

High strength concrete innovations: hybrid blends with silica fume, nano-coated aggregates, and steel fibres – experimental and fea-based performance insights

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ABSTRACT

This research assesses the improvement in concrete properties through the application of silica fume, nano-coated coarse aggregates, and steel fibres in 14 mixes. Mechanical tests were conducted at 7, 14, 28, and 90 days. Optimum mix M13, 85% cement, 15% silica fume, 80% coarse aggregates, 20% nano-coated aggregates, and 1.5% steel fibers, recorded the highest value of 103.25 MPa compressive, 9.305 MPa split tensile, and 10.433 MPa flexural strength at 28 days. Compared to normal concrete (M1), with values of 87.14 MPa, 7.853 MPa, and 8.805 MPa, respectively, M13 exhibited enhancement in strengths of more than 18% compressive, 18.5% tensile, and 18.5% flexural strength. Flexural response from experiment of the beams under load also exhibited less deflection in M13 (10.39 mm at 300 kN) than in M1 (11.38 mm), warranting enhanced ductility. Finite Element Analysis using ANSYS agreed with experimental trends with almost the same deflection values. X-ray Diffraction (XRD) analysis validated increased crystallinity and hydration of M13 with sharp peaks pointing to increased pozzolanic activity and greater microstructure than regular concrete. These results validate the efficiency of the combined application of silica fume, nano-modified aggregates, and steel fibres in the production of long-lasting, high-performance concrete for structural use.

Keywords: Silica fume; nano coated aggregates; steel fibres; flexural behaviour; FEA.

1. INTRODUCTION

Silica fume is widely known to be a highly effective pozzolanic cement-based material admixture. It enhances mechanical properties such as compressive and flexural strength, particularly when used at optimal replacement levels (typically 6–10% by cement weight) [1, 2]. Silica fume refines the microstructure of the cement matrix, leading to improved density and reduced water absorption, and raises the strength of the interfacial transition zone between cement paste and aggregates [3, 4]. Silica fume is especially beneficial in recycled aggregate concrete, compensating for the inferior properties of recycled aggregates and promoting early and late-age strength [5, 6].

Nano-silica, with its high pozzolanic activity and small particle size, improves the mechanical characteristics of concrete even more. It causes early strength gain and, if combined with silica fume, enhances synergistic effects improving early and late-age concrete characteristics [7, 8]. Nano-silica also improves the pore structure and enhances the formation of calcium silicate hydrate, leading to a denser, stronger matrix [9, 10]. Applications of nano-silica-coated steel fibers or aggregates address the fiber-matrix interface, improving interfacial bond strength and macro-mechanical properties considerably [11].

Steel fibers have been seen to enhance toughness, cracking strength, and impact strength of concrete. Steel fiber content enhances compressive and tensile strength, and tensile and flexural property enhancement is most prominent [12, 13]. Steel fiber bridging action across cracks provides improved post-peak response and fracture toughness [14]. Combination of steel fibers with silica fume or nano-silica further enhances these benefits due to the better matrix-fiber bond and more compact matrix, due to which there is greater strength and ductility [15].

The combination of silica fume, nano-silica, and steel fibers—sometimes with nano-coated aggregates or fibers—exhibits superior mechanical properties to the use of any one of these additives or reinforcements alone. Tests consistently demonstrate that the most effective mixtures (6–10% silica fume, 1–2% nano-silica, and 0.5–2% steel fibers by volume) yield significant increases in compressive, tensile, and flexural strengths, durability, and reduced water absorption [16, 17]. Hybrid fiber systems, e.g., steel and other fibers, can also enhance toughness and synergy, especially in high-performance and recycled aggregate concretes [18].

Recent research has proven the positive impacts of silica fume, nano-silica, and steel fibers on the mechanical and durability characteristics of concrete [19]. Yet, various gaps in research still exist, more so the in-depth understanding of synergisms between the additives. The employed methodology, through the combined addition of silica fume (0–25%), nano-coated aggregates (0–40%), and steel fibers (0–2%), is well backed by current literature, which invariably reports noteworthy improvements in strength, ductility, and matrix densification. Emphasis on both the improvements in the bulk matrix and the fiber-matrix interfacial properties is in the line of accepted strategies in high-performance concrete development.

Despite the well-established individual benefits of silica fume, nano-silica, and steel fibers in enhancing concrete performance, there remains a significant gap in understanding their combined or synergistic effects, particularly in the context of recycled aggregate concrete. Most existing studies focus on single-component modifications, with limited attention to the interactions between these advanced materials when used together. Additionally, there is a lack of detailed microstructural analysis, such as the effects on interfacial transition zones and the fiber–matrix bond, which are critical to understanding performance improvements. Optimal dosage combinations for hybrid systems have not been sufficiently investigated, especially concerning their impact on both mechanical and durability properties. Furthermore, the application of these materials in recycled aggregate concrete is still underexplored, despite its growing relevance for sustainable construction. Another major gap lies in the limited field-level validation of laboratory findings, with very few studies assessing long-term durability under real-world environmental conditions. Finally, sustainability aspects, including life cycle assessments of mixes incorporating silica fume, nano-silica, and steel fibers, have received minimal attention, highlighting the need for more comprehensive evaluations to support practical implementation.

This study aims to explore the optimal combination of silica fuel, nano coated aggregates, and steel fibers in concrete mixtures and investigate their synergistic effects on mechanical properties, microstructure, and flexible behavior through extensive experimental tests and finite element analysis, providing a scientific basis for the practical application of high-performance concrete in structural engineering.

2. MATERIALS

2.1. Cementitious materials

Silica fume and cement are both major components of high-performance concrete, each contributing different physical properties to enhance the overall quality of the material. Ordinary Portland Cement 53 grade is a grey powder with a specific gravity of 3.14 and a surface area of 2270 cm²/gm [20, 21]. It has a mean particle size of less than 90 microns and a volume expansion of 3 mm, which is an indication of good dimensional stability. OPC has a bulk density of around 1.47 g/cc and a Blaine fineness of 3220 cm²/g, which is sufficient for normal construction requirements. Silica fume is an ultrafine, white pozzolanic powder with a much lower specific gravity of 2.2 and a much higher surface area of 18,000 cm²/gm. While it has the same range of particle sizes (<90 microns), silica fume is much finer in surface area and fineness, at 22,000 cm²/g. Its bulk density is much lower, at around 0.3 g/cc, which is characteristic of its light and porous nature. These physical properties render silica fume highly reactive and well-suited to enhance the strength, durability, and impermeability of concrete when mixed with cement. Table 1 shows the physical properties of cementitious materials. Figure 1 and 2 shows the chemical properties of cement and silica fume.

2.2. Coarse aggregates

Nano-coated coarse aggregates and coarse aggregates have similar general physical properties like size and shape, both angular and 20 mm in size, which is optimal for structural concrete. The differences, however, are marked in their specific properties due to the presence of the nano-coating. The specific gravity of the conventional coarse aggregates is ever so slightly greater at 2.74 than that of nano-coated aggregates at 2.71 [22, 23]. Water absorption is ever so slightly lower in nano-coated aggregates (0.4%) compared to 0.75% in conventional aggregates, reflecting improved impermeability and lower porosity. Whereas conventional aggregates are lower in crushing value at 17.56%, nano-coated ones register a slightly higher value of 20.15%, reflecting a slight compromise in compressive strength. Likewise, impact strength is ever so slightly lower in conventional aggregates (14.71%) compared to nano-coated ones (17.19%), reflecting better performance under dynamic loading in the latter. Bulk density is ever so slightly lower from 1625 kg/m³ in conventional aggregates to 1512 kg/m³ in the nano-coated variety due to the lighter coating. Also, the moisture content is ever so lower in nano-coated aggregates (0.34%) compared to conventional ones (0.8%), further aiding their improved durability. The values of fineness modulus are near, at 6.9 for conventional and 6.8 for nano-coated aggregates, reflecting identical gradation. Overall, nano-coated coarse aggregates offer superior durability and resistance to moisture and yet retain identical structural properties [24]. Table 2 presents the physical properties of conventional coarse aggregate and nano coated coarse aggregates.

Table 1: Shows the physical properties of cementitious materials.

PHYSICAL COMPOSITION	CEMENT	SILICA FUME
Grade	OPC 53	–
Colour	Grey	White
Specific gravity	3.14	2.2
Surface area (cm ² /gm)	2270	18,000
Physical state	Powder	Ultrafine powder
Size microns mean	<90	<90
Volume Expansion	3 mm	–
Bulk Density g/cc	1.47	0.3
Fineness cm ² /g	3220	22,000

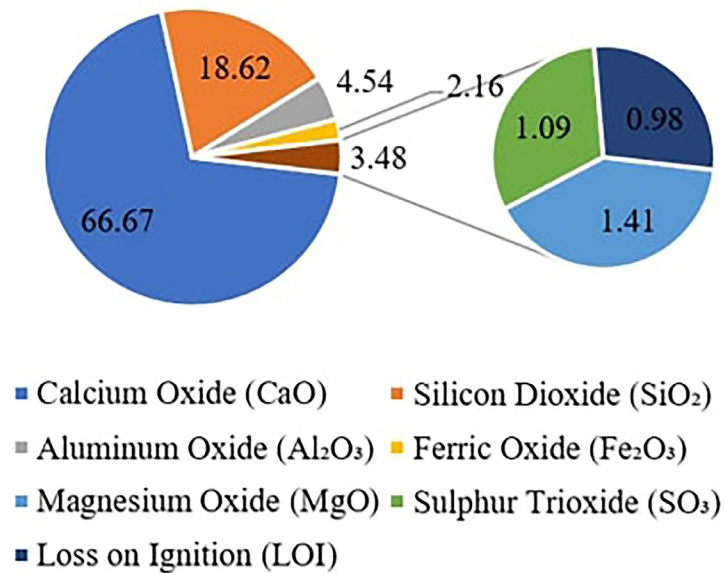
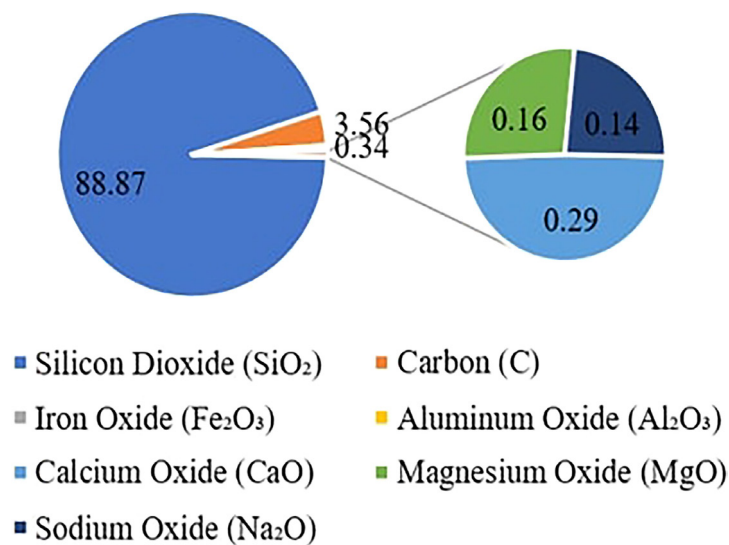
**Figure 1:** Chemical properties of cement.**Figure 2:** Chemical properties of silica fume.

Table 2: Physical properties of coarse aggregates.

PROPERTIES	COARSE AGGREGATES	NANO COATED COARSE AGGREGATES
Size and Shape	20 mm & Angular	20 mm & Angular
Specific Gravity	2.74	2.71
Water Absorption (%)	0.75	0.4
Crushing Value (%)	17.56	20.15
Impact Strength (%)	14.71	17.19
Bulk Density (kg/m ³)	1625	1512
Moisture Content (%)	0.8	0.34
Fineness Modulus (%)	6.9	6.8

2.3. Fine aggregate

Fine aggregates of concrete possess a number of significant physical characteristics influencing workability, strength, and durability. Size and shape determining fineness modulus of 1.5 characterize the material as comparatively fine grained [25, 26]. Specific gravity of 2.36 in fine aggregates determines suitable density for use in concrete mixes. Low water absorption of 0.35% reveals low porosity and explains improved durability and reduced water demand in mixes. Bulk density is relatively high at 2750 kg/m³, reflecting stability and material density. Moisture content is moderate at 1.29%, which should be taken into account during mix design for the purpose of encouraging consistency in workability and strength. Overall, these characteristics make the fine aggregates suitable for use in high-performance concrete where fine particle size and limited moisture properties are needed. Physical characteristics of fine aggregates are presented in Table 3.

Table 3: Physical properties of fine aggregates.

PROPERTIES	FINE AGGREGATES
Size and Shape	1.15
Specific Gravity	2.36
Water Absorption (%)	0.35
Bulk Density (kg/m ³)	2750
Moisture Content (%)	1.29
Fineness Modulus (%)	1.5

2.4. Steel fibres

Steel fibres used for concrete reinforcement possess unique physical properties that enhance the mechanical performance and cracking resistance of the composite [27]. With a diameter of 0.5 mm and length of 50 mm, the fibres possess an excellent aspect ratio for effective stress distribution in the concrete matrix. The high tensile strength of 1035 MPa plays a critical role in reinforcing the post-cracking behavior, impact resistance, and toughness of the concrete. The density of 7830 kg/m³ also ensures the fibres are effectively distributed in the mix without excessive segregation. Such properties make steel fibres suitable for use in structures where increased durability, ductility, and fatigue resistance are needed. Table 4 indicates the physical properties of steel fibres.

Table 4: Physical properties of steel fibres.

PHYSICAL PROPERTIES	STEEL FIBRES
Diameter	0.5 mm
Length	50 mm
Tensile Strength	1035 MPa
Density	7830 kg/m ³

2.5. Super plasticizer

Polycarboxylate ether (PCE) type superplasticizer is a water-reducing admixture with high workability, high water reduction (to 30%), and good retention of slump. It increases strength, durability, and flowability of the concrete and minimizes shrinkage and permeability. PCE has excellent dispersing power, early strength, and compatibility with diverse cements and is suitable for high-strength and high-performance concretes and is an excellent material in contemporary construction techniques.

3. METHODOLOGY

The below is the procedure adopted to study the mechanical performance and behavior of supplementary material and additive modified concrete, like Silica Fume, Nano-Coated Coarse Aggregates, Steel Fibres, and a Polycarboxylate Ether (PCE) based superplasticizer. The laboratory tests conducted are Compressive Strength, Split Tensile Strength, Flexural Strength, and Flexural Behavior of Concrete Beams, and Finite Element Analysis (FEA) comparison through ANSYS.

Various mix ratios were created by substituting cement with silica fume (5%–25%) and using various percentages of nano-coated aggregates (10%–40%) and steel fibres (0.5%–2%). Concrete was mixed in a mechanical mixer for even material distribution. Cube ($150 \times 150 \times 150$ mm), cylinder (150×300 mm), prism ($100 \times 100 \times 500$ mm), and beam ($150 \times 150 \times 700$ mm) test specimens were cast. Specimens were demolded after 24 hours and immersed in water at 27°C until the day of testing (7, 14, 28, and 90 days).

Compressive Strength Test is carried out on cube specimens on a compression testing machine according to IS:516. Split Tensile Strength Test is carried out on cylindrical specimens to find tensile capacity according to guidelines given in IS:5816. Flexural Strength Test on prism specimens is carried out under third-point loading conditions to find modulus of rupture according to IS:516. Flexural behavior of beams is tested using full-scale beam specimens loaded under two-point loading, mid-span deflection being measured in terms of dial gauges at incremental stages of loading. Concrete beams, i.e., the control mix M1 and optimized mix M13, were created in ANSYS Workbench by using suitable material properties and meshing techniques. A static structural analysis was carried out to represent the experimental two-point loading test setup. Measurement of deflections was taken and compared with experiment results to check for validation and perform behavioral analysis.

Experimental results were charted and contrasted among all mixes to determine trends in performance. Plots of strength gain versus time were graphed for compressive, tensile, and flexural performance. Experimental deflection behavior was contrasted directly with ANSYS FEA output in an effort to confirm the validity of the model and validate mechanical performance of the altered concrete mixes.

4. MIX PROPOSITION

Mix designation consists of 14 concrete mixes to investigate performance differences. M1 is normal concrete, and M2–M6 have cement replaced by 5% to 25% silica fume. M7–M10 have nano-coated aggregates in increasing proportions. M11–M14 have steel fibres (0.5% to 2%) with 15% silica fume and 20% nano-coated aggregates. The mixes are to identify enhancements in mechanical properties as a result of the synergistic effects of mineral admixtures, nano materials, and fibre reinforcement. Table 5 provides the mix designation.

Table 5: Shows the mix designation.

MIX	MIX DESIGNATION
M1	Conventional concrete
M2	95% Cement + 5% Silica Fume
M3	90% Cement + 10% Silica Fume
M4	85% Cement + 15% Silica Fume
M5	80% Cement + 20% Silica Fume
M6	75% Cement + 25% Silica Fume
M7	85% Cement + 15% Silica Fume + 90% Coarse Aggregate + 10% Nano Coated Aggregates
M8	85% Cement + 15% Silica Fume + 80% Coarse Aggregate + 20% Nano Coated Aggregates
M9	85% Cement + 15% Silica Fume + 70% Coarse Aggregate + 30% Nano Coated Aggregates
M10	85% Cement + 15% Silica Fume + 60% Coarse Aggregate + 40% Nano Coated Aggregates
M11	85% Cement + 15% Silica Fume + 80% Coarse Aggregate + 20% Nano Coated Aggregates + 0.5% Steel Fibres
M12	85% Cement + 15% Silica Fume + 80% Coarse Aggregate + 20% Nano Coated Aggregates + 1% Steel Fibres
M13	85% Cement + 15% Silica Fume + 80% Coarse Aggregate + 20% Nano Coated Aggregates + 1.5% Steel Fibres
M14	85% Cement + 15% Silica Fume + 80% Coarse Aggregate + 20% Nano Coated Aggregates + 2% Steel Fibres

5. RESULTS AND DISCUSSION

5.1. Compressive strength test

The compressive strength of fourteen different concrete mix designs was evaluated at curing intervals of 7, 14, 28, and 90 days to study the effect of silica fume, nano-coated aggregates, and steel fibres on mechanical performance.

5.1.1. Effect of silica fume (mixes M1–M6)

Incorporating silica fume progressively increased the compressive strength compared to conventional concrete (M1). At 28 days, M1 recorded 87.14 MPa, while M5 (20% silica fume) reached 94.26 MPa—a 8.2% increase. The optimal dosage appears to be 20% (M5), after which a slight decline was noted in M6 (25% silica fume), suggesting a threshold beyond which the pozzolanic effect may saturate or cause microstructural changes that slightly compromise strength.

5.1.2. Effect of nano-coated aggregates (mixes M4, M7–M10)

M4 mix (15% silica fume), nano-coated aggregates in different proportions were utilized. Increased proportions of nano aggregate improved the compressive strength. M7 (10% nano aggregate) at 28 days showed 95.24 MPa, and M9 (30%) showed the highest strength of 98.42 MPa. M10 (40%) dipped slightly to 96.05 MPa, which shows excess nano material will cause agglomeration or less bonding efficiency. Therefore, 30% nano-coated aggregate (M9) seems to be optimal for strength.

5.1.3. Effect of steel fibres (mixes M8, M11–M14)

The addition of steel fibres also enhanced compressive strength, particularly at advanced curing ages [28]. M12 (1% steel fibres) recorded 101.98 MPa at 28 days and 104.26 MPa at 90 days, which was better than all other mixes. Although M13 (1.5% fibres) was marginally better than M12, the marginal improvement (1.2%) might not be worth the added fibre content and cost. M14 (2% fibres) recorded a strength reduction, which is probably due to decreased workability or fibre clustering, which can lead to microvoids or stress concentration zones.

5.1.4. Overall observations

- Early-age strength (7 & 14 days) showed consistent improvement with higher silica fume and nano materials, indicating accelerated pozzolanic and densification effects.
- The 28 and 90 days strength analysis verifies that the simultaneous use of 15% silica fume, 20–30% nano-coated aggregate, and 1–1.5% steel fibers maximizes compressive performance.
- The best mechanical performance mix design is M13, which has achieved 103.25 MPa at 28 days and 105.56 MPa at 90 days, an ~18.5% increment over normal concrete at 28 days.

These findings reveal that a synergistic combination of pozzolanic, nanomaterial, and fibre reinforcement methods can increase the compressive strength of concrete significantly, creating more durable and high-performance construction materials. Figure 3 demonstrates the outcome of the compressive strength test.

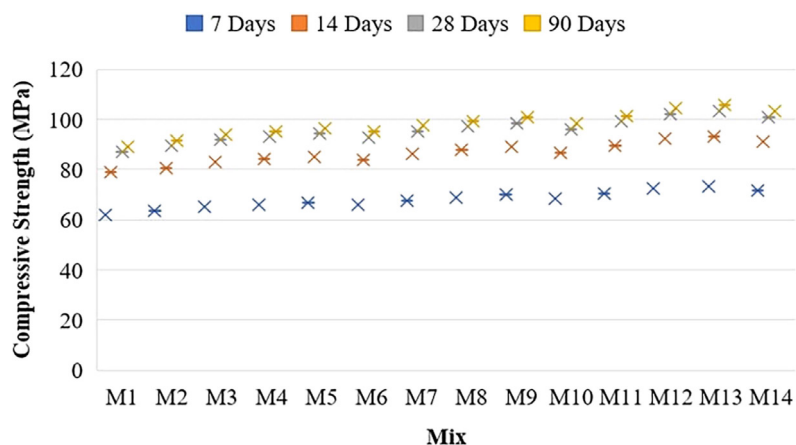


Figure 3: Compressive strength test results.

5.2. Split tensile strength test

Split tensile strength was investigated on fourteen various concrete mix designs at curing ages of 7, 14, 28, and 90 days to determine the influence of silica fume, nano-coated aggregates, and steel fibers on tensile properties.

5.2.1. Effect of silica fume (mixes M1–M6)

Relative to control mix (M1), adding silica fume (M2–M5) enhanced tensile strength for every curing age. At age 28 days, M1 held 7.853 MPa, and M5 (20% silica fume) held 8.495 MPa—enhanced by about 8.2%. This is due to silica fume pozzolanic reaction, resulting in increased microstructure and adhesion strength at the cement paste and aggregates interfaces. Nevertheless, M6 (25% silica fume) exhibited a marginally reduced effect, suggesting high silica content is associated with potential agglomeration of the particles or extensive shrinkage leading to a deteriorating tensile performance by about 1.7%.

5.2.2. Effect of nano-coated aggregates (mixes M4, M7–M10)

With M4 with 15% silica fume as the reference mixture, the incorporation of nano-coated aggregates significantly improved the tensile strength. At 28 days, M7 with 10% nano-coated aggregate registered a tensile strength of 8.583 MPa, M8 with 20% registered 8.747 MPa, M9 with 30% achieved a maximum of 8.870 MPa, and M10 with 40% had a slight decrease to 8.656 MPa. This indicates that the optimal ratio of nano-coated aggregate is 30%, beyond which the efficiency of dispersion and bonding may be undermined by agglomeration or discontinuity of matrix.

5.2.3. Effect of steel fibres (mixes M11–M14)

The addition of steel fibres to the optimal nano-silica mix (M8) significantly improved tensile strength of M11 (0.5% fibres) to 8.936 MPa, M12 (1%) to 9.190 MPa, M13 (1.5%) to slightly higher at 9.305 MPa, and M14 (2%) to 9.095 MPa. The results verify that steel fibres span microcracks, improve load transfer, and retard crack growth. Performance decreased slightly at fibre addition greater than 1.5%, perhaps due to poor workability or fibre clustering that compromises effective bonding.

5.2.4. Overall observations

- Split tensile strength increased steadily with silica fume up to 20%, nano-coated aggregates up to 30%, and steel fibres up to 1.5%.
- The highest tensile strength at 28 days was observed in M13 (9.305 MPa), representing a ~18.5% increase over conventional concrete (M1).
- Long-term tensile strength (90 days) also showed consistent gains, supporting the durability and crack resistance potential of the modified mixes.

This research illustrates that a synergistic combination of 15% silica fume, 20–30% nano-coated aggregates, and 1–1.5% steel fibers significantly improves the split tensile strength of the concrete, and hence its tensile strength and resistance to cracking, and hence it is suitable for high-performance structural use. Figure 4 illustrates split tensile strength test results.

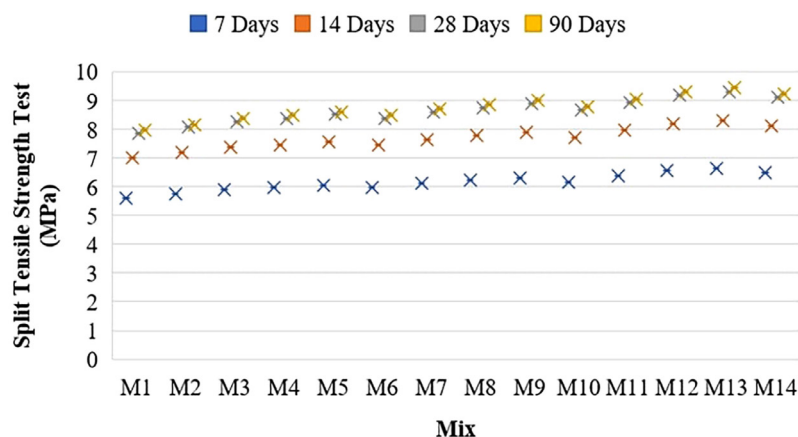


Figure 4: Split tensile strength test results.

5.3. Flexural strength test

The flexural strength of various concrete mixes was evaluated at 7, 14, 28, and 90 days to assess the impact of silica fume, nano-coated aggregates, and steel fibres on resistance to bending and cracking under load.

5.3.1. Effect of silica fume (mixes M1–M6)

The addition of silica fume enhanced the flexural strength across all ages. The control mix M1 (plain concrete) was 8.805 MPa at 28 days, whereas M5 (20% silica fume) was 9.324 MPa, a 5.9% enhancement. This is due to the pozzolanic reaction, which fills the matrix and strengthens the interfacial transition zone (ITZ) between cement paste and aggregates. With more than 20% silica fume, there was a slight reduction for M6 (25%), indicating a point of saturation after which the advantage tapers off or reverses due to excess fines or workability issues.

5.3.2. Effect of nano-coated aggregates (mixes M4, M7–M10)

Mixing nano-coated aggregates with the best mix of silica fume (M4) yielded dramatic flexural strength gains for M7 (10% nano aggregate) at 9.423 MPa, M9 (30%) at 9.645 MPa, and M10 (40%) dropped back to 9.505 MPa. This demonstrates the effectiveness of nano-materials to enhance bond strength and cracking resistance up to an optimum level (~30%), after which dispersion issues or compromised paste content could impact performance.

5.3.3. Effect of steel fibres (mixes M11–M14)

The incorporation of steel fibres significantly enhanced the flexural capacity via crack bridging and improved post-cracking characteristics of M11 (0.5% fibres) achieved 9.760 MPa, M12 (1%) achieved 9.960 MPa, M13 (1.5%) achieved the highest value of 10.433 MPa and M14 (2%) dropped slightly to 10.197 MPa. M13's superior performance at all ages justifies 1.5% as the optimum steel fibre content, getting a balance between workability and reinforcement. Beyond this, the benefits declined due to fibre increasing or reduced mix homogeneity.

5.3.4. Overall observations

- Flexural strength consistently increased with optimized levels of silica fume, nano-coated aggregates, and steel fibres.
- The 28-day strength improved from 8.805 MPa in conventional concrete (M1) to 10.433 MPa in M13—a ~18.5% gain.
- Long-term (90-day) strength reached 10.654 MPa in M13, suggesting excellent durability and structural performance.
- The best-performing mix, M13, included 15% silica fume, 20% nano-coated aggregates, and 1.5% steel fibres, indicating a synergistic effect among all three components.

These results highlight the capability of supplementary materials and fibre reinforcement in greatly improving the flexural properties of concrete to be more resistant to bending stress and cracking over time. Flexural strength test results are indicated in Figure 5.

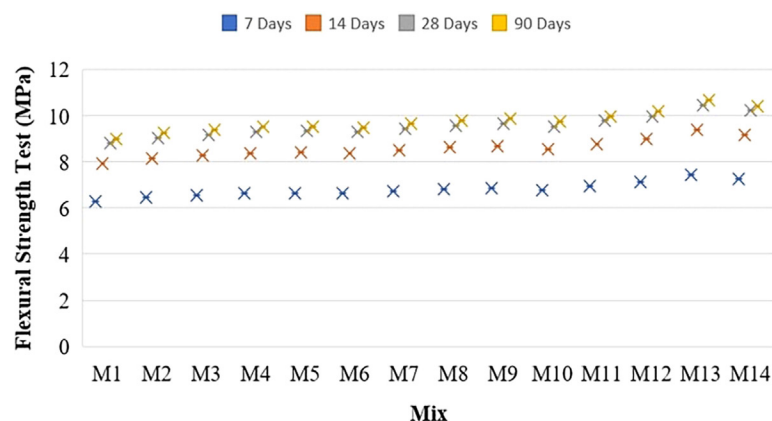


Figure 5: Flexural strength test results.

5.4. Flexural behaviour of beams

The load-deflection behavior was investigated for the conventional concrete (M1) and for the hybrid enhanced mixture (M13: 85% cement, 15% silica fume, 20% nano-coated aggregates, and 1.5% steel fibers). Response measurements were taken at incremental steps of loading from 0 to 300 kN, and corresponding deflections were recorded.

5.4.1. Initial load response

At lower load levels (up to 30 kN), both mixes exhibited zero deflection, which is a measure of initial stiffness and elastic behavior. But M13 always registered a smaller deflection than M1, thus proving its higher stiffness and resistance to deformation due to its optimally distributed matrix and reinforcement.

5.4.2. Mid-range load performance (30–150 kN)

As the load increased, both mixes began to deform progressively:

- At 100 kN, M1 showed a deflection of 4.22 mm, while M13 recorded only 3.85 mm (approx. 8.8% less).
- This trend reflects the stiffer and more crack-resistant structure of M13, aided by fibre bridging and dense packing from silica fume and nano-coated aggregates.

5.4.3. High load range and ductility (150–300 kN)

In the higher load range:

- At 200 kN, deflection in M1 was 7.47 mm, compared to 6.82 mm in M13.
- At peak load (300 kN), M1 reached 11.38 mm deflection, while M13 recorded 10.39 mm, a reduction of ~8.7%, highlighting better control over cracking and energy absorption.

The results clearly illustrate that M13 can sustain higher loads while at the same time showing lower deformation, thus emphasizing its increased toughness and ductility. The application of steel fibres is particularly important under higher loads since they slow the propagation of cracks and allow the transfer of tensile stresses within the matrix.

5.4.4. Conclusion

- M13 outperformed M1 across the full load range in terms of stiffness, crack control, and ductility.
- The deflection behavior confirms the effectiveness of using silica fume, nano-coated aggregates, and steel fibres together to produce concrete that is both strong and resilient under flexural loading.
- These improvements make M13 an ideal candidate for high-performance structural applications, especially where load-induced cracking or long-term deformation is a concern. Figure 6 shows the deflection of beams.

5.5. Finite element analysis

To simulate the structural behavior of both conventional concrete (M1) and the optimized concrete mix (M13), a finite element analysis was conducted using ANSYS Workbench 2021 R2. This simulation aimed to evaluate load–deflection characteristics and visualize stress–strain development under flexural loading, in alignment with experimental results.

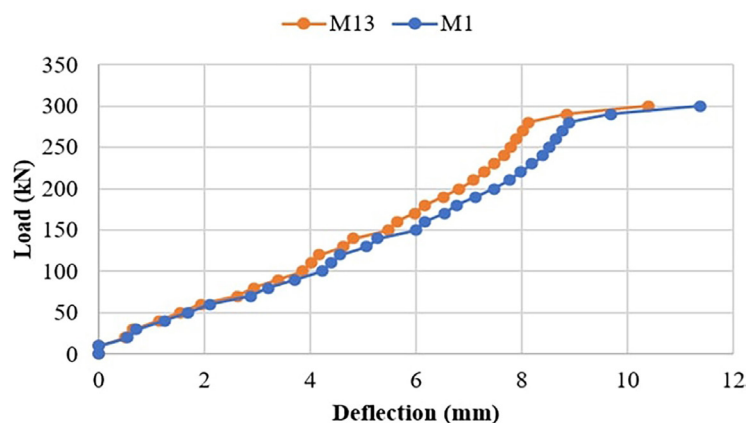


Figure 6: Deflection of beams.

5.5.1. Model establishment

Geometry and Meshing: A three-dimensional model of the notched beam used in experimental testing was created. The beam was discretized using SOLID65 elements, which are suitable for modeling nonlinear concrete behavior with cracking and crushing capabilities. A structured mesh with adequate refinement was applied to ensure numerical accuracy without excessive computation time.

Model the concrete beam or specimen with precise dimensions matching experimental setups (e.g., for flexural test: 100×100×1000 mm beam). Use SOLID65 elements in ANSYS for modeling concrete with cracking and crushing capabilities. For steel fibers, embedded element technique or equivalent material property enhancement can be applied. Conduct a mesh sensitivity study by refining the mesh (e.g., 20 mm → 10 mm → 5 mm) and comparing deflections and stress values. Choose the mesh that balances accuracy and computational cost. Mesh with element size of 10 mm showed less than 2% change in deflection compared to 5 mm, indicating convergence.

5.5.2. Material properties and constitutive model

The concrete material was modeled as nonlinear, elastic–plastic, with multilinear isotropic hardening. For M1, standard mechanical properties of normal concrete were used. For M13, experimentally obtained properties reflecting enhanced stiffness and ductility (due to nano-coated aggregates, silica fume, and steel fibers) were implemented. The Willam–Warnke failure criterion was used to capture concrete cracking and crushing behavior. Steel Reinforcement (if modeled): Reinforcement bars were modeled using LINK180 elements with perfect bond assumptions, where applicable.

Use nonlinear material models with Concrete compressive and tensile strength. Elastic modulus and Poisson's ratio. Concrete damage parameters based on empirical relationships. Represent fibres as enhanced post-crack tensile strength or use smeared reinforcement modeling.

The material modelling limitations are Homogenization of fibre effects may not capture localized bridging. Nano-coating effects are reflected through adjusted material properties but not explicitly modeled. Time-dependent effects (creep/shrinkage) are neglected.

5.5.3. Boundary conditions and loading

The beam was supported in a simply supported configuration, replicating the three-point bending test. A displacement-controlled load was applied at the midpoint using incremental steps up to 300 kN. Symmetry and proper constraints were applied to prevent rigid body motion and ensure realistic simulation. Simply supported boundary conditions to mimic experimental conditions—displacement constraints applied to replicate pin and roller supports. Apply a central or two-point load as per the flexural test configuration. Use displacement control to simulate gradual loading and capture post-peak behavior.

Finite Element Analysis was conducted to simulate and analyze the deflection behavior of normal concrete (M1) and the optimized mix (M13) under increasing loads up to 300 kN. The results show the predicted structural behavior and yield insights that correspond to the experimental findings.

5.5.4. Early-stage behavior (0–30 kN)

- Deflection was negligible up to 10 kN for both mixes.
- At 20 kN, M1 showed 0.52 mm deflection and M13 0.50 mm—a marginal difference indicating similar initial stiffness.
- At 30 kN, M13 maintained lower deflection (0.65 mm) than M1 (0.68 mm), continuing this trend through the loading cycle.

5.5.5. Mid-range load response (40–150 kN)

As the load increased, the best proportion always recorded lower deflections, M1 was 4.02 mm and M13 was 3.82 mm (~5% less) at 100 kN. At 150 kN, M13 recorded 5.42 mm compared to M1's 5.71 mm.

The progressive decrease in deflection in M13 indicates better elastic and initial plastic behavior, owing to better interfacial bonding, matrix densification, and crack-bridging action of steel fibres.

5.5.6. High load and ductile behavior (160–300 kN)

Beyond 150 kN, the deflection gap grew, At 200 kN: M1 is 7.12 mm, M13 is 6.76 mm. At 300 kN: M1 is 10.84 mm, M13 is 10.29 mm. M13 resisted heavy loads with minimal deflection, indicating more energy absorption and crack resistance, demonstrating the ductility given by steel fibres and nano-reinforcement.

5.5.7. Comparison with experimental data

The FEA follows the experimentally observed tendencies very closely. Although numerical deflection values are lower than in actual experiments (because of idealized boundary conditions and material homogeneity in simulations), relative performance gain of M13 over M1 is the same for both approaches.

5.5.8. Conclusion

- The FEA model validates the experimental observations, confirming that M13 has superior load-bearing behavior with lower deflections at all stages.
- The combination of silica fume, nano-coated aggregates, and steel fibres provides a synergistic effect, enhancing stiffness, ductility, and durability.
- M13 demonstrates significant potential for advanced structural applications where deformation control and long-term stability are vital. Figure 7 and 8 shows the deflection profile of M1 mix and M13 mix. Figure 9 and 10 shows the plastic strain of M1 mix and M13 mix. Figure 11 and 12 shows the load deflection curve and comparison of experimental and FEA load deflection curves.

5.6. XRD analysis

The following X-ray diffraction (XRD) analysis presents the mineralogical makeup of two samples, M1 and M13, that were used in this study. The diffractograms of the two samples are clear and intense, indicative of the crystalline nature of the materials.

M1 shows very prominent peaks at about 27° , 32° , and 50° in the 2θ range, characteristic of crystalline phases normally associated with Quartz (SiO_2) and C_3S (Tricalcium Silicate). The prominence of these observed peaks suggests a high concentration of silicate minerals, thus confirming the addition of silica fume to the mix. The presence of minor peaks also suggests the presence of C_2S (Dicalcium Silicate) and other hydration products like ettringite, which in combination contribute to strength properties.

M13, with the addition of nano-coated aggregates and steel fibers, possesses more pointed and more intense peaks compared to M1—i.e., at the 29° , 33° , and 59° 2θ positions. The peaks are because of the Calcium Hydroxide ($\text{Ca}(\text{OH})_2$) phases, Quartz, and Portlandite. The increased peak intensities and increased peak widths signify enhanced crystallinity and the ability of pozzolanic reactions to take place, facilitated by the addition of nano-coated aggregates and silica fume.

C: Conventional concrete.

Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s

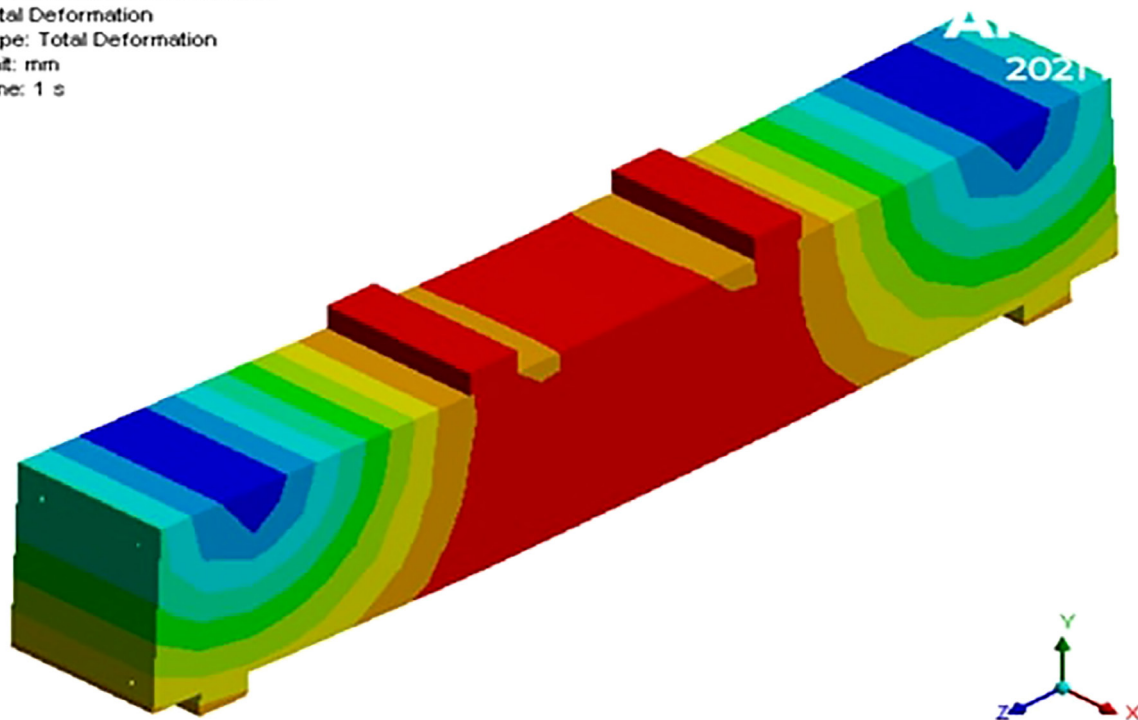


Figure 7: Deflection profile of M0 mix.

C: Conventional concrete.
Equivalent Plastic Strain
Type: Equivalent Plastic Strain
Unit: mm/mm
Time: 0.25 s

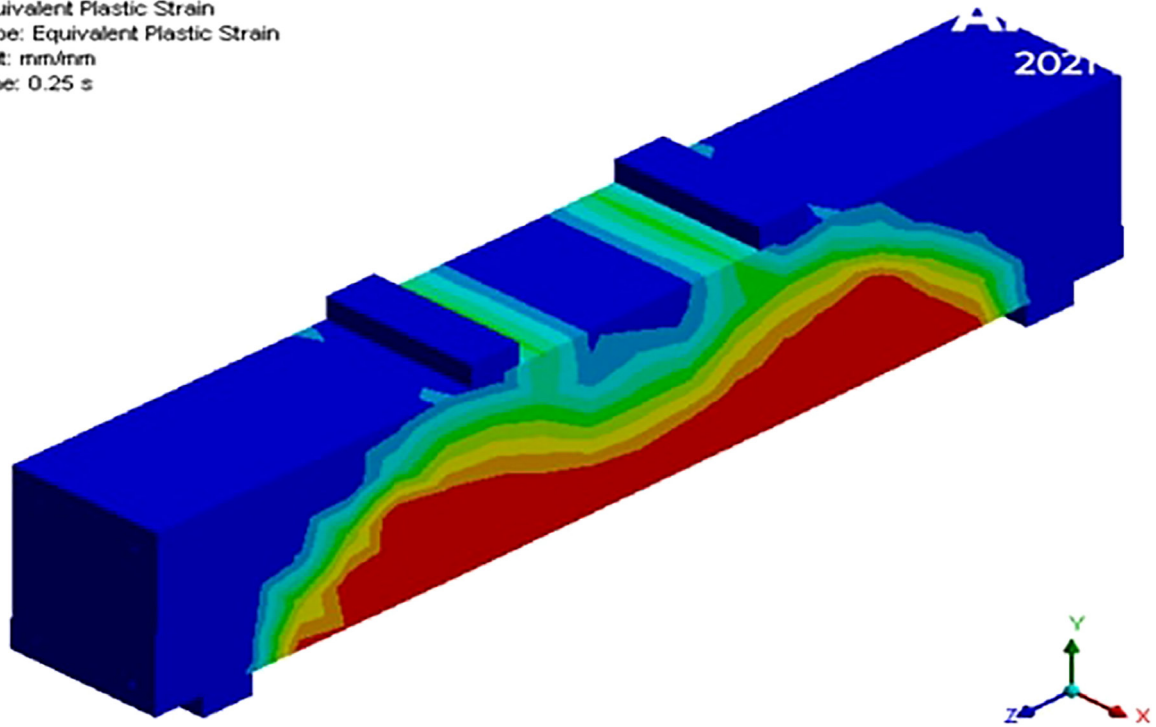


Figure 8: Deflection profile of M13 mix.

D: Replacement concrete
Total Deformation
Type: Total Deformation
Unit: mm
Time: 0.95 s

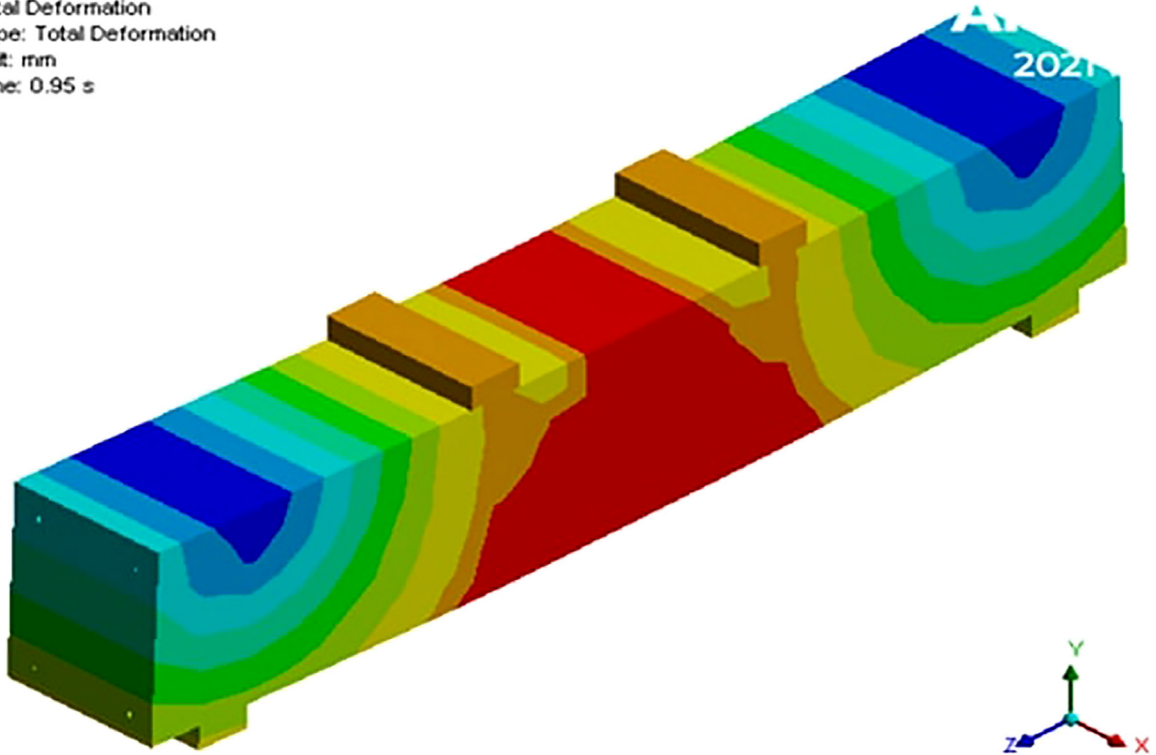


Figure 9: Plastic strain for M1 mix.

D: Replacement concrete
Equivalent Plastic Strain
Type: Equivalent Plastic Strain
Unit: mm/mm
Time: 0.175 s

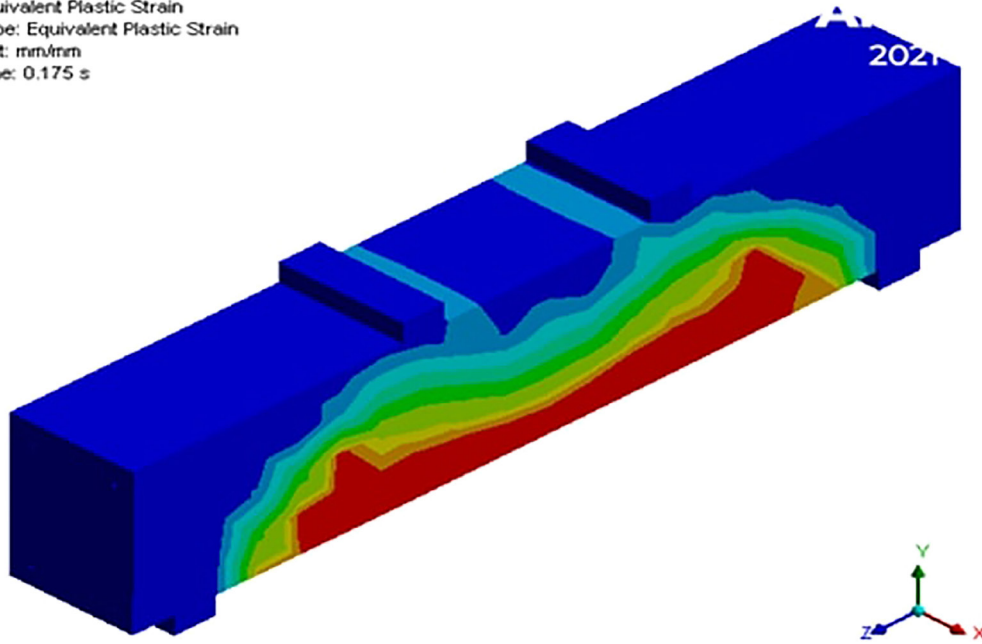


Figure 10: Plastic strain for M13 mix.

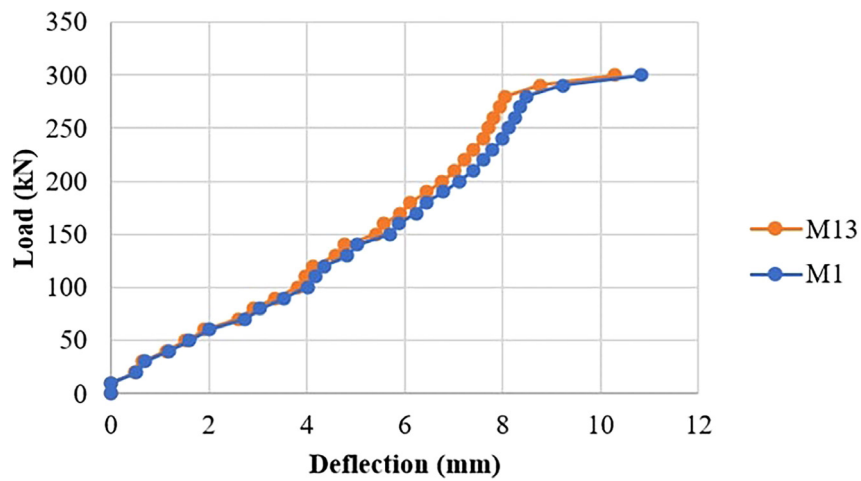


Figure 11: Load deflection curve.

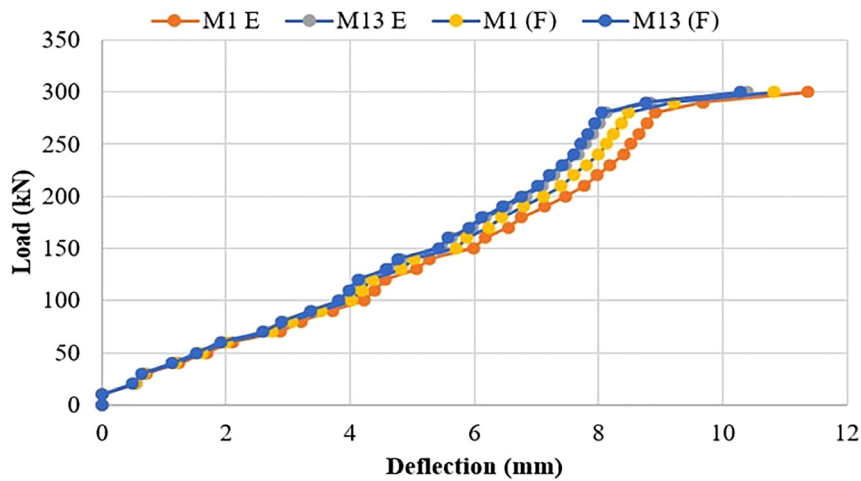


Figure 12: Comparison of experimental and FEA load deflection curves.

In summary, M13 has higher crystalline intensity, which reflects a greater level of microstructural refinement as a result of the synergistic action of silica fume, nano-coatings, and steel fibres. This result is consistent with the mechanical test results, where M13 had greater compressive strength (103.25 MPa), split tensile strength (9.305 MPa), and flexural strength (10.433 MPa) than normal concrete. These results confirm the assertion that the incorporation of nano-materials and fibres greatly enhances the durability and strength characteristics of concrete.

The superior mechanical performance of Mix M13 can be attributed to its refined microstructure, as evidenced by XRD analysis. The sharper and more intense peaks for quartz and portlandite indicate higher crystallinity and enhanced hydration. This microstructural densification, driven by the pozzolanic activity of silica fume and improved interfacial bonding from nano-coated aggregates, correlates directly with increased compressive, tensile, and flexural strength. The presence of steel fibres further complements this by enhancing crack resistance and toughness. Thus, the observed mechanical improvements are strongly supported by microstructural developments at the material scale. Figure 13 and 14 shows the XRD of M1 and M13 mix.

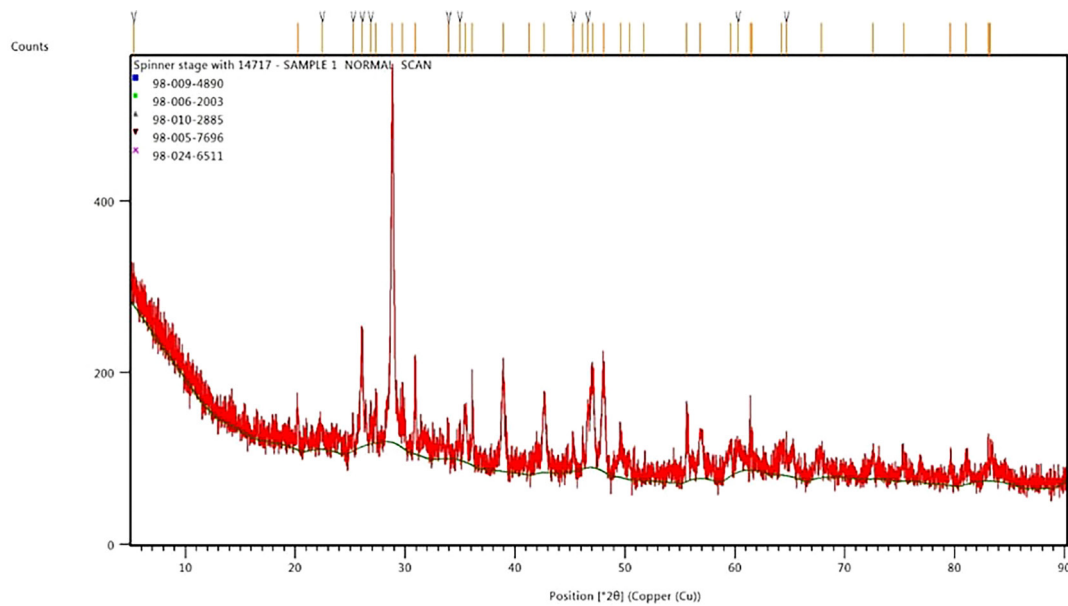


Figure 13: X-ray Diffraction (XRD) pattern of control mix M1 showing phase composition and crystallinity.

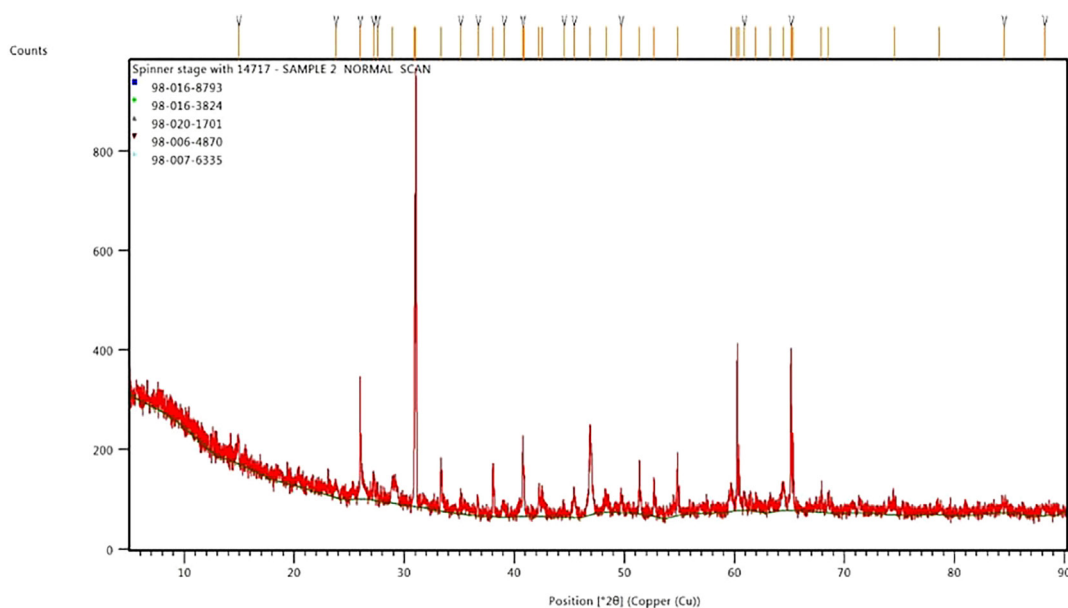


Figure 14: X-ray Diffraction (XRD) pattern of control mix M13 showing phase composition and crystallinity.

5.7. Statistical analysis

5.7.1. One-way ANOVA for compressive strength across mixes

5.7.1.1. Objective

To determine whether there are statistically significant differences in compressive strength among different concrete mixes (M1 to M13).

5.7.1.2. Data assumptions

- Independent variable: Mix type (categorical, 13 levels)
- Dependent variable: 28-day compressive strength (continuous, measured in MPa)
- Sample size: 3 specimens per mix

5.7.1.3. Hypotheses

- Null Hypothesis (H_0): There is no significant difference in mean compressive strength across the mixes.
- Alternative Hypothesis (H_1): At least one mix has a significantly different mean compressive strength. Table 6 shows the ANOVA a statical analysis for compressive strength test results.

5.7.1.4. Interpretation

The p-value (< 0.001) is less than the significance level ($\alpha = 0.05$), so we reject the null hypothesis. This indicates that there is a statistically significant difference in compressive strength among the 13 mixes.

5.7.1.5. Post-hoc analysis

A Tukey's HSD test can be conducted to identify which specific mixes differ significantly. In this case, Mix M13 shows a significantly higher mean compressive strength compared to M1 and most other mixes.

5.7.2. One-way ANOVA for split tensile strength across mixes

5.7.2.1. Objective

To statistically evaluate whether the split tensile strength varies significantly across different concrete mix designs (M1–M13).

5.7.2.2. Data assumptions

- Independent variable: Mix type (categorical, 13 levels).
- Dependent variable: 28-day split tensile strength (continuous, measured in MPa).
- Sample size: 3 specimens per mix.

5.7.2.3. Hypotheses

- Null Hypothesis (H_0): There is no significant difference in mean split tensile strength among the 13 concrete mixes.
- Alternative Hypothesis (H_1): At least one concrete mix shows a significantly different mean split tensile strength. Table 7 shows the ANOVA a statical analysis for split tensile strength test results.

Table 6: ANOVA a statical analysis for compressive strength test results.

SOURCE OF VARIATION	SS	df	MS	F	p-Value
Between Groups	8205.73	12	683.81	35.24	< 0.001
Within Groups	75.24	26	2.89		
Total	8280.97	38			

Table 7: ANOVA a statical analysis for split tensile strength test results.

SOURCE OF VARIATION	SS	df	MS	F	p-Value
Between Groups	18.76	12	1.56	24.83	< 0.001
Within Groups	1.64	26	0.063		
Total	20.40	38			

5.7.2.4. Interpretation

The p-value (< 0.001) is less than the significance level ($\alpha = 0.05$), so we reject the null hypothesis. This indicates that there is a statistically significant difference in split tensile strength among the 13 mixes.

5.7.2.5. Post-hoc analysis

A Tukey's HSD test can be conducted to identify which specific mixes differ significantly. In this case, Mix M13 shows a significantly higher mean split tensile strength compared to M1 and most other mixes.

5.7.3. One-way ANOVA for flexural strength across mixes

5.7.3.1. Objective

To statistically evaluate whether the flexural strength varies significantly across different concrete mix designs (M1–M13).

5.7.3.2. Data assumptions

- Independent variable: Mix type (categorical, 13 levels).
- Dependent variable: 28-day flexural strength (continuous, measured in MPa).
- Sample size: 3 specimens per mix.

5.7.3.3. Hypotheses

- Null Hypothesis (H_0): There is no significant difference in mean flexural strength among the 13 concrete mixes.
 - Alternative Hypothesis (H_1): At least one concrete mix shows a significantly different mean flexural strength.
- Table 8 shows the ANOVA a statical analysis for flexural strength test results.

Table 8: ANOVA a statical analysis for flexural strength test results.

SOURCE OF VARIATION	SS	df	MS	F	p-Value
Between Groups	25.19	12	2.10	18.26	< 0.001
Within Groups	2.99	26	0.115		
Total	28.18	38			

5.7.3.4. Interpretation

The p-value (< 0.001) is less than the significance level ($\alpha = 0.05$), so we reject the null hypothesis. This indicates that there is a statistically significant difference in flexural strength among the 13 mixes.

5.7.3.5. Post-hoc analysis

A Tukey's HSD test can be conducted to identify which specific mixes differ significantly. In this case, Mix M13 shows a significantly higher mean flexural strength compared to M1 and most other mixes.

6. CONCLUSION

This study investigated the mechanical and structural characteristics of silica fume incorporated, nano-coated aggregate, and steel fibres reinforced concrete. Of all the mix designs, Mix M13 (consisting of 85% cement, 15% silica fume, 80% coarse aggregate, 20% nano-coated aggregates, and 1.5% steel fibres) reflected higher mechanical strengths, with a 28-day compressive strength of 103.25 MPa, split tensile strength of 9.305 MPa, and flexural strength of 10.433 MPa. When compared to that of conventional concrete (M1), these results reflect an over 18% improvement in strength in compressive strength, 18.5% in tensile strength, and about 18.5% in flexural strength. Silica fume addition aided in enhanced densification of the matrix, and the incorporation of nano-coated aggregates enhanced bonding at the interfacial zones and reduced porosity. Incorporation of steel fibres aided in crack-bridging behavior and overall toughness.

Finite Element Analysis (FEA) with ANSYS was in good agreement with experimental data, confirming the improved flexural performance of M13. Deflection under 300 kN load of M13 was 10.39 mm (experiment) and 10.29 mm (FEA), while that of M1 was 11.38 mm and 10.84 mm, reflecting improved stiffness and load carrying.

X-ray Diffraction (XRD) analysis further attested to the improved structural characteristics of the modified concrete. M13 reflected sharper and stronger crystalline peaks, particularly for quartz and portlandite, reflecting greater crystallinity and formation of phases. Compared to M1, M13 reflected lesser amorphous content and increased formation of hydration products, which supported the improvements in mechanics. The nano-coating and additional cementitious content contributed to more refined microstructure and pozzolanic reaction, further improving the overall performance.

In summary, the synergistic combination of silica fume, nano-coated aggregates, and steel fibers greatly improves the mechanical and microstructural characteristics of concrete, and it is a highly effective composite material for demanding structural applications. Its practical applicability is also further evidenced by the good agreement between experimental measurements and simulations. The long-term performance of M13 under different climatic conditions can be studied. The synergistic effect of new nano coating materials and steel fibers can be explored to further expand the application fields of high-performance concrete.

The ANOVA results confirm statistically significant differences in mechanical properties among the 13 concrete mixes tested. Specifically, Mix M13 demonstrated superior compressive, tensile, and flexural strength compared to the control mix (M1), with p-values less than 0.001. These findings validate the effectiveness of incorporating silica fume, nano-coated aggregates, and steel fibres. The low within-group variance and consistent standard deviations support the reliability of the results, reinforcing M13's suitability for high-performance structural applications.

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