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Impact of Nano-Silica on Mechanical and Durability Properties of Cement Mortar

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Abstract— Nanoscience and nanotechnology are at the forefront of fields that drive modern innovation and foster new scientific advancements. This study explores the influence of nano-silica (NS) with an approximate particle size of 40 nm on the properties of cement mortar, aiming to enhance its mechanical characteristics and durability. Various NS percentages (0.5% to 2.5%) were integrated into the mortar, and their effects were evaluated through compressive strength tests at 7 and 28 days, along with steel corrosion and hardness tests. Characterization of NS was conducted using FTIR, XRD, and SEM techniques. Results indicated that up to 2% NS additions significantly enhance mortar strength, durability, and microstructure, outperforming traditional mortar mixes. These findings suggest the potential for producing crack-resistant concrete for sustainable construction.

Index Terms- Nano Silica; Mortar; Characterization; Strength; Durability Properties.

I. INTRODUCTION

Nanotechnology is making significant strides across various fields, including structural engineering and construction materials. Historical structures built with durable materials have stood the test of time, indicating the potential benefits of integrating nanotechnology into modern construction for improved longevity and strength [1]. Nanotechnology has been pivotal in fields like microbiology, medicine, telecommunications, and materials science, and its application in civil engineering is now burgeoning [2]. The advent of nanotechnology in civil engineering promises enhancements such as lighter construction materials, stronger composites, advanced cementitious products, superior thermal insulation, and innovative self-cleaning surfaces, among other benefits [3].

Nanomaterials, defined by their sub-100 nm particle size and a specific surface area greater than 60 m²/g, offer substantial improvements over conventional materials. Nano-silica (NS), characterized by its 5-100 nm diameter and high surface area, enhances matrix properties due to its fine particle size and substantial physical and chemical effects [4]. As a result, NS exhibits high pozzolanic activity, filling voids and densifying the microstructure, improving the mechanical properties and durability of cementitious materials [5]. Additionally, NS enhances early compressive strength and improves the segregation resistance of self-compacting concrete (SCC) [6].

Cement mortar, consisting of cement, fine aggregates, and water, is a fundamental building material for binding construction blocks and masonry work. Its quality is assessed based on properties like mobility, workability, strength, and durability, which are influenced by its constituent materials. Optimal mortar should be cost-effective, workable, elastic, durable, and chemical resistant [7,8]. Integrating NS in cement mortar can fill voids in the cement matrix, reduce pore volume, and refine pore size, enhancing chemical resistance and reducing water permeability. The high reactivity of NS facilitates hydration reactions, leading to early hardening and improved microstructure [9].

This research aims to:

- Assess the impact of NS on the fresh properties of cement mortar, including durability, setting time, and workability.
- Evaluate the effect of NS on the hardened properties of cement mortar, specifically compressive strength at various curing stages.

- Investigate the durability properties of cement mortar with NS, focusing on steel corrosion resistance.
- Compare the pozzolanic behaviour of NS through SEM, XRD, and FTIR studies.
- Determine the optimal NS percentage for mortar use.

II. MATERIALS AND METHOD

2.1 Cement, Fine Aggregate, and Water

In this construction context, Ordinary Portland Cement (OPC) of 43 Grade, adhering to Indian standards, served as the foundational material. It met specified purity criteria, ensuring optimal performance. Fine aggregates, devoid of impurities, underwent meticulous sieving through a 4.75 mm IS sieve, retaining particles within the range of 150 µm. These aggregates, comprising well-graded siliceous quartz, contributed to the structural integrity and stability of the concrete matrix. Potable water, characterized by a neutral pH ranging from 7 to 8, facilitated the mixing process, enhancing the cement's hydration properties and promoting optimal bonding with the fine aggregates (Table 1). The properties of both the cement and fine aggregates, crucial for determining the strength, durability, and workability of the resulting concrete, were meticulously accounted for and aligned with construction standards. This attention to detail ensures the structural reliability and longevity of the constructed elements.

Table 1 Properties of Cement and Fine Aggregate

Sl. No	Properties	Value	Instruments Used	Reference
Cement				
1	Fineness	5.7%	90-micron sieve	[10]
2	Standard Consistency	28%	Vicat Apparatus	[11]
3	Initial and Final Setting Time	35 and 400 mins	Vicat Apparatus	[12]
4	Specific Gravity	3.15	Hydrometer	[13]
Fine Aggregate				
5	Fineness Modulus	3	Sieve Shaker	[14]
6	Specific Gravity	2.68	Pycnometer	[15]
7	Bulk Density	1604.28 kg/m^3	Core Cutter	[16]

2.2 Nano Silica

Nano silica (NS) can be sourced from natural crystalline minerals or synthesized in laboratories, resulting in high-purity forms primarily found as amorphous silica gels, pyrogenic silica, and polished silica. The synthesis of NS involves several methods, each suited to specific applications and desired characteristics. Common techniques include ion exchange, where ions are swapped to purify the silica; neutralization, which adjusts pH levels to precipitate silica; and electrodialysis, which uses electric fields to remove impurities. Peptization involves breaking down larger silica particles into nanoscale dimensions, while silica gel milling physically reduces silica gels to nanoscale particles. Another prevalent method is the hydrolysis of silicon compounds, where chemical reactions break down silicon precursors into nano silica [17]. Each method ensures the production of high-purity NS with specific properties tailored for industrial applications, such as enhancing material strength, improving thermal stability, and providing unique optical features.

2.3 Characterization of Nano Silica

The characterizations of nanosilica (NS) are detailed in Table 2. X-ray diffraction (XRD) analysis was conducted to examine the structural properties of NS. The XRD patterns of both as-prepared and 300°C calcined NS, shown in Figure 1, reveal an amorphous structure characterized by a broad hump around $2\theta = 20°$. This indicates that the NS does not have a well-defined crystalline structure, which is typical for amorphous silica. Scanning electron microscopy (SEM) images at different magnifications, presented in Figure 2, depict the calcined NS's nanoflake morphology, illustrating the fine and layered texture of the nanoparticles. Figure 3 shows the Fourier-transform infrared (FTIR) spectra for both as-prepared and calcined NS, confirming the presence of silica through characteristic absorption bands [18]. These characterizations highlight the unique structural features of NS, such as its amorphous nature and nanoflake morphology, which contribute to its effectiveness in enhancing the properties of cement mortar.

Table 2 Characterization of Nano Silica

Diameter(nm)	Surface Volume Ratio (m^2/g)	Density (g/cm^3)	Purity (%)
35±2	160±10	<0.20	>99.7

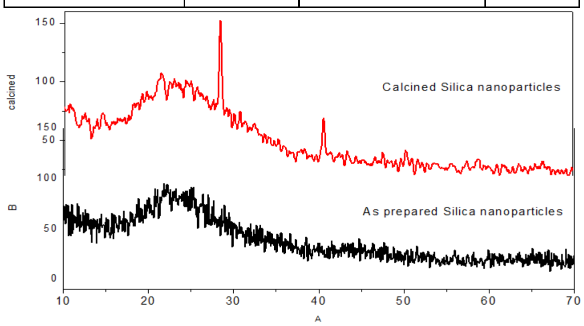

Fig 1. XRD for Nano Silica

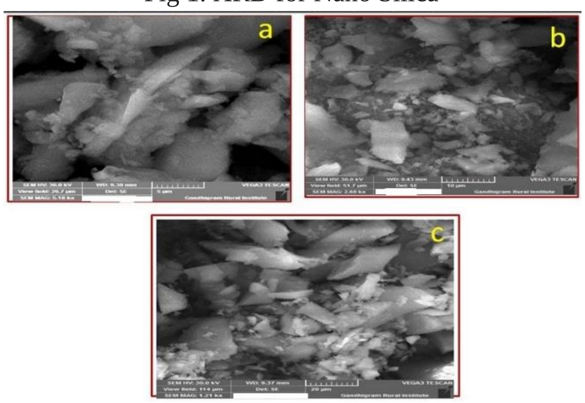

Fig 2. SEM image of Nano Silica

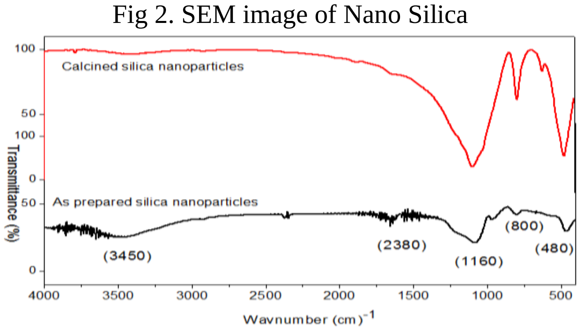

Fig 3. FTIR of Nano Silica

2.4 Methodology

The impact of NS as a partial cement replacement was studied through:

- Preliminary tests on cement, fine aggregates, and NS.
- Determining the mix proportions for cement mortar with NS.
- Fresh property tests are performed to set the time and flowability of cement mortar with varying NS percentages.
- Casting mortar cubes for compressive strength and durability tests with different NS percentages.
- Conducting compressive strength tests at 7 and 28 days.
- Evaluating durability through steel corrosion tests at 28 days.
- Performing SEM, XRD, and FTIR characterization of mortar with and without NS.

2.5 Mix Proportion and Specimen Description

In this study, nanosilica (NS) was incorporated into cement mortar in five different proportions, ranging from 0.5% to 2.5% by weight of cement, to assess its impact on the material properties compared to conventional mortar. A constant water-to-cement ratio of 0.5 and a cement-to-standard sand ratio of 1:3 were maintained throughout the experiments. A total of seventy-two specimens were cast, with NS content varying in 0.5% increments. These specimens were designated as NS1 (0.5% NS), NS2 (1.0% NS), NS3 (1.5% NS), NS4 (2.0% NS), and NS5 (2.5% NS), alongside a control group with no NS, designated as NS0. This systematic variation allowed for a detailed comparison of the effects of increasing NS content on the mortar's mechanical and durability properties, facilitating a comprehensive understanding of the optimal NS content for enhancing cement mortar performance.

III. RESULTS AND DISCUSSIONS

3.1 Preliminary Test on Mortar

3.1.1 Setting Time

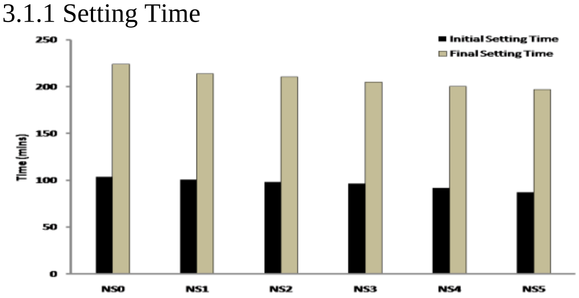

Fig 4. Setting Time of Mortar

Adding nanosilica (NS) to cement paste significantly reduces the setting time when compared to control mortar. This reduction is primarily attributed to the fine particle size of NS, which enhances the hydration process of the cement. The fine particles provide additional nucleation sites, accelerating the formation of calcium-silicate-hydrate (C-S-H) gel, which is crucial for the setting and hardening of cement. As the NS content increases, the setting time decreases further, indicating a direct relationship between NS concentration and the rate of hydration. This accelerated hydration is beneficial in applications where faster setting times are required, improving early strength development and reducing construction times. The effect of varying NS content on setting time is quantitatively depicted in Fig. 4, where the trends clearly show the inverse relationship between NS concentration and setting time. This enhancement in the hydration process due to NS addition can lead to more efficient and faster construction practices [19].

3.1.2 Flowability Test

The flowability of mortar decreases with the addition of nanosilica (NS) as the fine NS particles fill the gaps within the cement matrix. This results in enhanced packing density and increased stiffness of the mortar mix. The finer particles occupy the spaces between the cement grains, reducing the free water content that facilitates flow. Consequently, the mortar becomes less workable and more challenging to handle, reflecting a significant trade-off between improved mechanical properties and reduced flowability. The stiffer mix due to higher NS content also implies that more effort is needed for mixing and placement, potentially affecting the ease of application in construction processes. The impact of substituting cement with varying amounts of NS on the flow characteristics of cement mortar is depicted in Figure 5. This figure clearly shows the inverse relationship between NS content and mortar flowability, highlighting the practical considerations that must be balanced when incorporating NS into cementitious materials [20].

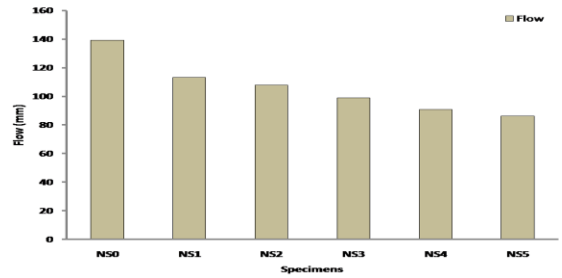

Fig. 5. Flowability of Mortar

3.2 Compressive Strength

Compressive strength tests conducted at 7 and 28 days demonstrated that mortar specimens incorporating nanosilica (NS) exhibited significantly higher strength compared to the control mortar. This increase in strength is attributed to the dual effects of NS: its filler effect and its pozzolanic activity. The fine NS particles enhance matrix packing and homogeneity by filling the voids and reacting with calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H) gel, which is crucial for strength development. The compressive strength showed a marked improvement with NS content up to 2%, but slightly decreased at 2.5% NS. This reduction at higher NS content is likely due to nanoparticle accumulation, which can create weak points within the matrix. Figure 6 illustrates this trend, showing the increase in compressive strength of all mortar specimens as the curing age progresses. These results confirm the beneficial role of NS in enhancing the early and long-term strength of cement mortars [21].

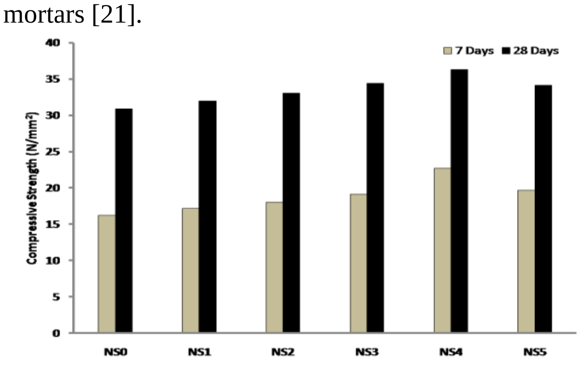

Fig. 6. Compressive Strength of Mortar

3.3 Durability Test

3.3.1 Steel Corrosion Test

The setup for the electrochemical treatment is detailed in Figure 7. In the steel corrosion test, which utilized electrochemical treatment with a sodium carbonate solution, the incorporation of nanosilica (NS) demonstrated a significant reduction in voids within the cement matrix. This densification effect of NS led to a delay in the onset of steel corrosion, thereby enhancing the durability of the embedded steel. The fine NS particles improve the microstructure by filling voids and reducing the permeability of the concrete, which limits the ingress of corrosive agents such as chloride ions and moisture. Consequently, the steel reinforcement is better protected from corrosive environments, prolonging its service life. Figure 8 illustrates the improved corrosion resistance of specimens with NS, showing a delayed onset of corrosion compared to the control specimens. These findings highlight the efficacy of NS in improving both the mechanical and durability properties of reinforced concrete structures [22].

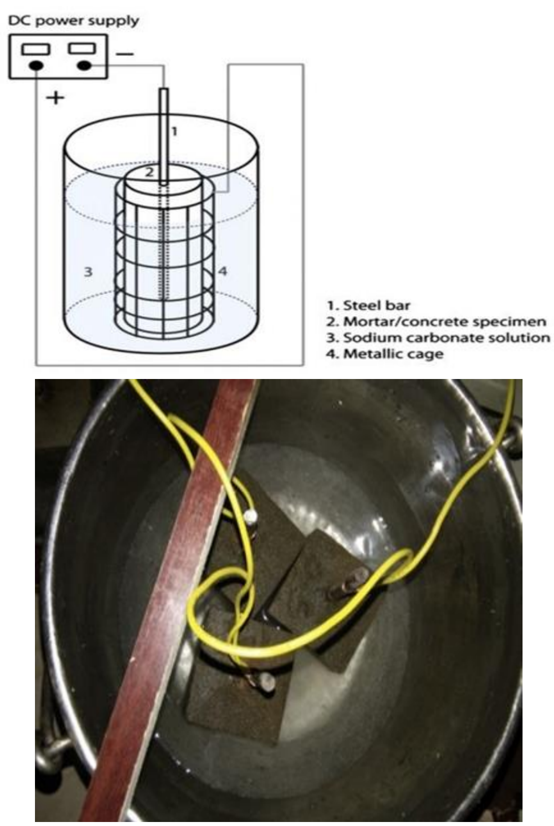

Fig 7 Set-up for Electrochemical Treatment and Steel Corrosion Test on Mortar

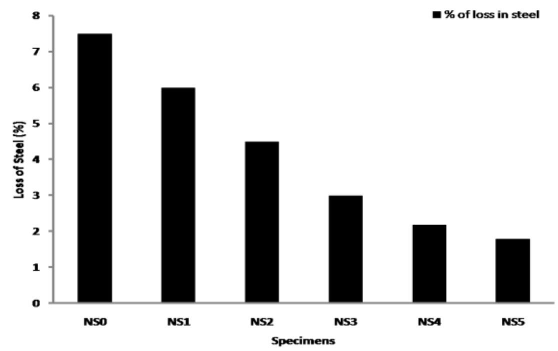

Fig. 8 Loss of Steel Corrosion

3.4 Characterization of Nano Silica Incorporated Mortar

The X-ray diffraction (XRD) patterns for nominal mortar and nanosilica (NS)-incorporated mortar are presented in Figure 9. These patterns confirm the presence of silica in the modified mortar, which contributes to enhanced crystallinity and improved overall properties. The incorporation of NS leads to the formation of additional calcium-silicate-hydrate (C-S-H) gel, which is crucial for the strength and durability of the mortar [23]. Scanning electron microscopy (SEM) images provide further insight, showing a uniform dispersion of NS nanoparticles throughout the mortar matrix. These nanoparticles effectively fill the pores, significantly reducing the porosity of the mortar and consequently increasing its compressive strength [24]. Figure 10 highlights the presence of NS nanoparticles, visible as white agglomerates between the lines in the SEM images. This uniform distribution of NS particles ensures a more compact and less permeable structure, thereby enhancing the mechanical properties and durability of the mortar.

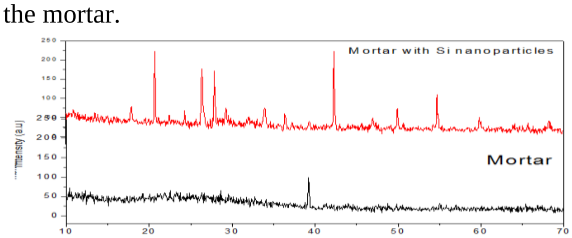

Fig. 9 XRD of Mortar

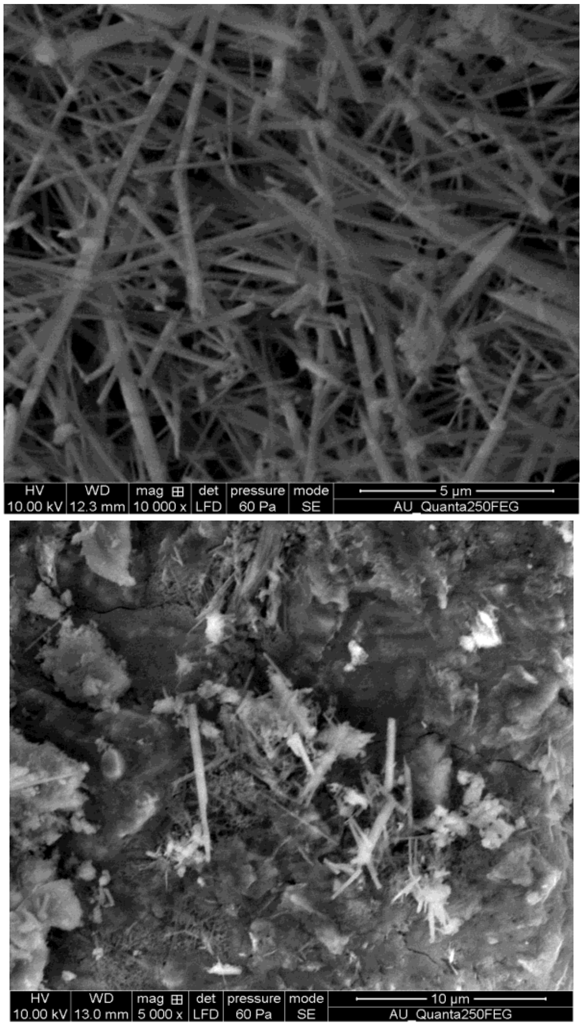

Fig. 10 Mortar without and with Nanoparticles

CONCLUSION

This study explored the effects of NS as a partial cement replacement on cement mortar's fresh, hardened, and durability properties. Key findings include:

- NS addition (0.5% to 2.5%) reduced setting time due to the thickening effect of ultra-fine particles.
- NS improved homogeneity and stiffness, resulting in lower flowability values.
- Compressive strength increased with NS content up to 2%, with a slight decrease at 2.5% due to nanoparticle agglomeration.
- NS improved durability by delaying steel corrosion through reduced pore volume and enhanced matrix density.
- The optimal NS percentage for improved mortar properties is 2%.
- Future research will investigate the effects of higher NS percentages and different curing conditions on mortar properties.

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