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Research Article

Experimental investigation on the mechanical properties of concrete with steel fibers and colloidal nano-silica

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Abstract

Concrete is a commonly used construction material, although it possesses brittle behavior and low tensile resistance. This research evaluates how adding steel fibers and colloidal nano-silica influences the strength characteristics of M30 grade concrete. Concrete specimens were prepared using steel fibers ranging from 0.5% to 2.0% by cement volume along with a constant 2.5% colloidal nano-silica content by cement weight and compared with a control mix. All specimens were cast, cured, and tested in accordance with relevant Indian Standard provisions. Compressive, splitting tensile, and flexural strength tests were performed at 7 and 28 days. The results highlight that use of nano-silica alone increase the 28-day compressive strength by 15% and the splitting tensile strength by 45% compared with the control mix. Adding steel fibers further improved tensile and flexural strength, with a smaller rise in compressive strength. The concrete mix with 2.0% steel fibers and 2.5% colloidal nano-silica exhibited the best overall performance, showing 20% higher compressive strength, 54% higher tensile strength, and 25% higher flexural strength.

1. Introduction

In construction, concrete is widely used because of its versatility, strength, and economic advantages. Despite its advantages, conventional concrete exhibits brittle behavior with limited tensile and flexural strength. These drawbacks limit its use in structural applications demanding high ductility, impact resistance, or enhanced durability [1]. The incorporation of nanomaterials into cementitious composites has created new possibilities for improving concrete microstructure. Colloidal nano-silica (CNS) is a highly reactive silica source that can be added as a liquid suspension, thereby avoiding the agglomeration problems associated with dry nano-silica powders [2]. CNS functions both as a filler material that refines pore distribution and as a pozzolanic material that consumes calcium hydroxide in order to generate a supplementary calcium-silicate-hydrate (C-S-H) gel [2, 3]. Several studies have reported that a modest replacement of cement by 2 to 4 % CNS yields significant mechanical benefits relative to a control mix [2 -6]. Studies also show that CNS generally enhance mechanical properties, although a high concentration of CNS can negatively impact workability and strength due to agglomeration [5-8]. NS also accelerates early-age strength development, with notable gains within the first 3-7 days of curing [5,9,10]. The densification effect of CNS also improves durability parameters; for instance, M20-M40 concretes with 40 % nano-solid CNS showed a 5.36 % reduction in water absorption and a 49.5 % decrease in chloride permeability [11].

Steel fibers (SF) are discontinuous steel reinforcements with high aspect ratios distributed randomly within the concrete matrix. Their primary contribution is to control and bridge crack propagation, thereby increasing post-cracking tensile capacity, flexural toughness, and impact

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resistance [12]. Experimental programmes on SFRC have demonstrated that fiber volume fractions between 0.5 % and 2.0 % (by cement volume) significantly raise compressive, flexural and split-tensile strength [13, 14]. Layered concrete specimens in which steel-fiber-reinforced zones are placed at the bottom and top layers recorded even larger gains 19 % higher compressive, 101 % higher split-tensile, and 127 % higher flexural strengths illustrating the benefit of strategic fiber placement [13]. The presence of SF also improves the post-peak ductility of high-strength and ultra-high-performance concretes, as reported in several reviews and experimental studies [12, 15].

The combined incorporation of CNS and SF produces complementary effects within the concrete matrix. CNS improves the interfacial transition zone (ITZ) by producing additional C-S-H gel, which enhances the bonding between the steel fibers and the cement matrix [16, 17]. Investigations on high-performance concrete (HPC) that contain both silica fume (as a supplementary cementitious material) and steel fibers have reported synergistic improvements in compressive strength and flexural toughness, especially at 1 %-1.5 % fiber volume and 15 % silica-fume replacement [18]. In recycled-aggregate concretes, the simultaneous use of SF (1 %) and silica fume (8 %) markedly increased compressive strength, stiffness, and post-peak ductility, confirming that nanomaterials can compensate for the weaker matrix of recycled aggregates [19]. Moreover, CNS-modified geopolymer mortars (volcanic-ash-based) with 2 % CNS achieved up to an 11 % compressive strength gain and superior high-temperature resistance, underscoring the relevance of nano-silica in alternative binders [20].

Although the individual benefits of CNS and SF are well documented, relatively few investigations have examined simultaneous incorporation of a fixed CNS dosage (2.5 % by cement weight) with varying steel-fiber volume fractions (0.5 %–2.0 %). Existing work either varies CNS content while keeping fiber content constant, or explores fiber content without nano-silica, making it difficult to identify the optimal fiber proportion when the nano-silica dosage is held fixed.

The present investigation evaluates the effect of steel fibers and colloidal nano-silica on M30 grade concrete. The objective is to evaluate how different fiber contents with a fixed nano-silica dosage influence compressive, tensile, and flexural strengths. The findings aim to identify an optimal combination that enhances strength and ductility for use in structural applications.

2. Experimental Work

2.1 Materials

2.1.1 Cement

OPC 43 grade cement conforming to IS 8112:1989 was utilized entirely for the investigation. The cement used in the study was fresh, consistently colored, and free from any lumps or foreign impurities. The properties of the cement were evaluated in accordance with IS 8112:1989, the obtained results are presented in Table 1.

Table 1. Characteristics of cement

Parameters	Characteristics
Specific gravity	3.15
Fineness (%)	2
Normal consistency (%)	32
Initial setting time (minutes)	144
Final setting time (minutes)	280

2.1.2 Fine Aggregate

Locally obtained river sand that passes through a 4.75 mm sieve under Zone II as per IS 383:1970 was used as fine aggregate. The sand was clean, free from organic contaminants, and properly washed and dried prior to use. The physical characteristics of the utilized fine aggregate are listed in Table 2.

Table 2. Characteristics of fine aggregate

Parameters	Characteristics
Sand classification	conforming to Zone II grading requirements as specified in IS 383:1970
Fineness modulus	2.74
Specific gravity	2.62

2.1.3 Coarse Aggregate

Crushed coarse aggregates of 10 mm and 20 mm nominal sizes were adopted in the study. The physical characteristics of the coarse aggregates are listed in Table 3.

Table 3. Characteristics of coarse aggregate

Parameters	Characteristics
Shape	Angular
Surface texture	Rough
Specific gravity	2.81 for 20 mm, 2.78 for 10 mm
Fineness modulus of combined aggregate	7.30

2.1.4 Water

Potable water free from impurities was used for mixing of concrete and for curing operations.

2.1.5 Superplasticizer

CONPLAST SP-430 A2 manufactured by FOSROC Chemicals was used as the superplasticizer in order to reduce water and achieve the desired workability. It is a Sulphonated Naphthalene Formaldehyde-based brown liquid that disperses easily in water. Table 4 presents the characteristics of the superplasticizer.

Table 4. Characteristics of CONPLAST SP-430 A2

Parameters	Characteristics
Chloride content	Nil as per IS 456 and BS:5075
Specific gravity	1.18 to 1.24 at 25°C
Air entrainment	1%

2.1.6 Steel Fiber

Rounded crimped steel fibers that have a length of 30 mm with diameter 0.5 mm, and aspect ratio of 60 were incorporated in the study, as illustrated in Figure 1. These fibers are widely adopted in civil engineering applications as they have ability to enhance both fresh and hardened concrete properties.

Fig. 1. Rounded crimpled steel fiber

2.1.7 Colloidal Nano-silica

A stable dispersion of extremely fine silica particles in a liquid medium having range of 50-100 nanometers with the pH value of 10.2 and specific gravity 1.209 g/ml was adopted.

2.2 Mix Proportioning

M30 grade concrete was selected for the study since this is a most commonly used concrete mix. According to IS 10262:2009 and IS 456:2000 provisions, the mix design for M30 concrete was carried out for normal concrete having water-cement ratio of 0.42. Mix design along with mix calculations are presented in Table 5.

Table 5. Mix proportions

Concrete grade	Mix proportion			
	Cement	Fine aggregates	Coarse aggregates	w/c
M30	1.0	1.75	3.05	0.42

2.2.1 Rationale for Selection of Mix Proportions

The concrete mix proportions were selected to systematically evaluate the individual and combined effects of colloidal nano-silica (CNS) and steel fibers on the mechanical performance of M30 concrete. The reference concrete was designed as M30 grade concrete with a water-to-cement ratio of 0.42, following the provisions of IS 10262:2009 and IS 456:2000. The resulting control mixture had a cement-to-fine aggregate-to-coarse aggregate proportion of 1:1.75:3.05. This mix was retained as the reference mixture against which all modified concrete mixtures were evaluated.

Table 6. Mixture nomenclatures

S.N.	Mixture Details	Designation
1	concrete with normal aggregate	CC
2	concrete with 2.5% cement replaced with colloidal nano silica	CCNS2.5
3	concrete with 2.5% cement replaced with colloidal nano silica and 0.5% of steel fibers	CCNS2.5SF0.5
4	concrete with 2.5% cement replaced with colloidal nano silica and 1.0% of steel fibers	CCNS2.5SF1.0
5	concrete with 2.5% cement replaced with colloidal nano silica and 1.5% of steel fibers	CCNS2.5SF1.5
6	concrete with 2.5% cement replaced with colloidal nano silica and 2.0% of steel fibers	CCNS2.5SF2.0

The CNS dosage was fixed at 2.5% by weight of cement. This dosage was selected based on the reported effective range of approximately 2% to 4% for nano-silica-modified concrete, within which improvements in mechanical properties have been reported. [2-6] At higher nano-silica contents, particle agglomeration and increased water demand may adversely affect workability and strength development. [5-8] Therefore, 2.5% was selected as a moderate dosage within the reported effective range, while keeping the CNS content constant throughout the experimental program. This approach allowed the effect of steel-fiber dosage to be evaluated without introducing an additional variable associated with changes in CNS content. Previous studies have also reported that CNS improves the cementitious matrix through filler and pozzolanic effects, while excessive nano-silica content may reduce workability because of particle agglomeration [2,3,5,9].

The steel-fiber dosage was selected as the primary experimental variable. Four fiber volume fractions, namely 0.5%, 1.0%, 1.5%, and 2.0%, were adopted. This range was selected based on previous experimental investigations reporting measurable improvements in the mechanical performance of steel-fiber-reinforced concrete within this range [13,14]. The selected range also enabled the response of the concrete to be evaluated progressively from a relatively low fiber content to a higher fiber content.

The experimental matrix therefore consisted of one control mixture, one mixture containing 2.5% CNS without steel fibers, and four hybrid mixtures containing 2.5% CNS with 0.5%, 1.0%, 1.5%, and 2.0% steel fibers. This arrangement was selected to establish three levels of comparison: the effect of CNS relative to conventional concrete, the incremental effect of increasing steel-fiber content at a constant CNS dosage, and the final performance of the combined CNS-steel-fiber system. The resulting six mixtures were designated as CC, CCNS2.5, CCNS2.5SF0.5, CCNS2.5SF1.0, CCNS2.5SF1.5, and CCNS2.5SF2.0 and presented in Table 6.

2.3 Preparation of Test Specimens

Specimens were cast using standard molds, which included cubes of 150×150×150 mm, cylinders of 150 mm diameter and 300 mm height, and prisms of 100×100×500 mm. Altogether six concrete mixes were produced, that includes a control mix and mixes containing steel fibers and nano-silica. The prepared specimens were demolded after 24 hours and subjected to water for curing. In total, 108 specimens were prepared to evaluate their mechanical properties.

All compression tests and split-tensile tests were carried out using a 300T compression testing machine. as in Figure 2 and 3 respectively. Flexural strength tests were carried out on 100T universal testing machine (UTM), as shown in Figure 4.

Fig. 2. Compressive strength testing carried out using 300T CTM

Fig. 3. Split tensile strength testing carried out using a 300T CTM

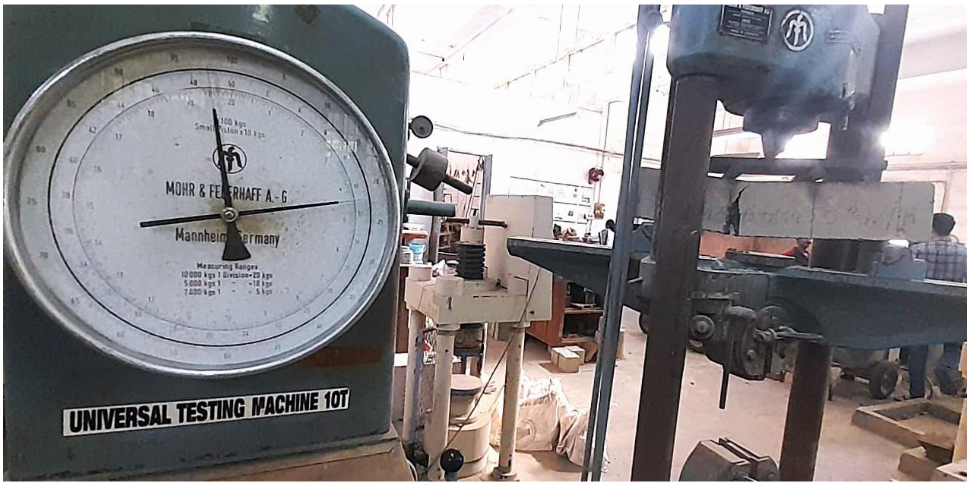

Fig. 4. Flexural strength testing carried out using 100T UTM

3. Results and Discussion

3.1 Workability

The slump test was used to examine the workability of each mixture of concrete prepared. All fresh concrete mixes containing steel fibers and colloidal nano-silica showed a uniform and consistent appearance. Figure 5 shows that with the increase in steel fiber content up to 2.0% with 2.5% colloidal nano-silica, the slump value reduced from 85 mm to 45 mm.

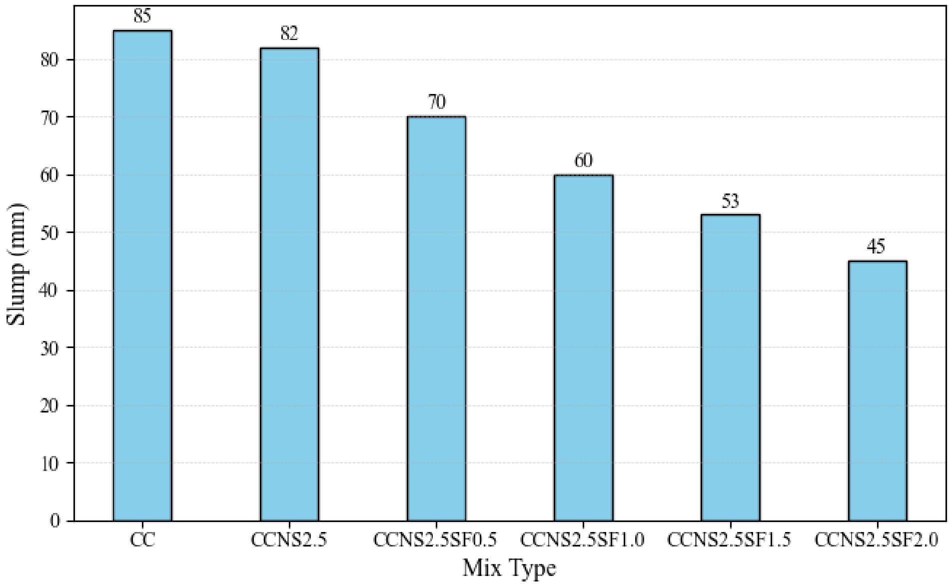

Fig. 5. Variation in slump values of concrete containing different percentages of steel fibers and colloidal nano-silica

3.2 Compressive Strength

The control concrete specimens recorded an average compressive strength of 33.7 N/mm^2 and 44.74 N/mm^2 at 7 days and 28 days respectively. When 2.5% nano-silica was added, the strength increased by 22.8% at 7 days and 6.07% at 28 days. This improvement is attributed to the pozzolanic reaction and filler action of nano-silica, which densifies the microstructure and improve strength development [21]. With the steel fibers, the 7 days strength of CCNS2.5SF0.5, CCNS2.5SF1.0, CCNS2.5SF1.5 and CCNS2.5SF2.0 increased by 31.0%, 16%, 6%, and 16.9%, respectively, which shows an improvement in strength over the conventional mix. Similarly, strength of CCNS2.5SF0.5, CCNS2.5SF1.0, CCNS2.5SF1.5 and CCNS2.5SF2.0 increased by 17.0%, 18.9%, 18.6%, and 19.1%, respectively of that of the conventional mix at 28 days (Figure 6).

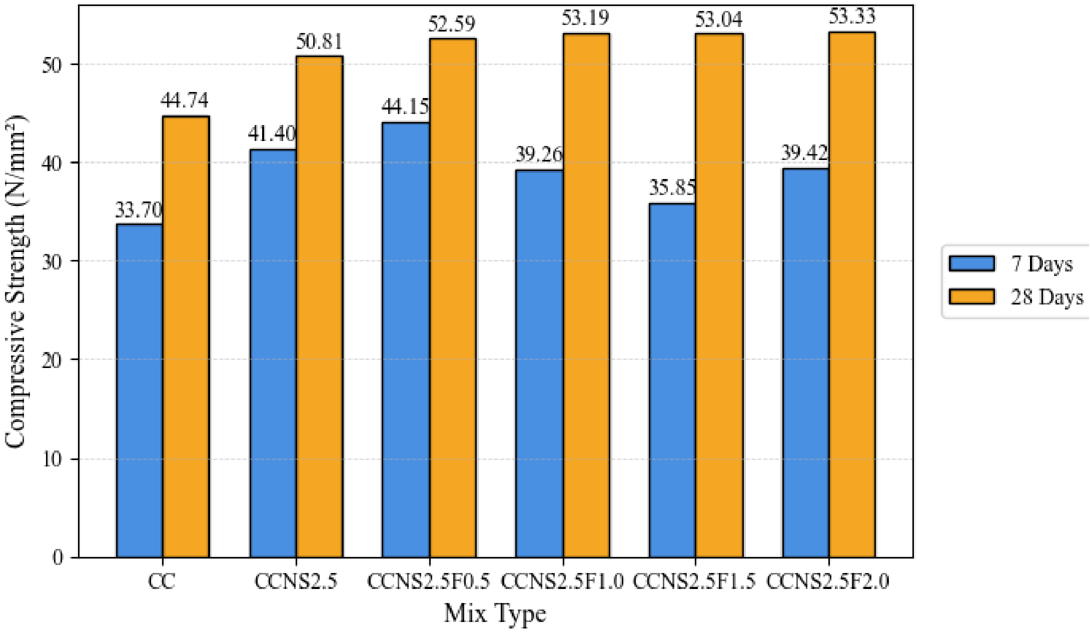

Fig. 6. Variation in compressive strength values at 7 and 28 days

Overall, the integrated incorporation of nano-silica and steel fibers considerably improved compressive strength, especially at 28 days, suggesting the delayed contribution of steel fibers during longer curing periods and achieving maximum improvement at higher fiber dosages [22]. The observed trends confirm the mutual effect of NS and SF in refining the concrete matrix and controlling crack propagation leading to improved performance [16, 22].

The increase in compressive strength with the incorporation of CNS can be attributed to its filler and pozzolanic effects, which contribute to a denser cementitious matrix. The additional improvement obtained with steel fibers is comparatively moderate, which is consistent with the primary role of fibers in crack control rather than matrix strengthening. The 28-day strength increase of approximately 17.0% to 19.1% for the steel-fiber mixes is consistent with previous studies reporting improved compressive strength from the combined use of nano-silica and steel fibers [8,16]. The relatively small difference between the 1.0%, 1.5%, and 2.0% fiber mixes suggests that increasing fiber content beyond a certain level provides limited additional benefit in compression. This behavior may be related to the relatively minor contribution of discrete fibers to the compressive resistance of concrete.

3.3 Split Tensile Strength

Split tensile strength tests help to evaluate the tensile performance of concrete modified with nano-silica and varying dosages of steel fibers. The control mix achieved an average split tensile strength of 2.49 N/mm^2 at 7 days and 3.0 N/mm^2 at 28 days. The addition of 2.5% nano silica (NS) alone enhanced the strength by 44.1% at 7 days and 46.2% at 28 days. When steel fibers were added, the 7-day strength of mixes CCNS2.5SF0.5, CCNS2.5SF1.0, CCNS2.5SF1.5, and CCNS2.5SF2.0 increased by 27.0%, 36.5%, 50.6%, and 63.8% compared to the control mix. Similarly, these mixes showed strength gains of 24.4%, 28.3%, 44.0%, and 54.1%, respectively at 28 days (Figure 7).

A gradual rise of split tensile strength with higher fiber content underscores the role of fibers in improving the post-cracking behavior and enhancing the overall ductility of the concrete [23, 24]. The results suggest that with optimum combination of NS and steel fibers can substantially improve the splitting tensile strength, which is vital for structural elements subjected to indirect tensile stresses [25]. The splitting tensile results show a clearer influence of steel fibers than the compressive strength results. The strength increased progressively with fiber content, reaching a 54.1% improvement at 28 days for the 2.0% steel-fiber mixture. This trend agrees with previous studies, which reported that steel fibers improve tensile resistance by bridging cracks and transferring stresses across developing cracks [12,24].

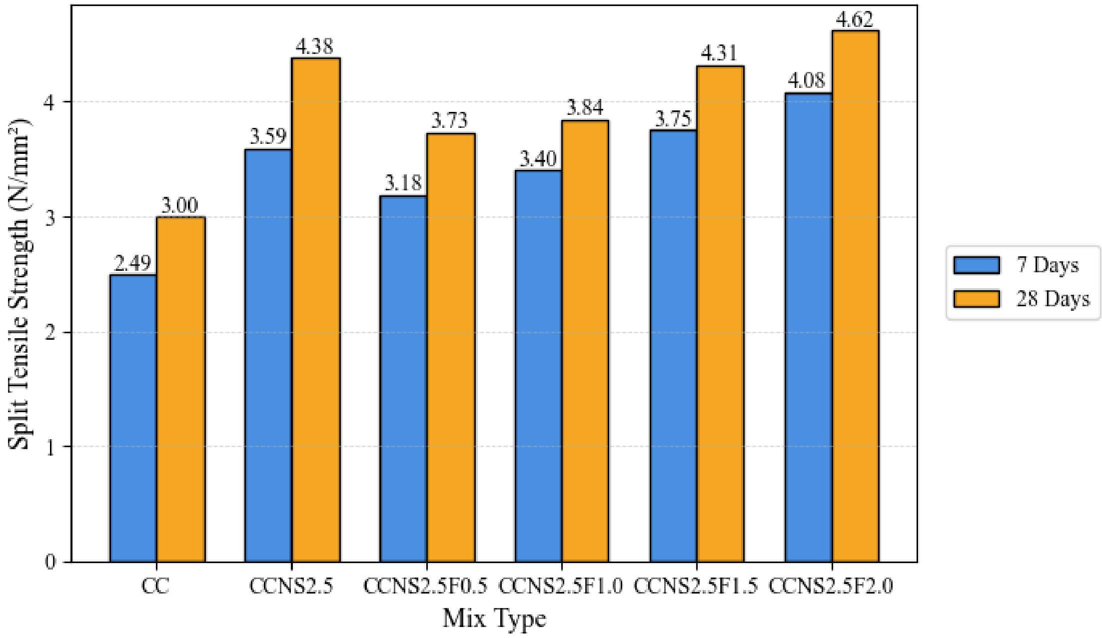

Fig. 7. Variation in split tensile strength values at 7 and 28 days

The larger improvement in splitting tensile strength compared with compressive strength is therefore expected because fiber bridging directly contributes to resistance against crack opening and propagation. The results also indicate that the combined use of CNS and steel fibers provides a complementary effect, where CNS improves the cementitious matrix and fiber reinforcement improves crack resistance. Similar improvements in the mechanical performance of concrete containing nano-silica and steel fibers have been reported by Ashokan et al. [16].

3.4 Flexural Strength

The flexural strength results indicate the load-bearing and crack resistance performance under bending. The conventional concrete mix achieved an average flexural strength of 4.41 N/mm^2 at 7 days and 6.95 N/mm^2 at 28 days. The incorporation of 2.5% nano silica led to a 7.0% reduction in strength at both 7 and 28 days. With the addition of steel fibers, the 7-day strength of mixes CCNS2.5SF0.5, CCNS2.5SF1.0, CCNS2.5SF1.5, and CCNS2.5SF2.0 increased by 25.6%, 43.9%, 56.0%, and 53.3%, respectively, compared to the control mix. At 28 days, mix CCNS2.5SF0.5 showed an 11.2% decrease in strength, while CCNS2.5SF1.0, CCNS2.5SF1.5, and CCNS2.5SF2.0 exhibited strength gains of 2.4%, 8.5%, and 24.0%, respectively, as shown in Figure 8.

The result shows a gradual increase in flexural strength along with rising fiber content. Moreover, the results highlight the combined integration of NS and steel fibers not only improves tensile resistance but also significantly enhances flexural capacity, which is critical for elements subjected to bending and flexural stresses in service [16, 22].

The flexural results further demonstrate the importance of steel-fiber content in improving the tensile behavior of the concrete. Unlike the splitting tensile results, the mixture containing CNS alone showed a 7.0% reduction in flexural strength, indicating that the addition of CNS does not necessarily improve every mechanical property at the selected dosage. With the introduction of steel fibers, the flexural strength increased progressively, with the 2.0% fiber mixture showing a 24.0% improvement at 28 days. The initial reduction observed with CNS alone and the subsequent improvement with steel fibers highlight the different roles of the two materials. CNS primarily modifies the cementitious matrix, whereas steel fibers provide crack bridging and improve resistance after crack initiation. Similar improvements in flexural performance due to steel-fiber incorporation have been reported in previous studies [8,16,22]. The differences in the magnitude of strength improvement between the present study and previous investigations may be related to variations in concrete grade, fiber geometry, fiber content, curing conditions, and mix proportions.

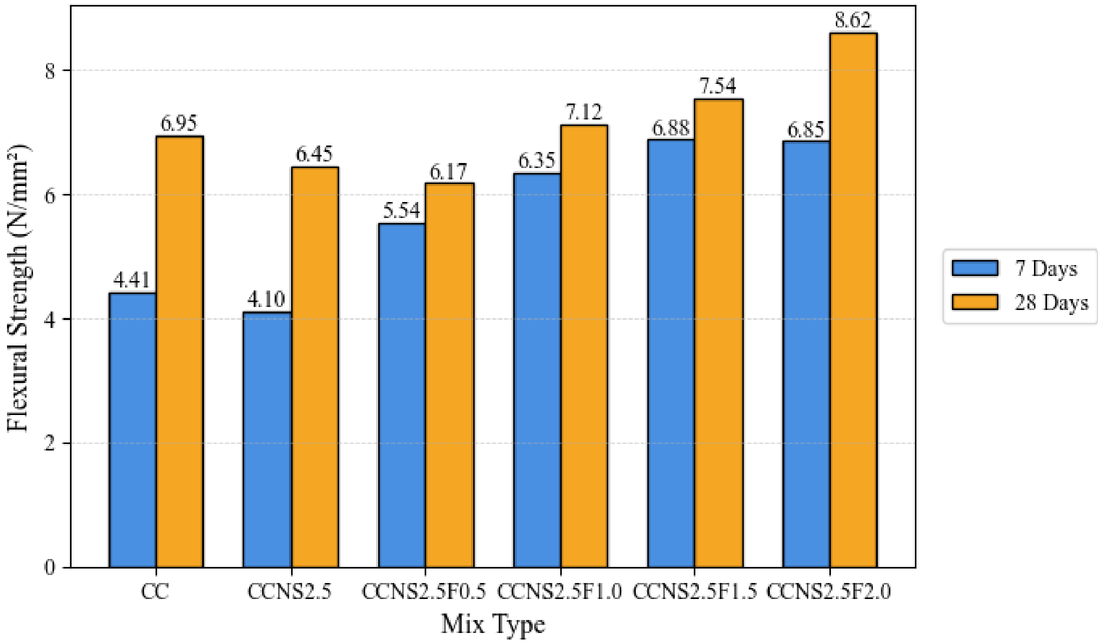

Fig. 8. Variation of flexural strength values at 7 and 28 days

Overall, the experimental results indicate that CNS and steel fibers contribute to concrete performance through complementary mechanisms. CNS primarily contributes to matrix modification, while steel fibers have a stronger influence on tensile and flexural behavior through crack bridging. This explains why the increase in splitting tensile and flexural strength is more pronounced than the increase in compressive strength. The CCNS2.5SF2.0 mixture provided the highest overall performance among the investigated mixes, confirming that the combined use of CNS and steel fibers is more effective than CNS alone for improving the mechanical properties considered in this study. These observations are consistent with previous experimental investigations on nano-silica and steel-fiber-reinforced concrete [8,16,22].

3.5 Mechanism of Strength Enhancement

The enhancement in mechanical properties observed in the present study can be explained based on the well-established microstructural mechanisms reported in previous investigations. Colloidal nano-silica consists of ultrafine amorphous silica particles that act as nucleation sites for cement hydration while simultaneously filling micro voids within the cement matrix. During hydration, nano-silica reacts with calcium hydroxide liberated from cement hydration to produce additional calcium-silicate-hydrate (C-S-H) gel. This secondary C-S-H gel refines the pore structure, reduces capillary porosity, and densifies the interfacial transition zone (ITZ), thereby improving the overall strength and durability of concrete [2,3,7].

Steel fibers enhance concrete through a different strengthening mechanism. Rather than modifying the hydration products, the fibers bridge microcracks, delay crack initiation and propagation, and improve stress redistribution after cracking. The denser ITZ produced by nano-silica further strengthens the fiber-matrix bond, resulting in more efficient stress transfer and enhanced crack resistance. Consequently, the synergistic interaction between colloidal nano-silica and steel fibers contributes to higher compressive, splitting tensile, and flexural strengths [8, 12, 18].

Although SEM, EDS, and XRD analyses were not conducted in the present study, the observed improvements in mechanical properties are consistent with the hydration mechanisms, pore refinement, and crack-bridging behavior reported in previous experimental and microstructural investigations [3, 16].

4. Practical Applicability

The proposed concrete mix with 2.5% colloidal nano-silica and steel fibers up to 2.0% shows good potential for practical construction applications. The main consideration is workability. The slump decreased from 85 mm for the control mix to 45 mm for the mix containing 2.5% CNS and 2.0% steel fibers. Although the reduction in workability should be considered during placement, the concrete remained suitable for specimen preparation in the present study. The use of a superplasticizer also provides a practical means of maintaining the required workability.

The production of the proposed concrete does not require major changes to conventional concrete production. CNS can be introduced during mixing, while the steel fibers need to be uniformly dispersed to avoid fiber clustering. Proper control of mixing sequence, fiber addition, and batching would therefore be important for large-scale production.

The initial material cost of the proposed mix is expected to be higher than conventional concrete because of the additional cost of CNS and steel fibers. However, the improved mechanical performance may provide benefits in applications where higher tensile and flexural resistance and better crack control are required. A detailed life-cycle cost assessment was beyond the scope of the present study and should be considered in future research.

The denser cementitious matrix produced by CNS and the crack-bridging effect of steel fibers are also expected to contribute to improved durability. Previous studies have reported improvements in pore structure, permeability, and durability in nano-silica-modified concrete [3,5,17]. However, durability tests were not included in the present investigation, and further experimental work is required to quantify the long-term performance of the proposed mix.

The materials used in this study are commercially available and the mix proportions are based on conventional M30 concrete, which supports the potential for scale-up. Based on its improved compressive, splitting tensile, and flexural strengths, the proposed mix may be considered for applications where crack resistance and improved mechanical performance are important. The mix is scalable and suitable for a wide range of structural applications, including industrial floors, bridge decks, precast elements, high-rise buildings, and marine structures.

5. Conclusions

Based on the experimental study conducted, the following conclusions were drawn.

- A reduction in concrete workability was observed with the addition of colloidal nano silica and greater volumes of steel fibers, showing a reduction of up to 47% for the mix containing 2.5% colloidal nano silica and 2.0% steel fibers. Although the reduction in slump was evident, the use of a superplasticizer provided a practical means of maintaining the required workability during mixing and specimen preparation.
- Concrete mixture containing 2.5% colloidal nano-silica and 2.0% steel fibers demonstrated the best overall performance among all proportions, with increases of 16.9% and 19.1% in compressive strength, 46.2% and 54.1% in split tensile strength, and 53.3% and 24.0% in flexural strength at 7 and 28 days respectively in comparison with the control mix.
- The incorporation of steel fibers in the high-strength mixes significantly enhanced the split tensile strength, followed by an improvement in flexural strength over compressive strength.
- The addition of 2.5% colloidal nano-silica alone improved the compressive and splitting tensile strengths compared with the control concrete. The improvement is attributed to the filler and pozzolanic effects of nano-silica, which contribute to a denser cementitious matrix. However, the addition of nano-silica alone resulted in a reduction in flexural strength, indicating that the effect of nano-silica varies with the type of mechanical loading.
- Increasing the steel-fiber content generally improved the tensile and flexural performance of the concrete. The improvement was more pronounced in splitting tensile strength than in compressive strength, which reflects the important role of steel fibers in bridging cracks and transferring tensile stresses across developing cracks.

The results indicate that colloidal nano-silica and steel fibers provide complementary effects. Nano-silica primarily contributes to modification and densification of the cementitious matrix, while steel fibers improve crack resistance and stress transfer. Their combined use therefore produced better overall mechanical performance than the use of nano-silica alone. Within the range investigated in this study, the mixture containing 2.5% colloidal nano-silica and 2.0% steel fibers was identified as the best-performing combination based on its combined compressive, splitting tensile, and flexural strength. This dosage should be considered the optimum within the investigated range rather than a universal optimum.

6. Limitations

The present study has some limitations. First, microstructural characterization using SEM, EDS, or XRD was not performed. Therefore, the proposed mechanisms involving C-S-H formation, pore refinement, and ITZ densification are based on findings reported in previous studies rather than direct observations from the tested specimens. Second, the investigation was limited to M30 concrete with a fixed CNS content of 2.5% and steel-fiber contents ranging from 0.5% to 2.0%. Thus, the 2.0% steel-fiber content represents the best-performing dosage within the range investigated and should not be considered a universal optimum. Third, the study evaluated mechanical properties only at 7 and 28 days, without investigating long-term strength or durability. Finally, detailed cost and life-cycle assessments were beyond the scope of this study. Future research should investigate a wider range of CNS and steel-fiber contents, together with microstructural characterization, long-term durability, and economic assessment, to further evaluate the suitability of the proposed concrete for practical applications.

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