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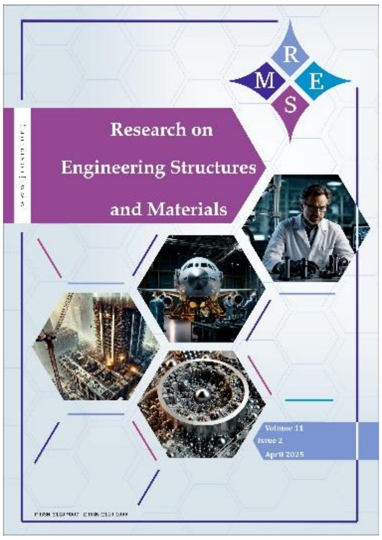

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Research Article

Mechanical performance of slurry-infiltrated fibrous concrete with varying ratios of scrap tire steel fibers and commercial steel fibers

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Abstract

The limitation of using a high volume of fibers in concrete can be addressed with Slurry Infiltrated Fibrous Concrete (SIFCON), a high-performance fiber-reinforced concrete made by placing fibers in a mold and infiltrating them with cement slurry. Typically, commercially available steel fibers of various shapes and sizes are used in the production of SIFCON. This study explores the use of steel fibers extracted from scrap tires as a sustainable alternative to reduce energy consumption in fiber production. Compressive and split tensile strengths of SIFCON with 4% to 7% scrap tire steel fibers were tested and compared to SIFCON made with same volumes of commercially available steel fibers. The M20 design concrete mix and SIFCON slurry were prepared as reference mixes. Compressive and split tensile strengths of SIFCON and M20 concrete were tested using 100 mm and 150 mm cubes, and cylinders of 100×200 mm and 150×300 mm. Results showed that SIFCON with scrap tire fibers achieved about 80% of the compressive and 35% of the split tensile strength of SIFCON with commercial fibers, both significantly outperforming the reference mixes. Advanced techniques, like XRD and SEM were used to analyze SIFCON's internal structure, revealing details about its phase composition, morphology, and microstructure. Specimens were examined and compared to reference mixes, revealing a similar hydration phase in SIFCON. Experimental results show that randomly dispersed steel fibers from scrap tires and commercial sources enhance SIFCON's mechanical properties, making them suitable for its production.

1. Introduction

In the current context, energy crises, as well as their impacts on our planet, are major global challenges. These problems are brought on by the growing population, the speed at which cities are being developed, and the production of large amounts of solid waste. Car and commercial vehicle manufacturing have increased dramatically due to rising demand, leading to a proportional increase in scrap tire production. The increasing use of automobiles in the modern world for the movement of people and goods has led to a problem regarding what to do with scrap tires when their usefulness has come to an end [1–3]. The high carbon content of scrap tires makes them a commonly used energy source in cement kilns [4].

High-strength steel fibers extracted from old tires can be reused as raw materials in steel manufacturing. Additionally, rubber from recycled tires serves as an energy source in various industries. To minimize the demand for commercially produced high-strength steel fibers, the focus

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has been on recovering high-strength steel fibers from scrap tires as a means for the extraction of resources from waste. Scrap tires can be processed using pyrolysis, cryogenic, or mechanical techniques to recover steel fibers and rubber [5,6]. Steel fibers recovered from scrap tires, unlike manufactured commercial ones, may exhibit irregular shapes and inconsistent aspect ratios.

In the construction sector, steel fibers are utilized to produce steel fiber-reinforced concrete. Fiber-reinforced concrete with 1% coir or plastic fibers boosts durability, with coir enhancing tensile and flexural strength by 10% and 20%, and plastic fibers increasing them by 50% and 30%. It is a sustainable option for improving concrete strength and durability [7]. Experimental results showed a 13.6% increase in compressive strength for PPC with glass microfiber compared to control PPC. Adding glass microfiber to PPC reduced plastic shrinkage cracks and drying shrinkage while maintaining similar mechanical and durability properties. Glass microfiber showed no significant mechanical improvement in concrete at elevated temperatures [8]. Due to its higher fiber content, Slurry Infiltrated Fibrous Concrete (SIFCON) is considered an advanced form of Fiber-Reinforced Concrete (FRC). It enhances hardened properties such as strength, toughness, impact resistance, and modulus of rupture. In general, the fibers used to prepare SIFCON provide advantages equivalent to those of reinforced steel in RCC.

Higher fiber concentrations cannot be used to prepare fiber-reinforced concrete, though, because of the balling effect. Slurry Infiltrated Fibrous Concrete (SIFCON) is an advanced type of steel fiber-reinforced concrete, known for its high-performance, cementitious composition [9,10]. SIFCON is made differently from traditional fiber-reinforced concrete, which involves prepacking fibers into molds and allowing cement-mortar slurry to penetrate. The prepacking process allows the use of higher fiber content and a cementitious slurry with a lower water-to-cement ratio. This results in improved toughness and energy absorption compared to traditional steel fiber-reinforced concrete. Steel fibers from scrap tires are effectively used in SIFCON production, as they are manually arranged and infused with a cement mortar slurry matrix, preventing fiber balling. Available literature shows that few studies have explored the use of scrap steel fibers in SIFCON manufacturing. A higher fiber content in SIFCON improves homogeneity and enhances mechanical properties such as flexural strength, compressive strength, and energy absorption. Under blast loading, SIFCON incorporating waste steel fibers outperformed that made with industrial fibers, due to the hybrid nature of the fibers [11–15]. It has been found that the split tensile strength, compressive strength, and flexural strength of SIFCON are optimal at 9% fiber content. SIFCON's maximum flexural strength may be attained with fiber volumes and aspect ratios of 9% and 80, respectively [16]. It has been found that SIFCON has splendid quality in bond for all types of tests when cement is replaced with 15% of silica fume and 35% of volume of plain smooth steel fibers [17].

It has been shown that increasing the volume of hooked-end steel fibers in SIFCON mixes containing silica fume and fly ash enhances the impact energy-to-failure [18]. It has been demonstrated that the splitting tensile strength of SIFCON increased by increasing the fiber percentage in SIFCON [19]. SIFCON made with hooked-end steel fibers achieves maximum compressive and flexural strength when fiber volume is increased up to 10% [20]. Increasing the steel fiber content improves SIFCON's mechanical performance [21]. In comparison to plain cement and fiber-reinforced concrete slab specimens in flexure, SIFCON slab specimens exhibit superior stiffness, energy absorption, and load-carrying ability [22]. SIFCON's flexural and splitting strengths have increased due to its higher waste fiber content. However, compressive strength was unaffected by the use of discarded steel fibers. Waste steel fibers can be an attractive alternative in the creation of SIFCON, according to multi-objective optimization research [23]. Research has shown that incorporating SIFCON into regular concrete enhances strength properties while reducing the likelihood of crack propagation [24].

SIFCON has been successfully produced utilizing the two-layer method employing 6% fibers of steel from old tires. Furthermore, SIFCON with steel fibers from old tires matches the flexural strength of commercial fibers and surpasses reference mixes [25]. SIFCON with hooked-end fibers shows improved performance compared to crimped-end fibers, with a noticeable strength increase when 40% of the binder is replaced with GGBS. Microstructural analysis indicates that SIFCON exhibits an equivalent level of hydration but at a faster pace compared to conventional concrete [26]. Incorporating scrap-steel fibers (SSFs) enhances the elastic modulus and splitting strength of scrap-steel fiber-reinforced concrete (SSFRC), while reducing linear shrinkage compared to concrete without SSFs [27]. Waste Recycled Tire Steel Fibers (WRTSFs) can enhance concrete's mechanical properties, but optimal results require careful control of fiber shape, aspect ratio, surface characteristics, quality, and dosage. The effectiveness of WRTSFs in concrete depends on their dispersion, orientation, distribution, and bond strength, with uniform dispersion significantly enhancing load-bearing capacity, toughness, and energy absorption [28].

This experimental study investigates the potential of using scrap tire steel fibers as an alternative to commercially available steel fibers in the production of SIFCON. The research focuses on evaluating the compressive and split tensile strengths of SIFCON reinforced with both scrap and commercial steel fibers. The study compares the mechanical performance of the variants, to show that scrap tire steel fibers are a viable, cost-effective option for structural and repair applications.

2. Experimental Program

2.1 Materials

2.1.1 Cement

43-grade OPC was utilized in the experimental program, complying with Indian standards [29]. Tables 1 and 2 present the physical characteristics and chemical composition of the cement, respectively.

Table 1. Physical properties of cement

Physical Characteristics	Test result
Specific gravity	3.13
Fineness	311.5 m^2/kg
Normal consistency	33 %
Setting time: Initial	47 min
Setting time: Final	252 min

Table 2. Chemical composition of cement

Type of oxide	Value (%)
CaO	61.81
SiO_2	20.65
Al_2O_3	5.67
Fe_2O_3	4.13
MgO	2.60
SO_3	2.79

2.1.2 Fine Aggregate

Throughout the experimental work, SIFCON specimens and the reference mix were prepared using natural sand that was collected from the riverbed. The maximum size of fine aggregate that can be utilized in the SIFCON slurry matrix is limited to 0.60 mm.

Table 3. Physical characteristics of fine aggregates

Physical Characteristics	Value
Fineness Modulus	2.80
Specific Gravity	2.65
Water Absorption	0.25 %
Bulk density	1650 kg/m^3

During the experimental work, the maximum particle size of the aggregate is maintained to produce SIFCON. Table 3 displays the fine aggregate's physical characteristics that were used in the experiment. The maximum size of the fine aggregate that can be utilized in M20 grade design mix concrete is 4.75 mm. The fine aggregate used in SIFCON and M20 grade concrete complies with the standards stipulated in IS: 383-1970 [36] and IS: 2386 (Part III)-1963 [37].

2.1.3 Coarse Aggregate

Throughout the experimental work, M20 grade concrete was prepared using natural granite stone, which was collected from the local quarry. The maximum size of coarse aggregate that can be utilized in M20 grade design mix concrete is 20 mm. Table 4 displays the coarse aggregate's physical characteristics that were used in the experiment which comply with the standards stipulated in IS: 383-1970 [36] and IS: 2386 (Part III)-1963 [37].

Table 4. Physical characteristics of Coarse Aggregates

Physical Characteristics	Value
Fineness Modulus	6.30
Specific Gravity	2.70
Water Absorption	0.40 %
Bulk density	1475 kg/m3

2.1.4 Mixing Water

Potable water available in the laboratory was used for producing the SIFCON specimens and reference mixes, as well as for their curing.

2.1.5 Chemical Admixture

A poly carboxylic ether superplasticizer with a high water-reducing range was used to achieve the required fresh properties of the SIFCON slurry mix, such as workability and flowability. Table 5 displays the characteristics of AURAMIX 450 from FOSROC Chemicals.

Table 5. Properties of superplasticizer

Color of appearance	Light yellow
Value of PH	Minimum 6.0
Volumetric mass	1.09–1.11
Content of chloride	Nil

2.1.6 Steel Fibers

2.1.6.1 Scrap Tire Steel Fibers

Steel fibers were collected from scrap tires through a survey. Recycling tires involves various technologies aimed at reclaiming valuable materials like rubber, steel, fiber etc., and converting them into useful products. Mechanical Processing, Pyrolysis, Devulcanization, Cryogenic Grinding and Biological Methods are the key technologies used in tire recycling. A scrap tire recycling facility was explored where a mechanical method is used to recover steel fibers from discarded tires, which were then used to prepare SIFCON specimens. Mechanical shredders at the recycling facility initially shred discarded tires into fragments. Next, the shreds undergo magnetic separation, where powerful magnets extract the steel fibers from the rubbery substance. By passing the remaining material through screens and filters, any residual steel fibers are further separated from the rubber fragments. The recycled steel fibers were manually cleaned to remove textiles and rubber before use in SIFCON fabrication. The collected steel fibers have irregular shapes. Figure 1 shows the steel fibers selected for testing from scrap tires. Table 6 presents the length and diameter of randomly selected scrap tire fibers.

Fig. 1. Scrap tire steel fibers

Table 6. Characteristics of scrap tire steel fibers

Fiber diameter (mm)	Fiber length (mm)	Aspect ratio (Average)	Fiber content by weight (%)
0.15 ± 0.01	26 ± 23	173	9.70
0.19 ± 0.01	13 ± 2	68	3.20
0.27 ± 0.02	37 ± 17	137	11.30
0.31 ± 0.01	45 ± 28	145	46.80
0.34 ± 0.01	30 ± 15	88	11.30
0.39 ± 0.03	46 ± 19	118	12.90
0.46 ± 0.01	68 ± 4	148	4.80

2.1.6.2 Commercial Steel Fibers

Additionally, the commercially available steel fibers used in the experimental work were round crimped steel fibers. The commercially available steel fibers selected for the study are displayed in Fig. 2. Table 7 displays the mechanical characteristics of the commercially available steel fibers.

Fig. 2. Commercially available steel fibers

Table 7. Mechanical characteristics of commercially available steel fibers

Fiber type	Crimped
Dia of fiber in mm	0.45
Length of fiber in mm	35
Aspect ratio of fiber (l/d)	77.77
Tensile Strength of fiber	1260 N/mm^2

2.2 Methodology

The concrete mix design for the M20 grade has been carried out in compliance with IS: 10262-2019 [30]. Table 8 lists the ingredient proportions used in M20 grade concrete. The cement utilized in the experiment underwent testing for multiple characteristics, such as consistency, fineness, specific gravity, and both initial as well as final setting times. In accordance with IS codes, tests were carried out on the aggregates for specific gravity, fineness modulus, bulk density, and water absorption. When choosing the chemical admixture and commercially available steel fibers for the study, data from the manufacturer was considered. The diameter, length, aspect ratio, and other properties of the steel fibers that were collected from the scrap tires used in the study were measured.

Table 8. Ingredients of M20 grade concrete mix

	Water	Cement	Aggregate	
			Fine	Coarse
Weight (kg)	160	320	667	1131
Volume (m^3)	0.50	1	2.08	3.53

As advised by EFNARC [31], a mini slump cone was used to conduct the flow test. The mini slump cone has internal dimensions of 70 mm at the top and 100 mm at the bottom, and it is 60 mm height. Figure 3 displays the apparatus used for flow testing in this investigation. After filling the mold with the SIFCON slurry and lifting it, the slurry mix's spread diameter was recorded. As per the guidelines specified in EFNARC [31], the slump flow was observed to be between 240 and 260 mm.

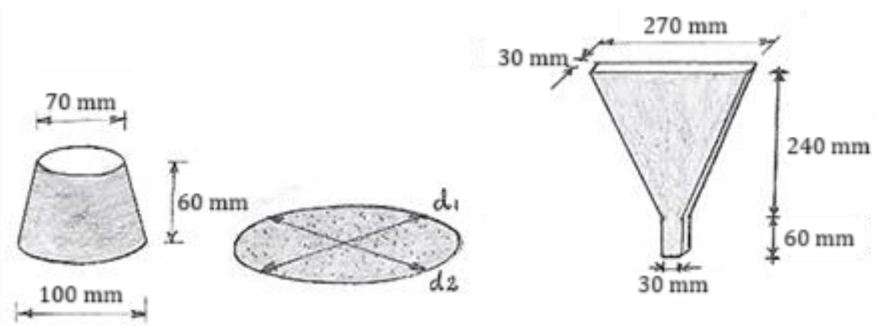


Fig. 3. Mini slump and V-funnel testing equipment

A mini-V-funnel test was also performed on the freshly prepared slurry mix of SIFCON. Figure 3 depicts the size and type of equipment used in this investigation. The test apparatus was filled with SIFCON slurry, and the amount of time needed to empty it was recorded. According to the requirements outlined in EFNARC [31], the test equipment had to be emptied between 7 and 11 seconds. As previously mentioned, fresh tests have been carried out with a 1:1 ratio of cement to fine aggregate. The water–cement ratio has been varied between 0.30 and 0.40 in 0.01 increments, as well as the superplasticizer between 0.50 and 2.00% by cement's weight in 0.1% increments. Figures 4 and 5 illustrate the steps for flow testing and the V-funnel test, respectively. The slurry mixes of SIFCON, with a 1:1 cement-to-sand ratio, was selected after extensive test trials, using a superplasticizer equal to 0.80% of the cement by weight and a water-to-cement ratio of 0.33. Table 9 gives the final proportion of the SIFCON slurry mix with the workability test results.

Table 9. Composition of SIFCON slurry mix

Cement	Fine Aggregate	Water to Cement ratio	Super plasticizer	Test results	
				Mini slump (mm)	Mini V-funnel (s)
1	1	0.33	0.80% of the cement weight	245	7.48

Upon finalizing SIFCON's slurry mix ratio, the production process is as follows: To make demolded specimens easier to remove, waste oil is applied to the molds used for specimen fabrication after the molds have been cleaned. Dry mixing must be done first using a 1:1 ratio of cement to fine aggregate. The dry mix must then be added with water and superplasticizer in accordance with the determined ratios. In order to ensure that the proper mixing of slurry mix, the entire slurry has to be mixed for at least two minutes.

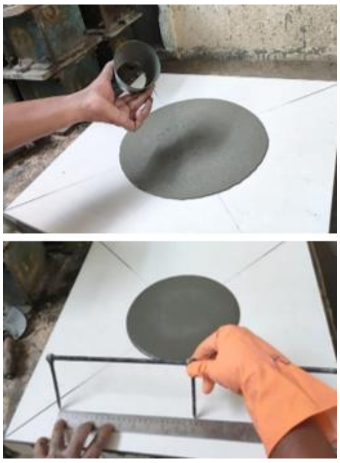


Fig. 4. Slump cone test

Fig. 5. V-funnel test

In order to ensure correct compaction and avoid honeycombing, the fibers in the molds are filled using a two-layer method. As a result, the initial layer of the mold is randomly hand-spread with 50% of the volume percentage of fibers. After the first layer is in place, the fiber bedding is filled with the produced SIFCON slurry mix and compacted using a table vibrator and hand tamping. Same procedure has been followed for second layer. The cast specimens remained at room temperature for a full day. The following day, the specimens are removed from their molds and subjected to the appropriate curing duration in a curing chamber. The irregular shapes and varying aspect ratios of the steel fibers from scrap tires, when randomly placed, caused difficulties in manufacturing specimens with a 6% fiber volume. Considering this, SIFCON specimens containing 7% steel fibers were produced using a three-layer technique, where they encountered difficulty in prepacking of final layer of fibers and compaction of the specimen. Figure 6 illustrates the steps in production of SIFCON specimens.

Fig. 6. Manufacturing of SIFCON

2.3 Compressive Strength Test

SIFCON cube specimens measuring 100x100x100mm, using different volume fractions of scrap tire steel fibers, commercially available steel fibers, and SIFCON reference specimens, were cast to determine compressive strength. SIFCON specimens contained fiber quantities of 314, 392.5, 471, and 549.5 kg/m^3, representing 4%, 5%, 6%, and 7% of volume of the concrete. However, M20 grade reference cube specimens were cast with a size of 150x150x150 mm. The specimen designations are shown in Table 10.

Table 10. Compressive strength specimen designations

Specimen	Size (mm)	Details of steel fiber		Quantity	Designation
		Source	Volume (%)		
M20 grade cube	150x150x150	----	----	9	RMCM20-1 to 9
SIFCON slurry cube	100x100x100	----	0	9	RMCF0-1 to 9
SIFCON cube	100x100x100	Steel fibers from scrap tires	4	9	S1CWF4-1 to 9
			5	9	S1CWF5-1 to 9
			6	9	S1CWF6-1 to 9
			7	9	S1CWF7-1 to 9
SIFCON cube	100x100x100	Commercially available steel fibers	4	9	S1CMF4-1 to 9
			5	9	S1CMF5-1 to 9
			6	9	S1CMF6-1 to 9
			7	9	S1CMF7-1 to 9

The specimen's compressive strength was tested with a universal testing machine. The test was conducted following the guidelines stipulated in IS: 516-1959 [32]. Figure 7 illustrates the arrangement for the compressive strength test. The specimens were tested after 3, 7, and 28 days of curing.

Fig. 7. Arrangement for compressive strength testing

2.4 Split Tensile Strength Test

SIFCON cylinders (100×200mm) were cast to assess split tensile strength. These specimens included various volume fractions of scrap tire steel fibers, commercially available steel fibers, and reference specimens. However, M20 grade reference cylinder specimens were cast with a size of 150mm in diameter and 300mm in height. Table 11 presents the specimen designations.

Table 11. Split tensile specimen designations

Type of specimen	Size (mm)	Details of steel fiber		Quantity	Designation
		Source	Volume (%)		
M20 grade cylinder	150 dia. & 300 high	----	----	9	RMCyM20-1 to 9
SIFCON slurry	100 dia. & 200 high	----	0	9	RMCyF0-1 to 9
SIFCON cylinder	100 dia. & 200 high	Steel fibers from scrap tires	4	9	S1CyWF4-1 to 9
			5	9	S1CyWF5-1 to 9
			6	9	S1CyWF6-1 to 9
			7	9	S1CyWF7-1 to 9
SIFCON cylinder	100 dia. & 200 high	Commercially available steel fibers	4	9	S1CyMF4-1 to 9
			5	9	S1CyMF5-1 to 9
			6	9	S1CyMF6-1 to 9
			7	9	S1CyMF7-1 to 9

The Specimens split tensile was tested with a universal testing machine. The test was conducted following the procedures stipulated in IS: 5816-1999 [33]. Figure 8 illustrates the setup for the split tensile strength test. Specimens were tested at 3, 7, and 28 days.

Fig. 8. Test setup of split tensile strength

2.5 Microstructural Analysis

This study analyzed the microstructural properties of SIFCON using XRD (X-Ray Diffraction) and SEM (Scanning Electron Microscopy) to understand its internal structure and characteristics. SIFCON with 6% scrap tire steel fibers was found to have enhanced mechanical properties. However, compaction was found to be challenging at this percentage of scrap tire steel fibers. Therefore, SEM and XRD analyses were conducted on SIFCON manufactured with 5% steel fibers from scrap tires. Further, SIFCON with 5% of commercially available steel fibers are also used for SEM and XRD. The samples were extracted from the tested specimens. Additionally, the analysis was carried out on reference samples for comparison.

3. Results and Discussion

3.1 Compressive Strength

Table 12 presents the compressive strength of SIFCON with different scrap tire steel fiber percentages, commercially available steel fibers, and reference specimens at 3, 7, and 28 days. Table 12 show compressive strengths of 16.69 and 36.46 N/mm^2 at 3 days, 22.12 and 41.54 N/mm^2 at 7 days, and 30.84 and 56.65 N/mm^2 at 28 days for the M20 mix and SIFCON slurry mix, respectively.

Table 12. Compressive strength of specimens

Sl. No	Type of Specimen	Steel Fibers		Specimen designation	Average Compressive strength (N/mm²)		
		Type	Percentage		3 days	7 days	28 days
1	M20 grade cube	----	----	RMCM20	16.69	22.12	30.84
2	SIFCON slurry cube	----	0	RM1CF0	36.46	41.54	56.65
3	SIFCON cube	Steel fibers from scrap tires	4	S1CWF4	39.97	44.84	59.60
4	SIFCON cube		5	S1CWF5	40.34	45.45	62.19
5	SIFCON cube		6	S1CWF6	42.86	46.15	63.36
6	SIFCON cube		7	S1CWF7	36.88	38.89	49.16
7	SIFCON cube	Commercially available steel fibers	4	S1CMF4	49.24	61.85	74.76
8	SIFCON cube		5	S1CMF5	49.76	68.60	81.13
9	SIFCON cube		6	S1CMF6	60.67	74.92	92.48
10	SIFCON cube		7	S1CMF7	59.09	73.33	86.50

Table 12 and Figure 9 present the 3-day compressive strengths of SIFCON containing 4% to 7% scrap tire steel fibers as 39.97, 40.34, 42.86, and 36.88 N/mm^2, respectively. These values are 139%, 142%, 157%, and 121% higher compared to the M20 mix, and 10%, 11%, 18%, and 1% higher compared to the SIFCON slurry mix. At 7 days, the corresponding values are 44.84, 45.45, 46.15, and 38.89 N/mm^2. These values are 103%, 105%, 109%, and 76% higher compared to the M20 mix, and 8%, 9%, 11%, and -6% higher compared to the SIFCON slurry mix. At 28 days, the compressive strengths for the same fiber percentages are 59.60, 62.19, 63.36, and 49.16 N/mm^2, respectively. These values are 93%, 102%, 105%, and 59% higher compared to the M20 mix, and 5%, 10%, 12%, and -13% higher compared to the SIFCON slurry mix.

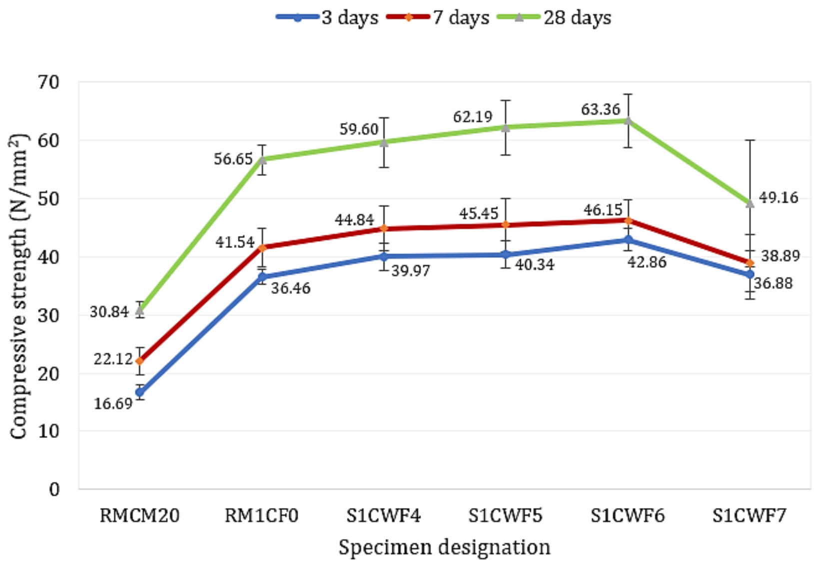


Fig. 9. Effect of scrap tire steel fiber content on compressive strength at 3, 7 and 28 days

According to Table 12 and Figure10, the 3-day compressive strength of SIFCON with 4% to 7% commercially available fibers is 49.24, 49.76, 60.67, and 59.09 N/mm^2, respectively. These values are 195%, 198%, 264%, and 254% higher compared to the M20 mix, and 35%, 36%, 66%, and 62% higher compared to the SIFCON slurry mix. At 7 days, the corresponding values are 61.85, 68.60, 74.92, and 73.33 N/mm^2. These values are 180%, 210%, 239%, and 232% higher compared to the M20 mix, and 49%, 65%, 80%, and 77% higher compared to the SIFCON slurry mix. Additionally, at 28 days, the compressive strengths for the same fiber percentages are 74.76, 81.13, 92.48, and 86.50 N/mm^2, respectively. These values are 142%, 163%, 200%, and 180% higher compared to the M20 mix, and 32%, 43%, 63%, and 53% higher compared to the SIFCON slurry mix.

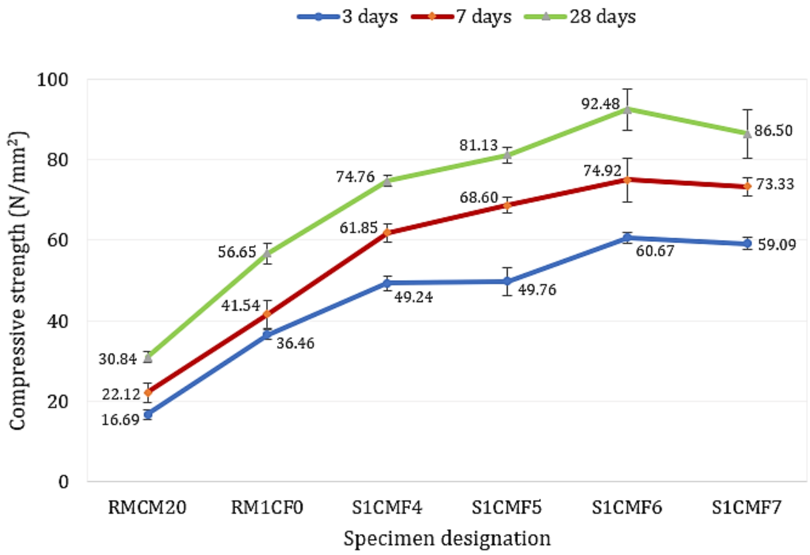


Fig. 10. Effect of commercial steel fiber content on compressive strength at 3, 7 and 28 days

Figure 11 shows the overall comparison of the compressive strengths of SIFCON and the reference mixes after curing periods of 3, 7, and 28 days. In summary, after 3 days of curing, increasing the amount of scrap tire and commercially available steel fibers in SIFCON from 4% to 7% resulted in a compressive strength improvement of up to 157% and 254% compared to M20 grade concrete, respectively. Additionally, the compressive strength increased by up to 18% and 66% compared to the SIFCON slurry mix, respectively. After 7 days of curing, increasing scrap tire and commercially available steel fibers in SIFCON from 4% to 7% boosted compressive strength by up to 109% and 239% over M20 grade concrete. Furthermore, the values increased by up to 11% and 77% compared to those of the SIFCON slurry mix, respectively.

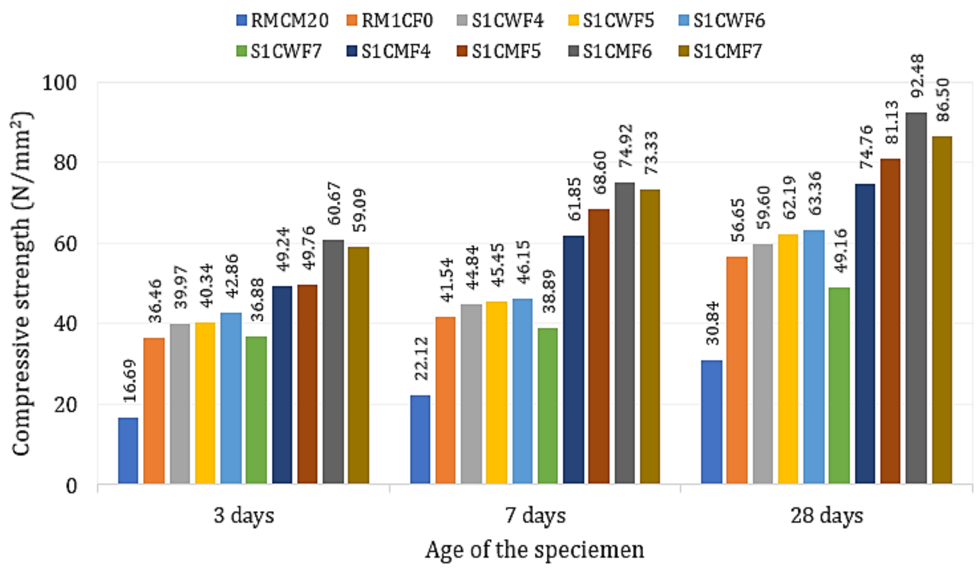


Fig. 11. Comparison of compressive strength between SIFCON and the reference mixes

After 28 days of curing, increasing the scrap tire and commercially available steel fibers in SIFCON from 4% to 7% boosted compressive strength by up to 105% and 200% over M20 grade concrete. Furthermore, the values increased by up to 12% and 63% compared to those of the SIFCON slurry mix, respectively. The results obtained were like those obtained in previous studies on SIFCON produced with waste steel fibers. SIFCON with 4% to 7% scrap tire steel fibers achieves 62% to 81%, 53% to 73%, and 57% to 80% of the compressive strength of SIFCON made with commercially available steel fibers at 3, 7, and 28 days, respectively.

These results are in good agreement with findings reported in previous studies on SIFCON incorporating waste steel fibers [23], where fiber inclusion was shown to substantially improve strength properties due to enhanced crack-bridging, improved fiber-matrix interaction, and increased energy dissipation. The current study further confirms that while scrap tire steel fibers are slightly less effective than their commercial counterparts, they still contribute significantly to compressive strength development. However, a limitation in the use of fiber volume was identified, as an increase beyond a certain point led to a reduction in strength. This aligns with the understanding that a higher fiber ratio can negatively impact mechanical properties by increasing void content [26]. This demonstrates the potential of using recycled fibers as a sustainable and cost-effective alternative without a substantial compromise in performance.

3.2 Split Tensile strength

Table 13 presents the split tensile strength of SIFCON with different scrap tire steel fiber percentages, commercially available steel fibers, and reference specimens at 3, 7, and 28 days.

Table 13. Split tensile strength of specimens

Sl. No	Type of Specimen	Steel Fibers		Specimen designation	Average Split tensile strength (N/mm²)		
		Type	Percentage		3 days	7 days	28 days
1	M20 grade cylinder	----	----	RMCyM20	1.61	2.12	2.71
2	SIFCON slurry cylinder	----	0	R1MCyF0	2.61	3.20	4.69
3	SIFCON cylinder	Steel fibers from scrap tires	4	S1CyWF4	2.88	3.84	4.96
4	SIFCON cylinder		5	S1CyWF5	3.23	4.08	5.98
5	SIFCON cylinder		6	S1CyWF6	4.49	4.80	7.88
6	SIFCON cylinder		7	S1CyWF7	4.55	5.82	7.29
7	SIFCON cylinder	Commercially available steel fibers	4	S1CyMF4	10.13	11.97	14.18
8	SIFCON cylinder		5	S1CyMF5	11.02	12.27	14.62
9	SIFCON cylinder		6	S1CyMF6	11.75	13.55	16.06
10	SIFCON cylinder		7	S1CyMF7	14.84	17.41	19.48

Table 13 show split tensile strengths of 1.61 and 2.61 N/mm² at 3 days, 2.12 and 3.20 N/mm² at 7 days, and 2.71 and 4.69 N/mm² at 28 days for the M20 mix and SIFCON slurry mix, respectively. Table 13 and Figure 12 show the 3-day split tensile strength of SIFCON with 4% to 7% scrap tire steel fibers as 2.88, 3.23, 4.49, and 4.55 N/mm², respectively. These values are 79%, 101%, 179%, and 183% higher compared to the M20 mix, and 10%, 24%, 72%, and 74% higher compared to the SIFCON slurry mix. At 7 days, the corresponding values are 3.84, 4.08, 4.80, and 5.82 N/mm². These values are 81%, 92%, 126%, and 175% higher compared to the M20 mix, and 20%, 28%, 50%, and 82% higher compared to the SIFCON slurry mix. At 28 days, the compressive strengths for the same fiber percentages are 4.96, 5.98, 7.88, and 7.29 N/mm², respectively. These values are 83%, 121%, 191%, and 169% higher compared to the M20 mix, and 6%, 28%, 68%, and 55% higher compared to the SIFCON slurry mix.

According to Table 13 and Figure 13, the 3-day compressive strength of SIFCON with 4% to 7% commercially available fibers is 10.13, 11.02, 11.75, and 14.84 N/mm², respectively. These values are 529%, 584%, 630%, and 822% higher compared to the M20 mix, and 288%, 322%, 350%, and 469% higher compared to the SIFCON slurry mix. At 7 days, the corresponding values are 11.97, 12.27, 13.55, and 17.41 N/mm². These values are 465%, 479%, 539%, and 721% higher compared to the M20 mix, and 274%, 283%, 323%, and 444% higher compared to the SIFCON slurry mix. Additionally, at 28 days, the compressive strengths for the same fiber percentages are 14.18, 14.62, 16.06, and 19.48 N/mm², respectively. These values are 423%, 439%, 493%, and 619% higher compared to the M20 mix, and 202%, 212%, 242%, and 315% higher compared to the SIFCON slurry mix.

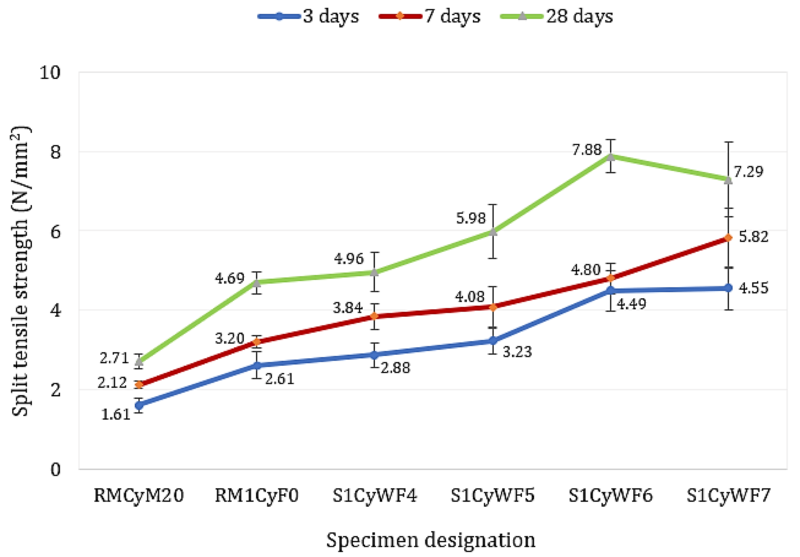


Fig. 12. Effect of scrap tire steel fiber content on split tensile strength at 3, 7 and 28 days

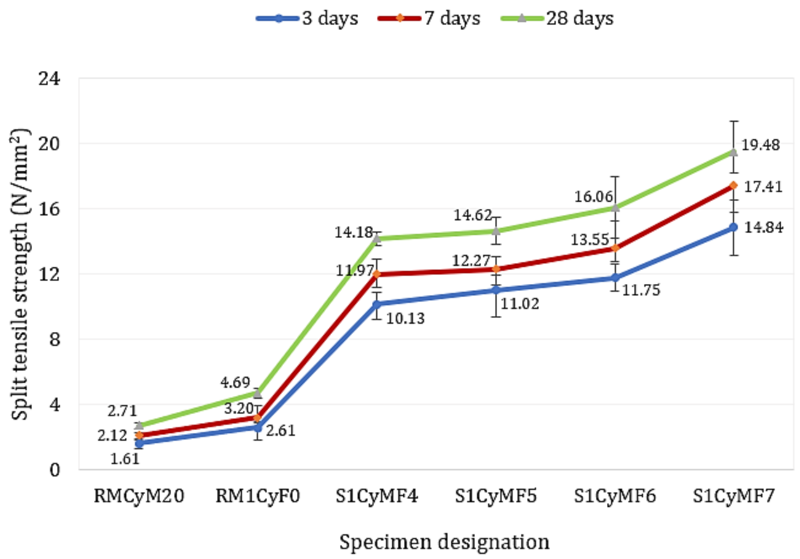


Fig. 13. Effect of commercial steel fiber content on split tensile strength at 3, 7 and 28 days

Figure 14 shows the overall comparison of the split tensile strengths of SIFCON and the reference mixes after curing periods of 3, 7, and 28 days. In summary, after 3 days of curing, increasing the amount of scrap tire and commercially available steel fibers in SIFCON from 4% to 7% boosted split tensile strength by up to 132% and 822%, respectively, compared to M20 grade concrete. Additionally, the values increased by up to 74% and 469% compared to the SIFCON slurry mix. After 7 days of curing, increasing scrap tire and commercially available steel fibers in SIFCON from 4% to 7% boosted split tensile strength by up to 175% and 721% over M20 grade concrete. Furthermore, the values increased by up to 82% and 444% compared to those of the SIFCON slurry mix, respectively. After 28 days of curing, increasing the scrap tire and commercially available steel fibers in SIFCON from 4% to 7% boosted split tensile strength by up to 191% and 619% over M20 grade concrete. Furthermore, the values increased by up to 68% and 315% compared to those of the SIFCON slurry mix, respectively. The results obtained were like those obtained in previous studies on SIFCON produced with commercial steel fibers. SIFCON with 4% to 7% scrap tire steel fibers achieves 28% to 38%, 32% to 35%, and 35% to 49% of the split tensile strength of SIFCON made with commercially available steel fibers at 3, 7, and 28 days, respectively.

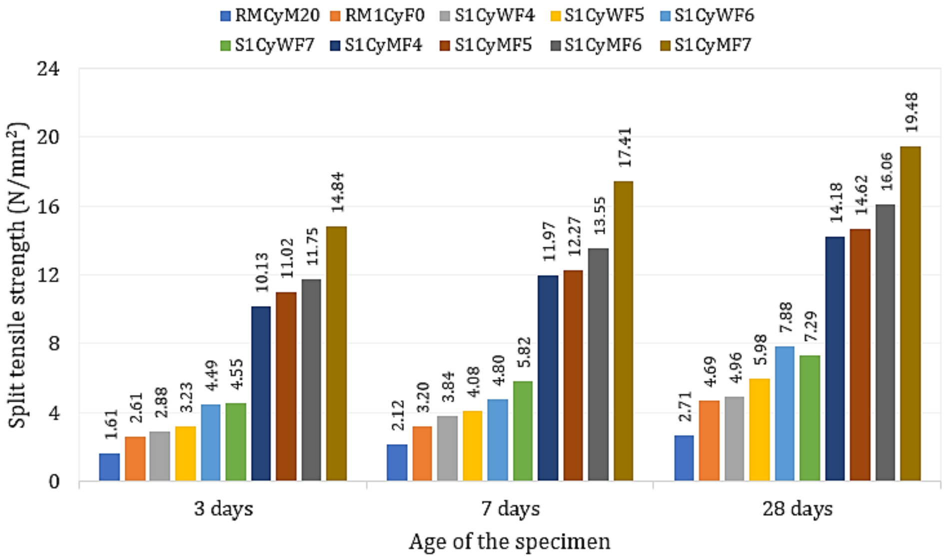
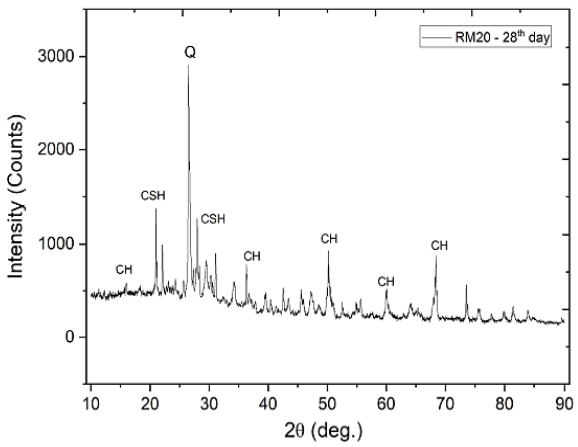


Fig. 14. Comparison of split tensile strength of SIFCON and reference mixes

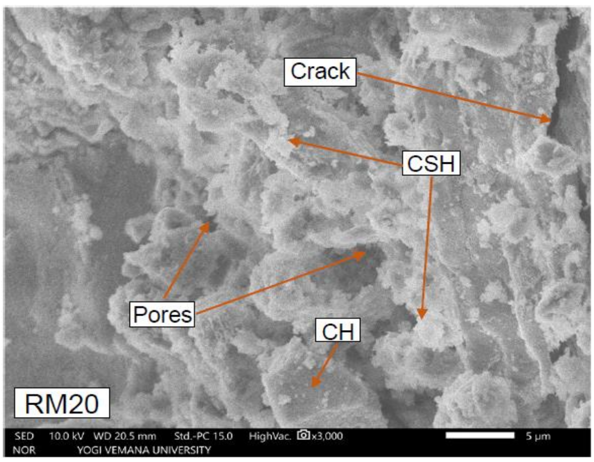
These findings are consistent with previous studies on SIFCON produced using commercial steel fibers [23], which also reported significant improvements in tensile performance due to the bridging action of fibers and their ability to control crack propagation. The present study further reveals that although scrap tire steel fibers yield comparatively lower tensile strength than commercial fibers, they still contribute substantially to enhancing the performance of SIFCON. However, the fiber length of scrap tire steel fibers has been found to influence performance, aligning with the understanding that optimizing recycled steel fiber content for any mix requires careful consideration of dimensional factors, particularly fiber length [35]. These results support the viability of using recycled steel fibers as a sustainable reinforcement alternative, particularly where moderate tensile strength is acceptable.

3.3 Microstructural Analysis

Microstructural analysis was conducted on samples taken from specimens fractured during compression and split tensile testing. The microstructural analysis examined the Interfacial Transition Zone (ITZ) between the steel fibers and the cement paste to assess its hydration behavior [34]. The microscopic analysis of the specimens at 28 days was conducted at magnifications ranging from 2 to 500 µm. Samples of SIFCON containing 5% steel fibers from scrap tires, commercially available steel fibers, and reference mixes were used for SEM and XRD analyses. The results of XRD and SEM analyses are presented in Figures 15–19.

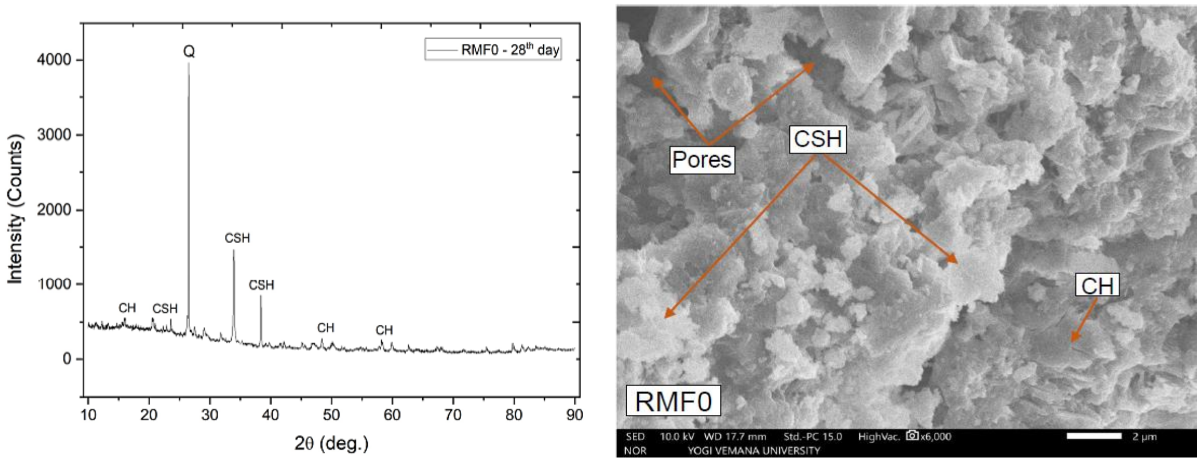


(a)



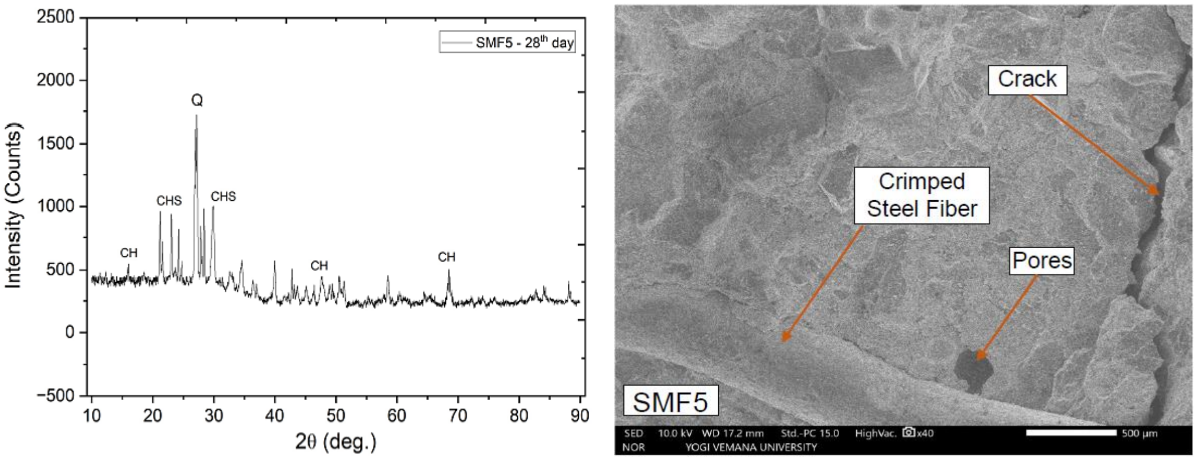
(b)

Fig. 15. Images of reference M20 mix (RM20) (a) XRD (b) SEM



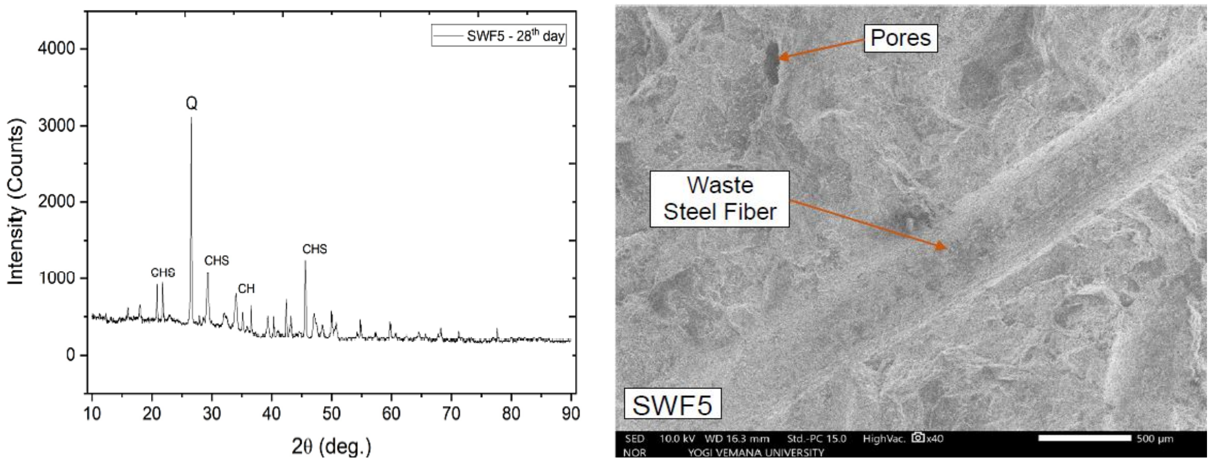
(a) (b)

Fig. 16. Images of reference SIFCON mix with 0% fibers (RMF0) (a) XRD (b) SEM



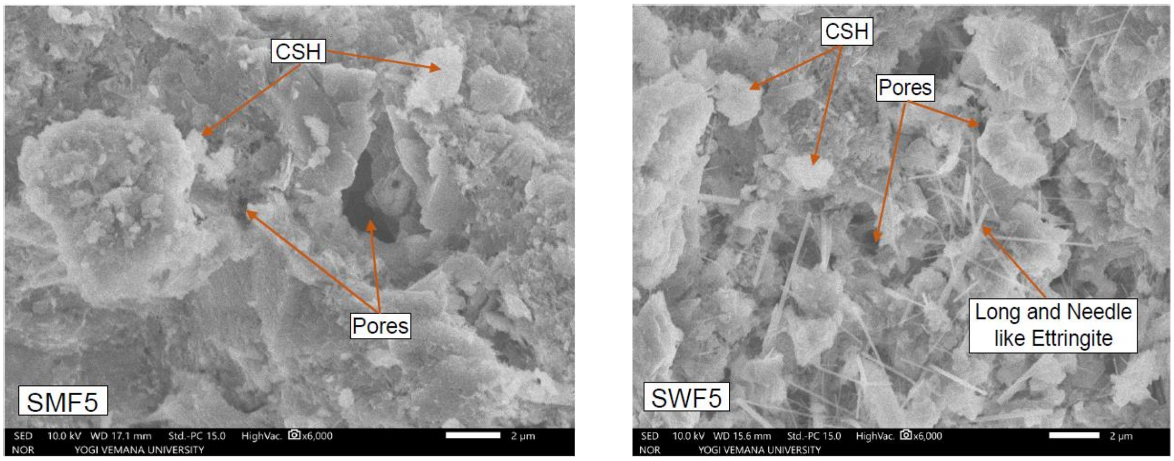
(a) (b)

Fig. 17. Images of SIFCON with 5% commercial steel fibers (SMF5) (a) XRD (b) SEM



(a) (b)

Fig. 18. Images of SIFCON with 5% scrap tire steel fibers (SWF5) (a) XRD (b) SEM



(a) (b)

Fig. 19. SEM images of SIFCON with 5% commercial and scrap tire steel fibers (a) SMF5 (b) SWF5

Figures 15(a)–18(a) illustrate the XRD analysis results for angles between 10° and 90°, demonstrating the presence of several hydrated phases, such as Calcium Silicate Hydrate (CSH), ettringite, and calcium hydroxide (CH). The major crystalline peaks observed represent the CSH phase, while ettringite appears with a lower peak. Figures 15(b)–18(b) and 19 depict bands of Calcium Silicate Hydrate (CSH), unreacted amorphous calcium hydroxide, and needle-shaped ettringite resulting from the hydration process.

4 Conclusions

Based on the evaluation of compressive and split tensile strengths of SIFCON reinforced with scrap tire and commercially available steel fibers, the following conclusions are drawn.

- The study shows that adding 4% to 7% of scrap tire and commercially available steel fibers significantly improves SIFCON's compressive strength at curing ages of 7, 14, and 28 days, with optimal performance observed at 6% fiber content. A slight drop at 7% is attributed to reduced workability of the mix and fiber clustering. SIFCON with both fiber types outperformed M20 concrete and plain SIFCON, emphasizing the importance of fiber content. While SIFCON with commercial steel fibers delivered higher strength, SIFCON with scrap tire steel fibers achieved 57–81% of that performance, demonstrating its potential as a sustainable and cost-effective alternative.
- Similarly, split tensile strength improved significantly with both scrap tire and commercially available steel fibers, steadily increasing from 4% to 7% fiber content across all curing ages. Commercial steel fibers provided the highest gains, but scrap tire steel fibers still outperformed M20 concrete and plain SIFCON, achieving 28–49% of the strength of commercial steel fibers. Nevertheless, they delivered significant improvements over M20 concrete and plain SIFCON, while serving as an eco-friendly and sustainable reinforcement alternative.
- SEM and XRD analyses revealed effective hydration and microstructural development in the Interfacial Transition Zone (ITZ) of SIFCON with both scrap tire and commercial steel fibers. The detection of C-S-H, ettringite, and unreacted CH at 28 days indicates continued hydration and strong fiber–matrix integration, aligning with the observed mechanical performance.
- This study highlights the effectiveness of recycled steel fibers, particularly from scrap tires, as a sustainable alternative to commercial steel fibers in SIFCON. Despite their irregular geometry, scrap tire steel fibers significantly enhanced compressive and split tensile strengths. Using up to 6% fiber content with a two-layer casting method yielded performance comparable to commercial fibers. These results demonstrate the potential of optimized scrap

tire fiber use as a cost-effective and eco-friendly reinforcement strategy for sustainable construction.

This study confirms that adding 4–7% steel fibers, especially 6%, significantly improves SIFCON's mechanical performance. Scrap tire fibers achieved up to 81% of the strength of commercial fibers and enhanced both compressive and tensile strengths, despite minor workability issues at higher doses. Microstructural analysis showed strong fiber–matrix bonding, highlighting recycled fibers as a viable, sustainable alternative for construction.

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