Research Article

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Enhancement of flexural behavior of hybrid flat slab by using SIFCON

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Abstract: Flat slab systems are widely utilized in construction due to their versatility and efficient use of space. Nevertheless, they are susceptible to flexural failure, particularly in the tension zone. To address this issue, slurry-infiltrated fiber concrete (SIFCON) has been proposed as a solution owing to its exceptional strength and durability. This research examines the effect of utilizing SIFCON in the tension zone of flat slab systems to enhance their flexural performance. The study encompasses testing eight identical slabs, two of which were cast with normal concrete, while the remaining six were hybrid slabs incorporating SIFCON. The specimens were subjected to vertical loading to compare their flexural behavior and identify the optimal dimensions for the SIFCON layer. The slabs had identical dimensions but varied in reinforcement. Group A had a reinforcement ratio of ρ = 0.5%, whereas Group B had a ratio of ρ = 0.335%. All slabs had a constant thickness of the SIFCON layer of 20 mm in the tension zone but varied in the dimensions of the SIFCON layer (100, 50, 30%) from the slab dimensions. A square plate with dimensions (140 × 140 × 20) mm supported the load for all slabs. The load was applied gradually until failure, and the load–deflection curves were recorded for each slab. The result showed that using SIFCON in the tension zone improved the flexural resistance of flat slab systems. The hybrid slabs with SIFCON demonstrated higher ultimate loads and lower deflections than the control slabs that used regular concrete. In particular, the hybrid slabs with a 100% SIFCON layer exhibited the best results, with a rise in ultimate load of 179 and 100% for Groups A and B, respectively, compared to the control slabs. In addition, there was a significant decrease in deflection of 62.35 and 52.38% for Groups A and B, respectively, relative to the control slabs. The study found that the optimal combination of the SIFCON dimension was when the 50% slab dimension was covered and the reinforcing bar area for the hybrid reinforcement system was smaller.

Keywords: flat slab, SIFCON, hybrid concrete, flexural, flexural shear

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1 Introduction

Reinforced concrete slabs are commonly used in the construction industry. However, conventional reinforced concrete slabs have limitations such as low tensile strength, cracking, and corrosion of reinforcing bars. The slab's high strength and durability depend on high concrete quality. Slurry-infiltrated fiber concrete (SIFCON) is a relatively new reinforcement system proposed as an alternative to conventional reinforcing bars. SIFCON is a high-strength, fiber-reinforced concrete (FRC) that can reinforce concrete structures. Hybrid reinforcement systems that combine traditional reinforcement with SIFCON have been proposed to improve the performance of reinforced concrete structures. This study investigates the effect of two parameters, SIFCON dimension and reinforcing bar area, on the performance of a hybrid reinforcement system for reinforced concrete slabs. Several studies have been conducted on its effectiveness in improving reinforced concrete slabs' flexural strength and durability. In a study by Rao and Ramana [1], the flexural behavior of bound two-way SIFCON slabs with different percentages of steel fibers and volume fractions was investigated. The results showed that SIFCON slabs with a steel fiber volume fraction of 12% had superior load-bearing capacities, energy absorption, and ductility compared to FRC and plain concrete slabs. Jaafer [2] studied the effect of SIFCON on the response of ferrocement slabs, where different volume ratios of steel fiber were used in SIFCON. The results showed an increase in the ultimate load capacity and a decrease in crack width for slabs with SIFCON compared to those without. The use

Figure 1: Flexural reinforcement of slab.

of SIFCON in hybrid two-way slabs has been studied in limited research.

In other research by Hamid and Mohammed [3], steel fibers (0.5, 1, 1.5%) were added to reactive powder concrete with two-way plate loads of dimension (1,000 × 1,000 × 70) mm to enhance flexural strength. Results indicated that increasing steel fiber content led to significant improvements: first crack load increased by 32.2–52.3%, final load by 17–36.1%, and energy absorption by 128 and 20.2%. The samples also exhibited increased hardness and ductility during loading, along with delayed crack propagation and improved control over energy absorption and final deflection.

Hussain et al. [4] investigated the extent of the effect of steel fibers type and the friction volume of steel fiber on the flexural behavior of two-way reinforced concrete slabs. The types of fibers they used were straight, hook, and corrugated; each type of fiber was added in proportions of 0, 0.5, 1, and 1.5% of the total volume of concrete; and the slab's dimensions were (800 × 800 mm × 100). They are cast and subjected to flexural tests. It was observed that when adding of each type of fiber to concrete, the results showed a good improvement in energy absorption and load, especially for hook fibers, and better results when using 1%, but when adding 1.5% of steel fibers to concrete, it weakens the workability by 83–92%. Figures 2 and 3 show the failure slab.

Azoom and Rama [5] tested ten slabs with mortar infiltrated fiber concrete (MIFC) casting with varying types of fiber (steel, polypropylene, and hybrid fibers) in different ranges of volume fraction. The specimens with dimensions of (600 × 600 mm) and thickness of 50 mm are adopted for punching shear studies, as shown in Figures 2–6. The mix contained cement, ground-granulated blast-furnace slag, and sand in the ratio of 1:1:2. Water-to-binder ratio (w/b)

Figure 2: Cast slab with SIFCON layer.

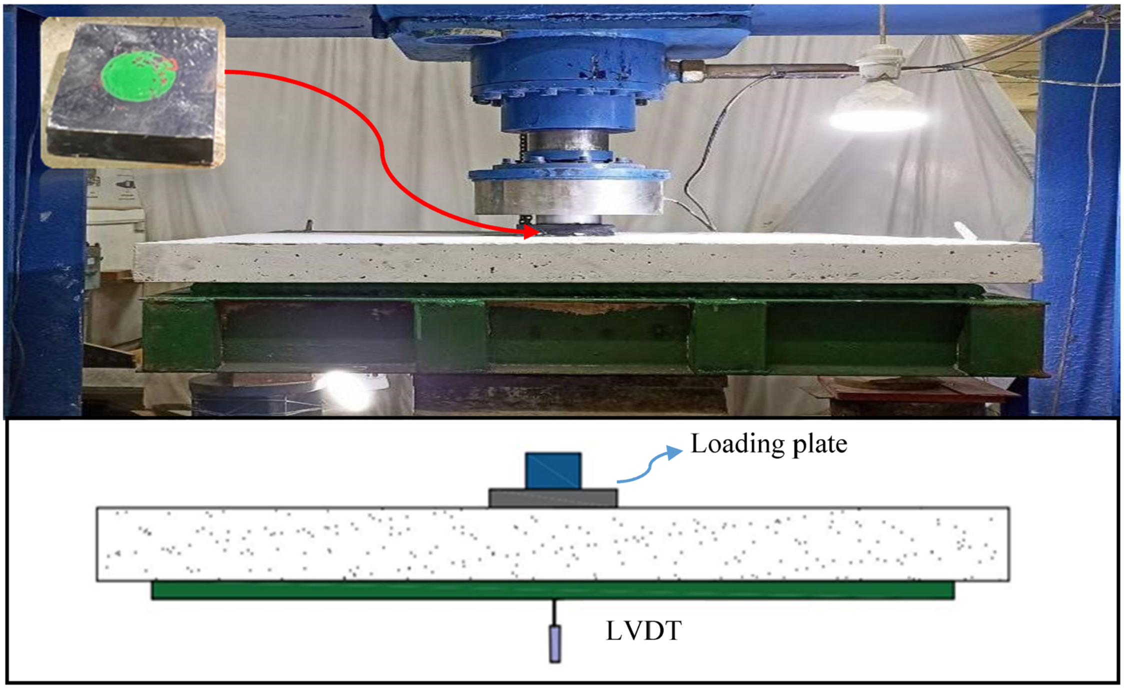


Figure 3: Universal testing machine in the laboratory of the University of Kerbala.

adopted is 0.45, and the superplasticizer dosage is found to be 1%. This study concluded that the punching shear of the MIFC slabs is much higher than that of normal strength concrete (NSC) and was up to nine times higher with steel fibers, two times higher with polypropylene fibers, and three times higher with hybrid fibers. Punching strength increased with an increase in fiber volume, varying from 2 to 12 times in the case of specimens with polypropylene fibers and from 0 to 27 times in the case of specimens with steel fibers. Impact resistance was also found to be much higher for MIFC specimens, up to ten times with steel fibers and seven times with polypropylene fibers compared to NSC.

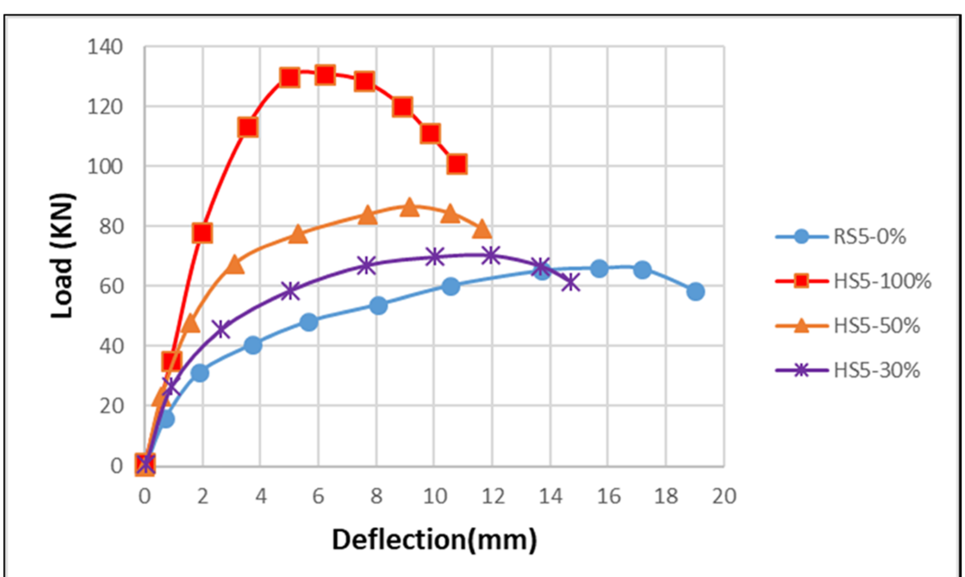


Figure 4: Load–deflection curves for hybrid slab compared with the reference in group (A).

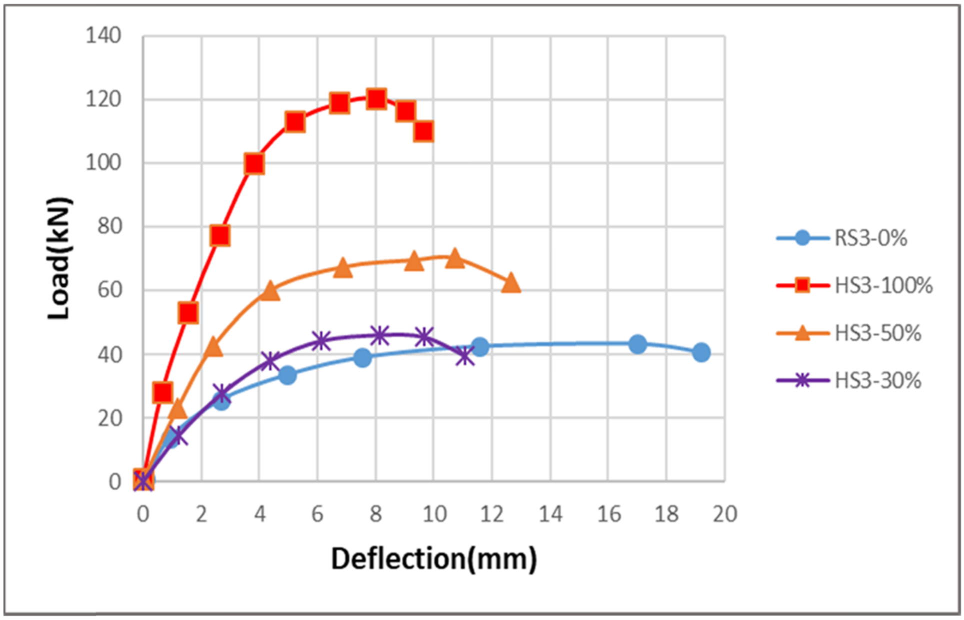


Figure 5: Load–deflection curves for hybrid slab compared with the reference in group (B).

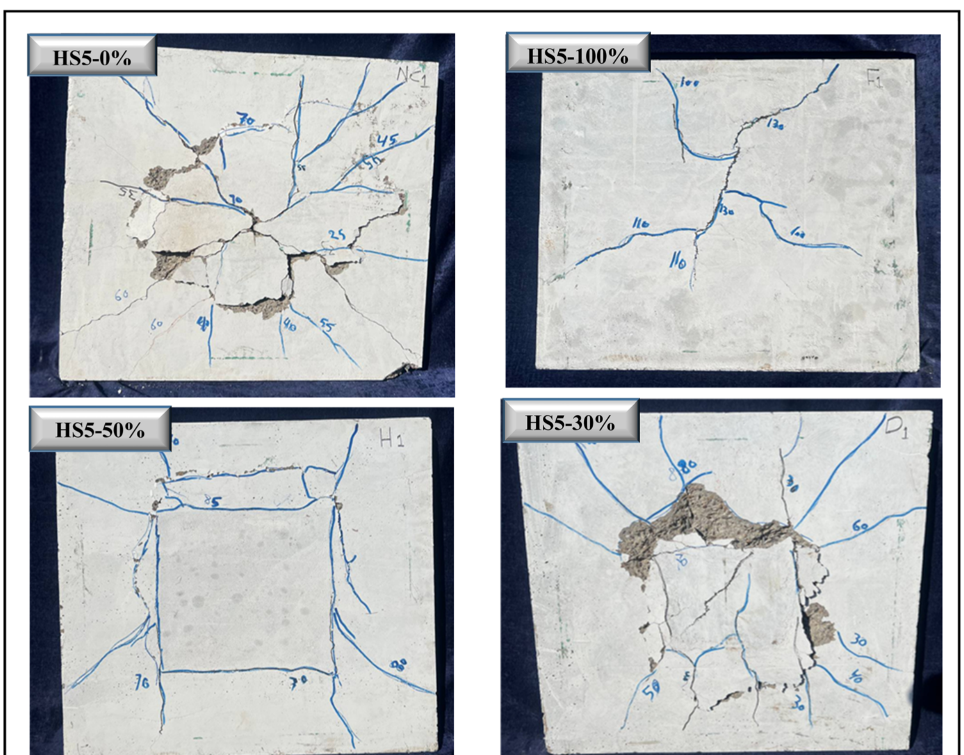


Figure 6: The final shape for tested slabs shows the crack pattern in group (A).

The use of SIFCON in hybrid two-way slabs has been studied in limited research. SIFCON typically consists of a slurry made of cement and additives such as sand, silica fume, and steel fibers. The slurry is often made more flowable using superplasticizers to ensure thorough infiltration without increasing the water–cement ratio. Steel fibers are added to increase ductility and residual tensile strength, bridging cracks and improving crack control by mixing steel fiber with slurry [6–8].

SIFCON, also known as Engineered Cementitious Composite, is a high-performance construction material that combines cementitious matrix and randomly distributed short fibers. It offers several enhanced properties compared to traditional concrete, including improved tensile strength, crack resistance, and ductility. The beneficial effects of SIFCON on the properties of slabs are primarily attributed to its unique microstructural characteristics and fiber reinforcement.

1. Fiber reinforcement: SIFCON incorporates a significant volume fraction of short fibers (usually less than 10% by volume) into the concrete matrix. These fibers are randomly distributed throughout the material. When the slab is subjected to tensile or flexural loads, the fibers provide reinforcement by bridging across cracks, resisting crack propagation, and enhancing the overall toughness of the material [9].
2. Multiple cracking: SIFCON exhibits a unique behavior called multiple cracking. Unlike traditional concrete, which typically fails in a brittle manner with a single major crack, SIFCON undergoes multiple microcrackings under tensile or flexural loading. These microcracks form at different locations within the material, effectively dissipating energy and preventing the propagation of a single catastrophic crack. As a result, the slab has improved crack resistance and durability [10].
3. Strain hardening: SIFCON also displays strain-hardening behavior, meaning it can undergo significant deformation and strain beyond the initial cracking stage. Short fibers in the matrix enable the material to exhibit pseudo-ductility, where it can sustain deformation and strain without sudden failure. This characteristic enhances the structural integrity of the slab and allows it to withstand larger deformations without catastrophic collapse [11].
4. Improved bonding and infiltration: During the manufacturing process of SIFCON, a slurry containing cementitious materials is infiltrated into a prearranged fibrous network. The slurry infiltrates the voids between the fibers, resulting in improved interfacial bonding between the fibers and the matrix [12,13]. This strong bonding ensures effective load transfer between the fibers and the matrix, further enhancing the overall mechanical properties of the slab.

This study investigated new technical of SIFCON with gradual steel mix method of a volume fraction of 6% steel fiber to enhance flexural failure in a hybrid two-way slab. The variables studied were the percentage of reinforcing steel used in the slab and the dimensions of the SIFCON layer.

2 Materials used for cast specimens and concrete mix

In this experiment, two types of concrete were used: normal concrete and SIFCON. The materials used to prepare the concrete were as follows:

1. Cement: The cement used in both types of concrete conformed with the Iraqi Standard Specification IQS No. 5/2019 [14].
2. Sand: The sand used in normal concrete conformed to the IQS No. 45/1984 zone 3 limitation, while the sand used in SIFCON conformed to the IQS No. 45/1984 zone 4 limitation [15].
3. Gravel: The gravel used in normal concrete had a size of 4–15 mm and conformed to the Iraqi Specification No. 45/1984 specifications.
4. Silica fume: Silica fume was used in the SIFCON mixture, and the results showed that the silica fume used in this study conformed to the requirements of ASTM C1240-05, 2015 [16].
5. Superplasticizer: A superplasticizer was used in the SIFCON mixture and conformed to ASTM C494/C494M, 2017 [17].
6. Steel fiber: Straight steel fibers with 13 mm length and 0.2 mm diameter were used in the SIFCON mixture.

Several trial mixtures were made to obtain the required strength for both types of concrete, and experimental mixtures were made to reach the proper proportions shown in Table 1.

3 Process of casting specimen

The specimen casting process for this experiment involved several steps. First, the materials were prepared and weighed according to the required volume of the mixture. All samples were cast in plywood molds with clear dimensions of 1,000 × 1,000 × 80 mm, and plywood and steel molds were properly cleaned and lubricated with oil to prevent adhesion with hardened concrete. All slabs were cast with two flexural reinforcements of $\rho 1$ = 0.5% with 6Ø8 at 192 mm and $\rho 2$ = 0.335% with 4Ø8 at 320 mm. The yield strength of reinforcement was 570 MPa, as shown in Figure 1. Second, the hybrid slab was cast by pouring SIFCON in a way that was used after casting

Table 1: Mix proportions

Mix type	Cement (kg/m^3)	Sand (kg/m^3)	Silica fume (kg/m^3) 10% rep	Gravel (kg/m^3)	Steel fiber (%)	w/b or w/c ratio	Superplasticizer (by wt. of binder) (%)	Compressive strength (f_c') (MPa)
SIFCON	875.7	973	97.3	—	6	0.28	2.4	86
Normal concrete	360	700	—	1,070	—	0.55	—	33

cubes and testing them to ensure strength compared to the multi-layered SIFCON. In this work, the gradual mix method was used, which involved mixing the slurry with a steel fiber for 2 min and then casting it according to the layer's dimensions in the tension zone. After that, standard concrete was poured, and vibration was used for the standard concrete and around the area cast with SIFCON, as shown in Figure 2. Finally, all slabs were left to cure for 28 days before testing to ensure they had reached the desired strength. This casting process was used for all six flat slabs, including the reference and hybrid slabs with SIFCON.

4 Test of slab

This experiment's tested slabs were supported along the slab's perimeter. A square plate centrally loaded them with a dimension of 140 × 140 × 20 mm, identical for all specimens. A hydraulic jack with a loading capacity of 2,000 kN was used to test the slabs. The testing machine was located at the University of Kerbala, as shown in Figure 3. During the testing process, the deflection of the slabs was measured using an electronically controlled gage, a linear variable differential transformer located at the center of the slab. The data for load and deflection were collected using a computer system programmed with LABVIEW software. This allowed for accurate and reliable measurements of the behavior of the slabs during loading.

5 Description and identification of the slab specimens

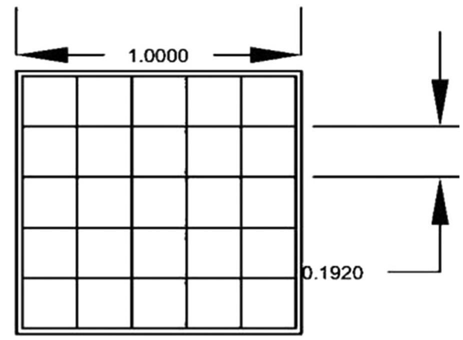
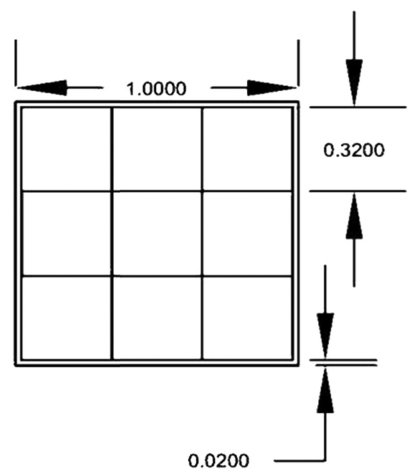
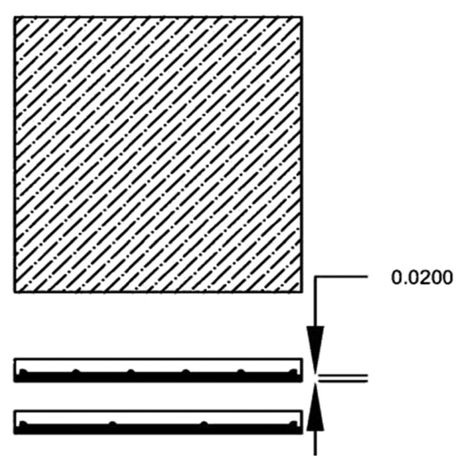
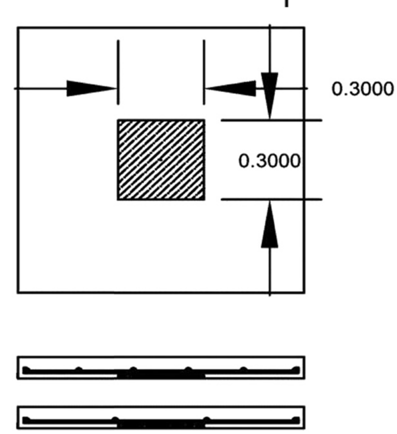
The slabs used in this work were explained in detail, as shown in Table 2.

6 Results and discussion

The tested slabs failed with three types of failure, some of which were flexural failure, flexural-shear failure, and debonding, as shown in Table 3.

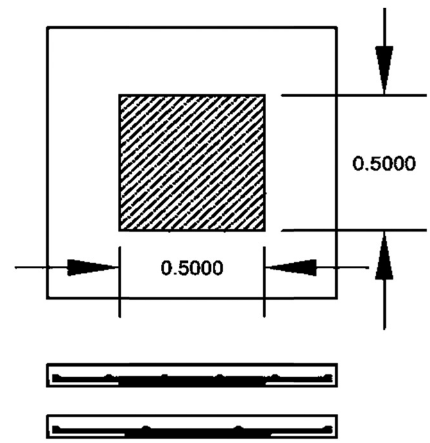
From Table 3, two types of failure were observed: flexural and shear failures in HS5-50% and HS3-50%. It initially occurred as a shear failure at the contact area of the two types of concrete. With the slab's continued loading, flexural failure emerged and propagated toward the slab's edges, forming yield lines.

Table 2: Summary of all slabs (all units in m)

Symbol	Area cast with SIFCON	Details
RS5-0%	Cast slab normal concrete with flexural reinforcement $\rho = 0.005$	
RS3-0%	Cast slab normal concrete with flexural reinforcement $\rho = 0.00335$	
HS5-100%	Cast SIFCON whole area with thickness 20 mm at the tension zone with $\rho = 0.005$	
HS3-100%	Cast SIFCON whole area with thickness 20 mm at the tension zone with $\rho = 0.00335$	
HS5-30%	Square (30% of the total dimension of the slab) at the center of the slab with a thickness of 20 mm at the tension zone with $\rho = 0.005$	
HS3-30%	Square (30% of the total dimension of the slab) at the center of the slab with a thickness of 20 mm at the tension zone with $\rho = 0.00335$	

(Continued)

Table 2: *Continued*

Symbol	Area cast with SIFCON	Details
HS5-50%	Square (50% of the total dimension of the slab) at the center of the slab with a thickness of 20 mm at the tension zone with ρ = 0.005	
HS3-50%	Square (50% of the total dimension of the slab) at the center of the slab with a thickness of 20 mm at the tension zone with ρ = 0.00335	

The debonding failure occurred in HS5-30% and HS3-30%, where the SIFCON layer slipped from the slab's reinforcement during continued loading. This failure was caused by the small dimensions of the SIFCON layer, which could not withstand the applied load, resulting in the separation of the SIFCON layer at the interface in the tension zone of the two concrete types.

6.1 Ultimate load and central deflection

Based on the results, using the SIFCON layer in hybrid slabs can significantly improve their flexural behavior. This improvement was observed regardless of the type of tensile reinforcement used in the slab. The convergence of results for the two cases (HS5-100% and HS3-100%), when compared to each other, indicates that the SIFCON layer had a significant impact on the final load and deflection of the slabs. In particular, the results showed that using a 20 mm thick SIFCON layer poured over the entire slab area in specimens HS5-100% and HS3-100%, as shown in Figures 4 and 5, resulted in a 100% increase in the final load for HS5-100% and a 179% increase for HS3-100%, compared to the reference slabs RS5-0% and RS3-0%, respectively. In addition, the maximum deflection decreased by 62.35 and 52.38% for HS5-100% and HS3-100%, respectively, compared to their respective reference slabs [18,19]. The SIFCON layer in the hybrid slab underwent elastic and plastic deformation. The load carried during the plastic stage is higher than in the flexible stage, and the ultimate load and deflection of the slab increase rapidly during the plastic stage.

In hybrid slabs, HS5-50% and HS3-50% resulted in significant improvements in their load-bearing capacity and

Table 3: The result of the slab test

Group	Specimen	Ultimate load (kN) Pu	Max. deflection (mm) Δu	Increase in ultimate load (Pu) with respect to control (%)	Decreases in deflection (Δu) concerning management (%)	Type of failure
Group A	RS5-0%	65	17	Reference	Reference	Flexural
	HS5-100%	130	6.4	100	62.35	Flexural
	HS5-50%	88	8	35.38	52.94	Flexural + shear
	HS5-30%	70	12	7.69	29.41	Debonding
Group B	RS3-0%	43	16.8	Reference	Reference	Flexural
	HS3-100%	120	8	179	52.38	Flexural
	HS3-50%	70	10.6	62.79	36.9	Flexural + shear
	HS3-30%	46	9	6.97	46.42	Debonding

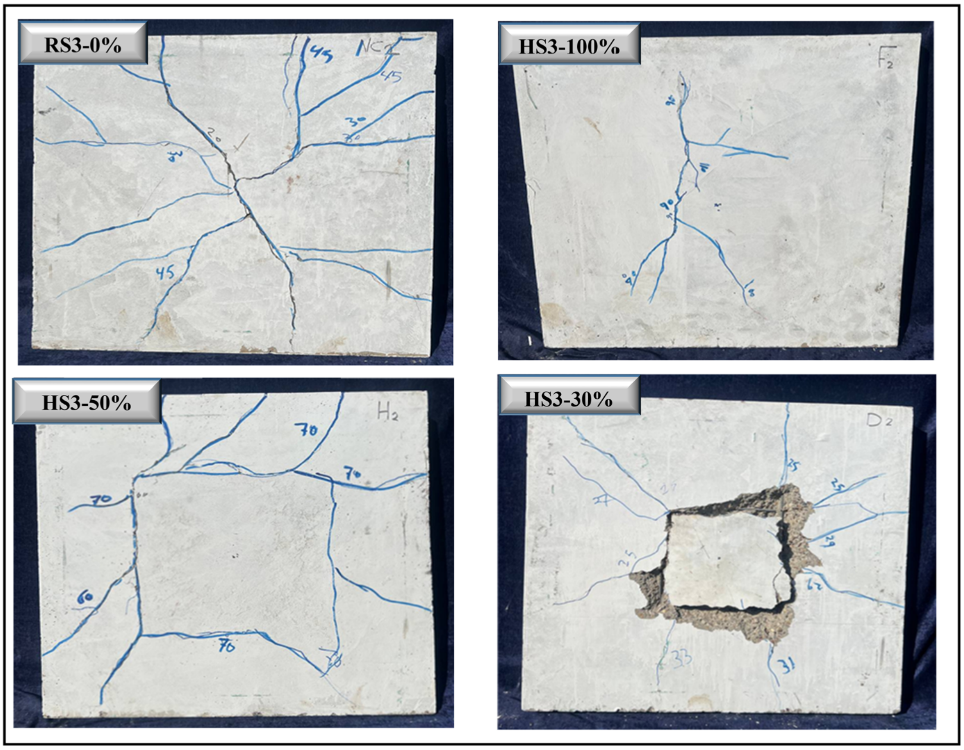


Figure 7: The final shape for tested slabs shows the crack pattern in group (B).

resistance to deflection. Specifically, the final load increased by 35.38% for HS5-50% and 62.79% for HS3-50%, compared to their respective reference slabs, RS5-0% and RS3-0%. In addition, the maximum deflection decreased by 52.94% for HS5-50% and 36.9% for HS3-50%. It is also worth noting that the addition of SIFCON reinforcement altered the failure mode of the slabs from flexural to flexural shear, as shown in Figures 6 and 7. This is likely due to the difference in the endurance strength of SIFCON and normal concrete, which resulted in cracks at the meeting point of the two types of concrete. However, despite this change in failure mode, using SIFCON in both types of flexural reinforcement ultimately improved the flexural behavior of the slabs. In both stages, elastic and plastic for both slabs HS5-50% and HS3-50%, the load was increased in the elastic stage, and the deflection was increased in the plastic stage.

It was discovered that for the remaining two cases (HS5-30% and HS3-50%), there was no significant improvement in the final load values when the SIFCON layer with dimensions 300 × 300 × 20 mm was cast. The results of the two specimens were compared to the two reference specimens, and it was found that the ultimate load increased by 7.69 and 6.97% for HS5-30% and HS3-30%, respectively, when compared with RS5-0% and RS3-0%. In addition, there was a decrease in deflection of 29.41% for HS5-30% and 46.42% for HS3-30% when compared with RS5-0% and

Table 4: Stiffness of slab tested

Group	Specimen	0.7Pu (kN)	Deflection at 0.7Pu (mm)	Stiffness (*K*) (kN/mm)	Increase in stiffness with respect to control (%)
Group A	RS5-0%	45.5	5.9	7.71	Reference
	HS5-100%	91	2.15	42.32	448.9
	HS5-50%	59.5	2.6	22.88	196.75
	HS5-30%	49	3.6	13.61	76.52
Group B	RS3-0%	30.1	5.3	5.67	Reference
	HS3-100%	84	2.45	34.28	504.5
	HS3-50%	49	3.2	15.31	170
	HS3-30%	32.2	3.5	9.2	62.25

RS3-0%, respectively, as shown in Figures 4 and 5. The improvement in deflection value can be attributed to the presence of a layer of SIFCON with high resistance, converting the failure from flexural to debonding, as shown in Figures 6 and 7. However, the layer ratio is not recommended for use in terms of the applied load, but the deflection value was given a significant contribution.

The increase in ultimate load agreement with other research [20].

6.2 Stiffness of slabs

The stiffness of a structural member is the load needed for it to deform, which is calculated at 70% of the ultimate load using the load–deflection curve [21,22]. The stiffness values for all slabs measured are shown in Table 4. This table reveals that the stiffness increases as the SIFCON area increases, especially in HS5-100% and HS3-100% hybrid slabs. This indicates that the size of the SIFCON layer significantly impacts the stiffness of the hybrid slab. The higher area of SIFCON in the tension zone of the hybrid slab provides more bearing capacity to apply and absorb loads, thus delaying the appearance of cracks and increasing stiffness.

$K = 0.7\text{Pu}/\Delta u_{0.7\text{pu}}$

Reduction ratio% = Ki − Kr/Kr × 100%

Kr = Stiffness of the reference slab.

Ki = Stiffness of the hybrid slab.

7 Conclusion

1. The use of SIFCON in the tension area enhances the flexural behavior of slabs based on the dimension of the SIFCON layer, resulting in an increase in the ultimate load-carrying capacity by a range of 7.69–100% in group A and 6.97–179% in group B when compared with the reference slab.
2. The effectiveness of the SIFCON was attributed to the method of production, which resulted in a homogenous mix of steel fibers with the slurry and prevented straight steel fibers from slumping down.
3. Using a hybrid slab led to a decrease in deflection at the ultimate load based on the dimension of the SIFCON layer. In addition, using a hybrid slab converted the failure mode from flexural to flexural-shear and debonding failure based on the dimension of the SIFCON layer.
4. The results showed that using SIFCON had a positive effect on the flexural behavior of the slab, even when using a reduced amount of flexural reinforcement.
5. It was observed that the stiffness of the slab increased in direct proportion to the increase in the dimension of the SIFCON layer.
6. The failure in a normal concrete slab is sudden, but in a hybrid slab, it occurs gradually.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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