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Optimization of Nano-Silica Content for Enhanced Mechanical Properties of Concrete

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ABSTRACT

The impact of adding nano-silica (NS) to concrete of M40 grade on its mechanical characteristics is examined in this study. At 7, 28, 56, and 90 days, the compressive, flexural, and split tensile strengths of concrete mixes containing nano-silica contents ranging from 0% (control) to 1.5% by weight of cement were assessed. Results demonstrate a consistent and significant enhancement in mechanical performance with increasing nano-silica dosage. At 1.5% NS, compressive strength increased by approximately 22–24%, flexural strength by 11.8–13.3%, and split tensile strength by 12.5–13.9% compared to the control mix across all curing ages. The improvement is attributed to the pozzolanic activity of nano-silica, which promotes the production of calcium silicate hydrate (C-S-H) gel, accelerates hydration, and refines the microstructure and interfacial transition zone (ITZ). According to these results, nano-silica is a useful ingredient for creating high-performance concrete with exceptional strength and durability properties.

Keywords: *Nano-Silica, Mechanical Properties, Concrete Durability*

1. INTRODUCTION

Because of its adaptability, toughness, and affordability, One of the most significant and widely used building materials worldwide is concrete. Nevertheless, the manufacturing of cement, a crucial component of concrete and a major source of CO2 emissions worldwide,has increased significantly as a result of the expanding demand for concrete. The calcination process and high energy needs of the cement industry alone are the main causes of the almost 8% worldwide carbon dioxide emissions. Researchers and engineers have been investigating a number of methods to lessen the environmental impact of concrete in response to the pressing demand for sustainable building techniques. The use of nanomaterials and supplemental cementitious materials (SCMs) to partially replace cement and enhance concrete performance is one such strategy. Among the various nano-materials being studied, nano-silica (nS) has garnered considerable attention due to its high pozzolanic reactivity, fine particle size, and ability to enhance the microstructure of concrete. Nano-silica, typically produced through sol-gel processes or vapor-phase synthesis, has a large surface area of very small particles. These particles are added to concrete to fill micro-voids, densify the matrix, and aid in the development of more calcium silicate hydrate (C-S-H), the main binding phase that gives concrete its strength and durability. Despite the promising benefits, the commercial application of nano-silica remains limited due to production costs and uncertainties related to its large-scale performance. The purpose of this study is to assess the mechanical performance of concrete that has been changed with nano-silica and determine if it is suitable for real-world uses. In conclusion, this study contributes to the growing body of knowledge on nanotechnology in construction materials by providing a detailed assessment of nano-silica's effect on M40 grade concrete. It aims to bridge the research gap related to the practical application of nano-silica, especially in high-strength concrete used for structural elements. With increasing emphasis on sustainability, the findings of this research could support the development of greener construction practices by reducing cement consumption and enhancing the performance of concrete. Furthermore, this work highlights the importance of nano-level understanding of material behavior, which is becoming increasingly essential in designing next-generation construction materials. As the industry moves toward more efficient, durable, and environmentally responsible solutions, nano-modified concrete stands out as a promising innovation for the future of civil engineering.

2. LITERATURE REVIEW

Concrete technology has rapidly evolved with the advent of nanotechnology, and nano-silica (nS) is one of the most promising nano additions. Numerous studies have confirmed the beneficial effects of nS on the mechanical, durability, and microstructural properties of concrete. The dosage, type (powder or colloidal), dispersion method, and water-to-cement (w/c) ratio are the primary factors that determine the impact of nS. According to Dheeresh Kumar Nayak and Abhilash P.P. (2021), incorporating nS in cement composites enhances durability and mechanical strength through mechanisms like pore refinement, pozzolanic reaction, and the filler effect. They highlight that an optimum nS dosage of 2–3% yields improved compressive strength, tensile strength, and a denser Interfacial Transition Zone (ITZ). However, dosages exceeding 3% result in reduced strength due to particle agglomeration and increased porosity. Similarly, J. Sridhar and D. Vivek (2019) observed that 3% nS addition in high-performance concrete maximized its mechanical performance, including compressive and tensile strength, as well as flexural behavior. The RC beams incorporated with 3% nS showed superior fracture and ultimate load characteristics, underlining its effectiveness in structural applications. F. Lavergne and R. Belhandi (2018) confirmed accelerated hydration of cement paste with 5% nS through calorimetric analysis. Although a reduction in Portlandite was observed after 90 days. Their results also indicated that nS does not significantly alter the alkalinity of pore solution, making it suitable for steel-reinforced structures. In terms of early-age strength, Billa Mahender and B. Ashok (2017) reported that nS additions up to 1% significantly increased compressive strength. The C-S-H gel matrix's microvoids were filled by nS particles, which made the microstructure denser and more uniform. S. Yuvraj and D. Sujimohankumar (2014) focused on permeability in fly ash-blended nS concrete. They reported 12–14% higher permeability resistance after 28–56 days, confirming nS's role in refining pore structures and enhancing resistance against water ingress. Hongjian Du and Suhuan Du (2014) supported these findings, noting significant pozzolanic activity even at low nS dosages (0.3%). SEM and MIP tests confirmed denser microstructures and reduced ITZ porosity, which translated to better water and chloride resistance.

3. COLLECTION OF MATERIALS

The following materials were carefully selected and utilized for the preparation of M30 and M40 grade concrete specimens incorporating nano-silica (nS). All materials conform to relevant Indian Standard (IS) codes and specifications to ensure the reliability and reproducibility of the experimental results.

1. **Cement**

In this investigation, the main binder was Ordinary Portland Cement (OPC) of grade 43. It conforms to IS:8112–2013 standards. OPC 43 grade is known for its moderate strength gain and is widely used in general construction applications. The cement was kept in a dry setting to prevent moisture absorption and maintain its reactivity.

2. **Fine Aggregate (Sand)**

The fine aggregate was zone II river sand, which complies with IS:383-2016 requirements. The sand was sieved, cleaned, and ensured to be free from organic impurities and silt. Zone II grading ensures optimal workability and strength in concrete mixes, making it suitable for structural applications.

3. **Coarse Aggregate**

Crushed granite coarse aggregates were procured from local quarries near Pangidigudem, Andhra Pradesh. The aggregates comply with the grading and quality requirements specified in IS:383–2016. The aggregates had a specified maximum size of 20 mm and were angular in form.They were washed and dried before use to eliminate dust and deleterious materials.

4. **Water**

For the mixing and curing procedures, the laboratory's potable tap water was utilized. Impurities including oils, acids, alkalis, and salts that might compromise the strength and longevity of concrete were absent from the water. Based on the water-to-cement ratio, the amount of water added was calculated and modified for workability using admixture use.

5. **Nano-Silica (nS)**

Sigma Aldrich, a reliable provider of scientific materials, provided high-purity nano-silica with a particle size of fewer than 100 nanometers (<100 nm). Because of its huge specific surface area and ultrafine particle size, nano-silica has significant pozzolanic activity, which helps to increase the strength, decrease porosity, and prolong the life of concrete.

6. **Admixture**

To improve the workability and dispersion of nano-silica particles inside the concrete matrix, a high-range water-reducing additive (HRWR) based on polycarboxylate ether (PCE) chemistry was employed. The admixture was procured from Lawrence Industries and complies with IS:9103–1999 specifications. It was used in precise dosages to achieve the desired slump and maintain uniform mixing without segregation.

4. METHODS OF TESTS

Compressive strength test:

Concrete's strength under compression is one of its key characteristics. There is a clear correlation between concrete's strength in compression and all other characteristics; that is, when compressive strength increases, so do these other characteristics. Therefore, this one test may be used to assess whether concrete has been done correctly. In India, cube molds with dimensions of 15 cm by 15 cm by 15 cm are commonly used. To ensure there are no cavities, the concrete is produced in a certain proportion, put into the mold, and correctly tempered. A day later, test specimens are submerged in water to cure, and these molds are removed. The top of this specimen need to be flat and smooth. This is achieved by covering the entire specimen with cement paste and smoothing it out. These specimens are tested utilizing compression testing equipment after being cured for 3, 7, 28, 56, and 90 days. At a rate of 14 N/mm2 per minute, the load should be given gradually until the specimen fails. The area of the specimen divided by the load at failure yields the compressive strength of concrete. For every chosen age, a minimum of three specimens undergo testing. The specimen's failure is referred to as "hour glass" failure. This occurs as a result of the cubes' lateral restriction from the plates.

Flexure Strength Test:

To determine the load at which tension-induced bending might lead to the fracture of concrete containing nano-silica, the flexural strength test is used. The test indicates the tensile strength of concrete enhanced with nanosilica. Applications such as ports, oil wells, nuclear power plants, buildings, and coastal areas require unreinforced cement-based materials and their nano-composites to have a high flexural strength.

To determine flexural strength, beam samples are typically evaluated using either third-point loading or central point loading. Here, typical concrete beams are tested using third-point loading since it lowers variability. The next sections offer a thorough examination of the many samples that were produced in order to gain a better understanding of how water and sand affect the material behavior of ordinary concrete under flexural loading.

Split Tensile Test :

An indirect way to assess concrete's tensile strength, originally developed in Brazil. In this test, cylindrical specimens are subjected to a compressive load applied along their diameter, generating tensile stresses perpendicular to the load's direction.

Regular concrete and concrete containing nano-silica are evaluated for indirect tensile strength using cylindrical molds that are 150 mm long and 75 mm in diameter. First, ordinary concrete is used to cast the specimens, followed by concrete containing nano-silica. After 28 days of curing, the samples are assessed using a 50-ton Universal Testing Machine (UTM). To guarantee even load distribution, two strips are positioned at the top and bottom of the cylinder.

Compressive Strength test Results:

Table : 1 Consolidated Compressive Strength Results for M40 Grade Concrete

S.No	Nano-Silica Content	7 Days Avg (N/mm²)	28 Days Avg (N/mm²)	56 Days Avg (N/mm²)	90 Days Avg (N/mm²)
1	0% (Control)	31.99	48.11	49.23	51.01
2	0.5%	33.53	50.19	51.39	53.35
3	1.0%	35.88	53.11	54.22	56.34
4	1.5%	39.21	59.14	61.07	63.34

Several significant patterns and insights are shown by the compressive strength test results for M40 grade concrete that contains different proportions of nano-silica (NS). The information unequivocally shows that adding nano-silica to concrete improves its compressive strength at all curing ages—7, 28, 56, and 90 days. Strength increases steadily and progressively as the NS content rises, with the maximum strength values regularly occurring at 1.5% nano-silica replacement.

The control mix (0% NS) reached a 31.99 MPa compressive strength at just 7 days of age. The strength rose by 4.8% at 0.5%, 12.1% at 1.0%, and a noteworthy 22.6% at 1.5% upon the addition of nano-silica.

This suggests that the pozzolanic activity and filler effect of NS caused early strength growth and hastened hydration. The control mix recorded a strength of 48.11 MPa at 28 days, whereas mixes with 0.5%, 1.0%, and 1.5% NS increased by 4.3%, 10.4%, and 22.9%, respectively. At larger NS doses, these enhancements point to a notable microstructural densification and a greater creation of C-S-H (calcium silicate hydrate) gel.

Longer-term strength gains were also notable. At 56 days, compressive strength rose from 49.23 MPa in the control mix to 51.39 MPa, 54.22 MPa, and 61.07 MPa for 0.5%, 1.0%, and 1.5% NS mixes, marking strength gains of 4.4%, 10.1%, and 24.0% respectively. At 90 days, the control mix strength was 51.01 MPa, while NS mixes achieved 53.35 MPa (4.6%), 56.34 MPa (10.4%), and 63.34 MPa (24.2%). These figures confirm the long-term pozzolanic benefits of nano-silica, as well as its ability to sustain hydration and strength development beyond 28 days.

Overall, the analysis confirms that nano-silica is a highly effective additive for enhancing the compressive strength of concrete. The optimum performance was recorded at 1.5% nano-silica replacement, yielding strength improvements of approximately 22–24% across all ages. This enhancement is attributed to multiple synergistic effects, including improved particle packing C-S-H gel and a denser, more refined interfacial transition zone (ITZ) between cement paste and aggregate were produced as a result of improved pozzolanic processes brought about by the nano-filler effect.

Flexural Strength test Results:

Table : 2 The flexural strength test results at 7, 28, 56, and 90 days for M40 grade concrete with varying percentages of nano-silica:

S.No	Nano-Silica Content	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)	90 Days (N/mm²)
1	0% (Control)	4.15	4.52	5.26	6.26
2	0.5%	4.43	4.74	5.41	6.44
3	1.0%	4.52	4.97	5.65	6.75
4	1.5%	4.64	5.08	5.93	7.09

The flexural strength results of M40 grade concrete modified with varying nano-silica (NS) content across 7, 28, 56, and 90 days reveal a clear and consistent enhancement in performance with the addition of nano-silica. The strength values progressively increase with the incorporation of 0.5%, 1.0%, and 1.5% NS, with the highest strength consistently observed at 1.5% across all curing periods. At 7 days, the control mix (0%) records an average flexural strength of 4.15 N/mm². This value improves to 4.43 N/mm² (6.7% increase) at 0.5% NS, 4.52 N/mm² (8.9% increase) at 1.0%, and 4.64 N/mm² (11.8% increase) at 1.5%. These gains suggest that nano-silica enhances early-age hydration and microstructural development through its pozzolanic and filler effects.

At 28 days, the trend continues, with the control mix achieving 4.52 N/mm² and strength increases of 4.9%, 10.0%, and 12.4% for 0.5%, 1.0%, and 1.5% NS respectively. This improvement indicates better microstructure densification and C-S-H gel formation due to the presence of nano-silica. By 56 days, the control sample records 5.26 N/mm², while strength values rise to 5.41 N/mm², 5.65 N/mm², and 5.93 N/mm² with 0.5%, 1.0%, and 1.5% NS additions—representing gains of 2.9%, 7.4%, and 12.8% respectively. This demonstrates nano-silica's continued contribution to long-term pozzolanic reactions and ITZ refinement.

Finally, at 90 days, the control mix reaches a flexural strength of 6.26 N/mm². The NS-modified mixes exhibit enhancements to 6.44 N/mm² (2.9%), 6.75 N/mm² (7.8%), and 7.09 N/mm² (13.3%) for 0.5%, 1.0%, and 1.5% NS respectively. These results confirm the long-term effectiveness of nano-silica in improving the mechanical behavior of concrete. Overall, 1.5% nano-silica addition emerges as the optimal dosage, providing significant flexural strength gains at all curing periods without evidence of strength plateau or decline. The strength enhancements can be attributed to improved hydration kinetics, micro-filling action, enhanced C-S-H formation, and densification of the interfacial transition zone. These outcomes support the incorporation of nano-silica as a valuable additive in high-performance concrete formulations for structural applications.

Split Tensile Strength test Results:

Table: 3Average Split Tensile Strength of M40 Grade Concrete with Nano Silica Addition

Nano Silica Addition (%)	7 Days (N/mm²)	28 Days (N/mm²)	56 Days (N/mm²)	90 Days (N/mm²)
0%	2.48	2.76	3.90	4.32
0.5%	2.58	2.87	4.04	4.51
1%	2.67	2.97	4.17	4.68
1.5%	2.79	3.10	4.40	4.92

The split tensile strength results of M40 grade concrete modified with varying nano silica (NS) content across 7, 28, 56, and 90 days show a consistent and significant improvement in tensile performance with increasing nano silica dosage. At 7 days, the control mix (0% NS) exhibits an average split tensile strength of 2.48 N/mm². This strength increases to 2.58 N/mm² (4.0% gain) at 0.5% NS, 2.67 N/mm² (7.7% gain) at 1.0% NS, and 2.79 N/mm² (12.5% gain) at 1.5% NS, indicating accelerated early hydration and improved microstructure due to the pozzolanic and filler effects of nano silica. At 28 days, the control strength reaches 2.76 N/mm², while the nano silica modified mixes show enhanced values of 2.87 N/mm² (4.0%

increase), 2.97 N/mm² (7.6% increase), and 3.10 N/mm² (12.3% increase) for 0.5%, 1.0%, and 1.5% NS respectively. This trend reflects ongoing densification of the microstructure and formation of C-S-H (calcium silicate hydrate) gel promoted by the nano silica. By 56 days, the control mix attains 3.90 N/mm², with NS additions further improving strengths to 4.04 N/mm² (3.6% increase), 4.17 N/mm² (6.9% increase), and 4.40 N/mm² (12.8% increase) respectively, demonstrating the sustained pozzolanic activity and refinement of the interfacial transition zone (ITZ). At 90 days, the tensile strength of the control mix reaches 4.32 N/mm², while the mixes containing nano silica record values of 4.51 N/mm² (4.4% gain), 4.68 N/mm² (8.3% gain), and 4.92 N/mm² (13.9% gain) for 0.5%, 1.0%, and 1.5% NS respectively. These results confirm the long-term beneficial impact of nano silica on the mechanical performance of concrete, with 1.5% nano silica emerging as the optimal dosage for maximizing split tensile strength without any observed decline. The improvements are mainly attributed to enhanced hydration kinetics, micro-filling effect, increased C-S-H gel formation, and densification of the ITZ, all contributing to improved tensile resistance and durability. Consequently, nano silica proves to be a valuable additive for producing high-performance M40 concrete with superior tensile properties suitable for structural applications.

5. CONCLUSION

The mechanical performance of M40 grade concrete improved significantly at all curing ages (7, 28, 56, and 90 days) based on an experimental investigation into the partial replacement of cement with nano-silica (NS). The compressive strength measurements demonstrate a consistent improvement with increasing nano-silica concentration, improving by up to about 24% at 1.5% NS in comparison to the control mix.The quicker hydration process, better particle packing, and the pozzolanic reaction that produces C-S-H gel, which densifies the interfacial transition zone, is increased and refines the microstructure—are all responsible for this improvement.

Similarly, the flexural strength results indicate progressive gains with increased NS dosage, with the highest increase (around 13.3%) observed at 1.5% nano-silica after 90 days of curing. The improved flexural performance underscores nano-silica’s role in enhancing the concrete’s tensile characteristics and its microstructural integrity through micro-filling and pozzolanic effects.

The split tensile strength data also follow the same positive trend, showing an approximate 14% strength improvement at 1.5% nano-silica addition at 90 days. These results further confirm the enhanced tensile resistance due to refined hydration products and densification of the ITZ, contributing to the overall durability and structural capacity of the concrete.

Overall, the study identifies 1.5% nano-silica as the ideal replacement amount to optimize M40 grade concrete's mechanical qualities. The synergistic effects of nano-silica improve early-age strength development and sustain long-term strength gains, making it a valuable additive for producing high-performance, durable concrete suitable for demanding structural applications.

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