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Production of SIFCONs: Effect of Mixing Techniques on Mechanical Performance

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ABSTRACT

Slurry-infiltrated fiber concrete (SIFCON) is a special type of fiber-reinforced concrete (FRC) characterized by its relatively high fiber content; therefore, it requires a special fabrication method to ensure homogeneity between the fibers and the matrix. In this study, five mixing techniques were used to produce SIFCON (sustainable slurry with micro steel fibers) to highlight the effect of the fabrication method on its mechanical properties. The fibers were placed in one layer, two layers, and three equal layers, while two other techniques involved mixing all or part of the fiber content with the slurry. These latter two techniques recorded the best performance at 28 days, with improvements of 20.8% and 22.3% in dry density, and 30.8% and 47.7% in compressive strength, respectively. Meanwhile, the other methods showed either a reduction or a gradual improvement. In addition, visual observations were recorded for certain mixing techniques, which may directly influence the efficiency of this type of fiber-reinforced concrete.

Keywords: FRC, SIFCONs, Mixing techniques, Production, Dry density.

1. INTRODUCTION

Slurry-infiltrated fibrous concrete (SIFCON) can be classified as a modern type of fiber-reinforced concrete (FRC), distinguished by relatively high fiber percentage (5–20) %; however, the practical range is typically between 4 % and 10 % **(Manolia et al., 2018).** For this fiber content, it requires a specific fabrication method **(Lankard, 1984; Naaman, 1992).** The slurry typically consists of a mixture of cement, fine sand, pozzolanic materials, water, and chemical admixtures, without coarse aggregate **(Gok and Sengul, 2023; Najeeb and Fawzi, 2022)** . The production of SIFCON differs significantly from conventional FRC, in which fibers are added to a wet or dry concrete mix, and the cement slurry is infiltrated into a bed of fibers that is preplaced and tightly packed in the molds **(Elavarasi, 2016; Gilani, 2007)**. In general, SIFCON performance is affected by four main factors: slurry strength, fiber volume fraction, fiber type, and fiber alignment **(Vijayakumar et al., 2019)**. The high fiber content, together with the high-performance slurry strength, gives this type

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of concrete superior mechanical properties such as compressive, flexural and splitting tensile strength, as well as ductility and toughness. These properties have made it suitable for heavy-duty applications, including explosion-proof structures, bridge piers exposed to high deformation, and industrial floors **(Alcan and Bingöl, 2019).** The well-known fabrication method of SIFCON involves sprinkling fiber into the mold, then using a flowable slurry to penetrate the dense fiber network. However, the maximum fiber content that can be incorporated and, consequently, the overall performance of SIFCON depends on several factors, particularly the placement and packing technique and the vibration (compaction) procedure **(Ipek and Aksu, 2019; Soylu and Bingöl, 2019)**. Additionally, most previous studies agree that specific methods should be adopted when using fiber volumes greater than 5% **(Ahmed et al., 2023)**

To avoid the difficulties associated with manual SIFCON production, researchers have adopted various placement and mixing techniques to achieve the highest possible fiber content while ensuring system homogeneity. In **(Penda and IV 2024)** study, fiber volume fractions ranging from 4% to 7% were used. For the lower contents (4% and 5%), a two-layer technique was adopted. However, as the fiber content increased, it became necessary to modify the fabrication method, and the fibers were divided into three layers. While (Hamed and Abass 2022) used fiber volume fractions ranging from 8% to 12%, they adopted different vibration durations depending on the fiber content, increasing the vibration time as the fiber percentage increased. A table vibrator was applied for 6–10 seconds at 8%, 15–20 seconds at 10%, and 20–30 seconds at 12% to ensure complete penetration of the SIFCON mortar into the fiber network. **Table 1** illustrates the different mixing techniques reviewed from previous studies.

Table 1. Some of the different mixing and casting techniques to produce SIFCON were adopted in previous studies.

No	Mixing Technique	Key finding
1.	16 % of Hooked-end steel fibers were distributed in two different ways: random and oriented placement **(Yazıcı et al., 2010)**	Excellent performance of oriented distribution in flexure and impact resistance strength.
2.	The mold was filled in layers using different heights (full height, 2/3 height, and 1/3 height). This was combined with steel fibers of 60 mm and 35 mm length, as well as polypropylene fibers used with 60 mm steel fibers. A fiber volume fraction of 10% was adopted (**Ipek and Aksu, 2019**)	The best performance was recorded for full-height placement, while reducing the fiber zone to 2/3 h and 1/3 h led to decreases in flexural strength and toughness.
3.	Plastic strips and sheets were used to ensure uniform fiber distribution within SIFCON, with crimped steel fibers at volume fractions of 9% and 7% **(Najeeb and Fawzi, 2021)**	The results show that plastic sheets provide higher compressive and flexural strength compared to plastic strips.
4.	Two methods were adopted to incorporate the fibers with the slurry: the traditional layering method inside the mold and gradual mixing directly in the mixer drum. A 6% volume fraction of micro steel fibers was used **(Alsheameri et al., 2023)**	The gradual mixing technique showed clear superiority in all hardened properties.

Over the last 25 years, many studies have investigated the properties of SIFCON by varying fiber parameters (e.g., fiber type, volume fraction, and aspect ratio), as well as slurry composition (e.g., type of pozzolanic material, replacement level, and fine aggregate characteristics). However, the influence of mixing and casting techniques on SIFCON behavior has not been fully addressed and remains insufficiently studied. This study focuses on producing SIFCON using different mixing and casting techniques and highlights the most effective technique that ensures the best performance while remaining practical and easy to apply. This is achieved by testing compressive strength and dry density, and comparing the results with the slurry used as a reference method.

2. EXPERIMENTAL WORK

2.1 Material

In this experimental work, six materials were used to produce SIFCON, as illustrated in **Table 2,** along with their descriptions and properties.

Table 2. Materials description used for SIFCON production

Material	Properties	Specification	Picture
Cement	Sulphate Resistance Portland Cement (SRPC) conforming to IQS 5 – CEM I 42.5 R-SR3.5 was used. • Compressive strength: 21.9 Mpa at 2 days and 43.8 Mpa at 28 days. • fineness 382 m^2/kg (Blaine method) • setting time: 90 minutes for initial and 4 hr. for final • C_3A content: 1.326 %	**(IQS No.5, 2019)**	
Silica Fume	A non-crystalline, amorphous form of SiO_2, usually referred to as silica. It is an extremely fine dark grey powder that is obtained as a by-product material during the manufacturing process of pure silicon or ferrosilicon alloys.	**(ASTM C1240, 2020)**	
Fine aggregate	Its natural river sand passed through a 600 μm sieve and complied with Zone 4 requirements with 0.3% SO_3 content	**(IQS No.45 1984)**	
Micro steel fiber	A copper-coated straight micro steel fiber was used in this experimental program. The fiber has a length of 25 mm and a diameter of 0.25 mm, resulting in an aspect ratio (l/d) of 100. The fibers were free from oil and rust and had a tensile strength of 2700 Mpa and a density of 7860 kg/m^3.	**(ASTM A820/ A820 M 2016)**	

Material	Properties	Specification	Picture
Water	Tap water was used in casting and curing	(IQS No.1703 2018)	
Chemical Admixture	HRWRA used to accelerate strength and reduce water content from Sika ViscoCrete -171 Precast,3rd Generation type E	(ASTM C494 2024)	

2.2 Mix design

Based on **(Al-Abdalay et al., 2020; Beglarigale et al., 2016; Hameed et al., 2020; Jerry and Fawzi 2023)**, the ratio between cementitious materials and fine aggregate adopted for producing SIFCON slurry generally ranged from 1:1 to 1:1.1, indicating that both components are used in relatively high and nearly equal quantities, typically within the range of 800–1000 kg/m^3 for each. Silica fume was commonly used as a partial replacement for cement to enhance strength and durability, while a chemical admixture (HRWRA) was incorporated to reduce water content and maintain the required workability.

Many trial mixes were conducted in the Construction Laboratory at the University of Baghdad to obtain a slurry that satisfies the flow properties within the limits of (EFNARC 2002) while also ensuring effective penetration through the dense network of micro steel fibers. Therefore, the mini slump-flow and mini V-funnel tests were used to evaluate its rheological state.

For the mini slump-flow test, the mini cone is placed on a clean, smooth, levelled plate, filled with slurry, and then lifted slowly by hand. The average of two perpendicular spread diameters is measured in millimeters, with a recommended target range of 240–260 mm **(EFNARC, 2002)**, as shown in **Fig. 1.** For the mini V-funnel test, the funnel is filled, and the gate is opened to allow the slurry to flow under its own weight without vibration. The flow time (s) is recorded from the moment the gate is opened until the pan below becomes clearly visible through the outlet. The recommended flow-time range is 7–11 seconds, indicating appropriate viscosity for infiltration without segregation **(EFNARC, 2002)**, as shown in **Fig. 2.**

The adopted fresh properties of slurry were 260 mm for slump flow and 10 sec for V-funnel. The mix proportions of SIFCONs used in this experimental work are summarized in **Table 3**.

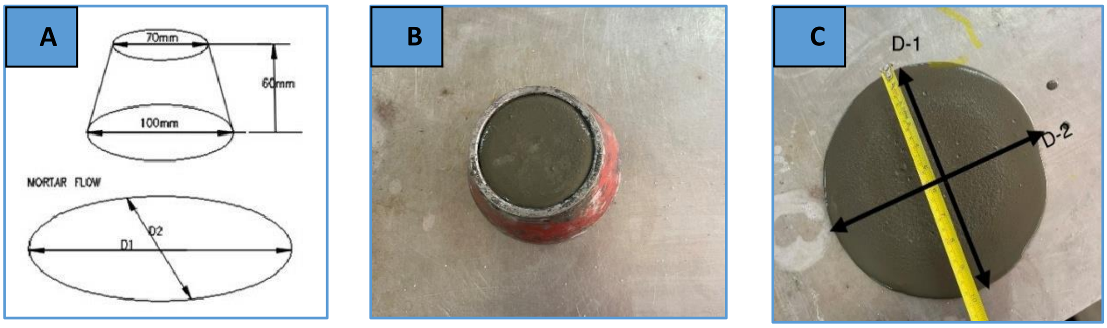


Figure 1. Steps for slump flow test for SIFCONs Slurry (A) apparatus dimension (**EFNARC, 2002**), (B) mini cone (C) measure average diameter for slurry

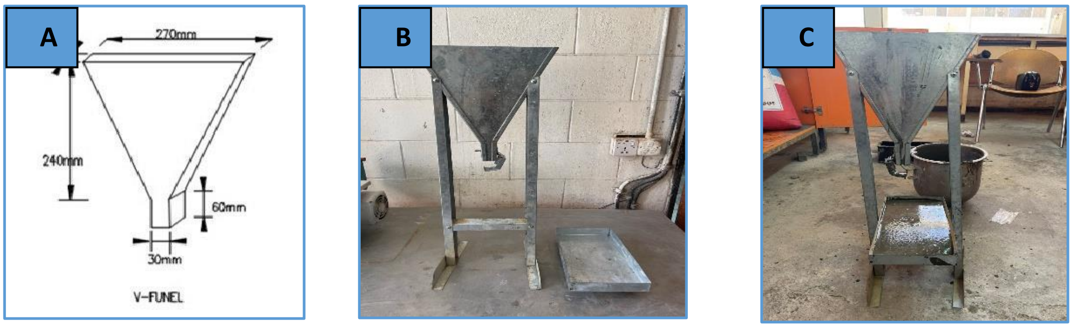


Figure 2. Steps for V-Funnel test for SIFCONs slurry (A) apparatus dimension **(EFNARC, 2002)**, (B) V-funnel (C) measure time in (sec).

Table 3. Mix proportion to produce 1 m^3 of SIFCONs (kg/m^3)

Slurry (94%)					Fiber (6%)
Cement	**Silica fume (1)**	**Sand**	**Water (2)**	**HRWRA**	**Micro steel fiber**
841	94	935	234	12.6	471.6

(1) Silica fume was used at 10% of total weight of cementitious material
(2) Water to cementitious materials ratio was 0.25.

2.2 SIFCONs Production

In this part of the experimental work, five mixing techniques were used to incorporate the fibers into the slurry, aiming to identify the method that provides the best mechanical performance and facilitate slurry infiltration through the dense fiber network. For ease of comparison among all methods, the following considerations were adopted:

- The same slurry mix proportions were used for all techniques, and this was considered as a reference mix (R-S) to evaluate the success of slurry penetration among the five mixing techniques
- Same specimens were used for all techniques, with cube dimensions of (100 × 100 × 100) mm. For each different mixing technique, three cubes were tested at each age (7 and 28 days) for both bulk dry density and compressive strength.
- Same micro-steel fiber quantity was used, which is 6% of the mold volume (471.6 g). The fibers were distributed manually using steel tongs while wearing gloves, and a steel rod with a pointed end was also used to separate the agglomerated steel fibers.

- A table vibrator (8 seconds) was applied for all methods. However, for method No. 4, compaction was carried out manually using a tamping rod, as the slurry and fiber network were pre-mixed and had good homogeneity.

2.3.1 One Layer Technique (1-L)

In this mixing technique, the traditional method of SIFCON production was adopted, in which the entire calculated quantity of fibers was placed as a single layer in the mold. The slurry was then poured to infiltrate the dense fiber network, as shown in **Fig. 3.**

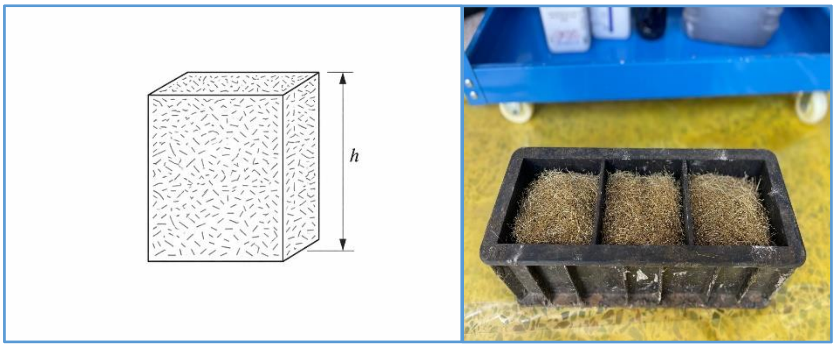


Figure 3. One layer technique

This technique has a practical limitation, as manually placing the required fiber quantity in the mold as a single layer is difficult. In addition, slurry penetration through the dense fiber network was not easy, even when a vibrating table was used.

2.3.2 Two Layers Technique (2-L)

In this technique, the total fiber content was divided into two equal portions, forming two layers (50 mm per layer). First, the fibers were placed and lightly compacted by hand in the mold until reaching half of the mold depth. Then, the slurry was poured to fill the mold up to that level, as shown in **Fig. 4 (Ipek and Aksu, 2019)**.

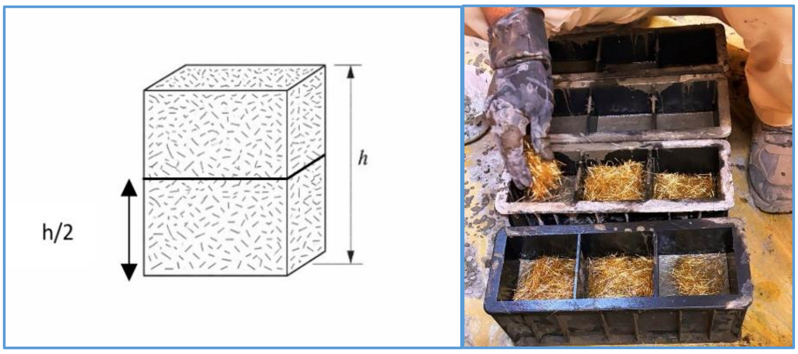


Figure 4. Two-layer technique

2.3.3 Three Layers Technique (3-L)

The same procedure was followed as in the 2-layer method, but the fibers were divided into three layers to reduce the distance required for slurry penetration **(Penda and IV, 2024)**

2.3.4 Direct Mixing Technique (D-M)

As shown in **Fig. 5,** instead of placing the fibers in the mold, all fibers were mixed with the wet constituents during the mixing process. The fibers were added gradually while mixing until a homogeneous mixture was obtained and the fibers were well dispersed within the slurry **(Alsheameri et al., 2023).**

Figure 5. Direct mixing technique

2.3.5 Hybrids Mixing Technique (H-M)

This mixing technique is a hybrid system between the three-layer technique and the direct-mixing technique, as shown in **Fig. 6**. It was adopted after producing SIFCON specimens using the previous four methods and identifying the limitations of each. In this method, the calculated fiber content is divided into two parts: 50% is directly mixed with the dry materials in the drum mixer, while the remaining 50% is divided into three layers. This approach reduces the amount of fiber placed in the mold at one time, making it easier to distribute and improve uniformity.

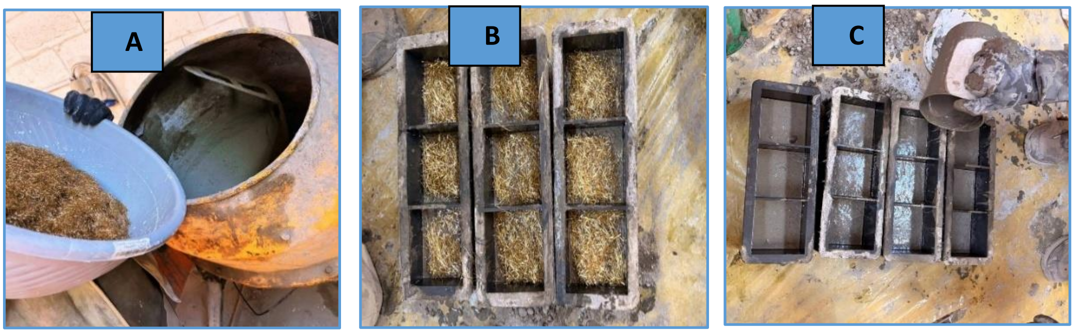


Figure 6. Hybrid mixing technique (A) mix 50 % of fiber directly with dry material (B) 50% of divided into three layers (c) pour the slurry into the mold

2.4 Curing

All specimens were cured under normal conditions. This curing practice was adopted in accordance with the recommendations of **(ASTM C192/C192M, 2025)**. All specimens were demolded after 24 hours of casting and then immersed in a water tank under laboratory conditions at a curing temperature of (23 ± 2) °C until the testing day.

2.5 Testing

To evaluate the efficiency of the mixing techniques and identify the variations among them, three types of tests were conducted for each technique (1-L), (2-L), (3-L), (D-M), and (H-M). The results were compared with reference slurry samples (R-S). These tests included dry density, compressive strength, and visual assessment.

2.5.1 Bulk Dry Density

As shown in **Fig. 7,** this test was done at 7 and 28 days according to the **(ASTM C642, 2021).** It was carried out on samples with dimensions of (100x 100x100) mm. An average bulk density of three specimens for this test was determined by using Eq. (1)

$$\text{Dry bulk density (kg/m}^3\text{)} = \frac{A}{C-D} * \rho \tag{1}$$

Where:
A = Weight of oven-dried sample in air, (g).
C = Weight of surface-dry sample in air after immersion and boiling, (g)
D = Apparent weight of surface-dry sample in air after immersion and boiling, (g)
ρ= Density of water, (kg/m^3).

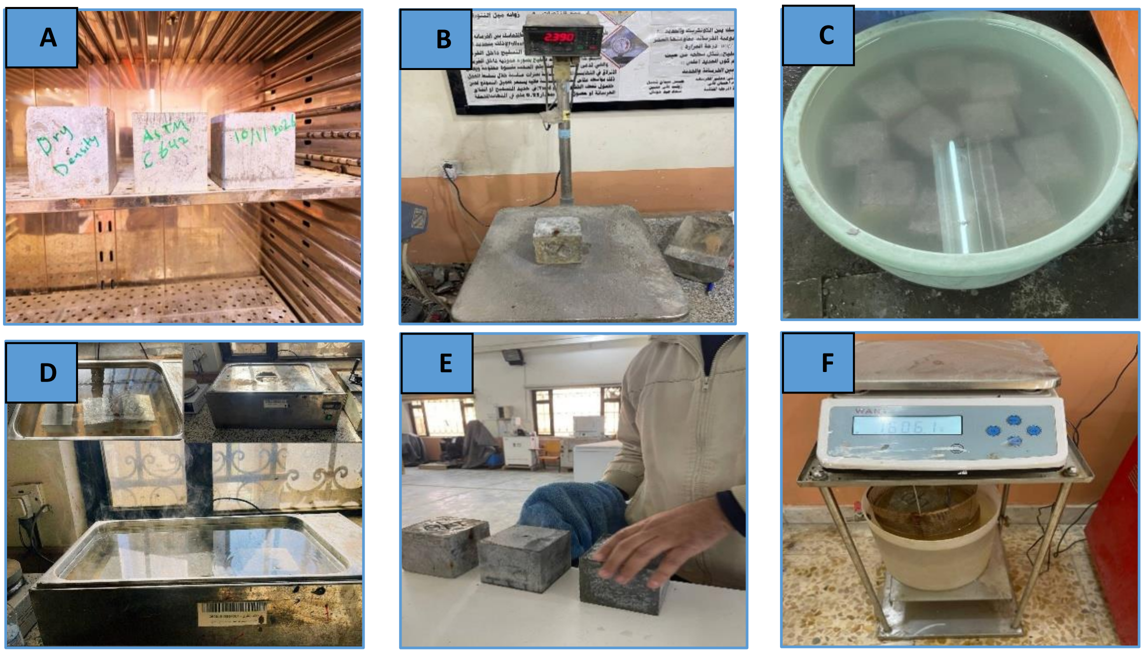


Figure 7. Measuring bulk dry density **(A)** Drying in oven 100 C 24hr.**(B)** Weight the sample in the air **(C)** Immersion in water 48 hr. **(D)** Boiling the samples 5 hr. **(E)** Dry with a towel to get SSD **(F)** Weight the apparent mass

2.5.2 Compressive Strength

The average compressive strength calculated in accordance with **(BS EN 12390-4, 2025)** at 7 and 28 days, as shown in **Fig. 8.** An average of three specimens for this test was determined by using Eq. (2)

$$Fc' = \frac{P}{A} \tag{2}$$

Fc': Compressive strength (MPa)
P: Maximum applied load indicated by the testing machine (N)
A: Area exposed to load (mm^2)

Figure 8. Compressive strength test

3. RESULTS AND DISCUSSIONS

9.1 Dry Density

To evaluate the degree of slurry infiltration and compaction efficiency, the dry density of each mixing technique was measured, as variations in fiber distribution can influence void content, microstructure, and consequently the overall performance. As shown in **Table 4 and Fig. 9**, there is a clear variation among all techniques when compared with the reference slurry mix (R-S), which reflects the amount of slurry penetrating the fiber layers. Method (1-L) showed the worst performance, with a reduction of 6.5% compared to the reference((R-S). This is mainly attributed to placing the entire fiber content as a single layer, which formed a dense network that was difficult for the slurry to fully penetrate, leading to significant voids, honeycombing, and a non-homogeneous structure.

Table 4. Dry density (kg/m^3) for different mixing techniques

Mixing technique	**Dry density (kg/m^3)**	
	7 days	**28 days**
R-S	2110	2200
1-L	2000	2057
2-L	2390	2530
3-L	2410	2557
D-M	2500	2658
H-M	2568	2690

In contrast, performance improved gradually as the thickness of the fiber layer to be penetrated decreased, with improvements of 15% and 16.2% for methods (2-L) and (3-L), respectively **(Gok and Sengul, 2023; Shamran and Abbas, 2023)**. For the two methods where all or part of the fibers were mixed with the slurry, a higher improvement was observed, reaching 20.8% and 22.3% for (D-M) and (H-M), respectively.

The slight superiority of the hybrid method over the direct method is attributed to the difficulty of achieving complete homogeneity between the matrix and fibers when the entire fiber content is mixed with the slurry using conventional mixers. It was also observed that part of the fibers settled at the bottom of the mixer, while the slurry constituents tended to rise upward due to the relatively high density of the steel fibers.

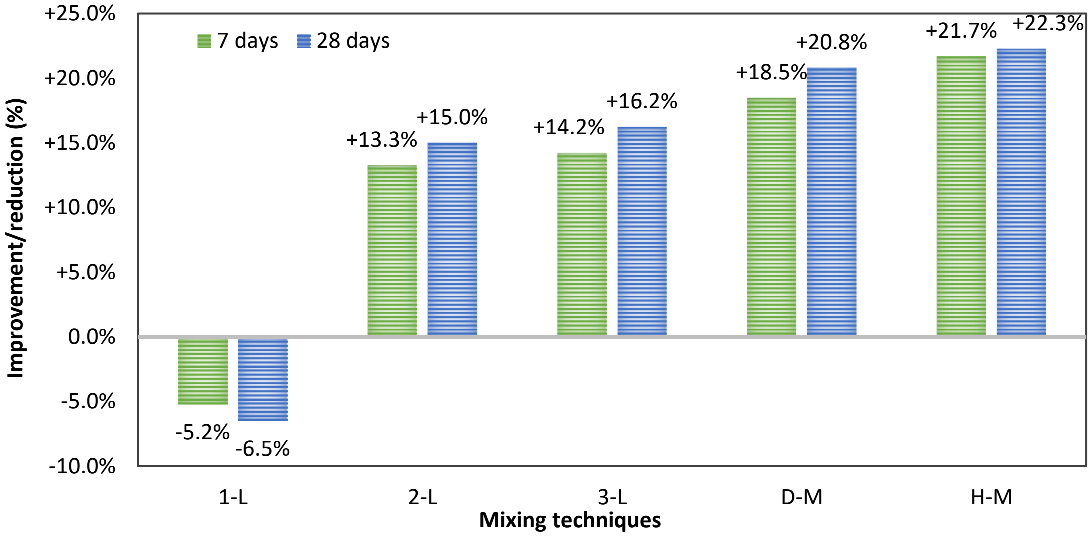


Figure 9. Effect of mixing techniques on bulk dry density of SIFCONs compared with slurry mix

3.2 Compressive Strength

Compressive strength was tested at 7 and 28 days because it is used as a measure of resistance and the overall quality of concrete **(Mehta and Monteiro, 2001)**. The compressive strength trend was consistent with the dry density results. At 28 days, the values ranged from 55 MPa for (1-L), reflecting a clear reduction because the slurry was not sufficient to properly penetrate the fiber network, leading to a heterogeneous system, as clearly shown in **Table 9** of the visual assessment, while (H-M) comes with improvement, reaching 96 Mpa for (H-M), which showed the best performance due to the fiber placement condition It was also observed that the compressive strength values at 7 days for all methods exceeded 75% of their corresponding 28-day values. This behavior can be attributed to the pozzolanic effect associated with the high silica fume content **(Luti and Abbas, 2024; Ullah et al., 2025)**

Moreover, (D-M) and (H-M) recorded the best improvement compared to the reference slurry mixture, with increases of 30.8% and 47.7%, respectively. This improvement can be attributed to the more homogeneous fiber distribution, which reduces crack initiation and promotes a more uniform transfer of both internal and external stresses through an efficient reinforcing network. Additionally, the fibers help densify the slurry matrix, leading to an increase in the compressive strength of SIFCON **(Abbas et al., 2022; Alsheameri et al., 2023)**. The results and the effect of mixing techniques are clearly shown in **Table 5** and **Fig. 10**, respectively.

Table 5. Compressive strength (Mpa) for different mixing techniques

Mixing technique	Compressive strength (Mpa)	
	7 days	28 days
R-S	56	65
1-L	48	55
2-L	60	70
3-L	64	75
D-M	72	85
H-M	78	96

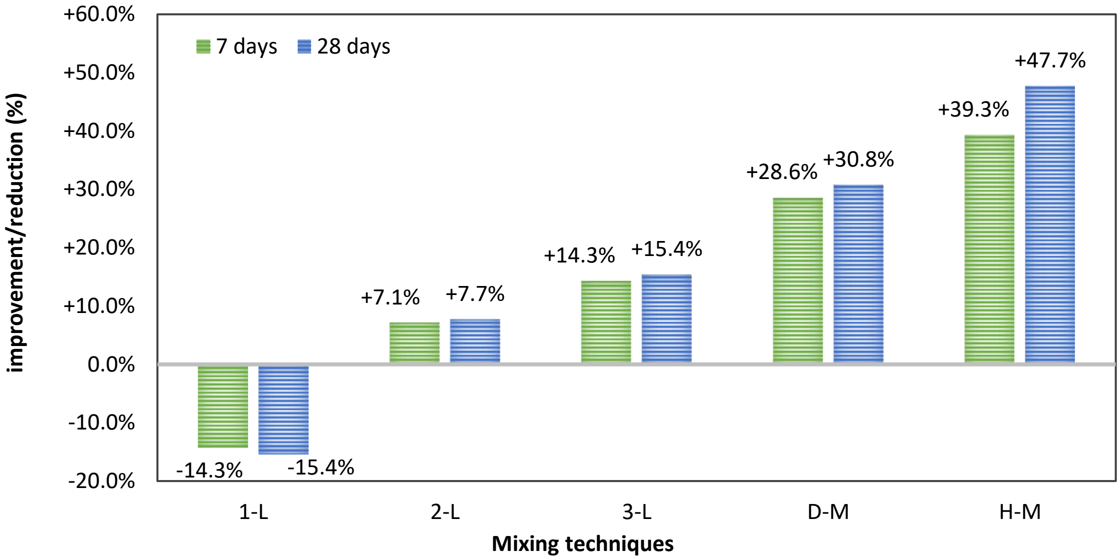


Figure 10. Effect of mixing techniques on compressive strength of SIFCONs compared with slurry mix

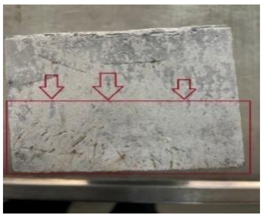
3.3 Visual Observation

Some visual observations were recorded for selected mixing techniques, and this could be used as primary assessment for fiber distribution and efficiency of compaction efforts and slurry penetration, **Table 6** showed most important of these observations.

4. STATISTICAL ANALYSIS

Simple statistical analysis was made and its showed that the coefficient of variation (COV) ranged between about 2.4% and 6.5% for values of compressive strength and less 2% for bulk dry density. Higher variability was noticed in the (1-L) mix technique due to poor slurry infiltration through one layer of dense fiber network, while more consistent results were obtained for (D-M) and (H-M) techniques, confirming better homogeneity of composite and best way to fiber distribution.

Table 6. Visual observation

Visual observations	Descriptions
 	some specimens, clear rust spots were observed, reflecting the difficulty of manual fiber placement, which resulted in fibers being positioned close to the concrete cover. This was mainly due to the confinement of the entire fiber content within the mold, which reduced the concrete cover thickness. These spots may act as potential rust paths and can facilitate the initiation and propagation of corrosion throughout the fiber network, which directly affects durability and accelerates the degradation of the concrete. These observations were noted in the techniques where all fibers were placed into the mold (2-L and 3-L).
 	Poor slurry penetration: A fractured specimen showed a dense fiber network with insufficient slurry infiltration, leaving significant honeycombing and voids, which explains the reduction in dry density compared to the reference slurry specimens. This observation was noted when all fibers were placed as a single layer (1-L).

5. CONCLUSIONS

1. SIFCON, as a concrete with a relatively high fiber content, requires special practices in the fabrication method because its mechanical performance is significantly affected by how it is produced.
2. The hybrid mixing technique (H-M) showed the best performance, 22.3% improvement in dry density and 47.7% increase in compressive strength at 28 days, compared with slurry, while placing all fibers as a one layer (1-L) resulted in the worst performance. The other three mixing techniques showed gradual improvement.
3. The variation among the five mixing techniques is mainly related to how the fibers are placed, ensuring successful penetration of the slurry through the dense fiber network.
4. As the thickness of the fiber layer decreases, the efficiency of slurry infiltration increases, and the formation of voids and honeycombing is reduced.
5. From a practical perspective, all fibers can be mixed with the slurry; however, this process requires high-efficiency mixers to ensure proper homogeneity of the slurry with the entire fiber. Therefore, part of the fibers can be mixed during the mixing process, while the remaining portion is distributed as layers inside the required mold.

Credit Authorship Contribution Statement

Sadiq Salim: Visualization and draft writing, discussion and linguistic review. Zena K. Abbas: Conducting and analyzing results and writing references

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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إنتاج الخرسانة الليفية المتسربة (سيفكون): تأثير تقنيات الخلط على الأداء الميكانيكي

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الخلاصة

تُعد الخرسانة الليفية المتسربة (سيفكون) نوعاً خاصاً من الخرسانة المسلحة بالألياف يتميز بارتفاع محتواه الليفي، مما يتطلب أسلوب تصنيع مناسباً لضمان تجانس الألياف مع المصفوفة الإسمنتية وتحقيق نفاذية جيدة للملاط داخل الشبكة الليفية. تهدف هذه الدراسة إلى تقييم تأثير تقنيات الخلط/الصب على الخواص الميكانيكية لسيفكون المصنّعة باستخدام ملاط مستدام مع ألياف فولاذية دقيقة. تم اعتماد خمس تقنيات إنتاج مختلفة؛ شملت تقنيات تعتمد على رص الألياف على شكل طبقة واحدة، وطبقتان، وثلاث طبقات متساوية، بالإضافة إلى تقنيتين تعتمدان على خلط كامل أو جزء من الألياف مع الملاط. أظهرت النتائج عند عمر 28 يوماً تفوق تقنيتي الخلط مع الملاط، إذ حققتا تحسناً مقداره 20.8% و22.3% في الكثافة الجافة، و30.8% و47.7% في مقاومة الانضغاط مقارنةً بطريقة المرجع. في المقابل، تراوحت نتائج بقية التقنيات بين انخفاض في الأداء وتحسن تدريجي محدود. كما تم تسجيل ملاحظات بصرية مرتبطة ببعض التقنيات، والتي قد تؤثر بشكل مباشر في كفاءة نفاذية الملاط وجودة البنية الداخلية لهذا النوع من الخرسانة.

الكلمات المفتاحية :الخرسانة المسلحة بالألياف، الخرسانة الليفية المتسربة (سيفكون)، تقنيات الخلط، الإنتاج، الكثافة الجافة