Research Article

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Performance Evaluation of Self-compacting Concrete Incorporating Glass Fibers and Nanomaterials

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ABSTRACT

This study investigates the role of nano-silica and Cem FIL Anti Crack HD glass fibers in enhancing the performance of Self Compacting Concrete (SCC). Although SCC possesses excellent workability, its tensile and flexural strengths remain relatively low compared to its compressive strength. To address this limitation, a modified mix designated as Glass Fiber and Nano Reinforced SCC (GFNSCC) was prepared and compared with conventional SCC. The experimental results showed a clear improvement in mechanical performance. The compressive strength increased from 26.22 to 33.16 N/mm^2 in SCC to 31.02 to 38.27 N/mm^2 in GFNSCC, the splitting tensile strength improved from 2.62-3.32 N/mm^2 to 3.10-3.83 N/mm^2, and the flexural strength increased from 3.15-3.98 N/mm^2 to 3.88-4.79 N/mm^2. These results confirm that the combined addition of nano-silica and glass fibers provides a synergistic effect, producing significant gains in strength characteristics. The findings highlight the potential of GFNSCC for applications requiring high durability and improved resistance to cracking in complex structural systems.

Keywords: Self-compacting concrete; Nano-silica reinforcement; Glass fiber reinforced concrete; Compressive strength; Splitting tensile strength; Flexural strength.

1. INTRODUCTION

Self-compacting concrete has garnered considerable research attention over the past few years, particularly in the optimization and development of self-compacting fiber-reinforced concrete and self-compacting sustainable concrete. Advanced machine learning and modeling have been prominent in forecasting compressive strength and other performance measures.

The present study proposes fiber-reinforced SCC and provides a sensitivity analysis, implying that the data-driven approach offers a high degree of forecasting accuracy for the compressive strength. Revilla-Cuesta *et al.* (2021) and Mai *et al.* (2023) examined models of non-destructive testing for CS estimation of SCC, focusing on the use of recycled concrete aggregate and slag-based binders to achieve sustainability and preserve structural performance. A comparison of various SCCs modified with fly ash, carried out by Farooq *et al.* (2021), showed that the choice of fly ash content and modelling methods greatly impacted the CS outcomes.

Mostafa *et al.* (2022) and Saif *et al.* (2023) examined ultra-high-performance fiber-reinforced SCCs containing additives of nano and agricultural wastes at different temperatures and revealed that their nano-based additions allow improving their strength at elevated temperatures and thermal stability. In the same way, ensemble machine learning has been used by De-Prado-Gil *et al.* (2022) to predict CS of SCC with recycled aggregates, with promising performance in a complicated material system.

Regarding sustainable SCM (supplementary cementitious materials), Al-Mughanam *et al.* (2020) modeled CS with an ANN to SCC using treated palm oil fuel ash. In contrast, Ahmad *et al.* (2021) considered wheat straw ash and bentonite clay as partial cement replacements, focusing on eco-efficiency. Haruna *et al.* (2021) compared the conventional FFNN with emotional artificial neural networks (EANN) relating to SCC reinforced using rice husk ash and calcium carbide wastes, and the EANN models demonstrated superior performance. Studies were conducted on the addition of nano-materials. Hosseini *et al.* (2017) and Afzali Naniz and Mazloom (2018) showed a positive change in short-term properties and strength of SCCs with the addition of clay and Nano-silica, respectively.

The study by Jalal *et al.* (2015) compared the properties of Class F fly ash, nano-silica, and silica fume in SCC with high performance, and the results indicated improved mechanical and durability characteristics. Similarly, Saini and Vattipalli, (2020) evaluated the use of alkaline-activated GGBS-based geopolymer SCC, promoting fewer environmental contributions.

In an effort to give attention to enhanced impact resistance, Murali *et al.* (2021) experimented on two-stage expanded clay aggregate concrete integrated with MWCNTs, steel and glass fiber mesh. A metaheuristic RBF-NN model was used by Pazouki *et al.* (2022) to predict CS in fly ash SCC with high-level accuracy, and SVM models were used as input by Azimi-Pour *et al.* (2020) to indicate fresh and hardened properties of high-volume fly ash SCC. With an eye toward sustainable building applications, Kandasamy *et al.* (2025a) examined the mechanical and durability performance of interlocking geopolymer mud blocks by adding industrial by-products like fly ash and slag. In comparison to traditional mud blocks, their investigation showed that the usage of these by-products significantly improved the compressive strength, water resistance, and thermal stability of geopolymer blocks. By lowering reliance on conventional cementitious binders, the incorporation of waste materials also enhanced environmental sustainability. Sabari *et al*. (2025) reported that the incorporation of nanoparticles significantly enhances its mechanical properties by improving microstructural density and hydration kinetics. Nanoparticles are characterized by their exceptionally high surface area to volume ratio, which directly influences their mechanical properties. At the nanoscale, materials often exhibit enhanced hardness, higher elastic modulus, and improved strength compared to their bulk counterparts (Sabari *et al.* 2025).

The load-deformation behavior of reinforced concrete (RC) slabs treated with nano-silica (SiO_2) and natural coconut fibers was compared in a different study by Kandasamy *et al.* (2025b). According to their findings, adding nano-SiO_2 to concrete increased its microstructural densification, while adding coconut fibers improved its flexural toughness.

Although self-compacting concrete (SCC) has been widely studied in the enhanced state of using fibers or nano-materials, little research is carried out to evaluate the overall impact of glass fiber and nano-reinforcement on SCC, especially in terms of the influences of mechanical strength and workability. Available publications focus on the single aspect of fiber reinforcement or nano-additives alone. Furthermore, in previous research studies, compressive strength is frequently studied at the cost of split tensile and flexural properties (Damodaran *et al.* 2024). The effect of the strength and flow behavior due to different dosages of glass fibers is still little explored. This work examines the synergistic impact of glass fibers and nano-materials on GFNSCC. It also states the best fiber content to get optimum strength with minimal effect on workability. Accordingly, the study can contribute to the structural efficiency and provide practical workability guidelines for advanced SCC formulations.

Previous studies on SCC with nano-silica have consistently reported improvements in compressive strength and microstructural densification through enhanced C–S–H formation, yet contradictory findings exist regarding its effect on workability, with some authors noting reduced flowability due to high surface area demands. Similarly, research on glass fiber reinforced SCC highlights notable gains in tensile and flexural strengths through crack-bridging, though challenges such as fiber dispersion and potential reduction in flowability have also been observed. While these works establish clear trends, they largely investigate nano-silica and glass fibers in isolation. Only a few studies have attempted hybrid approaches, and these often lack systematic evaluation of synergistic effects on overall strength performance. This gap in the literature justifies the present investigation, which critically examines how the combined use of nano-silica and glass fibers influences compressive, tensile, and flexural behavior in SCC, thereby addressing both the microstructural refinement and crack-bridging limitations observed in prior single-addition studies.

This study demonstrates that adding nano-silica with Cem-FIL Anti-Crack HD glass fibers significantly improves compressive (31.02–38.27 N/mm²), tensile (3.10–3.83 N/mm²), and flexural strengths (3.88–4.79 N/mm²) compared to conventional SCC. These gains exceed those achieved by either additive alone, confirming a synergistic effect. The combined approach bridges particle-level and crack-level reinforcement, offering new knowledge for overcoming tensile and flexural limitations of SCC.

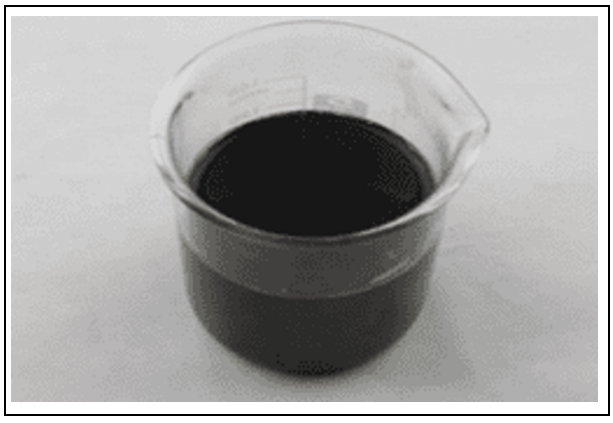


Fig. 1: Superplasticizer

2. MATERIALS AND METHODS

The work was carried out in the concrete Technology laboratory. The goal was to determine the effects of glass fiber and nano-reinforcement on the compressive strength of SCC. These tests and mixes were conducted in two groups, consisting of M20 grade SCC under controlled laboratory conditions.

2.1 Design, Concrete Mix

All the concrete mixtures made were using M20 of SCC grade. In both groupings, 0.6 % of L R range water-reducing admixture (superplasticizer) was used to achieve self-compacting properties, characterized by sufficient flow and workability. A fixed ratio of water to cement (w/c) mixture of 0.45 was used to mix all the mixes.

2.2 Control Group (Ordinary SCC)

Ordinary Portland cement was taken as the binder and fine and coarse aggregates as aggregates of this mixture. No additional fiber and nano reinforcement was added, except 0.6 % superplasticizer and water.

2.3 Experimental Group (Glass Fiber and Nano-Reinforced SCC - GFNSCC)

It had 0.6 % of superplasticiser, 3.0 % Cem-FIL Anti-Crack HD glass fibres (with high dispersion properties), and nano-reinforcements. The nano-reinforcement used was nano-silica, chosen for its large surface area and ability to fill the micropores in the cement matrix, thereby improving the microstructure. Nano-silica has been added to the experiment at a ratio of 1.5 % by weight on a cement-to-cement basis.

2.4 Materials Notes

2.4.1 Cement

All mixes were conducted using Ordinary Portland Cement (OPC) of 43-grade, ensuring uniformity by using cement from the same batch. The cement utilised was of standard IS and a homogenous mixture of clayey and calcareous substances, including gypsum.

2.5 Other Additives

2.5.1 Nanomaterial (Nano-silica)

Nano-silica in powder form, with a mean particle size of 20-40 nm, was added to enhance the extent of cementitious matrix packing. It was required to be dispersed in the water before the mix through an ultrasonic procedure to ensure that it is well distributed.

2.5.2 Fine Aggregate

Manufactured sand (M-sand), with a fineness modulus of 2.74 and a specific gravity of 2.63, was used. The sand was sieved at a size of 4.75 mm, and there were no impurities present in it.

2.5.3 Coarse Aggregate

The stones used were crushed stones of irregular shapes, with particles ranging from 20 mm to 80 mm sieve. The SCC-products met the IS specification of aggregates.

2.5.4 Water

Tap water was used throughout the study for mixing and curing, with no residues present to affect the hydrating process. The kind of water also conformed to the IS requirement concerning concrete mix.

2.6 Process of Mixing

The two-stage mixing was employed because it is necessary for the homogeneous mixing of the nanomaterials. Nano-silica was initially dispersed by mixing water with the help of a high-shear mixer and subsequently sonicated with ultrasonic agitation. This nano-silica solution was then further developed by combining it with other dry ingredients in a pan mixer.

2.7 Testing and Statistical Analysis

Cylinders and beams, as well as standard cubes (150 mm × 150 mm × 150 mm), were cast and cured under the same conditions. The split tensile strength and flexural strength were measured at 28 days. Independent sample t-test was used. The power of the t-test was 0.8, with an alpha set to 0.05 and a beta set to 0.2 to capture a Type I error. It was also found to be statistically significant when comparing compressive strength ($p = 0.04$), proving that nano-reinforcement actually works in making concrete perform better.

Fig. 1 shows a beaker filled with superplasticizer, a dark liquid admixture that is used to increase the flow and workability of concrete without adding more water.



Fig. 2: Glass fiber

Fig. 2 shows bundles of glass fibers, which are small, thread-like strands of glass used to boost tensile and flexural strength in concrete. These fibers help prevent cracking, improve durability, and are often employed as reinforcement in high-performance composites.



Fig. 3: Conventional concrete mix



Fig. 4: Universal testing machine

Fig. 3 shows the conventional concrete mix. Fig. 4 shows the UTM machine used for compressive strength analysis

2.8 Statistical Analysis

Separate sample t-tests were used to differentiate between the fiberglass-reinforced and conventional groups. The study's independent variables were concrete strength, concrete type, water-to-cement ratio, current type, and curing age; dependent variables were excluded. The compressive strength tool was used to calculate the mean, SD, and standard error of the mean.

3. RESULTS

The compressive strength was analysed experimentally, showing a significant rise in the mechanical properties of SCC under the addition of glass fibres and nano-reinforcements. To be more precise, the average compressive strength of the Glass Fiber and Nano-Reinforced SCC (GFNSCSCC) was found to be 34.78 N/mm^2, which is much higher when compared with the 29.85 N/mm^2 obtained on account of normal SCC with no reinforcement. The standard deviation (SD) of compressive strength of GFNSCC was 2.06834. In contrast, the conventional SCC had an SD of 1.83342, indicating a slightly higher variation as a result of composite content in the mixture because of fiber and nano-materials.

A measure of equality of variances in the two groups was done using the Levene Test of Equality of Variances. The test produced results showing that the variances were statistically similar; thus, it was valid to apply parametric tests during further analysis. Even though the specific strengths of the 18 samples are listed in Table 4, details of the test, such as the failure mode and load-time curves, are not reported due to space limitations.

One area of concern in this study was the influence of nano-reinforcement, i.e. nano-silica, in the development of compressive strength. The presence of nano-silica, which was of excellent particle size and highly reactive as pozzolana, greatly enhanced the micro-structure of the cement matrix. It plugged micro-pores and pores between cement particles, enhanced the packing density of particles and lowered permeability. It caused an increase in the density and strength of the matrix, which increased the strength of GFNSCC.

Further, the nano-silica was used with the calcium hydroxide (remnant of cement hydration) to produce more calcium silicate hydrate (C-S-H) gel, which comprises the main strength imparting component of the concrete. This not only enhanced compressive strength but also lightened up the bonding interface between glass fibers and cement matrix, leading to superior load transfer and crack resistance.

As a validation of statistics, a two-sample t-test was done on mean compressive strengths at a significance level of $p = 0.05$. The variation in compressive ability of GFNSCC compared to normal SCC was statistically significant, confirming the positive impact of both glass fibre and nano-reinforcement.

In addition to that, error bars of a 95% confidence interval were used to illustrate the graphical representation of the more precise data and predicted compressive strengths in GFNSCC. A mixture of independent glass fiber reinforcement, nano-silica, and a high-performance water-reducing agent was set in one of the experimental groups to achieve workability and strength. The combination of the two helped improve the mechanical properties of the SCC as well as the control involved in the rheology.

Table 1. Physical properties of cement used in nano-reinforced SCC

S. No.	Property Tested	Result
1	Fineness (Retention on 90 µm sieve)	90 Micron
2	Specific Gravity	3.10
3	Standard Consistency	30%
4	Initial Setting Time	30 Minutes
5	Final Setting Time	600 Minutes

Table 1 shows the physical properties of cement used in nano-reinforced self-compacting concrete (SCC). The fineness of the cement, measured by retention on a 90-micron sieve, is 90 microns, indicating a suitable particle size for good workability. The specific gravity of 3.10 suggests the cement has a typical density for standard construction materials. The standard consistency is 30%, which means this is the water content required for normal paste consistency. The initial setting time is 30 minutes, allowing sufficient time for placement. The final setting time is 600 minutes, indicating a more extended setting period suitable for complex applications.

Table 2 presents the key properties of fine aggregates used with nano-silica in concrete. The maximum particle size is 4.75 mm, suitable for fine aggregate classification. The fineness modulus is 9.59, indicating the relative coarseness of the sand. Water absorption is 3.0%, showing the amount of moisture that the aggregates can retain. The specific gravity of 2.65 reflects the density of the material, typical for natural sand. These properties influence the workability and strength of the concrete mix.

Table 2. Properties of fine aggregates (Used with nano-silica)

S. No.	Property Tested	Result
1	Maximum Particle Size	4.75 mm
2	Sieve Analysis (Fineness Modulus)	9.59
3	Water Absorption	3.0%
4	Specific Gravity	2.65

Table 3. Properties of coarse aggregates in nano-reinforced SCC

S. No.	Property Tested	Result
1	Maximum Particle Size	20 mm
2	Sieve Analysis	Confirmed at 20 mm
3	Water Absorption	3.14%
4	Specific Gravity	2.68

Table 3 details the properties of coarse aggregates used in nano-reinforced SCC. The maximum particle size is 20 mm, making it suitable for structural concrete. Sieve analysis confirms that the aggregate size is within the 20 mm limit. Water absorption is measured at 3.14%, indicating moderate moisture uptake. The specific gravity is 2.68, typical for coarse aggregates, and affects the concrete's density and strength. These characteristics are essential for achieving desired performance in concrete applications.

Table 4. Compressive strength of conventional concrete

S. No.	Weight (kg)	Strength (kN)	Compressive Strength (N/mm^2)	Splitting Tensile Strength (N/mm^2)	Flexural Strength (N/mm^2
1	8.132	590	26.222	2.62	3.15
2	8.543	672	29.866	2.99	3.58
3	8.231	659	29.288	2.93	3.51
4	8.987	680	30.222	3.02	3.63
5	9.011	674	29.955	3.00	3.59
6	8.654	685	30.44	3.04	3.65
7	8.256	725	32.22	3.22	3.86
8	8.987	689	30.622	3.06	3.67
9	9.233	617	27.422	2.74	3.29
10	8.765	693	30.08	3.01	3.61
11	9.043	662	29.42	2.94	3.53
12	8.798	653	29.022	2.90	3.48
13	8.675	696	30.933	3.09	3.71
14	8.793	699	31.066	3.11	3.73
15	9.045	720	32	3.20	3.84
16	8.894	650	28.88	2.89	3.46
17	9.406	597	26.53	2.65	3.18
18	9.654	746	33.155	3.32	3.98

Table 4 illustrates the compressive, tensile, and flexural strength values of standard concrete samples. The compressive strength ranges from 26.22 to 33.16 N/mm^2, suggesting varied load-bearing capabilities. The concrete's resistance to tensile stress is indicated by splitting tensile strength values, which range from 2.62 to 3.32 N/mm^2. The material's bending resistance is marked by its flexural strength, which ranges from 3.15 to 3.98 N/mm^2. The data also contains the weight and applied load (in kN) for each test sample.

Table 5. Compressive strength of the glass fiber reinforced concrete

S. No.	Weight (kg)	Strength (kN)	Compressive Strength (N/mm^2)	Splitting Tensile Strength (N/mm^2)	Flexural Strength (N/mm^2)
1	8.232	797	35.42	3.54	4.43
2	8.576	784	34.84	3.48	4.40
3	8.284	742	32.97	3.30	4.12
4	8.999	763	33.91	3.39	4.24
5	9.032	702	31.02	3.10	3.88
6	8.693	752	33.42	3.34	4.18
7	8.273	779	34.62	3.46	4.33
8	8.989	745	33.11	3.31	4.17
9	9.238	738	32.08	3.21	4.01
10	8.769	813	36.13	3.61	4.52
13	9.052	763	33.91	3.39	4.24
12	8.799	781	34.71	3.47	4.41
13	8.682	818	36.35	3.63	4.54
14	8.799	747	33.2	3.32	4.18
15	9.065	833	37.02	3.70	4.62
16	8.899	845	37.55	3.75	4.69
17	9.412	861	38.266	3.83	4.79
18	9.661	824	36.622	3.66	4.58

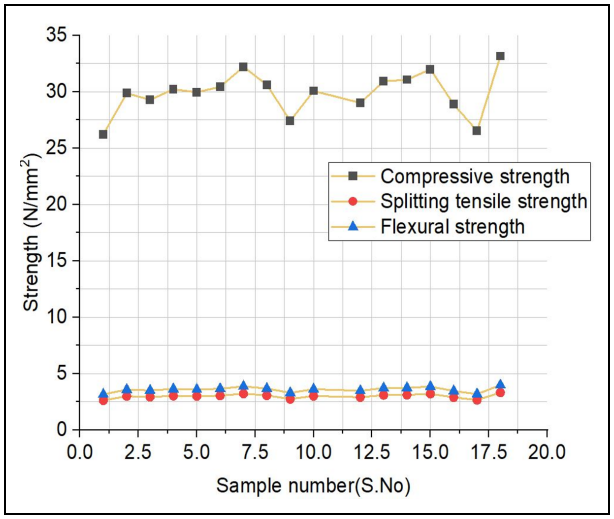


Fig. 5: Conventional concrete strength properties

The strength characteristics of the glass fiber reinforced concrete samples are shown in Table 5. With a range of 31.02 to 38.27 N/mm^2, the compressive strength is superior to that of traditional concrete. Better tensile resistance is indicated by splitting tensile strength, which ranges from 3.10 to 3.83 N/mm^2. The range of flexural strength, which emphasizes improved bending performance, is 3.88 to 4.79 N/mm^2. The measured weights and applied loads support the observed strength improvements owing to the introduction of glass fibers.

Fig. 5 displays a graph of typical concrete's strength characteristics. Compressive strength, represented by the yellow line with round markers, varies moderately among the 18 samples, ranging from about 26 to 33 N/mm^2. The orange line defines the splitting tensile strength, and it stays constant mainly between 2.6 and 3.3 N/mm^2. Flexural strength is shown by the pink line with square markers, which continuously ranges from 3.1 to 4.0 N/mm^2. As might be anticipated from traditional concrete, compressive strength is often much higher than the other two qualities; however, tensile and flexural strengths vary slightly between samples.

The strength characteristics of glass fiber reinforced concrete that was improved using nano-silica additions are depicted in Fig. 6. Due to the combined

effect of glass fibers and nano-reinforcement, the yellow line consistently exhibits compressive strength exceeding that of regular concrete, ranging from approximately 31 to 38 N/mm^2. Improved tensile performance is indicated by the orange line, which represents the splitting tensile strength, which ranges from 3.1 to 3.8 N/mm^2. Better bending resistance is indicated by the pink-marked flexural strength, which ranges from 3.9 to 4.8 N/mm^2. The graph shows that, in comparison to traditional concrete, nano-silica and glass fiber reinforcement greatly enhance all strength characteristics.

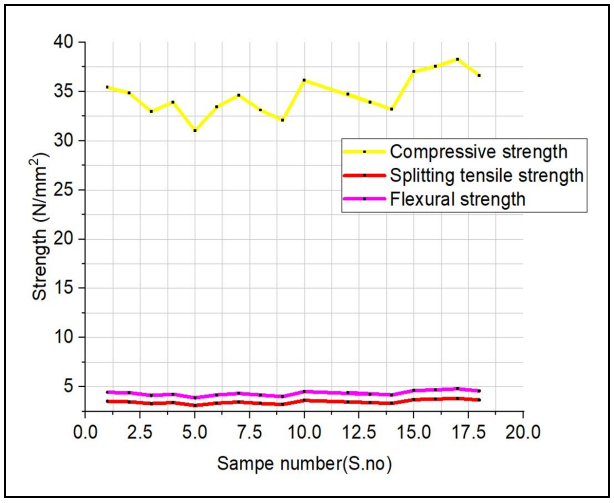


Fig. 6: Nano-silica reinforcement

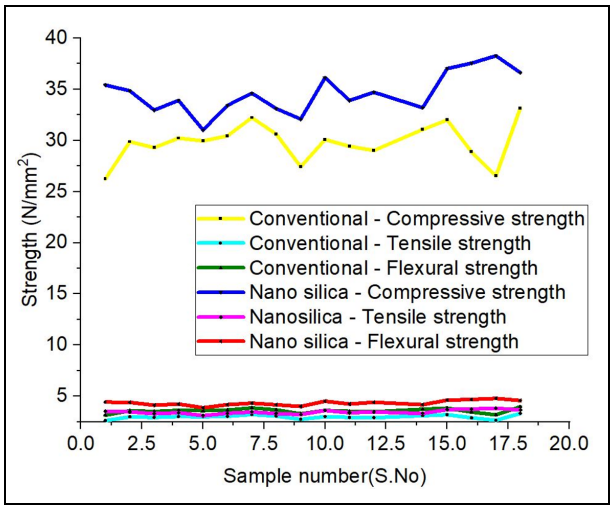


Fig. 7: Strength comparison of conventional and nano-silica reinforced concrete

The strength characteristics of regular concrete and glass fiber reinforced concrete boosted with nano-silica are contrasted in Fig. 7. The yellow, red, and pink lines show the compressive, tensile, and flexural strengths of conventional concrete. In contrast, the blue, cyan, and magenta lines represent those of nano-reinforced glass fiber concrete. The compressive strength of nano-reinforced concrete is consistently greater than that of conventional concrete (about 32–38 N/mm^2) (about 26–32 N/mm^2). Splitting tensile strength (cyan vs. red): While traditional concrete maintains a lower tensile strength of 2.6 to 3.3 N/mm^2, nano-reinforced concrete exhibits an enhanced tensile strength range from 3.1 to 3.8 N/mm^2. Flexural strength (pink vs. magenta): Nano-reinforced concrete has a much greater flexural strength (4.0 to 4.8 N/mm^2). Compared to conventional concrete's 3.1 to 4.0 N/mm^2.

Table 6(a). Compressive strength with and without fiber

	Group	N	Mean	Standard Deviation	Std Error Means
Compressive Strength	Without Fiber	18	29.8500	1.83342	0.43214
	With Fiber	18	34.7867	2.06834	0.48751

The compressive strength of concrete samples with and without glass fiber reinforcement is contrasted in Table 6(a). With a standard deviation of 1.83 and an average (mean) compressive strength of 29.85 N/mm^2 for the fiber-free group, there is slight variance across samples.

The accuracy of the average value is demonstrated by the standard error of the mean, which is 0.43. On the other hand, the fiber-reinforced group's mean compressive strength is greater at 34.79 N/mm^2, with a standard error of 0.49 and a somewhat larger standard deviation of 2.07. According to this research, the addition of fiber considerably raises the concrete's compressive strength.

Table 6(b). Splitting tensile strength with and without fiber

	Group	N	Mean	Standard Deviation	Std. Error Mean
Splitting Tensile Strength	Without Fiber	18	2.9811	0.18334	0.04322
	With Fiber	18	3.4784	0.20683	0.04875

Concrete's splitting tensile strength with and without glass fiber and nano-silica reinforcement is contrasted in Table 6(b). With an average tensile strength of 2.98 N/mm^2 and a standard deviation of 0.18, regular concrete (without fiber) performs consistently across samples. The precision of the mean is demonstrated by the standard error, which is 0.043. On the other hand, the mean tensile strength of 3.48 N/mm^2, with a standard deviation of 0.21 and a standard error of 0.049, is greater for the nano-reinforced fiber concrete. This demonstrates unequivocally how adding glass fiber and

nano-silica increases tensile strength and strengthens the concrete's ability to withstand cracking.

The flexural strength of concrete with and without glass fiber and nano-silica reinforcement is contrasted in Table 6(c). The average flexural strength in the conventional group (without fiber) is 3.58 N/mm^2, with a standard deviation of 0.22, indicating very slight sample variation. Reliable mean estimation is indicated by the standard error of 0.052. With a standard variation of 0.26 and a standard error of 0.061, the mean flexural strength of the fiber-reinforced nano-concrete rises to 4.36 N/mm^2. This illustrates how adding glass fiber and nano-silica greatly increases the flexural strength, strengthening the concrete's resistance to bending and cracking.

Table 6(c). Flexural strength with and without fiber

Flexural Strength	Group	N	Mean	Standard Deviation	Std. Error Mean
	Without Fiber	18	3.5822	0.22001	0.05186
	With Fiber	18	4.3622	0.25854	0.06094

Table 7(a). Independent samples T-test

Independent Samples T-test									
t-test for Equality of Means									
Compressive Strength	Levene's Test for Equality of Variances							95% Confidence Interval of the Difference	
	F	sig	t	df	Sig (2-tailes)	Mean difference	Std Error Difference	Lower	Upper
Equal variances assumed	0.698	.041	7.578	34	0	4.936	0.6514	6.26062	3.61272
Equal variances not assumed	-	-	7.578	33.51	0	4.936	0.6514	6.26132	3.61202

Table 7(b). Independent samples T-test – splitting tensile strength

Test	Levene's Test for Equality of Variances	t	df	Sig (2-tailed)	Mean Difference	Std Error Difference	95% Confidence Interval of the Difference
	F	Sig	-	-	-	-	Lower
Equal variances assumed	0.592	0.048	7.482	34	0.000	0.4973	0.0665
Equal variances not assumed	-	-	7.482	33.44	0.000	0.4973	0.0665

Concrete reinforced with glass fiber and nano-silica exhibits a significantly higher compressive strength than conventional concrete, according to the Independent Samples t-test. The statistical significance of the discrepancy is shown by the p-value of 0.000. With a 95% confidence interval between 3.61 and 6.26 N/mm^2, the average strength increase is 4.94 N/mm^2. This demonstrates how concrete's compressive strength is significantly increased by nano-reinforcement.

The independent samples t-test confirms that, in comparison to regular concrete, concrete reinforced with glass fiber and nano-silica has a noticeably higher splitting tensile strength. With a p-value of 0.000 and a mean of 0.4973 N/mm^2, the result is statistically significant. This demonstrates how effective nano-reinforcement is in increasing tensile strength because it makes the concrete more resistant to cracking.

The statistical analysis of the flexural strength of nano-reinforced concrete is done in Table 7(c). According to the Levene Test, there exists a major difference between the variances across the groups ($F = 0.683$, $p = 0.039$). The t-test ($t = -7.586$, $p = 0.000$) value shows that nano-silica and glass fiber reinforcement in flexural strength increased the flexural strength in the material (statistically meaningful outcome). The accuracy and reliability of the measurement is presented by the value of mean difference (0.78 N/mm^2) and a low standard error (0.1028). Besides, the 95 % confidence interval confirms the consistency of this improvement. This result holds even at each equality in variance and inequality in variance, and this adds value to the result.

Table 7(c). Independent samples t-test – flexural strength

Test	Levene's Test for Equality of Variances	t	df	Sig (2-tailed)	Mean Difference	Std Error Difference	95% Confidence Interval of the Difference
	F	Sig	-	-	-	-	Lower
Equal variances assumed	0.683	0.039	7.586	34	0.000	0.7800	0.1028
Equal variances not assumed			7.586	33.49	0.000	0.7800	0.102

4. DISCUSSION

The paper analysed the impact of glass fiber and nano-silica reinforcement on the mechanical behavior of SCC, mainly compressive, tensile, and flexural strength. The experimental results showed that a combination of nano-silica and high-dispersion glass fiber resulted in a significant improvement of the mechanical properties of SCC in comparison to traditional SCC.

The GFNSCC showed a more significant gain in compressive strength, averaging 16.5%, compared to reinforced SCC. This has been facilitated by the ultra-fine particle size of the nano-silica (20-40 nm), which facilitated even better particle packing and cement paste microstructure refinement. The nano-silica was also observed to have pozzolanic activity, where it reacted with the calcium hydroxide to produce extra calcium silicate hydrate (C-S-H), said to be the primary contributor to the strength of concrete. Such secondary C-S-H formation has not just created stronger compressive strength but has also led to better fiber bonding (increased load transmission and crack mitigation) to the cement matrix.

Compared with the tensile and flexural strength split, GFNSCC had 16.7 and 21.7 % enhancements, respectively. The synergistic effect of these nano-reinforcements and fiber dispersion leads to an increase in ductility and toughness of SCC. Glass fibers did an excellent job in sealing micro-cracks, whereas nano-silica made a dense, well-bonded matrix, thereby checking the spread of cracks when they experienced tensile and bending stresses.

t-Tests of independent samples based on statistical analysis proved that the difference in strength between the conventional SCC and GFNSCC was of high order ($p < 0.05$). Also, although there was a slight decrease in workability at increased content of the fibre (0.50%), incorporation of nano-silica mitigated it to some acceptable rheological characteristics, and was assisted by a 0.6 % dose of a high-range water-reducing admixture.

According to these results, nano-silica is essential for improving the mechanical properties and longevity of SCC, especially when combined with anti-crack glass fibers. The improved strength, reduced porosity, and enhanced fiber-matrix interaction position GFNSCC as a viable solution for high-performance concrete applications, especially in complex and heavily reinforced structures where conventional SCC may underperform in tensile or flexural aspects.

4.1 SEM Analysis

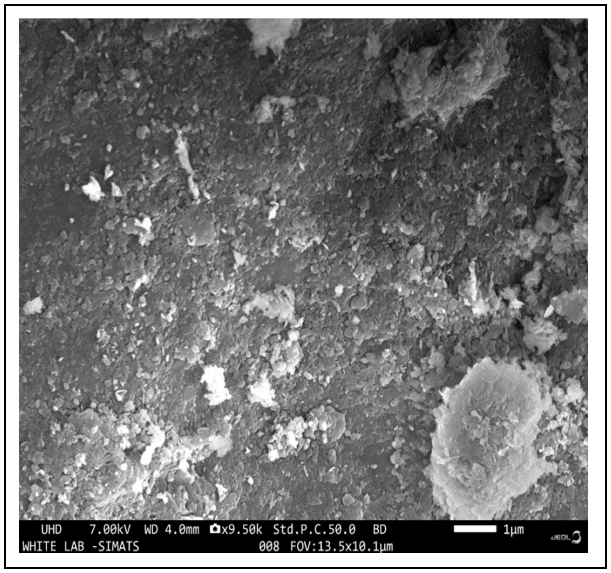


Fig. 8: SEM analysis of nano-silica reinforced glass fibre

The nano-silica reinforced glass fiber composite SEM image at 9500x magnification is seen in Fig. 8. Better interfacial bonding is facilitated by the surface's consistent distribution of nano-silica particles inside the matrix. The rough texture shows improved mechanical interaction between the fibers and matrix. In certain areas, agglomerated silica particles are visible, which might compromise homogeneity. All things considered, the microstructure points to improved load transmission and potential composite strength enhancement.

SEM analysis of GFNSCC reveals that nano-silica particles are uniformly dispersed throughout the cement matrix. These particles fill microvoids and pores, reducing overall porosity. The densification of the matrix enhances the interfacial transition zone between cement

paste and aggregates. Nano-silica also promotes additional C–S–H gel formation, contributing to stronger bonding within the matrix. The micrographs show that glass fibers are well embedded and act as bridges across microcracks. These fibers restrict crack propagation, enhancing tensile and flexural performance. The SEM images indicate improved adhesion between fibers and the cementitious matrix. The combined presence of nano-silica and fibers creates a more homogeneous and compact microstructure. Microcracks observed in conventional SCC are significantly minimized in GFNSCC. Voids around aggregates are reduced due to particle packing effects of nano-silica. Fiber alignment appears uniform, which aids in effective stress transfer under loading. The densified microstructure explains the observed increase in compressive strength. The SEM analysis also shows fewer void clusters compared to unreinforced SCC. The microstructural observations correlate directly with improved mechanical properties. Thus, SEM confirms that nano-silica densification and fiber bridging act synergistically to enhance the performance of GFNSCC as shown in Fig. 8.

4.2 FTIR Analysis

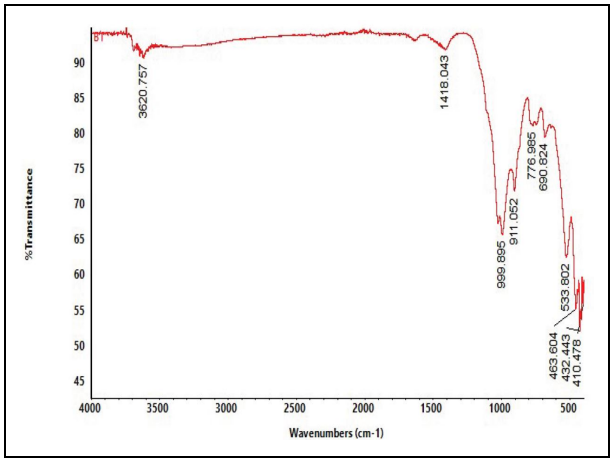


Fig. 9: FTIR analysis of nano-silica reinforced glass fibre

The FTIR spectra of the glass fiber composite reinforced with nano-silica is shown in Fig. 9. O-H stretching is represented by the wide peak at about 3420 cm^{-1}, which denotes moisture or hydroxyl groups. The C-H bending vibrations are responsible for the peak at 1410 cm^{-1}. The existence of silica is confirmed by strong peaks between 1100 cm^{-1} and 800 cm^{-1}, which reflect Si-O-Si asymmetric and symmetric stretching. Si-O bending is suggested by additional peaks below 700 cm^{-1}, which shows that micro silica was successfully included into the composite.

The FTIR analysis of GFNSCC shows characteristic peaks corresponding to Si–O and Al–O bonds, indicating the formation of additional silicate and aluminosilicate phases. The intensity of these peaks increases with nano-silica incorporation, confirming enhanced C–S–H gel development. Glass fiber addition does not alter the chemical structure significantly but supports matrix reinforcement through mechanical bridging. The combined effect of chemical densification and fiber reinforcement is reflected in the improved mechanical properties of the composite. The FTIR results corroborate the SEM findings and explain the observed enhancements in compressive, tensile, and flexural strengths.

5. CONCLUSION

This study clearly demonstrates that the synergistic incorporation of nano-silica and glass fibers markedly improves the mechanical strength, crack resistance, and durability of Self-Compacting Concrete, making it suitable for demanding structural applications. The combined addition of nano-silica and glass fibers increased compressive strength by 16.53% (29.85 N/mm^2 to 34.78 N/mm^2), tensile strength by 16.69% (2.98 N/mm^2 to 3.48 N/mm^2), and flexural strength by 21.75% (3.58 N/mm^2 to 4.36 N/mm^2), demonstrating significant mechanical enhancement. SEM analysis confirmed that nano-silica filled microvoids and promoted additional C–S–H gel formation, while glass fibers bridged microcracks, providing a denser and more cohesive matrix. FTIR results indicated intensified Si–O and Al–O bonding, supporting chemical densification that correlates with the observed strength improvements. Statistical validation using independent sample t-tests ($p < 0.05$) confirmed the significance of the observed mechanical gains. Workability was maintained despite the addition of 0.50% glass fibers, due to particle packing of nano-silica and optimized superplasticizer dosage. The GFNSCC exhibited reduced permeability and water absorption, indicating improved durability for harsh or complex environments. The hybrid reinforcement provides a synergistic effect, making GFNSCC a high-performance, sustainable, and durable material suitable for structural applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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