International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 11 | Nov - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Enhancing Strength and Durability of M60 Grade Concrete Using Nano-Silica: An Experimental Investigation

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Abstract - The incorporation of nanomaterials in concrete has shown significant potential in improving its mechanical and durability characteristics. This study investigates the influence of nano silica and micro silica as partial replacements for cement in the development of M60 grade high-performance concrete. Three mixes were considered: Conventional Concrete (CC), Concrete with nano silica (NS1), and Concrete with combined nano silica and micro silica (NS2). Mechanical properties such as compressive strength, split tensile strength, flexural strength, and modulus of elasticity were evaluated experimentally. Durability performance was assessed through water absorption, sulphate attack, chloride penetration, acid attack, and corrosion resistance tests. The results demonstrate that the addition of nano silica and micro silica significantly enhances the strength and durability of concrete compared to the control mix. Among all mixtures, the combination containing 5% nano silica and 5% micro silica exhibited the highest improvement in mechanical properties and resistance to environmental degradation. The outcomes align with previous findings reported in the literature and confirm that the synergistic use of nano silica and micro silica leads to superior performance in high-strength concrete.

Key Words: Nano silica, Micro silica, High-performance concrete, Compressive strength, Durability, Chemical attack, Corrosion resistance.

1. INTRODUCTION

Concrete is one of the most widely used construction materials across the world and plays a vital role in infrastructure development. With global consumption exceeding 11 billion metric tons annually, concrete remains indispensable due to its versatility, ease of molding into various shapes, adequate resistance to water, and adaptability to diverse structural applications. Despite its extensive use, conventional concrete is associated with environmental concerns arising from the production of Portland cement, which contributes nearly 7% of global CO_2 emissions. Increasing cement demand due to rapid infrastructure growth further intensifies these sustainability challenges.

To address these issues, researchers have focused on incorporating Supplementary Cementitious Materials (SCMs) such as fly ash, micro silica, nano silica, metakaolin, and rice husk ash. These materials enhance hydration, improve microstructural characteristics, and reduce overall cement consumption, thereby lowering environmental impact. Among these SCMs, nano silica and micro silica have shown significant potential in improving the mechanical and durability properties of high-strength concrete.

Particle packing plays a crucial role in determining concrete performance. The introduction of ultrafine materials, including micro silica and nano silica, helps fill capillary pores, refine the microstructure, and enhance the strength of the cementitious matrix. Nano silica, due to its extremely fine particle size and high pozzolanic reactivity, accelerates hydration, increases calcium silicate hydrate (C-S-H) formation, and improves bonding in the interfacial transition zone (ITZ). Similarly, micro silica contributes to strength enhancement, reduced permeability, and improved resistance to aggressive environmental conditions.

High-performance and high-strength concretes benefit greatly from the addition of nano and micro silica. These materials enhance early-age strength, increase chemical resistance, lower water permeability, and improve long-term durability. Their combined use results in denser packing, reduced porosity, and superior mechanical performance compared to conventional concrete.

Given the increasing demand for sustainable, durable, and high-strength construction materials, the present study focuses on evaluating the influence of nano silica and micro silica on the strength and durability characteristics of M60 grade concrete. The research includes experimental investigation, microstructural analysis, and comparative evaluation of mechanical and durability properties across different concrete mixes.

1.1 OBJECTIVES OF THE STUDY

- To study the fundamental properties and behavior of nano materials used in concrete, with specific focus on nano silica and micro silica.
- To evaluate the fresh and hardened properties of M60 grade high-strength concrete incorporating nano silica and micro silica as partial replacements for cement.
- To investigate the mechanical performance, including compressive strength, split tensile strength, and flexural strength, of concrete with varying proportions of nano silica and micro silica.
- To assess the durability characteristics of modified concrete mixes through water absorption, sulphate attack, chloride attack, acid attack, and corrosion resistance tests.
- To compare the performance of conventional concrete with nano silica–based mixes, and to identify the optimal replacement levels that provide maximum improvement in strength and durability.

2. SUMMARY OF LITERATURE REVIEW

The use of nano silica and micro silica as supplementary cementitious materials has been widely investigated due to their potential to enhance the mechanical and durability properties of concrete. Early studies by Björnström *et al.* [1] demonstrated that colloidal nano silica significantly accelerates the hydration process by promoting rapid formation of calcium silicate hydrate (C–S–H), resulting in improved early-age strength. Similarly, Jo *et al.* [2] and Qing *et al.* [3] reported that the incorporation of nano silica in cement mortar increases compressive strength, refines pore structure, and enhances the interfacial transition zone (ITZ) due to its extremely high fineness and pozzolanic reactivity.

The synergistic behavior of nano silica and micro silica has also been explored extensively. Jalal *et al.* [4] and Nili and Ehsani [5] showed that combining both materials leads to superior densification of the cement matrix and improved mechanical performance compared to using either material alone. In particular, the addition of nano silica at levels between 1–3% has been found to significantly enhance hydration kinetics and reduce permeability, as observed by Tang *et al.* [6] and Stefanidou and Papayianni [7]. However, excessive nano silica content can result in particle agglomeration, reducing workability and negatively impacting long-term strength development, as noted by Rong *et al.* [8].

Durability improvement is another major benefit of nano silica-modified concrete. Several researchers, including Said and Zeidan [9] and Ghafari *et al.* [10], reported that nano silica greatly enhances resistance to chloride penetration, sulphate attack, and water absorption by refining microstructure and reducing capillary porosity. Ji [11] highlighted the role of nano silica in reducing calcium hydroxide crystal formation and strengthening the ITZ, which contributes to long-term durability. Studies by Bahadori and Hosseini [12], Shamsai *et al.* [13], and Han *et al.* [14] further confirmed significant reductions in permeability and improvement in chemical resistance due to nano silica addition.

Comparative investigations between nano silica and traditional micro silica have shown that while both materials improve matrix densification, nano silica offers faster reaction kinetics and greater improvements in early-age properties. Raki *et al.* [15] and Saravanan and Sivaraja [16] concluded that nano silica enhances cohesion, durability, and strength development more effectively than micro silica alone. Li *et al.* [17] and Zhang *et al.* [18] reported notable increases in compressive, tensile, and flexural strength with nano silica incorporation, emphasizing its effectiveness in high-performance and ultra-high-performance concrete (UHPC).

Overall, existing literature consistently demonstrates that the inclusion of nano silica—either alone or in combination with micro silica—leads to improved hydration behavior, enhanced mechanical strength, reduced porosity, and superior durability. These findings form a strong foundation for exploring optimized nano silica–micro silica combinations in high-strength concrete applications, particularly for M60 grade concrete in aggressive environments.

3. EXPERIMENTAL INVESTIGATION

A. General

Concrete is primarily composed of cement, aggregates, and water. In this study, nano silica and micro silica were incorporated into M60 grade concrete to enhance its mechanical and durability characteristics. The following sections describe the materials, mix design methodology, specimen preparation, and testing procedures adopted in the experimental program.

B. Materials Used

1) Cement

Ordinary Portland Cement (OPC) of 53 grade was used as the primary binder. The cement properties—including specific gravity of 3.15, initial setting time of 38 minutes, and final setting time of 3 hours—are summarized in Table 3.1.

2) Water

Potable tap water was used for both mixing and curing. Water quality was ensured as per IS 456:2000 requirements to avoid contaminants that might adversely affect hydration, strength, or durability.

3) Fine Aggregate

Naturally available river sand conforming to Zone II of IS 383–1970 was used. The material exhibited a specific gravity of 2.74 and a fineness modulus of 2.86.

4) Coarse Aggregate

Crushed angular aggregates of 20 mm and 12.5 mm sizes were used in a 60:40 ratio. Both aggregates possessed a specific gravity of 2.74.

5) Superplasticizer

A high-performance superplasticizer (Conplast SP430), based on sulphonated naphthalene polymers, was used to enhance workability. Its specific gravity was 1.22 at 30°C.

6) Nano Silica

Nano silica, a non-crystalline ultrafine powder with an average particle size of 49 nm and a specific gravity of 1.06, was used as a cement replacement (2–10%).

7) Micro Silica

Micro silica (silica fume) with particle sizes ranging from 0.15–1 µm and a specific gravity of 2.17 was used as a mineral admixture.

8) Steel Reinforcement

Fe415 grade steel bars of 8 mm diameter were used in the reinforced beam specimens.

C. Mix Proportion

1) Mix Design

The concrete mix design followed IS 10262:2009 guidelines for M60 grade concrete. The target strength was calculated as 68.25 MPa. A water–cement ratio of 0.35 was adopted.

The final mix proportion obtained was:

Cement: 440 kg/m³

Fine Aggregate: 712 kg/m³

Coarse Aggregate: 1161 kg/m³

Water: 154 L/m³

Superplasticizer: 4.4 L/m³

The resulting proportion was 1 : 2.35 : 3.5 by weight.

D. Workability Test

A slump cone test, as per IS 1199–1959, was used to evaluate concrete workability. Fresh concrete was placed in three layers, each compacted with 25 tamping strokes. The slump value was measured as the difference between the mould height and the subsided concrete.

E. Hardened Concrete Properties

1) General

The hardened properties of concrete were evaluated on cube, cylinder, and prism specimens. Additional reinforced concrete beams were cast to study structural performance under monotonic and cyclic loading.

2) Specimen Details

Cubes: 150 × 150 × 150 mm (strength)

Cylinders: 150 × 300 mm (split tensile)

Prisms: 100 × 100 × 500 mm (flexural strength)

Durability cubes: 100 × 100 × 100 mm

3) Casting and Curing

Concrete was placed in cast-iron moulds in three layers and compacted using a table vibrator. Specimens were demoulded after 24 hours and water-cured for 28 days.

F. Testing Procedure

1) Compressive Strength Test

Compression tests on 150 mm cubes were conducted using a 2000 kN CTM as per IS 516–1959. The compressive strength was calculated using:

$$f_c = \frac{P}{A}$$

where P is the maximum load and A is the cross-sectional area.

2) Split Tensile Test

Cylinders (150 × 300 mm) were tested as per IS 5816–1999. The split tensile strength was calculated using:

$$f_{st} = \frac{2P}{\pi DL}$$

where D is the diameter and L is the length.

3) Flexural Strength Test

Prisms were tested under two-point loading. The modulus of rupture was computed using:

$$f_r = \frac{PL}{bd^2}$$

where b and d are the cross-sectional dimensions. (Fig. 3.1)

Fig. 3.1 - Test Setup for Flexural Strength

G. Durability Studies

Durability tests were conducted on 100 mm cubes to assess resistance to chemical and environmental attacks.

1) Water Absorption

Performed as per ASTM C1585-04. Water absorption was calculated as: (Fig. 3.2).

$$\%\text{Absorption} = \frac{W_s - W_d}{W_d} \times 100$$

Fig. 3.2 - Cubes in Water Absorption

2) Sulphate Attack

Specimens were immersed in 2.5% Na_2SO_4 and $MgSO_4$ solutions for 60 days. Weight loss and strength deterioration were evaluated (Fig. 3.3).

Fig. 3.3 - Sulphate Attack Test

3) Chloride Attack

Cubes were immersed in 5% NaCl solution. Weight change and compressive strength reduction were recorded (Fig. 3.4)

Fig. 3.4 - Chloride Attack Test

4) Acid Attack

Specimens were immersed in 5% HCl solution for 60 days. Final mass loss and residual strengths were measured (Fig. 3.5).

Fig. 3.5 - Acid Attack Test

5) Corrosion Test

Cylinder specimens embedded with steel bars were subjected to impressed current corrosion using a 12 V DC power supply in a 5% NaCl environment. The setup is shown in Fig. 3.6.

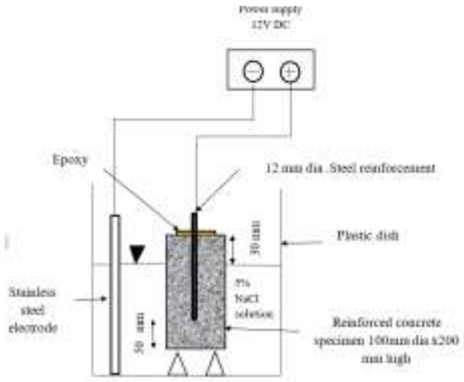

Fig. 3.6 - Accelerated Corrosion Test setup

6) Half-Cell Potential Test

Corrosion probability was assessed using a $Cu/CuSO_4$ reference electrode and high-impedance voltmeter, as illustrated in Fig. 3.7.

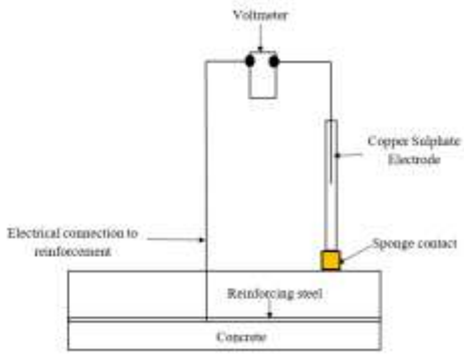

Fig. 3.7 -Half-Cell potential Test setup

4. STRENGTH AND DURABILITY PROPERTIES

A. General

This chapter presents the strength and durability characteristics of M60 grade high-strength concrete containing nano silica and micro silica. Experimental observations include compressive strength, split tensile strength, and flexural strength, followed by durability assessments such as sulphate attack, water absorption, chloride attack, and acid attack. The influence of nano silica and micro silica on the mechanical and durability performance of concrete is discussed.

B. Strength Properties of Concrete

1) Compressive Strength

a) Introduction

Concrete containing micro silica tends to gain strength slowly at early ages but exhibits significant strength improvement at later ages. Nano silica and micro silica react gradually with calcium hydroxide released during cement hydration, contributing to matrix densification beyond 28 days [Aggarwal et al., 2015].

b) Results and Discussion

Compressive strength at 28 days was evaluated for three mixes: conventional concrete (CC), nano-silica concrete (NS1), and combined nano- and micro-silica concrete (NS2). Table 4.1 shows the results.

Table 4.1 — Compressive Strength Results

Mix	Strength (N/mm²)
CC	56.77
NS1	68.45
NS2	70.11

The addition of 3% nano silica (NS1) and combined 5% nano silica + 5% micro silica (NS2) significantly increased compressive strength. The improvement is attributed to enhanced gel formation, refinement of the pore structure, and a denser interfacial transition zone (ITZ).

c) Concluding Remarks

The improved compressive strength in NS1 and NS2 mixes is due to particle packing, reduced porosity, and enhanced C–S–H formation. NS2 achieved the maximum gain (19.10% higher than CC). These results align with findings from Zhidon Rong et al. (2014) and Mahmoud Nili and Ehsani (2015), who observed that nano silica up to 3% and combined nano–micro silica produce optimal improvements in concrete strength.

2) Split Tensile Strength

a) Introduction

Although micro silica introduces fine voids into the matrix, the combined use of nano silica and micro silica enhances tensile strength due to improved hydration kinetics and matrix refinement.

b) Results and Discussion

Table 4.2 — Split Tensile Strength

Mix	Strength (N/mm²)
CC	2.21
NS1	2.83
NS2	3.97

The NS2 mix exhibited a substantial improvement (43.18%) over CC. The reduction in pore size and formation of additional C–S–H improved tensile resistance, reducing shrinkage-induced cracking.

c) Concluding Remarks

Nano silica significantly enhances tensile strength due to its ultra-fine particle size and pozzolanic reactivity. The NS2 mix produced the highest performance, as more refined microstructure minimizes crack propagation.

3) Flexural Strength

a) Introduction

Flexural strength tests were conducted using a 1000 kN UTM under two-point loading as per IS 516:1959.

b) Results and Discussion

Table 4.3 — Flexural Strength

Mix	Strength (N/mm²)
CC	4.94
NS1	5.25
NS2	5.55

Significant improvements were recorded for NS1 and NS2 mixes due to the densification of concrete and reduced voids. Nano silica enhances tensile strength, contributing to improved flexural capacity.

c) Concluding Remarks

Flexural strength increased consistently with the addition of nano silica and micro silica. The NS2 mix provided the best performance owing to minimized porosity and better ITZ structure.

C. Durability Properties of Concrete

1) Sulphate Attack Test

a) Introduction

Concrete exposed to sulphates undergoes expansive reactions forming gypsum and ettringite, leading to cracking and loss of strength. Resistance depends on permeability, w/c ratio, cement type, and exposure conditions.

b) Results and Discussion

Table 4.4 — Weight Loss Due to Sulphate Attack

Mix	% Loss
CC	0.96
NS1	0.85
NS2	0.67

Table 4.5 — Strength Loss Due to Sulphate Attack

Mix	% Loss
CC	5.62
NS1	5.30
NS2	4.45

NS2 showed the least deterioration. Nano silica and micro silica refine pore structure, reducing ion ingress and mitigating damage.

c) Concluding Remarks

Combined nano–micro silica significantly enhances sulphate resistance by minimizing porosity and blocking transport channels. These results support findings from Hongjian Du et al. (2014) and L.G. Li et al. (2017), showing synergistic effects of nano silica and micro silica.

2) Water Absorption Test

a) Introduction

Water absorption indicates permeability and pore continuity. Lower absorption reflects denser concrete microstructure.

b) Results and Discussion

Table 4.6 — Water Absorption

Mix	% Absorption
CC	1.79
NS1	1.11
NS2	0.96

NS2 shows the lowest absorption due to effective pore refinement by nano and micro silica.

c) Concluding Remarks

The combined use of nano silica and micro silica reduces capillary porosity and permeability. Higher degrees of hydration contribute to microstructural densification and reduced absorption.

3) Chloride Attack Test

a) Introduction

Chloride ingress accelerates reinforcement corrosion and is a critical factor affecting durability.

b) Results and Discussion

Table 4.7 — Weight Gain Due to Chloride Attack

Mix	% Gain
CC	1.75
NS1	1.11
NS2	0.93

Table 4.8 — Strength Loss Due to Chloride Attack

Mix	% Loss
CC	4.63
NS1	3.77
NS2	3.31

The NS2 mix exhibited the least chloride penetration and minimal strength degradation.

c) Concluding Remarks

Nano silica and micro silica reduce chloride permeability by refining pore structure. This correlates with findings by L.G. Li et al. (2014), who observed significant improvements in chloride resistance with nano–micro silica mixes.

4) Acid Attack Test

a) Introduction

Acid attack is a major concern for concrete structures in coastal or industrial environments. Acids react with calcium compounds, forming soluble salts and weakening the cement matrix.

b) Results and Discussion

Table 4.9 — Weight Loss Due to Acid Attack

Mix	% Loss
CC	2.67
NS1	1.62
NS2	1.33

Table 4.10 — Strength Loss Due to Acid Attack

Mix	% Loss
CC	8.86
NS1	6.78
NS2	4.89

c) Concluding Remarks

Concrete modified with nano silica and micro silica demonstrated superior resistance to acid attack. The reduced porosity delays acid penetration and limits dissolution of calcium-bearing phases, resulting in higher retained strength.

5. CONCLUSIONS

A. Conclusions from Experimental Investigation

1. The incorporation of nano silica and micro silica significantly enhanced the mechanical properties of concrete, including compressive strength, split tensile strength, and flexural strength, when compared with conventional concrete.
2. The mix containing 5% nano silica and 5% micro silica exhibited the maximum strength, outperforming mixes with only nano silica or without any supplementary cementitious materials.
3. The modulus of elasticity increased with the addition of nano silica and micro silica, indicating the formation of a stiffer and more refined cementitious matrix.
4. While the addition of NS and MS reduced workability due to their ultrafine particle sizes, adequate workability was achieved using an appropriate dosage of superplasticizer.
5. Improvements in mechanical strength were primarily attributed to the pozzolanic reactivity and filler effect of nano silica and micro silica, which refined the pore structure, reduced voids, and enhanced the bond between paste and aggregates.

B. Conclusions from Durability Studies

1. The durability performance of concrete improved significantly with the incorporation of NS and MS, demonstrating superior resistance to aggressive environments.
2. The mix containing 5% NS + 5% MS exhibited the lowest water absorption and permeability, confirming the formation of a denser microstructure with reduced pore connectivity.
3. The resistance to sulphate and acid attack was substantially improved in the modified mixes, resulting in minimal deterioration and reduced loss of strength.
4. Chloride penetration resistance increased considerably with NS and MS addition, lowering the risk of reinforcement corrosion and improving long-term durability.
5. The synergistic effect of nano silica and micro silica enhanced chemical stability, minimized porosity, and increased service life, demonstrating their effectiveness as mineral admixtures in durable concrete systems.

C. Overall Conclusions

1. The combined incorporation of nano silica and micro silica provides a balanced enhancement in both strength and durability characteristics of high-performance concrete.
2. The mix containing 5% nano silica and 5% micro silica is identified as the optimum blend, offering superior structural performance without adversely affecting workability.
3. Nano silica and micro silica improve the microstructural quality of concrete by refining the interfacial transition zone (ITZ), reducing permeability, and increasing density.
4. The overall experimental results confirm that NS and MS can be effectively utilized to produce sustainable, high-performance concrete suitable for modern infrastructure applications requiring enhanced mechanical strength and long-term durability.

6. FUTURE SCOPE

- **Investigation of alternative nano materials:** Future studies may explore the use of nano alumina, nano titanium dioxide, nano clay, and graphene-based additives to compare their performance with nano silica.
- **Hybrid supplementary cementitious systems:** The combined effect of NS and MS with other SCMs—such as fly ash, slag, metakaolin, or rice husk ash—may be examined to develop cost-effective and high-performance hybrid binders.
- **Optimization of replacement levels:** A wider range of NS and MS replacement percentages can be examined using statistical tools or machine learning models to determine the global optimum mix proportions.

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