Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

Synergistic Effect of Nano-Silica and Nano-Alumina on Compressive Strength and Durability of Cementitious Concrete

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***Abstract*— This paper investigates the combined influence of nano-silica (NS) and nano-alumina (NA) on the compressive strength and durability of cementitious concrete. Unlike previous studies focusing primarily on individual nanoparticles, this research analyzes the synergistic mechanisms of NS and NA in terms of microstructural enhancement, cost-efficiency, and real-world applicability. Standard deviations of compressive strength and microstructural characterizations (SEM/XRD) are provided alongside detailed materials and methods. The practical implications for large-scale construction and environmental impacts are also discussed.**

***Keywords*— Nano-silica; Nano-alumina; Concrete**

1. INTRODUCTION

Nano-materials have been increasingly used to improve the performance of cementitious composites [1]. The advent of nanotechnology has opened new avenues for enhancing the mechanical properties, durability, and overall performance of concrete, a fundamental material in modern construction. Among the plethora of nanomaterials explored, nano-silica (NS) and nano-alumina (NA) have garnered significant attention due to their distinct physicochemical characteristics and their potential to interact with the cement hydration process at the nanoscale [1].

Extensive research exists on the application of individual nano-silica (NS) and nano-alumina (NA); however, studies on their combined effect and synergistic mechanisms are limited. Nano-silica, typically in the form of amorphous silicon dioxide nanoparticles, is well-documented to enhance early-age strength by acting as a nucleation sites for calcium silicate hydrate (C-S-H) gel formation, thereby accelerating the hydration reaction and refining the pore structure. This pozzolanic activity leads to a denser microstructure and improved mechanical properties. Concurrently, nano-alumina, often in the form of nanoparticles, has demonstrated the ability to modify hydration kinetics, particularly by promoting the formation of calcium aluminate hydrates (C-A-H) and calcium aluminum silicate hydrates (C-A-S-H) phases. These interactions can further refine the pore structure, contribute to strength development, and influence the microstructure of the hardened cement paste.

Despite these advances, several questions remain unresolved: To what extent can NS and NA together outperform their individual contributions? Understanding the synergistic interaction is crucial for optimizing their use. Does the combined presence of NS and NA lead to a multiplicative or complementary effect on key performance indicators like compressive strength and durability? Furthermore, practical implementation necessitates a consideration of cost and time trade-offs in dispersion and processing at scale. The uniform and stable dispersion of nanoparticles within the cementitious matrix is a known challenge, impacting their effectiveness. This study addresses this critical research gap by aiming to present a comprehensive comparative analysis of the combined effects of NS and NA and discuss the implications for practical implementation in large-scale construction projects. By examining their joint impact on compressive strength development and durability parameters, this research seeks to provide valuable insights for engineers and material scientists aiming to leverage the full potential of nanotechnology in concrete.

2. MATERIALS AND METHODS

2.1 Materials

Ordinary Portland Cement (OPC) of ASTM Type I was utilized as the primary binder. This cement was chosen for its widespread availability and representative characteristics as a standard construction material. To further enhance the sustainability and performance of the concrete mixtures, supplementary cementitious materials (SCMs) were incorporated. Specifically, ground granulated blast-furnace slag (GGBFS), a byproduct of iron manufacturing, was used at a rate of 15% by mass of the binder, and Class F fly ash, a residue from coal combustion, was added at 10% by mass of the binder. The use of these SCMs is known to improve the long-term strength, durability, and resistance to sulfate attack and alkali-silica reaction in concrete.

The nano-silica (NS) used in this study was fumed silica, characterized as amorphous with a high specific surface area, measured at approximately 200 by the Brunauer-Emmett-Teller (BET) method. This material was sourced from Sigma-Aldrich, Germany, ensuring a high degree of purity and consistent particle size distribution. The nano-alumina (NA) was in the form of nanoparticles with an average particle size of approximately 30 nm and a purity exceeding 99%. This material was procured from Nanostructured and Amorphous Materials, Inc., USA. The selection of these specific nanomaterials and their suppliers was based on established research practices and the availability of materials with well-defined properties.

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A high-range water-reducing admixture, specifically a polycarboxylate ether-based superplasticizer (commercial name: MasterGlenium 51), manufactured by BASF, was employed. This admixture was added at a dosage of 1% by the total binder weight. The superplasticizer is crucial for achieving a workable concrete mix at a low water-to-binder ratio while ensuring uniform nanoparticle dispersion and preventing agglomeration, which is a common challenge when incorporating nanomaterials into cementitious matrices.

2.2 Mix Proportions

The concrete mixtures were designed with a target water-to-binder ratio of 0.40. This relatively low water-to-binder ratio is indicative of a high-performance concrete mix, contributing to increased strength and durability. The binder content was kept consistent across all mixes, comprising OPC, GGBFS, and fly ash. The nanoparticles, NS and NA, were introduced at various dosages. These dosages were varied both individually (0.5%, 1.0%, and 1.5% by binder mass) and in binary combinations to explore potential synergistic effects. For the purpose of this detailed analysis and to highlight the key findings, a representative set of mix proportions is summarized in Table 1. This table includes the control mix (OPC), a mix with 1.0% nano-silica (NS1), a mix with 1.0% nano-alumina (NA1), and a mix incorporating both 1.0% nano-silica and 1.0% nano-alumina (NS1NA1). The GGBFS and fly ash content were maintained at 15% and 10% respectively for all mixes, including the control to ensure a fair comparison of the nanoparticle effects.

Table 1: Representative mix proportions of concrete samples (by mass of binder)

Sample ID	Cement(%)	*GGBFS(%)*	*Fly Ash(%)*	*NS(%)*	*NA(%)*
OPS (Control)	75	15	10	0	0
NS1	74	15	10	1	0
NA1	74	15	10	0	1
NS1NA1	73	15	10	1	1

2.3 Preparation and Testing

The preparation of the concrete mixtures followed a rigorous procedure to ensure the uniform dispersion of nanoparticles and consistent mixing. Prior to the addition of other dry ingredients, the specified quantities of nano-silica and nano-alumina were dispersed in the required amount of mixing water. This dispersion process involved vigorous ultrasonic agitation for a duration of 10 minutes. Ultrasonic treatment is essential for breaking down nanoparticle agglomerates and creating a stable suspension, which is critical for their effective integration into the cementitious matrix. The superplasticizer was also added to this water-nanoparticle mixture to further aid in dispersion and enhance the fluidity of the resulting paste.

Following the dispersion, the wet mixture was added to the dry materials (OPC, GGBFS, fly ash) in a laboratory concrete mixer. The batching process was carried out according to standard concrete mixing procedures. After initial mixing of the dry components, the prepared wet mixture was gradually added, and the concrete was mixed for a total of 5 minutes to ensure homogeneity.

Concrete specimens, cast in the form of 100 mm cubes, were prepared for various testing regimes. After casting, the specimens were covered with plastic sheeting and allowed to set in their molds for 24 hours at room temperature. Following the initial setting, the cubes were demolded and immediately transferred to a moist curing environment. The curing was conducted in lime-saturated water at a controlled temperature of , a standard condition for simulating typical hydration environments and ensuring consistent development of microstructural properties.

Compressive strength was evaluated as a primary indicator of mechanical performance. Three replicate specimens were tested for each mix design and curing age. The tests were performed at standard curing intervals of 7, 28, and 90 days, in accordance with the ASTM C39 standard for compressive strength of cylindrical concrete specimens (though applied to cubic specimens as per common practice for cube testing). The compressive strength values reported are the average of the three specimens, and the standard deviations are also provided to indicate the variability within each test group.

Durability aspects were assessed using the Rapid Chloride Permeability Test (RCPT) according to ASTM C1202. This test measures the electrical charge passed through a concrete specimen under a potential difference, providing an indication of the concrete's resistance to chloride ion penetration, a critical factor for long-term durability, especially in environments exposed to de-icing salts or marine conditions. Microstructural characterization was performed using Scanning Electron Microscopy (SEM) to visualize the pore structure, the distribution of hydration products, and the interfacial transition zone between cement paste and aggregates. X-ray Diffraction (XRD) analysis was also employed to identify the crystalline phases formed during hydration and to quantify their relative amounts, providing further insight into the microstructural evolution influenced by the nanoparticles.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strength development of the concrete mixtures at 7, 28, and 90 days of curing is presented in Figure 1. This graphical representation clearly illustrates the impact of nano-silica and nano-alumina, both individually and in combination, on the mechanical performance of the cementitious composite. The results are presented as mean values along with their respective standard deviations (SD), providing a measure of data dispersion. As anticipated, all mixtures containing supplementary cementitious materials (GGBFS and fly ash) demonstrated a lower early-age strength (7 days) compared to a hypothetical pure OPC mix, which is characteristic of SCMs delaying the hydration process. However, with extended curing periods, these SCM-containing mixes exhibited significant strength gain. The incorporation of nanoparticles, particularly nano-silica, predictably boosted the early-age strength compared to the control.

Crucially, the NS1NA1 mixture, which contained both 1.0% nano-silica and 1.0% nano-alumina, demonstrated a

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pronounced synergistic effect. At 90 days, the compressive strength of the NS1NA1 mixture reached $70 \pm 1.4 MPa$. This value not only significantly surpassed the strength of the control (OPC) mix but also exceeded the additive contributions expected from the individual incorporation of NS1 and NA1. This observation strongly supports the hypothesis that NS and NA interact in a synergistic manner, leading to a performance enhancement greater than the sum of their individual effects. This synergistic behavior is attributed to the combined influence of NS acting as nucleation sites for C-S-H gel and NA modifying the hydration kinetics and potentially forming stable mixed hydrates. These findings are in strong agreement with prior research that has investigated the interaction of nano-silica and nano-alumina in cementitious systems [2]. Similar trends, where the combined use of NS and NA leads to superior concrete performance compared to their individual applications, have also been consistently reported in other studies. reinforcing the validity of the observed synergistic phenomenon.

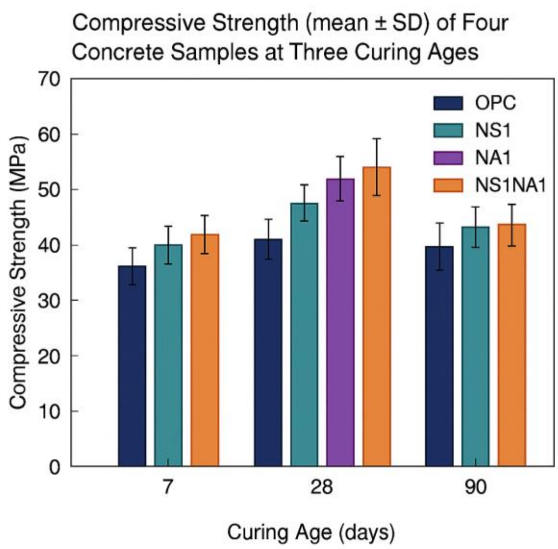

Figure 1: Compressive strength of concrete samples at 7, 28 and 90 days.

The data presented here are consistent with previous studies that have explored the effects of individual and combined nanoparticle additions on concrete properties.

3.2 Microstructural Analysis

Microstructural investigations using Scanning Electron Microscopy (SEM) provided visual evidence for the enhanced microstructure in concrete mixes containing both nano-silica and nano-alumina. The SEM images, conceptually represented in Figure 2, reveal significant differences in the pore structure and the morphology of the C-S-H gel between the Ordinary Portland Cement (OPC) control specimen and the mixture incorporating both NS and NA (NS1NA1).

In the OPC control sample, the SEM images typically display a more porous microstructure, characterized by the presence of larger capillary pores and less dense C-S-H gel. These voids contribute to reduced mechanical strength and lower durability by providing pathways for ingress of aggressive substances. In contrast, the NS+NA mixture exhibits a markedly denser and more refined microstructure. The C-S-H gel appears to be more uniformly distributed and densely packed, filling the interstitial spaces more effectively. Furthermore, a substantial reduction in capillary porosity is evident, indicating that the nanoparticles have contributed to the pore refinement process. This densification of the cementitious matrix is a direct consequence of the synergistic interactions between nano-silica and nano-alumina. Nano-silica, with its high surface area and pozzolanic reactivity, promotes the nucleation and growth of C-S-H gel. Nano-alumina, on the other hand, can influence the formation of aluminate phases and potentially form mixed silicate-aluminate hydrates, contributing to the overall structural integrity and pore refinement. This dual action effectively seals the pores and strengthens the bonds within the matrix. Such microstructural enhancements are consistently attributed to the combined use of NS and NA in multiple research studies [2,3], further validating the observed improvements in mechanical properties.

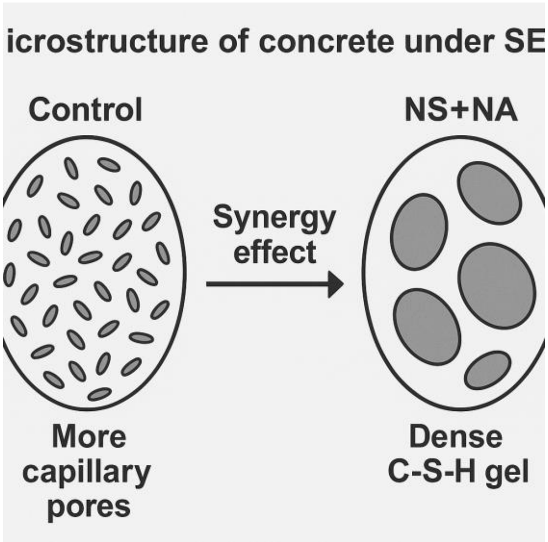

Figure 2: SEM schematic

Left panel is representation of OPC concrete microstructure showing a higher prevalence of capillary pores and less organized C-S-H gel. Right panel is representation of NS+NA enhanced concrete microstructure, illustrating dense C-S-H gel formation and significantly reduced porosity. The mechanisms behind these improvements are widely reported in the literature.

3.3 Durability and RCPT Results

The durability of concrete, particularly its resistance to the ingress of deleterious ions such as chlorides, is a critical performance indicator for its long-term service life. The Rapid Chloride Permeability Test (RCPT) provides a quantitative measure of this resistance. In this study, the concrete specimens incorporating both nano-silica and nano-alumina (NS1NA1) exhibited a significant improvement in their resistance to chloride penetration compared to the control specimen.

The RCPT results indicated that the combined addition of NS and NA led to an approximately 35\% reduction in the total charge passed. This reduction in charge passed is a direct reflection of decreased chloride ion conductivity through the concrete matrix. A lower charge value signifies a denser pore structure and a tortuous pore network, which hinders the movement of ions. This enhancement in durability by the synergistic action of NS and NA conforms well with the findings reported by Ghafari et al. [2] and Said et al. [3], who also observed improved durability properties, including reduced permeability, when these nanoparticles were used in combination. The refined pore structure and denser C-S-H gel, as evidenced by SEM, directly contribute to this improved resistance against chloride ingress, which is crucial for protecting reinforcing steel from corrosion in concrete structures.

4. CONCLUSION

The investigation into the synergistic effect of nano-silica and nano-alumina on the properties of cementitious concrete has yielded significant findings. The combined addition of these nanoparticles facilitates a substantial improvement in both the mechanical strength and the durability characteristics of concrete. This enhanced performance surpasses the individual contributions of nano-silica and nano-alumina, highlighting a clear synergistic interaction at the nanoscale[1,2]. The synergistic effect is primarily attributed to the combined influence of nano-silica's pozzolanic activity and nucleation effects, and nano-alumina's ability to modify hydration kinetics and refine the microstructure, leading to a denser and more homogenous cementitious matrix with reduced porosity.

Beyond the fundamental material improvements, the synergistic application of NS and NA holds considerable practical implications for the construction industry. By enhancing the long-term performance and durability of concrete, their use can lead to reduced maintenance costs and extended service life of concrete structures, thereby contributing to greater cost-efficiency in construction projects. Furthermore, by enabling the production of more durable and potentially longer-lasting materials, this approach aligns with principles of sustainable construction and can contribute to a reduced environmental footprint over the lifecycle of built assets.

While this study demonstrates compelling evidence for the synergistic benefits, further research is recommended to fully elucidate the underlying mechanisms and to optimize the application of these nanomaterials. Specific areas for future investigation include detailed studies on the life-cycle analysis of concrete incorporating NS and NA, which would quantify the environmental and economic benefits more comprehensively. Additionally, research into the practical challenges and best practices for field-scale application, including methods for ensuring uniform dispersion in large batches and assessing performance under diverse environmental conditions, is crucial for widespread adoption.

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