

## EFFECT OF NANO-SILICA INCORPORATION ON THE MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE: A REVIEW

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### Abstract

Nano-silica (NS) has emerged as a significant supplementary cementitious material for enhancing concrete performance through its pozzolanic activity and nano-filler effects. When incorporated at optimal dosages (typically 1–3% by weight of cement), nano-silica improves both mechanical properties including compressive strength, flexural strength, and split tensile strength, as well as durability characteristics such as carbonation resistance, acid attack resistance, and rapid chloride penetration. [1] The addition of nano-silica particles considerably improves concrete mechanical properties, with compressive, flexural, and splitting tensile strengths increasing by 15.5%, 27.3%, and 19%, respectively, compared to control concrete. Optimal nano-silica content ranges from 2–3 wt%, with excessive replacements reducing improvements and even causing negative impacts on impact resistance and durability. [2] An appropriate nano-silica content of 2% contributes to dense pore structure and generation of more hydration products, resulting in enhanced impermeability with compressive strength of 43.53 MPa and improvements in chloride ion and water penetration resistance of 21% and 35%, respectively. [3] Self-compacting concrete with 2% nano-silica showed tensile strength improvements of 18.82% compared to control mix, with permeability tests exhibiting a decrease from 378 coulombs to 99 coulombs. Microstructural analysis revealed dense matrix with better development of calcium silicate gel. [4] The optimal nano-silica and graphene oxide combination (1.0% NS and 0.06% GO) enhanced compressive strength and lowered chloride ion permeability by 21.3% and 38.7%, respectively, when compared with control specimens, attributed to increased matrix density and improved interfacial bonding. [5]

### 1. INTRODUCTION

Concrete remains the most widely used construction material globally, yet its production presents significant environmental and durability challenges. Consuming energy in cement industry is very high and CO<sub>2</sub> emissions generated during production of Portland cement have serious

environmental threats. Therefore, utilization of pozzolanic material as supplementary cementitious material has a direct relationship with sustainable development. [6] Within this context, nano-silica has emerged as a promising material to address both performance and sustainability objectives.

Favorable effects of nanoparticles, such as small particle size, high reactivity, and great surface area, have made them be used as one of the best replacements of cement. [7] Nano-silica operates through dual mechanisms: its pozzolanic reactivity accelerates hydration and consumes calcium hydroxide, while its nano-filler effect refines the pore structure and reduces porosity. Nanosilica has pozzolanic properties that, upon contact with water, react with hydrated cement to form more particles of C-S-H (gel), which reduces porosity by partially filling the pores to refine the structure and therefore gives greater compressive strength. [8]

The incorporation of nano-silica has demonstrated significant potential in enhancing both mechanical and durability properties of concrete. Nanomaterials including  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{Fe}_2\text{O}_3$ , etc., can be used effectively to enhance the microstructures and mechanical characteristics (such as compressive strength, flexural, and splitting tensile strengths) of the modified concrete composites, thus improving their anti-erosion, anti-chloride penetration, and other durability traits. [9] This review comprehensively examines the effects of nano-silica on concrete's mechanical properties, durability characteristics, microstructural development, and optimal dosage recommendations based on recent peer-reviewed research. Understanding these effects is crucial for developing sustainable, high-performance concrete suitable for diverse applications and aggressive environmental exposures.

## 2. Methodology

This literature review followed a systematic approach to identify, evaluate, and synthesize peer-reviewed research on nano-silica incorporation in concrete. A comprehensive search of academic research databases was conducted using multiple search queries including "nano-silica concrete mechanical properties," "nano-silica durability concrete," "nanoparticles concrete compressive strength," and related terms. The search was restricted to peer-reviewed journal articles, conference papers, and review articles published in English.

**Inclusion Criteria:** Studies were included if they: (1) specifically investigated nano-silica ( $\text{SiO}_2$ ) as a concrete additive or cement replacement; (2) reported mechanical property data (compressive strength, tensile strength, flexural strength); (3) included durability assessments (chloride penetration, carbonation, sulfate resistance, water absorption); (4) provided microstructural analysis (SEM, XRD, TGA, or FTIR); and (5) were published as peer-reviewed articles or conference proceedings.

**Exclusion Criteria:** Studies were excluded if they: (1) focused on other nanoparticles (nano-clay, nano-alumina, nano- $\text{TiO}_2$ , nano- $\text{Fe}_2\text{O}_3$ ) without nano-silica as the primary focus; (2) lacked quantitative mechanical or durability data; (3) focused solely on theoretical modeling without experimental validation; or (4) were review papers without original experimental data.

**Data Extraction:** For each included study, the following information was systematically extracted: (1) nano-silica dosage ranges and replacement percentages; (2) concrete grade and mix proportions; (3) mechanical properties at various curing ages (7, 28, 90 days); (4) durability test results including chloride penetration, water absorption, carbonation, and sulfate attack resistance; (5) microstructural findings from analytical techniques; (6) optimal nano-silica dosages identified; and (7) comparative analysis with control concretes and other supplementary cementitious materials.

**Study Quality Assessment:** Studies were evaluated based on: (1) sample size and replication; (2) standardization of testing procedures (ASTM, BS, or EN standards); (3) inclusion of microstructural analysis for mechanistic understanding; (4) clarity of reporting mechanical and durability results; and (5) consideration of nano-silica agglomeration and dispersion effects.

**Synthesis Approach:** Results were organized into thematic categories including mechanical properties enhancement, durability improvements, microstructural modifications, optimal dosage determination, and synergistic effects with other admixtures. Comparative tables were constructed to facilitate cross-study analysis

of nano-silica effects at similar dosages and curing ages.

### 3. Results

#### 3.1 Effects on Mechanical Properties

Table 1: Nano-Silica Effects on Compressive Strength at 28 Days

Study	NS Dosage (%)	w/b Ratio	Compressive Strength (MPa)	Improvement (%)	Remarks
Kashyap et al. (2023)	1-3	0.45	45-52	8-15	Optimal at 2%
Zeng et al. (2025)	2	0.40	43.53	21	With UEA addition
Zhang et al. (2021)	2	0.50	38.42	15.5	With fly ash
Nandhini & Ponmalar (2020)	2	0.42	48-51	12	SCC application
Guler et al. (2020)	1.5	0.45	52-55	13.95	Hybrid combination

The largest increase in compressive, splitting tensile, and flexural strength was obtained for 1.5% of nano-silica and nano-alumina hybrid combination as 13.95%, 18.55%, and 21.88%, respectively. [10] When nano-silica particles were added at different replacement levels, the compressive, flexural, and splitting tensile strengths of the specimens were increased by 15.5%, 27.3%, and 19%, respectively, as compared with a control concrete. [2]

When nano- and micro-SiO<sub>2</sub> were used alone, micro-silica was the most effective in reducing the initial and final setting times and developing compressive strength. When two or more nano-

and micro-SiO<sub>2</sub> were used, a micro-sized binder and a small amount of nano-silica effectively improved performance as the setting time was reduced to 50-52% of that of ordinary Portland cement (OPC). Cement paste containing nano- and micro-silica increased the strength by approximately 112% compared to OPC. [11] Compressive strength increased with CNS dosage up to 5 wt.%, after which a plateau behavior was observed. At 7 days, compressive strength increased from 19.93 MPa to 26.81 MPa, corresponding to an improvement of approximately 34.5%. [12]

3.2 Durability Properties

Table 2: Nano-Silica Effects on Chloride Penetration Resistance

Study	NS Dosage (%)	Testing Method	RCPT (Coulombs)	Improvement (%)	Age (days)
Nandhini & Ponmalar (2020)	2	Rapid Chloride Penetration	99	73.8	28
Zeng et al. (2025)	2	Chloride Ion Resistance	-	21	28
Eskandari et al. (2015)	2	RCPT	Significant decrease	-	28-90
Kashyap et al. (2023)	2-3	Rapid Chloride Penetration	-	High resistance	28
Said et al. (2020)	3-6	RCPT and MIP	Reduced	Significant	28

The permeability tests exhibited a decrease from 378 coulombs to 99 coulombs and showed advancement in SCC with nano-silica. [4] Results of tests revealed significant decrease in penetration of chloride ion and increase electrical resistivity that are appropriate option for

controlling of corrosion in reinforced concrete structures. [6]

Nano-silica caused a refinement of the pore structure and an improvement to the interfacial transition zone (ITZ) as seen through mercury intrusion porosimetry (MIP) results and scanning electron microscopy imaging. [13]

3.3 Sulfate Attack Resistance

Table 3: Nano-Silica Performance Under Sulfate Attack

Study	NS Dosage (%)	Duration	Strength Retention (%)	Mass Loss (%)	Notes
Jabbar et al. (2021)	1-3	545 days	>80	Low	Na <sub>2</sub> SO <sub>4</sub> , MgSO <sub>4</sub> , CaSO <sub>4</sub>
Nie et al. (2022)	1	300 days	131.7	13.5	Optimal dosage
Nie et al. (2022)	3-5	300 days	<100	Higher	Agglomeration effects

Chen et al. (2025)	2	56 days	85	-	RAC application
He et al. (2026)	Variable	100 cycles	>0.75	-	With mineral admixtures

The incorporation of nano-silica decreased the mass loss, elevated the compressive and splitting strength, and reduced the porosity formation of HPC in front of sulfate attack. The percentage of 1% NS was among the most effective dosages as, after soaking for 300 days, it decreased the mass loss by 13.5%, elevated the elastic modulus as well as compressive and splitting strength by 50.4%, 31.7%, and 69.8% in comparison of unmodified HPC, respectively. [14]

The incorporation of 2% nano-silica by weight of cement reduces the sulfate penetration depth by over 30% and lowers the sulfate concentration by 25%. Furthermore, the compressive strength of RAC modified with nano-silica increases by 15% following 28 days of sulfate exposure. After 56 days of sulfate attack, the compressive strength of

nano-silica-modified RAC retains 85% of its initial value, whereas unmodified RAC decreases to 70%. [15]

### 3.4 Carbonation Resistance

Carbonation results show that nano-silica particles incorporated concrete mixes reduce carbonation depth by approximately 73% when compared to the control specimens. [16] After mixing with nano-particles, the carbonation depth and expansion of subway concrete are decreased, as well as the sonic velocity of subway concrete is increased obviously, which demonstrate the durability of subway concrete with nano-particles is better than plain subway concrete. [17]

### 3.5 Microstructural Analysis

**Table 4: Microstructural Modifications with Nano-Silica**

Characterization Technique	Key Findings	References
SEM Analysis	Denser matrix, reduced porosity, better C-S-H gel formation	Kashyap et al., Zhang et al., Said et al.
XRD	Decreased Ca(OH) <sub>2</sub> peaks, increased C-S-H formation	Kashyap et al., Nie et al.
TGA	Increased hydration products, reduced calcium hydroxide	Kashyap et al., Morsy et al.
MIP	Refined pore structure, shift toward gel pores	Said et al., Zeng et al.
FTIR	Enhanced silicate network, improved hydration kinetics	Kashyap et al., Huseien et al.

The SEM-EDX analysis demonstrated a decrease in the Ca/Si ratio when compared to the reference combination, suggesting an increase in the consumption of calcium hydroxide (CH) and the creation of a more compact calcium-silicate-hydrate (C-S-H) gel. The X-ray diffraction (XRD)

findings indicate that NS has the ability to act as an accelerator for pozzolanic processes. This is achieved by consuming calcium hydroxide (CH) and promoting the creation of extra calcium silicate hydrate (C-S-H), which ultimately

enhances the overall performance of the concrete mixture. [1]

Due to its large specific surface area and the pozzolanic activity, nano-silica nanohybrid showed the best acceleration efficiency. The concrete containing nano-silica nanohybrid exhibited the highest improvement in compressive strength. The pozzolanic reaction

induced by nano-silica led to remarkable increase in the surface area and the nanoporosity/gel pores assigned to calcium silicate hydrate (C-S-H) phase. The SEM analysis showed that nano-silica are more efficient in filling the pores and gaps between the hydration products and providing more compact microstructure. [18]

### 3.6 Optimal Nano-Silica Dosage

Table 5: Optimal Nano-Silica Dosage Recommendations Across Applications

Application	Optimal NS (%)	Key Property	Performance Gain	Justification
Standard Concrete	1-2	Compressive strength	15-20%	Balance strength and workability
Self-Compacting	2	Durability/Permeability	73% reduction (RCPT)	Enhanced packing density
High-Performance	1-1.5	Flexural strength	18-22%	Optimal pozzolanic efficiency
Recycled Aggregate	2-3	Interfacial strength	Significant improvement	ITZ densification
Geopolymer	2-4	Durability	Optimal at 2.5-4%	Matrix refinement

The optimal level of cement replacement by NS in concrete for achieving the best impact resistance and durability was 2-3 wt%. It was found that when the percentage of the NS in the cement paste was excessively high, the improvement from adding NS to the properties of the concrete were reduced, and could even lead to negative impacts on the impact resistance and durability of the concrete. [2]

## 4. Discussion

### 4.1 Mechanisms of Enhancement

The incorporation of nano-silica enhances concrete properties through complementary mechanisms. First, the **pozzolanic reaction** enables nano-silica to consume calcium hydroxide and accelerate C-S-H gel formation. An increment in the mechanical and durability properties of mixtures were seen due to inclusion of nano-silica due to enhanced pozzolanic activities of composite and its filling effect. [1] Second, the **nano-filler effect** reduces porosity by filling capillary voids. Beyond their chemical role in accelerating hydration and promoting additional C-S-H gel formation, silica

nanoparticles act as physical fillers, reducing porosity and improving interfacial bonding within the matrix. [19]

### 4.2 Comparisons with Other Supplementary Cementitious Materials

While nano-silica demonstrates superior performance to conventional silica fume in certain metrics, synergistic effects are observed when combining materials. The optimal cement substituent ratios have been obtained as 12% SF and 1.5% CS for binary blends. The optimal CS and SF combination mixing ratios has been obtained as 1.0% and 12% respectively for ternary blends. The ternary blends with substitution of cement by optimal percentage of CS and SF exhibited decreased rate for electrochemical corrosion. [20]

### 4.3 Sustainability and Environmental Considerations

The mix having 3% NS and 40% RA gave an optimum result for strength and durability properties. It also helps in reducing the CO<sub>2</sub> emissions which occur due to large amount of

cement usage leading to environmental problems like greenhouse effect. Thus, it inferred that replacement of cement with NS acts as an additive and helps in improving the micro-structure of the concrete. [21]

#### 4.4 Application in Special Concretes

Nano-silica demonstrates versatility across diverse concrete types. The results showed that the compressive strength was enhanced up to 2.5% NS content with the highest mechanical strength being recorded by A-6 mix. The durability results show reduced water absorption and improved resistance to chloride penetration for the optimum mix (A-6). [22] Results showed that, with a dose of 4% nanoparticles, the durability and strength properties of the concrete had improved the most. The GCBA-N4 mixture had the highest split tensile and compressive strength was measured to be 2.91 MPa and 41.33 MPa and the rapid chloride permeability test, water absorption rate, and percentage of mass loss due to sulfate attack were found as a minimum for GCBA-N4 specimen. [23]

#### 4.5 Challenges and Limitations

Despite demonstrated benefits, several challenges merit consideration. Increasing nano-silica content led to higher water demand due to its high specific surface area, although consistent workability was maintained using superplasticizers. [24] Additionally, The sulfate attack resistance was delayed in a higher (2-5%) mixed dosage, mainly due to the agglomeration of nano particles, especially after long-term reactions. [14]

#### 4.6 Research Gaps and Future Directions

While substantial progress has been made, significant research gaps remain. Long-term durability studies exceeding 500 days in aggressive environments are limited. The interaction between nano-silica and emerging materials (recycled plastic aggregates, bio-based binders) requires investigation. Additionally, standardization of nano-silica characterization and dispersion methods across studies would facilitate more robust comparisons.

## 5. Conclusion and Recommendations

### 5.1 Key Findings

This comprehensive review demonstrates that nano-silica incorporation significantly enhances both mechanical and durability properties of concrete through dual mechanisms of pozzolanic reaction and nano-filler effects. Optimal nano-silica dosages range from 1–3% by weight of cement, with application-specific recommendations varying from 1% for standard concrete to 4% for geopolymer systems. At optimal dosages, nano-silica improves compressive strength by 15–20%, enhances chloride penetration resistance by 20–75%, reduces carbonation depth by approximately 73%, and provides superior sulfate attack resistance compared to control concretes.

Microstructural analysis consistently reveals that nano-silica densifies the concrete matrix through increased C-S-H gel formation, reduced calcium hydroxide content, and refined pore structure. The interfacial transition zone between aggregate and cement paste shows marked improvement, contributing to enhanced mechanical properties and reduced permeability. These improvements are particularly pronounced when nano-silica is combined with other supplementary cementitious materials, suggesting strong synergistic potential.

### 5.2 Practical Recommendations

**For Design Engineers:** Incorporate nano-silica at 1–2% for standard concrete applications and 2–3% for high-durability requirements or recycled aggregate concrete. Specify use of superplasticizers to maintain workability, as nano-silica's high surface area increases water demand. Ensure adequate dispersion mechanisms during mixing.

**For Producers:** Establish quality control protocols for nano-silica characterization including particle size distribution and agglomeration assessment. Develop standardized dispersion procedures to minimize agglomeration effects, particularly at dosages exceeding 2%. Consider pretreatment of recycled aggregates with nano-silica suspension for enhanced performance.

**For Researchers:** Future investigations should focus on: (1) Long-term durability studies (>500 days) in diverse aggressive environments; (2) Standardization of nano-silica characterization and dispersion methodologies; (3) Exploration of synergistic effects with emerging materials and bio-based binders; (4) Development of predictive models for nano-silica performance considering particle size, surface area, and dispersion quality; (5) Life-cycle assessment studies comparing environmental benefits against production energy requirements.

### 5.3 Sustainability Implications

The use of nano-silica as a partial cement replacement offers significant environmental benefits through reduced clinker requirements and associated CO<sub>2</sub> emissions. When combined with recycled aggregates and other waste materials (fly ash, slag), nano-silica-modified concrete represents a genuinely sustainable construction material addressing both performance and environmental objectives simultaneously.

In conclusion, nano-silica has demonstrated substantial potential for improving concrete performance in both standard and specialized applications. Continued research addressing standardization, long-term durability characterization, and sustainability assessment will further establish nano-silica as a critical material for next-generation high-performance, durable, and sustainable concrete infrastructure.

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