A State-of-the-Art Review of the Behavior of SIFCON As a Structural Member

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Abstract: The "Slurry Infiltrated Fiber Concrete (SIFCON)" composites can be considered as a new trend in civil engineering fields that have a motivate impact. Such composites are usually synthesized by infiltrating cement slurry with steel fibers matrix to get high level of mechanical properties. Portland cement concrete is weak in tensile and might not illustrate large tensile strains margins. Materials such as steel and pre-stressed tendons were historically used to avoid these limitations of cement. The last fifteen years. Interest has increased among using discontinuous, separated steel fibers for alternate or supplementary reinforcement. Fibers for this utilization have diameters that takes levels between 0.01 to 0.35 in. (0.25 to 0.9 mm) and lengths ranging from 0.5to 3.0 in. (12.7 to 76.2 mm). However, the principal functions of steel fibers are to enhance resistance to impact. By the means of posy cracking ductility, the cracking and mode of failure can be controlled. To increase the performance with respect to tensile strength, flexural strength as well as the fatigue strength.

Keywords: SIFCON, hooked–end steel fiber, Micro steel fiber, Splitting strength, Flexural strength, Compressive strength, SIFCON Slurry.

1. Introduction

During this decade, there is a strong desire to innovate new materials in the fields of civil engineering for a specific structural behavior like strength, stiffness, impact and abrasion resistance. Many structures were found using different types of fiber reinforced concretes. However, the primary determinant of the ductility of fiber reinforced concrete is the amount of fiber that is used in the mix. It also depends on many different factors like fiber type, tensile strength, the aspect ratio. Efforts are devoted to create fiber reinforced concrete that incorporates up to 6% fiber, but these efforts are suffering from difficulties in placing and mixing large amounts of fiber. In order to pass such problem, modern manufacture advance was developed that have led to the advent of a high-performance material called concrete slurry (SIFCON) [1].

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The SIFCON was first created by structuring large amounts of steel to make the fibers in a very dense network. Then, the underground network will be infiltrated with a fine particle cement-based slurry or mortar [2]. However, SIFCON can be categorized as a particular kind of fiber reinforced concrete (FRC). SIFCON is a somewhat new trend that differs FRC in two aspects; the way it's produced and fiber content.

In normal FRC, fiber amounts normally takes levels between 1 and 3 % whereas SIFCON takes 5 and 20 % which is function of considerations like diameter, shape, fiber cross sectional aspect ratio (method used in packing, orientation as well as vibration effectiveness). SIFCON shows capacity and elasticity better than traditional FRC at a moderate steel content [3].

The matrix of SIFCON consists of a flowing fluid of cement, which has no large aggregates but a high cement content. The main issue is that the material used in concrete may be a coarse aggregate but it may contain fine or coarse sand. So, FRC is made by mixing fibers with fresh concrete whereas SIFCON is made by prior placing of fibers, then the fiber matrix is sprinkled by cement slurry or flowing mortar. The vibration is applied throughout the running of mortar [4].

2. The "Slurry Infiltrated Fiber Concrete (SIFCON)"

In fact, SIFCON can be considered as an innovative type of "Fibrous Reinforced Concrete (FRC)" which can absorb high energy, illustrate good impact / explosion resistance as well as having good ductility characteristics.

SIFCON has a good successful application in engineering fields such as pavement overlays, refractory applications and structures subjected to blast and dynamic loading **[5, 6, 7].**

3. SIFCON Preparation

As a matter of fact, due to the congestion in fibers, the ordinary mixing of concrete is impossible, instead of that, the fibers are put at first then the desired network is formed. Then the cement-based slurry (mortar) has to be infiltrated by hand (by gravity), however the fibers can be infiltrated manually or by fiber-dispending apparatuses for big sections [8,9].

The general steps for preparing SIFCON includes fiber placement in the mold, the dry mixing, slurry preparation as well as the finishing of [7].

If the SIFCON has to be implemented within any project, many factors should be taken into account, such factors comprise slurry mechanical strength capacity, volume of fibers, alignment of fibers and the selected type of fibers. That was because the fibers volume / alignment affects the workability and short fibers helps to achieve the highest density of the whole matrix.

Incorporating the steel fibers in the matrix may be done by three different ways; the first includes the preplacing of steel fiber in the mold and the slurry is allowed to sequence through the fiber (single-layer technique) as shown in figure (1). the second technique includes implementing the same procedure but by splitting the total height of section into three parts (three-layer technique). The third includes prefilling of slurry for one third of height and then placing fiber till total height of section can be gain (immersion technique). For all the three techniques, the vibration should be accompanied [11].

Figure 1: Casting procedure of SIFCON [12].

4. Mix Proportions and Materials

It is known that the main materials that should be used in SIFCON production are the cement-based slurry and the steel fibers.

4.1 SIFCON Slurry

In fact, volume amounts of sand and cement usually used for creating SIFCON are 1:1, 1:1.5, or 1:2. Silica fume or fly ash equal from (10 % - 15%) times cement weight may be used also in the mix. It is common that, only fine sand is needed that passes through the 1.18 mm sieve or with maximum particle size of (1, 0.6, 0.5 mm) to establish full infiltration through the steel fibers matrix.

In addition, the water cement ratio can vary in the range (0.3 and 0.4), whereas proportions of “super plasticizer” takes (2 %- 5 %) times cement weight. In addition, fibers amounts are commonly takes (4 % - 20 %), although the present experience ranges only from (4% - 12%) [4]. Table (1) shows the common mix proportions that reported throughout the literature.

It is known that the excessive amount in cement has many negative effects in addition to the "high cost" including the heat of hydration which causes the shrinkage and consequent cracks, therefore, some cementitious materials can be replaced to the mix to overcome this problem [13]. Additionally, superplasticizers are usually used as "water-reducing admixtures" to improve the flow capability of the slurry and establish full penetration without dictating the water-cement ratio (W/C) to be increased. Superplasticizer's dosage has the highest influence on cement slurry cohesiveness, fluidity and penetration [14].

Table 1: Mix proportions of SIFCON slurry (by weight of cement) from recent contributions

References	Cement	Sand	Silica fume %	Fly ash	Water /binder	HRWR (by wt. of cement) %.
(Yan et al., 1999) [15].	1	1	15*	-	0.28	1.5
(Elavarasi and Mohan, 2016)[16].	1	1	5,10,15, 20,25**	-	0.4	2
(Wang and Maji, 1994)[17].	1	-	-	0.3	0.3	1.9
(Parthiban et al., 2013) [1].	1	1	-	-	0.5	-
(Rao and Amana, 2005) [18].	1	1	-	-	0.45	1.5
(Parameswaran et al., 1993) [19].	1	1	-	-	0.38 0.38 0.35 0.32	2 1 2 1

*"Silica fume was used as additives not replacement by weight of cement".

** "Silica fume was used as replacement by weight of cement".

4-2 Steel Fiber

Cementing networks like concrete illustrate low strength in tension and fail in a brittle fashion. Including fibers within the network improves the mechanical characteristics, especially their energy absorbing capacity, ductility, toughness, and damage endurance in structural elements under cyclic loading.

In addition, the fiber cross section can be square, circular, rectangular, diamond, flat, polygonal and triangular. To propose good fastening between matrix and fiber, the fiber can be adjusted along its length by roughing up surface / increasing the permissible deformation capacity. Therefore, the fibers can be, indented, smooth, twisted, crimped, coiled, by paddles, end hooks, buttons, scarred with "typical lengths" between 6 mm and 150 mm and thicknesses that take values between 0.005 mm and 0.75 mm. In some fibers the surface is inscribed or treated by plasma to enhance glue at the level of microscopic view.

Moreover, the basic factors that govern the behavior of the composite material are: matrix strength and the relevant physical properties of fibers in addition to glue between fibers and matrix [20, 21, 22].

However, there are large number of kinds of fiber that can be utilized to fabricate SIFCON as illustrated in Figure (2). The most extensively utilized are crimped and hooked. Deformed and straight fibers can be used also despite that they not common than other types.

It can be stated that lower fiber size can pack more than higher fiber size and vibration can be used to produce higher fiber volumes.

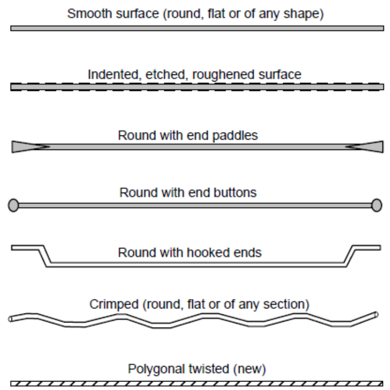

Figure 2: Steel fibers profiles of that are usually utilized in SIFCON [20].

5. SIFCON Ductility, Toughness and Stiffness

Grossly, ductility is the ability to tolerate extension beyond an initial yield point for a structure [23]. In addition, Ductility defines also a measure of the deformation at fracture as written in equation (1) [24]. Figure (3) presents the difference between brittle and ductile materials.

$$El\% = \left(\frac{L_f - L_o}{L_o}\right) * 100 \qquad (1)$$

$El\%$ = Percent elongation.

L_o = Length of the original sample.

L_f = Sample length at fracture.

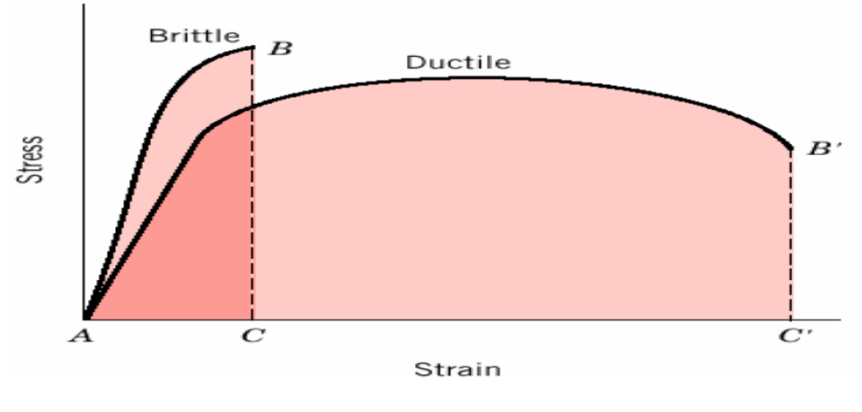

Figure 3 Stress strain curve of brittle and ductile materials [24].

Generally, stiffness is the ability to produce specified deformation at a given applied force or it is the degree to which an object can or deform with a specific force **[25]**. The stiffness of a material is defined as the slope of its stress-strain relation as stated in Figure (4).

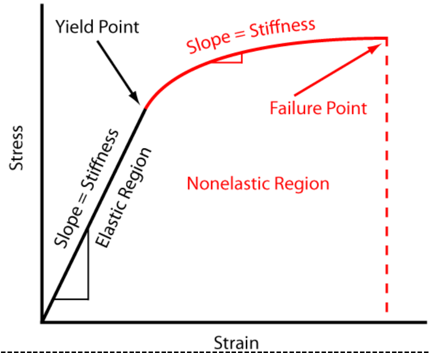

Figure 4: Stress-strain curve [26].

On the other hand, toughness is defined as how much of a material or structure can absorb energy before it fails. Such significant property may be characterized by the "area under the curve" of load-deformation. In the same context, "toughness" depends upon the final load carrying capacity as viewed in Figure (5).

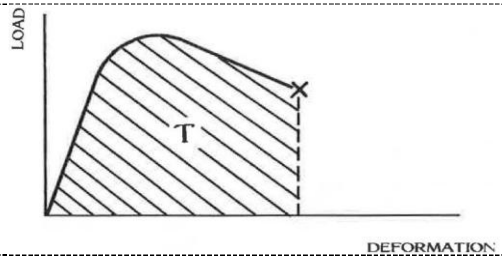

Figure 5 : Toughness as area under load-deformation curve [27].

6. SIFCON Mix Design and The Relevant Properties

SIFCON illustrates a number of good mechanical properties that are directly relevant to its mix design like **[7]**:

1. SIFCON illustrates good energy absorption, durability, impact, toughness and resistance to abrasion.
2. In SIFCON specimens, the values of modulus of elasticity (*E*) are more compared with plain concrete.
3. Highly ductile and greater strength.

However, dissimilar cracks that appeared in a continuous reinforced concrete element, the cracks in the SIFCON do not stretch through the entire sample. Alternately, cracks will appear randomly in the loaded volume taking short lengths, i.e., on the surface and through the depth of the specimen. additionally, SIFCON can illustrate ultimate tensile strength (20 – 40) MPa according to the mix proportions and amount of steel fibers [28].

Giridhar et al., (2015) [29] studied SIFCON mechanical properties taking various length and amounts of steel fibers. In such study, two kinds of steel fibers were utilized taking various levels of aspect ratios. The first type has length 50 mm and diameter 1 mm, while the second type of fiber has 35 mm length and 0.55 mm diameter. The volume fraction used in this research was 4%, 6% and 8%. The split tensile strength was carried out for 8% volume fraction of steel fiber of length 35 mm. The flexure strength was carried out for 4%, 6% and 8% volume fraction for 35 mm length. The results indicated that the. Compressive strength, flexure and split tensile strength increased as fiber volume increases as shown in Figure (6). it also deduced during that research that the low fiber length SIFCON produces higher compressive strength if compared with higher levels of fiber length SIFCON.

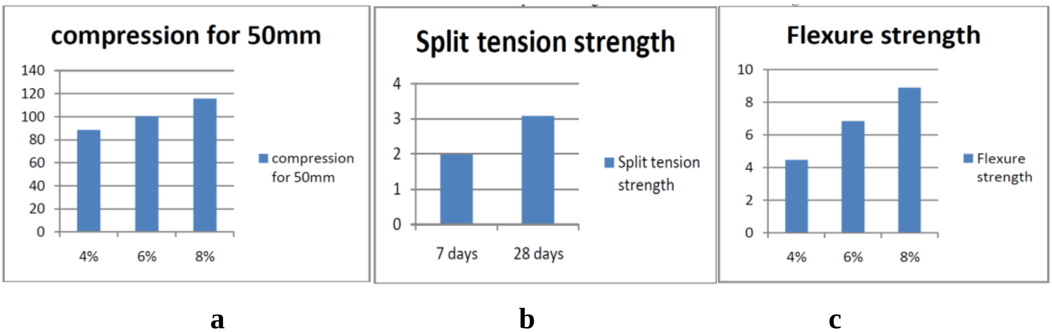

Figure 6: Work of Giridhar et al., (2015) [29] (a) compression test results after 28days for 50 mm steel fibers, (b) split tension results, (c) flexure strength results.

Elavarasi and Mohan, (2016) [16] studied the silica fume effect within SIFCON concrete to the consequent split tensile strength, compressive strength, ductility, toughness, and flexural strength. The 10% of fiber amount was established whereas the amount of silica fume was taken as (5%, 10%, 15%, 20% and 25%).

In addition, such study included casting reinforced SIFCON beams of 1.2 x 0.1 x 0.2 m having 15% of silica fume taking various amounts of steel fiber content (6%, 8% and 10%). The test results indicated that the SIFCON beams with 10 % fiber content exhibited a good performance with respect to ductility and energy absorption. Increasing the fiber amount increased the toughness and ductility as illustrated in Figure (7).

Finally, it is also observed through that results that adding 15% of silica fume represents the optimum choice in regard with tensile and compressive strength.

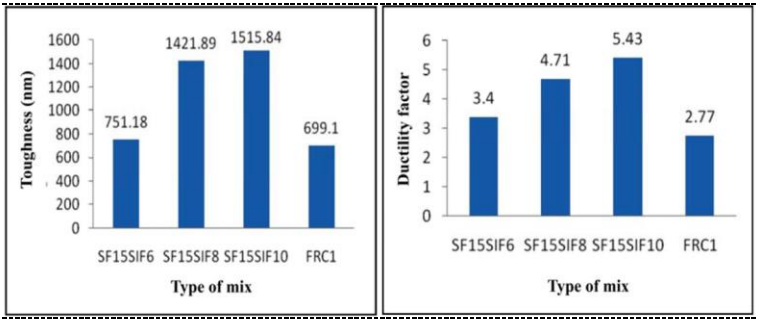

Figure 7 : Ductility and toughness of SIFCON (6%, 8% and 10% fiber) and FRC [16].

Kani, (2016) [13] investigated the strength and durability of SIFCON. The basic aim of that contribution is to calculate the "silica fume" and "ground granulated blast furnace slag (GGBFS)" role to the consequent "splitting tensile strength", "compressive strength", "durability behavior" and "flexural strength". The amount of steel fibers was established as 10% and the amounts of silica fume were taken as (5%, 10%, 15%, 20%, 25%) while the amounts (15%, 30%, 45%, 60%, 75%) were selected to GGBFS. It is found during that study that utilization of supplementary cementitious materials enhances the workability and consistency of fresh concrete due to the additional quantities of fines that were added to mixture. These materials adjust the "microstructure" of concrete and diminish its permeability through inhibiting the penetration of water. It is also deduced that replacement of silica fume increases the split tensile strength and compressive strength and 15% replacement was revealed as an optimum choice.

Additionally, the GGBFS addition illustrated good role with respect to durability and strength if compared to silica fume addition.

Pradeep and Sharmila, (2015) [23] evaluated the mechanical properties and flexural properties of SIFCON beams under cyclic loading comparison with traditional concrete. In that study, variables such as stiffness, maximum load, "energy absorption" and ductility were included. The slurry during that program comprised cement, fly ash, silica fume as well as GGBFS.

The findings of that study found that the performance of SIFCON beams were more than traditional. The compression strength and modulus of rapture of

SIFCON was higher than normal concrete by 33% and 179% respectively. The cumulative ductility factor of SIFCON beam was 131% more than conventional beam and the stiffness of SIFCON beam was 134% more than conventional beam, therefore, it is also concluded that SIFCON may be utilized as a good option where the concrete or conventional steel fiber reinforced concrete cannot achieve the desired levels where high strength is required.

7. Past Experience of Hybrid Fiber Concrete

As a matter of fact, when using one type of fiber in concrete some improvements are shown on the properties of the compound. If fibers are combined to form a hybrid that have two or more combinations, the hybrid composites show higher good engineering characteristics if compared with single form addition of fibers within the composites due to one fiber's capacity to serve as a trigger for the efficacy of the other. Past experience studies apparently illustrated that the inclusion of different array of hybrid fibers in concrete enhance the engineering role of concrete and advances to higher mechanical characteristics if compared with respect to the mono fiber reinforced concrete [30,31].

Kanagavel and Kalidass, (2017) [31] inspected the mechanical characteristics of hybrid fiber reinforced concrete. The mechanical characteristics were studied with respected to “flexural strength”, “splitting tensile strength”, “compressive strength” and impact resistance. The hybrid pattern of fibers that utilized during that study comprised polypropylene fibers Steel fibers in addition to carbon fibers.

The results of that research revealed the fact that the use of (polypropylene – steel – carbon) hybrid form may give an excellent mechanical strength concerning “compressive strength”, “flexural strength” and “splitting tensile strength”. figure (8) shows failure pattern of different specimens.

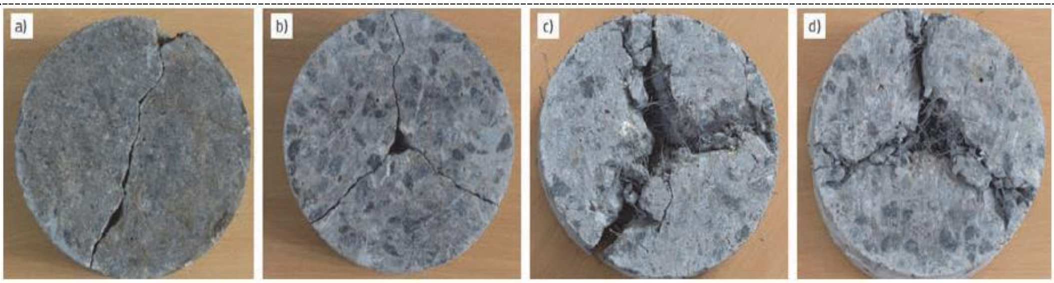

Figure 8: Failure modes: (a) Reference. (b) Carbon fiber only concrete. (c) Steel / carbon. (d) Polypropylene – steel – carbon [31].

Ali, (2018) [32] studied the hybrid SIFCON specimens that consisted of 6 %

hooked steel fibers and 2.5 % micro steel fibers. That study compared the results with hooked end specimens. The specimens have 100 mm for cubs and 100 x 200 mm for cylindrical specimens. The results showed that specimens reinforced with hybrid fiber have higher compressive, tensile strength, and density, impact, and lower loss in strength subsequent to cycles of "freeze- thaw" when compared with the "hooked specimens". Figure (8) shows the effect of hooked and hybrid form on the compressive strength of SIFCON mixes at different ages where M3-F8.5 refers to mortar of SIFCON with "8.5%" "end hooked" fibers and (20% fly ash +10% "silica fume") replacement defined by cement weight and M3- HF8.5 refers to mortar of SIFCON with "(+ 2.5% of micro steel fiber +6% of hooked end steel fiber)" and (10% silica fume+ 20% fly ash) replacement, defined by cement weight.

8. Reinforced Concrete Columns

8.1 The Slenderness Ratio

Columns can be classified as short or long with respect to slenderness ratio. The slenderness quantitative relation given by "kL/r", wherever kL is "the effective length" of column and r is the "radius of gyration" of column.

It is known that capacity decreased as the slenderness ratio increased since low level of slenderness ratio, lesser will be the strength of the column.

According to the (IS 2000) [33], the column is considered as "long" if the length is more than 12 times the smallest dimension of cross section and vice versa.

8.2 Reinforced Concrete Column Ductility

Ductility is the measure of a material to withstand plastic strain before fracture. In general, concrete is brittle material, but conversely, structural reinforced concrete members may illustrate a suitable ductile behavior if the proper design was followed. The main governing factor that influences the ductile nature of reinforced concrete members is the yielding point of steel reinforcement, therefore, full capacity of stress / strain of concrete within such members will be usually reached.

The ductility of a column is a measure of how much it loses strength at increased axial strain once the cover starts to fail. All the reinforced concrete members have a known concept regarding ductility according to the followed Codes. However, it is also known that the confinement of columns ingresses the consequent axial load capacity and ductility [34].

8.3 Reinforced Concrete Column Stiffness

Stiffness is the concept used to describe the rigidity of an object and / or the degree to which that object resists a change in shape. The correspondent conception is flexibility or pliability which draw the concept that when the object is stiff, the flexibility is low.

Within the same context, the stiffness (k) of an object tests the resistance to deformation that is given by that object. [34]. For an elastic body, the general mathematical relation that utilized to evaluate its stiffness (Hooke's law) as illustrated in Figure (9) is:

$$k = \frac{F}{\delta} \qquad (2)$$

Where:

F: is the force on the body.

δ: is the displacement produced by the force.

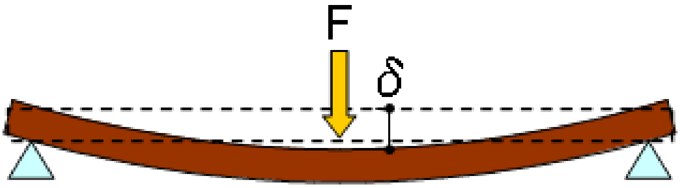

Figure 9: The stiffness of beam [40].

It is known that distribution of internal forces response, displacement and the fundamental period are basically estimated depending upon the column stiffness. In addition, the cross-sectional stress distribution / intensity and the extent of cracks will determine initial stiffness of a structural member. Due to flexural cracking increasing, the column's cross-sectional area and moment of inertia will be decreased and the column's initial flexural rigidity is decreased. This results in increasing uncertainty in the initial stiffness of RC members [36].

9. Pate Experience of Hollow Reinforced concrete Columns

Gaikwad and Kannan, (2017) [37] proved that the use of hollow columns has an economic advantage, it reduces the cost of construction and able to withstand the seismic load without failure. The research program comprised analyzing of a commercial building that have columns of solid section analyzed numerically by the software ETABS2016. The same building was re analyzed alternating hollow column sections ultimate possible load combinations by CSICOL9 software. That study included proposal of design data depending on the analyses results. Such presented research revealed the possibility utilizing columns that have concrete sections as an alternative to solid sections.

Kamath and Shilpa, (2017) [38] conducted numerical modelling to SIFCON columns utilizing ANSYS software to represent the response of combined SIFCON columns with reinforced concrete. That study investigated the nonlinear behavior of SIFCON. The amounts of SIFCON during that study program were taken as (0, 100, 20, 30, 40, 50) % which mean that the complementary amounts of reinforced concrete were (100, 0, 80, 70, 60, 50) %. All the sections during that research have section dimensions of 100 mm x100 mm and 1000 mm in length.

The results showed that the buckling load may be increased by 405 due to SIFCON replacement. Figure (10) show the displacement for 100% SIFCON column.

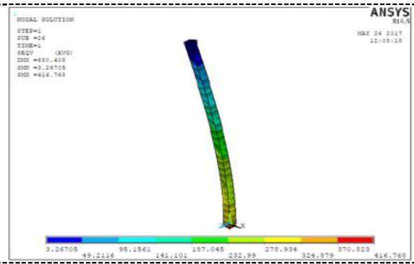

Figure 11: Displacement for 100% SIFCON column (Kamath and Shilpa, 2017) [38].

Mal, (2018) [39] investigated the behavior of hollow concrete column confined with PVC (Poly Vinyl Chloride) pipe. PVC materials have good mechanical properties as compared to other plastics and remarkable durability. “Concrete specimens” after 28 days curing tested for “splitting tensile strength”, “compressive strength” and “flexural strength”.

Concrete short columns were confined with polyvinyl chloride pipes (PVC). Two PVC pipes were used of diameter 110 mm and 315 mm with a thickness of 2 mm and 7.2 mm respectively and height of 510 mm. A total of 3 short hollow column specimens of external diameter 315 mm and internal diameter 110 mm and height 510 mm were cast as shown in plate (3). These reinforced hollow columns with and without PVC confined specimens are subjected to concentric compression loading.

a b

Figure 12: Specimen Details: (a) Conventional Columns (b) PVC Columns [39].

Test results indicated that as ultimate load carrying capacity for PVC confined columns is more than conventional columns. Ultimate strength for columns with hollow section confined with PVC, increased by 48.41% as compared to reinforced concrete conventional hollow columns.

Failure of conventional columns was observed to be brittle and by crushing of core concrete, while the failure of PVC confined columns occurred to be ductile and by bulging of core concrete.

10.Conclusions

The reviewed literature demonstrates in the field of SIFCON that there have been a limited number of studies conducted in studying and mechanical characteristics of SIFCON. Future work in this area needs to be focused on developing detailed analytical model which should be capable of accounting for these factors. The following remarks can be evaluated from the review of recent contributions:

- Compared with plain concrete, SIFCON has outstanding properties such as durability, energy absorption capability, ductility, stiffness, impact and abrasion resistance.
- The matrix strength, composition and the fiber orientation have great effect on the strength characteristics of SIFCON.
- The flexure / split tensile strength and compressive strength increase as fiber volume increase.
- The hybrid composites show excellent mechanical characteristics if compared with the inclusion of a one type of fibers in the matrix.
- Fiber shape controls the level of mechanical intertwine (between fiber and

matrix) as well as (the fibers themselves).

- The cement slurry (no fibers) employed within creating SIFCON typically produces 25 to 35 MPa in one day, and strength levels of 50 - 70 MPa in 28-day, While the comparable levels in SIFCON are 40 - 80 MPa and 90 - 160 MPa related to the steel fibers content incorporated in the network

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مراجعة حديثة لسلوك السيفكون كعضو هيكلي

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المستخلص: يمكن اعتبار مركبات "خرسانة الألياف المتسربة الطينية (السيفكون)" بمثابة اتجاه جديد في مجالات الهندسة المدنية التي لها تأثير محفز. عادة ما يتم تصنيع هذه المركبات عن طريق تسلل ملاط الأسمنت مع مصفوفة ألياف الصلب للحصول على مستوى عالٍ من الخواص الميكانيكية. خرسانة الأسمنت البورتلاندي ضعيفة الشد وقد لا توضح هوامش شد كبيرة. تم استخدام مواد مثل الفولاذ والأوتار سابقة الإجهاد تاريخياً لتجنب هذه القيود المفروضة على الأسمنت. الخمسة عشر عاما الماضية. زاد الاهتمام بين استخدام ألياف فولاذية متقطعة ومنفصلة للتعزيز البديل أو التكميلي. الألياف لهذا الاستخدام لها أقطار تتراوح بين 0.01 إلى 0.35 بوصة (0.25 إلى 0.9 ملم) وأطوال تتراوح من 0.5 إلى 3.0 بوصة (12.7 إلى 76.2 ملم). ومع ذلك ، فإن الوظائف الرئيسية للألياف الفولاذية هي تعزيز مقاومة الصدمات. عن طريق ليونة التكسير الإيجابي ، يمكن التحكم في التكسير ونمط الفشل. لزيادة الأداء فيما يتعلق بقوة الشد وكذلك قوة الانحناء.

الكلمات المفتاحية: سيفكون ، حديد فولاذي ذو نهاية معطوفة ، حديد فولاذي ميكروي ، مقاومة الشد ، مقاومة الكسر ، مقاومة الانضغاط ، خلطة السيفكون

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