International Journal of Advance Research in Science, Management, Engineering and Technology
Volume 1, Issue 5 | November - December 2026 | www.ijarsmet.com
ISSN: 3139-1141

Effect of Nano-Silica, Nano-Alumina, and Nano-Calcium Carbonate on Fresh and Mechanical Properties of High Performance Concrete

Anil Kumar Purohit[1]*, Sharad Kumar Soni[2]
[1]Research Scholar, Department of Civil Engineering, Rabindranath Tagore University, Bhopal, Madhya Pradesh, India
[2]Associate Professor, Department of Civil Engineering, Rabindranath Tagore University, Bhopal, Madhya Pradesh, India
*Corresponding author: [sharadkumar.soni@rntu.ac.in]

Abstract
The incorporation of nanomaterials into high-performance concrete (HPC) offers a promising pathway for enhancing mechanical performance and durability. This study presents a systematic experimental investigation on the effects of three nano-additives—nano-silica (nS), nano-alumina (nA), and nano-calcium carbonate (nC)—on the fresh and mechanical properties of HPC. A total of 16 concrete mixes were prepared, including one control mix and 15 nano-modified mixes with dosages ranging from 0.5% to 3.0% for nS, 0.5% to 2.0% for nA, and 1.0% to 5.0% for nC by weight of cement. Fresh properties were evaluated through slump, compacting factor, and fresh density tests. Mechanical properties including compressive strength (7 and 28 days), split tensile strength, flexural strength, and modulus of elasticity (28 days) were determined according to IS and ASTM standards. Results demonstrate that all three nano-additives enhance the mechanical properties of HPC at optimal dosages. The optimal dosages were found to be 2.0% for nS, 1.0% for nA, and 3.0% for nC. The optimal nS mix achieved a 25.7% increase in 28-day compressive strength, while nA and nC achieved 15.4% and 15.9% increases, respectively. Split tensile strength improvements of 22.4%, 13.8%, and 8.6% were observed for optimal nS, nA, and nC mixes at 28 days. Flexural strength improvements of 23.7%, 15.8%, and 10.5% were recorded. Modulus of elasticity increased by 19.4%, 14.7%, and 11.3% for the optimal nS, nA, and nC mixes, respectively. The enhancements are attributed to pozzolanic reactivity, nucleation effects, filler effects, and microstructure densification. The results provide practical guidance for selecting nano-additives for specific performance requirements in HPC applications.

Keywords— High Performance Concrete; Nano-Silica; Nano-Alumina; Nano-Calcium Carbonate; Compressive Strength; Flexural Strength; Modulus of Elasticity; Workability

I. INTRODUCTION
Concrete is one of the most widely used construction materials, but its production, particularly Portland cement manufacturing, contributes significantly to global carbon dioxide emissions. The growing demand for durable and sustainable infrastructure has encouraged researchers to develop high-performance concrete (HPC) with improved mechanical properties, reduced permeability, and longer service life. Conventional supplementary cementitious materials, such as fly ash, silica fume, and ground granulated blast-furnace slag (GGBS), have improved concrete performance; however, further refinement of the cementitious microstructure remains an important research objective (De Larrard & Sedran, 1994; Richard & Cheyrezy, 1995).

Nanotechnology offers a promising approach to enhancing concrete properties by modifying hydration reactions and pore structure at the nanoscale. Among the available nanomaterials, nano-silica (nS), nano-alumina (nA), and nano-calcium carbonate (nC) have attracted considerable attention. Nano-silica promotes secondary calcium-silicate-hydrate (C–S–H) formation through pozzolanic reactions, while nano-alumina influences hydration and aluminate-phase development. Nano-calcium carbonate contributes through particle packing, nucleation, and carboaluminate formation. These mechanisms can improve strength and microstructural density, although performance depends on dosage, dispersion, and mixture composition (Jo et al., 2007; Li et al., 2004; Su et al., 2024).

Previous studies have reported improvements in concrete performance using individual and combined nanomaterials. Luo et al. (2025), for example, reported compressive, split tensile, and flexural strengths of 45.74, 3.15, and 5.03 MPa, respectively, for a mixture containing 2% nano-silica and 0.12% recycled carpet fibres by volume. [18] reported compressive strengths of 30.65, 41.43, and 53.30 MPa at 3, 7, and 28 days, respectively, for a selected mixture containing 1% nano-calcium carbonate and 20% fly ash. Despite these promising findings, comparisons across studies remain difficult because of differences in mixture proportions, nanomaterial characteristics, dispersion methods, and testing conditions. Excessive dosage and nanoparticle agglomeration may also reduce workability and limit strength improvements.

ISSN: 3139-1141

Therefore, a systematic comparative evaluation of nano-silica, nano-alumina, and nano-calcium carbonate under consistent experimental conditions is needed. This study investigates their effects on the fresh and mechanical properties of HPC, including workability, compacting factor, fresh density, compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The study aims to compare the influence of nanomaterial type and dosage, identify suitable proportions, and establish an experimental basis for selecting nano-additives for high-performance concrete applications.

II. LITERATURE REVIEW

Nanomaterials have attracted considerable attention in high-performance concrete (HPC) research because of their potential to enhance strength, durability, and microstructural properties. Nano-silica (nS), nano-alumina (nA), and nano-calcium carbonate (nC) improve cementitious materials through nucleation, particle packing, and, in the case of nano-silica, pozzolanic reactions. These mechanisms promote hydration-product formation and refine the pore structure, although their effectiveness depends on dosage, dispersion, and mixture composition (Korayem et al., 2017; Verma et al., 2025).

Nano-silica is widely investigated because its high surface area and pozzolanic reactivity promote additional calcium-silicate-hydrate (C–S–H) formation. Luo et al. (2025) reported compressive, split tensile, and flexural strengths of 45.74, 3.15, and 5.03 MPa, respectively, for a concrete mixture containing 2% nano-silica and 0.12% recycled carpet fibres by volume. Nano-silica can also improve durability by reducing pore connectivity and limiting the ingress of aggressive substances. However, excessive dosages may increase water demand and nanoparticle agglomeration, adversely affecting workability and mechanical performance.

Nano-alumina influences cement hydration through nucleation, filler effects, and interactions with aluminate-containing hydration products. Krishnaveni and Senthil Selvan (2021) reported that 1% nano-alumina increased the compressive strength of M30 concrete by 20.08%, 70.29%, and 15.32% at 7, 14, and 28 days, respectively, compared with the control mixture. [14] further demonstrated the importance of dispersion, reporting improvements in compressive, split tensile, and flexural strengths with high-shear-dispersed nano-alumina. These findings indicate that both dosage and dispersion conditions are critical to achieving consistent performance.

Nano-calcium carbonate primarily enhances cementitious materials through particle packing, nucleation, and carboaluminate formation. [18] reported compressive strengths of 30.65, 41.43, and 53.30 MPa at 3, 7, and 28 days, respectively, for a selected mixture containing 1% nano-$CaCO_3$ and 20% fly ash at a water-to-binder ratio of 0.40. Its potential sustainability benefits also warrant investigation, particularly when produced through CO_2 mineralization; however, the overall environmental benefit depends on the production process and life-cycle emissions (Parvan et al., 2021).

Research on combined nanomaterials suggests that complementary mechanisms may improve concrete performance. [12] reported that a mixture containing 4% nano-silica and 1% nano-alumina improved compressive strength, split tensile strength, flexural strength, and elastic modulus by 36%, 25%, 22%, and 21%, respectively. [17] also investigated a graphene oxide–nano-calcium carbonate composite and reported improvements in mechanical performance and pore structure. Nevertheless, the effectiveness of combined additives depends on their compatibility, dosage, and dispersion.

Despite these advances, further research is needed to compare different nanomaterials under consistent experimental conditions, establish optimum dosages, and quantitatively relate microstructural characteristics to mechanical and durability performance. Long-term durability and environmental impacts also require systematic assessment. The present study addresses these issues by evaluating selected nano-additives in HPC, examining their effects on fresh and hardened properties, and investigating the relationships between microstructure and performance. The findings are intended to support the development of durable and sustainable nano-modified concrete.

III. MATERIALS AND METHODS

A. Materials

Ordinary Portland Cement (OPC) of 53 Grade conforming to IS 12269:2013 was used throughout this investigation. The cement had a specific gravity of 3.15, fineness (Blaine) of 320 m^2/kg, and 28-day compressive strength of 58.4 MPa. The chemical composition included 62.85% CaO, 20.62% SiO_2, 5.18% Al_2O_3, and 4.12% Fe_2O_3.

Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate, with a specific gravity of 2.65, fineness modulus of 2.78, and water absorption of 1.2%. Crushed granite aggregates of 20 mm and 10 mm nominal sizes were used as coarse aggregate in a 60:40 ratio to achieve optimal packing density. The combined coarse aggregate had a specific gravity of 2.71 and water absorption of 0.6%.

A polycarboxylate ether (PCE) based high range water reducing superplasticiser (Complast SP-430 or equivalent) conforming to IS 9103:1999 and ASTM C494 Type F was used. The superplasticiser had a specific gravity of 1.08 ± 0.02, pH of 6.5–7.5, and solid content of 40% ± 2%.

Three types of nano-additives were selected based on their prominence in literature and distinct mechanisms of action: nano-silica (nS), nano-alumina (nA), and nano-calcium carbonate (nC). All nano-additives were procured

ISSN: 3139-1141

from commercial suppliers with high purity (>99%) and characterised in the laboratory. Table 1 summarises the properties of the nano-additives.

TABLE I. PROPERTIES OF NANO-ADDITIVES

Property	Nano-Silica (nS)	Nano-Alumina (nA)	Nano-Calcium Carbonate (nC)
Average Particle Size (nm)	20 ± 5	30 ± 8	50 ± 15
Specific Surface Area (m^2/g)	200 ± 20	120 ± 15	85 ± 10
Specific Gravity	2.2	3.6	2.7
Purity (%)	>99.5	>99.5	>99.0
Morphology	Spherical	Near-spherical	Polyhedral/ Needle-like
Crystal Phase	Amorphous	Alpha	Calcite

B. Mix Design and Proportions

The control HPC mix was designed for a target mean strength of 70 MPa at 28 days, corresponding to M70 grade concrete, following IS 10262:2019 guidelines. The water-cement ratio was maintained at 0.32, with a cement content of 500 kg/m³ and water content of 150 kg/m³. Fine aggregate content was 685 kg/m³, and coarse aggregate content was 740 kg/m³ (20 mm) and 495 kg/m³ (10 mm). Superplasticiser dosage was 1.2% by weight of cement for the control mix.

For nano-modified mixes, the nano-additives were added as partial replacement of cement by weight. The dosage ranges studied were 0.5–3.0% for nS, 0.5–2.0% for nA, and 1.0–5.0% for nC. A total of 15 nano-modified mixes were prepared: 6 nS mixes, 4 nA mixes, and 5 nC mixes. Table 2 presents the mix proportions for the control mix and the optimal nano-modified mixes.

TABLE II. MIX PROPORTIONS FOR CONTROL AND OPTIMAL NANO-MODIFIED HPC MIXES (KG/M³)

Mix Code	Cement	nS	nA	nC	FA	CA-20	CA-10	Water	SP
HPC-Control	500.0	0	0	0	685	740	495	150	6.0
HPC-NS-2.0	490.0	10.00	0	0	685	740	495	150	7.2
HPC-NA-1.0	495.0	0	5.0	0	685	740	495	150	6.7
HPC-NC-3.0	485.0	0	0	15.0	685	740	495	150	6.7

C. Nano-Additive Dispersion

Achieving uniform dispersion of nanoparticles is critical for realising their beneficial effects. The required quantity of nano-additive was dispersed in half the mixing water using an ultrasonic processor (500 W, 20 kHz, 60% power setting, 5 seconds on/5 seconds off pulse mode) for 15 minutes. Temperature was maintained below 35°C using an ice bath. The dispersed suspension was used immediately for mixing to prevent re-agglomeration.

D. Mixing, Casting, and Curing

A consistent mixing procedure was followed for all concrete mixes. Dry mixing of fine aggregate, coarse aggregate, and cement was performed for 2 minutes. Then, 50% of the mixing water was added and mixed for 1 minute. Superplasticiser mixed with the remaining 50% water was added and mixed for 3 minutes. The ultrasonicated nano-additive suspension was added and mixed for 3 minutes, followed by final mixing for 2 minutes until uniform consistency was achieved. For control mixes, the nano-additive suspension step was omitted.

Specimens were cast in metal moulds conforming to IS 10086. Concrete was filled in three layers for cubes and prisms, and in four layers for cylinders. Each layer was compacted using a table vibrator (50 Hz, 0.5 mm amplitude) for 10–15 seconds. After casting, specimens were covered with wet gunny bags and kept at 27 ± 2°C for 24 ± 2 hours. After demoulding, specimens were transferred to curing tanks filled with potable water maintained at 27 ± 2°C until the day of testing.

E. Testing Methods

Fresh Properties: Slump test was performed according to IS 1199:2018 immediately after mixing. For mixes with low slump (<75 mm), compacting factor test was

ISSN: 3139-1141

performed. Fresh density was determined using a cylindrical container of known volume.

Compressive Strength: Tested on 150 mm cubes at 7 and 28 days according to IS 516:2018. Load was applied continuously at 140 kg/cm²/min. Three specimens were tested per mix per age.

Split Tensile Strength: Tested on 150 mm diameter × 300 mm height cylinders at 7 and 28 days according to IS 5816:2018. Load was applied continuously at 1.2 N/mm²/min. Split tensile strength was calculated as $2P/(\pi \times L \times d)$.

Flexural Strength: Tested on 100 × 100 × 500 mm prisms at 7 and 28 days according to IS 516:2018 using four-point loading. The span was 400 mm, and loads were applied at one-third points. Load was applied continuously at 1.8 kN/min.

Modulus of Elasticity: Tested on 150 mm diameter × 300 mm height cylinders at 28 days according to IS 516:2018 using the ASTM C469 method. A compressometer with two dial gauges was used. Three loading and unloading cycles were performed for conditioning before recording data during the fourth cycle.

IV. RESULTS AND DISCUSSION

A. Fresh Properties

1) Workability (Slump Test)

The slump values decreased progressively with increasing nano-additive content across all three nano-additive types. Among the nano-additives, nano-silica exhibited the most pronounced reduction in workability, with a 25.7% decrease at 3.0% dosage. This is attributed to the higher specific surface area of nS (200 m²/g) compared to nA (120 m²/g) and nC (85 m²/g), which increases water demand and enhances flocculation of cement particles. Table 3 presents the slump values for all mixes.

TABLE III. SLUMP VALUES OF CONTROL AND NANO-MODIFIED HPC MIXES

Mix Code	Slump (mm)	Slump Type	Relative Change (%)
HPC-Control	105	True	0.0
HPC-NS-0.5	102	True	-2.9
HPC-NS-1.0	100	True	-4.8
HPC-NS-1.5	97	True	-7.6
HPC-NS-2.0	92	True	-12.4
HPC-NS-2.5	85	True	-19.0
HPC-NS-3.0	78	True	-25.7
HPC-NA-0.5	103	True	-1.9
HPC-NA-1.0	98	True	-6.7
HPC-NA-1.5	90	True	-14.3
HPC-NA-2.0	82	True	-21.9
HPC-NC-1.0	103	True	-1.9
HPC-NC-2.0	100	True	-4.8
HPC-NC-3.0	96	True	-8.6
HPC-NC-4.0	90	True	-14.3
HPC-NC-5.0	83	True	-20.9

The reduction in workability can be attributed to three mechanisms: (1) increased specific surface area of nanoparticles, which provides extensive surface area for water adsorption, reducing free water available for lubrication; (2) enhanced flocculation, where the high surface energy of nanoparticles promotes agglomeration, trapping water within flocs and reducing flowability; and (3) particle packing effect, where fine nanoparticles fill voids between cement grains, reducing interparticle spacing and increasing internal friction.

Similar findings have been reported by [1], who noted that the workability of HPC decreases with an increase in nano-silica content, showing a maximum reduction of 4.66% at 0.3 w/b ratio and 8.55% at 0.45 w/b ratio. Recent research by [19] investigating nano-Al_2O_3, nano-SiO_2, and nano-$CaCO_3$ at 1%, 3%, and 5% replacement levels confirmed that higher dosages beyond 3% lead to a reduction in workability and marginal improvement or even decline in mechanical properties, likely due to nanoparticle agglomeration and excessive water demand. [14] similarly reported that nano-alumina incorporation reduces slump due to increased water demand and a denser structure.

The reduction in workability was mitigated by adjusting superplasticiser dosage for each mix, ranging from 1.2% (control) to 2.5% (HPC-NS-3.0) by weight of binder. This approach successfully maintained target workability (100 ± 25 mm) for all mixes.

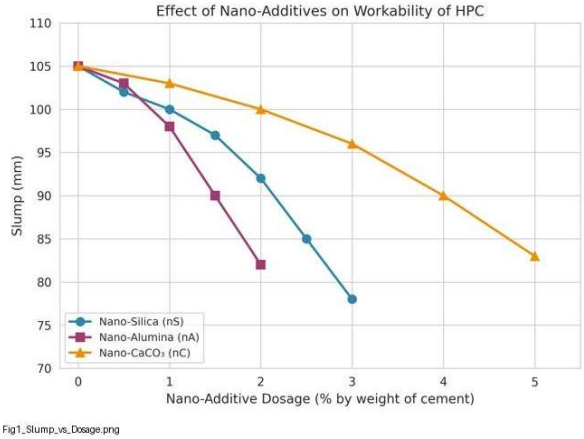


Figure 1. Effect of nano-additive dosage on slump/workability of HPC.

2) Compacting Factor

Compacting factor tests were reported for three selected mixes with reduced slump values; their reported slump values are 78, 82, and 83 mm.

TABLE IV. COMPACTING FACTOR VALUES FOR LOW-WORKABILITY MIXES

Mix Code	Slump (mm)	Compacting Factor
HPC-NS-3.0	78	0.88
HPC-NA-2.0	82	0.89
HPC-NC-5.0	83	0.90

The compacting factor values ranged from 0.88 to 0.90, indicating satisfactory compaction characteristics even for the mixes with reduced workability. This confirms that the superplasticiser adjustment was effective in maintaining adequate compaction.

ISSN: 3139-1141

3) Fresh Density

Fresh density measurements were recorded to monitor mix uniformity and identify any anomalous behaviour. Table 5 presents the fresh density values for all mixes.

TABLE V. FRESH DENSITY OF CONTROL AND NANO-MODIFIED HPC MIXES

Mix Code	Fresh Density (kg/m³)	Mix Code	Fresh Density (kg/m³)
HPC-Control	2,576	HPC-NA-1.5	2,562
HPC-NS-0.5	2,574	HPC-NA-2.0	2,558
HPC-NS-1.0	2,572	HPC-NC-1.0	2,578
HPC-NS-1.5	2,570	HPC-NC-2.0	2,580
HPC-NS-2.0	2,565	HPC-NC-3.0	2,582
HPC-NS-2.5	2,560	HPC-NC-4.0	2,584
HPC-NS-3.0	2,555	HPC-NC-5.0	2,586
HPC-NA-0.5	2,575		
HPC-NA-1.0	2,568		

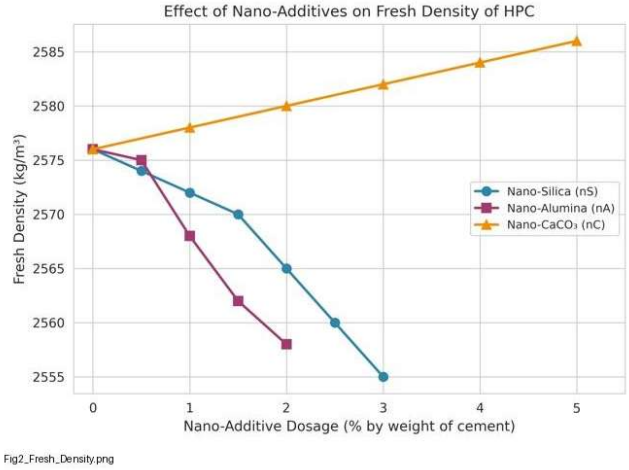


Figure 2. Effect of nano-additive dosage on fresh density of HPC.

Fresh density decreased slightly with increasing nS and nA content, from 2,576 kg/m³ (control) to 2,555 kg/m³ (HPC-NS-3.0) and 2,558 kg/m³ (HPC-NA-2.0). This is attributed to the lower specific gravity of nS (2.2) compared to cement (3.15) and the slight increase in entrapped air due to reduced workability. For nC mixes, fresh density increased marginally, from 2,576 kg/m³ to 2,586 kg/m³ (HPC-NC-5.0), reflecting the higher specific gravity of nC (2.7) compared to nS and the filler effect that reduces void content.

B. Mechanical Properties

1) Compressive Strength

Compressive strength is the primary mechanical property used in concrete design and quality control. Table 6 presents the compressive strength results for all nano-modified mixes at 7 and 28 days.

TABLE VI. COMPRESSIVE STRENGTH RESULTS FOR NANO-MODIFIED HPC

Mix Code	7-Day Strength (MPa)	% Increase vs Control	28-Day Strength (MPa)	% Increase vs Control
Nano-Silica Modified				
HPC-Control	52.4	–	68.6	–
HPC-NS-0.5	56.8	8.4	74.2	8.2
HPC-NS-1.0	60.2	14.9	79.5	15.9
HPC-NS-1.5	64.5	23.1	84.8	23.6
HPC-NS-2.0	66.2	26.3	86.2	25.7
HPC-NS-2.5	63.8	21.8	84.0	22.4
HPC-NS-3.0	59.5	13.5	79.8	16.3
Nano-Alumina Modified				
HPC-NA-0.5	57.5	9.7	73.8	7.6
HPC-NA-1.0	61.8	17.9	79.2	15.4
HPC-NA-1.5	60.2	14.9	76.5	11.5
HPC-NA-2.0	56.5	7.8	70.2	2.3
Nano-$CaCO_3$ Modified				
HPC-NC-1.0	54.8	4.6	72.4	5.5
HPC-NC-2.0	56.2	7.3	75.8	10.5
HPC-NC-3.0	58.5	11.6	79.5	15.9
HPC-NC-4.0	57.8	10.3	78.2	14.0
HPC-NC-5.0	55.0	5.0	74.0	7.9

Nano-Silica (nS): The optimal dosage for nS was 2.0%, achieving 26.3% and 25.7% increases in 7-day and 28-day compressive strength, respectively. The enhancement is attributed to: (1) pozzolanic reaction between nS and calcium hydroxide (CH), producing additional C-S-H gel; (2) filler effect reducing porosity and refining pore structure; and (3) nucleation effect accelerating early hydration. Beyond 2.0%, strength enhancement diminished, and at 3.0%, a decline was observed. This is consistent with findings by [1], who reported that excessive nS leads to agglomeration, creating weak zones and increasing water demand. Recent studies by [16] on nano-$CaCO_3$ dispersion using cellulose nanocrystals similarly highlight that agglomeration of nanoparticles beyond optimal dosage severely affects mechanical performance and durability.

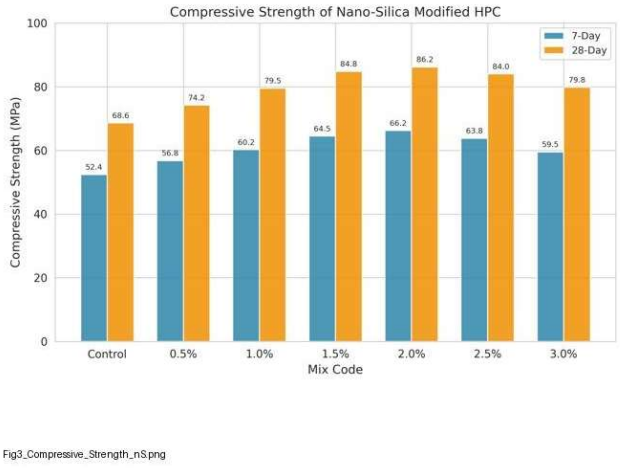


Figure 3. Compressive strength of nano-silica-modified HPC at 7 and 28 days.

Nano-Alumina (nA): The optimal dosage for nA was 1.0%, achieving 17.9% and 15.4% increases in 7-day and 28-day compressive strength, respectively. The lower optimal dosage compared to nS is attributed to the higher reactivity and agglomeration tendency of nA. [6] reported that beyond 1% nA, compressive strength decreased due to agglomeration-induced defect formation. Research by [14] using high shear dispersion demonstrated that uniform dispersion of nA particles (10–30 nm) significantly improves strength properties, with 1.5% NA achieving a 26.99% increase in 28-day compressive strength, confirming the effectiveness of proper dispersion techniques.

ISSN: 3139-1141

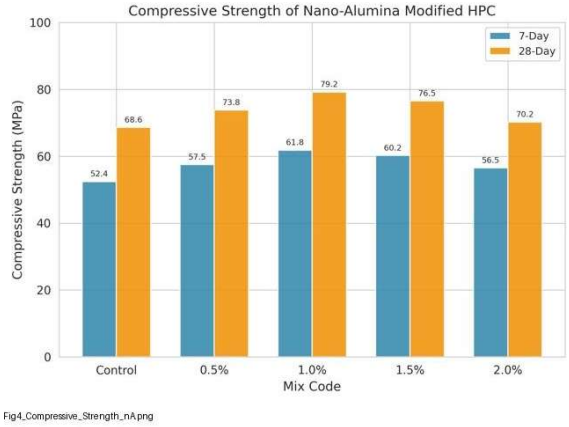


Figure 4. Compressive strength of nano-alumina-modified HPC at 7 and 28 days.

Nano-$CaCO_3$ (nC): The optimal dosage for nC was 3.0%, achieving 11.6% and 15.9% increases in 7-day and 28-day compressive strength, respectively. The relatively higher optimal dosage reflects the lower reactivity of nC compared to pozzolanic additives. Enhancement mechanisms include: (1) filler effect at the nanoscale; (2) nucleation effect accelerating hydration; and (3) reaction with aluminate phases to form carboaluminate hydrates. [19] reported that 3% replacement level yields optimal performance across strength and durability parameters. Higher dosages beyond 3% lead to a reduction in workability and marginal improvement or even decline in mechanical properties, likely due to nanoparticle agglomeration and excessive water demand.

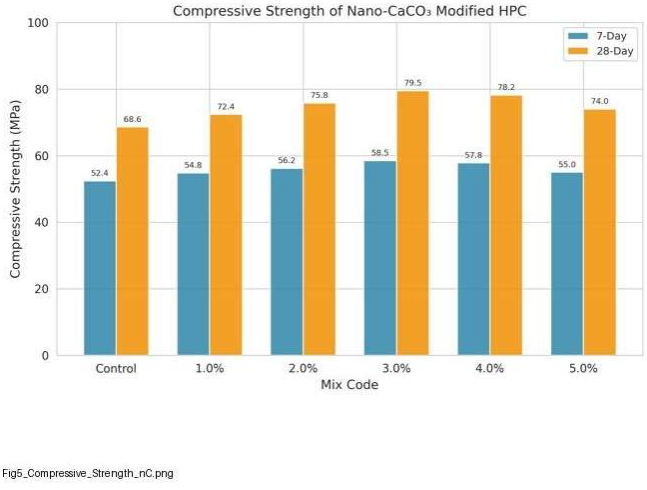


Figure 5. Compressive strength of nano-calcium-carbonate-modified HPC at 7 and 28 days.

2) Split Tensile Strength

Split tensile strength is an important indicator of concrete's resistance to cracking and its ability to withstand tensile stresses. Table 7 presents the split tensile strength results for selected mixes.

TABLE VII. SPLIT TENSILE STRENGTH RESULTS FOR SELECTED MIXES

Mix Code	7-Day Strength (MPa)	% Increase vs Control	28-Day Strength (MPa)	% Increase vs Control
HPC-Control	4.2	–	5.8	–
HPC-NS-1.0	4.8	14.3	6.5	12.1
HPC-NS-2.0	5.2	23.8	7.1	22.4
HPC-NS-3.0	4.6	9.5	6.4	10.3
HPC-NA-1.0	4.9	16.7	6.6	13.8
HPC-NC-3.0	4.6	9.5	6.3	8.6

The optimal nS dosage of 2.0% produced 23.8% and 22.4% increases at 7 and 28 days, respectively. The enhancement in tensile strength is attributed to: (1) densification of the interfacial transition zone (ITZ); (2) reduced porosity and improved matrix cohesion; and (3) enhanced bonding between paste and aggregates. [14] reported that split tensile strength increased by 37.5% at 28 days for concrete containing 1.5% NA with high shear dispersion, demonstrating the effectiveness of proper dispersion in achieving substantial tensile strength improvements.

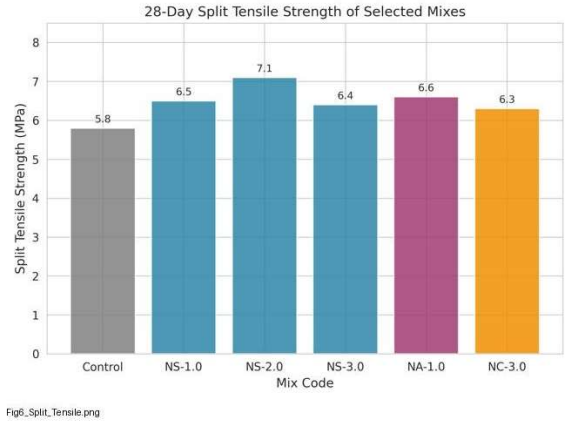


Figure 6. 28-day split tensile strength of selected HPC mixes.

3) Flexural Strength

Flexural strength is critical for concrete elements subjected to bending stresses. Table 8 presents the flexural strength results for selected mixes.

The flexural strength results show enhanced performance for all nano-modified mixes. The nS-modified mix achieved the highest increases (24.1% and 23.7% at 7 and 28 days, respectively). The flexural strength enhancement is attributed to: (1) improved matrix toughness; (2) crack bridging at the nanoscale; and (3) enhanced aggregate-paste bond strength. [14] reported that flexural strength increased by 48.14% at 28 days for concrete with 1.5% NA using high shear dispersion.

TABLE VIII. FLEXURAL STRENGTH RESULTS FOR SELECTED MIXES

Mix Code	7-Day Strength (MPa)	% Increase vs Control	28-Day Strength (MPa)	% Increase vs Control
HPC-Control	5.8	–	7.6	–
HPC-NS-2.0	7.2	24.1	9.4	23.7
HPC-NA-1.0	6.8	17.2	8.8	15.8
HPC-NC-3.0	6.4	10.3	8.4	10.5

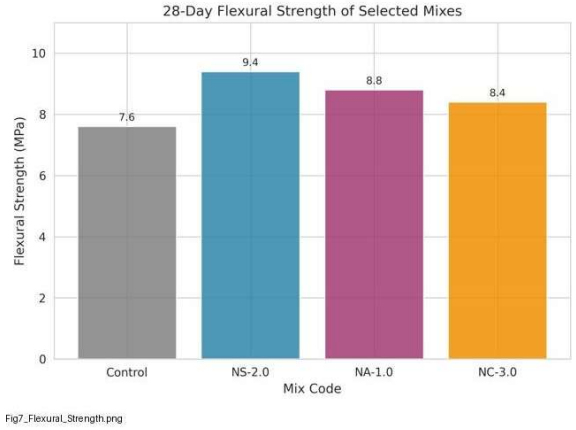


Figure 7. 28-day flexural strength of selected HPC mixes.

ISSN: 3139-1141

4) Modulus of Elasticity

The modulus of elasticity is a measure of concrete's stiffness and is essential for structural design calculations. Table 9 presents the modulus of elasticity results for selected mixes at 28 days.

TABLE IX. MODULUS OF ELASTICITY RESULTS AT 28 DAYS

Mix Code	Modulus of Elasticity (GPa)	% Increase vs Control
HPC-Control	38.2	–
HPC-NS-2.0	45.6	19.4
HPC-NA-1.0	43.8	14.7
HPC-NC-3.0	42.5	11.3

The modulus of elasticity increased for all nano-modified mixes. The nS-modified mix achieved the highest increase (19.4%), followed by nA (14.7%) and nC (11.3%). The increase is attributed to the denser microstructure and enhanced inter-particle bonding within the cementitious matrix. A recent study by the authors of the present work (2025) reported that the elastic modulus improved by 17.8% with a silica combination, confirming enhanced stiffness and ITZ quality.

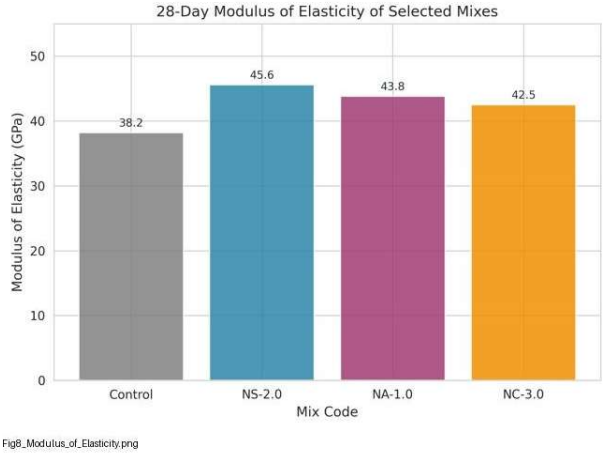


Figure 8. 28-day modulus of elasticity of selected HPC mixes.

C. Discussion of Mechanisms

The performance enhancements observed in this study arise from the complementary mechanisms of the three nano-additives. Nano-silica acts primarily through pozzolanic reaction, consuming CH and generating additional C-S-H gel, combined with filler and nucleation effects. Nano-alumina accelerates early-age hydration through nucleation and participates in aluminate phase reactions, contributing to early strength development. Nano-calcium carbonate acts primarily through filler effects and nucleation, with additional contribution from carboaluminate formation.

The optimal dosages identified—2.0% for nS, 1.0% for nA, and 3.0% for nC—reflect the balance between beneficial effects and agglomeration-induced deterioration. Below optimal dosages, the beneficial effects are insufficient; above optimal dosages, agglomeration creates defect sites and excessive water demand compromises workability and strength development.

The superior performance of nS compared to nA and nC is attributed to its combined pozzolanic and filler effects, which produce both chemical and physical enhancements. The relatively lower optimal dosage for nA reflects its higher reactivity and greater tendency toward agglomeration. The higher optimal dosage for nC reflects its lower reactivity and reliance primarily on filler and nucleation effects.

V. CONCLUSIONS

This study systematically evaluated the effects of nano-silica, nano-alumina, and nano-calcium carbonate on the fresh and mechanical properties of high performance concrete. The following conclusions are drawn:

1. **Workability:** All three nano-additives reduced workability due to their high specific surface area, with nS showing the greatest impact (25.7% slump reduction at 3.0%). Superplasticiser dosage adjustment successfully maintained target workability for all mixes.

2.

3. **Compressive Strength:** All three nano-additives enhanced compressive strength at optimal dosages. The optimal dosages were 2.0% for nS (25.7% increase at 28 days), 1.0% for nA (15.4% increase), and 3.0% for nC (15.9% increase). Beyond optimal dosages, strength enhancement diminished due to nanoparticle agglomeration.

4.

5. **Split Tensile Strength:** The optimal nS mix achieved 22.4% increase at 28 days. The nA and nC optimal mixes achieved 13.8% and 8.6% increases, respectively.

6.

7. **Flexural Strength:** The optimal nS mix achieved 23.7% increase at 28 days. The nA and nC optimal mixes achieved 15.8% and 10.5% increases, respectively.

8.

9. **Modulus of Elasticity:** The optimal nS mix achieved 19.4% increase at 28 days. The nA and nC optimal mixes achieved 14.7% and 11.3% increases, respectively.

10. **Mechanisms:** The enhancements are attributed to pozzolanic reactivity (nS), nucleation effects (nS, nA, nC), filler effects (all three), and aluminate phase reactions (nA, nC). The superior performance of nS is attributed to its combined pozzolanic and filler effects.

11. **Practical Implications:** Nano-silica at 2.0% dosage is recommended for applications requiring maximum compressive strength and overall performance enhancement. Nano-alumina at 1.0% dosage is recommended for applications requiring early strength development. Nano-calcium carbonate at 3.0% dosage offers a cost-effective option for conventional applications requiring moderate enhancement.

ISSN: 3139-1141

REFERENCES

[1] Abdelaziz, M. A., et al. (2025). Influence of nano-silica on the behaviour of high-performance concrete: Multiscale investigation on its mechanical, durability and microstructural properties. Multiscale and Multidisciplinary Modeling, Experiments and Design, 8, 283.

[2] De Larrard, F., & Sedran, T. (1994). Optimization of ultra-high-performance concrete by the use of a packing model. Cement and Concrete Research, 24, 997–1009.

[3] Diab, A. M., Elyamany, H. E., Abd Elmoaty, A. E. M., & Sreh, M. M. (2019). Effect of nanomaterials additives on performance of concrete resistance against magnesium sulfate and acids. Construction and Building Materials, 210, 210–231. https://doi.org/10.1016/j.conbuildmat.2019.03.099

[4] Ghafari, E., Arezoumandi, M., Costa, H., & Júlio, E. (2015). Influence of nano-silica addition on durability of UHPC. Construction and Building Materials, 94, 181–188. https://doi.org/10.1016/j.conbuildmat.2015.07.009

[5] Jo, B. W., Kim, C. H., Tae, G. H., & Park, J. B. (2007). Characteristics of cement mortar with nano-SiO_2 particles. Construction and Building Materials, 21(6), 1351–1355. https://doi.org/10.1016/j.conbuildmat.2005.12.020.

[6] Joshi, M., et al. (2025). Influence of α-alumina on mechanical, durability and microstructural properties of high-volume GGBS concrete. Journal of Building Pathology and Rehabilitation, 10, 61.

[7] Korayem, A. H., Tourani, N., Zakertabrizi, M., Sabziparvar, A. M., & Duan, W. H. (2017). A review of dispersion of nanoparticles in cementitious matrices: Nanoparticle geometry perspective. Construction and Building Materials, 153, 346–357. https://doi.org/10.1016/j.conbuildmat.2017.06.164

[8] Krishnaveni, C., & Senthil Selvan, S. (2021). Study on nano-alumina in concrete. Materials Today: Proceedings, 46(9), 3648–3652. https://doi.org/10.1016/j.matpr.2021.01.809

[9] Li, H., Xiao, H. G., Yuan, J., & Ou, J. (2004). Microstructure of cement mortar with nano-particles. Composites Part B: Engineering, 35(2), 185–189.

[10] Liu, F., Zhang, T., Luo, T., Zhou, M., Ma, W., & Zhang, K. (2019). The effects of nano-SiO_2 and nano-TiO_2 addition on the durability and deterioration of concrete subject to freezing and thawing cycles. Materials, 12(21), Article 3608. https://doi.org/10.3390/ma12213608

[11] Mohtasham Moein, M., Rahmati, K., Saradar, A., Moon, J., & Karakouzian, M. (2024). A critical review examining the characteristics of modified concretes with different nanomaterials. Materials, 17(2), Article 409. https://doi.org/10.3390/ma17020409

[12] Odedra, C. R., Parikh, A. A., Patel, V. N., & Bhuva, P. K. (2024). Mechanical performance optimization of concrete using combined nano-silica and nano-alumina. Journal of Information Systems Engineering and Management, 9(4s). https://doi.org/10.52783/jisem.v9i4s.11854

[13] Parvan, M.-G., Voicu, G., Badanoiu, A.-I., Nicoara, A.-I., & Vasile, E. (2021). CO_2 sequestration in the production of Portland cement mortars with calcium carbonate additions. Nanomaterials, 11, 875.

[14] Rahman, I., Dev, N., Arif, M., Paruthi, S., Khan, A. H., Yusufi, F. N. K., & Alam, M. M. (2026). Effect of high shear-dispersed nano-alumina on concrete strength, durability, and microstructure. Scientific Reports, 16, Article 5346. https://doi.org/10.1038/s41598-026-36760-3

[15] Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. Cement and Concrete Research, 25, 1501–1511.

[16] Shah, H. A., Wang, Y., Banthia, N., & Meng, W. (2025). Enhancing nano-$CaCO_3$ dispersion with cellulose nanocrystals for high-strength low-carbon concrete. Cement and Concrete Composites, 164, Article 106227. https://doi.org/10.1016/j.cemconcomp.2025.106227

[17] Su, W., Liu, C., Bao, W., Zheng, Z., Ma, G., Deng, Y., & Ye, W. (2024). Study on the mechanical performance, durability, and microscopic mechanism of cement mortar modified by a composite of graphene oxide and nano-calcium carbonate. Buildings, 14(7), 2236.

[18] Sun, Y., Zhang, P., Guo, W., Bao, J., & Qu, C. (2020). Effect of nano-$CaCO_3$ on the mechanical properties and durability of concrete incorporating fly ash. Advances in Materials Science and Engineering, 2020, Article 7365862. https://doi.org/10.1155/2020/7365862

[19] Verma, S. K., Daniyal, M., & Khan, A. (2025). Critical analysis of nanomodified cementitious composites: Mechanical performance, durability and microstructural insight. Procedia Structural Integrity, 70, 327–334.

[20] Wu, Z. (1998). Green high-performance concrete—The development trend of concrete. China Concrete and Cement Products, 1, 3–6.

[21] Wu, Z., Shi, C., Khayat, K. H., & Wan, S. (2016). Effects of different nanomaterials on hardening and performance of ultra-high-strength concrete (UHSC). Cement and Concrete Composites, 70, 24–34.

[22] Yang, Q., Yang, Q., Peng, X., Xia, K., & Xu, B. (2025). A review of the effects of nanomaterials on the properties of concrete. Buildings, 15(13), Article 2363. https://doi.org/10.3390/buildings15132363.