



Utilization of Nanosilica in M50-grade Concrete: Mechanical and Microstructural Performance for Sustainable Construction

A. D. Sheena^{1*}, M. Beena Mol², S. Sashmitha³ and Pachaivannan Partheeban⁴

¹Department of Civil Engineering, Vels Institute of Science, Technology and Advanced Studies (VISTAS), Chennai, TN, India

²Department of Civil Engineering, LBS Institute of Technology for Women, KL, India

³Department of Civil Engineering, C. K. College of Engineering and Technology, Cuddalore, TN, India

⁴Department of Civil Engineering, Chennai Institute of Technology (CIT), Chennai, TN, India

Received: 02.01.2026 Accepted: 23.03.2026 Published: 30.06.2026

*dr.sheenaad@gmail.com



ABSTRACT

The growing demand for green building materials has spurred the development of strategies to partially replace cement with nanoengineered additives, thereby minimizing the ecological footprint. This study evaluates the properties of M50-grade high-strength concrete with nanosilica (NS) as a partial replacement for cement, which can also assist in the reduction of CO₂ emissions into the atmosphere. Due to its high reactivity and small particle size, nanosilica was used as a partial replacement for cement at 0%, 5%, 10%, and 15% by weight. Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were evaluated at various curing ages to identify the optimal replacement level. For microstructural characterization, separate experiments were carried out using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) techniques to examine the formation of calcium silicate hydrate (C–S–H) gel and the refinement of the pore structure. The test results show that the addition of nanosilica improves the strength properties of the mix up to an optimum replacement level of 15%. At 28 days, the mix with 15% NS exhibited superior properties compared with all other mixes. The mix with 15% NS replacement exhibited a compressive strength of 58.21 N/mm², a split tensile strength of 8.83 N/mm², and a flexural strength of 5.34 N/mm². Thus, a 15% NS replacement level is optimal for producing high-strength M50-grade concrete suitable for environmentally friendly construction. The study further demonstrates that nanosilica is effective in developing sustainable concrete mixes through its use as a supplementary cementitious material.

Keywords: Environmentally friendly material; Microstructural analysis; Mechanical properties; Nanosilica; Sustainable concrete.

1. INTRODUCTION

The growing demand for high-performance and sustainable concrete has driven research into nanomaterials, particularly nanosilica (NS), as a partial replacement for cement (Tanimola and Steve, 2024). Due to its ultra-fine particle size, high surface area, and pozzolanic reactivity, NS enhances cement hydration, promotes additional calcium-silicate-hydrate (C–S–H) formation, refines the interfacial transition zone (ITZ), and densifies the concrete matrix. These effects collectively improve compressive, split tensile, and flexural strengths, reduce porosity, and enhance durability against aggressive environments (Al-hagri and Mahmud, 2022; Shafi *et al.* 2016). High-strength concretes, such as M50 grade, require optimized microstructural integrity, making the incorporation of NS particularly effective for strength development and long-term performance. Optimal NS dosages are generally reported between 1–4% by weight of cement. Dosages up to ~3% typically yield significant mechanical and durability improvements, while higher contents can lead

to particle agglomeration, reduced workability, and performance plateauing (Khan *et al.* 2022). NS also serves as nucleation sites for C–S–H growth, lowers calcium hydroxide content, refines capillary pores, and enhances ITZ bonding, thereby improving both mechanical behavior and durability (Al-saffar *et al.* 2023). In high-strength and self-compacting concretes, NS has been shown to increase early-age and 28-day compressive strength substantially, improve tensile and flexural performance, and contribute to acid and chloride resistance (Rakesha *et al.* 2024; Patil *et al.* 2024; Gopinath *et al.* 2012).

Partial replacement of cement with NS appears to be a promising approach for reducing the amount of clinker content and the resulting CO₂ emissions, while also enhancing the properties of the resulting concrete mix. Though nanosilica has been the focus of considerable attention in conventional concrete mixtures, very little has been done on the optimized content and integrated properties, in both macro- and micro-levels, for high-strength concretes. In particular, the relationship

between nano-level hydration products, pore refinement, and the resulting enhancement in the properties, along with the green benefits, has yet to be clearly established (Shafi *et al.* 2016).

This study examines the effect of nanosilica addition on high-strength M50-grade concrete through a comprehensive experimental investigation. In particular, it evaluates the influence of nanosilica on macroscopic properties, compressive, split tensile, and flexural strengths, along with microstructural characteristics using SEM and XRD analysis.

While in the previous studies, the main focus has been to improve the strength of the mix, in this study, the structural performance and reduction of environmental impact are combined to determine the optimal replacement of nanosilica. The results of this study reveal a direct relationship between the dosage of nanosilica, microstructural densification, mechanical enhancement, and the benefits of clinker reduction. However, existing studies remain limited, particularly with respect to the systematic optimization of dosage and the correlation between mechanical and microstructural improvements and environmental benefits. This research investigates the effect of NS on M50-grade concrete, evaluating mechanical properties and assessing microstructural modifications via SEM and XRD analyses to identify an optimal replacement level that maximizes performance while minimizing environmental impact.

2. MATERIALS AND METHODS

The building material is concrete, made by mixing cement with aggregates, water, and, occasionally, chemical additives, with the exact ingredients depending on the desired properties and application. Ordinary Portland Cement (OPC) of 53 Grade, conforming to IS 12269:2013, was used in the study, with a specific gravity of 3.15 and a normal consistency of 31%. Crushed granite aggregates with a maximum size of 20 mm were used as coarse aggregate, conforming to IS 383:2016 requirements, with a specific gravity of 2.70 and water absorption of 0.5%. Commercially available amorphous nanosilica was incorporated as a partial replacement for cement, featuring particle sizes of 20–30 nm, a specific surface area of approximately 180 m²/g, and a purity exceeding 99%, primarily composed of SiO₂ (≥ 95%) with minor traces of Al₂O₃ and Fe₂O₃. Potable water, free from impurities and organic matter, was employed for mixing and curing in accordance with IS 456:2000 guidelines. To improve workability and ensure uniform dispersion of nanosilica within the concrete matrix, a polycarboxylate ether (PCE)-based high-range water-reducing superplasticizer was also used.

Cement

Cement, the key binding component in concrete, when combined with water, initiates a hydration process that contributes to the setting and strength gain of the concrete. In this research, 53-grade Ordinary Portland Cement (OPC) was used, conforming to IS 12269:2013 and ASTM C150 (2020).

Nanosilica

Nanosilica is a highly fine pozzolanic material commonly incorporated into concrete to enhance its strength and long-term durability. Its extremely small particle size and high surface area allow it to fill microvoids and chemically interact with calcium hydroxide, producing additional calcium silicate hydrate (C-S-H) and enhancing the overall microstructure of the concrete. Nanosilica (NS) used in this study was procured from a commercial supplier as an amorphous powder with a purity greater than 99% and an average particle size of 10–30 nm. To ensure uniform dispersion and prevent agglomeration, the required amount of NS was first mixed with a portion of the mixing water and ultrasonicated for 20–30 min. A PCE-based superplasticizer was added during dispersion to enhance stability and workability. The prepared nanosilica suspension was then introduced into the concrete mix during batching to achieve uniform distribution.

A PCE-based high-range water-reducing superplasticizer was used to maintain workability in nanosilica-modified mixes. The superplasticizer had a specific gravity of approximately 1.08–1.12 and a solid content of 30–35%, as per the manufacturer's specifications. It was added at a dosage of 0.8–1.2% by weight of cementitious materials, depending on the nanosilica content, to achieve the desired consistency and ensure proper dispersion of nanoparticles without segregation.

M-sand

Manufactured sand (M-sand) is a fine aggregate produced by crushing durable granite rocks under controlled conditions, offering an eco-friendly alternative to natural river sand. Its increasing adoption in concrete applications is mainly due to the scarcity of natural sand and the environmental concerns associated with river sand extraction. In this investigation, M-sand with a specific gravity of 2.76 was sourced from a nearby quarry and utilized in accordance with IS 383:2016 standards.

Coarse Aggregate

Coarse Aggregate plays a crucial role in concrete by enhancing its strength, durability, and structural integrity. For this study, 20 mm coarse

aggregates were selected and used in accordance with the guidelines specified in IS 383:2016.

Water

Water is a fundamental ingredient in concrete, essential for mixing, setting, and curing. Its quality and quantity have a direct impact on the concrete's workability, strength, durability, and overall performance. In this research, clean, potable water was used in accordance with IS 456:2016.

2.1 Mix Design

Table 1. Properties of materials used in nanosilica-modified M50 grade concrete

Material	Property	Value / Specification
Cement (OPC 53 grade)	Specific gravity	3.15
	Fineness (Blaine)	325 m ² /kg
	Standard consistency	30%
	Initial/Final setting time	30 min / 600 min
Fine Aggregate (Sand)	Specific gravity	2.65
	Fineness modulus	2.6
	Water absorption	1.2%
Coarse Aggregate (20 mm)	Specific gravity	2.70
	Water absorption	0.8%
	Maximum size	20 mm
Nanosilica (NS)	Form	Amorphous powder
	Purity	>99%
	Particle size	10–30 nm
	Specific surface area	150–250 m ² /g
Superplasticizer (PCE-based)	Dosage	0.8–1.2% by weight of cement
	Specific gravity	1.08–1.12
	Solid content	30–35%

The mix design for M50 grade concrete was carried out in accordance with IS 10262:2019 and IS 456:2000 guidelines. The target mean compressive strength was determined based on a characteristic strength of 50 N/mm² and an assumed standard deviation of 6.0 N/mm² for good quality control. Using $f_{ck} = 50$ N/mm² (characteristic compressive strength of concrete) and $S = 6.0$ N/mm² (standard deviation), the target mean strength was calculated as 59.9 N/mm². Considering material properties, laboratory conditions, and preliminary trial mixes, a practical target mean strength of 56.6 N/mm² was adopted to ensure compliance with M50 grade requirements while maintaining workability and durability. The final mix proportions were established through iterative trial batches to achieve the desired strength, consistency, and performance, with

nanosilica incorporated as a partial replacement for cement. The properties of the materials used in the concrete mix are shown in Table 1. Based on the properties of the materials, the quantities required for different nanosilica dosages are presented in Table 2.

Table 2. Quantities of materials per m³ for M50-grade concrete

Material	Control Mix	5% NS Replacement	10% NS Replacement	15% NS Replacement
Cement (kg)	440	418	396	374
Nanosilica (kg)	0	22	44	66
Fine Aggregate (kg)	680	680	680	680
Coarse Aggregate (kg)	1100	1100	1100	1100
Water (l)	158	158	158	158
Superplasticizer (kg)	5.3	5.3	5.3	5.3

2.2 Methods

The study focuses on the use of nanosilica in M50-grade concrete, and the study's procedures and analysis are shown in Fig. 1.

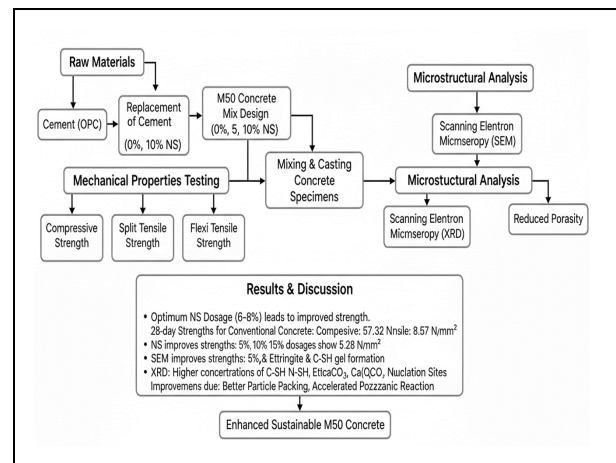


Fig. 1: Schematic representation of nanosilica utilization in M50-grade concrete

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

The study evaluated the compressive strength of concrete samples mixed with varying proportions of nanosilica (NS) as a replacement for cement. The samples were cured and examined at 3, 7, and 28 days. The compressive strength test was conducted as per IS 516:2018 for control concrete (CC) at 3, 7, and 28 days, with a maximum strength of 53.71 N/mm² obtained at 28 days. The compressive strength of concrete with nanosilica replacement levels of 5%, 10%, and 15% increased with curing time. After 3 days, the compressive strengths for NS-5%, NS-10%, and NS-15% were 17.25 N/mm², 17.49 N/mm², and 18.6 N/mm², respectively. The compressive strength at 7 days also varied, with NS-5%

achieving 28.61 N/mm², NS-10% registering 26.53 N/mm², and NS-15% attaining 27.28 N/mm². At 28 days, NS-5% had a compressive strength of 55.96 N/mm², NS-10% achieved 57.32 N/mm², and NS-15% reached 58.21 N/mm². At all curing ages, concrete mixes with NS as a partial replacement for cement exhibited equivalent or slightly higher compressive strength than normal concrete, suggesting its potential as a supplementary cementitious material (Fig. 2).

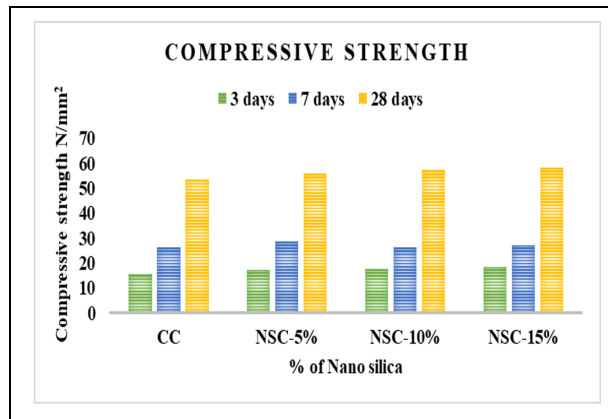


Fig. 2: Compressive strength of concrete at different curing ages with varying nanosilica content

3.2 Split Tensile Strength

The split tensile strength for the NS-5% replacement was 3.60 N/mm² at 3 days, 4.28 N/mm² at 7 days, and 8.52 N/mm² at 28 days; the corresponding values for the NS-10% replacement were 3.82 N/mm², 4.30 N/mm², and 8.57 N/mm². The split tensile strength was enhanced to 3.96 N/mm² at 3 days, 4.17 N/mm² at 7 days, and 8.83 N/mm² at 28 days with NS-15% replacement (IS 5816-2018). The tensile strength increased over the 28-day curing period as the nanosilica replacement proportion increased, with the NS-15% replacement exhibiting the maximum strength, as shown in Fig. 3.

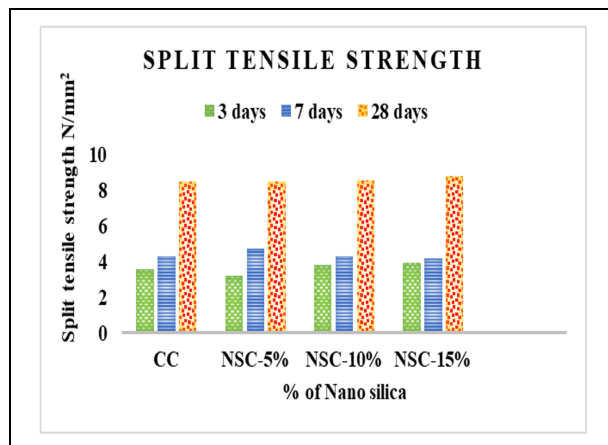


Fig. 3: Split tensile strength of concrete at different curing ages with varying nanosilica content

3.3 Flexural Strength

The concrete samples with nanosilica at different replacement levels were compared with a control group of conventional concrete (CC). The flexural strength increased gradually as the replacement level increased to 5%, 10%, and 15%, with values of 4.62 N/mm², 4.69 N/mm², and 5.34 N/mm², respectively. The concrete using NS exceeded the control concrete at all-time intervals during the curing phase, sustaining this pattern. The control concrete's flexural strength was 4.62 N/mm² at 28 days of curing, whereas the NS-15% mixture had the highest flexural strength among the compositions evaluated, at 5.34 N/mm². These results show that nanosilica can replace cement to increase concrete's flexural strength, thereby enhancing its mechanical properties, as shown in Fig. 4.

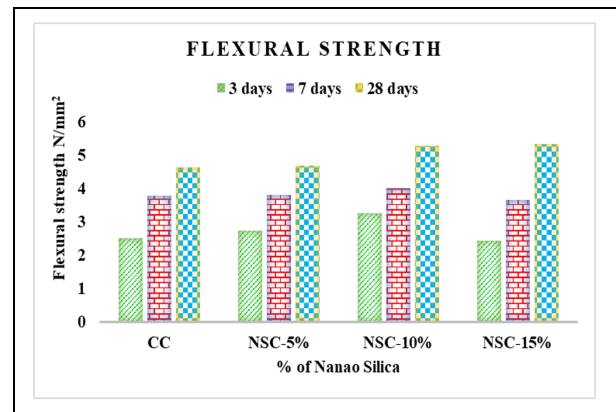


Fig. 4: Flexural strength of concrete at different curing ages with varying nanosilica content

3.4 Durability Test

Nanosilica is recognized for improving the durability of high-strength concrete by refining the microstructure and reducing porosity. One of the key durability assessments is the rapid chloride penetration test (RCPT), which evaluates the resistance of concrete to chloride ion ingress, a crucial factor for the longevity of reinforced concrete structures. In this test, concrete specimens, typically 100 × 50 mm cylinders, are exposed to a 60 V DC potential for 6 h. The total electrical charge passed, measured in coulombs, serves as an indicator of chloride ion penetration. According to ASTM C1202, a charge exceeding 4000 coulombs indicates high penetrability; 2000–4000 coulombs indicates moderate penetrability; 1000–2000 coulombs indicates low penetrability; and less than 1000 coulombs indicates very low chloride-ion penetrability.

Nanosilica enhances concrete durability by filling micro-pores and engaging in pozzolanic reactions with Ca(OH)₂, leading to the formation of additional C–S–H gel. This process densifies the concrete matrix and significantly reduces chloride-ion penetration, as

reflected in lower RCPT values. For M50-grade concrete, studies have shown that the control mix without nanosilica exhibits moderate chloride penetrability with an RCPT value of around 3200 coulombs. Incorporating 1% nanosilica reduces this to 2100 coulombs (low penetrability), while 2% lowers it further to 1500 coulombs (low penetrability). At 3% nanosilica, the RCPT value drops to 900 coulombs, indicating very low chloride penetration. These observations suggest that an optimal nanosilica content of approximately 2–3% markedly enhances resistance to chloride ingress in high-strength concrete. Nanosilica has been extensively documented as an effective nanomaterial for enhancing the durability of high-strength concretes through pore refinement, enhanced pozzolanic reactivity, and densification of the interfacial transition zone (ITZ). RCPT, as defined in ASTM C1202, remains a widely accepted procedure for assessing chloride-ion ingress. This test subjects 100×50 mm concrete specimens to a 60 V DC potential for 6 h, and the cumulative electric charge, expressed in coulombs, is used to determine chloride permeability (ASTM C1202, 2019).

In the present investigation, the control M50 concrete exhibited an RCPT charge of approximately 3200 coulombs, indicating moderate chloride penetrability. This outcome aligns closely with prior reports that high-strength cementitious systems without nano-modification typically exhibit moderate ion permeability due to higher paste density but incomplete pore refinement (Zhang *et al.* 2012; Nili and Ahmad, 2015). At 1% nanosilica, the RCPT value decreased to 2100 coulombs, demonstrating low penetrability. These reductions support the findings of Jo *et al.* (2007), who observed that small doses of nanosilica significantly refine the micro-pore structure by accelerating the formation of secondary C–S–H (Jo *et al.* 2007).

At 2% nanosilica, chloride permeability further declined to 1500 coulombs, which is consistent with the densified pore network reported in similar high-performance concretes containing 2–3% nanosilica (Patra and Mukharjee, 2016; Sadrmomtazi *et al.* 2018; Mukharjee and Barai, 2014). These studies highlight that this dosage range optimizes nanosilica dispersion and reactivity, producing a highly compact matrix. The 3% NS mix recorded an RCPT of 900 coulombs, indicating very low chloride penetrability according to ASTM standards. Similar low RCPT values have been observed in nano-engineered concretes where high pozzolanic activity and pore refinement significantly restrict chloride transport (Su *et al.* 2012; Mustakim *et al.* 2021). Nevertheless, several investigations caution that dosages beyond ~3% may induce nanoparticle agglomeration, hindering full reactivity and potentially increasing localized porosity (Christensen *et al.* 2020; Yu *et al.* 2014; Zhan *et al.* 2022). Thus, comparison with previous studies confirms that the nanosilica percentage range

consistently provides optimal chloride resistance, consistent with the results of the present study.

3.5 Microstructural Analysis

To inspect the microstructural properties of the concrete after 90 days of water curing, SEM and XRD were used. Powdered samples were collected from the interior core of the concrete specimens for this analysis. SEM was performed using a high-resolution microscope at $15,000 \times$ magnification with a $5 \mu\text{m}$ scale to observe surface features. XRD analysis was performed using X'Pert High Score software to identify crystalline phases in the samples. These analytical methods provide a comprehensive view of concrete's internal structure, aiding in assessing its durability, performance, and potential improvements.

3.5.1 SEM Analysis

The microstructural changes were observed in M50-grade concrete mixes incorporating varying levels of NS, as demonstrated by SEM images shown in Figs. 5 and 6. At 5%, 10%, and 15% replacement levels, NS particles were uniformly dispersed within the concrete matrix, enhancing interfacial bonding and reducing porosity. Hydration products such as calcium silicate hydrate (C–S–H) and calcium hydroxide were present in all specimens studied. At a 10% replacement level, the microstructure appeared significantly denser, with more refined hydration products and fewer voids. These findings suggest that nanosilica is an effective partial cement replacement, capable of enhancing the microstructural integrity and overall performance of M50 grade concrete.

Microstructural characterization was conducted on 90-day-cured concrete specimens using SEM and XRD. Powdered samples from the specimen core were analyzed under a $15,000 \times$ SEM magnification, and XRD was carried out using X'Pert HighScore software, providing insights into phase composition, hydration product distribution, and microstructural refinement. SEM images revealed distinct microstructural improvements with increasing nanosilica content:

5% NS Addition

The concrete exhibited improved particle packing, uniform nanoparticle dispersion, and a visible reduction in micro-voids. These enhancements are consistent with the findings of Yu *et al.* (2014), who noted that nanosilica effectively fills capillary pores and strengthens the ITZ.

10% NS Addition

Concrete appeared densest at this level, characterized by:

- Highly refined C–S–H gel
- Reduced porosity
- Tightened ITZ structure

Similar dense morphologies have been reported by Senff *et al.* (2009), Nazari and Shadi (2022), and Al-Hadithi and Hilal (2016), attributing the changes to rapid nucleation and pozzolanic reactivity induced by nanosilica.

15% NS Addition

The microstructure still appeared improved, but minor agglomerated nanosilica clusters emerged. These clusters can hinder cement hydration and obstruct uniform gel formation, confirming the observations by Yu *et al.* (2014) and Charkhtab *et al.* (2021) regarding diminishing returns at high NS contents.

Across all mixes, typical hydration phases, including C–S–H, portlandite ($\text{Ca}(\text{OH})_2$), and small crystalline phases, were noted. The decrease in the visibility of $\text{Ca}(\text{OH})_2$ plates with increasing NS is consistent with the enhanced pozzolanic consumption, as reported by Zhang *et al.* (2012).

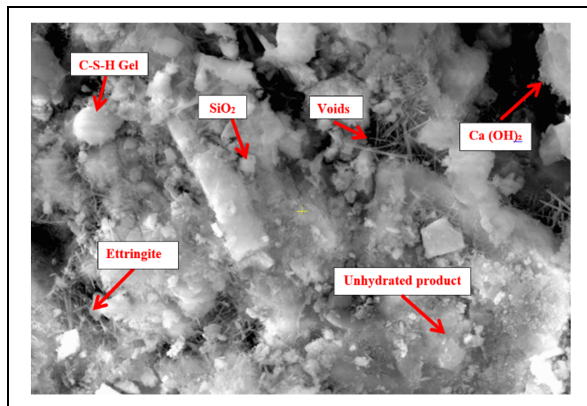


Fig. 5: SEM image of control concrete

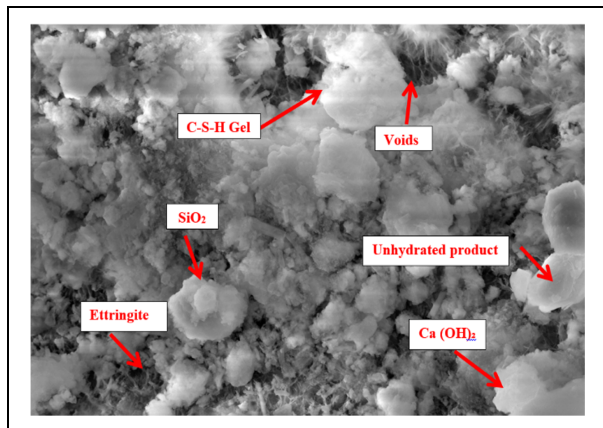


Fig. 6: SEM image of 10% nanosilica concrete

3.5.2 XRD Analysis

The XRD analysis was conducted to examine the phase composition of M50-grade concrete with 5%, 10%, and 15% NS, revealing distinct diffraction patterns. Figs. 7 and 8 show the diffraction peaks observed in all samples corresponded to calcium-based compounds and their hydration products used, such as calcium hydroxide and C–S–H gel. The intensity of these peaks increased with higher NS content, indicating that nanosilica actively participates in the hydration process by forming additional hydrated products, as reported in earlier research works. This suggests that adjusting the amount of nanosilica can be an effective strategy to tailor hydration-phase development and improve the overall performance of concrete.

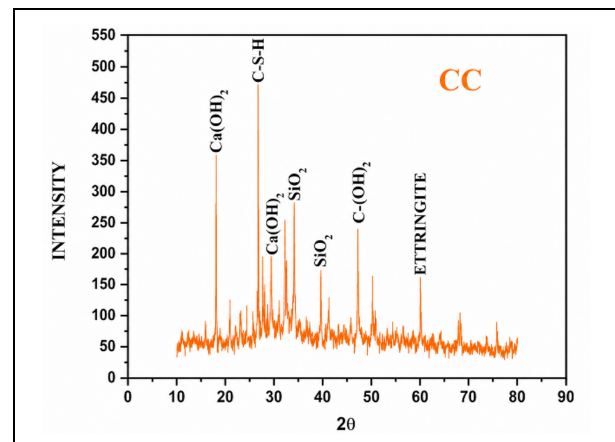


Fig. 7: XRD analysis of control concrete

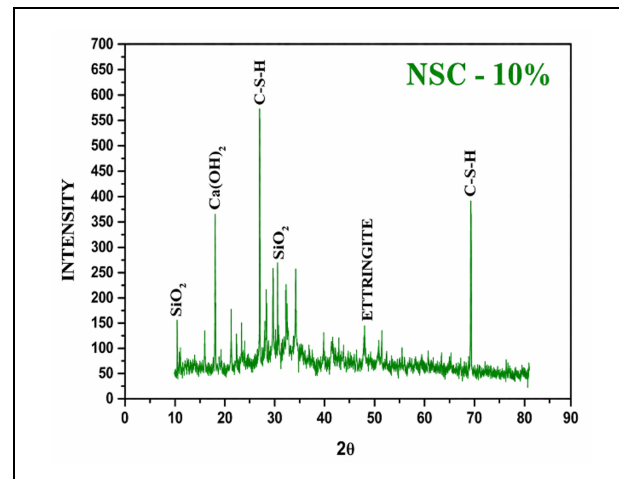


Fig. 8: XRD analysis of 10% nanosilica concrete

XRD analysis revealed that higher nanosilica contents reduced $\text{Ca}(\text{OH})_2$ peak intensities, confirming the ongoing pozzolanic reaction that converts portlandite into secondary C–S–H. Stronger amorphous C–S–H halos indicated enhanced gel formation and matrix densification, while peak broadening observed at 10% NS suggested the presence of nano-crystalline hydration

products. Minor traces of quartz and calcium carbonate were also detected, attributed to admixture characteristics and carbonation, consistent with previous reports (Tsampali *et al.* 2025).

SEM observations after 90 days of curing further corroborated these findings, showing progressive microstructural densification with increasing NS content, reduced microporosity, refined C–S–H gel morphology, and a more compact matrix, in agreement with high-resolution studies by Senff *et al.* (2009) and Yu *et al.* (2014). The combined SEM–XRD evidence aligns with RCPT results, as the reduction in $\text{Ca}(\text{OH})_2$ and densified microstructure limits continuous ionic pathways, thereby reducing chloride penetration and enhancing durability. These microstructural insights confirm that nanosilica contributes to significant enhancement in hydration, matrix compactness, and durability.

3.6 Strategies for Environmental Risks

Several strategies have been proposed to mitigate the potential environmental risks associated with nanosilica. One approach is encapsulating NS within the concrete matrix, particularly in high-strength mixes like M50-grade concrete, which effectively traps the particles in the hardened structure and reduces the likelihood of leaching into the environment. Controlled application and disposal practices are also critical, involving strict adherence to waste management protocols and environmental regulations to minimize potential ecological impacts. Furthermore, developing sustainable and eco-friendly production methods for NS can help reduce its environmental footprint by lowering energy consumption and associated emissions during manufacturing.

With the increasing use of NS in concrete, regulatory bodies are establishing guidelines to ensure its safe application. These regulations typically address permissible NS concentrations in concrete, safe handling procedures, and proper disposal of NS-containing materials. Compliance with these guidelines is essential to promote the responsible and sustainable use of nanosilica in construction projects.

Nanosilica can be considered environmentally safe in concrete when proper production, handling, and application practices are followed. Once incorporated, NS becomes encapsulated within the cement matrix, effectively immobilizing the nanoparticles and preventing their release into air, water, or soil, while also eliminating direct contact risks. Its use as a partial cement replacement reduces overall cement consumption, lowering CO_2 emissions and contributing to a reduced carbon footprint. Moreover, NS can be synthesized from industrial or agricultural by-products, such as rice husk ash or silica fume, promoting waste valorization and supporting a circular economy. While dry NS powder

requires safe handling measures to avoid inhalation, these risks are negligible once it is mixed into concrete. Thus, NS enhances concrete durability by improving resistance to chloride, sulfate, and chemical attacks, thereby extending the service life of structures and reducing the need for repairs or replacements, acting as a self-healing concrete for microcracks. This study, through immobilization in the concrete matrix, reduced cement use, enabled sustainable sourcing, and provided lifecycle benefits. Nanosilica demonstrates a high level of environmental safety in concrete applications, with primary considerations limited to production and handling stages.

3.7 Discussion

The use of nanosilica as a partial replacement for cement in the production of M50-grade concrete leads to notable improvements in mechanical properties when added in optimal amounts. This enhancement highlights the potential of NS to improve the overall performance of the concrete significantly. The objective of the analysis is to explore the maximum feasible replacement of cement with NS, based on a comprehensive evaluation of mechanical properties and the microstructural characteristics.

The conventional concrete mix achieved 28-day compressive, split tensile, and flexural strengths of 57.32 N/mm², 8.57 N/mm², and 5.28 N/mm², respectively. Incorporation of nanosilica at replacement levels of 5%, 10%, and 15% significantly enhanced the mechanical properties compared to the control mix, with 10% nanosilica identified as the optimum dosage for improving the performance of M50-grade concrete. SEM analysis revealed a denser microstructure characterized by increased formation of needle-like ettringite crystals and enhanced development of C–S–H gel. XRD results further confirmed higher concentrations of hydration products, including C–S–H, ettringite, calcium carbonate, and calcium hydroxide, indicating improved hydration and microstructural refinement in nanosilica-modified concrete. Thus, all strength parameters exhibited marked improvement, primarily due to better particle packing, increased nucleation sites, and accelerated pozzolanic conversion of portlandite into additional C–S–H gel. Among the evaluated dosages, the 10% nanosilica mix yielded the most balanced mechanical performance.

Despite numerous studies on the incorporation of nanosilica into low- and medium-strength concretes, systematic research on its application in high-strength M50-grade concrete remains limited. The research gaps include a lack of studies on optimized dosages that balance mechanical performance, durability, and workability, as well as insufficient integration of mechanical property improvements with microstructural analyses using SEM and XRD. Again, the long-term

durability under aggressive environmental conditions, such as chloride or sulfate exposure, has not been extensively evaluated for high-strength NS-modified concretes. Research quantifying the environmental and sustainability benefits of NS, including reductions in cement content, CO₂ emissions, and lifecycle impacts, is also scarce. This reduces clinker usage and associated CO₂ emissions, demonstrating its potential for sustainable, high-performance concrete.

The synergistic use of NS with supplementary cementitious materials and its potential in self-healing concrete systems have not been thoroughly explored for high-performance grades. Addressing these gaps is critical to fully understand and optimize the use of NS in sustainable, high-strength concrete applications.

4. CONCLUSION

The use of nanosilica as a partial cement replacement in M50-grade concrete has been shown to improve mechanical and microstructural performance substantially. An optimal NS content enhances compressive, split tensile, and flexural strengths. At the same time, SEM and XRD analyses reveal a denser, more uniform microstructure resulting from its pozzolanic activity and nano-filler effects. This nanosilica incorporation enhances the mechanical strength and durability of concrete, reducing maintenance requirements and promoting sustainable infrastructure development. Its encapsulation within the concrete matrix minimizes the risk of particle release, while adherence to proper handling and regulatory guidelines ensures environmental safety. Sustainable production approaches, particularly the utilization of industrial or agricultural by-products, can further reduce the environmental footprint and improve cost-effectiveness. Future research could focus on long-term performance under aggressive exposure conditions, synergistic use of nanosilica with other supplementary cementitious materials, and its potential in self-healing concrete systems. Thus, nanosilica represents a promising and environmentally responsible approach to developing sustainable, high-strength concrete.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons

Attribution (CC BY) license
(<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Al-Hadithi, A. I. and Hilal, N. N., The Possibility of Enhancing Some Properties of Self-Compacting Concrete by Adding Waste Plastic Fibers, *J. Build. Eng.*, 8, 20–28(2016).
<https://doi.org/10.1016/j.jobbe.2016.06.011>
- Al-hagri, M. G. and Mahmud, S. D., Effect and Optimization of Incorporation of Nano-SiO₂ into Cement-Based Materials – a Review, *Challenge J. Concrete Res. Lett.*, 13(1), 36–53 (2022).
<https://doi.org/10.20528/cjcr.2022.01.004>
- Al-saffar, F. Y., Sing, L. W. and Paul, S. C., An Elucidative Review of the Nanomaterial Effect on the Durability and Calcium-Silicate-Hydrate (C-S-H) Gel Development of Concrete, *Gels*, 9(8), 613(2023).
<https://doi.org/10.3390/gels9080613>
- ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, ASTM International, West Conshohocken, PA, USA, 2019.
- ASTM C150: Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA, USA, 2024.
- Charkhtab, M. S., Rahmat, M., Morteza, J. and Iman, N. M., Mechanical Properties of Fly Ash-Based Geopolymer Concrete with Crumb Rubber and Steel Fiber under Ambient and Sulfuric Acid Conditions, *Constr. Build. Mater.*, 281, 122571(2021).
<https://doi.org/10.1016/j.conbuildmat.2021.122571>
- Christensen, T. H., A. Damgaard, A., Levis, J., Zhao, Y., Bjorklund, A., Arena, U., Barlaz, M. A., Starostina, V., Boldrin, A., Asrup, T. F. and Bisinella, V., Application of LCA Modelling in Integrated Waste Management, *Waste Manage.*, 118, 313–22(2020).
<https://doi.org/10.1016/j.wasman.2020.08.034>
- Gopinath, S., Mouli, P. C., Murthy, A. R., Iyer, N. R. and Maheswaran, S., Effect of Nanosilica on Mechanical Properties and Durability of Normal Strength Concrete, *Arch. Civ. Eng.*, 58(4), 433–444(2012).
<https://doi.org/10.2478/v.10169-012-0023-y>
- IS 10262, Guidelines for concrete mix design proportioning, Bur. Indian Stand. New Delhi. (2019) 1–14.
- IS 12269 (1987): 53 grade ordinary Portland cement.
- IS 383: Coarse and Fine Aggregate for Concrete – Specification: 2016
- IS 456 (2016): Plain and Reinforced Concrete - Code of Practice 2016
- IS 516 - 2018, Method of Tests for Strength of Concrete, Bur. Indian Stand. (2018) 1–30.

- IS 5816-2018, Indian standard Splitting tensile strength of concrete- method of test, Bur. Indian Stand. (2018) 1–14.
- Jo, B. W., Kim, C. H., Tae, G. H. and Park, J. B., Characteristics of Cement Mortar with Nano-SiO₂ Particles, *Constr. Build. Mater.*, 21(6), 1351–1355(2007).
<https://doi.org/10.1016/j.conbuildmat.2005.12.020>
- Khan, K., Ahmed, W., Amin, M. N. and Nazar, S., Nanosilica-Modified Concrete: A Bibliographic Analysis and Comprehensive Review of Material Properties, *Nanomater.*, 12(12), 1989(2022).
<https://doi.org/10.3390/nano12121989>
- Mukharjee, B. B. and Barai, S. V., Influence of Nanosilica on the Properties of Recycled Aggregate Concrete, *Constr. Build. Mater.*, 55, 29–37(2014).
<https://doi.org/10.1016/j.conbuildmat.2014.01.003>
- Mustakim, S. M., Das, S. K., Mishra, J., Asif, A., Thamar, A. S., Hasan, A. S. and Kaze, C. R., Improvement in Fresh, Mechanical and Microstructural Properties of Fly Ash- Blast Furnace Slag Based Geopolymer Concrete By Addition of Nano and Micro Silica, *Silicon*, 13(8), 2415–2428(2021).
<https://doi.org/10.1007/s12633-020-00593-0>
- Nazari, A. and Shadi, R., Retraction Note to: Effects of CuO Nanoparticles on Compressive Strength of Self-Compacting Concrete, *Sadhana*, 47(4), 264(2022).
<https://doi.org/10.1007/s12046-022-02043-6>
- Senff, L., João, A. L., Victor, M. F., Dachamir, H. and Wellington, L. R., Effect of Nanosilica on Rheology and Fresh Properties of Cement Pastes and Mortars, *Constr. Build. Mater.*, 23(7), 2487–2491(2009).
<https://doi.org/10.1016/j.conbuildmat.2009.02.005>
- Shafi, L. S., Megha, G. and Geeta, M., Comparative Study of Nanosilica Induced Mortar, Concrete and Self-Compacting Concrete – A Review, *Ind. J. Sci. Technol.*, 9(44), (2016).
<https://doi.org/10.17485/ijst/2016/v9i44/105288>
- Su, X., Andoh, A. R., Cai, H., Pan, J., Amr, K. and Said, H. M., GIS-Based Dynamic Construction Site Material Layout Evaluation for Building Renovation Projects, *Automat. Constr.*, 27, 40–49(2022).
<https://doi.org/10.1016/j.autcon.2012.04.007>
- Tanimola, J. O. and Steve, E., Recent Advances in Nano-Modified Concrete: Enhancing Durability, Strength, and Sustainability through Nanosilica (NS) and Nano Titanium (NT) Incorporation, *Appli. Eng. Sci.*, 19, 100189(2024).
<https://doi.org/10.1016/j.apples.2024.100189>
- Tsampali, E., Eirini, C. T., Eleni, P. and Maria, S., The Mechanism Action of Crystalline Admixtures on Hydration, Microstructure, and Self-Healing of Cementitious Materials, *J. Build. Eng.*, 110, 112987(2025).
<https://doi.org/10.1016/j.jobbe.2025.112987>
- Yu, R., Tang, P., Spiesz, P. and Brouwers, H. J. H., A Study of Multiple Effects of Nanosilica and Hybrid Fibres on the Properties of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) Incorporating Waste Bottom Ash (WBA), *Constr. Build. Mater.*, 60 98–110(2026).
<https://doi.org/10.1016/j.conbuildmat.2014.02.059>
- Zhan, P., Jing, X., Juan, W., Junqing, Z. and Zhihai, H., A Review of Recycled Aggregate Concrete Modified by Nanosilica and Graphene Oxide: Materials, Performances and Mechanism, *J. Clean. Prod.*, 375 134116(2022).
<https://doi.org/10.1016/j.jclepro.2022.134116>
- Zhang, T., Qijun, Y., Jiangxiong, W. and Jianxin, L., Investigation on Mechanical Properties, Durability and Micro-Structural Development of Steel Slag Blended Cements, *J. Therm. Anal. Calorim.*, 110 (2), 633–639(2012).
<https://doi.org/10.1007/s10973-011-1853-6>