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The structural performance of fiber-reinforced concrete beams with nanosilica

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ABSTRACT

This study explores the enhanced performance of nano-silica-enriched concrete beams, with a focus on the effects of including steel fibers. A thorough examination was conducted on eighteen finely constructed beams, each three thousand millimeters long and with a 150 × 250 millimeter cross-section. This study's main goal was to evaluate how steel fibers affected these beams' mechanical characteristics. A number of static loading tests were used to carefully examine the specimens' structural strength. The overall effectiveness of the concrete beams was assessed by carefully using key parameters as indicators, such as the first crack load, yield load, yield load deflection, ultimate load deflection, deflection ductility, deflection ductility ratio, energy ductility, and energy ductility ratio. The findings of the extensive testing clearly show that adding steel fibers to concrete beams that contain nano silica improves their performance significantly. This enhancement was regularly seen in a number of important areas of structural behavior, proving without a shadow of a doubt the beneficial effect of steel fiber incorporation on the beams' mechanical characteristics.

Keywords: Cracking; Deflection; Ductility; Fibre reinforced concrete; Nano silica.

1. INTRODUCTION

Silica fume is created by the silicon and the ferrosilicon industries. Additionally identified as nano silica, volatilized silica, condensed SF, and silica dust. SF is a highly reactive chemically reactive substance because of its extreme refinement and high proportion of fragmented silicon dioxide in it [1]. The presence of SF in mortars affects the thickness of the transition phase and the degree of crystal orientation within it. SF removes the weak links by fortifying the cement paste-aggregate connection and creating an interfacial zone microstructure that is less porous and more homogeneous [2]. Physical characteristics and durability improve as a result of the improved bond or interfacial strength. The process is related to the interface's chemical synthesis of C-S-H (pozzolanic reaction) as well as the microstructure alteration (CH orientation, porosity, and transition zone thickness) [3].

Nano-silica (NS), characterized by its high silica purity, is manufactured through processes like sol-gel, vaporization, biological methods, or precipitation. Beyond its pozzolanic and filler actions, nano-silica plays a vital role in accelerating hydration kinetics due to its ultrafine nature. This multifaceted contribution underscores its significance in optimizing concrete performance and durability [4, 5]. The filler action of nano particles, such as silica fume, reinforces the bond between aggregates and the cement matrix, enhancing overall structural cohesion and durability in concrete application [6]. The effects of NS on cube strength and microstructure are considerable, but they also increase the need for high range water lowering admixture. First, the pozzolanic reaction of NS would occur, producing a reasonably high 7-day strength and a relatively high 28-day strength [7]. When compared to SF, NS has a higher pozzolanic activity and can produce a lot more early nucleation sites for hydration products. Therefore, adding NS could enhance the bond strength and compressive strengths of the cement paste-aggregate interface, particularly in the early stages, and it could significantly enhance the interface structure compared to SF. Because of this, cement-based goods' mechanical properties and durability can be significantly enhanced by adding a little amount of NS [8].

The incorporation of steel fibers into concrete enhances its impact strength, ductility, toughness, fatigue resistance, and post-crack resistance. This comprehensive improvement extends the applicability of concrete in demanding structural scenarios [9]. The utilization of silica fume, coupled with recycled steel fiber, not only enhances the mechanical characteristics of concrete but also significantly improves its impact resistance [10].

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This synergistic combination contributes to a more robust and durable material, extending its suitability for applications where both strength and resilience are vital [11]. The incorporation of nano silica and mineral fibers in fiber-cement composites accelerates the cement hydration process, resulting in substantial enhancements in both physical and mechanical properties. This synergistic combination contributes to improved durability and performance in various applications [12, 13]. This investigation was undertaken to assess the impact of introducing steel fibers on the mechanical and overall characteristics of concrete incorporating nano-silica. The study aims to provide insights into the synergistic effects of these components, contributing to a comprehensive understanding of their combined influence on concrete properties [14, 15].

The combined use of nano silica and fibers leads to a significant increase in the flexural strength and ductility of concrete beams. Nano silica enhances the matrix-fiber bond, while fibers provide the necessary reinforcement to bridge cracks and improve post-cracking behavior [16]. The integration of nano silica and fibers in RC beams has shown considerable potential in enhancing flexural performance [17]. Nano silica improves the microstructure and compressive strength of concrete, while fibers enhance its tensile strength and ductility [18], When used together, these materials create a synergistic effect that significantly improves the overall behavior of RC beams under flexural loads [19], The focus on optimizing mix designs and exploring the long-term durability of such composites in various environmental conditions [20].

2. EXPERIMENTAL PROGRAM

2.1. Materials

PPC cement, which is known for its superior quality manufacture, was obtained from Ultra Tech Cements and used in the development of the concrete compositions in this study. The major ingredient was cement, which had a specific gravity of 3.15. To guarantee even and ideal mixing, a precise water-to-binder ratio of 0.36 was carefully observed. The fine aggregate used was M-sand that was obtained locally and complied with IS 383:2016 requirements. Crushed granite that complied with IS 2386:2016 specifications and had a maximum particle size of 20 mm was used as the coarse aggregate. It was found that the fine and coarse aggregates had specific gravities of 2.67 and 2.72, respectively. Hooked end steel fibers from Stewols India (P) Ltd., Nagpur, were used into the reinforcement approach at different fiber volume fractions (0.5%, 1%, 1.5%, and 2%) that were investigated during the experiment. Because it replaced a large amount of the cement, nano-silica performed a crucial function. Table 1 lists all of the nano-silica's qualities in detail. In order to achieve the necessary levels of workability and strength, the concrete mix was supplemented with a superplasticizer, namely a sulphonated naphthalene-based superplasticizer in accordance with ASTM C494.

2.2. Mix proportion

The experimental configurations (M1 through M6) show various concrete mix compositions with differing amounts of steel fibers and nano silica (NS). M2 to M6 add additional fiber content (0%, 0.5%, 1.0%, 1.5%, and 2.0%, respectively) to a fixed NS ratio of 2.5%, with M1 acting as the control mix. This regular variation makes it possible to thoroughly investigate how steel fibers affect the characteristics of concrete that contains nano silica. Because of their reinforcing action, steel fibers are expected to improve structural properties including ductility and fracture resistance. The goal of the study is to determine the ideal fiber content that will enhance concrete's performance by maximizing its interaction with nano silica. By examining the outcomes of these mixes, it will be possible to get important knowledge about any potential benefits or drawbacks of including steel fibers and nano silica into concrete formulations. This knowledge will be useful in order to optimize mix designs for structural purposes. Table 2 lists the nomenclature for all test specimens. Table 3 lists the components of concrete mixtures.

The cement concentration in each mix stays at 412 kg, and different amounts of nano silica are added. Interestingly, steel fiber additions vary in amount from 0.5% to 2.0%. To provide a consistent comparison, these mixes keep the amounts of water, coarse aggregate (CA), and fine aggregate (FA) constant. The purpose of the

Table 1: Properties of nano silica.

PROPERTIES	REMARKS
Colour	White
Specific surface area	160 m^2/g
Specific gravity	1.1

Table 2: Nomenclature of test specimens.

M1	CONTROL MIX
M2	2.5% NS 0% Fibre
M3	2.5% NS 0.5% Fibre
M4	2.5% NS 1.0% Fibre
M5	2.5% NS 1.5% Fibre
M6	2.5% NS 2.0% Fibre

Table 3: Composition of concrete mixes.

MIX	DESCRIPTION	CEMENT (kgs.)	NANO SILICA (kgs.)	WATER (kgs.)	FA (kgs.)	CA (kgs.)	SP (lits)	FIBRE VOLUME %
M1	Conventional	412	0	160	642	1228	4.12	0
M2	2.5% NS + 0.5 Fibre	309	1.03	160	642	1228	4.12	0.5
M3	2.5% NS + 1.0 Fibre	309	1.03	160	642	1228	4.12	1.0
M4	2.5% NS + 1.5 Fibre	309	1.03	160	642	1228	4.12	1.5
M5	2.5% NS + 2.0 Fibre	309	1.03	160	642	1228	4.12	2.0

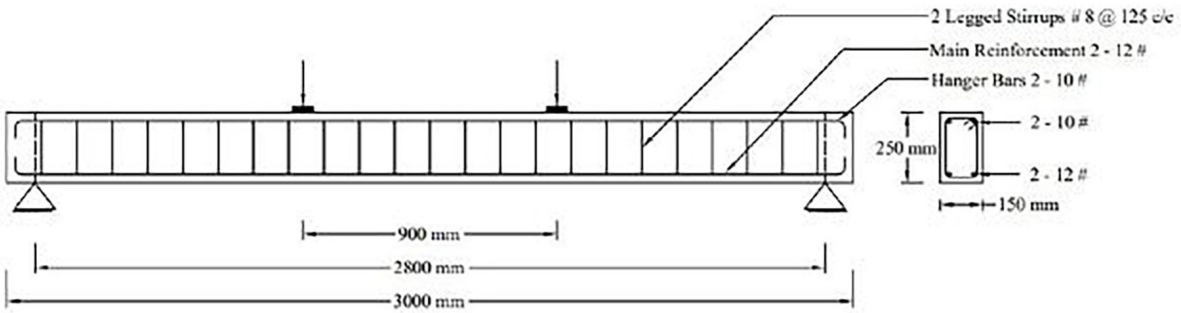

Figure 1: Reinforcement detailing of test beams.

formulations is to investigate how steel fibers and nano silica work together to improve the qualities of concrete. Precise changes in the amount of fiber enable a thorough examination of the ways in which these elements as a whole affect the mix's performance, providing important information for improving concrete mixtures for use in structural applications.

2.3. Details of test beams

In this research, a comprehensive study was conducted on a total of 18 beams, each measuring 3000 mm in length and featuring a cross-sectional dimension of 150 mm × 250 mm. The structural reinforcement strategy employed for these beams involved the strategic placement of two 12 mm diameter bars at the bottom, complemented by two 10 mm diameter bars at the top. Furthermore, two-legged stirrups, each with an 8 mm diameter, were strategically positioned at intervals of 125 mm to enhance the structural integrity of the beams. The reinforcing details of these beam specimens are visually represented in Figure 1, providing a clear and detailed illustration of the configuration employed to fortify the beams for testing and subsequent analysis.

2.4. Test instrumentation and loading

In a robust 500 kN loading frame, an extensive testing regimen was carried out on 18 beams subjected to four-point bending. The beams were strategically supported, with one end featuring a hinge and the other end supported by a roller, as illustrated in Figure 2. The test span was set at 2800 mm, accounting for 100 mm bearings

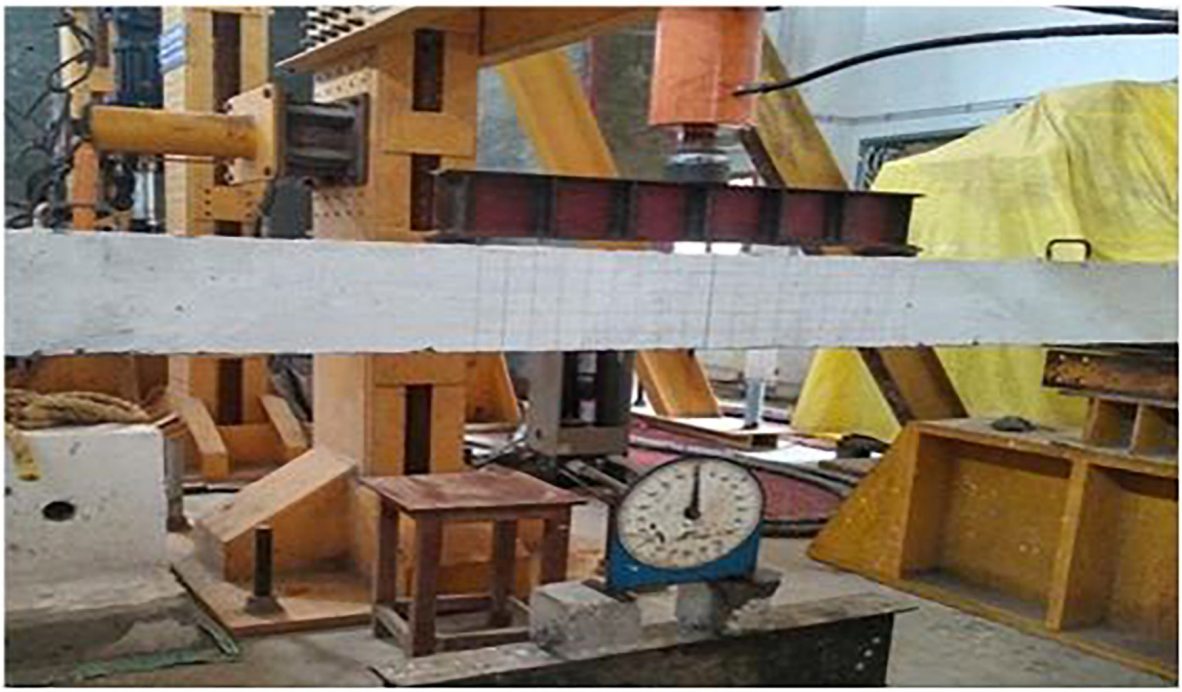

Figure 2: Test setup.

at both ends of the beams. Spreader beams facilitated the application of two-point loads, ensuring a controlled testing environment. To assess the beams' performance, mid-span and load point deflections were meticulously measured using mechanical dial gauges with a precision of 0.01 mm. Additionally, crack width was determined using a crack detection microscope with a minimum count of 0.02 mm. The testing protocol included continuous monitoring of crack initiation, progression, and overall structural response. All measurements, encompassing deflections and crack widths, were tracked until failure occurred at various loads, providing a comprehensive understanding of the beams' behavior under different loading conditions.

3. TEST RESULTS AND DISCUSSION

Using Figures 3 to 9, the results of an experimental investigation on 18 beams-including the control beam (M1) and beams built of steel fibre reinforced concrete and nano silica-are shown.

3.1. Effect on strength and deflection

The results of the experimental investigation, reveal notable variations in the mechanical performance of concrete mixes with varying steel fiber content. The First Crack Load (FCL), Yield Load (YL), and Ultimate Load (UL) are crucial indicators of the beams' structural behavior under loading conditions. Observing the progression from M1 to M6, a consistent trend of increasing load-bearing capacities is evident. M1, the control mix without steel fibers, exhibits a First Crack Load of 23.04 kN, Yield Load of 45.38 kN, and Ultimate Load of 66.23 kN. As steel fiber content increments in M2 to M6, there is a noticeable enhancement in load-carrying capabilities. M6, with the highest fiber content at 2.0%, demonstrates a substantial improvement, achieving a First Crack Load of 41.73 kN, Yield Load of 83.01 kN, and Ultimate Load of 108.11 kN. This progressive increase in load-carrying capacity indicates the positive influence of steel fibers on the structural strength of the concrete beams. The addition of steel fibers enhances the beams' resistance to cracking and increases their capacity to sustain higher loads, affirming the effectiveness of fiber reinforcement in improving the mechanical characteristics of the concrete. The findings for load and deformation were displayed in Figures 3 and 4, respectively.

3.2. Load deflection relationship

Concrete beams with different steel fiber contents (M1 to M6) exhibit progressive behavior, as seen by the load-displacement data shown in the table. The associated displacement numbers show how the beams' structural reaction changes as the load does. First, the elastic deformation zone is indicated by the minimum displacement measured across all mixtures up to a load of 15 kN. There is a noticeable divergence after this. M6, which has the

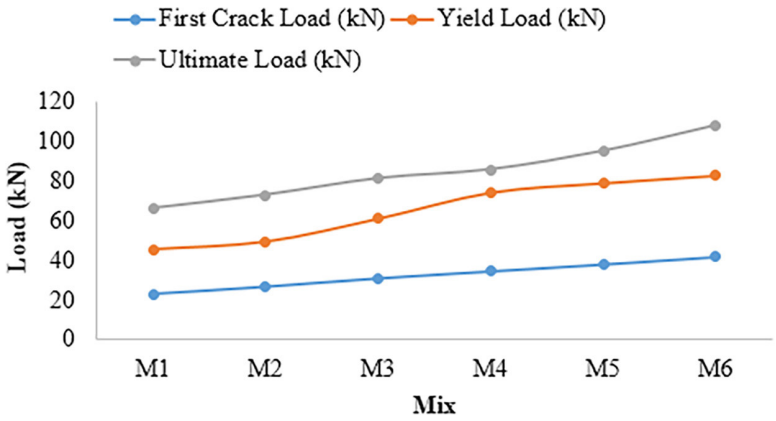

Figure 3: Effect on strength.

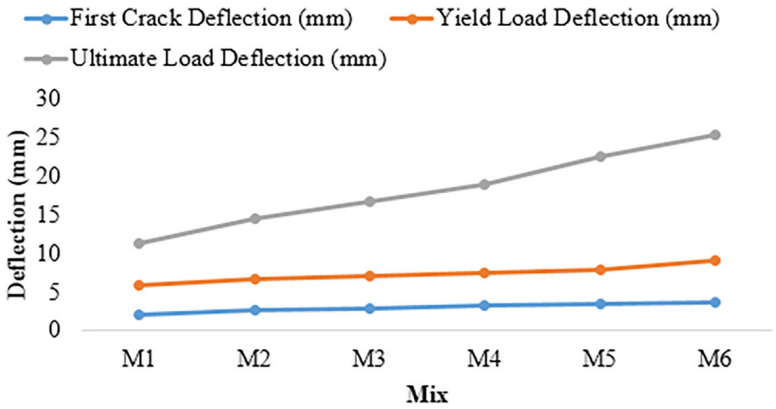

Figure 4: Effect on deflection.

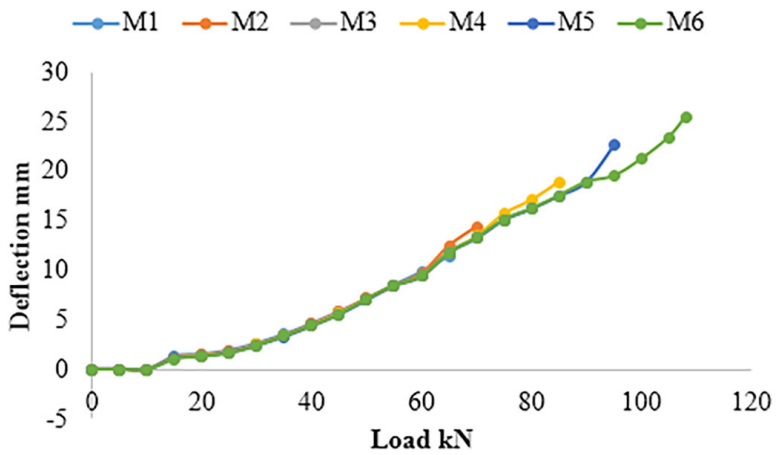

Figure 5: Load vs deflection plot.

greatest fiber concentration (2.0%), shows improved ductility through higher displacement. This is increasingly noticeable when the load increases, as seen by the significant deflection at the maximum load of 108.11 kN. The competitive performance of M3 and M4 suggests the ideal fiber content for balanced characteristics. The gradual emergence of notable deflection in M1 indicates restricted ductility in the absence of steel fibers. The behavior that has been seen is consistent with the predicted effect that steel fibers have on improving ductility and deformability. This effect is especially noticeable in M6, which highlights the beneficial effect that

fiber reinforcement has on the overall structural response of the concrete beams. Figure 5 displays the load-deflection response curves of each beam specimen evaluated during this inquiry.

3.3. Cracking history and failure modes

A thorough examination of the fracture characteristics for concrete mixes (M1 to M6) under different loading scenarios is provided by the data shown in Figure 6. The maximum number of cracks, average crack spacing, and maximum crack width are among the characteristics. When the maximum fracture width is analyzed, a trend from M1 to M6 is consistently seen, and as the steel fiber content rises, a significant decrease is noted.

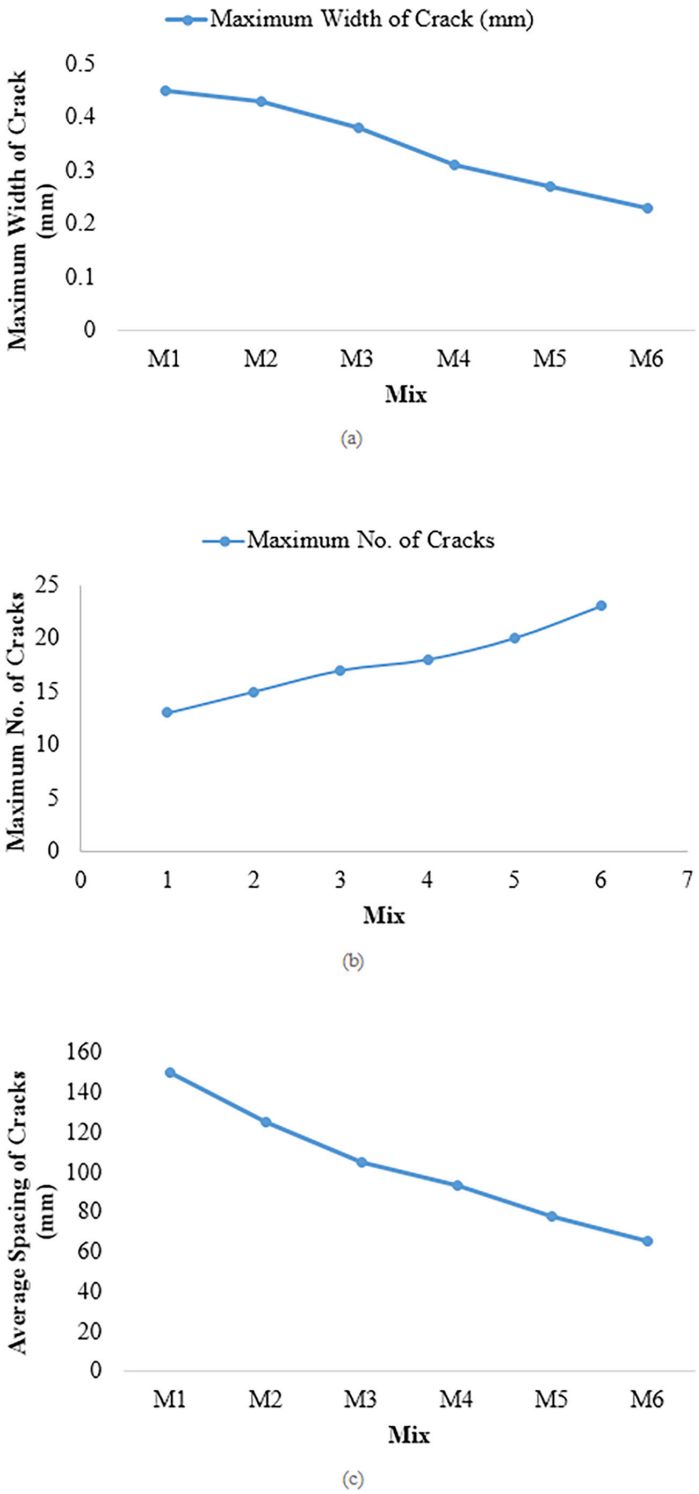

Figure 6: (a) Crack width, (b) number of cracks, (c) spacing of cracks.

Figure 7: Crack patterns of tested beams.

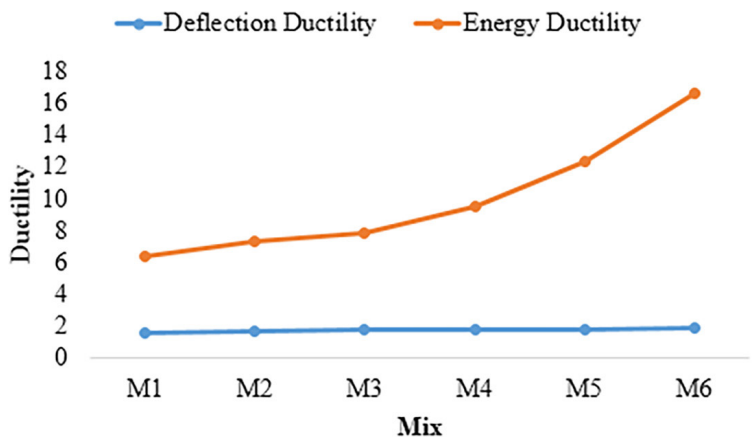

Figure 8: Effect on beam ductility.

M6, which has the biggest fiber content (2.0%), shows the greatest improvement (maximum fracture width of 0.23 mm). Concurrently, as the fiber content increases, there is a trend toward an increase in the maximum number of cracks. This demonstrates how steel fibers may disperse and regulate cracking to avoid the development of a single, dominating crack. As the steel fiber percentage rises, the average fracture spacing falls, showing a more closely spaced crack pattern in blends with greater fiber concentration. At 65 mm, the M6 sample with the greatest fiber concentration had the shortest average fracture spacing. Together, these results highlight the beneficial role that steel fibers play in reducing fracture widths, managing the distribution of cracks, and enhancing the overall pattern of cracks, all of which improve the performance and longevity of concrete structures.

Figure 7 displays the crack pattern of the beam specimen evaluated for this inquiry. In the constant moment zone, hairline fractures were seen during the initial loading stages. Along the loaded span, new cracks developed as the load increased, and those that already existed grew larger as well.

3.4. Ductility index

Prior to failure, a beam's ductility refers to its capability to withstand inelastic deformation without losing any of its load-bearing capacity. Deformation or energy can be used to show ductility. Figure 8 displays the ductility indices of all the beam specimens evaluated in this inquiry. The results shown in Figure 8 suggest that fibre insertion has a discernible impact on the beam ductility's. With a rise in fibre volume percentage, the ductility rose. The beam M5 demonstrated a maximum improvement over the control beam M1 of 30.06% in deflection ductility and 88.73% in energy ductility. The microfibers' increased robustness and the strengthened bonds at the matrix-fiber interface would have improved the beam ductility's.

3.5. Sulphate attack test

The sulphate attack of concrete with nano silica and steel fibre reinforced concrete after the attack was found to be less weight loss when compared to the normal concrete. The variation of test results are shown in Figure 9. Sulphate acid attack causes extensive formation of concrete in the region close to the surface. The regions close to the surface tends to cause disinserting mechanical stresses leading to spalling and lesser exposer of the concrete surface in the concrete prevent spalling. Due to the cohesiveness of the cement hydration products, there is a less loss in mass and strength. The percentage of relative linear expansion can be reduced by adding nano silica and

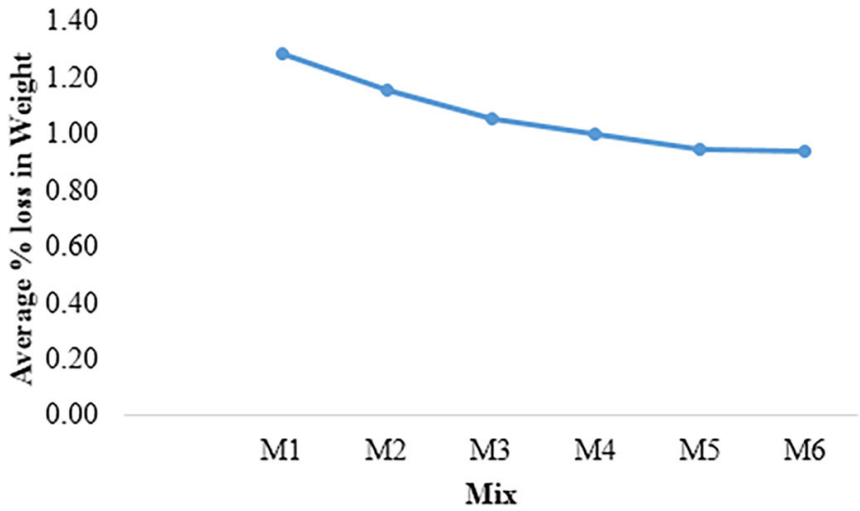

Figure 9: Variation of percentage gain of weight due to sulphate attack.

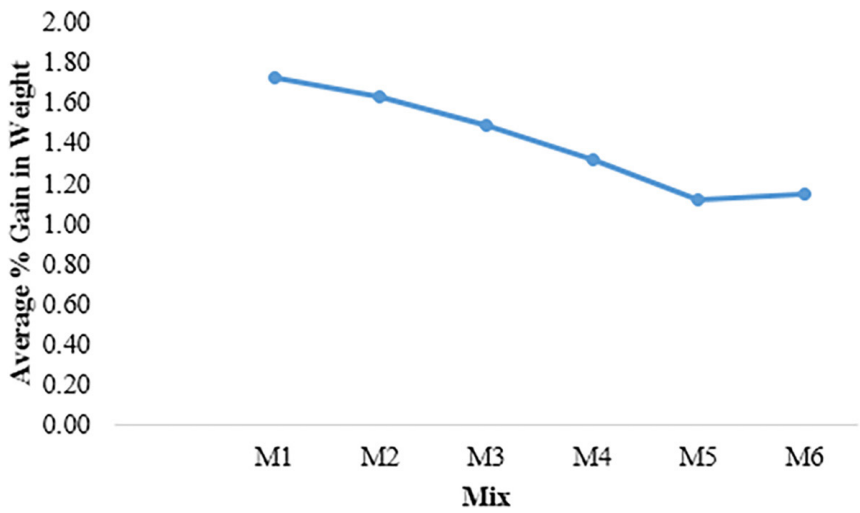

Figure 10: Variation of percentage gain of weight due to chloride attack.

steel fibre. Concrete with low permeability is the best protection against sulphate attack. This can be achieved using nano silica and steel fibre. By preventing sulphate attack, the effect of expansive forces generating tensile stresses in concrete is reduced. Deterioration of cement parts by the formation of gypsum reduces pH of the system and loss in the stiffness and strength. This results to expansion, cracking and transformation of non-cohesive mass. The cohesiveness can be maintained by the addition of nano particles.

3.6. Chloride attack test

The chloride attack of nano silica fibre reinforced concrete after the attack was found to be of less weight gain when compared to the normal concrete. The variations of test results are shown in Figure 10. In this research, chloride attack is one of the main important aspects while dealing with durability of concrete. In the six mixes M1 to M6 the statistics have indicated that over 10% of failure of structures is due to corrosion of concrete. The presence of chlorides increases shrinkage cracks in concrete and activates the corrosion of reinforcement in an aggressive environment. The addition of nano silica and fibre reinforced concrete reduces porosity and permeability thereby reducing the rate of penetration of chloride ions. The closer of voids reduces the penetration and increases the durability of concrete. The maximum permissible chloride content of concrete mixture is also specified in ACI Building Code 318. A very low chloride permeability can be achieved by using the nano and fibre materials.

3.7. Effect on acid resistance

Figure 11 presents data that illustrates the effects of different fiber volume fraction and nano silica concentration on concrete mixes (M1 to M6) in terms of mass loss and strength loss percentages. M1, the control mix, shows a 3.16% strength loss and a 0.56% mass loss with no additional steel fibers or nano silica added. A modest decrease in mass loss (0.52%) and strength loss (2.86%) is seen when 2.5% nano silica is added to M2. There is a decreasing tendency in mass loss and strength as the fiber volume percentage rises in M3 to M6. M6 exhibits a 0.36% mass loss and a 2.42% strength loss, indicating an increase in performance, with a 2.5% nano silica content and a 2% fiber volume fraction. The findings indicate that the incorporation of steel fibers and nano silica resulted in a decrease in mass loss and strength, signifying enhanced resilience and endurance. The ideal mix, shown in M6, demonstrates the possible benefits of steel fibers and nano silica working together to improve the overall durability and performance of the concrete mix.

3.8. Corrosion studies

The potential measurements (mV) for concrete mixes (M1 to M6) at various exposure times (0 hours, 10 hours, and 20 hours) in a corrosion monitoring scenario are shown in Figure 12. For all combinations, there is a discernible drop in potential readings across the exposure times, suggesting a possible move towards more negative values. Potential data for M1, the control mix, are 125 mV at 0 hours and 295 mV at 20 hours. M2 to M6 show similar tendencies, with possible readings declining with time. When the mixtures are compared, M6 consistently shows the lowest potential readings, pointing to a more pronounced shift towards the negative and possibly a larger danger of corrosion. M1, on the other hand, often maintains greater potential values, indicating a comparatively lesser danger. These possible measurements offer important information about the concrete mixtures' long-term vulnerability to corrosion. The declining patterns in potential readings emphasize the

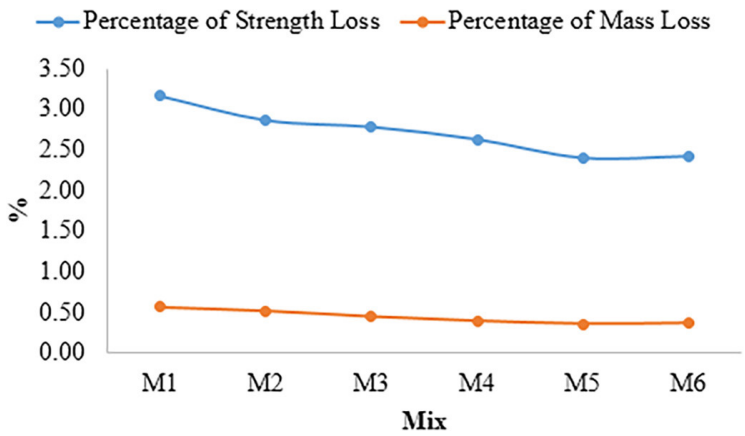

Figure 11: Effect of steel fibres on strength loss (acid resistance).

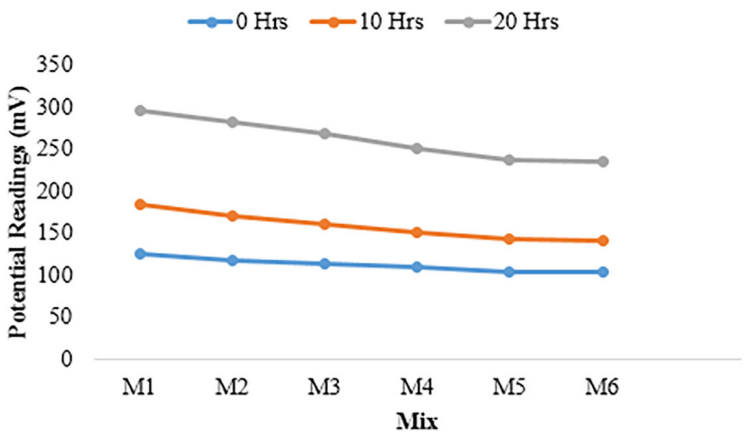

Figure 12: Result of half – cell potential.

significance of continuous monitoring to evaluate the concrete structures' long-term resilience to corrosion, with M6 perhaps needing further corrosion prevention measures. Table 4 shows the results of corrosion outcomes.

3.9. Microstructural characteristics of concrete

Three varieties of concrete are examined in this study: typical concrete, concrete with NS, and concrete with NS and steel fiber. The study also examines the chemical makeup of each type of concrete. The inquiry makes use of a scanning electron microscope (SEM), a device that uses a focussed electron beam to scan it in order to produce sample pictures. Different signals are generated as the electrons contact with the atoms in the sample, providing information about the structure of the material and surface topography. This method makes it possible to thoroughly compare the three concrete variations by allowing for an in-depth analysis of the interior composition and structure. Using SEM makes it possible to analyze in detail how the addition of steel and nano silica fibers affects the microstructure and composition of the concrete, offering important insights into the material's overall performance as well as possible areas for improvement with regard to structural characteristics and durability.

Table 4: Result of corrosion outcomes as per ASTMC 876 code of practice.

SI. NO.	HALF-CELL POTENTIAL MV	% CHANGE IN CORROSION
1	<200	10%
2	200 to 350	50%
3	>350	90%

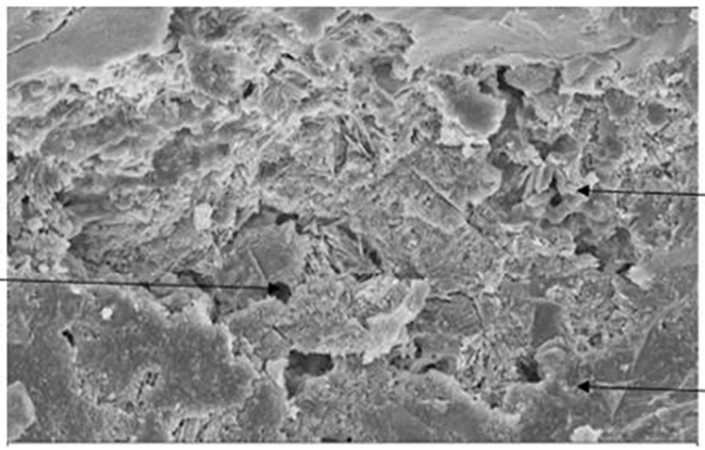

Figure 13: Microstructure of conventional concrete.

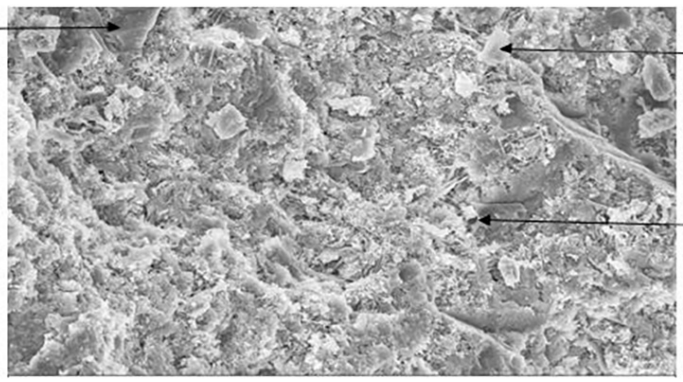

Figure 14: Microstructure of M5 mix.

The SEM analysis for conventional concrete is shown in Figure 13. The figures indicate the presence of large size of pores with unshattered hydration products. The presence of non-reactivity silica results for the improper hydration of products, where it may lead to the deterioration of the concrete in the subsequent period.

The Figure 14 indicate the concrete sample (M5) made with 2.5% Nano silica and 1% fibre. The outcome from the sample shows the presence of hydrated product along with the minute content of pores, where the presence of pores is found to be quite lesser than the conventional mix. This can be rectified in the subsequent reaction of calcium and silica products with the hydrogen molecules.

4. CONCLUSIONS

The findings of the trials are used to make the conclusions that are listed below.

- Adding steel fibres can substantially boost the load capacity. The ultimate load capacity of the beam M5 (with 2.5% NS and 2% fibre volume fraction) increased by a maximum of 48.23%.
- The deflections in the fiber-included beams were dramatically decreased at all load levels. With the beam M5, a maximum of 74.59% has been observed.
- Compared to the control beams, the steel fibre reinforced ternary mixed concrete beams had ductility indices up to 30.06% in deflection ductility and 88.73% in energy ductility.
- The steel fiber-reinforced ternary mixed concrete beams broke in flexure. The breadth and spacing of the fractures are considerably smaller than the control beams.
- By using nano silica (2.5%) and increasing the volume percentage of steel fibres up to 1.5%, acid resistance have been improved by 24.02%.
- Compared to the control mix, the steel fibre reinforced ternary mixed concrete had excellent resistance to sulphate attack with 2.5% nano silica and 1.5% steel fibre.
- The chloride attack of nano silica fibre reinforced concrete after the attack was found to be of less weight gain when compared to the normal concrete. A very low chloride permeability can be achieved by using the 2.5% nano silica and steel fibre materials.
- In acid resistance results compared to the reference mix, the percentage weight loss of all the combinations was much lower containing 2.5% NS and 1.5% fibre.

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