



Journal of Materials and Engineering Structures

Research Paper

Enhancing Mechanical Properties of High Strength Concrete with Nanomaterials, Copper Slag, and Steel Fibers: Experimental Study and Predictive Modeling

Pradeep Naladi ^{a,*}, Rajasekhar Konda ^b, Chandra Sekhar Rao Tanimki ^c

^a Research Scholar, Department of Civil Engineering, Andhra University, Visakhapatnam, India

^b Associate Professor, Faculty of Civil Engineering, Andhra University, Visakhapatnam, India.

^c Professor, Faculty of Civil Engineering, Bapatla Engineering College, Bapatla, India

ARTICLE INFO

Article history :

Received : 25 June 2025

Revised : 27 September 2025

Accepted : 12 October 2025

Keywords:

Copper Slag

Nanomaterials

Steel fibers

High Strength Concrete

Empirical equations

ABSTRACT

This research investigates methods to improve the performance of high-strength concrete (HSC) using advanced and sustainable materials. Nanomaterials such as Nano silica and Nano alumina were incorporated as partial replacements for cement, while copper slag was utilised to partially substitute fine aggregate. Additionally, steel fibers were added to assess their influence on the mechanical properties of HSC. The study developed three concrete mixtures: a control mix (CO) containing 30% Ground Granulated Blast Furnace Slag (GGBS) with a water-cement ratio of 0.38, a mix with varying copper slag replacements (CCS) at levels between 10% and 50%, and an optimised mix (CCSNSA) combining 2% nanomaterials with the most effective copper slag proportion. Steel fibers were introduced into all mixtures in varying amounts ranging from 0%–2% by volume. Experimental results demonstrated that including steel fibers significantly enhanced the compressive, tensile, and flexural strengths of concrete. Furthermore, predictive models were developed for the strength characteristics of all mixes, and their outputs showed a strong correlation with experimental data. This study highlights a sustainable and effective approach to enhancing the mechanical performance of HSC by integrating copper slag, nanomaterials, and steel fibers.

1 Introduction

High-strength concrete (HSC) has become a cornerstone of modern construction due to its superior mechanical properties, durability, and ability to support heavy structural loads. However, the production of HSC often relies heavily on cement and natural aggregates, leading to environmental concerns such as significant carbon dioxide emissions and depletion of natural resources. To mitigate these challenges, researchers have explored incorporating alternative materials

* Corresponding author.

E-mail address: pradeepnaladi@gmail.com

and innovative additives into concrete to enhance its performance while promoting sustainability. This study investigates the potential of using nanomaterials, industrial by-products, and steel fibers to enhance the mechanical properties of HSC. Nanomaterials, such as Nano silica and Nano alumina, are known for their ability to refine the microstructure of concrete, resulting in improved compressive strength, durability, and resistance to cracking. Copper slag, an industrial by-product of the copper industry, serves as a promising partial replacement for fine aggregate, offering an environmentally-friendly alternative to natural sand. Steel fibers, known for their ability to improve tensile and flexural strengths, are incorporated to further enhance the structural performance of the concrete mixes. The research focuses on three distinct types of concrete mixes: a control mix containing Ground Granulated Blast Furnace Slag (GGBS), a series of mixes with varying copper slag replacement levels, and an optimised mix combining nanomaterials with the ideal copper slag proportion.

By introducing steel fibers at different dosages, the study evaluates the combined effects of these materials on the compressive, tensile, and flexural properties of HSC. Additionally, predictive models are developed to analyse and validate the experimental results, offering insights into the reliability of the proposed enhancements.

The outcome of this research contributes to the development of a sustainable and high-performance construction material by leveraging waste products, advanced technologies, and fibers. This approach not only improves the mechanical properties of HSC but also aligns with global efforts to reduce environmental impact in the construction industry. By optimising material usage and utilising waste effectively, the findings of this study have the potential to influence future concrete design and construction practices worldwide.

Shi, C. et al. [1] have reviewed the characteristics of copper slag and its effects on the engineering properties of cement, mortars, and concrete. The use of copper slag in cement and concrete provides potential environmental as well as economic benefits for all related industries. Copper slag is a by-product obtained during matte smelting and refining of copper. Madhavi et al. [2] have carried out an experimental investigation and studied the effect of copper slag on concrete as a replacement material for sand. Copper slag was used in various percentages, keeping all other ingredients constant. It is observed that the optimum content of copper slag that can be used as a replacement for sand is 40% beyond which the strength starts decreasing. A study had reported that copper slag does not cause leaching [3]. Singh, T.P., et al. [4] have investigated the use of copper slag in concrete as a replacement material, exploring the possibility of reducing the environmental impact. Copper slag is granular material and has properties like sand. Noufal, E.R., et al. [5] studied the influence of copper slag and GGBS on the mechanical properties of concrete. Concrete specimens were prepared with a constant 40% copper slag alternative to sand and replacement of cement with GGBS at 0% to 50% with 5% increment. It was observed that copper slag and GGBS can be used as fine aggregate and cement in concrete, without compromising on the quality, which is the need of the hour. Gupta and Siddique [6] and Al-Jabri et al. [7] have reported that, in the recent past, besides normally used materials in concrete, fly ash, ground granulated blast furnace slag, silica fume, and metakaolin are normally used in concrete as and when the situation demands. Lokesh, et al. [8] have conducted an experimental investigation to study the effect of copper slag, fly ash, and Nano Material on the properties of concrete. Enhanced strength properties of concrete were achieved at 5% Fly Ash and 20% Copper Slag with the application of 5 % nano silica. Norhasri et al. [9] have faced problems in the introduction of nanomaterials into concrete, which are constantly being explored by researchers in practice. In recent years, the development of nanotechnology in concrete has accelerated. Liu et al. [10] have investigated the effect of nanoparticles, especially in concrete, due to the new uses of nanoparticles.

Çevik et al. [11] demonstrated that Nano Silica (NS) and fly ash improved both mechanical strength and chemical durability in geopolymer concrete, particularly under exposure to aggressive environments like sulphuric acid and seawater. Copper slag serves as a sustainable alternative to river sand in concrete, helping address the issue of resource depletion. Concrete can utilise copper slag as a substitute for fine aggregate, helping to reduce construction costs [12]. Research has explored using copper slag as a sustainable alternative to river sand in concrete. By partially replacing fine aggregate with copper slag in various concrete mixes (0% to 100%), the study assessed the fresh and mechanical properties of the resulting concrete. The findings suggest that copper slag is a viable, environmentally friendly substitute in construction [13]. Wu et al. [14] demonstrated that substituting up to 40% of sand with copper slag in high-strength concrete formulations results in mechanical properties that are on par with or even superior to those of the control mix. However, exceeding this 40% substitution threshold significantly impairs concrete performance, suggesting a critical limit beyond which the integrity and durability of the composite are compromised. Ojha et al. [15] conducted an experimental study on steel fiber-reinforced concrete, testing specimens for flexural strength and split tensile strength. Results were compared to international standards, leading to recommended ratios for split tensile to flexural strength in concrete with and without steel fibers, across a strength range of 100-120 MPa. Recent studies have also emphasized the combined effect of optimized particle packing and fiber

reinforcement in sustainable concretes. Abushama et al. [23] used a particle-packing approach to design “green” concretes incorporating GGBS and supplementary cementitious materials, showing that careful packing can enhance both macro- and micro-properties such as strength and permeability. In a related vein, Tawfeeq et al. [24] examined the flexural performance of reinforced concrete beams made with recycled block aggregates and steel fibers, demonstrating that fiber inclusion significantly improves load-deflection response, crack control, and energy absorption in concrete elements incorporating recycled materials. This study explores the use of alternative materials such as nano silica, nano alumina, and copper slag in M60-grade concrete. Copper slag, a by-product of the copper industry, has been investigated as a partial replacement for fine aggregates, while nano silica and nano alumina have been used as partial replacements for cement. The inclusion of steel fibers is intended to further improve the mechanical properties of the concrete.

2 Materials and Specimen Specifications

2.1 Materials

In this study, Ordinary Portland Cement (OPC) of 53-grade, conforming to IS: 12269–1987 standards, was utilised. The cement had an initial setting time of 45 minutes, a final setting time of 570 minutes, and a specific gravity of 3.14.

Fine Aggregate (FA): Locally sourced riverbed sand meeting IS: 383-1987 Zone II requirements was used. It had a bulk density of 1450 kg/m³ and a specific gravity of 2.65.

Coarse Aggregate (CA): Well-graded crushed granite with nominal sizes of 20 mm and 10 mm, conforming to IS: 383–1970, and obtained from a local crushing unit. The bulk density and specific gravity were 1500 kg/m³ and 2.83, respectively.

Water: Potable water, meeting IS: 456–2000 standards, was used for mixing and curing.

Ground Granulated Blast Furnace Slag (GGBS): Supplied from Vijayawada, GGBS had a specific gravity of 2.90 and complied with IS 16714: 2018 standards.

Copper Slag: Used as a partial replacement for fine aggregate, it had a bulk density of 2240 kg/m³ and a specific gravity of 3.1. Its chemical composition included silicon dioxide (SiO₂) at 33.05%, aluminium oxide (Al₂O₃) at 2.79%, ferric oxide (Fe₂O₃) at 53.45%, and calcium oxide (CaO) at 6.0%.

Nano Silica (NS) and Nano Alumina (NA): Procured from Chennai, India, these nanomaterials were introduced as partial replacements for cement at 1%. Table 1 provides the physical properties of Nano silica and Nano alumina.

Table 1 – Physical Properties of Nano Silica and Nano Alumina

Properties	Unit	Nano Silica	Nano Alumina
Specific surface area	m ² /g	220	200
Average particle size	nm	12	8
Density	g/cc	0.005	0.12
pH	-	3.7 – 4.7	6

Steel fibers, with a diameter of 0.5 mm, a length of 30 mm, and an aspect ratio of 60, were added to the concrete mixes to assess their impact on the mechanical properties. The fibers were incorporated in increments of 0.25%, ranging from 0% to 2%, with a modulus of elasticity of 200 GPa.

Conplast SP 430, a high-performance superplasticizer made from selected sulphonated naphthalene polymers, with a specific gravity of 1.18, was used as a water-reducing agent in the mix.

The high content of ferric oxide in the copper slag may also contribute to the observed reduction in compressive strength as the proportion of copper slag increases in the fine aggregate mix, consistent with findings by Velumani et al. [13] and Wu et al. [14].

2.2 Mix Proportions

This study explores the design and development of three variations of M60 grade high-strength concrete. The first variant, designated as CO, serves as the control mix, and is further modified by the addition of steel fibers, referred to as COSFn%. The second variant incorporates copper slag as a partial replacement for fine aggregate, with and without steel fibers, designated as CCS and CCSn%, respectively.

The third variant introduces a blend of nano silica and nano alumina in equal proportions to replace a portion of the cement content in both the control mix (CO, CO_n%) and the copper slag concrete mix (CCS, CCS_n%). These mixes are labelled CCSNSA and CCSNSA_n%, where "n%" refers to the percentage of steel fibers by weight of the binder.

The control mix (CO) is designed with 30% Ground Granulated Blast Furnace Slag (GGBS) and 70% Ordinary Portland Cement (OPC). The mix design follows the guidelines of ACI 363R-1992 for M60-grade concrete. A water-binder ratio of 0.38 is maintained, with the target mean strength of 70 MPa. The proportioning of the concrete mix is provided in Table 2 and Table 3.

Table 2 – Mix Proportion of Steel fiber reinforced concrete

Mix ID	Binder	Cement	GGBS	NS	NA	FA	CS	CA	%SF	Water	% SP
	Kg/m ³									Liters	
COSF 0.25	425	297.5	127.5	-	-	667	-	1180	0.25	162	1.2
COSF 0.5	425	297.5	127.5	-	-	667	-	1180	0.5	162	1.2
COSF 0.75	425	297.5	127.5	-	-	667	-	1180	0.75	162	1.2
COSF 1.0	425	297.5	127.5	-	-	667	-	1180	1.0	162	1.2
COSF 1.25	425	297.5	127.5	-	-	667	-	1180	1.25	162	1.2
COSF 1.5	425	297.5	127.5	-	-	667	-	1180	1.5	162	1.2
COSF 2.0	425	297.5	127.5	-	-	667	-	1180	2.0	162	1.2
CCS20SF 0.25	425	297.5	127.5	-	-	533.6	133.4	1180	0.25	162	1.2
CCS20SF 0.5	425	297.5	127.5	-	-	533.6	133.4	1180	0.5	162	1.2
CCS20SF 0.75	425	297.5	127.5	-	-	533.6	133.4	1180	0.75	162	1.2
CCS20SF 1.0	425	297.5	127.5	-	-	533.6	133.4	1180	1.0	162	1.2
CCS20SF 1.25	425	297.5	127.5	-	-	533.6	133.4	1180	1.25	162	1.2
CCS20SF 1.5	425	297.5	127.5	-	-	533.6	133.4	1180	1.5	162	1.2
CCS20SF 2.0	425	297.5	127.5	-	-	533.6	133.4	1180	2.0	162	1.2
CCSNSASF 0.25	425	291.5	127.5	3	3	533.6	133.4	1180	0.25	162	1.2
CCSNSASF 0.5	425	291.5	127.5	3	3	533.6	133.4	1180	0.5	162	1.2
CCSNSASF 0.75	425	291.5	127.5	3	3	533.6	133.4	1180	0.75	162	1.2
CCSNSASF 1.0	425	291.5	127.5	3	3	533.6	133.4	1180	1.0	162	1.2
CCSNSASF 1.25	425	291.5	127.5	3	3	533.6	133.4	1180	1.25	162	1.2
CCSNSASF 1.5	425	291.5	127.5	3	3	533.6	133.4	1180	1.5	162	1.24
CCSNSASF 2.0	425	291.5	127.5	3	3	533.6	133.4	1180	2.0	162	1.36

Table 3 – Mix Proportion of Plain Concrete

Mix ID	Binder	Cement	GGBS	NS	NA	FA	CS	CA	Water (Liters)	% SP
	Kg/m³									
CO	425	297.5	127.5	-	-	667	-	1180	162	1.0
CCS10	425	297.5	127.5	-	-	600.3	66.7	1180	162	1.0
CCS20	425	297.5	127.5	-	-	533.6	133.4	1180	162	1.0
CCS30	425	297.5	127.5	-	-	466.9	200.1	1180	162	1.0
CCS40	425	297.5	127.5	-	-	400.2	266.8	1180	162	1.0
CCS50	425	297.5	127.5	-	-	333.5	333.5	1180	162	1.0
CCS20NS1	425	294.5	127.5	3	-	533.6	133.4	1180	162	1.2
CCS20NA1	425	293.5	127.5	-	3	533.4	133.4	1180	162	1.2
CCS20NSA2	425	291.5	127.5	3	3	533.6	133.4	1180	162	1.24

Concrete specimens were cast in standard moulds: cubes (150x150x150 mm), cylinders (150x300 mm), and prisms (100x100x500 mm). After 24 hours, the specimens were demoulded and placed in a water-curing tank at 27°C for 28 days. To assess the fresh-state properties of high-strength concrete (HSC), the slump flow test was conducted. This test, performed according to IS 1199: Part 2: 2018, was used to determine the workability of the concrete. The slump for all mix designs was maintained at a minimum of 100 mm to ensure adequate workability, which was achieved by adjusting the superplasticizer dosage within the range of 1.0% to 1.36%.

3 Experimental Programme

All specimens were tested using a 300-ton capacity Universal Testing Machine (UTM) after 28 days of curing. The results for workability and strength characteristics, including compressive strength, split tensile strength, and flexural strength, are presented in Table 4. For each strength test, a minimum of three specimens were tested at each curing stage, and the average values were reported. The tests for compressive strength, split tensile strength, and flexural strength were conducted following the guidelines specified in IS 516 (Part-1/Sec-1)-2021. This standard ensures the reliability and consistency of the testing procedures used to evaluate the performance of high-strength concrete.

Table 4 indicates that replacing fine aggregate with copper slag up to approximately 10%-20% improves compressive strength. However, at higher replacement levels (40%-50%), the strength shows diminishing returns or even a slight reduction.

Table 4 – Test results of plain concrete with copper slag concrete

Mix ID	Compressive Strength (N/mm ²)		Prediction Error (%)	Split Tensile Strength (N/mm ²)	Flexural strength (N/mm ²)
	Prediction	Experimental			
CCS0	60.00	67.33	-10.89%	4.61	6.17
CCS10	67.72	71.20	-4.89%	4.70	6.42
CCS20	72.28	72.40	-0.15%	4.81	6.63
CCS30	72.70	71.82	1.22%	4.76	6.41
CCS40	70.44	70.06	0.54%	4.69	6.32
CCS50	67.89	67.54	0.52%	4.58	6.04

The observed reduction in compressive strength with an increasing replacement of fine aggregate by copper slag may be attributed to the elevated ferric oxide content in the copper slag. This also suggests that the prediction model generally aligns with the experimental results, although minor discrepancies are noted in some instances. Based on both predicted and experimental values, the CCS 20% mix can be considered optimal for compressive strength.

Table 5 – Test results of fiber-reinforced concrete mixes with copper slag, nano silica & nano alumina

Mix ID	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)		Slump (mm)
	Prediction	Measured	Prediction	Measured	Prediction	Measured	
M1-COSF0	60.00	67.33	5.28	4.92	6.40	6.20	115
M2-COSF0.25	63.92	68.82	5.34	5.16	6.47	6.64	113
M3-COSF0.5	67.71	69.12	5.35	5.25	6.48	6.98	110
M4-COSF0.75	71.35	71.63	5.45	5.34	6.60	7.13	107
M5-COSF1.0	74.86	75.11	5.58	5.48	6.76	7.21	106
M6-COSF1.25	78.23	78.46	5.70	5.82	6.91	7.24	104
M7-COSF1.5	81.47	80.96	5.79	5.96	7.02	7.31	102
M8-COSF2.0	87.52	79.92	5.76	5.52	6.97	7.20	100
M9-CCSSF0	72.39	72.30	5.94	5.42	6.590	6.420	122
M10-CCSSF0.25	74.20	75.40	6.01	5.84	6.672	6.919	120
M11-CCSSF0.5	76.80	78.30	6.11	6.02	6.788	7.039	116
M12-CCSSF0.75	79.00	80.90	6.20	6.27	6.885	7.139	114
M13-CCSSF1.0	84.20	83.10	6.40	6.51	7.108	7.370	110
M14-CCSSF1.25	86.70	85.10	6.50	6.63	7.212	7.479	110
M15-CCSSF1.5	88.70	86.80	6.59	6.90	7.295	7.565	108
M16-CCSSF2.0	87.40	89.30	6.52	6.79	7.241	7.509	106
M17-CCSNSASF0	85.30	92.76	7.17	6.86	7.154	7.418	110
M18-CCSNSASF0.25	87.40	95.92	7.26	7.14	7.241	7.509	110
M19-CCSNSASF 0.5	93.86	98.78	7.52	7.59	7.504	7.781	108
M20-CCSNSASF0.75	97.31	101.35	7.66	7.79	7.641	7.923	106
M21-CCSNSASF1.0	104.93	103.62	7.95	7.98	7.934	8.228	104
M22-CCSNSASF1.25	109.77	105.59	8.13	8.21	8.115	8.415	104
M23-CCSNSASF1.5	113.32	107.27	8.50	8.74	8.461	8.887	100
M24-CCSNSASF2.0	112.64	109.74	8.24	8.67	8.221	8.524	100

Table 5 presents the details of 24 distinct concrete mix variations, categorised into three groups: CO, CCS, and CCNSA, with and without the inclusion of fibers. For each mix, three test specimens were cast according to standard specifications to evaluate compressive strength, split tensile strength, and flexural strength. The reported test results represent the mean value from these three specimens, ensuring the reliability and accuracy of the comparative strength analysis. The incorporation of steel fibers up to 2.0% by volume enhanced compressive, tensile, and flexural strengths across all mixes; however, the most balanced performance was achieved at 1.5% dosage. In particular, the M23 mix

(CCSNSASF1.5) exhibited a 40.9% improvement in split tensile strength and a 43.6% increase in flexural strength compared to the reference mix M1.

Table 6 – Prediction error (%) of compressive, split tensile, and flexural strength for CO, CCS, and CCSNSA.

Mix ID	Mix Type	Prediction Error (%)		
		Compression	Tensile	Flexure
M1	COSF0	-10.89	7.32	3.23
M2	COSF0.25	-7.12	3.49	-2.56
M3	COSF0.5	-2.04	1.9	-7.16
M4	COSF0.75	-0.39	2.06	-7.43
M5	COSF1.0	-0.33	1.82	-6.24
M6	COSF1.25	-0.29	-2.06	-4.56
M7	COSF1.5	0.63	-2.85	-3.97
M8	COSF2.0	9.51	4.35	-3.19
M9	CCSSF0	0.12	9.59	2.65
M10	CCSSF0.25	-1.59	2.91	-3.57
M11	CCSSF0.5	-1.92	1.5	-3.57
M12	CCSSF0.75	-2.35	-1.12	-3.56
M13	CCSSF1.0	1.32	-1.69	-3.55
M14	CCSSF1.25	1.88	-1.96	-3.57
M15	CCSSF1.5	2.19	-4.49	-3.57
M16	CCSSF2.0	-2.13	-3.98	-3.57
M17	CCSNSASF0	-8.04	4.52	-3.56
M18	CCSNSASF0.25	-8.88	1.68	-3.57
M19	CCSNSASF 0.5	-4.98	-0.92	-3.56
M20	CCSNSASF0.75	-3.99	-1.67	-3.56
M21	CCSNSASF1.0	1.26	-0.38	-3.57
M22	CCSNSASF1.25	3.96	-0.97	-3.57
M23	CCSNSASF1.5	5.64	-2.75	-4.79
M24	CCSNSASF2.0	2.64	-4.96	-3.55

The statistical parameters, standard deviation (SD), mean, and coefficient of variation (COV) calculated for the 24 concrete mixes provide crucial insights into the dataset consistency and reliability from Table 5. The compressive strength shows moderate variability with SD values of 14.65 MPa (predicted) and 13.24 MPa (measured), which is typical for concrete testing scenarios and indicates a stable spread around the mean strength values of 85.04 MPa and 81.23 MPa, respectively. Split tensile and flexural strength tests demonstrate tighter variability reflected in lower SDs (1.02 to 1.15 MPa for split tensile and 0.57 to 0.64 MPa for flexural) and correspondingly lower COV percentages (8–17% for split tensile and around 8% for flexural), confirming better precision and repeatability in these measurements. The calculated COV values for all strengths being within commonly accepted ranges support the practical reliability and quality of the

concrete mixes. These collective findings reinforce the robustness of the experimental procedures and the predictive modeling across the entire array of mixes, validating the concrete mix designs for practical structural applications.

Table 6 summarises the prediction errors (%) between the models and experiments for compressive, split-tensile, and flexural strengths across CO, CCS, and CCSNSA. Errors are generally within $\pm 5\%$, with maximum deviation of -10.9% for compression (M1), $+9.6\%$ for tensile (M9), and -7.4% for flexural (M4). These results confirm good agreement between experimental data and the proposed predictive models. Negative values indicate underprediction, whereas positive values indicate overprediction.



Fig. 1 – (a) Testing of specimen for compression; (b) Testing of specimen for flexure

4 Results and Discussion

4.1 Slump

From Table 5 and Fig. 2, it is observed that increasing the fiber dosage in the control mix (M1) leads to a reduction in slump by 11.3% for mix M7 and 13.04% for mix M8, indicating a significant decrease in workability with higher fiber content.

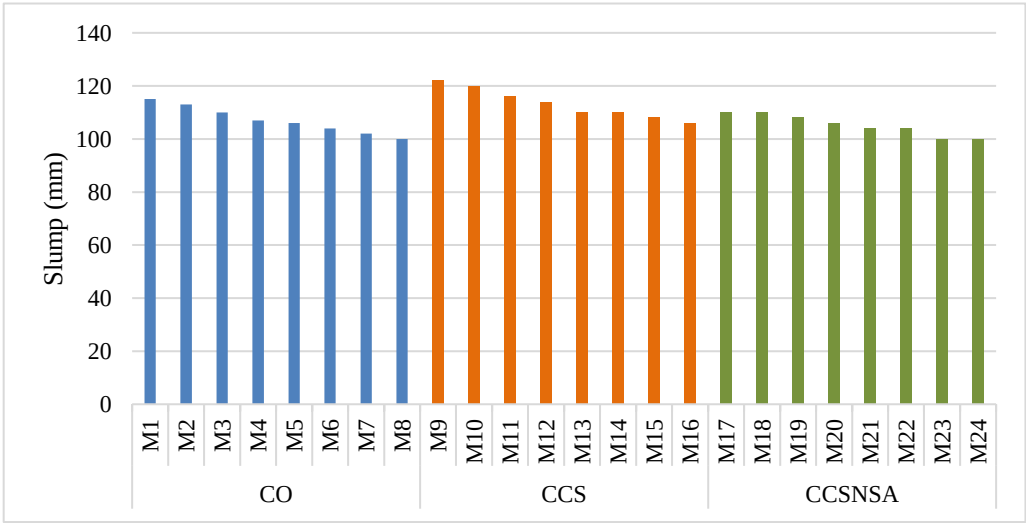


Fig. 2 – Effect of copper slag, nanomaterials, and steel fibers on the workability of HSC mixes

The copper slag modified mix (M9) shows a 6.09% improvement in workability, as evidenced by an increased slump value compared to the control mix (M1). Incorporating 20% copper slag as a fine aggregate replacement enhances the workability of fiber-reinforced mixes M15 and M16, with improvements of 5.9% and 6%, respectively. The low water absorption properties of copper slag help retain free water within the concrete matrix during hydration, thereby enhancing performance.

The optimised mix M17, which includes nano silica and alumina in the cement matrix along with copper slag as a partial fine aggregate replacement, exhibits reduced workability compared to M1 and M9. Specifically, M17 shows a decrease in workability of 4.35% compared to M1 and 9.84% compared to M9. This reduction is due to the high surface areas of nano silica and alumina, which increase the water demand in the cement matrix. Nano silica particles, known for their high pozzolanic reactivity and fine particle size, lead to denser packing of the particles. While this improves strength, it reduces the availability of free water, resulting in a stiffer mix and reduced workability. The combination of nano silica, alumina, and copper slag in M17 results in a denser and more compact matrix, which traps more water within the cementitious components, restricting flow and reducing the slump. In mixes M17 to M24, as the fiber content increases from 0.25% to 2.0%, a corresponding decline in workability, measured by slump, is observed. This reduction peaks at 9.09% for M23 and M24.

4.2 Compressive Strength

Table 5 presents the mechanical strength test results measured after 28 days of curing for all the mix variations studied. Figure 3 illustrates the variation in compressive strength resulting from different dosages of steel fibers, the addition of copper slag, and the incorporation of nano silica and nano alumina in the control mix. It also shows the deviation between the predicted values and the experimentally derived values for the three mix types (CO, CCS, and CCSNSA), emphasizing the contribution of fiber reinforcement in these compositions.

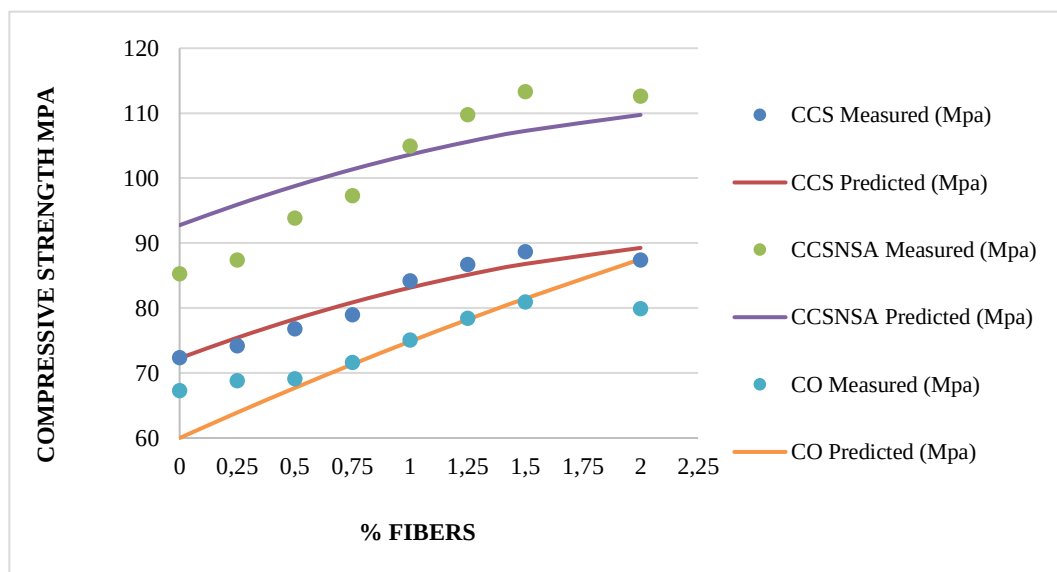


Fig. 3 – Variation of compressive strength w.r.t copper slag, nano silica, and nano alumina along with fibers in the concrete mixes

In the comparative analysis of the three mix categories, it was observed that incorporating steel fibers at a 1.5% dosage led to significant improvements in compressive strength across all mixes. Specifically, Mix M8 showed a 20.24% increase in compressive strength compared to Mix M1. Similarly, Mix M16 demonstrated a 22.53% higher strength than Mix M9, while Mix M24 exhibited a 39.88% increase over Mix M17. These results highlight the effectiveness of steel fiber reinforcement in enhancing compressive strength across various mix compositions. The findings emphasise that steel fiber reinforcement helps bridge microcracks, improves stress distribution, and increases overall compressive strength, thus enhancing the structural integrity of mixes containing nanomaterials and copper slag, as shown in Fig. 3.

Three regression-based predictive equations were developed to estimate the compressive strength for three distinct mix categories: a control mix, a control mix with copper slag, and a modified mix incorporating both copper slag and nanomaterials, each tested with varying steel fiber dosages. These equations are designed to capture the effect of steel fiber content on compressive strength, facilitating a comprehensive comparative analysis of the mechanical performance across each mix category.

$$f_{ck1} = C + K_1 V_f - K_2 V_f^2 \quad (1)$$

$$f_{ck2} = C + K_1 V_f - K_2 V_f^2 + K_3 X_{cs} \quad (2)$$

$$f_{ck3} = C + K_1 V_f - K_2 V_f^2 + K_3 X_{cs} + K_4 X_{nm} \quad (3)$$

The above three empirical equations were developed using regression analysis to predict the compressive strength of concrete (f_{ck}) concrete mixes considering the percentage of steel fibers (V_f), copper slag (X_{cs}), and nanomaterials (X_{nm}). C is the compressive strength of concrete in 60MPa.

Where, K_1 and K_2 are coefficients that relate to the volume fraction of the fiber reinforcement, quantifying its effect within the mix. K_3 and K_4 are the influencing parameters considering the % of copper slag (X_{cs}) and nano silica and nano alumina (X_{nm} -nanomaterial) addition in the concrete matrix. For this analysis, the values assigned to these coefficients are $K_1 = 15.96$, $K_2 = 1.1$, $K_3 = 0.73$, and $K_4 = 10.24$.

4.3 Split Tensile Strength

The split tensile strength test results for three concrete mix categories CO, CCS, and CCSNSA with varying steel fiber dosages reveal that the optimal fiber content for maximising tensile strength in fiber-reinforced concrete is 1.5%. Specifically, tensile strength improvements of 36.45%, 37.67%, and 27.27% are observed in mixes M7, M15, and M23, respectively, compared to their counterparts M1, M9, and M17. However, mixes M8, M16, and M24 show decreased workability, impacting ease of placement and finishing during casting. Additionally, segregation and fiber clumping (fiber balling) are present in these mixes, contributing to a reduction in tensile strength performance. Mix M23 has improved its tensile strength substantially by 40.92% compared to the control mix M1.

An empirical equation, derived from experimental data and prior research [15], was developed to predict tensile strength across 24 fiber-reinforced concrete mix designs. Predicted values aligned closely with experimental results, while the ACI 318-99 [16] equation consistently underestimated the tensile strength for high-strength concretes with copper slag, nanomaterials, and steel fibers, likely due to the code's basis in plain concrete without these material considerations Fig.4.

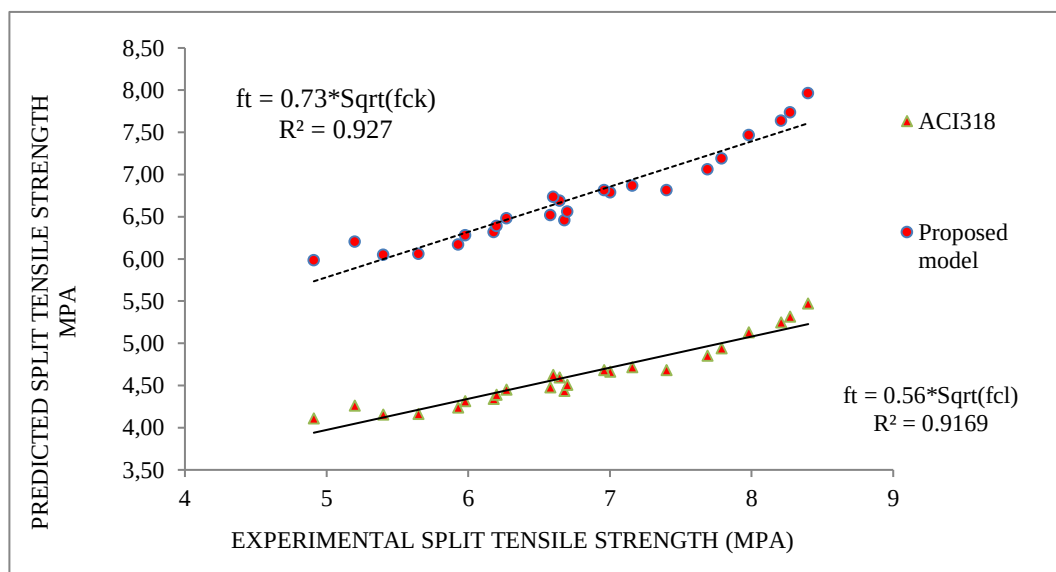


Fig. 4 – Correlation between predicted and experimental split tensile strength

The model developed for predicting the tensile strength is given in equation (4):

$$f_t = 0.73\sqrt{f_{ck}} \quad (4)$$

$$f_t = 0.56\sqrt{f_{cl}} \quad (5)$$

f_t , f_{ck} , and f_{cl} are tensile strength, characteristic cube, and cylindrical compressive strength of concrete mixes, respectively, in MPa.

Figure 4 compares the predicted splitting tensile strength f_t from two relations with the experimental values for all mixes (CO, CCS, CCSNSA). The proposed regression (Eq. 4) demonstrates strong agreement with the experimental data ($R^2 = 0.927$), whereas the ACI 318 relation (Eq. 5) also shows reasonable correlation ($R^2 = 0.917$) but consistently underestimates f_t at higher strengths. For this comparison, cube compressive strengths were converted to equivalent cylindrical strengths by applying a conversion factor of 0.8. These results confirm that Eq. (4), calibrated on the present dataset, more accurately captures the influence of copper slag, nanomaterials, and steel fibers on tensile performance.

4.4 Flexural Strength

The predicted and experimental flexural strength values for the mixes are presented in Table 5. In comparison, mixes with 1.5% steel fiber content show an improved performance. Mix M7, enhanced with 1.5% steel fiber, outperforms M1 in flexural strength, with a 17.94% increase, highlighting the effectiveness of steel fiber in improving concrete performance. Similarly, the flexural strength of M15 is approximately 17.82% higher than that of M9, demonstrating the significant impact of incorporating steel fibers. Although the predictive model captures this upward trend, it slightly overestimates the actual results. Additionally, the flexural strength of M23 exceeds that of M17 by 19.97%, confirming that the addition of steel fiber improves performance as expected. Compared to the control mix (M1), the combination of copper slag, nanomaterials, and steel fiber in M23 enhances flexural strength by 43.6%, demonstrating the effectiveness of this composite mix design in improving concrete's mechanical properties.

The equations presented in Table 7 provide an estimate of flexural strength based on the cylindrical compressive strength values provided by various authors. This study explores the relationship between compressive and flexural strength in concrete, focusing on an empirical approach to predict flexural strength from compressive strength. Since the compressive strength was initially measured using concrete cubes, the values were converted to equivalent cylindrical compressive strength by multiplying by a factor of 0.8. Using these cylindrical compressive strengths, an empirical formula was developed to predict flexural strength.

$$f_{cr} = 0.866 * \sqrt{f_{cl}} \quad (6)$$

In addition to the empirical predictions, experimental flexural strength values (f_{cr} - experimental) were directly obtained through laboratory tests on concrete prisms. These experimentally measured flexural strengths were then compared with the empirical predictions and with various models proposed by other researchers [17-20]. Each of these models offers an equation for estimating flexural strength based on compressive strength, as presented in Table 7.

Table 7 – Equation for Flexural strength of concrete by various references

Reference	Equation For Flexural Tensile Strength of Concrete (MPa)
Ramados Perumal (2014)	$0.259 * f_c^{0.843}$
ACI-363R-92 (2004)	$0.94 * f_c^{0.5}$
Rashid et al. (2002)	$0.42 * f_c^{0.68}$
Thomas And Ramasamy (2007)	$0.79 * f_c^{0.5}$

For all mixes (M1 to M24), a predictive model was developed using regression analysis based on cylindrical compressive strengths, which were derived by converting cube strength test results. The flexural strength models proposed by Ramados Perumal significantly overestimated values by an average of 29.28%, compared to the model developed by

the authors specifically for the M1 to M7 mixes. In contrast, the models from ACI-363, Rashid [17, 18] and the experimental flexural strengths provided more accurate predictions, with deviations of 7.8%, 0.39%, and -4.11%, respectively. For the M9–M16 mixes, which incorporate copper slag and steel fibers (0–2% Vf), the flexural strength trends align closely across formulations. The predictive model for these specific mixes shows minor deviations in strength compared to values calculated using the ACI-363, Rashid, and empirical test results, with respective variances of 8.55%, 2.81%, and 2.95%. On the other hand, the Ramadoss Perumal model overpredicts strength by 25.20%, while the Thomas & Ramasamy model underestimates strength by 8.78%.

The flexural strength results for mixes containing blended nano silica, nano alumina, copper slag, and steel fibers (designated M17–M24) show a close correlation between the experimental and model-predicted values, with a marginal deviation of 3.88%. However, the flexural strengths predicted for these mixes by the developed empirical model are lower by 35.15%, 8.55%, and 7.0% when compared to the prediction models by ACI-363, Rashid, and Ramadoss Perumal [17, 18, 20], respectively. In contrast, the developed model predicts 8.78% higher strength compared to the model proposed by Thomas and Ramasamy, indicating a stronger predictive capability in comparison to these latter models, as shown in Figures 5, 6, and 7.

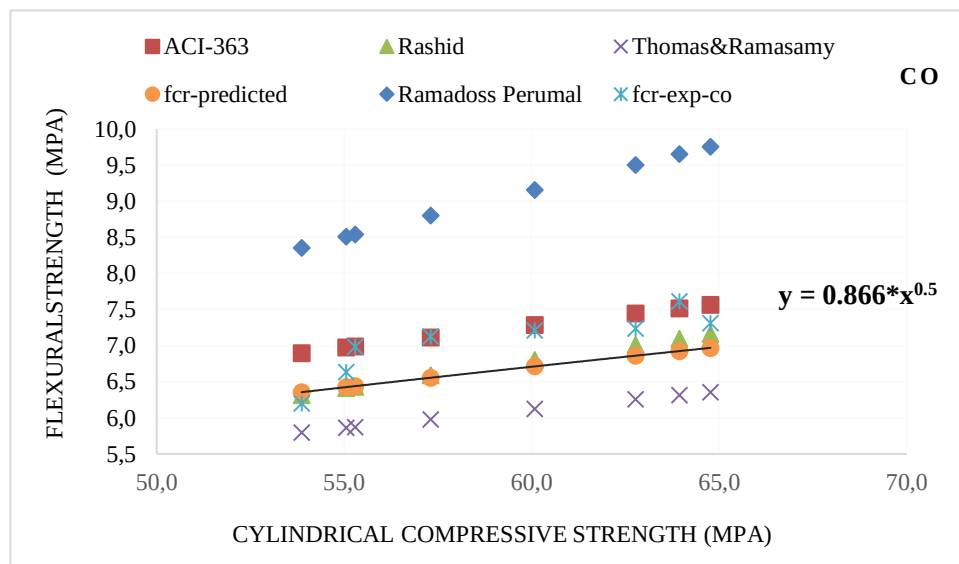


Fig. 5 – Relationship between flexural strength and cylindrical compressive strength for CO mix with steel fibers compared to various prediction models

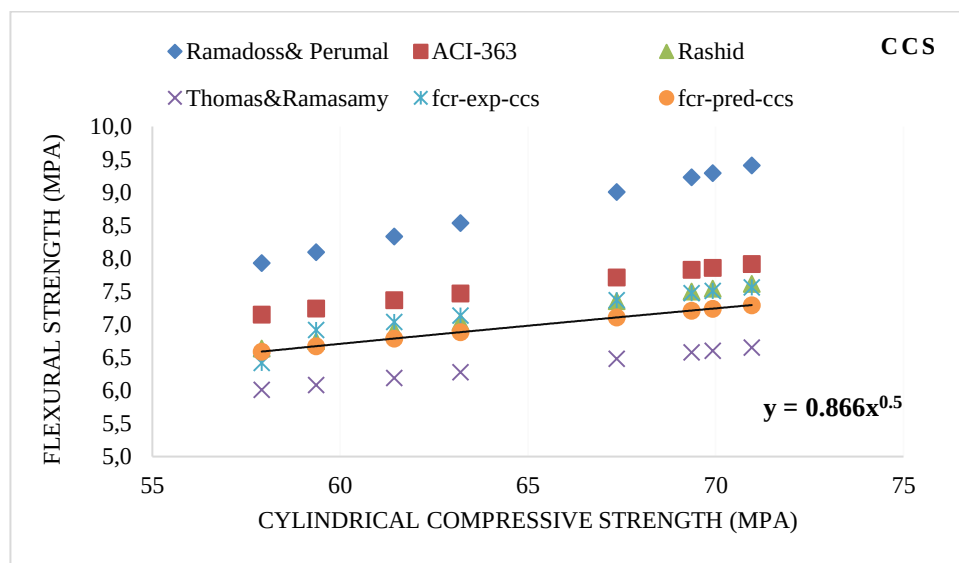


Fig. 6 – Relationship between flexural strength and cylindrical compressive strength for CCS mix with steel fibers compared to various prediction models

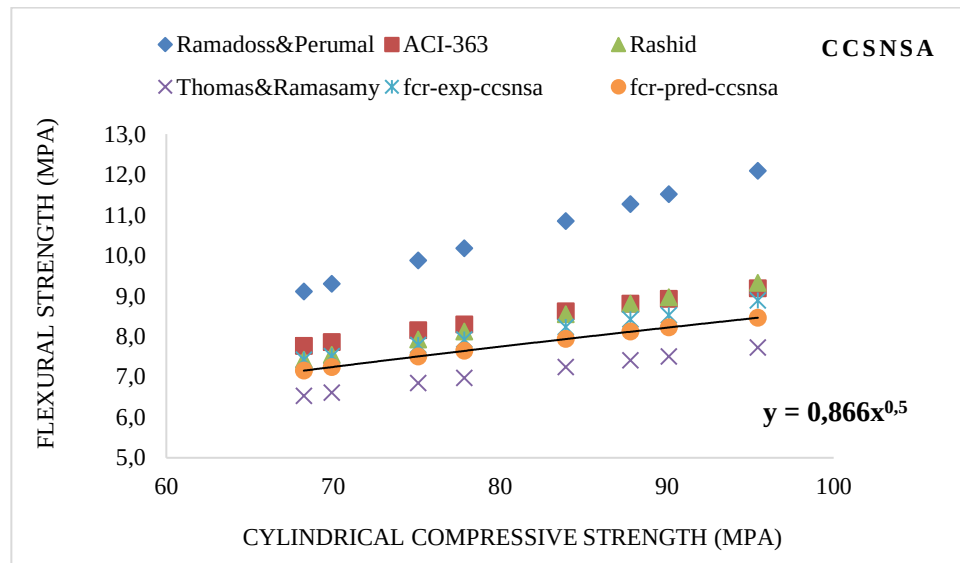


Fig. 7 – Relationship between flexural strength and cylindrical compressive strength for CCSNSA mix with steel fibers compared to various prediction models

5 Conclusions

The study evaluated the mechanical properties of HSC incorporating Copper slag, nano silica, nano alumina, and variable dosages of steel fibers. The experimental data reveal that integrating these materials significantly enhances the performance of HSC, providing both environmental benefits and improved structural capabilities. The primary findings and implications are as follows :

The incorporation of copper slag enhances workability due to its low water absorption, effectively offsetting the reduced slump typically caused by nano silica and nano alumina. This balance allows for an optimised mix that sustains both strength and workability. Replacing fine aggregate with copper slag up to 20% significantly boosts compressive strength; however, beyond this level, further replacement yields diminishing or slightly reduced strength, indicating an optimal threshold for copper slag utilisation.

The addition of steel fibers up to a 2.0% volume fraction across various concrete mixes significantly improved compressive, tensile, and flexural strengths, with optimal performance observed at a 1.5% dosage. Specifically, the M23 mix exhibited a 40.92% increase in split tensile strength and a 43.55% improvement in Flexural Strength of Concrete compared to the M1 mix.

For the mix CCSNSA series, increasing steel-fiber content from 1.5% to 2.0% produces a 2.3% gain in compressive strength while decreasing split-tensile (0.8%) and flexural (4.1%) strengths, so considering mechanical performance, serviceability, and constructability, 1.5% steel fiber is recommended as the overall optimal uniform dosage.

The predictive models developed in this study demonstrated strong alignment with experimental outcomes, accurately estimating compressive, tensile, and flexural strengths. The predicted splitting tensile (ft) and flexural (fcr) models showed high reliability, with minimal deviation from experimental data, ACI equations, and other researchers' models, confirming their applicability for similar concrete compositions.

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