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Utilization of Hybrid SIFCON to Improve Performance and Properties of Slab System Openings

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Abstract

This research aims to enhance Slurry Infiltrated Fibrous Concrete (SIFCON) by incorporating both long and short fibers, with the goal of increasing ductility and mechanical properties behavior. The study also evaluates the effectiveness of SIFCON in strengthening two-way reinforced concrete slabs with large openings. Various SIFCON mixes were created, integrating hooked-end fibers, micro steel fibers, and different volume ratios (Vf) of hybrid steel fibers (one-third, one-half, and two-thirds). A reference mix with 2% hybrid fiber-reinforced concrete (SFC) was formulated for comparison. Hybrid SIFCON samples demonstrated superior mechanical properties compared to those reinforced with hooked fibers, showing higher compressive strength, cylinder compressive strength, flexural strength, and direct tensile strength by 14%, 13.9%, 38.2%, and 58.2%, respectively, at 28 days, but a lower splitting tensile strength by 24%. Compared to micro steel fiber-reinforced samples, hybrid SIFCON exhibited higher compressive strength, cylinder compressive strength, flexural strength, and splitting tensile strength by 18.2%, 51%, 167.5%, and 43.6%, respectively, but a lower direct tensile strength by 7.4%. The study involved nine two-way square slabs with various mixtures of normal concrete, mortar-infiltrated fiber concrete, and full SIFCON. Control samples were constructed using normal-strength concrete. The application of SIFCON increased punching shear strength by 3.21% to 154.25% compared to the control samples.

Keywords: SIFCON; Hooked Steel Fiber; Hybrid Steel Fiber; Micro Steel Fiber; Split Strength; Flexural Strength; Slab System Openings.

1. Introduction

Reinforcing existing concrete structural components has developed as a highly necessary effort in civil engineering [1]. With the increase in urbanization and population, there is a need for infrastructure growth, which requires the services of the construction segment [2]. Concrete is a fundamental component of most infrastructure. The growing requirements of modern structural design have led to an increased use of reinforced concrete (RC) flat slabs with openings. These openings, while offering functional, economical, and decorative advantages, can lead to higher punching shear stresses in the slabs, reducing their punching shear capacity. Removing a large amount of reinforcement and concrete can cause undesirable effects on the RC panels. According to Casadei et al. [3], the opening could change the stress distribution of the element, affecting its structural behavior. Consequently, some studies have reported a decrease in bearing capacity and modification of failure modes [4]. In order to improve the punching shear behavior of these slabs, we need to evolve higher-performance engineering materials with great strength, durability, energy absorption, and toughness [5, 6]. Today, the greatest significant necessity of concrete is the ductility. Efforts to disband the brittleness difficulty of concrete have been made by using a high amount of fibers with the presence of coarse

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aggregate; this causes a boost in the ductility and stress-hardening property of the structural ingredient [7, 8]. Which effectively enhances its ductility as a structural component. However, due to the placing and mixing complications caused by the interconnecting effect of high volumes of fibers, there was an urgent need to improve special production methodologies. So, slurry infiltrated fibrous concrete (SIFCON) was made [9].

In traditional fiber-reinforced concrete (FRC) plus high-performance fiber-reinforced concrete (HPFRC), the usual range for fiber volume fraction is between 1% and 3%. However, certain special composites have been developed that exhibit fiber volume fractions (Vf) ranging from 3% to 20% [10]. SIFCON (Slurry Infiltrated Fiber Concrete) composites possess a unique combination of brilliant ductility and tensile strength along with great overall strength. Mechanical properties of SIFCON have been thoroughly explored, and it has been found to improve flexural toughness [11]. According to Abuzaid et al. [12] Suggested to use SIFCON containing silica fume (10%) and fly ash (20%) in the production of SIFCON, which has a high working capacity, as well as the effect of giving an additional increase in the mechanical properties of SIFCON mixtures. In the literature, the effect of using disjointed, short fibers, which are randomly distributed in concrete, gives enhanced strength, post-cracking capacity, impact resistance, stiffness, and energy absorption capacity, as well as a rise of the flexural strength. On the other hand, the incorporation of short and long fibers in concrete as hybrid fibers raises the ductility and gives superior softening behavior related to the concrete with one type of fiber [13, 14]. Different kinds of steel fibers can be used in the creation of SIFCON concrete, such as hooked, straight, crimped, and fiber [14, 15].

According to Zamrodah (2018) [15], the influence of fiber type on properties of SIFCON was studied. Samples with micro steel fiber were prepared and matched the results with hooked fiber and hybrid (hooked fiber + micro fiber) samples. The test result illustrations that samples casted by microfiber have exceptional performance in terms of tensile strength, compressive strength, energy, lower strength loss after freeze-thaw cycles, and impact resistance as matched with the hooked fiber plus hybrid samples. According to Elsayed et al. [16], the mechanical properties of concrete slabs incorporated with crumb rubber, i.e., rubberized concrete, were estimated, and the punching shear behavior of rubberized concrete slabs with openings was studied. Which are adjacent to columns. Results revealed that the use of crumb rubber exerted a negative effect on the mechanical properties of concrete. Meantime, adding more than 5% caused a small reduction in the tensile strength, compressive strength, and flexural strength of rubberized concrete. There is also the difficulty of producing large quantities of chopped rubber to cover the needs of projects, and the sizes of the openings used are not large.

According to Naser & Shadhan [17], the performance of slurry-infiltrated fiber concrete (SIFCON) Vierendeel trusses in applied load was studied by using numerical analyses. The numerical results express that the simulated numerical performance has a good agreement with experimental results of past tested samples, and the failure mode is like that recorded in the experimental test. It was found that when openings exist, the usual flow of stresses is interrupted or disrupted, which is the reason for early cracking and stress concentration in the region of the opening. According to Abbas & Mosheer [18], an experimental study was offered to develop the mechanical proficiency of SIFCON mixes with changing the fiber content. Several SIFCON mixes, incorporating hook end fiber with three different V_f (6, 7, and 8.5%), were organized. Results show that fresh mortar had proper flowability and filling properties, satisfying the spread diameter necessity (between 240 and 260 mm) for SIFCON mortar, which is 249 mm. For mechanical properties, the supreme compressive strength improved by 53% after 28 days for the blend's SF of 8.5%. In addition, when compared to the reference one, flexural enhancement and splitting increased by 91% and 44%, respectively.

As SIFCON is a relatively novel building material, there is a lack of knowledge on SIFCON flat slabs. From this point of view, to raise information in this field, this investigation seeks to get information that will help tackle these study gaps. Moreover, to highlight the advantage of using ultra-high-performance material like SIFCON in flat slabs and the possibility of using relatively big openings adjacent to columns, this offers interesting opportunities to achieve high-behavior flat slabs with openings that fulfill architectural, functional, economical, decorative advantages and service demands mentioned previously. The performance of SIFCON slabs was studied experimentally. The main experimental parameters were using a full SIFCON section, a hybrid SIFCON section, and different thicknesses of SIFCON layers and different locations of openings.

2. Experimental Work

2.1. Mix Proportion and Component Materials

In the current study, the next materials were used in preparing the SIFCON shown below in Table 1. Standard Portland cement type I with the requirements of IQS No. 45/1984 [19]. SIFCON mortars were prepared using fine sand that had undergone sieving with a 1.18 mm sieve to remove larger units with the requirements of IQS No. 45 [20]. High-performance concrete superplasticizer (Glenium 54) by BASF was used as an HRWR (Table 1). It is free from chloride and complies with ASTM C494-05 Type F (494-05 2005) [21]. As a cementitious material, microsilica fume was used as a fractional replacement (10%) by weight for cement in the concrete mixture that conforms to the requirement of ASTM C1240-20 [22]. Adding fly ash Class F as a partial replacement (20%) by weight of cement can make the SIFCON slurry more cohesive and less prone to segregation and bleeding (Figures 3 to 5). The fly ash used complies with the requests of ASTM C618-17a [23]. Two types of steel fiber were used in this study. The hooked-end steel fiber has dimensions of 0.7 mm in diameter by 35 mm in length, an aspect ratio of 50, and a density of 7,800 kg/m³. The tensile strength is 1100 MPa. The second type was micro steel fiber, with dimensions of this fiber kind being 0.5 mm in diameter by 13 mm in length, with a 65 aspect ratio and a density of 7825 kg/m³. The tensile strength is 2400 MPa, as shown in Figure 5.

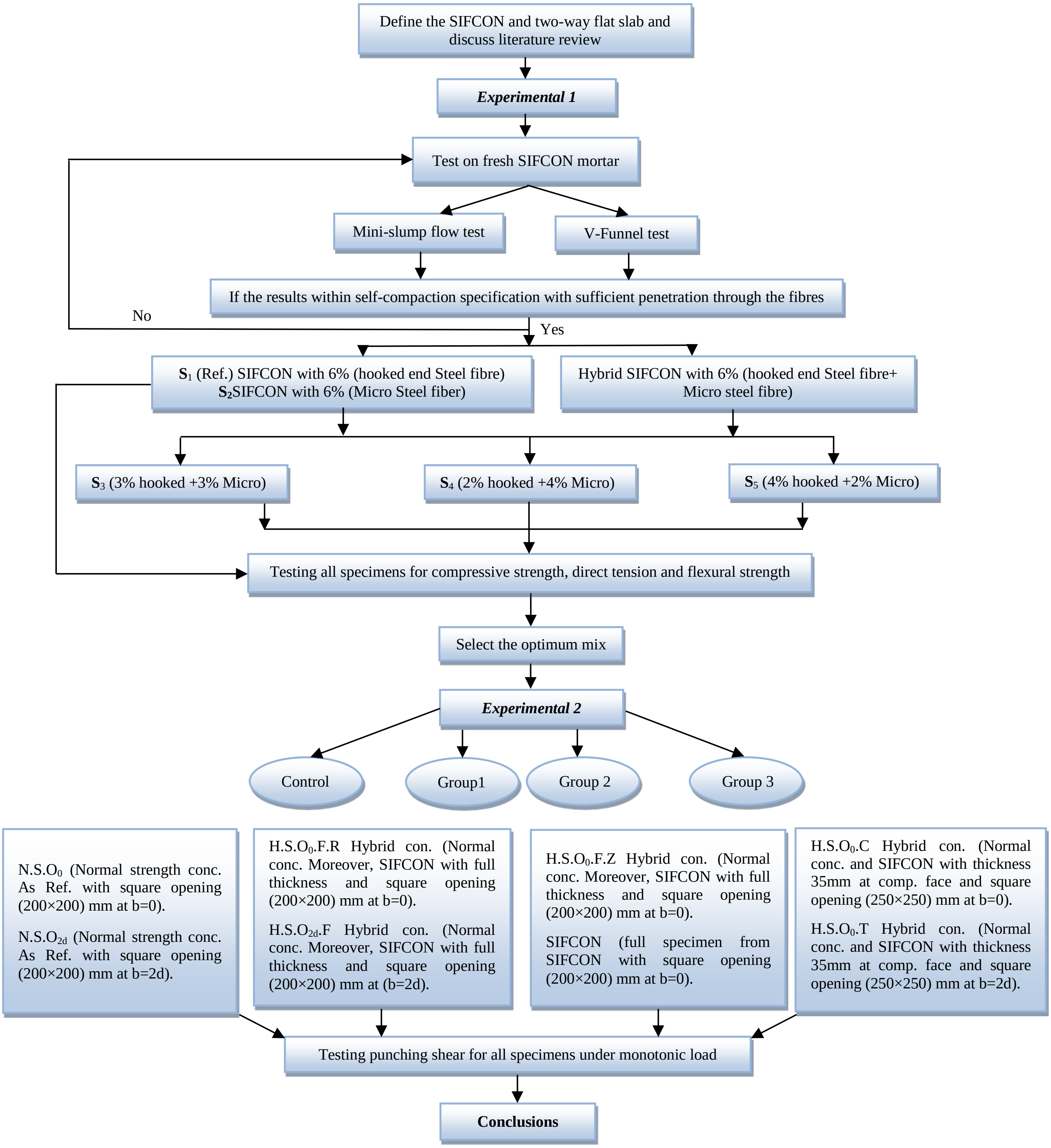


Figure 1. Flow chart of experimental program

Table 1. Mixing proportion of SIFCON and normal strength concrete

Mix Type	Mix Proportions							
	Cement kg/m³	Silica Fumes Kg/m³ 10% rep.	FA Kg/m³ 10% rep.	Ratio of w/b or w/c	Sand (kg/m³)	Gravel (kg/m³)	Steel fiber %	HRWR % by weigh of (cement+FA+SF)
SIFCON	619.5	88.5	177	0.38	885	-	6%	2.4
SFC	400	-	-	0.45	550	1000	2%	-
(N.C.)	400	-	-	0.45	550	1000	-	-

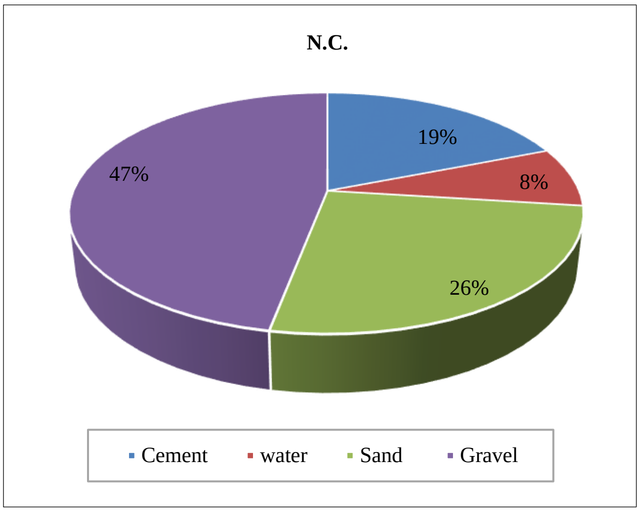


Figure 2. Materials ratio used in normal concrete mixture

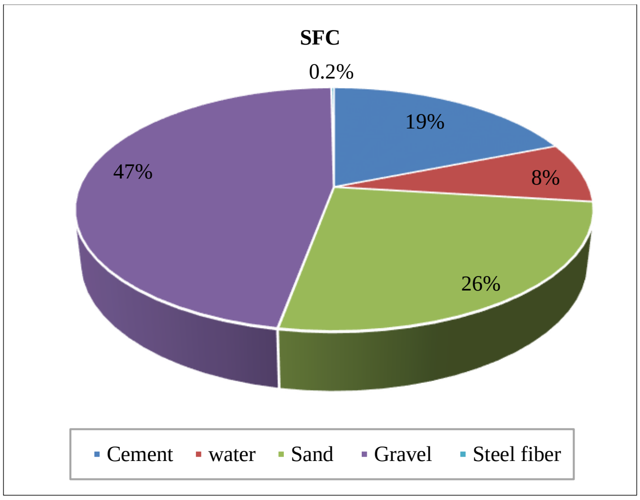


Figure 3. Materials ratio used in fiber-reinforced concrete mixture

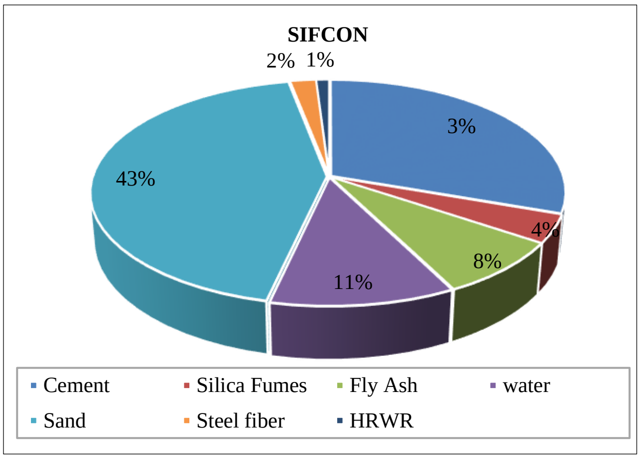


Figure 4. Materials ratio used in SIFCON mixture

Figure 5. Micro steel fiber and a hooked end

2.2. Preparation of SIFCON and Slab Specimens

The preparation of Slurry Infiltrated Fiber Concrete (SIFCON) and slab specimens involved several steps:

- The mixer was thoroughly cleaned to remove any remnants of fresh or dried ingredients from previous mixes.
- The entire amount of High-Range Water Reducer (HRWR) was blended separately with (1/3) of the mixing water to approximately one minute.
- The binder materials, including silica fume and cement, were combined in a separate mixer for a duration of one minute to ensure the dispersion of silica fume particles through the cement particles.
- Sand was then added to the mixture and mixed for an additional two minutes.
- (2/3) of the mixing water was supplementary to the rotating mixer and mixed for a minute.
- The mixer was then filled with the HRWR and the remaining one-third of the mixing water, and then the mixture was mixed for three minutes. This step aimed to achieve the desired workability of the SIFCON mixture.
- After the initial mixing process, the mixer was stopped, and any portions of the mixture that may not have been reached by the mixer blades were manually mixed to ensure homogeneity.
- To achieve the desired fluidity of the mortar, the ingredients were mixed for an additional one minute. This final mixing step ensured that the mortar had the required consistency for the intended application.
- After conducting many trials of molding techniques in the laboratory, the three-layer technique was determined to be the most effective method for incorporating fiber into the SIFCON matrix. This method was found to be more straightforward and easier to use in practice, especially when a large volume proportion of steel fiber was utilized.
- Initially, the fibers, which are randomly oriented, were placed and packed in the mold up to one-third of its depth. The mold was then filled with the SIFCON mortar up to the level of the fibers. The mortar should have sufficient flow ability to assure infiltration out of the fiber network.
- Vibrating the contents of the mold removed any voids or honeycombing, ensuring that the mixture was properly compacted and consolidated.
- The process was repeated for the second and third layers, where the total mold was filled with the required volume fraction of fiber. During these subsequent layers, very small vibrations were applied to achieve proper compaction without disturbing the already placed fibers.

By using the three-layer technique, researchers found it easier to achieve a uniform distribution of steel fibers in the SIFCON specimens. Additionally, this method facilitated the casting process, especially when working with a high steel fiber volume percentage. It is vitally important to test SIFCON mortar while it is in a fresh state. Its matrix must have enough liquid and fineness to flow through the thick fiber bed. Mini slump flow and V-funnel tests were used with SIFCON mortar. The fresh characteristics of SIFCON mortars are shown in Table 2.

Table 2. Mechanical Properties results at 28 days

Combine symbols	Compressive strength fc (MPa)	Cylinder compressive strength (MPa)	splitting tensile strength (MPa)	Flexural strength (MPa)	Direct tensile strength (MPa)	Elastic modulus (GPa)
Mortar	-	-	-	-	4.1	-
N.C	31.7	30	9.3	5.4	-	20
SFC	38	34.4	10.2	6.8	-	23.4
S-H	57.67	47.29	17.4	20.9	5.5	28

S-M	55.66	35.64	9.4	10.8	9.4	27.1
HS-$H_{1/2}$+$M_{1/2}$	65.78	53.94	12.6	28.9	8.7	30.1
HS-$H_{2/3}$+$M_{1/3}$	64.46	52.86	13.5	22.77	7.2	29.7
HS-$H_{1/3}$+$M_{2/3}$	62.73	51.44	8.4	21.51	7.9	28.5

To get the required results and homogeneity out of SIFCON (Slurry Infiltrated Fiber CONcrete) mortars, enough mixing is essential. It is also important to extend the mixing time to allow the High-Range Water Reducer (HRWR) to fully develop its potential and ensure that any agglomerated particles of silica fume are fully dispersed. All trial mixes were conducted in a small rotary mixer with a capacity of 0.01 m³. For the specimens' mixes, a horizontal rotary mixer with a capacity of 0.09 m³ was used. The mixing steps can be summarized as follows:

The mixer was completely cleaned before beginning the mixing process in order to get rid of any last bits of fresh or dried ingredients from earlier mixes. The entire amount of High-Range Water Reducer (HRWR) was mixed separately with (1/3) of the mixing water for approximately one minute. In the preparation of the SIFCON slurry, the binder materials, including silica fume and cement, were combined in a separate mixer for a duration of 1 minute. This step confirmed the dispersion of silica fume particles throughout the cement particles. Then, the sand was added to the mixture and mixed for an additional two minutes. Next, adding (2/3) of the mixing water to the rotating mixer, a minute of mixing was spent. After that, the mixer was filled with the HRWR and one-third of the combining water, and the mixture was incorporated for three minutes. By following these actions, the research aimed to achieve the wanted workability of the SIFCON mixture. Later, in the initial mixing process, the mixer is stopped, and any portions of the combination that may not have been reached by the mixer blades are manually mixed to ensure homogeneity. To complete the wanted fluidity of the mortar, the ingredients are mixed for an additional 1 minute. This final mixing step helps to ensure that the mortar has the required consistency for the meant application. After conducting many trials of molding techniques in the laboratory, the three-layer technique was determined to be the most effective method for incorporating fiber into the SIFCON matrix. In comparison to single- or two-level approaches, this method was found to be more straightforward and easier to use in practice, mainly when a big volume proportion of steel fiber was utilized. Initially, the fibers, which are randomly oriented, are placed and packed in the mold up to one-third of its depth. The mold is then filled with the SIFCON mortar up to the level of the fibers. The mortar should have sufficient flow ability to ensure infiltration through the fiber network. Vibrating the contents of the mold removes any voids or honeycombing. This guarantees that the mixture is properly compacted and consolidated. The process is reiterated for the second and third layers, where the total mold is filled with the required volume fraction of fiber. During these subsequent layers, very small vibrations are applied to achieve proper compaction without disturbing the already placed fibers.

By using the three-layer technique, researchers found it easier to achieve a uniform distribution of steel fibers in the SIFCON specimens. Additionally, this method facilitated the casting process, especially when working with a high steel fiber volume percentage. It is vitally important to test SIFCON mortar while it is in a fresh state. Its matrix must have enough liquid and smoothness to flow through the thick fiber bed. Mini slump flow plus V-funnel tests were used with SIFCON mortar. The fresh characteristics of SIFCON mortars are shown in Table 3.

To confirm the ratios of the mix and the results of the specifications, several specimens were cast and tested for each mix at the age of 28 days. These included cubes with dimensions of 100×100×100 mm, cylinders with dimensions of 100×200 mm and 150×300 mm, prisms with sizes of 100×100×500 mm, and cylindrical samples of 100×200 mm [24-28]. These were used to measure compressive strength, splitting strength, flexural strength, static modulus of elasticity, and direct tensile strength.

Nine reinforced concrete slab specimens were prepared, each with dimensions of 1000×1000×70 mm. These samples were subjected to an axial load applied from the top of the column. The study focused on investigating several variables, including the size of the opening (200×200 mm) and two different distances: next to the column and at a distance of 100 mm from the column. The reinforcement details and sizes of the samples can be found in Figure 6.

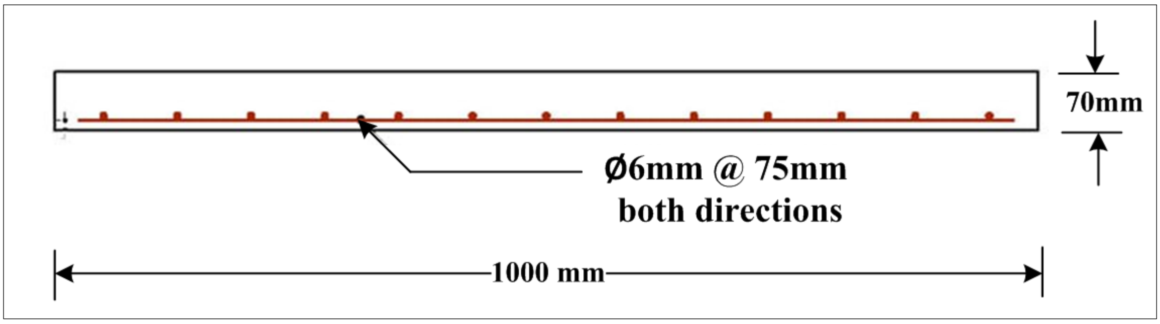


Figure 6. Details of slab specimens

- The size of the opening (200×200 mm) and its chosen rather big because the punching shear decreases plus an increase in opening size [16].
- Two different locations of openings were used: one next to the column and the other at a distance of 100 mm from the column. Openings in the flat slabs adjacent to the column face make a significant reduction in punching shear [16].
- Six different locations of SIFCON shown in Table 3, since SIFCON is a new material so it is needed to know the optimum location that will achieve the required strengthening and increase in punching shear strength while maintaining low cost.

Table 3. Specimen's designations

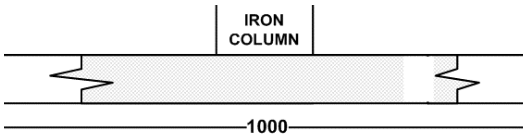
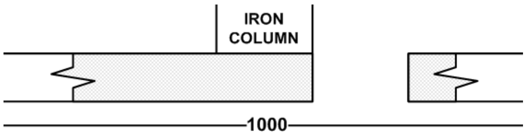
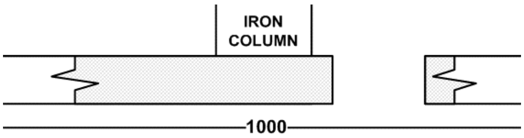
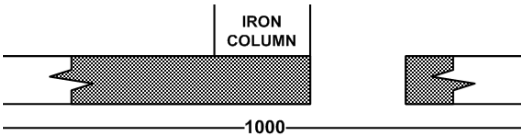
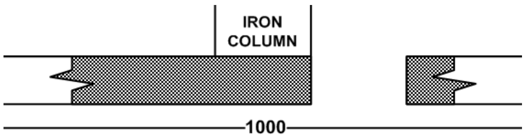
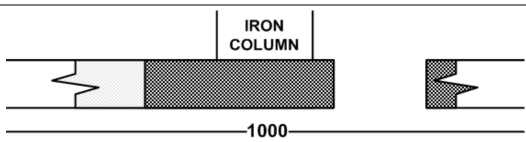
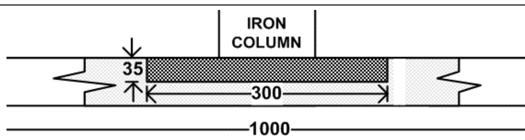
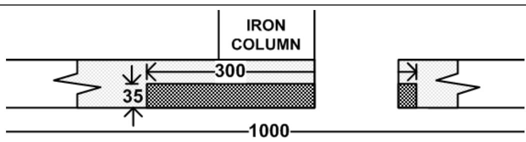
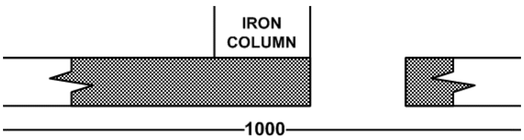
Slab Designation	Section where mortar infiltrated fiber concrete embedded	Flexural Reinforcement
N.S	Cast using just normal concrete	
N.S.O_0	Cast with just regular concrete with square opening at 0 from the face of column	
N.S.O_{2d}	Cast with just regular concrete with square opening at 2d from the face of column	
H.S.O_0.F.R	Rectangle (300*500 mm) middle span with a 70 mm thickness 	
H.S.O0.F.Z	Simi-rectangle (300*500 mm) middle span with a 70 mm thickness 	
H.S.O_{2d}.F	Rectangle (300*605 mm) middle span with a 70 mm thickness	
H.S.O_0.T	Rectangle (300*500 mm) middle span with a 70 mm thickness @tension zone	
H.S.O_0.C	Rectangle (300*500 mm) middle span with a 70 mm thickness @ com zone	
SIFCON	Full specimen 	

Table 3 presents all the reinforced concrete slab specimens. In the references, "N" denotes normal concrete that makes up the first group. "S" signifies any hybrid specimen that includes SIFCON. "O" represents a slab with an opening and a distance between the column and the openings equivalent to (0 & 2d). "F", "T", and "C" indicate the location of SIFCON, whether in full thickness or in half in the compression/tension zone.

3. Results and Discussion

3.1. Fresh SIFCON Mortars Properties

This study presents experimental test results of fresh and hardened SIFCON (Slurry Infiltrated Fiber Concrete) mixes, which were evaluated and contrasted with conventional fiber-reinforced concrete. Table 4 showcases the results of V-Funnel and mini slump flow tests, indicating that the three SIFCON mortars (M1, M2, and M3) meet the criteria for suitable flowability, sufficient viscosity, and filling ability. The outcomes for the reference mortar (M1) highlight the importance of including HRWR (High-Range Water Reducer) to achieve a mix with a low water-to-binder ratio while ensuring homogeneity and fulfilling other specified requirements.

Table 4. Fresh properties of SIFCON mortars

	Mini slump flow (mm)	V-funnel (s)	HRWR % by wt. of cement
M_1	250	9.5	1.2
M_2	257	9	2
M^*_3	260	7	2.4

M^*_3 = mixture that was used

3.2. Compressive Strength and Flexural Strength

The compressive strength and flexural strength are crucial properties of SIFCON, and their impact is demonstrated in Table 5 and Figures 7 to 10. These illustrate how various fiber forms—straight microfiber steel, hooked-end steel fiber, and hybrid fiber—affect SIFCON's compressive strength (fc) in comparison to conventional fiber-reinforced concrete and normal concrete. The test results reveal a notable enhancement in compressive strength and flexural strength for specimens having hooked-end steel fiber when compared to those with microfiber steel. This disparity can be attributed to the presence of weak points at the ends of microfiber steel, which results in reduced strength under loads.

Table 5. Outcomes of the slab tests

Samples	f'c for N.S.C. (MPa)	f'c for SIFCON (MPa)	First crack load (KN)	Ultimate Load (Pu) (KN)	Max. deflection (mm)	Type of failure	Increase in punching load % with Resp. to R_1	Increase in punching load % with Resp. to R_2
N.S	31.7		20	92.01	21.99	punching	-	-
$N.S.O_0$	31.7	-	15	60.33	21.11	punching	R_1	-
$N.S.O_{2d}$	31.7	-	22	77.81	15.29	punching	-	R_2
$H.S.O_{2d}.F$	31.7	65.7	32	97.57	10.46	Flexural	-	25.39
$H.S.O_0.F.R$	31.7	65.7	33	88.36	17.59	punching	46.46	-
H.S.O0.F.Z	31.7	65.7	32	81.56	16.92	punching	35.18	-
$H.S.O_0.C$	31.7	65.7	35	79.78	14.84	Flexural	32.23	-
$H.S.O_0.T$	31.7	65.7	32	68.62	10.03	punching	13.74	-
SIFCON	-	65.7	40	137.4	12.22	Flexural	127.75	-

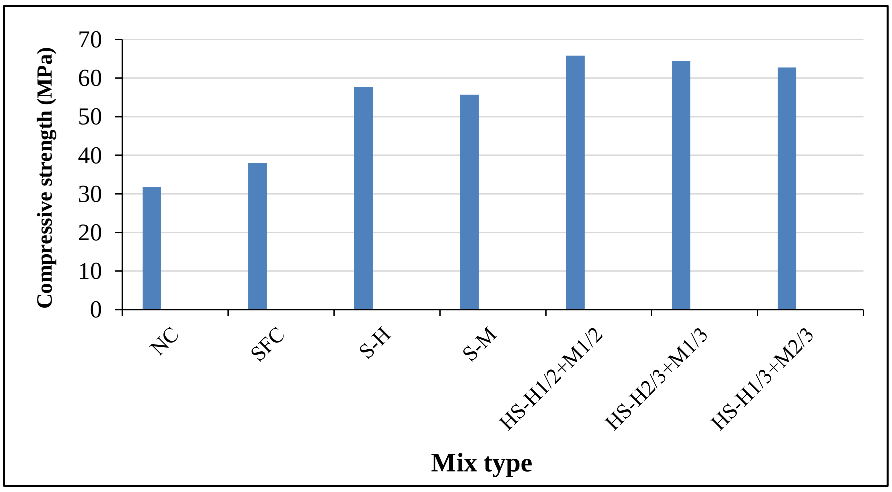


Figure 7. Compressive Strength levels at 28 days

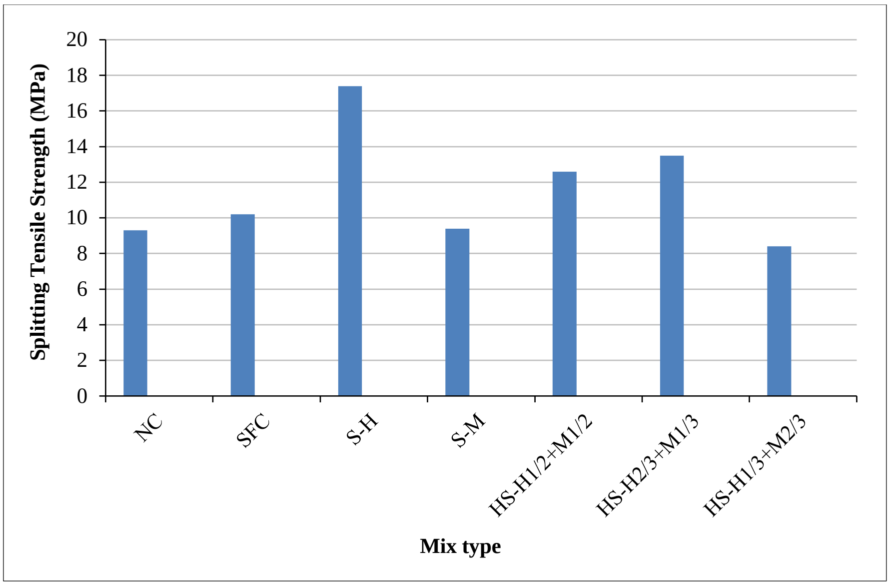


Figure 8. Levels of splitting tensile strength after 28 days

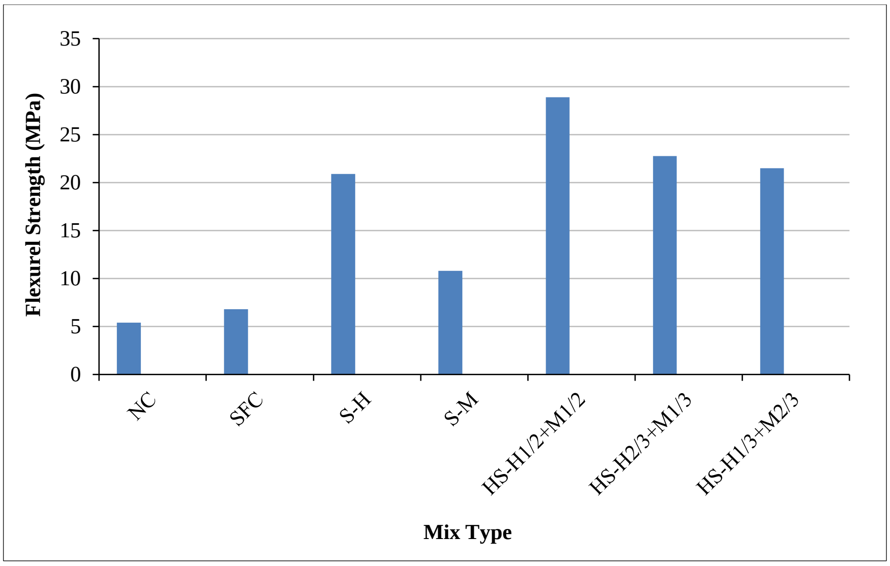


Figure 9. Flexural strength levels at 28 days

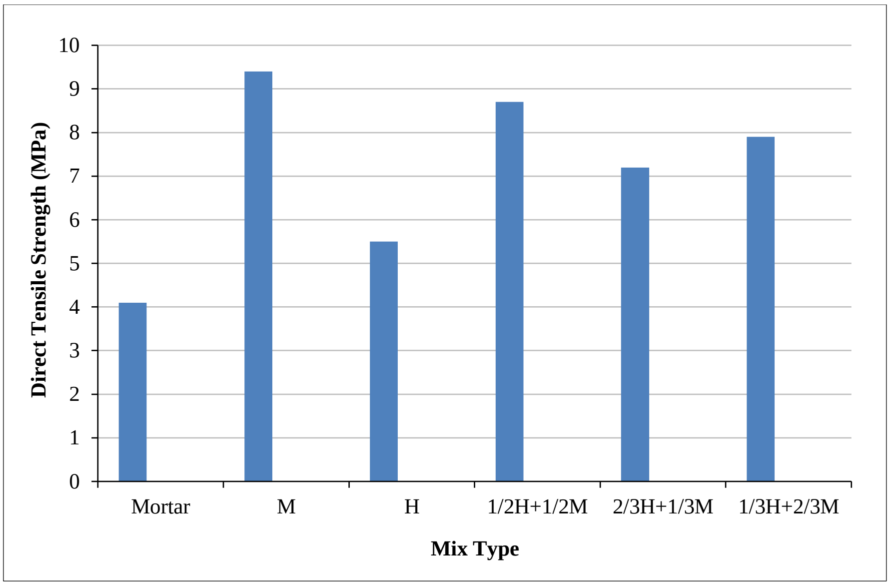


Figure 10. Direct Tensile strength levels at 28 days

The results clearly indicate that SIFCON samples incorporating hybrid fibers show superior strength compared to other specimens. The combined action of the straight micro steel fibers and the hooked ends of the steel fibers is responsible for this. The hybrid fibers effectively bridge the growth of micro cracks and improve the bond among the fibers and matrix, resulting in greater strength for the SIFCON mixes. These findings align with the research conducted by BS 1881-116 [24], where they observed that the adding of hybrid fibers created a synergistic effect in concrete, resulting in notable improvements for fiber-reinforced concrete.

3.3. Splitting Tensile Strength

As indicated in Table 2, SIFCON samples reinforced with hooked steel fibers exhibited slightly higher splitting tensile strengths compared to samples reinforced with hybrid and micro fibers. Which suggests that the use of hooked-end steel fibers slightly enhances the splitting tensile strength performance of the SIFCON specimens. The presence of hooked-end steel fibers in SIFCON contributes to improved tensile strength performance, as the bent ends of these fibers increase engagement between the two sides of sample failure. Essentially, the curved ends of the fibers aid in distributing the applied load more uniformly across the specimen, leading to a more balanced failure mode. This increased interaction between the failure sides contributes to the overall strength and performance of the SIFCON samples.

3.4. Direct Tensile Strength

Table 2 provides information on the direct tensile strength of SIFCON samples reinforced with micro steel fibers, hybrid fibers, and hooked end fibers. The data suggests that specimens reinforced with micro steel fibers exhibit a little higher direct tensile strength compared to those reinforced with hybrid and hooked end fibers. This strength increase can be attributed to the high aspect ratio of micro steel fibers compared to hooked-end fibers, which contributes to an improvement in the tensile strength of the samples. Furthermore, the strength improvement may be credited to the capacity of microfiber steel to manage the formation of micro cracks through mechanisms such as arrest and bridging.

3.5. Static Modulus of Elasticity

The results clearly indicate an increase in the values of hooked-end steel fiber over the rest of the mixtures. This increase can be attributed to the shape of the hook ends, where weak points are nearly non-existent, and the bond strength inside the concrete of this type is higher than that of micro straight steel fiber. Experimental results revealed that using a single type of fiber in SIFCON led to some enhancements in the composite's properties. However, when hybrid fibers containing two groups were added, the resulting hybrid compounds exhibited superior engineering characteristics compared to those with single fiber additions. This is because the presence of a single fiber type allows for the most efficient utilization of the potential properties of other fibers. This investigation clearly demonstrates that incorporating different kinds of hybrid fibers in concrete improves the engineering behavior of the concrete and results in superior mechanical properties compared to SIFCON reinforced with monofilament fibers. Furthermore, this enhancement could be referred to the fact that microcracks can be controlled by the arresting and bridging mechanism of fibers. Furthermore, the use of micro steel fiber leads to an enhanced bond between the matrix and fiber, resulting in an enhancement of SIFCON's mechanical properties [29].

3.6. Results of Reinforced Concrete Slabs

The slabs underwent testing subjected to monotonic flexural loading, utilizing a simply supported configuration along their perimeter, as depicted in the figure. The EPP300MFL system, capable of handling up to 3000 kN, served as the testing machine, as shown in Figure 11. A propagator beam was used to apply the load, transferring it to the slab via two loading points located at the ends of the span's middle third. To measure deflection, five Linear Variable Differential Transducers (LVDTs) were strategically positioned. One LVDT was placed beneath the slab's midpoint, two were aligned on the same line at a quarter point, and the remaining two were situated on either side of the opening's edge. In addition, a standardized load cell was employed to record the applied load. To monitor strain, three strain gauges were affixed to the slab's tension face. One gauge was located at the opening's edge, while the other two were placed at distances of d/2 and 2d from the face of the column. It's noteworthy that each strain gauge had a length of 30 mm.

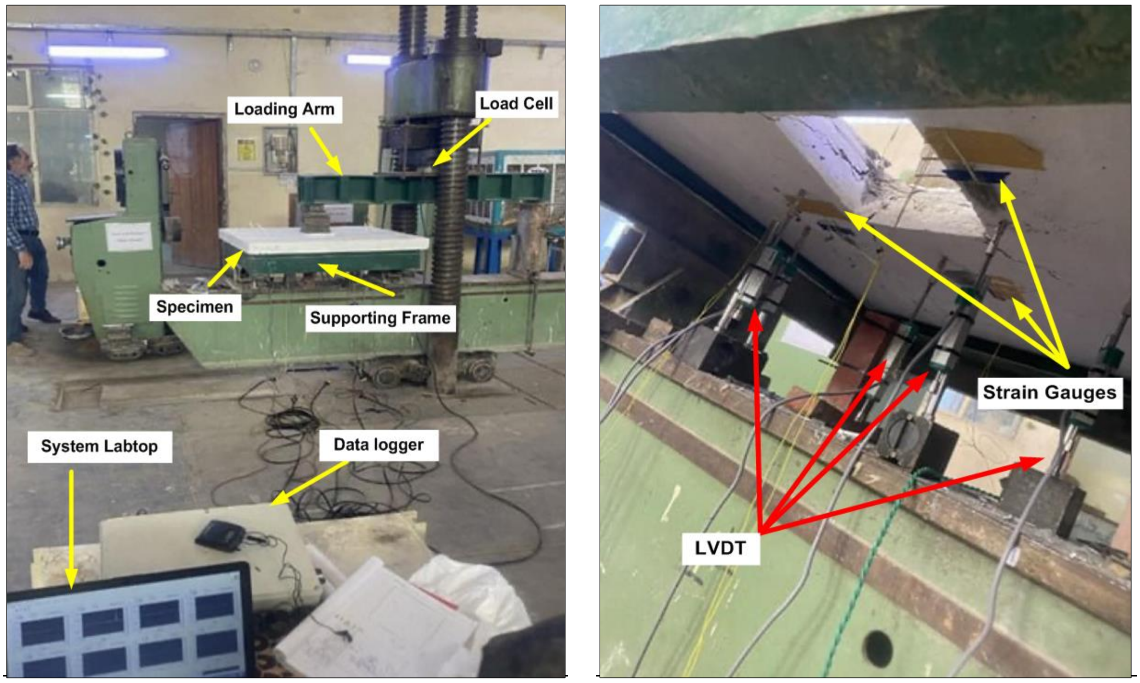


Figure 11. Testing Machine and Slabs

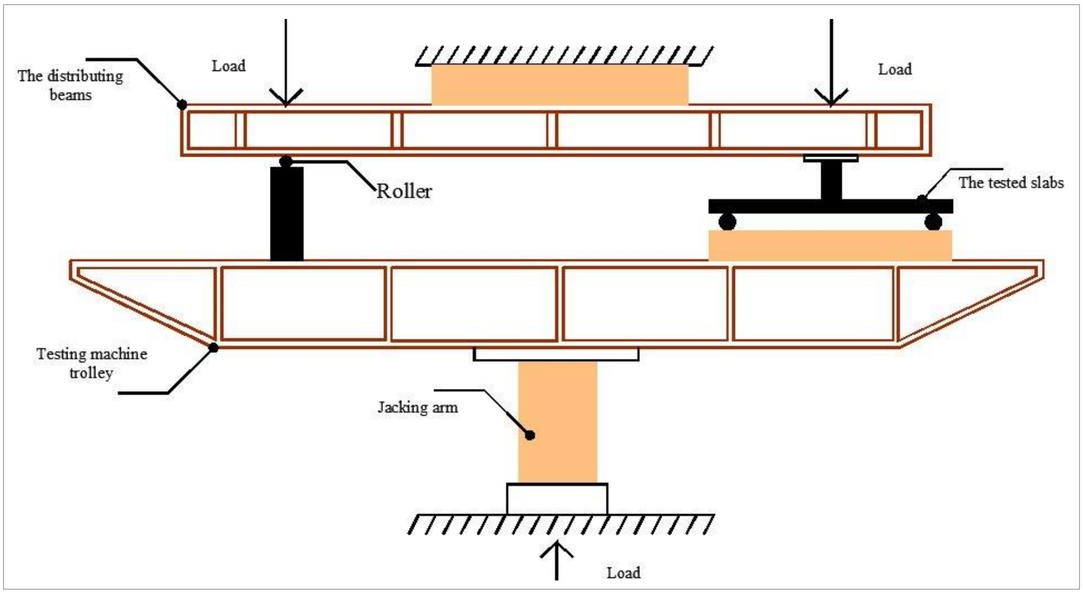


Figure 12. Schematic details of the test

3.6.1. Failure Pattern of Cracking

Figure 13 illustrates the patterns of failure cracks observed in the test samples. The samples exhibited failure due to punching shear, with signs of flexural failure evident in the specimens that utilized Infiltrated Fibrous Concrete. Upon load application, a sudden drop in load capacity was observed, accompanied by a roaring sound indicative of slab collapse and shear failure. As the load increased, the first crack surfaced on the tension side of the slabs. The number and width of cracks then expanded, propagating centrifugally from the column sides towards the slab edges. This was quickly followed up by the formation of circumferential cracks encircling the column stub. In samples that utilized Infiltrated Fibrous Concrete, the number of cracks significantly decreased compared to those without it. The hybrid Fiber, composed of steel fibers of varying sizes, served a dual purpose: thin fibers were used to control micro-cracks, while longer and thicker fibers were employed to bridge macro-cracks. For samples with openings, cracks originated from the edges of the openings in a radial direction and extended towards the slab edges. These cracks connected the opening corners with the condensed concrete cone, leading to spalling of the concrete cover at conformed locations of tension steel. Additionally, large diagonal shear cracks developed on the sides of the opening, with angles ranging from 25° to 40°. The existence of openings and the use of Infiltrated Fibrous Concrete altered the shear failure mechanism for a two-way to a one-way activity.

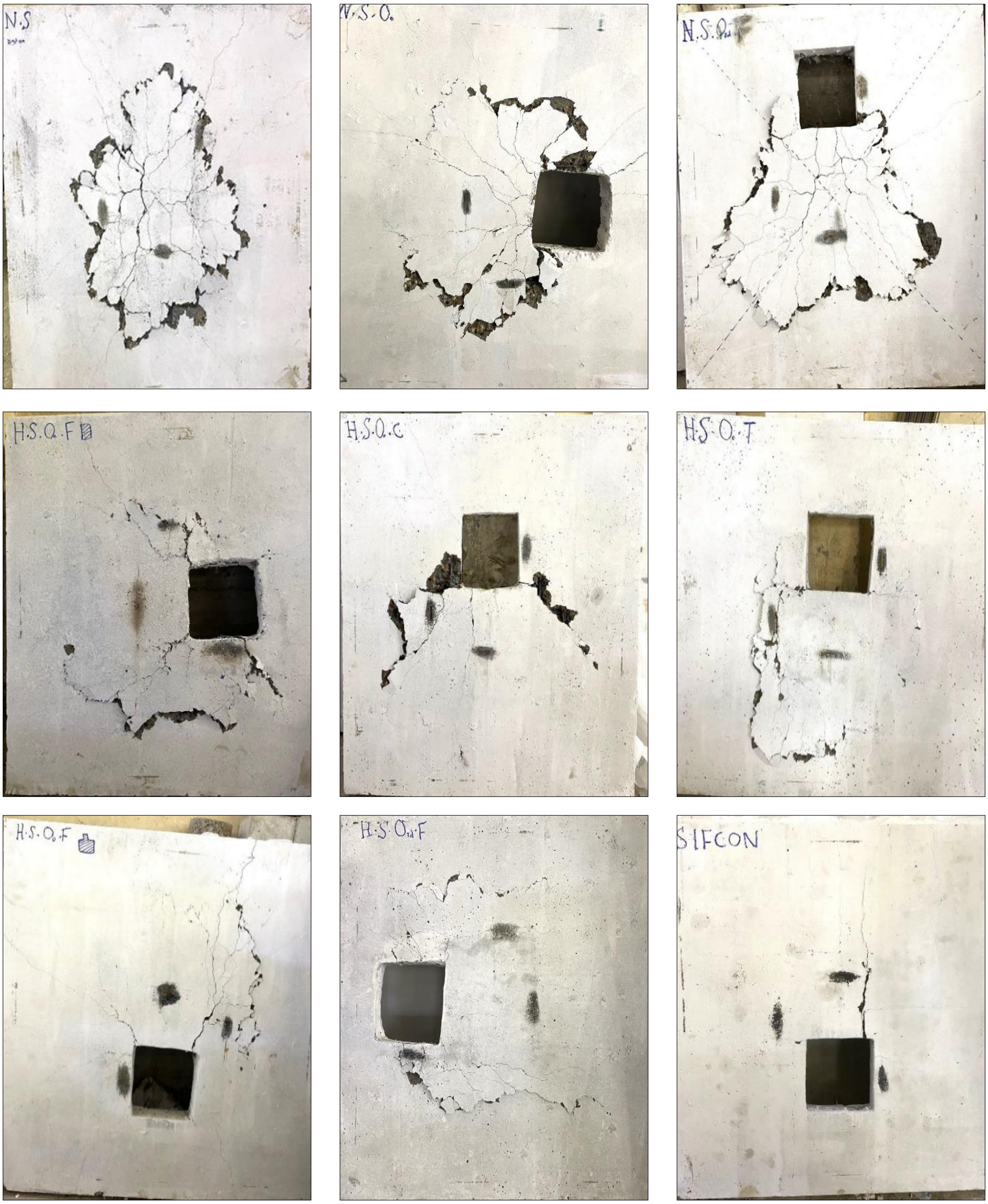


Figure 13. The crack pattern and punching perimeter

3.6.2. Curves of Load-Deflection

Figure 11 presents the load-deflection curves at the mid-span of the tested slab samples. The curves for most test samples display like behavior, with the slabs reaching peak load and exhibiting brittle failure characterized by a sudden decrease in punching shear capacity. This brittle failure indicates minimal ductility and remaining strength. The load-deflection curves can be separated into three distinct phases. The first phase, known as the uncracked stage, shows nearly linear performance with no significant cracking observed in the slabs. The second phase, referred to as the pre-yield cracked stage, extends from the cracking load to the yield load. In this phase, the curve's slope gradually decreases as flexural concrete cracking begins to occur on the slab's tension side. The final phase, the post-yield cracked stage, spans from the yield load to the punching or flexural failure load. In this phase, the curve's slope signifies the rate of deformation or deflection of the slabs.

It's noteworthy that the slope of the load-deflection curves for hybrid SIFCON concrete slabs is steeper than that of the regular concrete slabs. This suggests that the hybrid SIFCON concrete slabs demonstrate higher stiffness or resistance to deformation compared to the regular concrete slabs. Moreover, the position of the openings in the slab samples influences the slope of the load-deflection curves. The presence and location of openings affect the structural response and behavior of the slabs, leading to variations in the curve's slope. When the thickness of the mortar-infiltrated fiber concrete is limited to 35 mm at the tension face and does not exceed the flexural reinforcement, it has no impact on punching shear stress. This is due to the primary reinforcement at this location, with its dual action, providing sufficient resistance against punching shear. In closing, the load-deflection curves of the tested slabs reveal three distinct phases: the uncracked phase, the pre-yield cracked phase, and the post-yield cracked phase. The hybrid SIFCON concrete slabs exhibit higher stiffness compared to normal concrete slabs, as evidenced by their steeper load-deflection curves. Furthermore, the position of the openings significantly influences the slope of the curves, indicating the impact of openings on the structural response of the slabs.

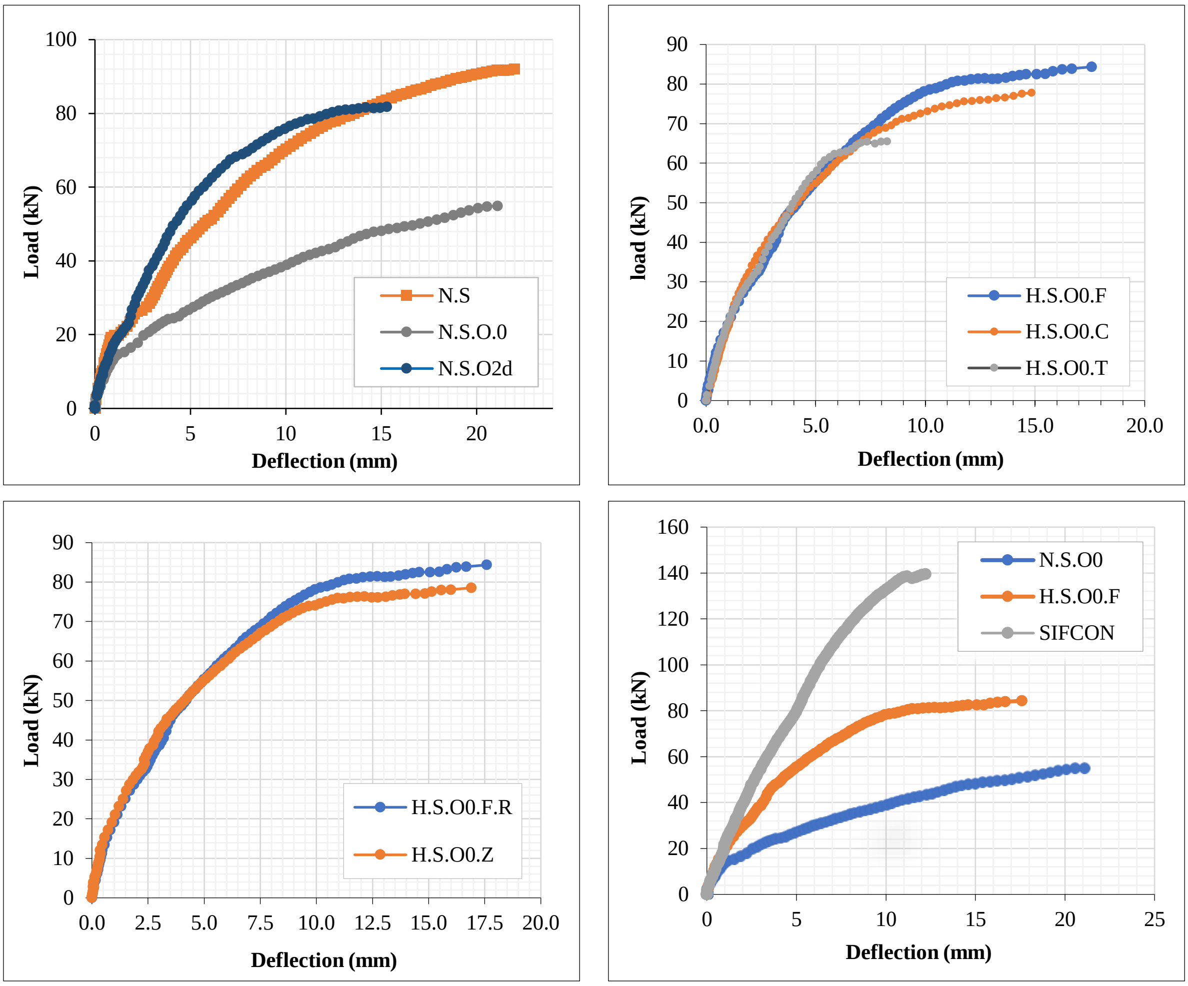


Figure 14. Load-Deflection curve

4. Conclusions

Several conclusions can be drawn based on the obtained results:

- Generally, SIFCON mixtures demonstrate superior mechanical properties compared to the reference mix (NC&SFC). The compressive strength of SIFCON ranges from 55.7 to 65.78 MPa at 28 days, compared to the strength of 30.7 and 38 MPa for the NC & SFC mix respectively.
- For the preparation of SIFCON mortars, exclusively fine sand sieved through a 1.18 mm sieve was used to separate larger particles. This specific sand size has proven effective for all SIFCON mixtures used in the experiments, as it enhances the homogeneity and workability of the mortar, and improves the final properties of the SIFCON product.
- SIFCON specimens exhibit higher splitting tensile, flexural strength, direct tension, and static modulus of elasticity, reaching about 87, 435, 129 and 48.5% respectively over the reference mix (NC) at 28 days.

- The inherent bridging capability and high strength of hooked steel fibers make them more effective in enhancing concrete's mechanical potential compared to micro steel fibers, which have weak points at their ends, resulting in reduced strength against loads.
- The inclusion of hybrid steel fibers in the production of SIFCON significantly improves their mechanical properties. The use of lightweight fibers, such as fine steel fibers, provides a load-bearing layer for the hooked-end steel, preventing it from sinking and achieving good distribution, thus eliminating the sinking phenomenon caused by the difference in densities between steel fibers and mortar.
- SIFCON specimens reinforced using hybrid fibers exhibit higher compressive, cylinder compressive strength, flexural strength, and direct tensile strength 14, 13.9, 38.2 and 58.2% respectively at 28 days, but have lower splitting tensile strength -24% compared to hooked ones.
- SIFCON specimens reinforced with hybrid fibers show increased compressive, cylinder compressive strength, flexural strength, and splitting tensile strength 18.2, 51, 167.5 and 43.6% respectively at 28 days, but have lower direct tensile strength -7.4% compared to micro steel fiber ones.
- When mortar-infused fiber concrete was used instead of control specimens, punching shear strength increased by 3.21% to 154.25%.
- The presence of openings and the use of Infiltrated Fibrous Concrete improved the shear failure mechanism for a two-way action to a one-way action.
- The technique involves using a special type of concrete called Infiltrated Fiber Concrete to cast a mortar layer with half the thickness of the slab directly beneath the column's compression face. This method aims to distribute the load over a larger area and redirect it away from the column's failure line in order to enhance the ultimate load capacity and increase deflection.
- When the thickness of SIFCON is restricted to the tension face at 35 mm and does not exceed the flexural reinforcement, it does not have any effect on punching shear strength. This is due to the main reinforcement in this area provides sufficient punching shear resistance due to its dual function.

5. Declarations

5.1. Author Contributions

Conceptualization, E.K. and S.A.; methodology, E.K.; software, E.K.; validation, E.K., S.A., and A.B.; formal analysis, E.K.; investigation, E.K.; resources, E.K.; data carnation, E.K.; writing—original draft preparation, E.K.; writing—review and editing, E.K.; visualization, E.K.; supervision, E.K.; project administration, E.K.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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