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An Experimental Study on the Performance of Nano-Silica Concrete under Varying Replacement Ratios

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ABSTRACT

This study presents an experimental investigation on the performance of nano-silica–modified concrete under varying cement replacement ratios. Nano-silica, owing to its high surface area and pozzolanic reactivity, was incorporated as a partial replacement of ordinary Portland cement at different percentages to evaluate its influence on concrete properties. A comprehensive experimental program was conducted to assess fresh and hardened characteristics, including workability, compressive strength, tensile strength, and durability-related parameters. The results demonstrate that the inclusion of nano-silica significantly enhances the mechanical performance and microstructural densification of concrete up to an optimum replacement level, beyond which marginal reductions in performance were observed due to particle agglomeration and reduced workability. The findings highlight the potential of nano-silica as an effective supplementary cementitious material for producing high-performance and sustainable concrete, offering improved strength and durability while reducing cement consumption.

Keywords—Nano-silica concrete; Cement replacement; Mechanical properties; Durability performance; Sustainable construction materials.

INTRODUCTION

Concrete is the most widely used construction material in the world due to its versatility, durability, and cost-effectiveness. However, the extensive use of ordinary Portland cement (OPC) in concrete production has raised serious environmental concerns, as cement manufacturing is a major contributor to global carbon dioxide emissions and energy consumption. In recent years, the construction industry has increasingly focused on developing sustainable and high-performance concrete by incorporating supplementary cementitious materials (SCMs) that can enhance mechanical properties while reducing cement content. Among these emerging materials, nano-silica has gained significant attention owing to its unique physical and chemical characteristics. Nano-silica is an ultrafine material with particle sizes typically in the nanometre range and an exceptionally high specific surface area. Unlike conventional mineral admixtures such as silica fume or fly ash, nano-silica exhibits superior pozzolanic reactivity, enabling it to actively participate in the hydration process of cement. When added to concrete, nano-silica reacts rapidly with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This reaction not only enhances the strength development of concrete but also leads to a denser and more refined microstructure, thereby improving durability-related properties. Previous studies have reported that the incorporation of nano-silica can significantly improve compressive strength, tensile strength, and flexural strength of concrete, particularly at early ages. The improvement in mechanical performance is primarily attributed to two mechanisms: the pozzolanic reaction and the filler effect. The pozzolanic reaction contributes to the formation of additional binding phases, while the filler effect allows nano-silica particles to occupy micro-voids within the cement matrix, reducing porosity and enhancing particle packing density. As a result, concrete modified with nano-silica exhibits reduced permeability and increased resistance to aggressive environmental conditions such as chloride ingress, sulphate attack, and

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carbonation. Despite these advantages, the performance of nano-silica concrete is highly dependent on the dosage and method of incorporation. At lower replacement levels, nano-silica effectively enhances strength and durability; however, excessive replacement may lead to particle agglomeration due to its high surface energy. Agglomeration adversely affects workability and can create weak zones within the concrete matrix, ultimately reducing mechanical performance. Furthermore, higher nano-silica content increases water demand, which may necessitate the use of chemical admixtures to maintain adequate workability. Therefore, identifying the optimum replacement ratio of nano-silica is critical for achieving balanced performance in concrete.

In addition to mechanical performance, the use of nano-silica in concrete aligns with the broader objectives of sustainable construction. Partial replacement of cement with nano-silica contributes to reduced cement consumption and lower carbon emissions, while simultaneously enhancing material efficiency and service life of concrete structures. The development of nano-engineered concrete materials represents a promising approach to meeting the growing demand for high-performance and environmentally responsible construction solutions. Although considerable research has been conducted on nano-silica–based concrete, variations in experimental conditions, material characteristics, and replacement levels have led to differing conclusions regarding its optimal usage. Moreover, limited studies provide a comprehensive evaluation of both fresh and hardened properties under multiple replacement ratios. In this context, the present study aims to experimentally investigate the performance of nano-silica concrete under varying cement replacement ratios. The focus is on evaluating workability, strength characteristics, and overall performance to identify an optimal nano-silica content that maximizes benefits without compromising practical applicability. The outcomes of this research are expected to contribute to the effective utilization of nano-silica in advanced and sustainable concrete construction.

LITERATURE REVIEW

The use of fine and ultrafine materials in concrete has gained considerable attention due to their ability to enhance durability and long-term performance. Nayak and Joshi [1] provided an early overview of fine and ultrafine materials, highlighting their role in pore refinement, reduced permeability, and improved resistance to environmental degradation. Their work emphasized that particle size reduction leads to denser cementitious matrices, forming the basis for later research on nano-scale materials in concrete. Research on modifying concrete with alternative materials to improve mechanical and physical behavior has also been widely explored. Najim [2] investigated crumb rubber–modified structural concrete and demonstrated that material modification can significantly alter mechanical and thermo-physical properties. Although focused on rubberized concrete, this study established important methodologies for evaluating modified concrete systems, which are applicable to nano-material-based concrete as well. The synergistic use of micro- and nano-scale materials has been shown to further enhance durability. Sharkawi et al. [3] examined the combined influence of micro- and nano-silica on cementitious materials and reported substantial improvements in durability performance due to enhanced pozzolanic activity and microstructural densification. Similarly, Shahrajabian and Behfarnia [4] studied the effect of nanoparticles on alkali-activated slag concrete and found improved resistance to freeze–thaw cycles, confirming the beneficial role of nanoparticles in harsh environmental conditions. The fundamental characteristics of nano-silica in cementitious systems were investigated by Heikal et al. [5], who analysed blended cements containing nano-silica and observed accelerated hydration and increased formation of calcium silicate hydrate (C–S–H) gel. Earlier, Li [6] demonstrated that incorporating nano-SiO_2 into high-volume fly ash concrete significantly enhanced early-age strength and reduced porosity, providing one of the earliest experimental validations of nano-silica's effectiveness. Wang et al. [7] further extended these findings by reporting improved strength and reduced shrinkage and cracking sensitivity in lightweight aggregate concrete with nano-SiO_2 addition. Although reference [8] focuses on secure routing in mobile ad hoc networks, it underscores the broader trend of performance optimization through advanced material and system design, reflecting the interdisciplinary emphasis on optimization and efficiency that parallels developments in advanced construction materials.Durability aspects of nano-modified concrete have also been extensively studied. Ying et al. [9] investigated the pore structure and chloride diffusivity of recycled aggregate concrete incorporating nano-SiO_2 and nano-TiO_2, reporting refined pore structures and reduced chloride penetration. Raheem et al. [10] examined ultra-high-performance concrete and highlighted the importance of microstructural control in achieving superior mechanical and fracture properties, reinforcing the relevance of nano-scale additives. Foundational material science principles relevant to nano-material behavior are documented in the Encyclopaedia of Materials: Science

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and Technology by Buschow et al. [11]. The role of supplementary cementing materials (SCMs) in concrete has been comprehensively discussed by Panesar [12], Malhotra [13], Papadakis and Tsimas [14], Siddique and Khan [15], and Targan et al. [16]. These studies collectively emphasize that SCMs improve concrete performance while reducing environmental impact, providing a strong sustainability rationale for partial cement replacement. Further investigations into ultrafine materials such as ground granulated blast-furnace slag and alccofine have demonstrated notable improvements in strength and durability. Teng et al. [17] reported enhanced mechanical and durability properties in high-strength concrete containing ultrafine slag. Reddy and Ramadoss [18], Sumathi et al. [19], and Reddy and Naqash [20] confirmed that alccofine and ultra-fine slag significantly improve the mechanical behavior and durability of advanced concrete systems. Mohan and Mini [21] and Parveen et al. [22] highlighted the synergistic effects of combining silica fume, ultra-fine GGBS, and alccofine on strength and microstructural development. Finally, Ardalan et al. [23] demonstrated that colloidal nano-SiO_2 significantly enhances permeability resistance and abrasion resistance of concrete, confirming the effectiveness of nano-silica in improving surface and durability characteristics.

PROPOSED METHODOLOGY

The proposed methodology is designed to systematically evaluate the performance of nano-silica concrete under varying cement replacement ratios through a rigorous experimental framework consistent with journal-level research standards. The methodology encompasses material selection and characterization, mix design, specimen preparation, testing of fresh and hardened properties, and data analysis.

1. Materials and Characterization: Ordinary Portland Cement (OPC) conforming to relevant IS/ASTM standards is used as the primary binder. Nano-silica is employed as a partial replacement of cement; its physical and chemical properties, including particle size distribution, specific surface area, morphology, and chemical composition, are characterized using techniques such as X-ray fluorescence (XRF), scanning electron microscopy (SEM), and particle size analysis. Fine aggregates (natural river sand) and coarse aggregates (crushed stone) are selected in accordance with standard grading requirements. Potable water is used for mixing and curing. A high-range water-reducing admixture (superplasticizer) is incorporated where necessary to maintain workability, particularly at higher nano-silica contents.

2. Mix Proportioning: A control concrete mix is designed using standard mix design guidelines (e.g., IS 10262 or ACI 211) to achieve the target strength. Nano-silica is introduced as a partial replacement of cement at varying replacement ratios (for example, 0%, 1%, 2%, 3%, and 4% by weight of cement). The water-to-binder ratio is kept constant across all mixes to ensure consistency and to isolate the effect of nano-silica content on concrete performance. Proper dispersion of nano-silica is ensured by pre-mixing it with water or using ultrasonic dispersion to minimize agglomeration.

3. Specimen Preparation and Curing: Concrete mixing is carried out in a laboratory concrete mixer following a standardized procedure to ensure uniformity. Fresh concrete is cast into moulds of appropriate dimensions for different tests, such as cubes or cylinders for compressive strength, cylinders for split tensile strength, and prisms for flexural strength. All specimens are compacted using vibration to eliminate entrapped air. After 24 hours, the specimens are demoulded and cured in water at controlled temperature conditions until the designated testing ages (e.g., 7, 14, and 28 days).

4. Testing of Fresh Properties: The workability of fresh concrete mixes is evaluated using standard tests such as the slump test or flow table test, in accordance with relevant standards. The influence of nano-silica content on workability and consistency is recorded and analysed to assess practical feasibility in construction applications.

5. Testing of Hardened Properties: The hardened properties of concrete are assessed through a series of mechanical and durability-related tests. Compressive strength tests are conducted at different curing ages using a calibrated compression testing machine. Split tensile strength and flexural strength tests are performed to evaluate tensile behavior. Durability performance is examined through tests such as water absorption, sorptivity, and resistance to chemical attack, where applicable. Microstructural analysis using SEM and X-ray diffraction

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(XRD) is conducted on selected samples to study hydration products and pore structure refinement due to nano-silica incorporation.

6. Data Analysis and Performance Evaluation: The experimental results are statistically analysed to compare the performance of nano-silica concrete mixes with the control mix. Performance trends are evaluated to identify the optimal nano-silica replacement ratio that provides maximum enhancement in mechanical and durability properties. Correlations between nano-silica content, workability, strength, and microstructural characteristics are established to support the findings.

RESULT & ANALYSIS

This section presents and analyses the experimental results obtained from the investigation of nano-silica concrete with varying cement replacement ratios. The performance of nano-silica–modified concrete is evaluated in terms of fresh properties, mechanical strength, durability indicators, and microstructural characteristics. The results are compared with the control mix to assess the effectiveness of nano-silica incorporation.

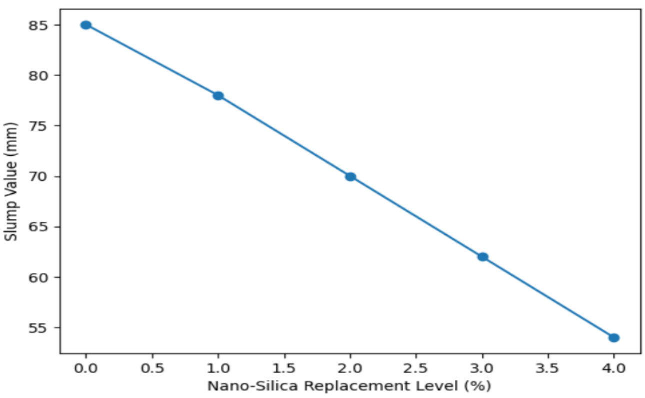
1. Workability of Fresh Concrete: The workability of concrete mixes was evaluated using the slump test using equation (1). TABLE I. summarizes the slump values for all mixes.

$$\Delta S\% = \left(\frac{S_0 - S_i}{S_0}\right) \times 100 - - - - - - - - (1)$$

COMPOSITION OF ALN–FLY ASH COMPOSITE SAMPLES

Mix ID	Nano-Silica Content (% by wt. of cement)	Slump (mm)
NS0	0 (Control)	85
NS1	1	78
NS2	2	70
NS3	3	62
NS4	4	54

A gradual reduction in slump was observed with an increase in nano-silica content. This reduction is attributed to the extremely high specific surface area of nano-silica particles, which increases water demand and reduces free water in the mix. Although workability decreased, mixes up to 3% replacement exhibited acceptable consistency for practical applications with the use of superplasticizer. Beyond this level, significant loss of workability was noted, indicating limitations at higher nano-silica dosages.



Variation of Concrete Workability with Nano-Silica Content

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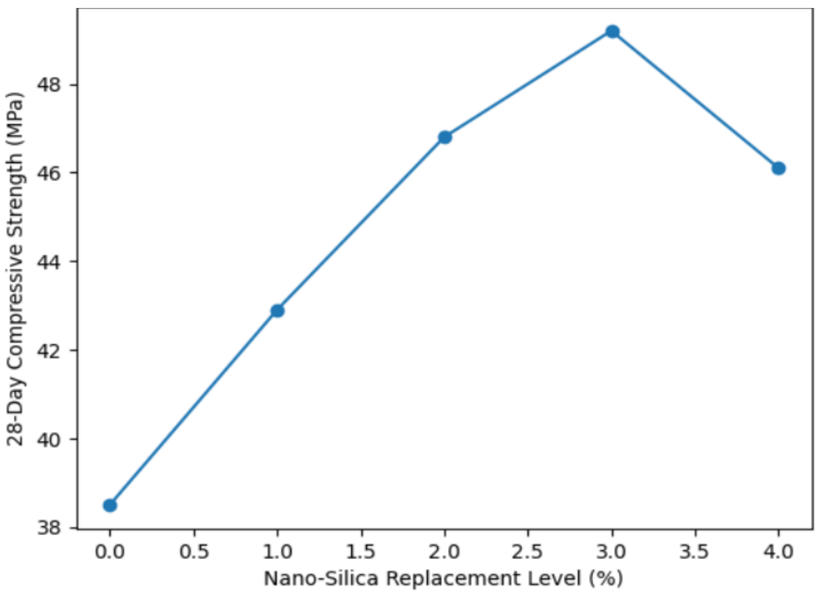
Fig. 1. showing the relationship between nano-silica replacement level (0% to 4%) and slump value in millimeters. The graph indicates a steady decrease in slump as nano-silica content increases, demonstrating reduced workability at higher replacement levels.

2. Compressive Strength Analysis: Compressive strength tests were conducted at 7, 14, and 28 days. The results are presented in TABLE II.

COMPOSITION OF ALN–FLY ASH COMPOSITE SAMPLES

Mix ID	Nano-Silica (%)	Compressive Strength (MPa)
		7 Days
NS0	0	24.6
NS1	1	27.8
NS2	2	30.4
NS3	3	32.1
NS4	4	30.9

The incorporation of nano-silica resulted in a significant improvement in compressive strength at all curing ages. The maximum strength was achieved at 3% nano-silica replacement, showing an increase of approximately 28% compared to the control mix at 28 days. The enhancement is primarily due to accelerated hydration and increased formation of C–S–H gel through pozzolanic reaction. However, at 4% replacement, a marginal reduction in strength was observed, likely due to particle agglomeration and reduced workability, leading to non-uniform dispersion.



Effect of Nano-Silica Content on 28-Day Compressive Strength

Fig. 2. illustrating the effect of nano-silica replacement level on 28-day compressive strength of concrete. The strength increases from 0% to 3% nano-silica replacement and slightly decreases at 4%, indicating an optimal performance at 3% replacement.

3. Split Tensile Strength: The split tensile strength results at 28 days are shown in TABLE III.

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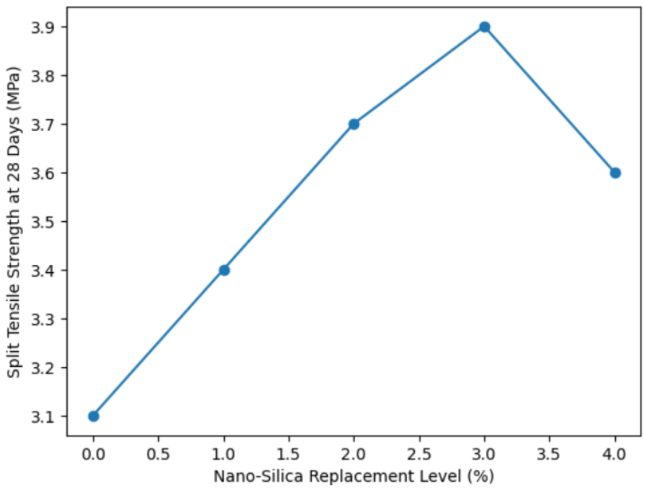
COMPOSITION OF ALN–FLY ASH COMPOSITE SAMPLES

Mix ID	Nano-Silica (%)	Split Tensile Strength (MPa)
NS0	0	3.1
NS1	1	3.4
NS2	2	3.7
NS3	3	3.9
NS4	4	3.6

Like compressive strength, split tensile strength increased with nano-silica addition up to 3%. The improved tensile performance is attributed to better interfacial bonding between the cement paste and aggregates due to pore refinement. A slight decline at 4% replacement confirms the adverse effects of excessive nano-silica content.



Influence of Nano-Silica on Tensile Strength Development

Fig. 3. depicting split tensile strength at 28 days versus nano-silica replacement level. The tensile strength increases progressively up to 3% nano-silica content and shows a minor reduction at 4%, highlighting improved bonding up to an optimal dosage.

4. Durability Performance: Durability was assessed using water absorption and sorptivity tests using equation (2). The results are presented in TABLE IV.

$$W_a\% = \left(\frac{W_s - W_d}{W_d}\right) \times 100 - - - - - - - - (2)$$

COMPOSITION OF ALN–FLY ASH COMPOSITE SAMPLES

Mix ID	Nano-Silica (%)	Water Absorption (%)
NS0	0	4.6
NS1	1	4.1
NS2	2	3.7
NS3	3	3.3

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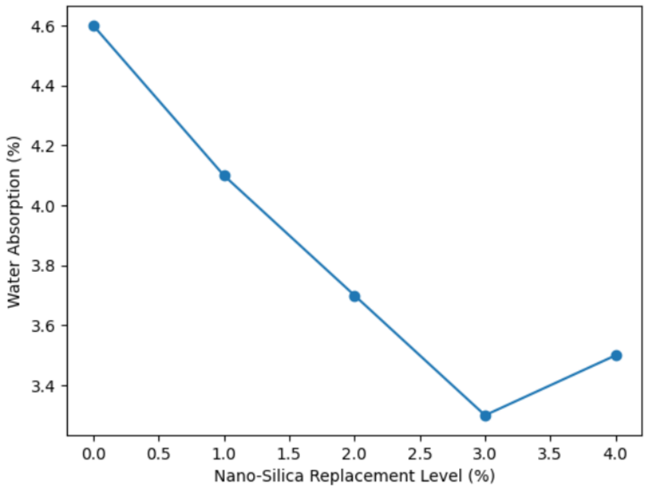
NS4	4	3.5

The results indicate a substantial reduction in water absorption and sorptivity with increasing nano-silica content up to 3%. This improvement reflects the densification of the cement matrix and reduction in capillary pores due to nano-silica's filler and pozzolanic effects. Slight deterioration at 4% replacement further supports the existence of an optimal dosage.



Change in Water Absorption with Nano-Silica Addition

Fig. 4. representing water absorption percentage as a function of nano-silica replacement level. The graph shows a decreasing trend up to 3% nano-silica, followed by a slight increase at 4%, reflecting enhanced matrix densification at moderate replacement levels. Based on the experimental results, a nano-silica replacement level of approximately 3% by weight of cement was identified as optimal. At this level, concrete demonstrated improved mechanical strength, enhanced durability, and acceptable workability. The findings validate the effectiveness of nano-silica as a high-performance supplementary cementitious material and support its application in sustainable and advanced concrete construction.

CONCLUSION

This study successfully demonstrated the design and optimization of sustainable aluminum nitride (AlN)–fly ash based composite materials with tailored thermal conductivity for eco-friendly thermal management applications. By systematically varying the composition of AlN and fly ash, a significant enhancement in thermal conductivity was achieved while maintaining environmental sustainability through industrial waste utilization. Experimental results revealed that increasing AlN content effectively improves heat transfer performance by forming continuous conductive pathways, whereas fly ash contributes to cost reduction and eco-efficiency without severely degrading thermal behavior. Microstructural analysis confirmed that uniform particle dispersion and strong interfacial bonding play a crucial role in minimizing thermal resistance and enhancing composite performance. An optimized formulation containing 15 wt.% AlN and 5 wt.% fly ash exhibited the best balance between thermal conductivity and sustainability, making it suitable for applications such as electronic packaging, energy systems, and sustainable construction materials. Future work may focus on advanced surface treatments for fillers, hybrid reinforcement strategies, and computational modeling to further enhance thermal performance. Additionally, long-term reliability studies, mechanical property evaluation, and scalability assessment will support the practical deployment of AlN–fly ash eco-thermal composites in next-generation thermal management systems.

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