Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Mechanical Performance Optimization of Concrete Using Combined Nano-Silica and Nano-Alumina

Chirag R. Odedra[1], Dr. Arpit A. Parikh[2], Dr. Vimalkumar N. Patel[3], Prashant K. Bhuva[4]
[1]Research Scholar, Department of Civil Engineering, Dr. Subhash University, Junagadh, Gujarat, India
[2] Professor, Department of Civil Engineering, Dr. Subhash University, Junagadh, Gujarat, India
[3]Professor & Principal, Department of Civil Engineering, B. H. Gardi College of Engineering & Technology, Rajkot, Gujarat, India,
[4]Assistant Professor, Department of Civil Engineering, Dr. Subhash University, Junagadh, Gujarat, India.

ARTICLE INFO

Received: 30 September 2024

Revised: 12 November 2024

Accepted: 26 November 2024

ABSTRACT

Concrete remains the most widely used construction material in the world, owing to its cost-effectiveness and durability. However, the brittle nature of concrete and its propensity for cracking limit those applications that involve high tensile/flexural strength. Incorporation of nanomaterials like nano-silica (nS) and nano-alumina (nA) will improve the mechanical properties of concrete through filler and pozzolanic effects. This work investigates the influence of adding nS and nA at replacement levels from 0 to 4% on certain important characteristics of concrete belonging to the M30 grade: compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The test results indicated that all the aforementioned properties improved when the dosage was optimized to 4% nS + 1% nA, which generated maximum enhancement in compressive strength, split tensile strength, flexural strength, and elastic modulus by about 36%, 25%, 22%, and 21%, respectively. The refinement of microstructure and interfacial transition zones brought about the increases. In contrast, excessive nano addition decreased the overall strength, while nS and nA enhanced properties, and offered sustainability benefits through an extended structural service life. More studies on optimizing nano-dosages are recommended.

Keywords: Nanoparticles, Sustainable Construction Materials, Nano Concrete, Mechanical Strength Enhancement.

INTRODUCTION

Concrete remains a cornerstone of infrastructure globally, underpinned by its cost-effectiveness, availability, and adaptability in construction applications. However, despite its advantages in compressive strength, concrete's inherent brittleness and susceptibility to cracking under tensile or flexural loads limit its utility in demanding structural applications (Zahedi, Ramezanianpour, & Ramezanianpour, 2015). These limitations often necessitate the use of steel reinforcement, which introduces additional concerns related to corrosion, long-term maintenance, and environmental impact (Quercia & Brouwers, 2010).

Inherent brittleness, however, often requires steel reinforcement due to low tensile and flexural capacities. Shrinkage cracking, corrosion of reinforcements, and degradation mechanisms such as sulfate attack or chloride ingress also take their toll on functional serviceability. With ever-increasing demands for infrastructure, these deficiencies increase the cost of maintenance and rehabilitation manyfold during the life cycle of such structures. All this has spurred increasing research and development (R&D) impetus on refining concrete properties and performance.

With growing demands for infrastructure that is both resilient and sustainable, research has increasingly focused on enhancing concrete's mechanical properties through supplementary materials. In particular, high-performance concrete has emerged as a promising alternative due to its improved durability, strength, and potential for reduced lifecycle costs. The development of high-performance concrete has involved innovations in mix design, incorporating materials such as fly ash, silica fume, and now, nano-materials.

Recent advancements in nanotechnology offer new pathways for enhancing concrete properties at the microstructural level. Nano-materials, including nano-silica (nS) and nano-alumina (nA), have demonstrated significant potential to improve concrete's compressive strength, durability, and resistance to environmental degradation. By filling micro-voids and refining the interfacial transition zone (ITZ) between aggregate and cement paste, these nano-materials contribute to a denser and more durable concrete matrix.

A growth area of interest involves high-performance concretes designed for superior durability and longer life. New binding materials such as fly ash and silica fume formed important ingredients in high-performance concrete, together with strict control over mixing, transportation, and placing techniques (Mugilvani, Murugan, Kaviya, & Sathishkumar, 2019). The optimization of particle packing density and pozzolanic contributions remains an issue under continued study (Mohtasham Moein, Rahmati, Saradar, Moon, & Karakouzian, 2024). These have recently stirred considerable interest in nanotechnology-enabled concrete or next-generation 'smart' composites (Abhilash, Nayak, Sangoju, Kumar, & Kumar, 2021). The addition of nano-materials such as nano-silica (nS), nano-titania, carbon nanotubes, or nano-clays can overcome typical concrete deficiencies. Certain driving factors for the adoption of new concrete include the development of new techniques to manufacture materials, and also the development of a deeper understanding through advanced characterization of materials (Anumeena & Karthiyaini, 2018).

Building on these advancements, the integration of nano-materials such as nano-silica (nS) and nano-alumina (nA) is emerging as a viable method for achieving next-generation concrete. These nano-particles not only densify the microstructure through filler effects but also engage in pozzolanic activity, producing additional calcium silicate hydrate (C-S-H) gel to enhance strength and durability.

The motivation behind this study lies in exploring the synergistic effects of combining nS and nA within concrete, which, despite their efficacy, have been minimally studied in tandem. This combined application aims to leverage the distinct contributions of nS and nA—specifically, the high pozzolanic reactivity of nS and the ITZ strengthening effect of nA—to improve concrete's compressive, tensile, and flexural strengths. Through an experimental approach, this research assesses the influence of different dosages of nS and nA on M30 grade concrete, contributing valuable insights into optimized nano-material applications for sustainable, high-performance concrete.

Nano-materials possess special morphological and physicochemical properties in the 1-100 nm range due to extremely high surface area versus volume ratios (Hou et al., 2013). When engineered to the nanoscale as particles, spheres, or tubes with sizes less than 0.1 microns, exciting mechanical enhancement, toughness gain, and multifunctional capability, such as self-sensing or self-healing capability, start to emerge (Mahdikhani, Bamshad, & Fallah Shirvani, 2018). As nanotechnology continues to evolve, numerous new infrastructure applications appear possible with this marriage of the ancient construction material, concrete, and high-tech advanced technology (Cuenca et al., 2021).

Literature shows that nano-silica (nS) and nano-alumina (nA) are two of the most promising candidate materials for improving aspects of concrete strength and longevity (Verma, 2021) (Zhang, Yang, Ge, Du, & Liu, 2021). Their use as partial cement replacement conveys benefits in terms of reduced carbon footprint and raw material depletion levels, hence appealing to notions of sustainability. A fine nano-scale size fills micro-voids in concrete and improves particle packing density, therefore refining the pore structure. Whereas highly reactive silica and alumina synergistically enhance the hydration processes due to the pozzolanic reaction with calcium hydroxide, the densification of the microstructure yields better mechanical performance and transport properties (Krishnaveni & Senthil Selvan, 2020) (Saloma, Nasution, Imran, & Abdullah, 2015).

Several studies show the acceleration in early age strength evolution along with reduced porosity and increased crystalline calcium silicate hydrate upon incorporation of nano-silica and nano-alumina. Sankaranarayannan SS et. Al. (Sankaranarayannan & Jagadesan, 2016) reported evident improvements in nano-concrete composite microstructure and strength compared to plain cement pastes. For example, Shashank R et. Al. (Shashank & Balaji, 2016), Hossain K et. Al. (Hossain & Rameeja, 2015), and Nasution A et. Al. (Nasution & Saloma, 2018) noted increased mechanical parameters with nano-silica in mortars and concretes. Sahinagic-Isovic M et. Al. (Šahinagić-Isović, Ćećez, & Ćatović, 2019) reported an increase in the degree of cement hydration and a more compact calcium silicate hydrate gel formation for nano-silica modified systems, reflecting positively on the changes in the microstructure. These nanoscale properties can be translated to bulk-form concretes, which can extend structural capabilities. However, challenges such as precise dispensing techniques or particle clustering need to be addressed for further scale-up (Amudhavalli & Ravi, 2019).

While early age behavior of concrete has gained research interest, for proper adoption by the construction industry, the long-term effects are equally significant, particularly concerning key mechanical properties (Rao, Rajasekhar, Vijayalakshmi, & Vamshykrishna, 2015). Most efforts focus on compressive strength, but relatively few systematic studies investigate essential tensile and elastic parameters, which are necessary for holistic performance profiling (S, N, & R, 2016). Research also remains heavily skewed toward global rather than Indian construction scenarios, warranting validation of the capability of these nano-materials to elevate concrete to a next-generation, smart, sustainable construction material.

Mechanics-Based Discussion on Nano-Enhanced Concrete

The integration of nano-silica (nS) and nano-alumina (nA) into concrete modifies its fundamental properties by altering both the microstructure and the interfacial transition zone (ITZ) between aggregate and cement matrix. The following mechanisms elucidate how these nano-materials contribute to enhanced performance:

A. Microstructure Refinement

Nano-silica and nano-alumina particles function as micro-fillers within the cement matrix, occupying interstitial spaces and reducing porosity. This densification not only increases compressive strength but also restricts water ingress pathways, which is essential for mitigating degradation in aggressive environmental conditions. Nano-silica, in particular, achieves microstructural refinement by filling micro-voids and reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), further densifying the matrix.

B. **Enhanced Pozzolanic Reaction**

The high surface area of nano-silica and nano-alumina particles accelerates the pozzolanic reaction with calcium hydroxide ($Ca(OH)_2$) produced during cement hydration. This reaction results in a secondary formation of C-S-H gel, which is instrumental in strength gain. The increased quantity of C-S-H gel enhances the ITZ, creating a more cohesive bond between the cement paste and aggregates, thereby improving tensile and flexural strengths. The additional C-S-H content also contributes to a lower porosity, enhancing durability by reducing permeability.

C. Crack Bridging and Toughening Mechanisms

Nanoparticles have been shown to act as crack-bridging agents within the concrete matrix. The inclusion of nS and nA restricts the propagation of micro-cracks under applied stress, thereby increasing resistance to tensile stress and enhancing flexural strength. This crack-bridging capability minimizes the development of stress concentration points, which are often responsible for brittle failure in concrete. Consequently, nano-engineered concrete exhibits greater toughness and resistance to dynamic loads.

D. Modulus of Elasticity Improvement

The compacted microstructure and additional C-S-H formation due to nano-inclusions lead to a stiffer and more resilient concrete matrix. This stiffness is quantified by an increased modulus of elasticity, which enhances load-bearing capacity and reduces deformability under load. The improvements in the modulus of elasticity, particularly due to nA's effect on ITZ integrity, make nano-modified concrete highly suitable for applications requiring elevated rigidity and load distribution.

By integrating nano-silica and nano-alumina, this study not only addresses sustainability by extending concrete's service life but also provides a mechanics-based approach to improving its fundamental structural properties.

Among the wide range of nanomaterials available for concrete enhancement, nano-silica (nS) and nano-alumina (nA) were specifically chosen in this study due to their proven compatibility with cementitious materials and their unique contributions to concrete's mechanical and durability properties. Nano-silica, with its high surface area and pozzolanic activity, plays a critical role in refining the microstructure of concrete. By reacting with calcium hydroxide, it promotes the formation of additional calcium silicate hydrate (C-S-H) gel, a key component that binds the concrete matrix, resulting in a denser and stronger material. This pozzolanic reaction is particularly effective in improving compressive strength and durability, aligning well with the structural demands placed on modern concrete.

On the other hand, nano-alumina contributes differently by enhancing the interfacial transition zone (ITZ), the region between aggregates and the cement paste, where structural weaknesses often arise. Its inclusion aids in particle packing and supports the overall structural integrity by reducing porosity and enhancing resistance to crack propagation. Together, nano-silica and nano-alumina complement each other, addressing different yet synergistic aspects of concrete performance.

Other nanomaterials, such as nano-titania or carbon nanotubes, though beneficial in certain respects, present challenges in dispersion and cost-effectiveness when used in concrete. In contrast, nS and nA not only offer established performance enhancements but also are more feasible for practical applications, especially when considering scalability and economic viability in the construction industry.

By focusing on nano-silica and nano-alumina, this research leverages materials that have demonstrated substantial improvements in both the mechanical and durability aspects of concrete, without introducing excessive cost or complexity, making them well-suited for sustainable construction.

While significant research has explored the individual effects of nano-silica (nS) and nano-alumina (nA) on concrete properties, this study introduces a novel approach by investigating their combined impact within the same concrete mix. This combined application of nS and nA is intended to leverage the distinct properties of each material to produce synergistic effects on the microstructure and mechanical performance of concrete.

Nano-silica is well-regarded for its high pozzolanic activity and ability to densify the cement matrix, particularly enhancing compressive strength and durability. Nano-alumina, on the other hand, primarily contributes to improved particle packing and strengthens the interfacial transition zone (ITZ), enhancing the bonding between aggregates and the cement matrix. By combining these two materials, the study aims to achieve a more balanced enhancement across a range of concrete properties, from compressive and tensile strength to flexural resilience and stiffness.

The novelty of this research lies in its exploration of how nS and nA interact within the cementitious environment when used together. Few studies have addressed this combination, focusing instead on these nano-materials in isolation. By evaluating the effects of different dosages of nS and nA on both the mechanical and microstructural aspects of M30 grade concrete, this study contributes new insights into optimized nano-material usage in concrete. The findings hold potential significance for advancing high-performance concrete mixes, particularly in applications requiring both durability and sustainability.

MATERIAL CHARACTERIZATION

Material characterizations, as utilized in the study, give a well-rounded understanding of the material properties and their suitability for use in concrete. Characterization by reliable and standardized methods ensures accuracy and repeatability of the experimental results. Material characterizations allow for the effect of individual materials on the properties of concrete to be understood.

Ordinary Portland Cement (OPC)

OPC 53 grade was used as the cementitious binder in all concrete mixes, sourced locally and tested for physical properties. The fineness test showed a specific surface area of 310 m^2/kg, with 91% of particles passing through a

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

90 µm sieve, meeting the minimum requirement of 225 m²/kg as per IS standards. These results indicate the cement's high consistency, suitable for achieving the targeted mechanical properties.

Fine and Coarse Aggregates

Locally available river sand, passing a 4.75 mm sieve, served as the fine aggregate, with a fineness modulus of 2.8 and water absorption of 1.5%, adhering to IS requirements. The coarse aggregate was a crushed granite stone with a nominal size of 20 mm, fineness modulus of 6.9, and impact and crushing values of 16% and 25%, respectively, indicating adequate strength and durability. The specific gravities of fine and coarse aggregates were measured as 2.60 and 2.72, respectively, while water absorption values were within acceptable limits at 1.2% for fine and 0.5% for coarse aggregates.

Nano-materials

High-purity nano-silica (nS) and nano-alumina (nA) were characterized using scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) to confirm particle size and purity, with average sizes in the range of 20–40 nm and 99% purity. The specific surface areas were 160 m²/g for nS and 40 m²/g for nA, respectively. X-ray diffraction (XRD) analysis verified the amorphous nature of nS and the crystalline structure of nA, each contributing uniquely to the microstructure of the concrete matrix.

Superplasticizer

A sulfonated naphthalene-based superplasticizer was utilized to maintain the workability of nano-enhanced concrete mixes. The superplasticizer met IS efficacy standards, ensuring that reduced water content did not compromise concrete workability, which is essential for achieving consistent mix quality with nano-material additives.

Water

Portable tap water available locally was used for all concrete mixing and curing purposes. Relevant pH, solids contents, and chlorides from typical water analysis reports for the construction industry usage, as per guidelines provided by Indian standards, were qualified as suitable.

MIX DESIGN

Before casting, some preliminary tests were conducted for the different constituents of the concrete mixture. Sieve analysis was carried out for the fine and coarse aggregates, which gave the particle size distribution. Fineness modulus and specific gravity tests were also conducted for the fine aggregate. The results of these tests are given in Table 1.

Table 1: Results of Basic Tests on Concrete Constituents

Constituent	Sieve Analysis	Fineness Modulus	Specific Gravity
Cement	Not Applicable	Not Applicable	3.15
Fine Aggregate	90.4% passing	2.50	2.63
Coarse Aggregate	98.4% passing	Not Applicable	2.67
Water	Not Applicable	Not Applicable	1.00

The concrete mix proportion was chosen from the literature review to achieve a target compressive strength of 30 MPa at 28 days. The mix proportion for one cubic meter of concrete is given in Table 2.

Table 2: Mix Proportions for One Cubic Meter of Concrete

Material	Quantity per m³ of concrete
Cement	350 kg
Fine aggregate	654 kg
Coarse aggregate	1097 kg
Water	181 L
Nano-SiO_2	0%, 1%, 2%, 3%, 4%

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Nano-Al_2O_3	0%, 1%, 2%, 3%, 4%
Superplasticizer	1.0% of cement weight

The water-cement ratio was constant for all concrete mixtures at 0.52. Superplasticizer will be used to maintain workability in concrete with reduced water content.

According to the literature review, the enhancing percentage of nano-SiO_2 and nano-Al_2O_3 in mechanical strength properties improvement varies from 1% to 4% of the cement weight. Therefore, in this paper, Nano-SiO_2 and Nano-Al_2O_3 of four different percentages are used to investigate their effects on the mechanical properties of concrete.

The percentages of nano-SiO_2 and nano-Al_2O_3 used in the study are presented in Table 3. The control mixture was prepared without using any nano-SiO_2 or nano-Al_2O_3. For preparing concrete, the nano-SiO_2 and nano-Al_2O_3 replaced a definite percentage of cement weight.

Table 3: Percentages of Nano-SiO_2 and Nano-Al_2O_3 used

Sample ID	% of Nano-SiO_2	% of Nano-Al_2O_3
NS0NA0	0	0
NS1NA1	1	1
NS2NA1	2	1
NS3NA1	3	1
NS4NA1	4	1
NS1NA2	1	2
NS2NA2	2	2
NS3NA2	3	2
NS4NA2	4	2
NS1NA3	1	3
NS2NA3	2	3
NS3NA3	3	3
NS4NA3	4	3
NS1NA4	1	4
NS2NA4	2	4
NS3NA4	3	4
NS4NA4	4	4

MIXING, CASTING AND CURING

With the mix design finalized, concrete casting was actualized in a controlled laboratory environment based on prescription. Accordingly, the molds to cast the requisite dimensions of specimens were fabricated and coated with release agents. Mixing equipment, tamping rods, and other apparatus were also checked beforehand for readiness.

Nano-materials were incorporated following standard mixing protocols, with modifications to ensure uniform dispersion. Aggregates and cement were initially dry-mixed, followed by the addition of 80% of the water. The superplasticizer, diluted in the remaining water, was then introduced. Finally, nano-silica and nano-alumina, pre-dispersed in water through ultrasonication, were gradually added to the mixture. This protocol ensured optimal integration of nano-materials, minimizing agglomeration and maximizing surface area interaction.

The concrete pan mixing started by mixing the coarse and fine aggregates along with cement in uniformity using a mixture machine of 40-liter capacity running at a speed of 20 rpm. After adding 80% of pre-measured water, mixing for 2 minutes was followed by superplasticizer diluted in the remaining water. Further mixing for 3 minutes ensued after a 5-minute interval while slowly introducing the ultrasonicated nano-silica and nano-alumina dispersions. This 7-minute cycle allowed for uniform nano-distribution and limited possible re-aggregation.

Slump tests to check workability and compacting factor for mix compatibility tests of fresh concrete were conducted immediately after mixing. Results qualified targeted M30 grade specifications, thereby permitting mould filling. Moulds assembled to desired dimensions were filled in three equal layers, compacting each run with a rounded-tip steel rod of 500 mm length and 10 mm diameter. Similarly, in the concreting cubes, three layers were ponded in each

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

run using the tamping rod and created 35 evenly distributed strokes. Care was taken at the time of tamping not to dislodge the corners or to cause uneven surfaces or honeycomb flaws due to segregation or bleeding. Specimen surfaces took a smooth look after trowel finishing upon topping.

Following casting, unique identification markings were made on moulds, which were then transferred for ambient curing by the water immersion method as per guidelines. A rectangular water tank of sufficient capacity to hold several moulds was filled with portable tap water. This performs the preliminary hydro-curing to reduce moisture loss, shrinkage, and strength reduction in early stages, particularly in high water/cement ratio mixtures. Water was replenished every 7 days to maintain adequate moisture and hydration kinetics. The specimens were de-moulded only after 28 days and tested immediately thereafter. Though the duration of moist curing could have been extended, 28-day parameter analysis suffices to show preliminary indicators of behavior.

Given the inherent variability in cementitious composites, particular attention was paid to the consistency of test results by casting and testing a sufficient number of specimens across each parameter. This study incorporated a total of 17 different combinations of nano-silica (nS) and nano-alumina (nA) dosages, and for each combination, a statistically sound number of specimens was tested to ensure result reliability.

Specifically, for the compressive strength tests, a total of 153 cube specimens were tested across three curing ages (7, 14, and 28 days) by casting 51 cubes per age group. Similarly, 51 cylindrical specimens were tested for split tensile strength, 51 beams for flexural strength, and 51 cylinders for modulus of elasticity. Each test result presented is the average of three specimens, minimizing the effects of individual sample variability and ensuring that the reported values accurately represent each mix's performance.

To further substantiate the consistency of results, statistical plots have been provided for each test category. These plots visualize the mean values and variation across different nano-material dosages, offering insight into the trends and reliability of the observed mechanical properties. This comprehensive testing approach confirms that the results are both consistent and reflective of the true performance of nano-modified concrete.

TESTING

The concrete specimens were tested after 28 days of standardized curing to assess the mechanical performance of the concrete. A series of destructive tests was carried out according to relevant Indian standard guidelines with calibrated equipment at room temperature. To minimize statistical variability, the average of three identical specimens was considered for reporting final test data.

Compressive Strength

Compressive strength was evaluated on cube specimens as per IS 516 using a 2000 kN capacity compression testing machine. The specimens were centered on loading platens with cushioning pads to avoid failure due to uneven loading. An axial load of 140 kg/cm^2/min was gradually applied until the specimen failed, and the maximum load resisted by the concrete was recorded. Compressive strength was calculated by dividing the failure load by the cross-sectional area and expressed in MPa units. Precision control was ensured through load applicator movement and cognition electronics according to prescribed loading rates.

Split Tensile Strength

Cylindrical specimens of 150 mm diameter and 300 mm height were tested according to IS 5816 in a 1000 kN servo-hydraulic universal testing machine. The specimens were placed horizontally between the loading surfaces, and an increasing compressive line load was applied along the length until the sample ruptured. Split tensile strength was computed by dividing the breaking load by the projected area in the MPa scale. Deformation instrumentation ensured a specified 40 kg/cm^2/min continuous loading without shocks.

Flexural Strength

The flexural strength test was carried out on 28-day cured beam specimens of size 150 x 150 x 700 mm according to the Indian Standard code of practice. The specimens were supported on two supports, and the load was applied at the center of the specimen. Uniform loading without shock or impact at a rate of 40 kg/cm^2/min was applied. The peak

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

load carried by the specimen was recorded in kN, and the flexural strength of the specimen was calculated in MPa.

Modulus of Elasticity

Cylinders of 150 mm diameter by 300 mm height were compressed to failure at 140 kg/cm²/min, acquiring the complete stress-strain signature. The secant modulus was quantified from the slope of the stress-strain curve, discounting initial settling effects. In this instance, higher load ratings targeted the extension of the elastic region for realistic static modulus values. The average modulus from three samples supplemented compressive strength data for performance profiling.

RESULTS AND DISCUSSION

The addition of nano-silica and nano-alumina has indeed brought about good improvements in mechanical performance parameters in the tested concrete samples.

Compressive Strength Test

The compressive strength test was carried out for all the samples after 7, 14, and 28 days of curing, following IS 516:1959. Compressive strength results are depicted in Fig.1 below.

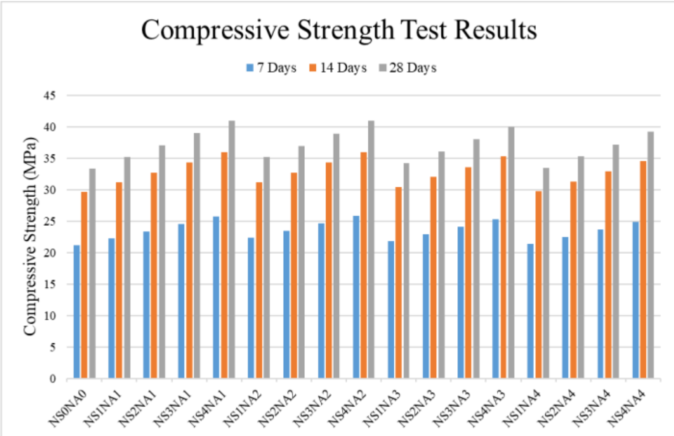

Figure 1: Compressive Strength Test Results

As depicted in Figure 1 Optimal performance was observed at a dosage of 4% nS and 1% nA, achieving an approximate 36% increase over control specimens. This enhancement can be attributed to the densification of the cement matrix and the improved ITZ, as nano-particles reduce micro-voids and increase calcium silicate hydrate (C-S-H) formation. Excessive additions, however, resulted in diminished returns due to particle agglomeration, underscoring the importance of dosage optimization. These findings align with previous studies indicating similar trends with controlled nano-silica incorporation.

However, excessive nano-addition tends to be detrimental, probably due to the clustering effect. These results are in good agreement with studies conducted by many researchers who showed noticeable compressive strength improvements with marginal reductions at higher percentages. In general, such significant compressive strength gains underpin the potential for developing high-performance concretes.

Tensile Strength Test

Fig.2 shows the tensile strength test results for the samples after 28 days of curing with different percentages of Nano-SiO_2 and Nano-Al_2O_3. These results are used to assess how these nanoparticles affected the tensile properties of the concrete.

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

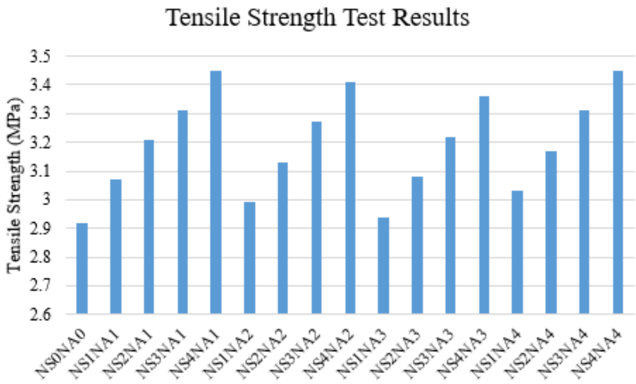

Figure 2: Tensile Strength Test Results

Fig.2 shows nano-modified concrete depicting considerable improvements in split tensile strength compared to their control counterparts. The 25% increase obtained for the 4% nS - 1% nA mix indicates enhanced resistance to cracking and improved long-term durability. Much of the literature has documented similar increases in tensile strength with appropriate nano-inclusions. These gains result from refined grain formations and improved densification of the microstructure. Additional porosity reductions, particularly in weaker interfacial transition zones, also play a crucial role in impeding crack propagation. Further porosity reductions, specifically in the weaker interfacial transition zones, contribute significantly to restricting crack propagation.

Flexural Strength Test

The results of the flexural strength tests for the samples after 28 days of curing, for different percentages of Nano-SiO_2 and Nano-Al_2O_3, are shown in Fig.3. These results demonstrate the effect of nanoparticles on the flexural properties of concrete.

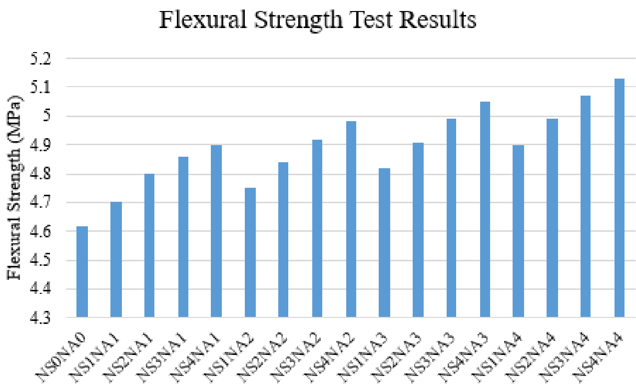

Figure 3: Flexural Strength Test Results

Notable flexural strength gains can be observed from Fig.3, with a maximum 22% gain for the 4% nS - 4% nA mix over control. Flexural capacities are fundamental in resisting the formation and widening of tensile cracks due to bending stresses developed under service loading. Nano-modified concrete thereby exhibits better resistance, useful in preventing early onset fatigue or impact deterioration. However, to fully exploit their potential in structural and infrastructural applications, attention is needed toward brittle failures after peaking effects.

Modulus of Elasticity Test

The modulus of elasticity test of the samples after 28 days of curing was carried out for various percentages of Nano-SiO_2 and Nano-Al_2O_3, as illustrated in Fig.4. These results depict the effects of nanoparticles on the stiffness characteristics of concrete.

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

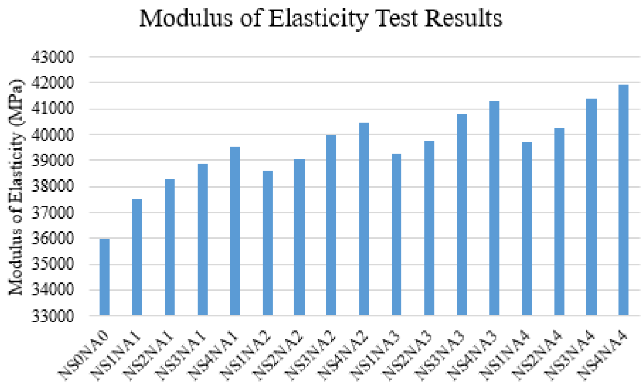

Figure 4: Modulus of Elasticity Test Results

Fig. 4 presents elastic modulus values increasing with nano-silica and nano-alumina inclusions, indicating improvements in concrete stiffness. The combination of 4% nS - 4% nA showed the maximum 21% gain compared to the control mix, aligning with strength patterns. Several researchers have identified key chemical reactions and morphological changes, particularly from nano-silica, that promote stiffness. Such improved modulus or deformation properties will be useful for structural lightweight concretes and concrete-filled steel tubular columns. However, influences on time-dependent creep still need verification. Overall, the strength and modulus improvements project favorably for balanced mechanical performance.

In other words, nano-engineered concretes have shown considerable resistance to compressive, tensile, and flexural stresses compared to conventional specimens. The targeted nano-inclusion allows for favorable combinations of properties, advancing the potential for next-generation sustainable construction materials. However, further research on optimal particulate quantities and compatible dispersion techniques appears sensible.

While the mechanical improvements achieved with nano-silica and nano-alumina might appear moderate at higher dosages, the purpose of their inclusion extends beyond immediate strength gains. In practical terms, these materials offer a pathway to improving long-term durability and microstructural integrity, which are critical for sustainable construction. Even incremental enhancements in strength and durability can lead to substantial reductions in maintenance needs and lifecycle costs, directly benefiting concrete performance over time.

From an academic perspective, this study is designed to explore and document the mechanisms through which nS and nA influence concrete properties, particularly in the context of microstructural changes. Detailed microstructural analyses, such as those provided in this study, contribute valuable insights into the filler and pozzolanic effects of nano-particles within the cement matrix. By refining the interfacial transition zone (ITZ) and enhancing particle packing, nS and nA not only improve strength metrics but also contribute to a denser, more cohesive microstructure. Mechanics-based investigations reveal that the modest strength increases observed are attributable to the nano-scale particle dispersion, which refines the concrete matrix at the microscopic level. This densification restricts crack propagation and improves load distribution, which is crucial for applications where durability under environmental and mechanical stressors is a priority. Moreover, the pozzolanic reactivity of nS and nA aids in secondary C-S-H formation, which further reinforces the concrete structure, albeit with diminishing returns at higher dosages.

Thus, the academic value of this study lies in its systematic exploration of how nano-particles like nS and nA can be leveraged to achieve balanced improvements across both mechanical properties and durability metrics. This contribution is vital as the field progresses toward the development of high-performance, sustainable concrete materials.

CONCLUSION

This research provides a comprehensive analysis of the combined effects of nano-silica (nS) and nano-alumina (nA) on M30 grade concrete, examining critical mechanical properties such as compressive, tensile, and flexural strengths, as well as modulus of elasticity. Key conclusions from this study include:

1. The combined addition of 4% nS and 1% nA delivered notable strength gains—36% in compressive strength, 25% in tensile strength, and 22% in flexural strength—relative to the control mix. These improvements highlight the effectiveness of nano-materials in enhancing load-bearing capacities and minimizing cracking under stress.
2. The synergy of nS and nA refined the microstructure and improved ITZ cohesion, effectively reducing porosity and enhancing durability. The dual effects of filler and pozzolanic reactions contributed to a denser, more resilient cementitious matrix, supporting extended service life.
3. The study emphasizes the importance of precise dosage control, as excessive nano-material additions showed reduced efficacy due to particle clustering. These findings provide a foundation for optimizing nano-material use in concrete, particularly for applications requiring enhanced mechanical performance and durability.
4. By demonstrating the practical advantages of nano-enhanced concrete, this study supports sustainable infrastructure development, with the potential for reduced maintenance and resource usage. Further research, particularly on alternative nano-materials and microstructural analysis through advanced characterization techniques, is recommended to expand the application of nano-engineered concrete.

The nano-engineered improvements in compressive, tensile, and flexural strengths, along with elastic modulus, carry significant implementation potential. Structural lightweight concretes, high-strength constructions, and concrete-filled steel tubes can benefit substantially from these enhancements, alongside sustainability merits such as extended longevity and service life. These benefits arise from the densification of grain boundaries and interfacial transition zones, driven by nano-participant filler, pozzolanic, and seeding actions.

Excessive nano-inclusion, however, tends to detract from properties, suggesting optimal particle thresholds. Effective dispersion remains an issue in production. In this study, only early age behavior was considered; however, correlations over expected structural life cycles will be crucial. Extensive field testing is also necessary before large-scale adoption. Attributes such as self-healing or self-sensing further open up smart multi-functional possibilities.

Therefore, it appears that holistic research across the areas of cementitious systems, curing ages, particle types, and shapes is warranted to take concrete, through nanomaterial amalgamation, toward its status as a next-generation sustainable construction material. Even with promising results, substantial further optimization—entailing ideal nano-dosages, dispersion, durability focuses, production scale-up, and implementation studies—will be required to attain the full envisaged potential.

LIST OF ABBREVIATIONS

1. C-S-H: Calcium Silicate Hydrate
2. ITZ: Interfacial Transition Zone
3. nA: Nano-Alumina
4. nS: Nano-Silica
5. OPC: Ordinary Portland Cement
6. HPC: High-Performance Concrete
7. SEM: Scanning Electron Microscopy
8. XRD: X-ray Diffraction

DECLARATIONS

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interest related to this study. This research was conducted purely in an academic setting under the Department of Civil Engineering at Dr. Subhash University. The study has been performed independently, without any commercial or financial ties that could influence the outcomes. All findings are solely based on experimental work aimed at enhancing the understanding of nano-engineered concrete for sustainable infrastructure.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AUTHOR'S CONTRIBUTIONS

1. Chirag R. Odedra: Conceptualization, Methodology, Data Collection, Analysis, Writing Original Draft.
2. Dr. Arpit Parikh: Resources, Supervision.
3. Dr. Vimalkumar N. Patel: Validation, Review.
4. Prashant K. Bhuva: Data Curation, Visualization.

ACKNOWLEDGMENT

The authors wish to express their gratitude to the Department of Civil Engineering, Dr. Subhash University, for providing the necessary resources and facilities to conduct this research.

REFRENCES

[1] Abhilash, P. P., Nayak, D. K., Sangoju, B., Kumar, R., & Kumar, V. (2021). Effect of nano-silica in concrete; a review. *Construction and Building Materials*, *278*, 122347. https://doi.org/10.1016/j.conbuildmat.2021.122347

[2] Amudhavalli, N. K., & Ravi, C. (2019). A review on nano technology in concrete. *International Journal of Civil Engineering and Technology*, *10*(1), 2990–2997.

[3] Anumeena, S. U., & Karthiyaini, S. (2018). An experimental investigation on the effect of nano silica in concrete. *International Journal of Civil Engineering and Technology*, *9*(3), 152–157.

[4] Cuenca, E., D'Ambrosio, L., Lizunov, D., Tretjakov, A., Volobujeva, O., & Ferrara, L. (2021). Mechanical properties and self-healing capacity of Ultra High Performance Fibre Reinforced Concrete with alumina nano-fibres: Tailoring Ultra High Durability Concrete for aggressive exposure scenarios. *Cement and Concrete Composites*, *118*, 103956. https://doi.org/10.1016/j.cemconcomp.2021.103956

[5] Hossain, K., & Rameeja, S. (2015). Importance of Nanotechnology in Civil Engineering. *European Journal of Sustainable Development*, *4*(1), 161–166. https://doi.org/10.14207/ejsd.2015.v4n1p161

[6] Hou, P., Kawashima, S., Kong, D., Corr, D. J., Qian, J., & Shah, S. P. (2013). Modification effects of colloidal nanoSiO2 on cement hydration and its gel property. *Composites Part B: Engineering*, *45*(1), 440–448. https://doi.org/10.1016/j.compositesb.2012.05.056

[7] Krishnaveni, C., & Senthil Selvan, S. (2020). Study on nano-alumina in concrete. *Materials Today: Proceedings*, *46*(xxxx), 3648–3652. https://doi.org/10.1016/j.matpr.2021.01.809

[8] Mahdikhani, M., Bamshad, O., & Fallah Shirvani, M. (2018). Mechanical properties and durability of concrete specimens containing nano silica in sulfuric acid rain condition. *Construction and Building Materials*, *167*, 929–935. https://doi.org/10.1016/j.conbuildmat.2018.01.137

[9] Mohtasham Moein, M., Rahmati, K., Saradar, A., Moon, J., & Karakouzian, M. (2024). A Critical Review Examining the Characteristics of Modified Concretes with Different Nanomaterials. In *Materials* (Vol. 17). https://doi.org/10.3390/ma17020409

[10] Mugilvani, P., Murugan, S. T., Kaviya, B., & Sathishkumar, K. (2019). Experimental investigation on nano concrete. *International Journal of Civil Engineering and Technology*, *10*(1), 907–912.

[11] Nasution, A., & Saloma. (2018). Nanomaterial Based Concrete. *Nano Material Based Concrete*.

[12] Quercia, G., & BROUWERS, H. J. . (2010). Application of nano-silica (nS) in concrete mixtures. *8th Fib PhD Symposium in Kgs, Lyngby, Denmark*, 6.

[13] Rao, N. V., Rajasekhar, M., Vijayalakshmi, K., & Vamshykrishna, M. (2015). The Future of Civil Engineering with the Influence and Impact of Nanotechnology on Properties of Materials. *Procedia Materials Science*, *10*(Cnt 2014), 111–115. https://doi.org/10.1016/j.mspro.2015.06.032
[14] S, M. P., N, P. D. S., & R, P. K. U. (2016). *Effect on Concrete by Partial Replacement of Cement by Colloidal Nano Alumina and Fly Ash*. *2*(5), 14–19.
[15] Šahinagić-Isović, M., Ćećez, M., & Ćatović, F. (2019). Nanotechnology in Civil Engineering. *Lecture Notes in Networks and Systems*, *42*, 585–589. https://doi.org/10.1007/978-3-319-90893-9_68
[16] Saloma, Nasution, A., Imran, I., & Abdullah, M. (2015). Improvement of concrete durability by nanomaterials. *Procedia Engineering*, *125*, 608–612. https://doi.org/10.1016/j.proeng.2015.11.078
[17] Sankaranarayannan, S. S., & Jagadesan, J. R. (2016). Comparison of High Performance Fly Ash Concrete Using Nano Silica Fume on Different Mixes. *Circuits and Systems*, *07*(08), 1259–1267. https://doi.org/10.4236/cs.2016.78110
[18] Shashank, R., & Balaji, M. E. (2016). Flexural Behavior Of Nano Silica Concrete. *International Research Journal of Engineering and Technology*, 799–803. Retrieved from www.irjet.net
[19] Verma, M. (2021). Evaluation survey of concrete composite using nano and micro silica materials for better properties. *Materials Today: Proceedings*, *81*(2), 1084–1087. https://doi.org/10.1016/j.matpr.2021.04.385
[20] Zahedi, M., Ramezanianpour, A. A., & Ramezanianpour, A. M. (2015). Evaluation of the mechanical properties and durability of cement mortars containing nanosilica and rice husk ash under chloride ion penetration. *Construction and Building Materials*, *78*, 354–361. https://doi.org/10.1016/j.conbuildmat.2015.01.045
[21] Zhang, A., Yang, W., Ge, Y., Du, Y., & Liu, P. (2021). Effects of nano-SiO2 and nano-Al2O3 on mechanical and durability properties of cement-based materials: A comparative study. *Journal of Building Engineering*, *34*, 101936. https://doi.org/10.1016/j.jobe.2020.101936