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A Critical Review of Mechanical, Physical and Durability Properties of Slurry Infiltrated Fibrous Concrete (SIFCON)

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ABSTRACT

The recent development of slurry infiltrated fibrous concrete (SIFCON) was discussed in this paper. The amount of fibers usually does not exceed 20% of the total concrete volume. SIFCON is of specific benefits in civil engineering owing to its excellent mechanical properties such as high compressive strength, high strain during compression, and good ductility. SIFCONs prepared using cement as a binder alone or by adding pozzolanic materials, such as silica or silica and alumina, were explored. The materials have a high degree of fineness (high surface area), and in the presence of water, they react chemically with calcium hydroxide at normal temperatures to form compounds, such as fly ash, slag, silica fume, and metakaolin, with cementitious properties. The effects of different types of fiber and their geometric shape, whether straight, hooked-ends, or other shapes, on the mechanical properties of SIFCON were reviewed. The properties of SIFCON, such as compressive strength, splitting strength, flexural strength, impact resistance, abrasion resistance, and water absorption, were discussed on the basis of important mechanical tests. The results of non-destructive tests, such as pulse transmission velocity test and rebound number by Schmidt hammer, were deliberated.

1. INTRODUCTION

Concrete is the most common material used in construction industries owing to its many applications such as slabs, columns, beams, and foundations. The main properties of concrete are high strength, compression stress, service life, durability, workability, and availability. Concrete is considered not expensive [1]. However, concrete has some limitations such as the weakness in tensile strength due to its brittleness. One of the methods to enhance the properties of concrete is by using steel fiber to prepare composite materials known as slurry infiltrated fibrous concrete (SIFCON) [2].

SIFCON is a unique type of high-performance concrete invented by Lankard in 1979; SIFCON is a highly specialized composite concrete material. It makes use of a low-viscosity cementitious slurry injected into a bed of steel or synthetic fibers that has already been put (5-20% by volume). it is a special state of concrete used in applications that require excess ordinary concrete tasks such as tensile strength, crack impedance, and stiffness [3]. SIFCON provides good tensile properties, improves toughness, and lowers concrete brittle function, these properties are improved by the effect of the fibers, as the fibers can withstand tensile and impact loads [4]. Conventional concrete is sufficient for many applications, so there is no need to use SIFCON if the construction requirements are low, as it should be taken into account that SIFCON concrete requires more cost and skill. In the present paper, the recent advancements in SIFCON, including preparation, the effect of different types of steel, and different types of binder, were discussed.

2. PREPARATION OF SIFCON

SIFCON is usually prepared using a consistent preparation of fibers, laying them in layers, followed by the work steps illustrated in Figure 1. Then, the cement slurry is poured in stages to ensure that the slurry penetrates all parts of the concrete. The percentage of fibers used depends on the length-to-width ratio of the fibers and their geometric shape, such as straight, hooked, and wavy, as shown in Figure 2, where increasing the amount of fibers is possible if the aspect ratios are high. In general, the volumetric fiber percentage ranges from 5% to 20% of the total volume of concrete [5]. Also, an ideal mixture for SIFCON cannot be determined in advance because this depends on a number of factors such as the surface area of the cement (fineness), the proportions of the cement components and the working temperature.

2.1 Effect of fiber types on mechanical properties of SIFCON

The mechanical characteristics of SIFCON change depending on the types, amount, dimensions, and mechanical properties of fibers. Thomas and Mathews [6] examined the effect of steel and polypropylene fibers on compressive strength, flexural strength, and split tensile strength. The steel fibers had a diameter of 1 mm and a length-to-diameter ratio of 50, and the polypropylene fibers had a length of 50.8 mm. Tests were conducted on SIFCON containing 4 vol%, 5 vol%, and 6 vol% fibers. The optimal properties were obtained for steel fibers with a 5 vol% volume ratio, resulting in a compressive strength of 39.8 MPa, a split tensile strength of 8.06 MPa, and a flexural strength of 12.8 MPa. Similarly, the optimal properties for polypropylene fibers exhibited a volume ratio of 5 vol%, a compressive strength of 32.3 MPa, a split tensile strength of 7.06 MPa, and a flexural strength of 7.13 MPa. Giridhar at al. [7] conducted an investigation on different volume fractions of steel fibers for SIFCON. Steel fibers manufactured by Bekaert Corporation were utilized specifically the Dramix 3D variant. The utilized fibers had two types: hooked-end fibers measuring 50 mm in length and 1 mm in diameter and hooked-end fibers measuring 35 mm in length and 0.55 mm in diameter. These fibers were incorporated into the concrete mixture at volume fractions of 4%, 6%, and 8%. The optimal outcomes were obtained with 8 vol% and steel fibers of 35 mm in length. The optimal SIFCON sample had a compressive strength of 120 MPa, a splitting strength of 3.08 MPa, and a flexural strength of 8.90 MPa. Sippriya et al. [8] investigated the properties of SIFCON by partially and completely replacing coarse aggregate with crimped steel fiber for concrete grade M20. The best result was achieved when completely replaced coarse aggregate with fibers, manifested by an increase in the compressive strength value by 44% and an increase in the splitting strength by 68% over the reference mixture that did not contain fibers. Kumar and Rajasekhar [9] used manufactured sand as an alternative to traditional sand in producing SIFCON and then subjected SIFCON to high elevated temperature (300℃). The mechanical properties of the overall samples improved at high temperature. Straight fibers were used in different percentages of 8 vol%, 10 vol%, and 12 vol%. The best result was obtained when 12 vol% fibers were used, with the compressive strength reaching 46.51 MPa and the splitting strength reaching 9.1 MPa.

Table 1. Mechanical properties of SIFCON with varying types of fiber

Amount of Cement kg/m^3	**Type and Percent of Fiber (Aspect Ratio)**	**Max. Compressive Strength MPa (the Percent of Increase %)**	**Max. Flexural Strength MPa (the Percent of Increase %)**	**Max. Splitting Strength MPa (the Percent of Increase %)**	**References**
1:2 cement: sand	4 vol%, 5 vol% and 6 vol% Hooked Steel fibers 4 vol%,5 vol% and 6 vol% Polypropylene (50%, 50.8 length)	39.8	12.8	8.06	Thomas and Mathews [6]
Grade 35 1:1 cement: sand	4% 6% and 8% hooked steel	120	8.90	3.08	Giridhar et al. [7]
383.16	Crimped Steel fiber 50 vol% and 100 vol% of coarse aggregate	32.23 (44%)		3.82 (68%)	Sippriya et al. [8]
1:1 cement: sand	Straight 8,10, 12 vol% (50)	46.51	------	9.1	Kumar and Rajasekhar [9]
960 kg/m^3	0, 0.5, 1, 2, 3, 4 and 5 vol% waste steel fibers from different tire recycling plants	96.4	63.8	25.4	Sengul [10]
1:1 1:1.5 Cement:sand	2,6and 8 vol% hooked and straight steel fibers	78.2	20.43	78.2	Ali and Riyadh [11]
900	Hooked end 6 vol% by volume (58)	77.7 (104%)	20.3 (480%)	-	Alrubaie et al. [12]
350	Steel fiber 2, 4, 6 vol%(50)	34.44	12.42	5.35	Kchaitanya et al. [13]
886	macro hooked end steel fibers 4% (70) micro steel fibers 7 vol% (65) micro polypropylene fibers 3 vol% (315)	49.8 (39.89)	17.61 (466)	--------	Naser and Abeer [14]
1:1.08 cement: sand	Crimped steel fibers (60) (60)	53.74 with plastic sheet	8.89 with plastic sheet	----	Najeeb and Fawzi [15]
None menthion	Straight	41.1	25.3	----	Çelikten and Canbaz [16]
885	6,7 and 8.5 vol% hooked steel	113.88	35	17	Abbas and Mosheer [17]
non	7 vol% hooked steel (55)	52.41	18.97	4.98	Bayrak [18]

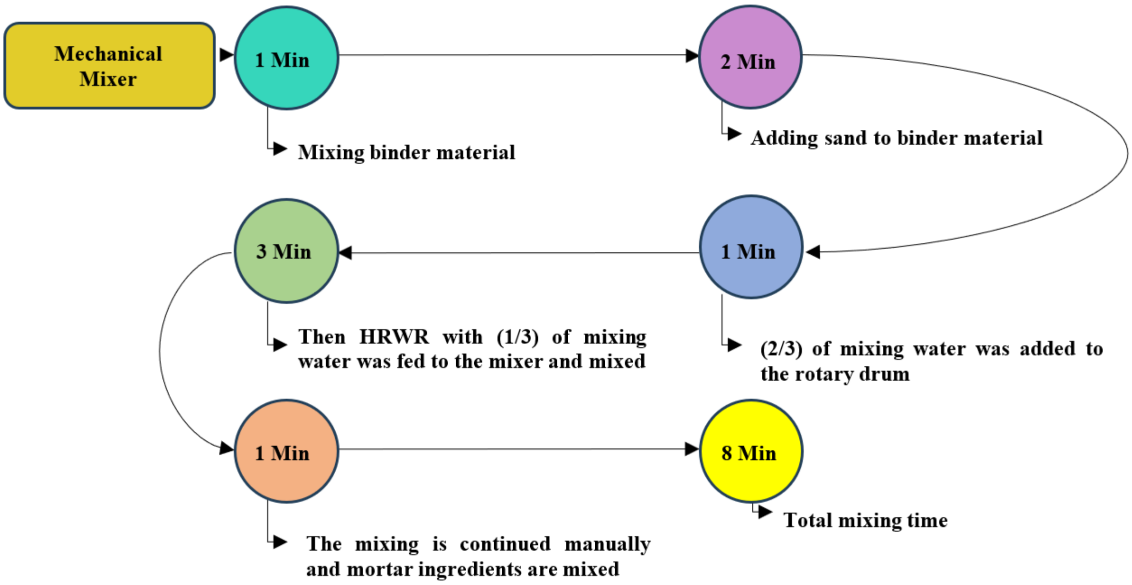

Figure 1. Steps of slurry mixing [5]

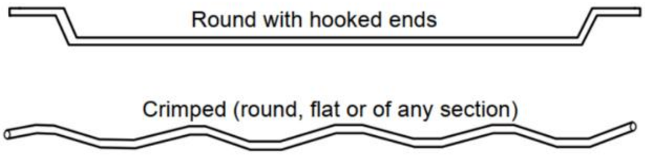

Figure 2. Types of steel fiber [5]

Sengul [10] utilized wasted steel fibers obtained from waste tires to manufacture SIFCON. The wasted steel fibers may be classified as a hybrid because of their diverse geometrical properties, and they were present in combination with various aspect ratios ranging from 0 vol% to 5 vol% by volume. The highest achieved values were 96.4 MPa for compressive strength, 25.4 MPa for split tensile strength, and 63.8 MPa for flexural strength. Ali and Riyadh [11] performed an experimental and computational investigation on slurry infiltrated fiber reinforcement by conducting tests on samples. Three distinct volume ratios of hooked and straight steel fibers were employed: 2 vol%, 6 vol%, and 8 vol%. The highest achieved results were a compressive strength of 78.2 MPa, a splitting strength of 16.21 MPa, and a flexural strength of 20.43 MPa.

Hameed et al. [12] investigated the mechanical properties of SIFCON with the addition of 6 vol% hooked steel fiber in concrete. The tests showed improvement in all mechanical properties with the addition of steel fiber. An increase in compressive strength by 104% was observed, and the flexural strength increased by 480% compared with that of fiber-free mixture. Kchaitanya et al. [13] studied the mechanical properties of SIFCON by using steel fibers cut from steel wire with an aspect ratio of 50 and subjected to annealing treatment. The following percentages were used: 2%, 4%, and 6 vol%. The best percentage of the fibers was 6 vol%, with the compressive, flexural, and splitting strengths reaching 34.44, 12.42, and 5.35 MPa, respectively.

Naser and Abeer [14] studied the effect of different types of fiber, such as straight and hooked steel fibers, and polypropylene fiber on the flexural and compressive strength of SIFCON. The best flexural strength was obtained when using 4 vol% hooked fibers. It was an increase of 466% compared with that in mixture without fibers. The best compressive strength value was obtained using 7 vol% straight fibers, achieving an increase of 39.89% compared with that in fiber-free mixture, because straight fibers have a higher aspect ratio than hooked fibers, and the effect of steel fibers is higher than that of polypropylene fibers. Najeeb and Fawzi [15] studied the influence of plastic strips and plastic sheets in SIFCON slurry containing crimped steel fiber. Three sets were established: normal SIFCON as control, SIFCON with plastic strips, and SIFCON with plastic sheet. The best result was obtained when using the plastic sheet, where the compressive strength value reached 53.74 MPa and the flexural strength value reached 8.89 MPa. Çelikten and Canba [16] conducted a study on the use of steel obtained from tires waste in the manufacturing of SIFCON concrete. This study involved the use of various types of cement, including high alumina cement, ordinary Portland cement, and kiln cement. The mechanical properties exhibited a 40% variation across various types of cement. The most optimal properties were attained using ordinary Portland cement, resulting in a compressive strength of 41.1 MPa and a flexural strength of 25.3 MPa.

Abbas and Mosheer [17] performed an empirical investigation to enhance the mechanical efficiency of a SIFCON mixture by altering the fiber quantity. Multiple SIFCON mixtures were produced using hook-end steel fibers with three distinct volume fractions (6 vol%, 7 vol%, and 8.5 vol%) and an aspect ratio of 60. The highest results obtained were 113.8 MPa of compressive strength, 17 MPa of split tensile strength, and 35 MPa of flexural strength. Bayrak [18] reported an experiment on the flexural, compressive, and splitting strengths of SIFCON reinforced with glass and steel fibers. The glass and steel fibers had an aspect ratio of 55:1 at 7 vol%. The maximum attained properties were 52.41 MPa of compressive strength, 4.89 MPa of split tensile strength, and 18.97 MPa of flexural strength.

In general, most research agrees that the aspect ratio is the main influencing factor for compression strength. As for splitting and bending strengths, the mechanical properties of SIFCON are affected by three factors: aspect ratio, amount of fibers and preference for fibers with hooked ends over straight fibers if they have a similar aspect ratio. It was also noted that the tensile properties (flexure and splitting) increase more with increasing amount of fibers as in study [12] compared to the low percentages of fibers in studies [6, 7, 10]. The most prominent results of the above are listed in Table 1.

2.2 Effect of various additives and types of fiber on mechanical properties of SIFCON

Many studies reported on the mechanical characteristics of SIFCON with different additives. Beglarigale et al. [19] studied the effect of water/binder ratio and slag on the flexural and compressive strengths of SIFCON containing 10 vol% hooked steel fibers. The maximum value of the results was 83 MPa compressive strength and 18.1 MPa flexural strength. Jain and Kumar [20] investigated the impact of incorporating slag into SIFCON at various proportions, ranging from 0 vol% to 30 vol%, on its flexural strength. Fibers were added at 3 vol%, 6 vol%, and 9 vol% relative to the total volume of concrete. The most effective combination was obtained for 9 vol% fiber content with the addition of 10 vol% slag, which led to a flexural strength of 19.9 MPa. Salih et al. [21] studied the effect of hooked fibers at 6%, 8.5%, and 11 vol% on the properties of SIFCON concrete that contained 10% silica fume. The optimal results were obtained with 11 vol% fiber, producing a compressive strength of 83.7 MPa and a splitting strength of 17.3 MPa. Sharma et al. [22] used hooked steel fibers (2 vol%, 3 vol%, and 4 vol%) of concrete and steel slag at 0 vol%, 10 vol%, and 20 vol% replacement of cement and studied the effect of these parameters on the mechanical properties of SIFCON. The best results were obtained when using fibers with 4 vol%, which increased the compressive strength by 10.9% when using 10% slag compared with slag-free mixture. The flexural strength increased by 2.9% and the splitting strength increased by 20.3% when using slag by 20% compared with the mixture without slag. Vijayakumar and Kumar [4] studied the effect of replacing 50 vol% of cement with fly ash on compressive strength when producing SIFCON by using straight steel fibers in different percentages of 5 vol%, 7 vol%, 9 vol%, and 11 vol% with adding 1 vol% of polypropylene fiber. The results showed an increase in compressive strength by 28% when using the above additives, with 9 vol% of steel fibers compared with that in the mixture devoid of fly ash and fibers.

Azoom and Pannem [23] used slag as a partial substitute for cement (half the amount of cement) and two types of fibers: straight steel fibers in different percentages of 6%, 8%, 10%, and 12 vol% and polypropylene fibers in different percentages of 0.7%, 1%, 1.3%, and 1.6 vol%. The best result of compressive strength was obtained when using 10 vol% steel fibers with fly ash, with an increase of 117% compared with the reference mixture. The exact percentage added above achieved an increase in splitting strength of 300%. The best value of flexural strength was obtained using 12 vol% steel fibers using fly ash, with an increment of 1014% compared with the reference mixture. Shelorkar and Jadhao [24] examined the impact of incorporating metakaolin and fly ash on the compressive strength of SIFCON concrete that includes end-hook fibers. Different ratios of 2 vol%, 3 vol%, and 4 vol% of the concrete volume were used. The most favorable outcomes were attained after using a fiber ratio of 4 vol%. The optimal proportion of metakaolin was 5% of the weight of the cement, and the ideal proportion of fly ash was found to be 7.5% of the weight of the cement. The compressive strength was 98.6 MPa, representing a substantial 70% enhancement compared with the reference mixture.

Patil et al. [25] replaced cement with 10%, 15%, 30% and 40% fly ash by weight of cement and used fiber by variable percent 2%, 4% and 6 vol% and have different aspect ratio 80, 90, 100 and 110. The best fly ash was obtained with 30% as replacement of cement, in which the properties increased with an increase in the aspect ratio of the fibers. The highest splitting strength was at 30% fly ash, with an increase of 447.44% compared with the reference mixture free of fibers and fly ash. Shelorkar and Jadhao [26] studied the mechanical properties of SIFCON containing 2 vol%, 3 vol%, and 4 vol% hooked fibers with 0%, 10%, and 20% wt. of slag replacement by weight of fine aggregate. The optimal results were achieved with 4 vol% fibers and 10% wt. of slag replacement, yielding a compressive strength of 70.67 MPa, a splitting strength of 10.41 MPa, and the highest flexural strength of 18.29 MPa. Soylu and Bingöl [27] conducted a study on the mechanical properties of SIFCON concrete with the addition of silica fume, which constituted 10% of the weight of the cement. Steel fibers were incorporated into the concrete mixture with varying 4 vol%, 8 vol%, and 12 vol% of the total volume of the concrete. The optimal mechanical performance was attained using 8 vol% of steel fibers, yielding a compressive strength of 80.12 MPa and a flexural strength of 35.85 MPa.

Ipek and Aksu [28] studied the effect of silica fume on the properties of SIFCON, which consisted of straight steel fibers with variable aspect ratios and polypropylene fibers. They used fibers with varying volume mixtures of 1:1, 1:3, and 2:3 and then analyzed the flexural strength. The best result was obtained when using two types of hooked steel fibers with different aspect ratios, with a replacement of 7.66 vol% of the concrete volume by steel fiber and over the entire height of the concrete, where the flexural strength reached 44.02 MPa.

Abd-Ali and Essa [29] reported on the effect of silica fume on the mechanical characteristics of SIFCON by using different percentages of 2 vol%, 6 vol%, 7.5 vol%, and 9 vol% of steel fiber with two different lengths of 6 and 3.5 mm and same diameter. The results showed that the concrete contained 20 wt% silica fume by weight of cement and 9 vol% of steel fiber by volume of concrete, with 6 mm length having better results than the reference sample. The compressive, flexural, and splitting strengths increased by 86%, 909%, and 561%, respectively, compared with the reference mixture free of fibers and silica fume. Meanwhile, SIFCON casted using 10 vol% steel fiber was difficult to cast because the slurry needed more workability.

Hashim and Kadhim [30] studied the effect of heat on the compressive strength of SIFCON that contained partial replacement of cement by silica fume. Straight and hooked-end fibers were used with aspect ratios of 65 and 60, respectively. The results showed that the higher the temperature and the longer the period the SIFCON was exposed, the more the SIFCON condition deteriorated. When SIFCON was exposed to 900℃ for 3 h, the compressive strength decreased by 47.9%. Nadia Moneem et al. [31] studied the effect of partial replacement of cement with silica fume and fly ash on the splitting, flexural, and compressive strengths. They replaced 10% of the weight of cement with silica fume and 20% of the weight of cement with fly ash. They used straight steel fibers with an aspect ratio of 65. The effect of fibers on the results of all mechanical tests caused an increase in compressive, flexural, and splitting strengths by 69%, 141%, and 164%, respectively, compared with the reference mixture that did not contain fibers.

Sonone et al. [32] investigated high-performance concrete by using SIFCON and used steel fiber in different volume fractions of 0 vol%, 3 vol%, 5 vol%, 7 vol%, 9 vol%, and 11 vol%. They reported that the mechanical properties were enhanced by increasing the percentage of steel fibers and concrete, in which 9 vol% fiber showed the optimal compressive, flexural, and splitting tensile strengths. They also reported that the aspect ratio of 100 gave better results than the aspect ratio of 80 in the flexural strength and splitting strength tests. However, an opposite behavior occurred in the compressive strength analysis. Khamees et al. [5] reported on the mechanical characteristics of SIFCON and how it is affected by aspect ratio, steel fiber shape, diameter, and length. Three groups with 6% fiber volume fraction were used: straight, hooked, and hybrid. In general, the results of straight steel fiber were better than those of hooked steel fiber because the former had a higher aspect ratio. Thus, the fibers exhibited high surface area for binding with concrete. The compressive strength test results when using straight fibers were 10% greater than the compressive strength when using hooked fibers. Moreover, the results of the splitting strength test when using straight fibers were 15% greater than when using hooked fibers.

Akçaözoğlu and Kıllı [33] conducted a study on the properties of SIFCON concrete. This form of concrete included two additives: silica fume and slag and end-hooked fibers. The steel fibers were added in proportions of 4 vol% and 8 vol% of the total volume of the concrete. The maximum compressive strength attained was 110.55 MPa, and the greatest recorded flexural strength was 38.28 MPa. Ali et al. [34] performed a study on SIFCON concrete, which involved using a substantial amount of fly ash (45% of the weight of the cement) and added bent steel fibers at rates of 5 vol%, 7.5 vol%, and 10 vol% of the volume of the concrete. The concrete was subjected to two distinct curing conditions: natural curing for the initial portion and steam treatment for rapid maturation in the subsequent portion. The optimal properties were achieved for the sample with 10 vol% steel fibers and applied steam treatment. The compressive strength exhibited a 55% increase compared with the reference combination. The splitting strength significantly surged by 410%, and the flexural strength soared by an impressive 820% over the values of the reference mixture.

Altuncı and Öcal [35] studied the impact of peanut shell ash on SIFCON, which was a mixture made of cement and silica fume. Steel fibers were added to the concrete at a rate of 10 vol% of the concrete volume. The results revealed that the mixture free from peanut shell ash yielded the most favorable effects. The compressive strength achieved 76.6 MPa, and the flexural strength was 12.05 MPa. Özalp [36] reported on the mechanical properties of SIFCON, in which the binder contained a combination of cement and silica fume. The study emphasized the utilization of two categories of fibers: hooked steel fibers integrated into the concrete at proportions of 4 vol% and 8 vol% of the overall volume and polyolefin fibers introduced at a proportion of 4 vol% of the overall volume. The best outcomes were obtained by adding hooked steel fibers at a rate of 4 vol%, which led to a compressive strength of 98.2 MPa, a flexural strength of 46.47 MPa, and a splitting strength of 18.47 MPa.

Hamed and Abass [37] used steel fiber with a dimension of 0.25–0.9 mm diameter and 12.7–76.2 mm length as a substitute reinforcement in ordinary Portland cement concrete with silica fume as additives to enhance tensile properties such as flexural and splitting strengths. The results showed that hooked fibers were generally better than straight fibers in enhancing tensile properties. The bending strength test was 32% greater than when using straight fibers. The splitting strength of SIFCON containing hooked fibers was 39% greater than that of straight fibers. Robayo-Salazar et al. [38] studied the possible utilization of ceramic waste in the production of SIFCON concrete, where ceramic waste was finely crushed and used as a substitute for cement, with weight ratios of 0% and 90%. Steel fibers with a wavy shape were added to the concrete mixture in a proportion of 4.5 vol% of the total volume of the concrete. The results revealed that the use of ceramic waste led to a reduction in compressive and flexural strengths. The maximum recorded compressive strength was 28 MPa, and the greatest achieved flexural strength was 15.9 MPa. Alsheameri et al. [39] investigated the compressive strength of SIFCON, where the binder consisted of a blend of cement and silica fume. Steel fibers were added to the concrete mixture at a rate of 6% of the total concrete volume, resulting in a significant 260% increase in compressive strength compared with the reference mixture. Jerry and Fawzi [40] investigated the impact of fiber additions on the splitting strength of SIFCON concrete that was composed of cement and silica fume as binding materials. Two types of fibers were employed at a rate of 6 vol% of the concrete volume: hooked steel fibers and polyolefin fibers. Various combinations of fibers were tested, including cases with only steel fibers, a mix of steel fibers and polyolefin fibers in ratios of 1:3 and 2:3, and polyolefin fibers alone. The results showed that using steel fibers alone yielded the highest splitting strength, reaching 18.8 MPa. Gültekin [41] explored the compressive strength of SIFCON concrete by combining a range of components such as kaolin, limestone aggregate or recycled aggregate from bricks and pavements. Steel fibers with hooks were incorporated into the concrete mixture at a proportion of 7.95% of the total volume of the concrete. The SIFCON with limestone aggregate yielded the highest compressive strength value, reaching 72 MPa. Hashim and Al-Shathr [42] investigated the flexural strength of SIFCON concrete, in which the binder was composed of cement blended with silica fume. The natural aggregate was altered by adding rubber powder at weight percentages of 0%, 5%, 10%, and 15%. Hooked fibers were incorporated into the concrete mixture at a proportion of 4 vol%. The concrete samples were exposed to 25℃ and 600℃. The findings revealed that the samples without rubber powder, subjected to 25℃, exhibited the highest flexural strength value of 22.5 MPa.

The findings above showed that adding pozzolanic powders improved the properties of SIFCON, especially the tensile properties, considering that they are not added in ratios exceeding 30% of the weight of the cement. Since pozzolanic materials are usually characterized by higher fineness (higher surface area) than cement, it is necessary to consider adding more plasticizers to obtain the required workability. It is necessary to go further when using high proportions of pozzolanic materials, as they reduce basicity and thus require the addition of basic solutions (as in geopolymers) such as sodium hydroxide, potassium hydroxide, glass water, etc. As for the fibers' shape and dimensions, their effect was discussed in a previous section. The most prominent research results mentioned above are listed in Table 2.

Table 2. Mechanical properties of SIFCON with varying additives and varying types of fibers

Amount of Cement kg/m³	Type and Weight of Additive kg/m³	Type and Percentage of Fiber (Aspect Ratio)	Max. Compressive Strength MPa (the Percent of Increase %)	Max. Flexural Strength MPa	Max. Splitting Strength MPa	References
400	Slag 400	Hooked end 10% (64)	83	18.1	------	Beglarigale et al. [19]
None mention	Slag (0, 10, 20 and 30)% of weight of cement	Straight (50)	-	19.9	-	Jain and Kumar [20]
885	Silica fume 10% of weight of cement	Hooked steel fiber (50)	83.7	-	17.3	Ali et al. [21]
714.28	Slag 0, 10, 20% of cement	Hooked end 2, 3, 4% (60)	70.76 (10.9%)	18.61 (2.9%)	10.41 (20.3%)	Sharma et al. [22]
1:1 cement: sand	Fly ash (50% of cement)	Straight steel 5, 7, 9, 11% (75) Polypropylene 1%	36.98 (28%)	-------	--------	Vijayakumar and Kumar [4]
1:1:2 cement: GGBS: sand	GBSS	Straight steel fiber 6, 8, 10, 12% (50) and polypropylene fiber 0.7, 1, 1.3, 1.6% (857)	71 (117%)	30.1 (1014%)	8.4 (200%)	Azoom and Pannem [23]
None mention	Fly ash and metakaolin (5, 7.5, 10)% of weight of cement	Hooked steel fiber (58.33)	98.6	-	-	Shelorkar and Jadhao [24]
1:1 cement: sand	Fly ash (10, 15, 30, 40) by weight of cement	Straight 2, 4, 6% (80, 90, 100, 110)	-	-	16.04 (447.44%)	Patil et al. [25]
None-mention	Slag (0, 10 and, 20)% by weight of sand	Hooked (2, 3, and 4) (58.33)	70.67	18.49	10.41	Shelorkar and Jadhao [26]
800	Silica Fume 80	Straight 4, 8, 12 (40, 55, 65, 80)	80.12	35.85	-	Soylu and Bingöl [27]
900	Silica fume 270	Hooked steel fiber (57.1), (63.6), and straight steel (37.5) and polypropylene fiber (500)	-	32.44	------	Ipek and Aksu [28]
800	Silica fume 80	Straight steel fiber 4, 8, 12 (40, 55, 65, 80)	80.12	35.85	-	Soylu and Bingöl [27]
1000	Silica fume 10, 15, 20%	Hooked end 0, 2, 6, 7.5 , 9 (30 & 60)	81.1 (86)	55.9 (909)	18.5 (561)	Abd-Ali et al. [29]
872.4	Silica Fume 96.9	Steel fiber 6% (Micro steel fiber 3% (65) and hooked end 3% (60))	98.41	--------	---------	Hashim and Kadhim [30]
1:1 cement: sand	Silica fume 10% of cement and fly ash 20% of cement	Micro steel fiber 6% (65)	110 (69)	24 (141)	19 (164)	Nadia Moneem et al. [31]
Non-mention	Silics fume (Non-mention)	Waved 3, 5, 7, 9, 11% (80 &100)	97.75 (204)	46.1 (919)	19.68 (496)	Sonone et al. [32]
872.1	Silica fume (96.9)	Straight 6% (65) and Hooked 6% (60)	124.7 (there is no reference sample)	-	20.8 (no reference sample)	Sonone et al. [32]
855.9	Silica fume 95.1	Straight 8, 10, 12 (65) and Hooked 8, 10, 12 (50)	-	41.54 (there is no reference sample)	19.63 (no reference sample)	Khamees et al. [5]
700	Slag 200 & silica fume 100	Hooked 4 & 8 (40and 55)	110.55	38.28	-	Akçaözoğlu and Kıllı [33]
550	Fly ash 450	Hooked 5, 7.5, 10 (54.45)	92.6	38.5	19.3	Ali et al.[34]
1000	Silica fume 74.36 Peanut shell ash (0, 2.5, 5, 7.5, 10)% by weight of cement	Straight 10% (53.33)	76.6	12.05	-	Altuncı and Öcal [35]
1000	Silica fume 250	Hooked steel fiber 4 and 8% (80) Polyolefin 4% (100)	98.2	46.47	18.47	Özalp [36]
1835.7	Ceramic waste (0, and 90)% by weight of cement	Crimped steel fiber 4.5% (16.66)	28	15.9	15.7	Robayo-Salazar et al. [38]
875.5	97.3	Straight steel fiber 6% (65)	86	-	-	Alsheameri et al. [39]
796.5	88.5	Hooked steel fiber 6% (63.6) and polyolefin 6% (66.67)	-	-	18..8	Jerry and Fawzi [40]
605 and 640	Kaolin 63 and 73	Hooked steel fiber 7.95% (40)	61.2	-	-	Gültekin [41]
872.4	96.9	Hooked steel fiber 4% (70)	-	22.5	-	Hashim and Al-Shathr [42]

2.3 Effect of fibers on water absorption of SIFCON

Water absorption property is characterized by the ability to absorb water, The presence of fibers with cement increases absorption, so that the absorption of cement containing fibers becomes two to five times higher than the same mortar without fibers [43], likely due to the emergence of an interfacial transition zone at the periphery of the fibers [44]. Algın et al. [45] reported that adding silica fume to SIFCON reduced the variation in absorption properties due to the role of silica fume in filling the interstitial spaces between the fibers and the binder, because silica fume is characterized by high fineness (high surface area) more than twice the surface area of cement, its small size allows it to penetrate into the spaces available in the concrete mixture, including the spaces between the fibers and the binding material.

Many studies have addressed the effect of fibers used in fiber-reinforced concrete on the percentage of water absorption. Okeola et al. [46] studied the effect of sisal fibers on the amount of water absorption of concrete reinforced with sisal fibers and used fibers at rates of 0%, 0.5%, 1%, 1.5%, and 2% of the volume of concrete. The highest absorption rate was obtained when using fibers at a rate of 2%, reaching 7.285%, which was an increase of 49% over the concrete without fibers. Ruben et al. [47] discussed the effect of glass fiber on fiber-reinforced concrete. The negative effect of fibers appeared when used at a rate of 3% or more of the concrete volume. An increase in absorption appeared when using 3% fibers by 30% compared with using 2.5% fibers. Jamshaid et al. [48] studied the effect of jute, sisal, sugarcane, and coconut fibers on the water absorption of fiber-reinforced concrete. Fibers were used in variable proportions of 0%, 0.5%, 1%, 1.5%, 2.5%, and 3% of the concrete volume. The results showed that the absorption increased with the increase in the amount of fibers, reaching the maximum value when using 3% coconut fibers, reaching 9.25%, an increase of 76% compared with using 0.5% fibers. Althoey et al. [49] studied the effect of bamboo fibers and bamboo fibers modified with rubber, used each type of fibers individually, and then explored their effect in a combined manner. Increasing the fibers increased the amount of absorption. The highest percentage of water absorption reached 9.2% when using bamboo fibers when adding 1.5% bamboo fibers modified with rubber at a rate of 1% together of the volume of the concrete, which was 56% more than the reference mixture without fiber. Hussien [50] discussed the effect of polyvinyl alcohol fibers on the amount of water absorption of fiber-reinforced concrete. Variable percentages of fibers at 0%, 0.125%, 0.25%, 0.375%, and 0.5% of the volume of the concrete were used. The results showed that the absorption percentage increased when using fibers in quantities greater than 0.25%, where the highest value reached 5.75% when using fibers in an amount of 0.5%, demonstrating an increase of 41% over the mixture without fibers. Tao and Hadigheh [51] discussed the effect of carbon fibers and glass fibers (each separately) on the water absorption of fiber-reinforced concrete. The fibers were used in variable proportions of 0.1%, 0.5%, and 1% of the concrete volume. The highest absorption value of 16.95% was obtained when using 1% glass fibers, where the increase rate was 34% compared with the mixture without fibers. Table 3 shows the results of researches above.

Table 3. Water absorption properties of SIFCON with varying additives and different type of fiber

Amount of Cement kg/m^3	Type and Weight of Additive kg/m^3	Type and Percent of Fiber (Aspect Ratio)	Water Absorption% (the Percent of Increase %)	References
885.1	-	Hooked & waved 7, 9.5, 12% (60&28)	6.5 (261)	Gilani [43]
900	Silica fume (100)	Basalt fiber (1714) 25, 50, 75, 100% replacement of hooked end steel fiber (54)	2.7 (3) 2.8 (7.6) 2.9 (11.5) 3.2 (23)	Algın et al. [45]
380	-	Sisal fiber 0, 0.5, 1, 1.5, 2% (230-300)	7.285 (49)	Okeola et al. [46]
438	-	Fiberglass 0, 0.5, 1, 1.5, 2.5, 3%	2.74 (30)	Ruben et al. [47]
None mention	-	jute, sisal, sugarcane, and coconut (136-400) 0.5, 1, 1.5, 2, 2.5, 3%	9.25 (76)	Jamshaid et al. [48]
Cement:sand:coarse agg. (1:2:4)	-	bamboo fiber, bamboo modified with natural rubber latex. 0, 0.5, 1, 1.5%	9.2 (56)	Althoey et al. [49]
424	-	PVA 0.125, 0.25, 0.375, 0.5%	5.75 (41)	Hussien [50]
None mention	-	Carbon fiber and glass fiber 0.1, 0.5, 1%	16.95 (38)	Tao and Hadigheh [51]

2.4 Effect of varying additives and fibers on impact test of SIFCON

The impact resistance test is an important test that gives a true indication of the ability of concrete to absorb energy before failure. The impact resistance of concrete can be improved using steel fibers because of their role in resisting the onset of cracks and hindering crack growth. Azoom and Pannem [23] conducted a comparative study between the effect of different proportions of straight steel fibers and polypropylene fibers on the impact property of SIFCON. They reported that steel fibers had better results, achieving 43% increase in compare the effect of polypropylene fibers. Sharma et al. [22] studied the impact energy characteristic of SIFCON under different conditions, where hooked steel fibers were used in different percentages of 2%, 3%, and 4%, and steel slag was used as a partial substitute for sand in different percentages of 0%, 10%, and 20%. The results showed that the impact energy was directly proportional to the percentage of fibers, and it increased slightly when the percentage of steel slag increased. The increase in impact resistance was 42% when using 4% steel fibers with 10% steel slag. However, upon further increasing the steel slag to 20%, the increase in impact value was 43% only compared with the reference mixture that did not contain steel slag. Al-wahab Ali et al. [52] investigated the impact loading behavior of SIFCON with varying fiber volume fractions and mortar types. A disc specimen was casted using 10% silica fume, 20% low calcium fly ash as a fractional surrogate by weight of cement, and 11%, 8.5%, and 6% of hooked-end steel fibers volume fraction and then compared with mortar consisting of 2% volume fraction. The results showed that high resistance for impact was achieved using 11% fibers volume fraction, silica fume and fly ash in SIFCON, and sufficient failure energy rising by 11.87 times compared to the control mixture after 90 days. In general, the rising of fiber volume fraction in SIFCON content showed important enhancement in resistance of impact.

Nadia Moneem et al. [31] studied the impact resistance of SIFCON containing 6% straight steel fibers and containing silica fume and fly ash. They reported that SIFCON achieved an improvement in impact resistance of more than eight times compared with the reference mixture containing 2% steel fibers. Jerry and Fawzi [53] studied the influence of using two-thirds of polyolefin fibers and one-third of hook-end steel fiber and vice versa with 6% volume fraction fiber in hybrid samples on the impact resistance. The results showed increased impact resistance by 43 times. Fibers played a major role in delaying the beginning of cracks and a major role in hindering the growth of the cracks, thus prolonging the life of concrete exposed to repeated loads. The most prominent results of the above research are listed in Table 4.

Table 4. Effect of varying additives on impact resistance of SIFCON

Amount of Cement	Type and Weight of Additive	Type and Percentage of Fiber	Max. Impact Energy at First Crack	Max. Impact Energy at Failure	References
kg/m³	kg/m³		N. m	N. m	
		(Aspect Ratio)	(the Percent of Increase%)		
1:1:2 cement:GGBS:sand	GBSS SP 1%	Straight 12% (50)	2052	4026	Azoom and Pannem [23]
714.28	Slag 10 and 20% of sand	Hooked end 2, 3, 4% (60)	-------	3343.67 (43.5%)	Sharma et al. [22]
619.5	Silica fume 88.5 and fly ash 177	Micro steel fiber 11%	34119.2 (1324)	109471.8 (1087)	Ali et al. [52]
1:1 cement:sand	Silica Fume and Fly Ash	Micro steel fiber 6%	21091.5 (877)	65089.35 (898)	Al-Abdalay [31]
796.5	Silica Fume 88.5	Straight (64)	-	35904.31 increase 4333.1%	Beglarigale et al. [19]

Table 5. Effect of varying additives and fiber on details abrasion of SIFCON

Amount of Cement	Type and Weight of Additive	Type and Percentage of Fiber	Min. Reduction in Abrasion	References
kg/m³	kg/m³	(Aspect Ratio)	(the Percentage of Decrease%)	
1:1 cement:sand 1:1.5 cement:sand	Fly ash	Straight steel fibers 6, 8% (75,100)	4.63 (54.6%)	Parameswaran et al. [54]
1:1 cement:sand	Fly ash	Straight steel fiber 5,7,9,11%, (75) & glass fiber type E 1%	2.86 (62.4%) By Bohm's method	Vijayakumar and Kumar [4]
900	Silica fume (100)	Basalt fiber (1714); 25, 50, 75, 100% replacement of hooked end steel fiber (54)	5.6 (27%) By Bohm's method	Algın et al. [45]

2.5 Effect of varying additives and fibers on abrasion test of SIFCON

Traditional concrete is poorly ductile and highly brittle. Therefore, steel fibers are relied upon to improve the concrete’s resistance to abrasion. Parameswaran et al. [54] reported on the abrasion resistance property of SIFCON and compared it with the abrasion resistance of fiber-reinforced concrete. They reported that the abrasion resistance of SIFCON was better than that of fiber reinforced concrete. The team also observed that the abrasion resistance of SIFCON increased with fibers having a higher aspect ratio, the more steel fibers there are, the better the abrasion resistance is because steel is a good abrasion resistant due to the alloying elements it contains such as carbon, chromium, manganese, etc. Vijayakumar and Kumar [4] studied the effect of the abrasion resistance property of SIFCON upon exposure to sulfate attack. Two types of fibers were used: 1% glass fiber in each mixture and the addition of straight steel fibers at 5%, 7%, 9%, and 11%. Fly ash was added. For the mixture, the best abrasion resistance was obtained for 9% of steel fibers, with an improvement in abrasion resistance of 62.4%. However, abrasion resistance was reduced when 11% steel fibers were added. This finding could be attributed to the slurry particles that did not penetrate perfectly into all parts of the concrete, causing weak bonding between SIFCON particles.

Algın et al. [45] studied the effect of replacing basalt fibers with straight steel fibers of different amount basalt fiber proportions in SIFCON. The abrasion resistance test showed that the best result was obtained for 25% of the basalt fibers replaced with steel fibers, and the abrasion resistance decreased when replacing 75% or more basalt fibers. The most prominent results of the above research are listed in Table 5.

2.6 Effect of varying additives, fiber, and other parameters on ultrasonic pulse velocity of SIFCON

The pulse transmission velocity test is considered as one of the most important non-destructive tests because it can estimate the value of the compressive strength, the kinetic modulus of elasticity, the shear modulus, and the Poisson’s ratio and detect defects in the concrete [55]. In general, the presence of steel inside the concrete increases the transmission velocity of pulses if the presence of fibers does not cause defects or voids in the concrete. Gowda and D’mello [56] studied the pulse transmission velocity of SIFCON which containing hooked-end steel fibers at a rate of 4%–10% of the concrete volume. The result showed that the value of the pulse transmission speed decreased when using fibers by more than 8%. The pulse transmission velocity decreased when the amount of steel fibers increased due to the formation of defects and voids that formed between the fibers and the binder (as mentioned in the water absorption test) or formation of voids due to the weak penetration of slurry particles when the amount of fibers increased, and thus increasing the voids will cause a slow transmission of the pulse.

Kchaitanya et al. [13] investigated the velocity of pulse transmission in SIFCON containing straight steel fibers. The fibers were previously subjected to heat treatment (annealing), and the percentage of fiber was varied at 2 vol%, 4 vol%, and 6 vol% of the concrete volume. The value of the pulse transmission velocity increased with the increase in fiber content. The use of 6% fiber resulted in higher velocity than using 2% fiber by about 5%. Ipek and Aksu [28] investigated the effect of type of fine aggregate used in SIFCON on the velocity of pulse transmission. Quartz aggregate was used as a reference mixture, and the aggregate was partially replaced in three stages with basalt aggregate. No effect of the type of aggregate was found on the velocity of pulse transmission. Aygörmez et al. [57] studied the effect of active powders, such as metakaolin and fly ash, on the transmission velocity of pulses through SIFCON. During the test, a slight advantage was observed when adding metakaolin at a rate of 25% by weight of cement, in which the velocity increased slightly, not exceeding 3%.

Akçaözoğlu and Kıllı [33] investigated the effect of changing the curing conditions of SIFCON that contained slag and silica fume as additives with straight steel fibers at different percentages of 4% and 8% of the concrete volume and aspect ratios of 55 and 40. The concrete was exposed to three curing conditions: standard, dry, and accelerated. The best pulse transmission velocity was at a fiber ratio of 4% and an aspect ratio of 40, with dry curing. Al-hadithi and Al-Hadithi [58] studied the pulse transmission velocity of a new type of SIFCON. They used polyethylene terephthalate fibers from waste materials and added them at rates of 3%, 6%, and 10% of the concrete volume. The results showed that the value of the pulse transmission velocity decreased with an increase in the amount of fibers despite the improvement of the mechanical properties. The behavior of these fibers did not match the behavior of steel fibers. The most prominent results of the above research are listed in Table 6.

Generally, no significant effect was observed in the pulse velocity test when adding active powders, whereas steel fibers have a clear role when present. However, the ideal limit must be maintained because its increase causes defects in SIFCON in some cases.

2.7 Effect of varying additives, fiber, and other parameters on rebound number test of SIFCON

The rebound number test, or the Schmidt hammer test, is considered as one of the important non-destructive tests in assessing the properties of concrete. However, one of the limitations of this test is that it deals with the surface of concrete and parts near to the surface. In general, the hardness of a steel is higher than that of a concrete, and therefore, the presence of steel fibers must increase the rebound number when the fibers do not cause defects in the concrete. Gowda and D'mello [56] discussed the rebound number for SIFCON containing silica fume and reinforced with steel fibers with hooked ends at different percentages of 4%, 6%, 8%, and 10% of the concrete volume. The highest value of the rebound number was at 8%, but the value of the rebound number decreased when the percentage of fiber increased more than 8%, this is because the increase in fibers can cause two effects. The first is that the increase in fibers will cause the emergence of spaces between the fibers and the binding material, which was mentioned previously. The second effect is that the increase in fibers and their abundance can cause difficulty in the penetration of the slurry material between the fibers, and thus create some spaces and defects in different areas.

Table 6. Effect of varying additives on ultrasonic pulse velocity of SIFCON

Amount of Cement	Type and Weight of Additive	Type and Percentage of Fiber	Max. UPV	References
kg/m³	kg/m³	(Aspect Ratio)	m/s (The Percent of Increase%)	
1:1.5 cement: Sand	Silica fume 10%	Hooked steel fibre 4, 6, 8 and 10%	4570	Gowda and D'mello [56]
350	-	Steel fiber 2, 4, 6% (50)	5737	Kchaitanya et al. [13]
900	Silica fume 270	Hooked end steel fiber	3470 (1.4%)	Ipek and Aksu [28]
100	Metakaolin 25, 50% Fly ash 25, 50%	Straight (35.29)	4274	Aygörmez et al. [57]
700	GGBFS 200 Silica Fume 100	4% and 8% steel fiber (55)(40)	4267 (8.9%)	Akçaözoğlu and Kıllı [33]
610	-	Polyethylene terephthalate fibers 3, 6, 10% (37.5)	4200	Al-Hadithi and Al-Hadithi [58]

Table 7. Effect of parameters on rebound number of SIFCON

Amount of Cement	Type and Weight of Additive	Type and Percentage of Fiber	Max. Rebound Number	References
kg/m³	kg/m³	(Aspect Ratio)	(The Percent of Increase%)	
1:1.5 cement:Sand	Silica fume 10%	Hooked 4, 6, 8, 10%	50	Gowda and D'mello [56]
350	-	Steel fiber (straight) 2, 4, 6% (50)	61.92	Kchaitanya et al. [13]

Kchaitanya et al. [13] used steel fibers that were previously subjected to annealing and cut them to obtain an aspect ratio of 50. They used the fibers at low percentages of 2%, 4%, and 6% of the concrete volume. The rebound number increased with an increase in the percentage of fibers. The rebound number value decreased when more fibers were used, because the mixture used was a poor mixture containing 350 kg of cement per cubic meter, in which obtaining high workability is difficult. The most prominent results of the above research are listed in Table 7.

The studies above showed that many factors affect the rebound number, such as the type of fiber, the percentage of fibers, the amount of binder, and all factors affecting workability.

3. CONCLUSION AND FUTURE PERSPECTIVE

Plain concrete has low tensile properties, and many approaches have been used to improve these properties, including the use of SIFCON concrete. The geometry of the steel fiber and aspect ratio considerably affect the value of the tensile properties. For example, the flexural strength and indirect tensile strength are improved more when using hooked fibers or crimped fibers than when using straight fibers if the fibers have same aspect ratio and as the fiber content increases to 6% and above, the improvement in tensile properties becomes apparent. The greatest increase in flexural strength value was 919% when wavy fibers were used with the addition of silica fume, and the greatest increase in the splitting strength value was 561% when hooked fibers were used with the addition of silica fume. Meanwhile, the effect of the geometry on the compressive strength property is less than other property. The greatest improvement in compressive strength was when using straight steel fibers with the addition of blast furnace slag, showing an improvement of 117% compared with the reference mixture. SIFCON provides excellent resistance to abrasion. In one study, abrasion resistance was improved by 62% when using straight steel fibers with the addition of fly ash. Considering that the geometric shape of fibers does not affect the abrasion resistance, the presence of steel fibers within the normal limit for adding fibers increases the value of the results in non-destructive tests (pulse penetration speed and rebound number), but the increase is slight.

It is not possible to determine an ideal mixture in advance due to the difference in components between one cement and another, as well as the difference in fineness between one cement and another, which means a difference in the amount of water and plasticizer to obtain the required workability. As for the cost, it is possible to benefit from recycling the steel wires found in damaged tires to reduce the cost of producing SIFCON concrete.

Previous studies on SIFCON showed a lack of mathematical relationships that link between destructive and non-destructive tests, as such relationships exist in plain concrete and are considered important factors in evaluating the quality of concrete after long periods of time or when the building is exposed to nature conditions or fire accidents.

Previous studies lack the effect of dynamic loading on the behavior of SIFCON, which can provide readers with a more comprehensive perspective on the overall performance impact of fiber types.

SIFCON suffers from an increase in the ability to absorb water due to the pores caused by the presence of steel fibers, making SIFCON vulnerable to attack by harmful substances such as sulphates, acids, and organic materials. This limitation must be treated. Moreover, the amount of fiber must not exceed the ideal percentage because increasing it creates many defects. Different types of filler must be studied to further improve the properties of SIFCON.

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