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Research Article

Flexural Behaviour of Blended Slurry-Infiltrated Fibrous Concrete Boards Made with Hybrid Fibers and Nano Slag

Adnan Kadhim Jawad [1]*, Isam Mohamad Ali[2], Mohammed Kareem Abed [3], Ikram Ameen Saeed [4], Mohammed Salah Nasr[5] , Tameem Mohammed Hashim[6]

[1] Al-Furat Al-Awsat Technical University, Najaf Technical College, Najaf, Iraq.
* **Corresponding Author Email:** adnan.jewad@atu.edu.iq- **ORCID:** 0000-0002-5247-785X

[2] Karbala Technical Institute, Al-Furat Al-Awsat Technical University, Karbala, Iraq
Email: inkr.asm@atu.edu.iq - **ORCID:** 0000-0002-5247-785X

[3] Technical Institute of Babylon, Al-Furat Al-Awsat Technical University, Babylon, Iraq.
Email: mohammed_k1965@atu.edu.iq - **ORCID:** 0000-0002-5247-785X

[4] Middle Technical University, Baghdad, Iraq.
Email: dr.ikram.a.t.c@mtu.edu.iq - **ORCID:** 0000-0002-5247-785X

[5] College of Engineering, University of Babylon,51005 Babylon, Iraq
Email: eng511.mohammed.nasr@uobabylon.edu.iq - **ORCID:** 0000-0002-5247-785X

[6] Building and Construction Techniques Engineering Department, College of Engineering and Engineering Techniques, Al-Mustaqbal University, 51001, Babylon, Iraq.
Email: tameemmohammed@uomus.edu.iq - **ORCID:** 0000-0002-5247-785X

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Abstract:

High volume fraction of fibers with notable improvements in strength, durability, ductility, and toughness are the main fundamental advantages of slurry infiltrated fibrous concrete (SIFCON). The experimental study presented in this work examines the flexural behavior of composite boards made of SIFCON. It also looks into the effect of hybrid fiber reinforcement on toughness and strength characteristics, as well as the addition of binary and ternary blends of SIFCON under flexural loading. Thirty boards measuring an effective span of 300 mm, width of 150 mm and 25 mm thickness were cast and tested at 28 days in order to examine the toughness, flexural strength, load-deformation and microstructural analysis characteristics. Various volume fractions of steel and plastic fibers of (8+0, 7+1, 6+2, 5+3, and 4+4%) respectively were used. After that, the specimens were divided into two groups: binary (cement+ micro silica) and ternary (cement+ micro silica+ nano slag). Also, a SEM test was used to track microstructural features of fractured surfaces. The results showed that adding nanomaterials clearly enhanced the microstructure's density and decreased the number of pores in the SIFCON boards that were created. Moreover, the steel fiber demonstrated a 40% increase in flexural strength compared to the hybrid fiber system composed of 4% steel fiber and 4% plastic fiber in the binary blend. In the ternary blend, this difference was reduced to 34%. Additionally, the incorporation of nano slag enhanced the strength properties of the produced SIFCON mixes by up to 22% in the ternary blends.

1. Introduction

Due to rapid advancements in the building and construction industry over the past decade, there is an urgent need to find alternatives or develop new construction materials [1,2]. Slurry infiltrated fibrous concrete (SIFCON) may considered as the best of these developments, which has many uses in concrete subjected to repeated loads, impact and vibrations. SIFCON enhances the performance of reinforced concrete structures and prolongs their service life due to its high strength, excellent flexibility, and enhanced energy absorption capacity [3].

To make SIFCON, employment of micro steel fibers within the molds then infiltrated by a slurry of cement-based materials without coarse aggregate [4]. The high fiber volume fraction made SIFCON having unique and superior strength and ductility properties [5]. The fiber content in SIFCON ranges from 5% to 20%, compared to 1% to 3% in conventional concrete [6].

Although SIFCON is new in use and application, it has been used successfully in construction projects since 1979 [7,8]. Anti-explosion treasury, repairing object, bridges, airplane runway and surfaces resistant to abrasion are most of importance applications [9]. To guarantee full infiltration, superplasticizers are typically employed to increase the slurry's flowability without raising the water cement ratio [10].

By causing mechanical deformations or roughening their surface, the fibers can be changed throughout their length to improve the mechanical anchoring and bond between them and the matrix. The fibers that are most frequently utilized are crimped and hooked [11].

For vibration exhaustion, elasticity, and toughness, SIFCON's distinctiveness is far more significant than conventional high strength concrete [12]. Measurements of modulus of elasticity for SIFCON specimens have been attempted by Sengul [13]. The relation between stresses to strain was applied to these measurements. The obtained values have often been between 14 and 24.5 GPa.

Both before and after being exposed to high temperatures, compressive strength and stiffness of (SIFCON) were measured by Ali et al. [14]. Two and three-hour fire exposure times are investigated. Three temperature ranges have been introduced: 400, 600 and 900 °C besides control. The results showed, after the exposition to these temperatures the compression resistance and stiffness were decreased. At 900°C, the residual compressive strength and stiffness vary between (31- 34%) and (52- 60%) respectively.

An investigation to increase a SIFCON mechanical efficiency with different fiber volume fractions was made by Abbas and Mosheer [15]. Three distinct volume fractions (6, 7, and 8.5%) of hooked-end steel fiber were manufactured. Their findings showed appropriate fresh qualities, meeting 249 mm flowing diameter recommendation for SIFCON mortar. At testing age, the mix's SF of 8.5% showed a 53% improvement in maximum compressive strength in terms of mechanical performance. Moreover, splitting and flexural augmentation rose by 44% and 91%, respectively, in comparison to the reference mix. However, strengthening is affected by the SIFCON failure form for all investigated combinations, which is related to the high SF content.

On the other hand, in the past two decades, the incorporation of fibers in cement composites has significantly increased [16]. One of the most notable cement composites is fiber cement board, available in both flat and corrugated forms. These boards are commonly used for roofs, as well as for interior and exterior walls and facades [17]. The cement board are used in construction since the early 20th century [18]. Initially, asbestos fibers were incorporated as a reinforcing component to improve the fracture toughness of these boards [19]. However, asbestos was later banned due to its carcinogenic properties [19,20]. Following the identification of the risks associated with asbestos fibers, there was a surge of research aimed at finding alternative materials. One such alternative has been natural fibers [21]. However, some natural fibers suffer from problems when in contact with cement due to the high alkalinity of the cement, as well as problems in the dimensional stability of these fibers with humidity changes [22]. Therefore, efforts to enhance the properties of cement boards are ongoing. This includes improving their performance through the selection of different fibers to increase ductility, as well as exploring the use of alternative cement materials to mitigate the carbon dioxide emissions associated with the cement industry.

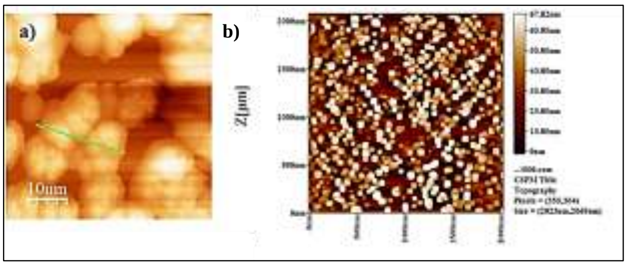
The effect of nano-slag on slurry infiltrated fiber concrete has been restricted, according to the literature [23–26]. According to the literature, there has been limited research on manufacturing composite boards using SIFCON (Slurry Infiltrated Fiber Concrete). Furthermore, to the authors' knowledge, there has not been much investigation into the combination of nano slag (NS) and micro silica (MS), which is the focus of the current study. This research explores the use of micro silica and nano slag both individually (as a binary mix) and in combination (as a ternary blend).

The primary aim of this study is to examine the flexural behavior of SIFCON boards made with nano slag and silica fume as cement replacement materials. Tests were conducted to assess flexural strength, toughness, and load-deflection behavior. Additionally, this work proposes a hybrid reinforcement strategy that incorporates both plastic and steel fibers to modify properties and reduce costs. Ultimately, the findings of this research can contribute to enhancing the performance of SIFCON while promoting the use of industrial waste materials.

2. Materials and methods

2.1 Materials Characteristics

The following fundamental raw materials were employed in this investigation: fibers (steel and plastic), tap water, Portland cement, micro silica, fine aggregate, nano slag, and superplasticizer. All of the examined boards were made using Portland cement that met Iraqi standard No.5/1984 [27]. According to ASTM C 494 Type F [28], the superplasticizer (known as Master RHEOBULD SP1) was imported from Sika firm in Egypt. Standard sand was utilized in accordance with ASTM C 778 specifications [29]. The study's micro silica (MS/Plate 1-a), according to the findings, complied with ASTM C 1240 [30] criteria. The features of the nano slag Grade 120 (NS/Plate 1-b), which followed ACI 233 [31] supplied by the Nanoshel Company (USA), are displayed in Table 1 that presents the chemical analysis of micro silica, and nano slag. The Sika Company supplied steel fibers (SF) with a tensile strength of 1220 MPa and a relative density of 7885 kg/m3 that had a diameter of 0.2 mm, a length of 13 mm, and an aspect ratio of 65. Polypropylene synthetic plastic fiber (PF) has a melting point of 175 degrees Celsius, a length of 40 mm, and a diameter of 0.8 mm associated with 0.9 g/mL at 25 °C fiber density associated with a tensile strength of 450 MPa.



* Tests according to supplier.

Plate 1. *AFM analysis of; (a) micro silica and (b) Nano slag grade 120*.*

Table 1. *Chemical composition of micro silica (MS) and nano slag (NS).*

Constituent	**Micro Silica (%)**	**Nano Slag (%)**	**Limits of ASTM C-618/05**
CaO	3.76	1.84	
SiO_2	91.6	71.5	≥ 70 %
Al_2O_3	1.21	16.36	
Fe_2O_3	0.88	7.42	
SO_3	0.97	0.21	≤ 5
NaOH+KOH	2.65	0.79	
Loss on Ignition	4.2	---	≤ 6 %
Fineness	≥ 15000 cm^2/g	= 60 nm *	

2.2 Experimental work

A number of variables, including fiber type, fiber dosage, and pozzolanic mixing, were taken into account while evaluating the strength of the boards. The flexural performance of each specimen must be compared to the control specimens. A number of tests were conducted to confirm the validity of binary and ternary blends in concrete was appropriate or not. In order to produce boards, ten distinct mixtures were utilized, each with a different volume percent and type of fiber. Four double hybrid fiber reinforced SIFCON mixes for steel fiber of 7, 6, 5, and 4% volume fraction plus four dosages of plastic fibers of 1, 2, 3, and 4% volume fraction, respectively, and one mono (single) fiber reinforced SIFCON mix with 8% volume fraction of steel fiber only (as a reference mix). Then, the two groups will be compensated either by 10% of micro silica powder as an additive by the weight of the cement, or by combining (10% MS+ 1% NS) together. Table 2 provides a summary of the mix proportions of SIFCON concrete mixes.

Table 2. *Mix proportions.*

Mix type	(SF+PF) (% by vol.)	Mix No.
Fiber vol. fraction, V_f	8+0 7+1 6+2 5+3 4+4	M1 M2 M3 M4 M5
Micro silica + nano slag (kg/m^3)	90+0 81+9	Binary (B) Ternary (T)
Cement (kg/m^3)	900	
Total Cementitious (kg/m^3)	990	
Standard sand (kg/m^3)	990	
SP (kg/m^3)	18	
Water (kg/m^3)	270	

2.3 Testing Procedures

Flexural testing was conducted at day 28 in compliance with ASTM C1185 [32] and ASTM C1186 [33] guidelines. Each sample measured 300 mm in length, 150 mm in width, and 25 mm in thickness. In a displacement-controlled mode (Plate

2), the specimens were simply supported and loaded at a displacement rate of 2 mm/min. The test data is recorded using a computer-controlled data acquisition system. Flexural strength and toughness are properties that define the load-deflection curves. The average of the test results for three specimens determined each flexural strength value. In addition, according to ASTM C856 [34], the scanning electron microscope (SEM) has been used. The SEM results are employed in this study to validate the findings of other methods, such as strength and toughness, even though they only offer qualitative information on cement hydration products and fracture surface methodology.

Plate 2. *experimental setup: specimen preparation and testing.*

3. Results and discussion

3.1 Flexural test

It became evident throughout the mixing process that the mixes with mono steel fiber flowed better than those with hybrid fibers. This is because plastic fibers have qualities including warping and clumping that complicate mixing and dispersion of cementitious slurry. Figures (1/ a, b) show the findings of the flexural tests conducted in this study for binary and ternary mixtures at day 28 in both mono and hybrid fiber SIFCON. As indicated in these figures, control boards (M1) resisted larger strength than other boards (M2, M3, M4, and M5) in both binary and ternary blends. The reason for this is that steel fibers have a higher tensile strength than plastic. Furthermore, confinement of the boards while loading by fibers, allowing the boards to encounter larger ultimate loads than boards with lesser content of steel fibers. Furthermore, the mixture of M1T was found to have the highest recorded flexural strength of 14.25 MPa, while the mixture of M5B was found to have the lowest recorded flexural strength of 7.12 MPa. The improvement in flexural strength after nano slag addition could be attributed to the extra pozzolanic action, which breaks down calcium hydroxide and forms more stable hydrated calcium silicate, filling in empty voids and reducing the width of the interfacial transition zone. They could also be the consequence of nanoparticles' filling ability, which reduces the size and sum of pores, as demonstrated later in the SEM micrographs. A similar finding was made by Salih et al. [35].

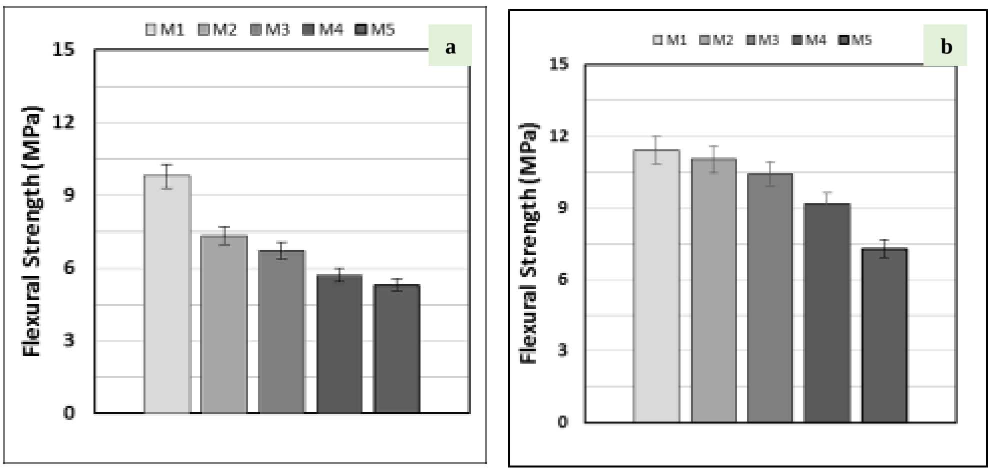


Figure 1: *Flexural strength of: (a) binary and (b) ternary SIFCON mixes at 28 day.*

3.2 Toughness index

The toughness index may be used to measure the energy-absorbing capacity and describes the post-cracking behavior of the concrete. Figures 2, 3 and 4 show that, as predicted, the toughness values rose as the quantity of steel fiber in the mix increased. One of the primary advantages of adding fibers to concrete is that it becomes more ductile, which is evident from the behavior of the specimens under the influence of loads. Further, M2 and M3 yielded higher toughness than control mixes by 19% and 14% for binary blends. Meanwhile, these differences were 22% and 16% for ternary blends. The reason for this lies in the overlapping effect of the properties of plastic fibers with those of steel to delay failure when the maximum load is reached. Additionally, the findings of the ternary mix showed that the inclusion of nanomaterials had a notable impact, boosting the toughness by 38%, 24%, and 20%. Moreover, it is evident from the ternary system that the performance of the SIFCON may benefit by the inclusion of two different kinds of cementitious materials. Results of mixing with ternary mixes (M2T) showed that the inclusion of nanomaterials had a noticeably impact on ITZ which increases the toughness. This is what was found by other researchers [36].

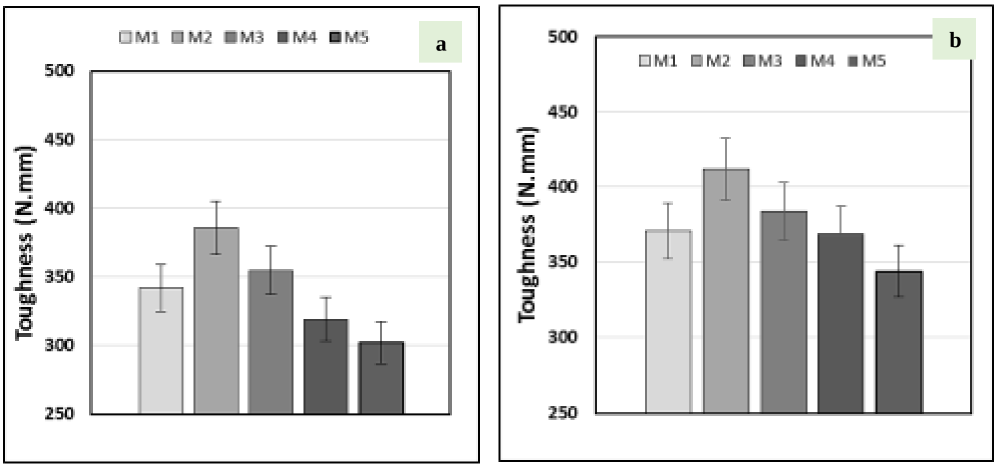


Figure 2. *Flexural toughness of: (a) binary and (b) ternary SIFCON mixes at 28 days*.

3.3 load-deflection behavior

The resulting load-deflection curves, which are depicted in Figures 3 and 4, demonstrated a notable degree of nonlinearity and demonstrated the energy-absorbing capacity of the SIFCON board. All boards act as an elastic-degrading plastic material with a noticeable decrease of strength after reaching peak load, according to the load-deflection curves. Furthermore, it was evident that the behavior was elastic up until the first fracture in the loading. After that, either the initial fracture had an unstable development that caused the board to split in two for a hybrid fiber system, or for mono steel boards, it developed into a macro-crack with a deflection of around 0.52 mm, where the fibers were able to stop the crack from growing. This is because, prior to nano addition, the bonding between the fibers and the cement slurry was weaker and the plastic fibers had a lower tensile strength. Among the most significant findings from the test was that plastic fibers are prone to ripping, whereas steel fibers experience pullout. Same findings were proven by [37,38].

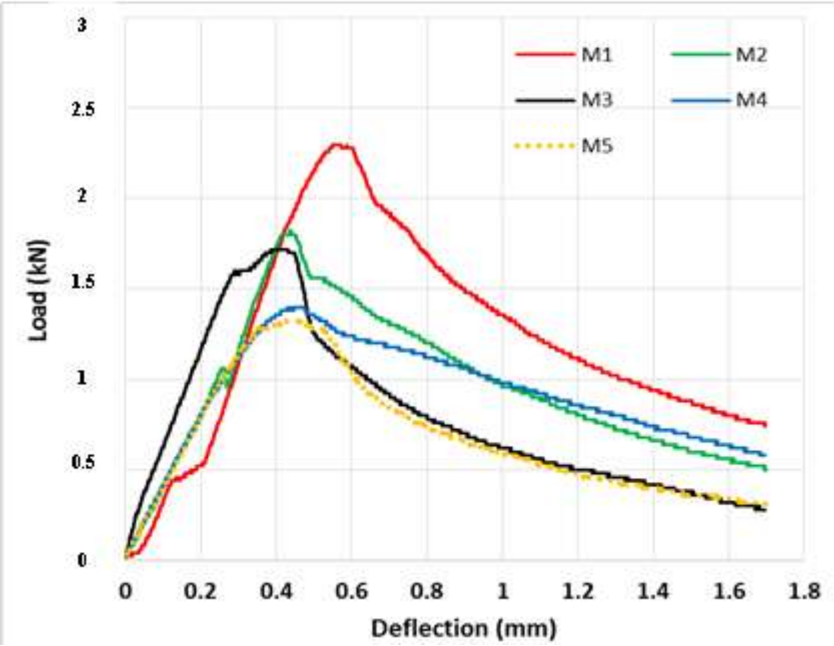


Figure 3. *Load-deflection curves of binary SIFCON mixes at 28 days.*

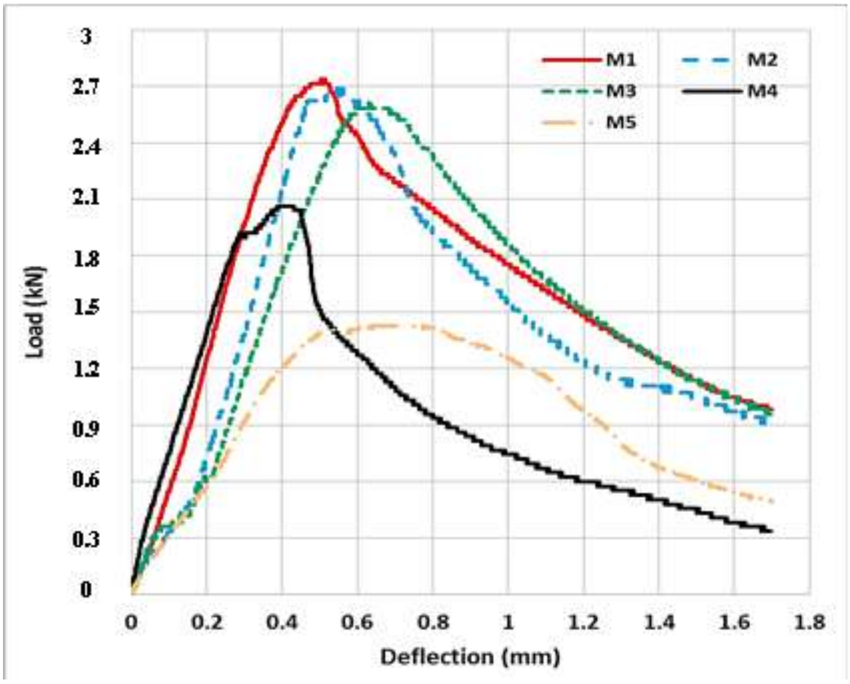


Figure 4. *Load-deflection curves of ternary SIFCON mixes at 28 days.*

3.4 Microstructural analysis

An excellent qualitative view of the minerals inside the SIFCON microstructure is provided by SEM examination. Following a close examination of the fractured surfaces of the steel and PF fiber specimens, images of many representative sites were captured and displayed in Figure 5. Figure (5/ a, b, c, d) shows four SEM micrographs of (M1B, M1T, M2B and M2T) mixes at 28 days. These mixtures were chosen because of the change in behavior of the studied properties. Overall, mix M1 (Fig.5/a) has a straightforward and uniform microstructure formed of dense structure, indicating a stronger microstructure and providing an explanation for the increase in flexural strengths. For the specimens containing nanomaterials (Fig.5/b), there are no obvious interfacial cavities or fissures. Moreover, the development of silicate compounds as a result of the pozzolanic interaction of nanomaterials is explained by the production of extremely thin fibers in the interface areas between the paste and the aggregate. Most plastic fibers suffer from fiber tear upon failure, while steel fibers only suffer from pullout (Fig.5/c). Fracture energy from the debonding stage is insignificant since the PF fiber debonding stage contributes less than pullout of SF. Steel fibers would also significantly boost total ductile capacity and supply the greatest fracture energy. However, this demonstrates that PF fibers have little effect on later ductile behavior and solely regulate strength and early-stage microcracks [39,40]. The chemical activity of the nano slag enhances the interfacial transition zone and adhesion between the fibers and the matrix, resulting in improved board over all toughness (Fig.5/d).

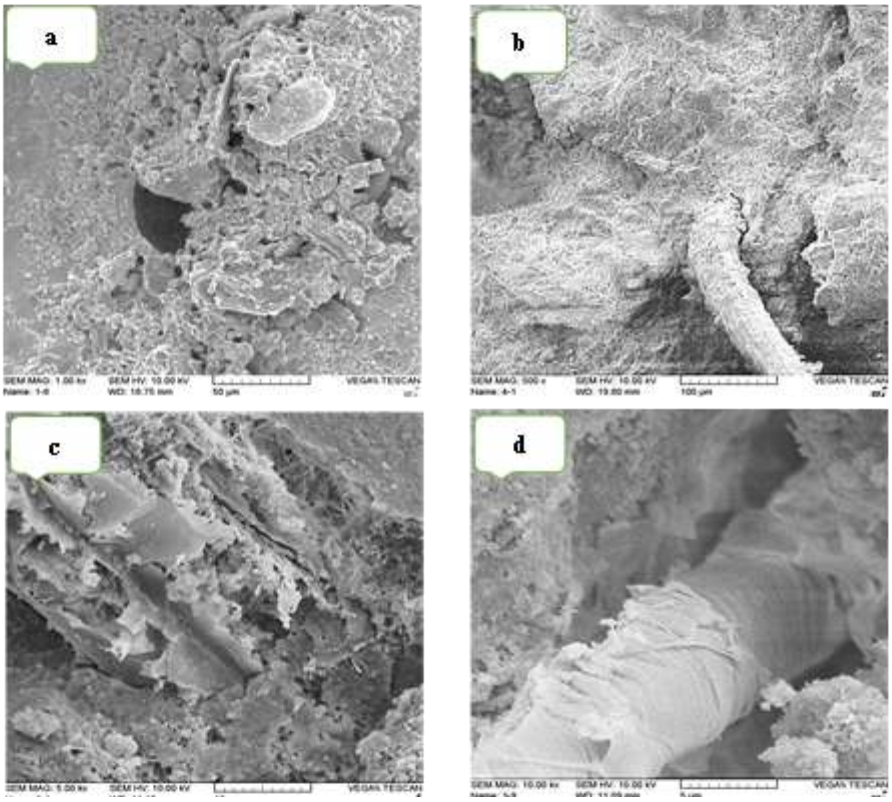


Figure 5. *SEM images of fractured surface for specimens: (a) M1B; (b) M2B; (c) M1T; and (d) M2T.*

4. Conclusions

This study's findings can lead to the following conclusions:

1. Mono steel fiber SIFCON yielded higher flexural strength than hybrid fiber system of (4% SF+ 4% PF) by 40% for binary blend, while, this difference become 34% for ternary blend.
2. The addition of nano slag improved the strength properties of produced SIFCON mixes up to 22% for M2T and 16% for M3T respectively in the ternary blends.
3. One of the most important observations from the test was that plastic fibers are prone to tearing, whereas steel fibers undergo pullout.
4. Plastic fibers only control strength and early-stage microcracks; they have little influence on later ductile behavior.
5. According to SEM, uniform microstructure composed of dense matrix, suggesting a more robust microstructure and explaining the rise in flexural strengths for mono steel SIFCON.
6. The pozzolanic activity of the nano slag caused extra-large hydrate crystals to form in the unfilled pores, as seen by electron microscope photos. The ITZ gets denser as a result, which tends to make the composite stronger.
7. Examining the outcomes makes it evident that adding plastic fibers in addition to steel fibers did not significantly increase the toughness attributes. Regarding economic factors, the optimal hybrid mix for the binary and ternary SIFCON mix types was M2 of (7% SF+ 1% PF).
8. Even after 50% of the steel fibers were replaced by plastic fibers, the flexural strength of boards remained higher than the minimum (1.89 MPa) value reported in ASTM C-1186-12. Thus, these mixtures may be used to non-structural as well as structural applications. This is very useful for economic purposes.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of 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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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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