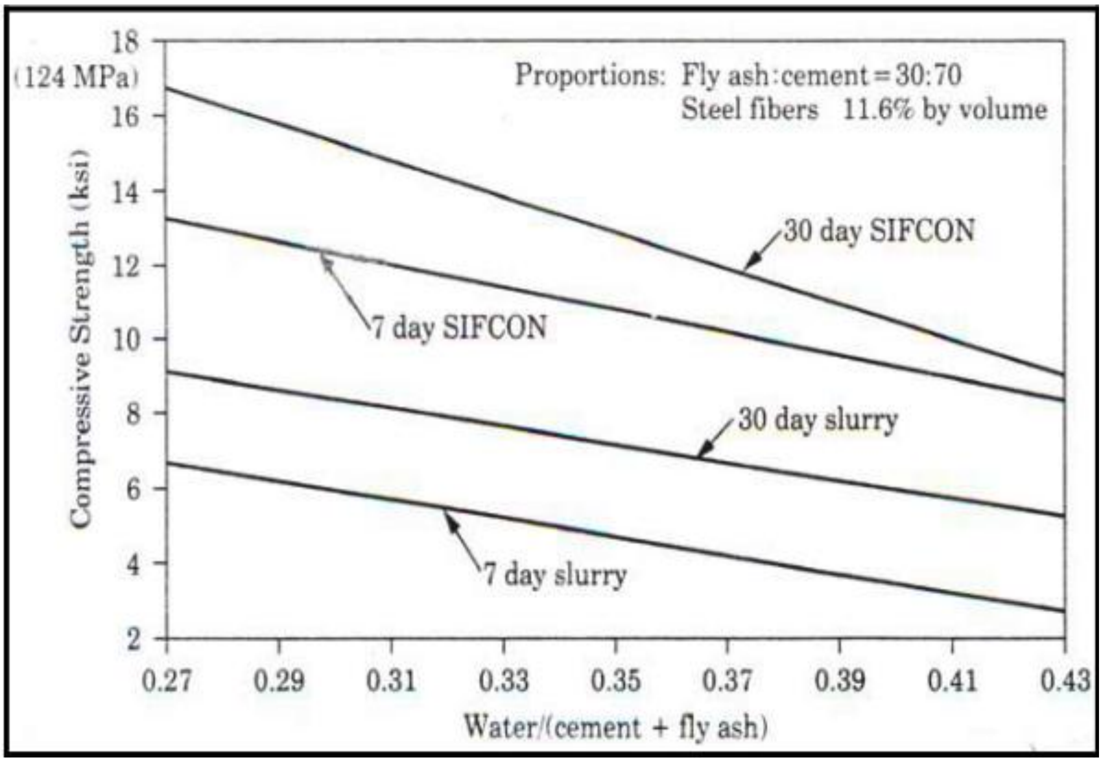


Figure 4 - Compressive strength vs. water/binder ratios

From Figure 4 it can be obtained that composite compressive strength is influenced by matrix strength. By using lower w/c ratio or lower fly ash content a higher strength matrix can be obtained. As the age of concrete increases higher strength will be obtained because of matrix matures.

Table 3 - Reported fiber properties

Fiber Type	Length (mm)	Diameter (mm)	Aspect Ratio, (l/d)	Volume Fraction, V_f (%)	Reinforcing Index, (V_f.l/d)
Crimped	25	0.9	28	20 to 23	560 to 644
Hooked	30	0.5	60	10 to 12	600 to 720
Deformed	30	0.5	60	10 to 12	600 to 720

The failure mode of SIFCON is shear failure. The size of cylinders for this study is 7.62×15.24 cm with l/d of 2. Longer specimens with l/d of 4 had shear failure as well (Homrich, 1987).

SIFCON can be characterized as a high ductile and high strength material. Ultimate flexural strength of 27 MPa to 69 MPa and compressive strength of 103 MPa to 207 MPa can be achieved by using fiber amount of 5 to 18 Percent (Lankard, 1984b).

The load-deflection behavior of SIFCON and conventional SFRC has been compared in Figure 5. As it can be seen, SIFCON can carry out almost 4 times more load than normal SFRC (Lankard, 1984a).

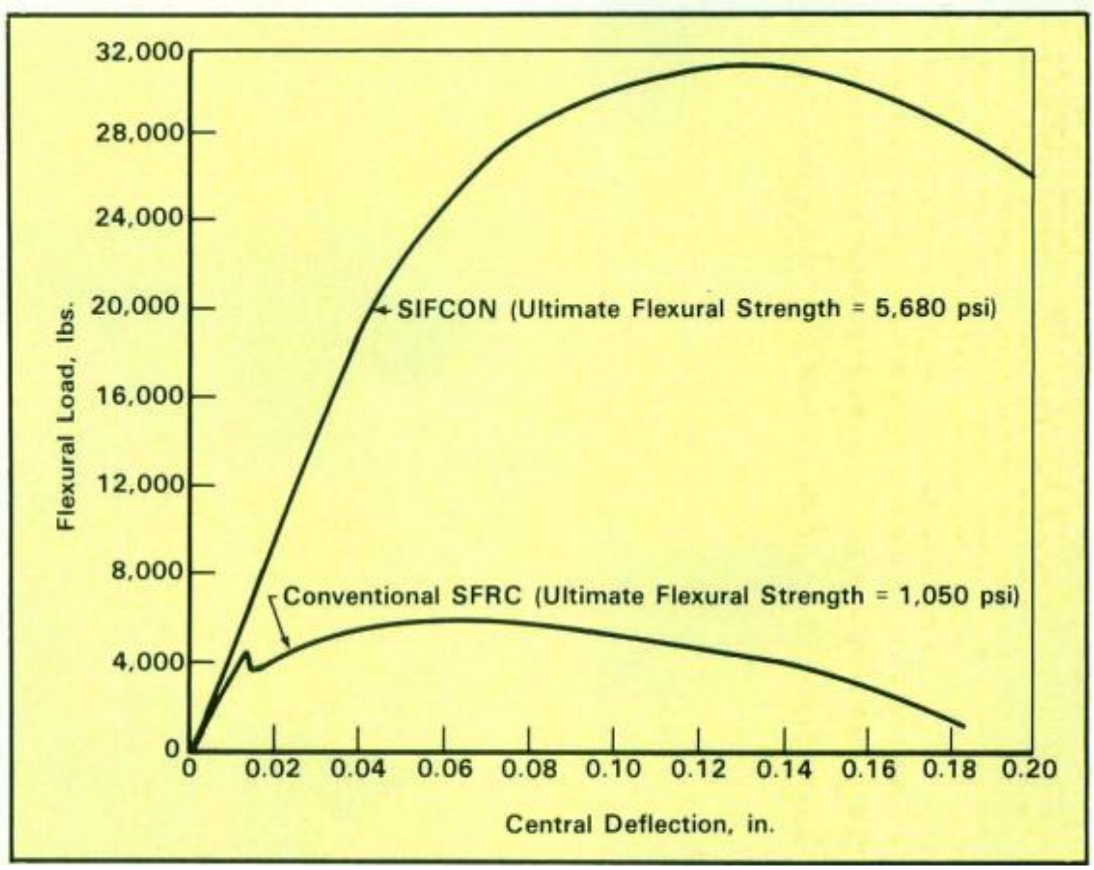


Figure 5 - Flexural load behavior of SIFCON

In Figure 5, the load deflection in compression for cylinder specimen with steel fiber of 12 percent has been compared to a conventional SFRC concrete.

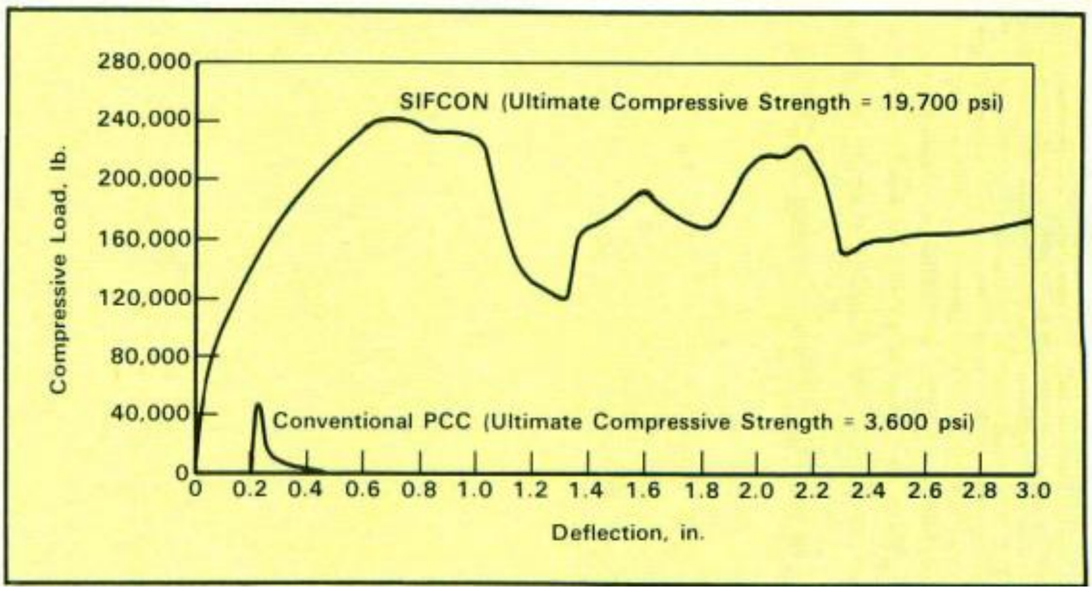


Figure 6 - Uniaxial compression load of SIFCON and conventional steel fiber

Most of the studies on mechanical properties of SIFCON have focused on compressive strength and bending stress. The following are summaries obtained by these studies:

1. Compressive strength of SIFCON can be up to 140 MPa, while the compressive strength of normal concrete is up to 20 MPa. By use of additives such as fly ash, silica fume and admixtures higher compressive strength can be achieved.
2. The area under compressive load deflection test of SIFCON is 50 times more than unreinforced concrete. Strain capacity of SIFCON is 10 percent more in high stresses.
3. The tensile stress reported for SIFCON is 41 MPa and tensile strain close to 2 percent has been achieved.
4. For SIFCON, the area under tensile load deflection curves is 1000 times more than unreinforced concrete.
5. Reports show the bending module of rupture up to 90 MPa for SIFCON.
6. Reports show shear strength more than 40 MPa for SIFCON (ACI544, 1987).

Figures 8 and Figure 9 are examples for stress-strain behavior of SIFCON.

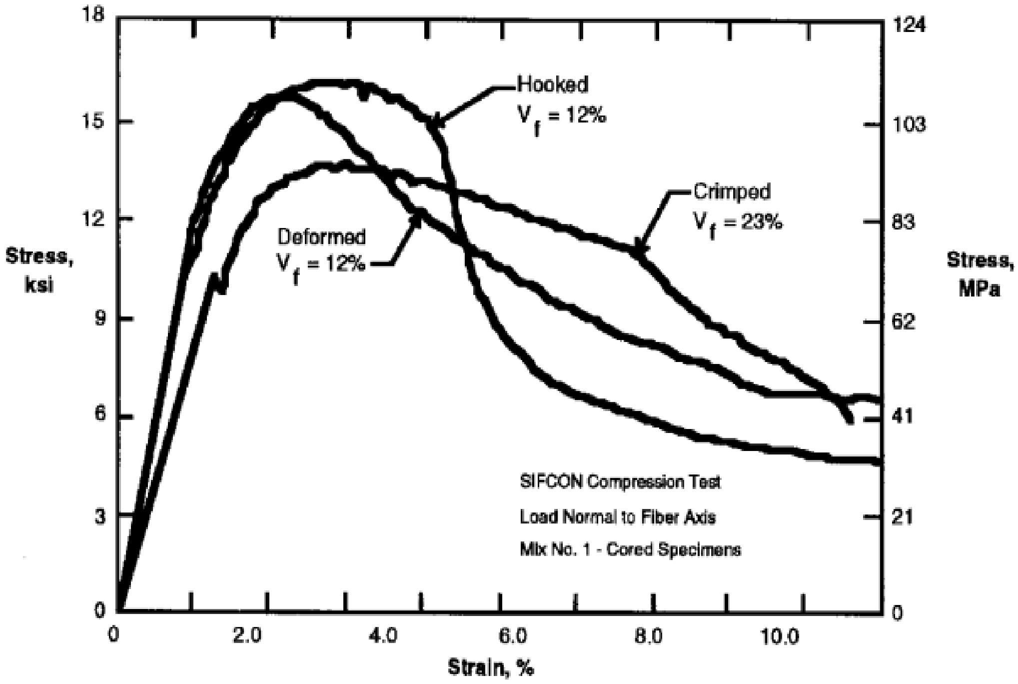


Figure 7 - Typical effects of fiber type on stress-strain curve of SIFCON in compression

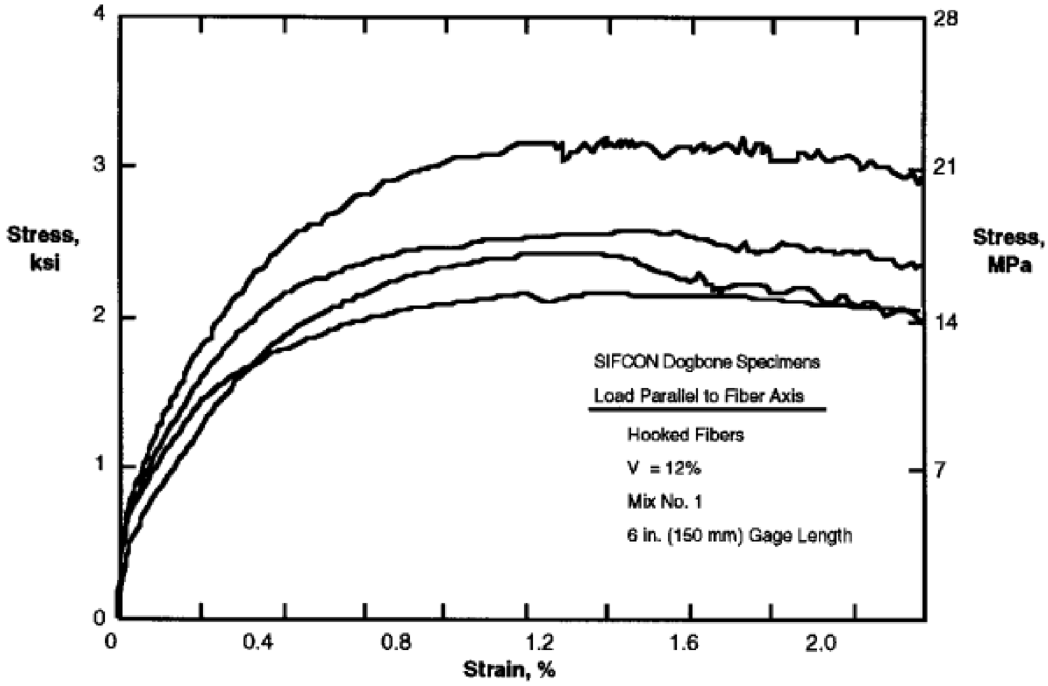


Figure 8 - Tensile stress-strain response of hooked fiber

2.6.3 Behavior under flexural loading

In most field applications, SIFCON is subjected to bending stress, at least partially. Hence, the behavior under flexural loading plays an important role in field applications. Flexural tests have been conducted using SIFCON beams both under static and cyclic loading (Lankard, 1984a). The investigations were designed to evaluate the various fiber lengths, types, contents, and matrix compositions. The typical load-deflection response is shown in Figure 9. The study dealt with 19 mm thick SIFCON beam specimens cut from a slab with a 76 mm width and 356 mm length.

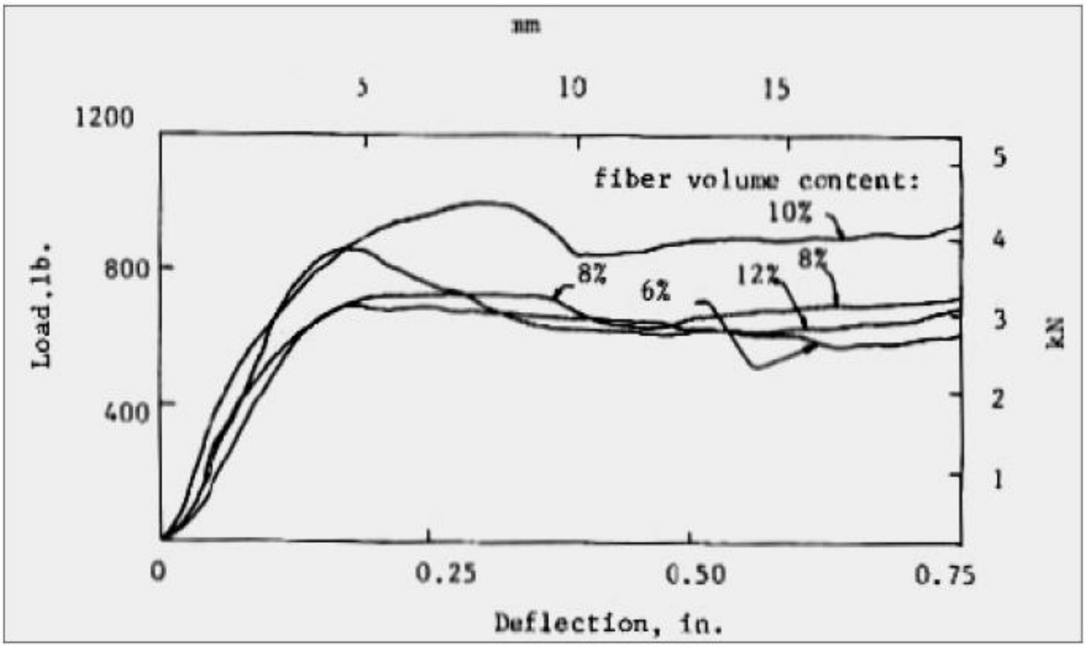


Figure 9 - Load-deflection curves in flexure for hooked-end

2.6.3.1 Flexural strengths

Table 4 represents the flexural strength of four fiber lengths and various fiber contents. In all cases, the slurry was made of cement +10% silicafume with a w/c ratio of 0.3. Amount of super plasticizer was 4.8% by weight of cement. The flexural strength was computed using the average maximum load of three specimens

Figure 11 presents the variation of flexural strength for different fiber contents and lengths. The study leads to the following observations. (Shah & Balaguru, 1992.)

Table 4 - Flexural strength of SIFCON

Fiber (length/dia.) (mm/mm)	Fiber Volume (%)	Maximum Flexural Strength (MPa)
30/0.5	6	55.2
	8	61.8
	10	91.9
	12	62.7
40/0.5	4	46.9
	6	67.7
	8	75.4
	10	76.5
50/0.5	4	36.5
	5	58.8
	6	78.6
	8	73.7
60/0.5	5	49.6
	6	53.7
	8	72.1
	10	63.4

a) The flexural strength of SIFCON is an order of magnitude greater than the flexural strength of normal fiber-reinforced concrete.

b) For a constant fiber length, the flexural strength increases with the volume fraction of fiber only up to a certain limit. After certain fiber content, the bond strength decreases because of the lack of matrix in between the fibers, thus reducing the flexural strength. The optimum fiber content seems to be in the range of 8% to 10%.

c) The optimum fiber volume seems to decrease with an increase in fiber length. For the same fiber volume, longer fibers provide a slight increase in flexural strength.

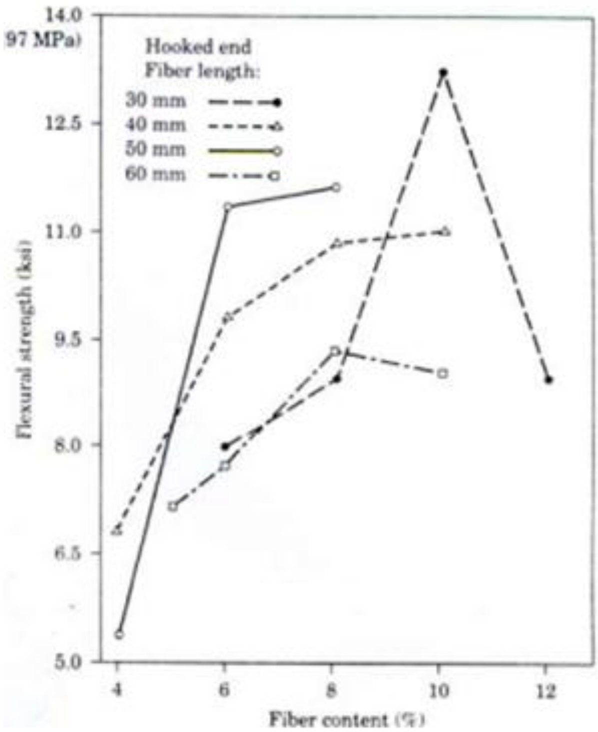


Figure 10 - Flexural strength versus fiber contents

2.6.3.2 Load-deflection behavior in flexure:

The load-deflection behavior of a SIFCON shown in Figure 10 is quite different from the load-deflection behavior of typical FRC beams. The curves have a relatively short linear elastic response and a considerable plateau at the peak. The beams can also sustain a high percentage of peak loads (more than 80% of peak load) even at large deflections. Figure 11 shows a comparison of the load deflection curves for a SIFCON specimen, a fiber reinforced concrete specimen, and a plain concrete specimen. While fiber length and fiber volume fraction influence strength, the ductility is not affected by either of the variables as shown in Figure 11.

Figure 12 presents the comparison of load-deflection behavior for specimens made with and without silica fume. All specimens had 8% fiber content. As can be seen from this figure, the use of silica fume increases the flexural strength, and hence the toughness substantially. This increase can be explained by the fact that the silica fume results in a much denser matrix.

The increase in the matrix density possibly provides as much improvement in bond between the matrix and the fiber as in the compressive strength. The predominant failure pattern is by the pulling out of the fibers.

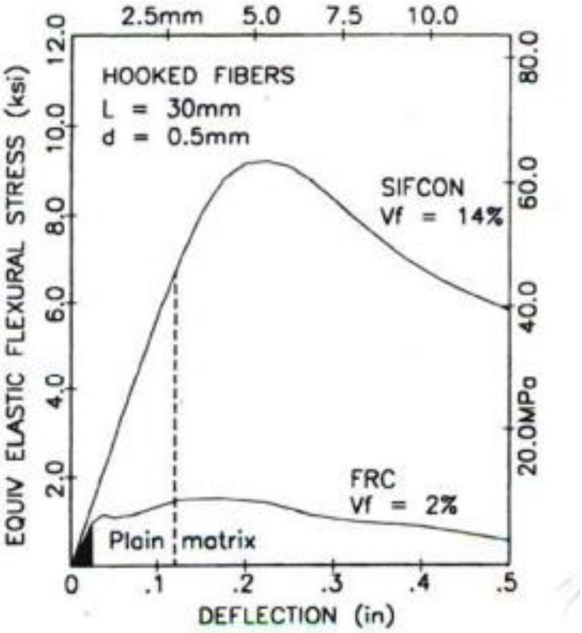


Figure 11 - Comparison of load-deflection curves for SIFCON with FRC

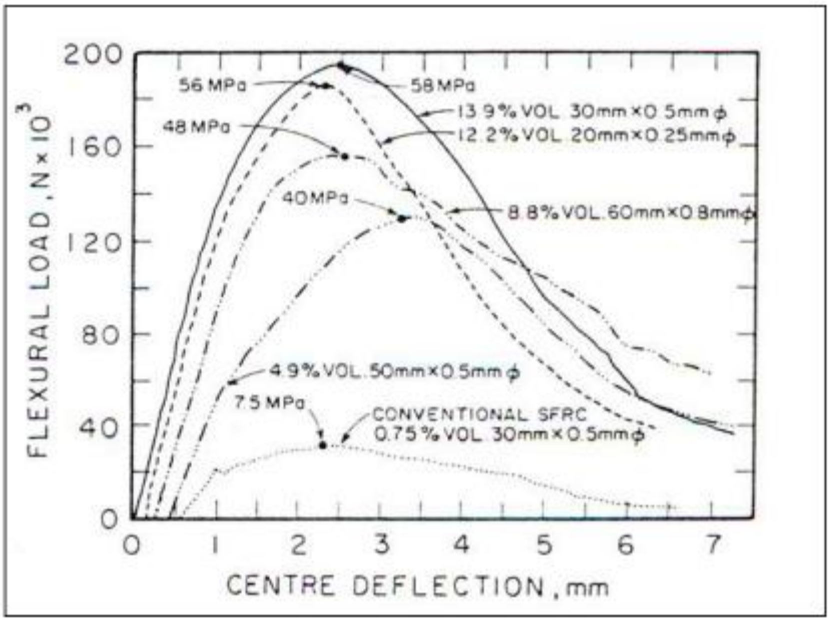


Figure 12 - Effect of fiber content on SIFCON

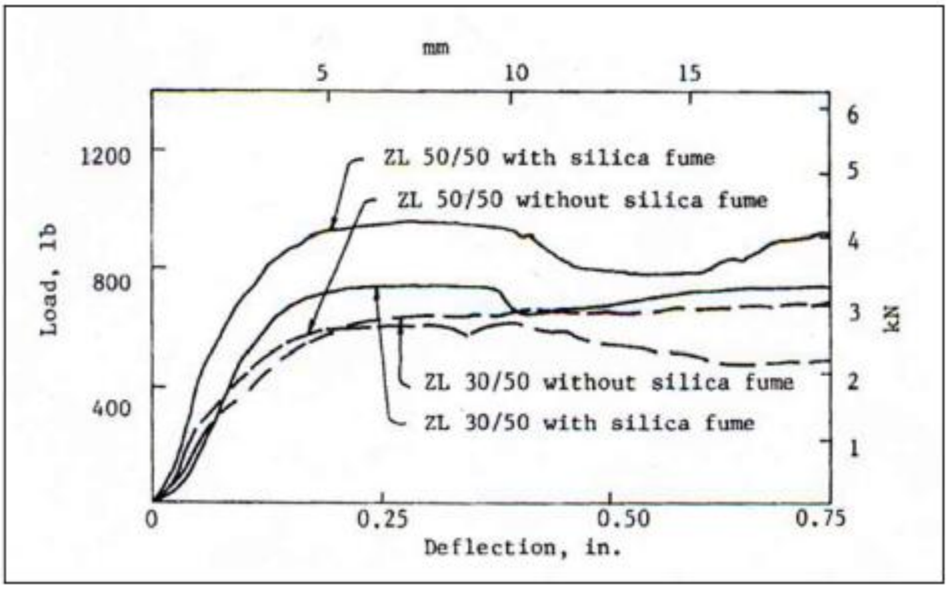


Figure 13 - Comparison of load-deflection behavior of Specimens with and without Silica fume

2.7 Applications of SIFCON

SIFCON is rather new material which is used mostly in areas where high ductility and high strength are needed at the same time. For instance, earthquake resistance structures, military installations, explosive resistance structures, airport pavement parking lots and bridge decks are some of these applications. The following are some applications of SIFCON from different literature.

2.7.1 Repair and retrofit of structural components

Because SIFCON is compatible with reinforced concrete in terms of stiffness and dimensional changes it is known as one of the best repair materials. It can be used in hard-to-reach places and fibers make excellent bond between old and new concrete. Depending on type of repair different methods can be taken, like rapid strength can be gained by accelerators (Shah & Balaguru,1992).

In New Mexico, USA, SIFCON has been applied to repair prestressed concrete beams spanning a highway (Doğan, 1998).

2.7.2 Precast concrete products

Precast slabs, small vaults and cast pipe section have been made from SIFCON (Lankard, 1984; Shah & Balaguru, 1992). This slabs made from SIFCON have been used in airport taxiways and the reports have shown that SIFCON precast slabs had been under load of Boeing 747 for maintenance period of one year (Lankard, 1984).

2.7.3 Explosive-resistant structures

High flexural, high strength and excellent ductility are parameters which make SIFCON suitable for structures with explosive loading. For containers which store ammunition SIFCON have been used. It can limit the explosion from container to container (Lankard,1984).

New Mexico Research Institute has used SIFCON as a material of construction for missile silo. Figure 14 shows schematic diagram of a hardened silo.

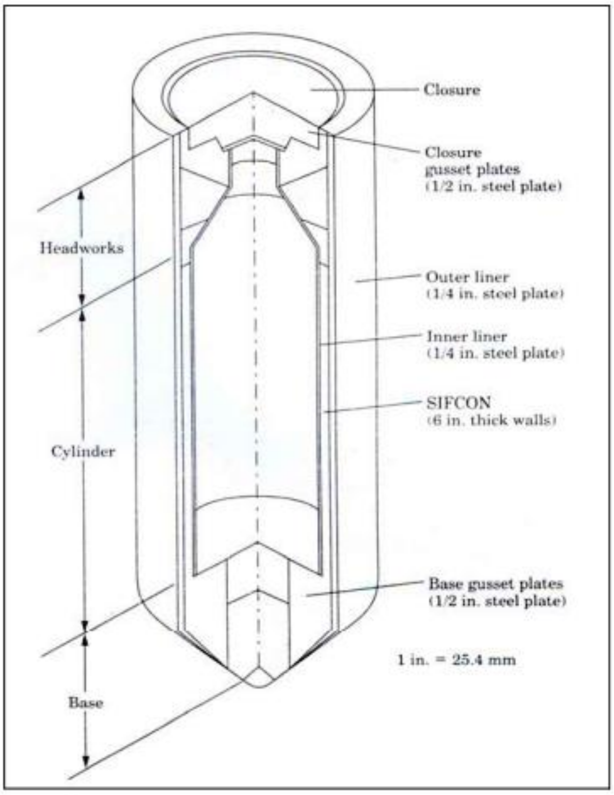


Figure 14 - Schematic diagram of a hardened silo

The silo made from the method explained had shown an excellent resistance (Schneider, 1984).

2.7.4 Security applications

For vault doors and safes, SIFCON has been used because of excellent resistant for blasting, drilling and chipping. Steel walls can be torched and concrete walls can be blasted or drilled, so both of them have got disadvantages. But SIFCON has got the advantage to resist deterioration by heat and slow down the head conduction. Because the composite has got high ductility, it can resist through blast. Chipping and drilling of SIFCON is not easy because of the fiber intrusions. Before infiltration with cement-based slurry the preplaced fibers were mixed with clean coarse aggregates and the mix was special type of SIFCON (Balaguru, 1992).

2.7.5 Pavement and bridge deck overlay

SIFCON have been used for bridge rehabilitation projects (Lankard,1983). First the area to be repaired is chipped off and cleaned thoroughly then the fibers are placed in position and infiltrated with slurry. In most projects, the infiltration is only done by gravity. In special applications, a thin layer of coarse aggregate were placed on the surface of the still fresh SIFCON and toweled into place to form a wearing surface. The repaired sections had excellent performance after more than 6 years of repair work.

2.7.6 Refractory applications

The concept of SIFCON has been also successfully used for refractory applications. Precast SIFCON elements should be used in these high temperature applications using stainless steel fibers and slurries based on calcium aluminate cement matrix. The applications included seal plates, tubes used in the pressure casting of metals, plunging bells and lances for steel desulfurizing, furnace lintels and saddle piers

(Lankard, 1984a). SIFCON composites provide excellent resistance to spalling under high temperature, thermal shock conditions and under conditions of high mechanical abuse.

Chapter 3

EXPERIMENTAL STUDY

3.1 Introduction

The main objective of this dissertation is studying the simultaneous effects of various geometric parameters of fibers (fiber types) and amounts of steel fiber on flexural behavior of SIFCON and control concrete. Also there are some durability issues like water permeability and energy absorption which are investigated accordingly.

In this study hooked end steel fibers having length/aspect ratio of 80/60, 80/50 and 30/65 were used for fiber amounts of 1%, 2%, 3% and 4% by volume of concrete then results were compared with control concrete. The experimental program involved conducting tests relevant with the durability aspects stated above on SIFCON and control mix. Each SIFCON was prepared by four hooked end fibers, with volume fractions of 1%, 2%, 3% and 4% and length/aspect ratios of 80/60, 80/50 and 30/65. For all the tests, comparative interpretations were made within each SIFCON, as well as with a control concrete aimed to have low permeability. Hence, the effects of the following parameters on SIFCON durability were investigated:

a) SIFCON (in comparison with control concrete)

b) Fiber contents (V_f)

c) Fiber types (fiber geometry)

3.2 Materials

SIFCON and control concrete with a w/c ratio of 0.65 in order to have high slump of 95 mm were used. OPC (Ordinary Portland Cement), limestone crushed (fine) aggregates and hooked end steel fibers were used to make SIFCON.

The properties of these materials are presented in the following sections.

3.2.1 Cement

The cement used for making concretes for this study was Ordinary Portland Cement which corresponds to ASTM C 150 Type I cement. Some properties of the cement used are listed in Table 5. All the results meet the requirements of ASTM C150 (ASTM-C150, 2002).

Table 5 - Chemical analysis of the cement used in the study

Oxide	**SiO_2 (%)**	**Fe_2O_3 (%)**	**Al_2O_3 (%)**	**CaO (%)**	**MgO (%)**	**SO_3 (%)**	**Alkali as Na_2O (%)**	**Chloride Content (%)**	**Densi ty**	**Specifi c surface area (cm_2/g)**
Content	21	3.4	5.9	64.7	0.9	2.6	0.4	0.004	3.15	3519

(*) The analysis was determined in accordance with (ASTM-C114)

3.2.2 Steel fibers

Trials were made in preliminary stages of research in order to choose the appropriate fiber types. For example, it was found that using fibers glued in bundles is not applicable for SIFCON. Fibers used in making SIFCON have to be in a loose state (single or discrete) in order for the mixture to infiltrate the fiber bed without clogging.

Figure 15 - Fibre types used in this study

Therefore, glued fibers had to be dissolved and separated from each other before placing them into the molds. The dissolving process by hot water was time consuming and impractical, but it had to be carried out to complete the investigation.

In addition, it was more helpful to choose fibers that make significant characteristics which will help to understand the effect of aspect ratio on properties of fiber easier. So, different fiber lengths of 30, 50 and 60 mm were chosen. The fibers had hooked end from Bekaert Company as shown in Table 6. The volume fractions of fibers (V_f) are calculated based on the density of steel fibers which is taken as 7800 kg/m ^{3} (ACI544, 2002).

Table 6 - Specifications of steel fibers used in the experimental work (Provided by the manufactures)

Fiber brand name	Shape	Length, l (mm)	Diameter, d (mm)	Aspect ratio, l/d	Tensile strength (MPa)	Fiber Volume (%)
RC80/60BN	Hooked-end (Dramix)	60	0.75	80	1050	1, 2, 3, 4
RC80/50BN	Hooked-end (Dramix)	50	0.62	80	1270	1, 2, 3, 4
ZP305	Hooked-end (Dramix)	30	0.55	65	1345	1, 2, 3, 4

Table 7 - Characteristics of fibers in this study

Characteristics	Explanation		
	Dramix RC80/60BN	**Dramix RC80/60BN**	**Dramix ZP305**
R	Hooked-end		
C	Glued fiber		
B	Bright		
N	Low carbon		
Length (mm)	60 mm	80 mm	30 mm
Diameter (mm)	0.75 mm	0.62	0.55
Aspect ratio	80	80	
Tensile strength (MPa)	1050 MPa	1270 MPa	1345 MPa
Coating	None	None	None
Number of fibers/kg	4600	8100	16750

3.2.3 Aggregates

Limestone crushed aggregate were used for this study. One size of crushed stones was used as aggregates for preparing concrete mixtures. The aggregates had a nominal maximum particle size of 5 mm.

3.2.4 Mixing water

The water used in all investigations was drinkable water available in Materials of Construction Laboratory of Civil Engineering Department, EMU. It is drinkable, clear and apparently clean, and does not contain any substances at excessive amounts that can be harmful for making concrete.

3.3 Preparation and casting of test specimens

3.3.1 SIFCON specimens

The first step in preparing SIFCON is placing the fibers into the molds, up to the pre-calculated volume fraction. No vibration was imposed during fiber placing for the specimens with a volume fraction f 1% to insure filling the molds without large voids, while a light vibration was applied in the case of 2% volume fraction, and the vibration was relatively intense in the case of the maximum 3% and 4% volume fraction to ensure filling the mold (Figure 16) with the required amount of fibers. The vibration was externally applied using a vibrating table.

Figure 16 - Filling molds with mortar

The weight of steel fiber to be put in the mold was decided to be as the following (Table 8):

Table 8 - Fiber amounts used in the study

Fiber amount (percent by volume of concrete)	**0**	**1**	**2**	**3**	**4**
kg per m^3	Control	29.6	44.4	74	103

After being filled with steel fibers up to the required volume fraction, the molds were filled with the slurry or mortar matrix which had to be flowable enough to ensure complete infiltration through the dense beds of fibers in the mold. Usually, vibration during matrix placing was necessary to avoid honeycombing or voids.

The mixing procedures for slurries (pastes) and mortars were in accordance with the requirements of ASTM C 305 (ASTM-C37, 2002).

3.3.2 Control concrete

Mixing of control concrete was done in a sequence that allowed sufficient time for thorough mixing of all the constituents. The concrete mixture was prepared in about 5 minutes mixing time with a rotating planetary mixer of 150 kg capacity. The utilized mixing procedures were as follows:

a) Firstly aggregates and cement were mixed in the mixer for about 2 minutes.

b) Then amount of required water was added to the mix and they were mixed for about 5 minutes.

In Table 9, proportions of concrete which used for SIFCON and control concrete are shown.

Table 9 - Proportions of concrete used in study

Materials	**Cement**	**Water**	**Sand**
Proportion	1:1	1:0.65	1:5.36

3.4 Experimental tests

Results obtained from compressive strength 28 days curing of conventional matrix in accordance with BS EN 12390-3 (2002) demonstrated compressive strength (σ_c) of 52 N/mm^2 for concrete used in the study.

Afterwards, a series of tests related to durability were performed on SIFCON specimens, and the results were compared with each other, and with the reference concrete. This set of tests included:

(a) Impact energy test,

(b) Depth of penetration of water under pressure.

The following sections discuss the details of the above mentioned tests.

3.4.1 Mix proportions

Table 10 demonstrates the mix properties by weight. W/C ratio was kept constant for all mixes. Because of the reason that, the matrix already had good workability, there was no need for using any chemical admixture.

Table 10 - Mixture proportions

Material	**Cement (kg)**	**Water (kg)**	**Sand (kg)**
Amount (per cubic meter of concrete)	346	225	1854

For 1% fiber volume fraction, there was not a necessity for long vibrating time and vibration of 1 minute seemed to be enough, while for 4% fiber volume fraction, vibrating time was kept more than other percentages and after 3 minutes of vibration time it seemed that time was sufficient for full compaction.

3.4.2 Flexural test

For specimens with size of 100×100×500 mm, flexural test was conducted on SIFCON and control concrete. Third point loading method of flexural strength test was performed in order to determine the flexural strength of specimens. The test was followed according to ASTM C78 (ASTM-C78, 2011). A constant deformation rate of 0.05 mm/min in accordance with standards (ASTM-C1609, 2010) was applied. The span length of the beams tested was measured to be 390 mm. The mid-span deflections of the test beam were measured by using two LVDTs (one on each side), and the average of the measurements represents the true net mid-span deflections. A yoke was used in the flexural strength test in order to eliminate the extraneous settlements of the supports so as to record only the net beam specimen deflection (Alyousif, 2010). The arrangement of the flexural strength test apparatus is shown in Figures 17, 18, and 19.

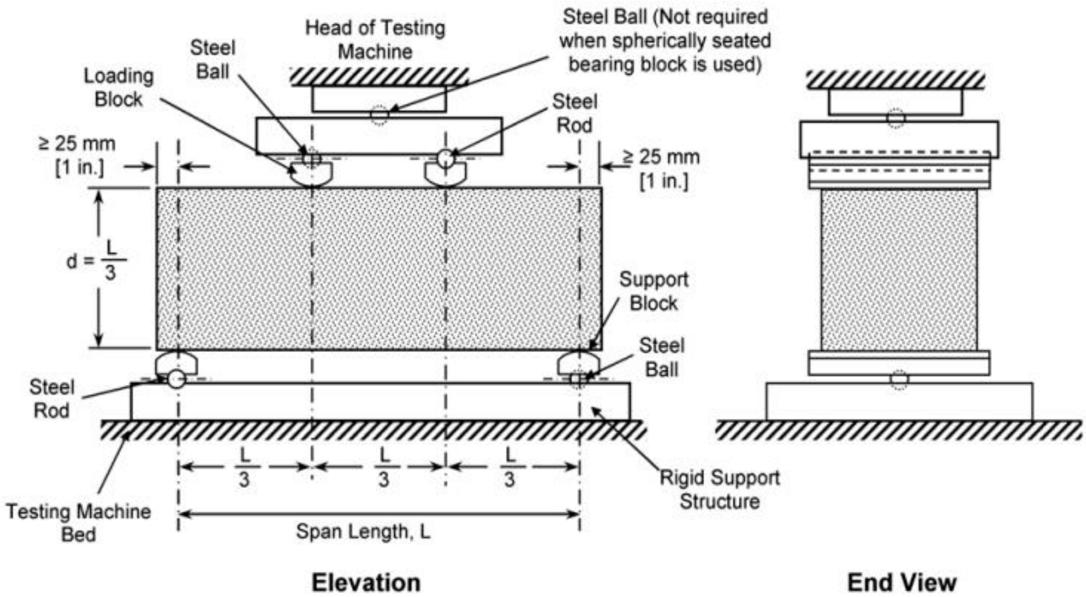


Figure 17 - Schematic diagram of a suitable apparatus for flexure test of third-point loading method

Calculation for module of rupture is as given below.

$$R = \frac{PL}{bd^2}$$ [2]

Where;

R = modulus of rupture in MPa [psi],

P = maximum applied load indicated by the testing machine in N [lbf],

L = span length in mm [in.]

b = average width of specimen in mm [in.], at the fracture,

d = average depth of specimen in mm [in.], at the fracture.

NOTE - The weight of the beam is not included in the above formula.

Figure 18 - Flexural third point test apparatus

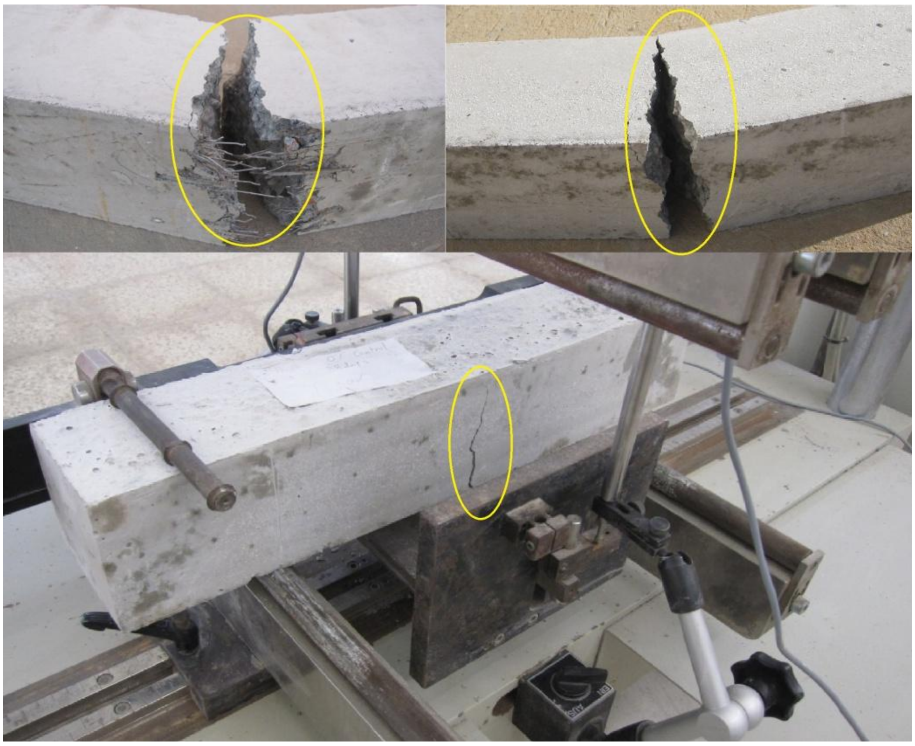


Figure 19 - Sample of beam for control concrete and SIFCON

3.4.3 Impact energy test

The test was conducted on 150 mm diameter and 60 mm length cylinders which were cut from cylinders having 150 mm diameter and 300 mm length. At 28 days impact energy test was done. Drop weight type impact test machine was used in accordance with method developed before by Eren et al. (1999). This machine (Figure 20) was a combination of aggregate impact value test machine and drop weight type test apparatus recommended by standards (ACI 544, 1987). The drop hammer for this test weighs 13.5 kg, and it is dropped from a height of 380 mm each time. Three cylinders were tested at 28 days age, and number of blows required to cause the first visible crack and ultimate failure was recorded. First crack is defined as the first visible crack. Ultimate failure is reached when the cracks have opened sufficiently to make the specimens touch each of the four positioning lugs at the base plate (Eren, 1999;(Alyousif, 2010). Figure 21 shows the specimens before and after failure by impact energy test.

Calculation of energy delivered to each specimen by each blow is by following equation: (Marar, 2000)

$$E_I = \tfrac{1}{2} M V_I^2 N \qquad [3]$$

Where;

E_I = Impact energy (N.m),

M = Mass of drop hammer (kg),

V_I =Impact velocity = 1.8088 (m/s), and

N = Number of blows

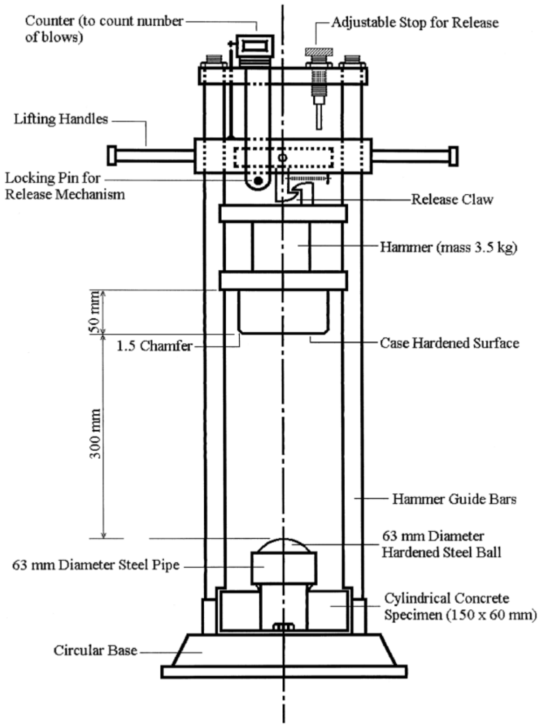


Figure 20 - Drop-weight impact testing machine for SIFCON and conventional concrete

Figure 21- Specimens before and after test energy Impact test

3.4.4 Depth of penetration of water under pressure

Durability of concrete is a great concern especially in aggressive environments. In this regard, penetration of water into SIFCON samples has been investigated. For each fiber type and volume, 150 mm cubic samples were tested at the age of 28 days under water curing. Preparation of test specimens was done in accordance with BS-EN standards (BS-EN-12390-8, 2002). The test specimen was inserted into water permeability testing apparatus cell with opposite direction of casting way. The arrangement for the test is shown in Figure 22 and Figure 23 .The water pressure may be applied to the surface of the test specimen either from the bottom, or the top.

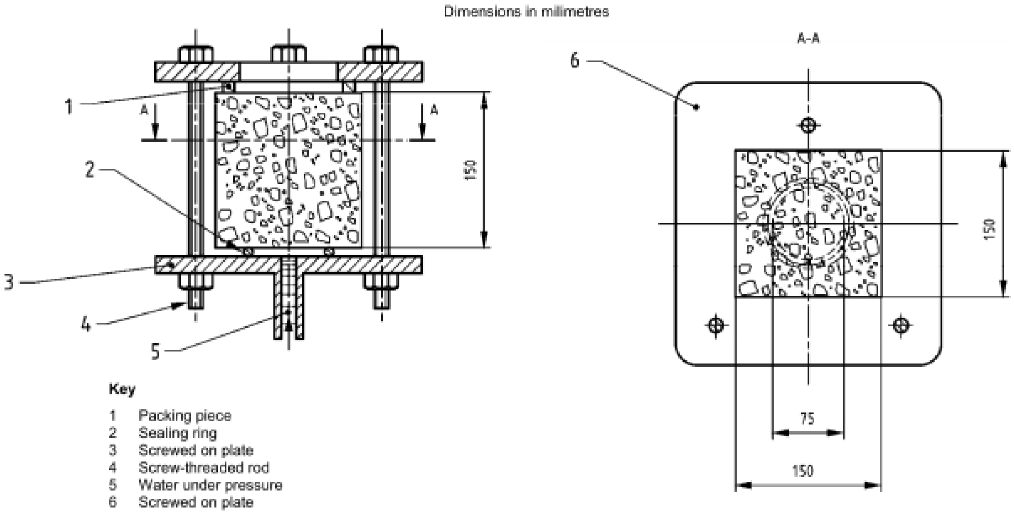


Figure 22 - Arrangement for water penetration test

Specimens were kept at a constant pressure of 500±50 kPa, in accordance to standards (BS-EN-12390-8, 2002).

Figure 23 - Apparatus for water permeability test

After the pressure has been applied for 72 hours, the specimens were ready to be examined. Specimens were splitted and maximum depth of penetration (Figure 24, Figure 25) under the test area was recorded as soon as the specimens were dried (5 to10 minutes).

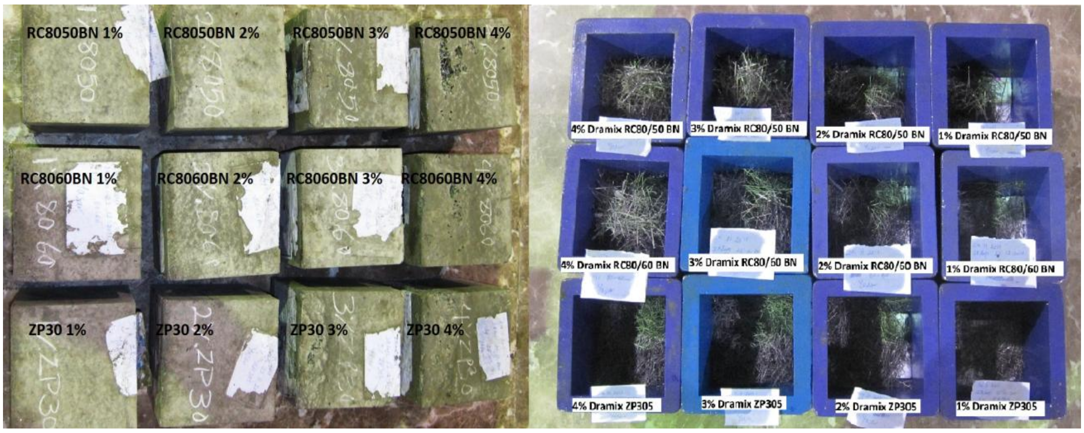


Figure 24 - Specimens used for water permeability

Figure 25- Depth of water penetration

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

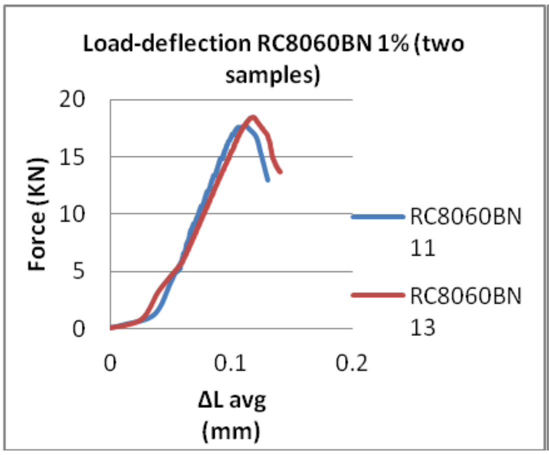
The following tests were carried out within the scope of this thesis.

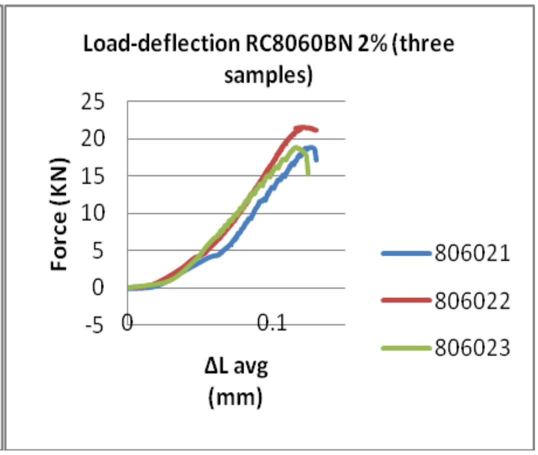
1) Load-deformation behavior in flexural third point test (absorbed energy)
2) Depth of water penetration
3) Impact energy test.

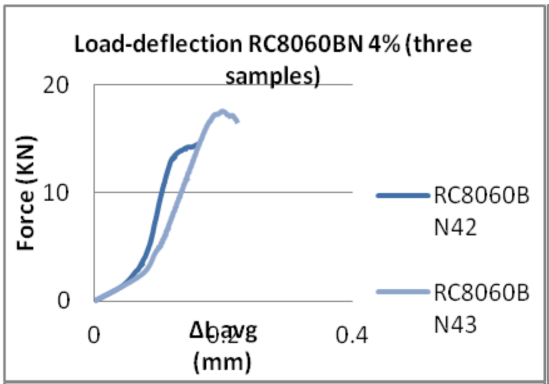
In the following sections, the results of these tests are presented and discussed.

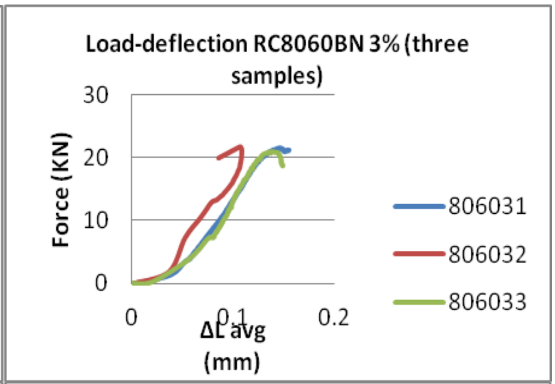
4.2 Load-deformation behavior of beams

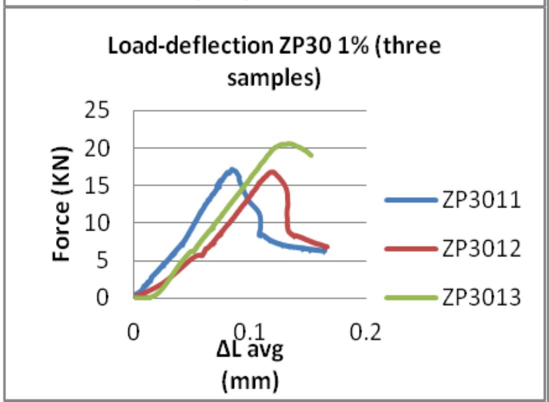
As mentioned earlier in Chapter 3, the properties of SIFCON specimens were tested under third point loading method according to (ASTM-C37,2011).The main focus of this study is to demonstrate clear information on the effect of related parameters such as fiber amount (V_f) and fiber type (fiber geometry) by concerning only one parameter for one class of concrete on each investigation, while other parameters were kept constant. Load deformation data was recorded and then load-deformation lines were drawn. Curves are given in Figure 26.

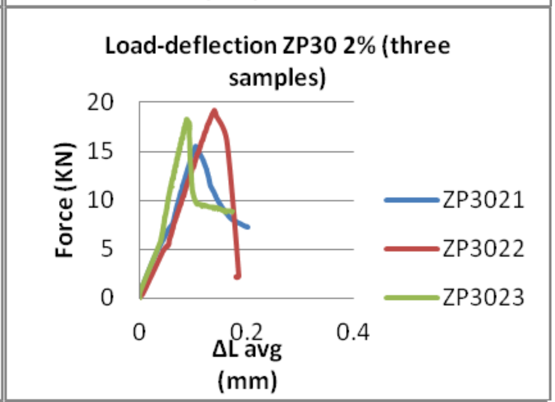

Load-deflection RC8060BN 1% (two samples)
Force (KN)
ΔL avg (mm)
RC8060BN 11
RC8060BN 13

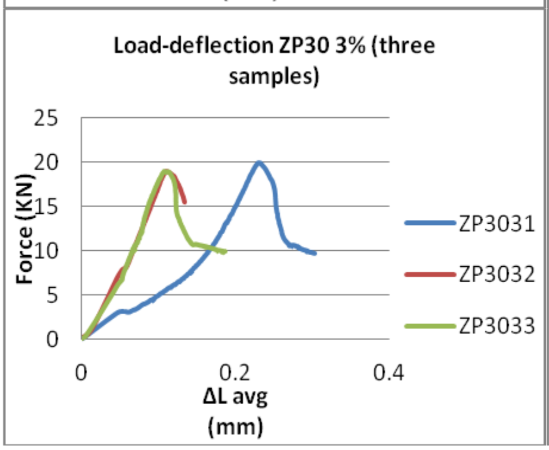

Load-deflection RC8060BN 2% (three samples)
Force (KN)
ΔL avg (mm)
806021
806022
806023

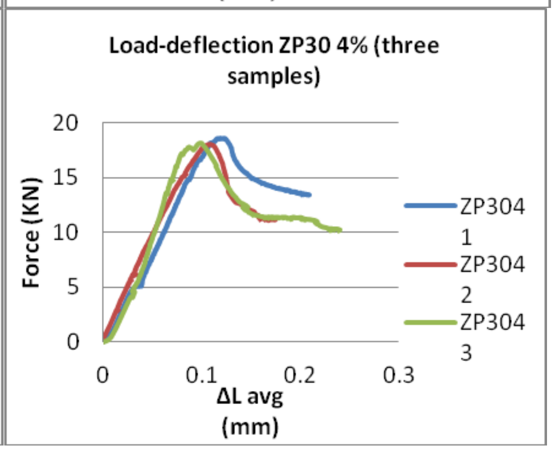

Load-deflection RC8060BN 4% (three samples)
Force (KN)
ΔL avg (mm)
RC8060BN42
RC8060BN43


Load-deflection RC8060BN 3% (three samples)
Force (KN)
ΔL avg (mm)
806031
806032
806033


Load-deflection ZP30 1% (three samples)
Force (KN)
ΔL avg (mm)
ZP3011
ZP3012
ZP3013


Load-deflection ZP30 2% (three samples)
Force (KN)
ΔL avg (mm)
ZP3021
ZP3022
ZP3023


Load-deflection ZP30 3% (three samples)
Force (KN)
ΔL avg (mm)
ZP3031
ZP3032
ZP3033


Load-deflection ZP30 4% (three samples)
Force (KN)
ΔL avg (mm)
ZP3041
ZP3042
ZP3043

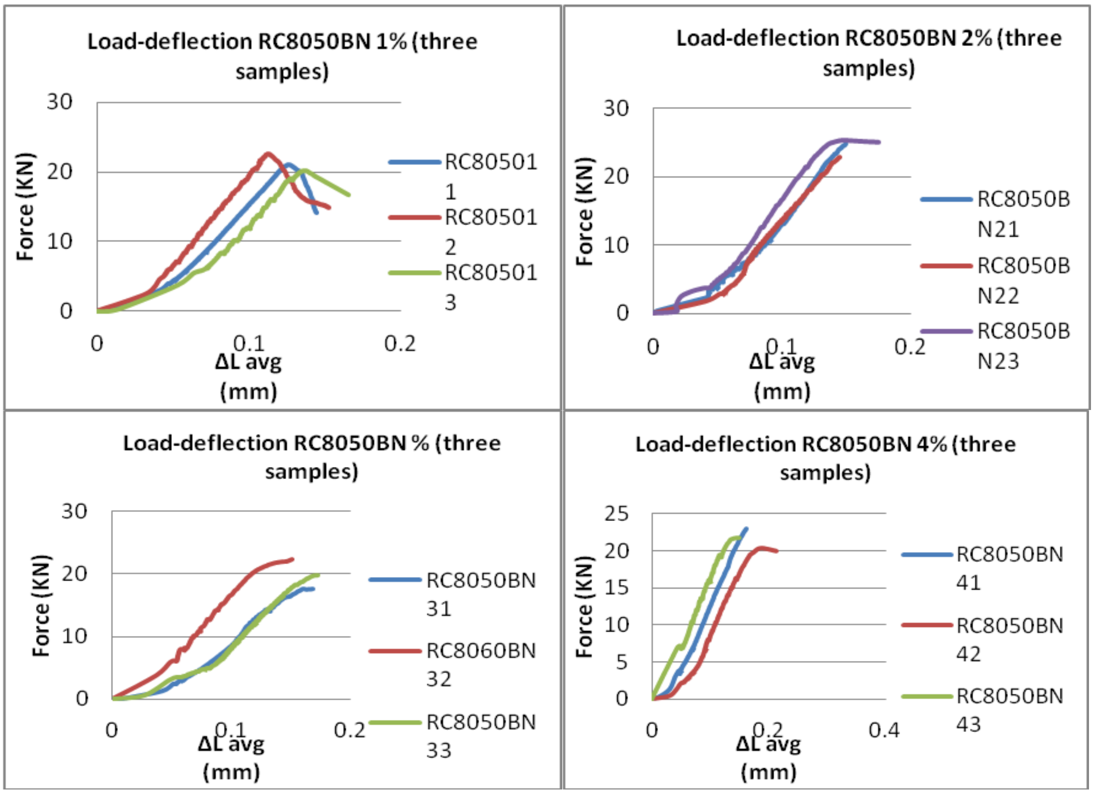


Figure 26 - Load-deformation for SIFCON

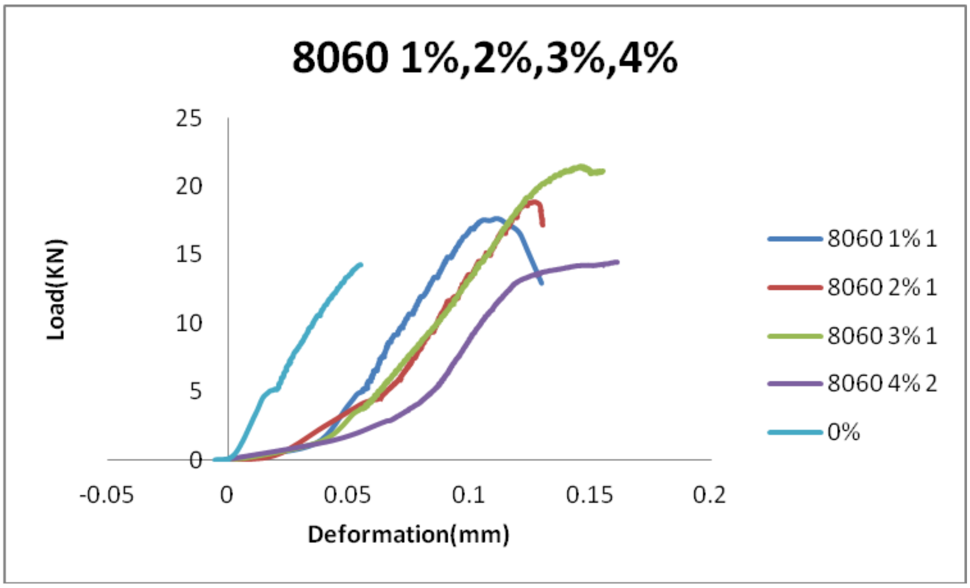


Figure 27 - Load-deformation curve for RC8060BN 1, 2, 3, and 4%

The result of load deformation results will be discussed regarding absorbed energy for each mixture. Absorbed energy is the area under curve of load-deformation figure. In order to demonstrate absorbed energy, area under curve of load-deformation was calculated. Three specimens were tested from every mix to calculate the average of each mix (Table 11).

Table 11 - Summary of absorbed energy obtained from flexural strength tests.

Fiber Percentage	The average (3 samples) results of absorbed energy(J) with respect to fiber type		
	RC8060BN	RC8050BN	ZP30
4	1398	1831	2396
3	1207	1469	1956
2	1042	1354	1712
1	1152	1570	1839
Plain	569	569	569

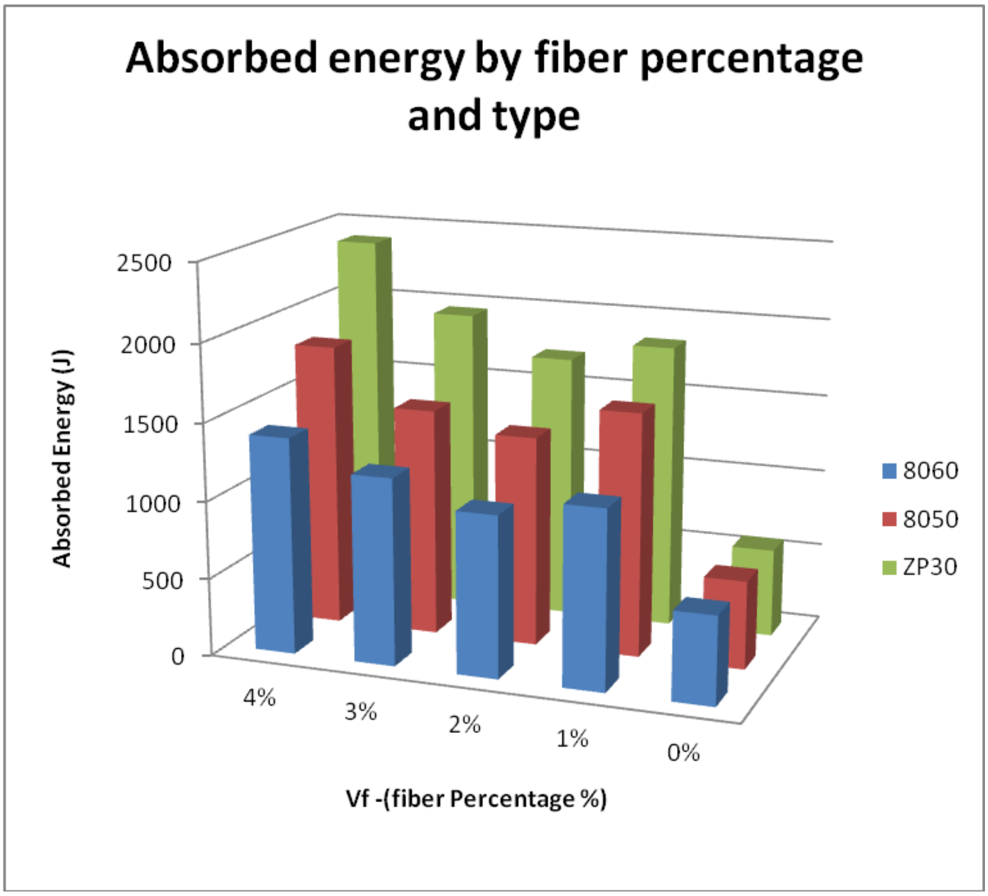


Figure 28 - Absorbed energy vs. fiber percentage and type (J)

In Flexural test, all specimens showed higher absorbed energy in comparison with control (plain) concrete. It can be observed that adding fiber to concrete has a considerable effect at start point which is 1%, while adding more fibers till 4%

doesn't improve the absorbed energy as it expected to. It could be also obtained that using SIFCON with ZP30 has more improvement in absorbed energy to SIFCON8050 and SIFCON 8060. For example for SIFCON ZP30 for 1% fiber, increased absorbed energy is 223% while adding fibers to SIFCON 8050 resulted in 175% improvement and increment of SIFCON 8060 is 102% by adding fibers.

4.2.1 Effect of fiber content on absorbed energy

The following can be stated about effect of fiber content:

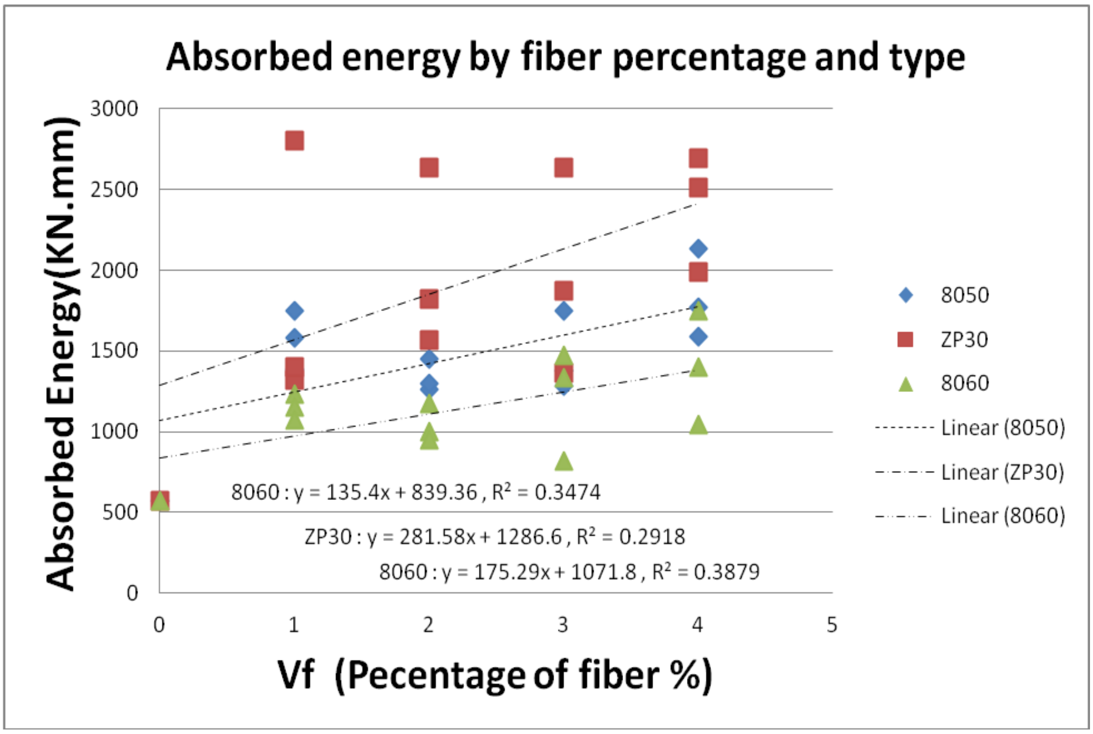


Figure 29 - Absorbed Energy for different hooked-end steel fiber types and volumes

a) It can be observed from comparative interpretations of Figure 29 that, for SIFCON, the higher the fiber amount the more absorbed energy. Similar behaviors were observed by other researchers (Lankard, 1984; Gilani, 2007).

b) Exceptionally for SIFCON with fiber amount of 1%, absorbed energy is more than expected, in comparison with 2% and 3% fiber amount. It can be due to better "concrete bonding and steel fibers and less voids in mix having fiber content of 1% compared to mix having fiber content of 2%.

c) Moreover it could be observed that SIFCON ZP30 has more energy absorption capacity than SIFCON RC80/50 and SIFCON RC80/50. Also SIFCON RC80/50 had more absorbed energy than SIFCON RC80/60. Changes in absorbed energy are summarized in Table 12.

Table 12-Increases in absorbed energy for SIFCON

Fiber Amount (%)	Percent increases in absorbed energy compared to control mix		
	RC8060BN	RC8050BN	ZP305
4	146	222	321
3	112	158	244
2	83	138	201
1	103	176	223
No fiber	0	0	0

The reason may be simply explained as “pores in the matrix of ZP30 can be filled with smaller fibers quite easier than fibers with higher length and diameter. In flexural strength test, all specimens showed higher absorbed energy in comparison with control concrete. It can be observed that adding fiber to concrete has a huge effect at starting point of 1%, while adding more fibers till 4% it doesn’t improve the absorbed energy as it expected.

For fiber type RC8060BN, adding fibers to control (which is considered to have 0% absorbed energy) at 1%,2%,3% and 4%, increment of absorbed energy was 103%,83%,112% and 146% respectively.

For fiber type RC8050BN, adding fibers to control mix by 1%, 2%, 3% and 4%

increased absorbed energy by 176%, 138%, 158% and 222% respectively.

For fiber type ZP305, adding fibers to control mix by 1%, 2%, 3% and 4% increased absorbed energy by 223%, 201%, 244% and 321% respectively.

4.2.2 Effect of length of fiber on absorbed energy

The effect of length of fibers was studied on absorbed energy and based on the results obtained (see Figure 30) it can be said that:

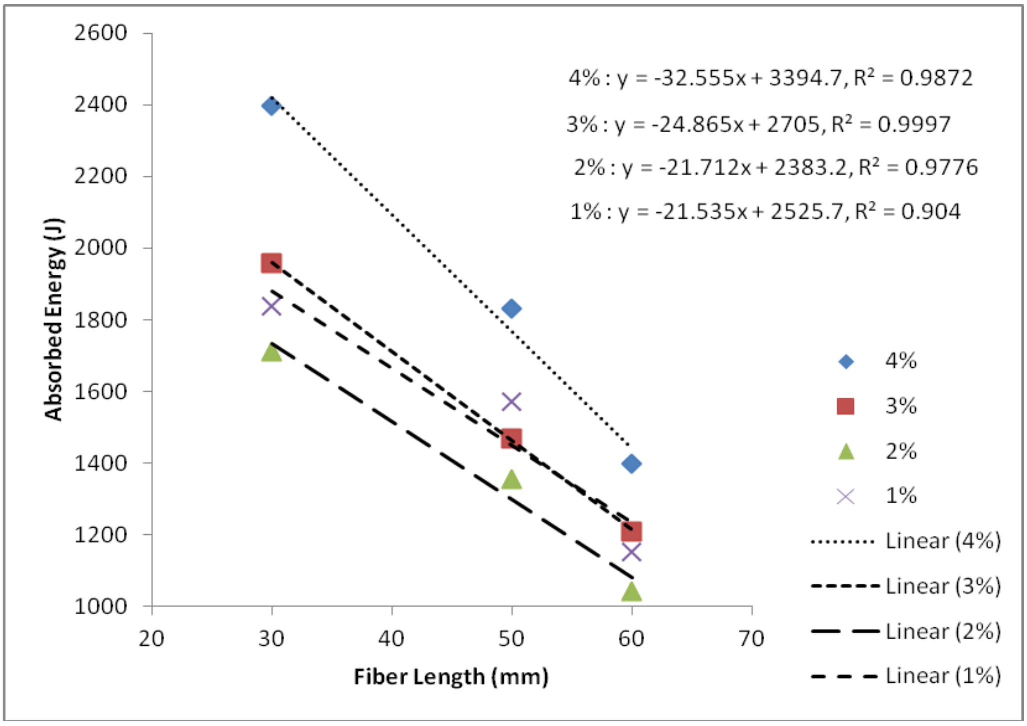


Figure 30 - Absorbed energy vs. length of fibers

SIFCON ZP30 had shown relatively higher absorbed energy among others in this study which could be due to better bonding that lower aspect ratio fibers can make with concrete and less pores made by application of ZP30 fibers in comparison with the other two. Beside, SIFCON ZP30 allows more compaction in layer of concrete and fiber in comparison to SIFCON 8060 and SIFCON 8050.

4.2.3 Effect of tensile strength of fibers on energy absorption

The effect of tensile strength (which has been reported by manufactures of fibers) has respectively studied on absorbed energy, and based on results from Figure 31 it can be stated that:

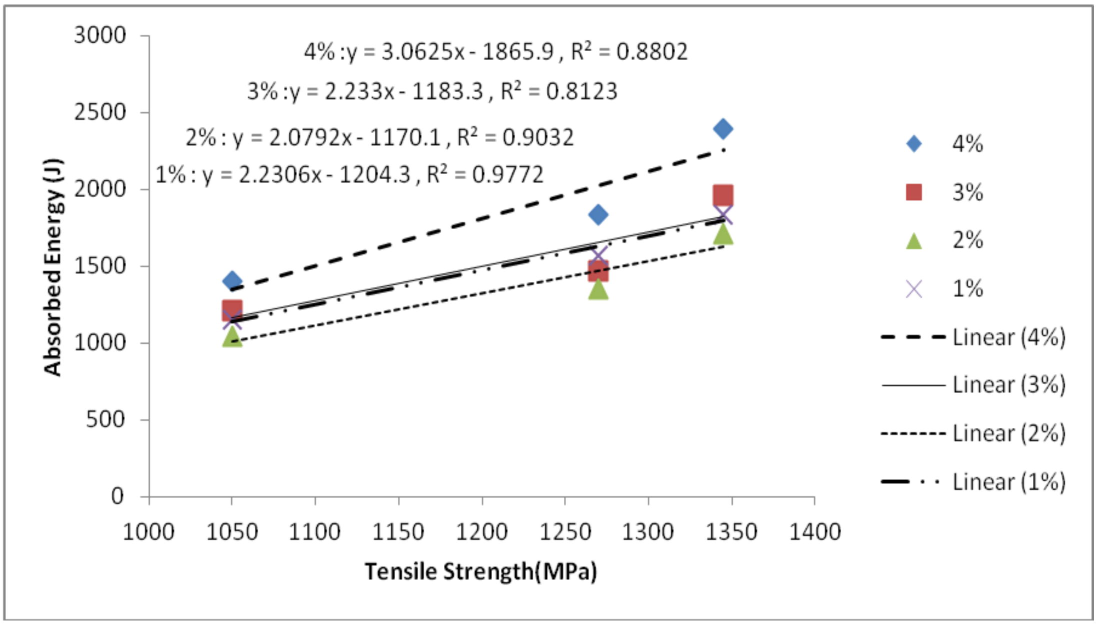


Figure 31 - Effect of fiber tensile strength on absorbed energy of SIFCON

The higher tensile strength, the higher absorbed energy. Since fiber did not show any fail, or break, and cut off during loading but they were just pulled out and exposed from fiber-mix layer. So, the tensile strength of fiber can increase the carried load if the bonding made by hooked end fibers would be enough, hence higher strength fibers can make stronger bond to cope with stress.

4.2.4 Effect of fiber diameter on energy absorption

The effect of fiber's diameter has respectively studied on absorbed energy and based on results in Figure 32, it can be concluded that:

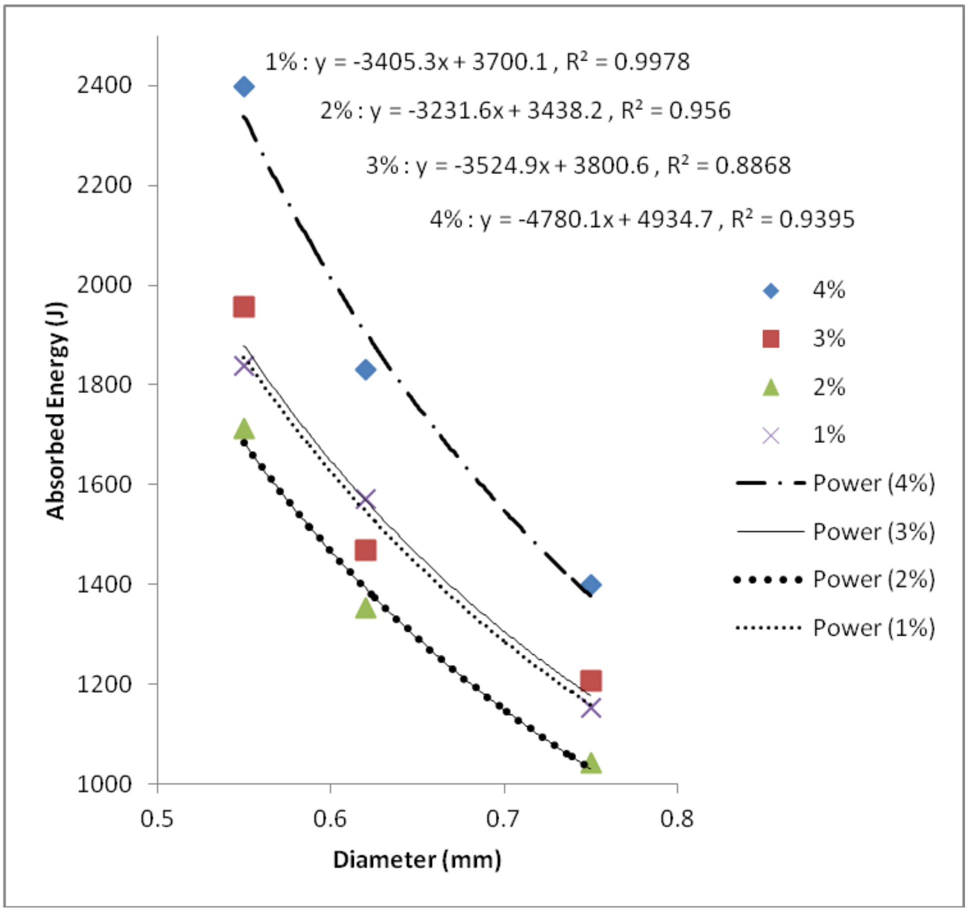


Figure 32 - Effect of fiber diameter on absorbed energy

The higher diameter of fibers in this study, the lower absorbed energy. This may be due to higher pores in the concrete. However for 1% fiber amount, results were higher than expected.

Based on results obtained, Table 5 shows the percentage change of absorbed energy with respect to fiber diameter.

For fiber diameter of 0.75 mm, 0.62 mm and 0.55 for 1% fiber volume, the improvement of absorbed energy is 103%, 176% and 223% respectively.

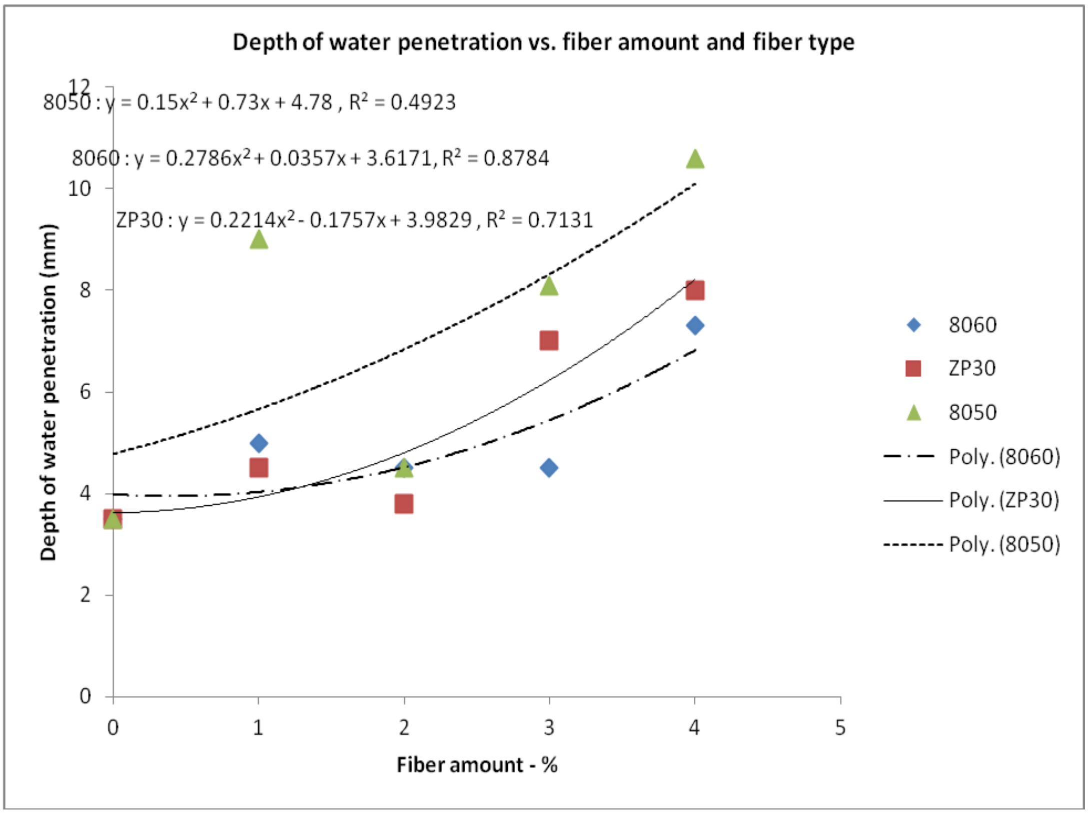
For fiber diameter of 0.75 mm, 0.62 mm and 0.55 mm for 2% fiber volume, the improvement of absorbed energy is 83%, 138% and 201% respectively.

For fiber diameter of 0.75 mm, 0.62 mm and 0.55 mm for 3% fiber volume the improvement of absorbed energy is 112%, 158% and 244% respectively.

For fiber diameter of 0.75mm, 0.62 mm and 0.55 for 4% fiber volume the improvement of absorbed energy is 146%, 222% and 321% respectively

4.3 Depth of penetration of water

SIFCON has been taken into investigation for depth of water penetration according to BS EN 12390-8 (2009). The specimens were kept under constant pressure of 500±50 kPa and after that the water permeability was measured accordingly. Figure 33 and Table 13 show summary of this test results.



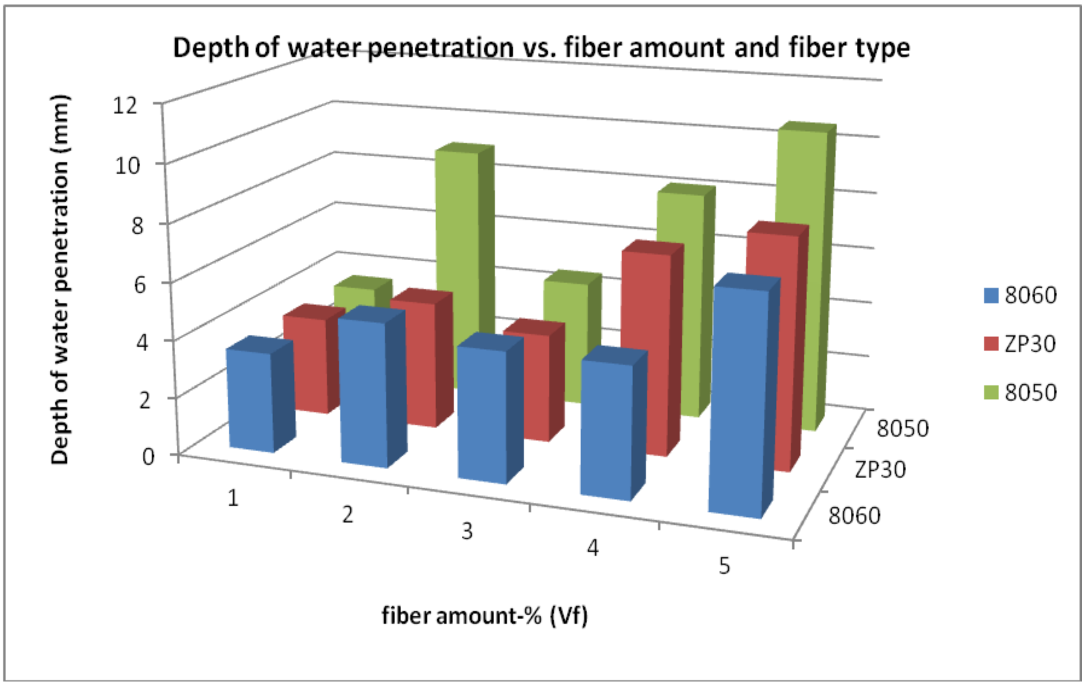


Figure 33 - Depth of water penetration influenced by fiber amount and fiber type

Table 13 - Results from depth of water penetration

fiber type	Fiber amount (Vf)				
	0 %	1%	2%	3%	4%
8060	35 mm	50 mm	45 mm	45 mm	73 mm
8050	35 mm	90 mm	45 mm	81 mm	106 mm
ZP30	35 mm	45 mm	38 mm	70 mm	80 mm

Results from this test show that:

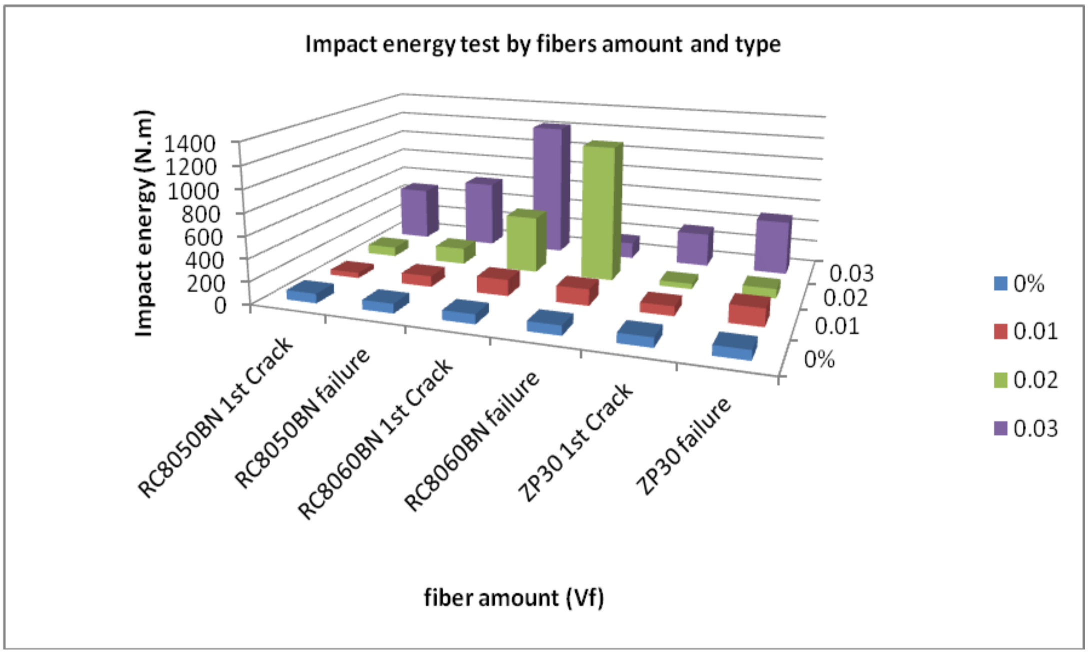
As fiber amount increases, depth of water penetration of concrete increases. This may be because fibers make more micro cracks and pores in concrete matrix. This cracks and pores are ready to take more water and damage the concrete. This can show application of fibers should be considered where durable concrete is needed.

4.4. Impact energy test

As mentioned in Chapter 3, impact energy test at first crack and complete failure have been carried out accordingly. The results are given in Table 14 and Figure 34 and following can be concluded:

Table 14 - Impact energy test results

Fiber Type	Fiber amount -% (Vf)			
	0	1	2	3
	Impact energy (N.mm)			
RC8050BN 1st Crack	85.47	48.84	85.47	488.38
RC8050BN final Crack	85.47	97.68	146.51	610.47
RC8060BN 1st Crack	85.47	146.51	512.79	1220.94
RC8060BN final Crack	85.47	146.51	1220.94	146.51
ZP30 1st Crack	85.47	85.47	48.84	305.23
ZP30 final Crack	85.47	158.72	85.47	488.38



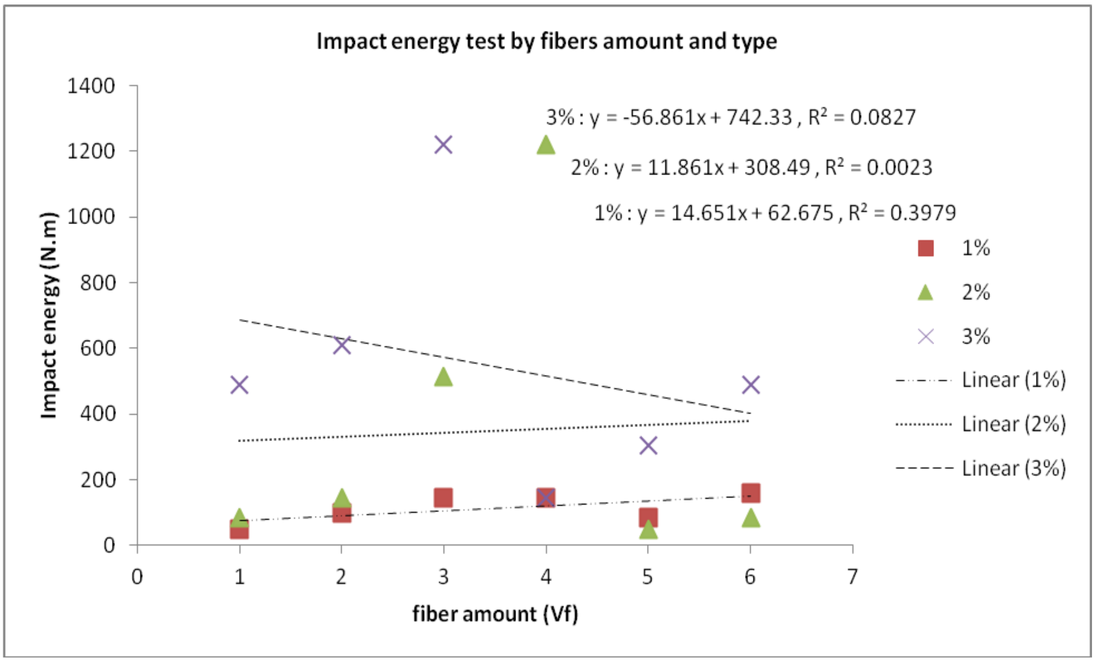


Figure 34 - Impact energy test

a) For fiber types RC8050 and ZP30, when fiber amount is 4%, the number of blows was higher than 50 blows, due to high impact energy needed. So test was stopped at 50 blows.

b) For RC8060BN with fiber content of 4%, results were not available, because of lots of pores happened in concrete in cylinder sample. Therefore, it was better to neglect result of this fiber amount. This could be due to not having a concrete with enough workability for 4%.

c) For control concrete, first crack and failure occurred at same number of drops.

d) It could be observed that fiber increases impact energy. Since fibers improve the strength of matrix and crack are harder to happen in fiber concrete than normal concrete.

Chapter 5

CONCLUSIONS

In this experimental study various properties of SIFCON such as flexural test, water permeability and impact energy have been carried out. Three types of hooked-end steel fibers, and five different volume percentages were considered for one class of concrete.

The following conclusions were drawn out based on results obtained from this study.

a) In flexural test, all SIFCON specimens showed higher absorbed energy in comparison with Control (Plain) concrete

b) In flexural test, for SIFCON, the higher the fiber amount, the higher the absorbed energy. Exceptionally for SIFCON with V_f =1% absorbed energy is higher than the expected amount, it might be because of good bonding and less pores in the V_f =1% and, more compaction in concrete-fiber layer in SIFCON 1%.

c) In flexural test, it could be observed that SIFCON ZP30 has more absorbed energy than SIFCON RC80/50 and SIFCON RC80/50. So using ZP30 has the priority to other fibers used in this study. Also SIFCON RC80/50 had more absorbed energy than SIFCON RC80/60.

d) In flexural test, SIFCON ZP30 which has the least aspect ratio had shown relatively higher absorbed energy among others in this study. It might be concluded that lower the aspect ratio the lower the absorbed energy. However study on more fiber types and other concrete classes are recommended.

e) The higher the diameter of fibers in this study, the lower the absorbed energy. However the absorbed energy was higher for higher amounts of fibers (V_f), but as an exception for V_f =1 % in which had higher absorbed energy than V_f =2% because of the same reason that has been explained before

f) As fiber amount increased, depth of water penetration of concrete increased due to increment of porosity.

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APPENDIX

Appendix A: A part of the data of a load-deflection Test for Control concrete

Specimen: Control Sample 1						
Time (S)	Force (kN)	LVDT1(mm)	LVDT2(mm)	ΔL1 (mm)	ΔL2 (mm)	ΔL avg (mm)
0	0.001	0.10475	0.1091	0	0	
0.2	0.012	0.10544	0.10849	0.00069	-0.00061	4E-05
0.4	0.012	0.10544	0.10849	0.00069	-0.00061	4E-05
0.6	0.006	0.10559	0.10338	0.00084	-0.00572	-0.00244
0.8	0.026	0.10559	0.10239	0.00084	-0.00671	-0.002935
1	0.021	0.10582	0.10185	0.00107	-0.00725	-0.00309
1.2	0.02	0.10551	0.10139	0.00076	-0.00771	-0.003475
1.4	0.02	0.10559	0.10094	0.00084	-0.00816	-0.00366
1.6	0.019	0.10597	0.10071	0.00122	-0.00839	-0.003585
1.8	0.024	0.10582	0.1004	0.00107	-0.0087	-0.003815
2	0.02	0.10536	0.10017	0.00061	-0.00893	-0.00416
2.2	0.032	0.10574	0.09995	0.00099	-0.00915	-0.00408
2.4	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
2.6	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
2.8	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
3	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
3.2	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
3.4	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
3.6	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
3.8	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
4	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
4.2	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
4.4	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
4.6	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
4.8	0.017	0.10559	0.09956	0.00084	-0.00954	-0.00435
5	0.001	0.1046	0.09804	-0.00015	-0.01106	-0.005605
5.2	0.001	0.1046	0.09804	-0.00015	-0.01106	-0.005605
5.4	0.001	0.1046	0.09804	-0.00015	-0.01106	-0.005605
5.6	0.396	0.13611	0.08286	0.03136	-0.02624	0.00256
5.8	3.28	0.12543	0.11063	0.02068	0.00153	0.011105
6	4.497	0.12596	0.11635	0.02121	0.00725	0.01423
6.2	4.905	0.12733	0.11955	0.02258	0.01045	0.016515
6.4	5.039	0.12718	0.12138	0.02243	0.01228	0.017355
6.6	5.082	0.12756	0.12291	0.02281	0.01381	0.01831
6.8	5.097	0.12756	0.12405	0.02281	0.01495	0.01888
7	5.139	0.12726	0.12482	0.02251	0.01572	0.019115

7.2	5.18	0.12756	0.1252	0.02281	0.0161	0.019455
7.4	5.152	0.12749	0.12566	0.02274	0.01656	0.01965
7.6	5.122	0.12741	0.12589	0.02266	0.01679	0.019725
7.8	5.143	0.12772	0.12627	0.02297	0.01717	0.02007
8	5.154	0.12756	0.12672	0.02281	0.01762	0.020215
8.2	5.123	0.12764	0.12672	0.02289	0.01762	0.020255
8.4	5.212	0.12772	0.12718	0.02297	0.01808	0.020525
8.6	5.173	0.12749	0.12711	0.02274	0.01801	0.020375
8.8	5.184	0.12756	0.12726	0.02281	0.01816	0.020485
9	5.207	0.12787	0.12741	0.02312	0.01831	0.020715
9.2	5.217	0.12756	0.12764	0.02281	0.01854	0.020675
9.4	5.294	0.12741	0.12779	0.02266	0.01869	0.020675
9.6	5.284	0.12764	0.12772	0.02289	0.01862	0.020755
9.8	5.323	0.12779	0.12794	0.02304	0.01884	0.02094
10	5.293	0.12756	0.1284	0.02281	0.0193	0.021055
10.2	5.484	0.12772	0.12802	0.02297	0.01892	0.020945
10.4	5.476	0.12794	0.12817	0.02319	0.01907	0.02113
10.6	5.464	0.12772	0.1281	0.02297	0.019	0.020985
10.8	5.493	0.12787	0.12794	0.02312	0.01884	0.02098
11	5.486	0.12772	0.12817	0.02297	0.01907	0.02102
11.2	5.514	0.12794	0.1281	0.02319	0.019	0.021095
11.4	5.53	0.12764	0.12825	0.02289	0.01915	0.02102
11.6	5.555	0.12779	0.12825	0.02304	0.01915	0.021095
11.8	5.555	0.12764	0.12863	0.02289	0.01953	0.02121
12	5.582	0.12756	0.12848	0.02281	0.01938	0.021095
12.2	5.516	0.12779	0.12856	0.02304	0.01946	0.02125
12.4	5.528	0.12772	0.12856	0.02297	0.01946	0.021215
12.6	5.547	0.12787	0.12871	0.02312	0.01961	0.021365
12.8	5.557	0.12787	0.12871	0.02312	0.01961	0.021365
13	5.573	0.12779	0.12917	0.02304	0.02007	0.021555
13.2	5.595	0.12772	0.12878	0.02297	0.01968	0.021325
13.4	5.554	0.12772	0.12878	0.02297	0.01968	0.021325
13.6	5.568	0.12764	0.12932	0.02289	0.02022	0.021555
13.8	5.576	0.12802	0.12886	0.02327	0.01976	0.021515
14	5.595	0.12772	0.12894	0.02297	0.01984	0.021405
14.2	5.618	0.12787	0.12909	0.02312	0.01999	0.021555
14.4	5.568	0.12772	0.12909	0.02297	0.01999	0.02148

A Part of data for load-deflection for SIFCON

Specimen RC806011						
Time (S)	Force (kN)	LVDT1(mm)	LVDT2(mm)	ΔL1 (mm)	ΔL2 (mm)	ΔL avg (mm)
0.2	0.003	0.11566	0.11444	0	0	0
0.4	0.003	0.11566	0.11444	0	0	0
0.6	0.01	0.1152	0.11284	-0.00046	-0.0016	-0.00103
0.8	0.01	0.1152	0.11284	-0.00046	-0.0016	-0.00103
1	0.01	0.1152	0.11284	-0.00046	-0.0016	-0.00103
1.2	0.005	0.1152	0.11368	-0.00046	-0.00076	-0.00061
1.4	0.005	0.1152	0.11368	-0.00046	-0.00076	-0.00061
1.6	0.001	0.11467	0.11406	-0.00099	-0.00038	-0.00069
1.8	0.006	0.11528	0.11353	-0.00038	-0.00091	-0.00065
2	0.006	0.11528	0.11353	-0.00038	-0.00091	-0.00065
2.2	0.006	0.11528	0.11353	-0.00038	-0.00091	-0.00065
2.4	0	0.11513	0.11322	-0.00053	-0.00122	-0.00088
2.6	0	0.11513	0.11322	-0.00053	-0.00122	-0.00088
2.8	0.008	0.11497	0.11292	-0.00069	-0.00152	-0.0011
3	0.008	0.11497	0.11292	-0.00069	-0.00152	-0.0011
3.2	0.284	0.13695	0.11497	0.02129	0.00053	0.01091
3.4	1.181	0.12138	0.18166	0.00572	0.06722	0.03647
3.6	3.932	0.1429	0.18654	0.02724	0.0721	0.04967
3.8	4.769	0.15526	0.18158	0.0396	0.06714	0.05337
4	4.888	0.15755	0.18143	0.04189	0.06699	0.05444
4.2	4.931	0.15877	0.18143	0.04311	0.06699	0.05505
4.4	4.938	0.15923	0.18166	0.04357	0.06722	0.055395
4.6	4.958	0.1593	0.1815	0.04364	0.06706	0.05535
4.8	4.975	0.1593	0.1812	0.04364	0.06676	0.0552
5	4.981	0.15938	0.18135	0.04372	0.06691	0.055315
5.2	4.998	0.16022	0.18135	0.04456	0.06691	0.055735
5.4	4.978	0.15999	0.18127	0.04433	0.06683	0.05558
5.6	4.979	0.16052	0.18158	0.04486	0.06714	0.056
5.8	4.986	0.16014	0.18127	0.04448	0.06683	0.055655
6	4.995	0.16045	0.18127	0.04479	0.06683	0.05581
6.2	5.001	0.16022	0.18143	0.04456	0.06699	0.055775
6.4	5.012	0.1606	0.1815	0.04494	0.06706	0.056
6.6	5.022	0.16052	0.18158	0.04486	0.06714	0.056
6.8	5.032	0.15999	0.18158	0.04433	0.06714	0.055735
7	5.045	0.16052	0.1815	0.04486	0.06706	0.05596
7.2	5.054	0.16006	0.18158	0.0444	0.06714	0.05577
7.4	5.066	0.16052	0.18166	0.04486	0.06722	0.05604
7.6	5.069	0.16098	0.18135	0.04532	0.06691	0.056115
7.8	5.084	0.16083	0.1815	0.04517	0.06706	0.056115
8	5.093	0.16068	0.1815	0.04502	0.06706	0.05604
8.2	5.098	0.16098	0.1815	0.04532	0.06706	0.05619

8.4	5.12	0.1609	0.18143	0.04524	0.06699	0.056115
8.6	5.119	0.16083	0.1815	0.04517	0.06706	0.056115
8.8	5.134	0.16029	0.18143	0.04463	0.06699	0.05581
9	5.146	0.16037	0.18166	0.04471	0.06722	0.055965
9.2	5.15	0.16068	0.18143	0.04502	0.06699	0.056005
9.4	5.169	0.16068	0.18166	0.04502	0.06722	0.05612
9.6	5.175	0.1609	0.18143	0.04524	0.06699	0.056115
9.8	5.183	0.16098	0.18166	0.04532	0.06722	0.05627
10	5.194	0.16113	0.18166	0.04547	0.06722	0.056345
10.2	5.198	0.16083	0.18173	0.04517	0.06729	0.05623
10.4	5.204	0.16205	0.18173	0.04639	0.06729	0.05684
10.6	5.181	0.16273	0.18158	0.04707	0.06714	0.057105
10.8	5.173	0.16273	0.18173	0.04707	0.06729	0.05718
11	5.171	0.16266	0.18158	0.047	0.06714	0.05707
11.2	5.163	0.16273	0.18166	0.04707	0.06722	0.057145
11.4	5.171	0.16273	0.18166	0.04707	0.06722	0.057145
11.6	5.177	0.16273	0.18173	0.04707	0.06729	0.05718
11.8	5.18	0.16266	0.18158	0.047	0.06714	0.05707
12	5.197	0.16296	0.18135	0.0473	0.06691	0.057105
12.2	5.2	0.16304	0.1815	0.04738	0.06706	0.05722
12.4	5.211	0.16281	0.18166	0.04715	0.06722	0.057185
12.6	5.216	0.16335	0.18166	0.04769	0.06722	0.057455
12.8	5.209	0.16373	0.18166	0.04807	0.06722	0.057645
13	5.213	0.16426	0.18158	0.0486	0.06714	0.05787
13.2	5.21	0.16373	0.18158	0.04807	0.06714	0.057605
13.4	5.22	0.16411	0.18188	0.04845	0.06744	0.057945
13.6	5.226	0.16327	0.1815	0.04761	0.06706	0.057335