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Enhancement Mechanical Properties of High Performance Concrete Using of Nano Silica

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Abstract: *High-performance concrete (HPC) is widely used in modern construction because of its superior strength and long service life. The incorporation of nano silica as a supplementary cementitious material has gained significant attention due to its ability to improve the microstructure and mechanical performance of concrete. This study investigates the effect of nano silica as a partial replacement of cement at replacement levels of 1%, 2%, and 3% by weight of cement in M40 grade high-performance concrete. Experimental investigations were carried out to evaluate the compressive strength, split tensile strength, and flexural strength after curing periods of 7, 14, and 28 days. The improved strength is attributed to the pozzolanic reaction and micro-filling effect of nano silica, which results in a denser cement matrix and reduced pore structure. The study concludes that nano silica is an effective supplementary material for producing stronger, more durable, and sustainable high-performance concrete suitable for modern infrastructure applications.*

Keywords: High-Performance Concrete (HPC), Nano Silica, Compressive Strength, Split Tensile Strength, Flexural Strength, Mechanical Properties

I. INTRODUCTION

Concrete is one of the most widely used construction materials due to its high compressive strength, availability, and cost-effectiveness. With the increasing demand for durable and sustainable infrastructure, the development of High-Performance Concrete (HPC) has become an important area of research. HPC provides superior mechanical properties and better resistance to aggressive environmental conditions compared to conventional concrete.

The production of ordinary Portland cement (OPC), however, contributes significantly to global carbon dioxide (CO_2) emissions. Therefore, researchers have focused on the use of supplementary cementitious materials (SCMs) to reduce cement consumption while improving the performance of concrete. Nano silica has emerged as one of the most promising nano-materials due to its extremely fine particle size, high specific surface area, and excellent pozzolanic activity.

Nano silica improves the hydration process by reacting with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C–S–H) gel. It also fills microscopic pores within the cement matrix, resulting in a denser microstructure with lower permeability. Consequently, concrete containing nano silica exhibits higher compressive strength, split tensile strength, flexural strength, and improved durability.

In the present study, nano silica was used as a partial replacement of cement at replacement levels of 1%, 2%, and 3% in M40 grade high-performance concrete. The mechanical properties were evaluated through compressive strength, split tensile strength, and flexural strength tests after 7, 14, and 28 days of curing to determine the optimum percentage of nano silica.

II. OBJECTIVES

- Determining the optimum replacement percentage of Nano Silica in High Performance Concrete (HPC).
- To examine the workability of concrete by using Nano Silica.
- To Enhance the mechanical properties of HPC, including compressive, tensile, and flexural strength.

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III. LITERATURE REVIEW

Several researchers have investigated the influence of nano silica on the mechanical and durability properties of high-performance concrete. Previous studies consistently indicate that nano silica enhances the hydration process, refines the pore structure, and improves the overall performance of concrete.

Alqamish & Al-Tamimi (2021) In the investigated the development and evaluation of concrete incorporating nano-silica in mixtures with large proportions of ground granulated blast-furnace slag (GGBS). They added 1% and 2% nano-silica to concrete mixes with 30% and 70% GGBS, and reported significant improvements in both early-age strength and overall performance of the concrete. This work shows that nano-silica can effectively enhance the pozzolanic reaction and refine the microstructure when combined with high volumes of supplementary cementitious material, thus promoting sustainable concrete design.

Vivek (2021) studied the performance of nano silica in high-performance concrete by replacing cement with 1%, 2%, and 3% nano silica. He found that 3% replacement gave the highest improvement in compressive and flexural strength. The nano silica particles filled micro pores within the cement matrix and enhanced hydration by forming more calcium silicate hydrate (C-S-H) gel. This resulted in denser and more durable concrete. The researcher also observed that higher dosages beyond 3% reduced workability, making the concrete sticky and harder to mix. Therefore, a small amount of nano silica was sufficient to achieve noticeable improvements in both strength and durability.

Zhang et al. (2022) and co-researchers studied the early-age properties of HPC using nano silica. They experimented with 1%, 2%, and 3% replacement of cement. Their results showed that 2% nano silica accelerated hydration and increased early compressive strength significantly. The researchers emphasized that excessive nano silica (above 3%) caused poor dispersion and reduced workability. Hence, maintaining proper particle distribution and mixing is critical for achieving uniform strength development.

Nie et al. (2022) and his team evaluated concrete mixes containing 0%, 1%, 2%, 3%, 4%, and 5% nano silica to study sulphate resistance and microstructure. Their findings showed that 2–3% replacement provided the best results in improving resistance to sulphate attack and reducing pore size. The concrete with nano silica developed a compact and refined internal structure that limited the movement of harmful ions. At higher levels (above 4%), nano silica caused excessive water demand and loss of flowability. The study concluded that moderate nano silica content helps increase the life span of structures exposed to aggressive environments.

Bharat et al. (2024) In the work "Performance Enhancement in Concrete Using Nano Silica and Fly Ash" (2024), Bharat and colleagues explored ternary blending of nano-silica and fly ash in concrete. They observed a synergistic effect: the combined use of fly ash (as a cement replacement) and nano- silica resulted in better microstructure refinement, higher compressive and tensile strength, and improved durability parameters compared to using either material alone. Their findings emphasise the importance of optimizing proportions of SCMs (supplementary cementitious materials) and nano-additives for achieving high- performance concrete.

IV. MATERIALS USED

4.1 Cement

OPC 53 Grade cement was used as the primary binding material in the concrete mix. It provides high early strength and is suitable for producing high-strength concrete

4.2 Fine Aggregate

Natural river sand conforming to IS 383:2016 was used as fine aggregate. It improves the workability and uniformity of the concrete mix

4.3 Coarse Aggregate

Crushed granite aggregate of 20 mm maximum size was used. Coarse aggregate provides strength, stability, and volume to the concrete.

4.4 Nano silica

Nano silica consists of extremely fine amorphous silica particles with sizes ranging from 10–50 nm. It enhances hydration, refines the microstructure, and improves compressive, tensile, and flexural strength.

4.5 Fly ash

Fly ash is a supplementary cementitious material obtained from thermal power plants. It improves workability, durability, and long-term strength while reducing cement consumption.

4.6 Superplasticizer

superplasticizer used to improve the workability of the High-Performance Concrete without increasing the water-cement ratio.

4.7 Water

The water used in the concrete mix was potable, colourless, and odourless, free from any organic impurities. It met the standards for drinking water quality and was suitable for use in the preparation of concrete without affecting its properties.

V. EXPERIMENTAL WORK MIX DESIGN

The concrete mix was designed for M40 grade High-Performance Concrete in accordance with IS 10262:2019 and IS 456:2000. Trial mixes were prepared to achieve the required workability, strength,. Cement was partially replaced with nano silica at 1%, 2%, and 3% by weight while maintaining the selected water-cement ratio throughout the investigation.

Concrete specimens were cast, compacted properly, demoulded after 24 hours, and cured in clean water until the required testing ages of 7, 14, and 28 days.

5.1 Testing Of Fresh Concrete (Slump Cone test)

Table No.1 Workability Test of Concrete

Mix	Nano Silica	Slump (mm)
Control Mix	0%	120
Ns-1	1%	115
Ns-2	2%	110
Ns-3	3%	105

5.2 Compressive Strength Test:

The compressive strength test for a 150mm x 150mm x 150mm cube after 28 days of curing involves applying a compressive load until the cube fails. The maximum load (P) at failure is recorded, and the compressive strength is calculated using the formula: fck = P / A

Where, A is the cross-sectional area of the cube

Table No21 Compressive Strength Test for Cubes (After 28 days)

% of Nano Silica	Compressive stress in 7 days (N/mm2)	Compressive stress in 14 days (N/mm2)	Compressive stress in 28 days (N/mm2)
1%	31.11	37.77	41.55
2%	33.21	40.22	44.35
3%	32.5	39.64	43.76

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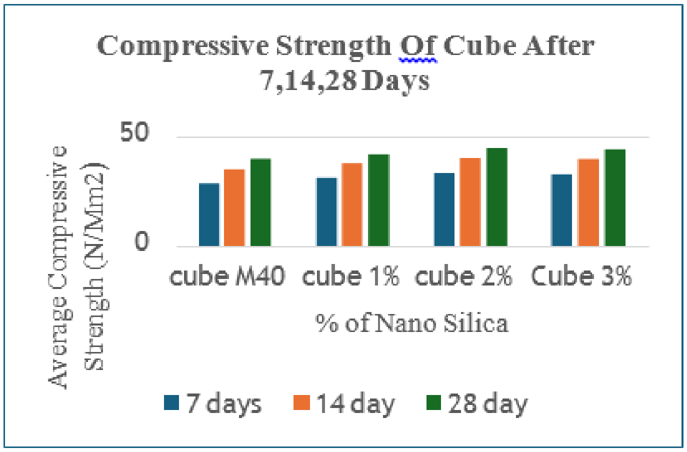

Graph 1 Compressive Strength Test

5.3 Split Tensile Strength Test

The split tensile strength test is an indirect method used to determine the tensile strength of concrete, which is a critical property for assessing the material's resistance to cracking and structural failure. Since concrete is inherently weak in tension, direct tensile tests are often difficult and unreliable, so this test provides a practical alternative. In this method, a cylindrical concrete specimen measuring 150 mm in diameter and 300 mm in length is placed horizontally in a compression testing machine. The compressive load is applied along the vertical diameter of the cylinder, which induces a tensile stress perpendicular to the direction of loading. As the load increases, the specimen splits along its vertical axis, and the maximum load at failure is recorded.

The split tensile strength fst is calculated using the formula:

$$fst = 2P / \pi LD$$

Where:

ft = Split tensile strength in N/mm2

P = Maximum applied load in Newtons (N) L = Length of the specimen

D = Diameter of the specimen π = approximately 3.1416.

Table No.3 Split Tensile Strength Test for Cylinders (After 28 days)

% of Nano Silica	Split tensile Strength in 28 days (N/mm2)
Normal mix	4.15
1%	4.6
2%	5.1
3%	4.95

% of Nano Silica Split tensile Strength in 28 days (N/mm2)

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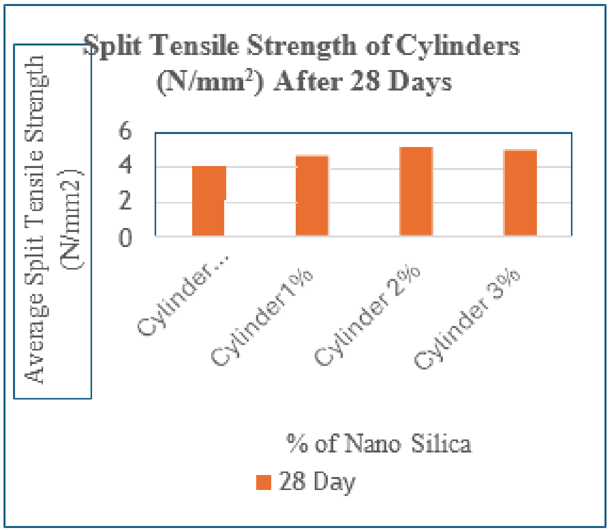

Graph 2 Split Tensile Strength Test

5.4 Flexural Strength Test

The Flexural Strength Test is conducted on a concrete beam specimen of size 150 mm × 150 mm × 750 mm at 28 days to determine the concrete's ability to resist bending or flexural tension, commonly referred to as the modulus of rupture. The beam is placed horizontally in a flexural testing machine, and a two-point loading method is typically used, where the load is applied symmetrically at one-third points of the span. As the load is increased gradually, tensile stresses develop at the bottom of the beam until it fails in bending. The maximum load (P) applied at failure is recorded, and the flexural strength (f_r) is,
calculated using the formula:

$$fr = P L / b d^2$$

- fr = Flexural strength in N/mm2
- P = Maximum load in Newtons (N),
- L = Span length between supports
- b = Width of the beam
- d = Depth of the beam

Table No. 4 – Flexural Strength of Beams (N/mm2)After 28 Days

% of Nano Silica	Flexural Strength in 28 days (N/mm2)
Normal mix	4.85
1%	5.135
2%	5.85
3%	5.7

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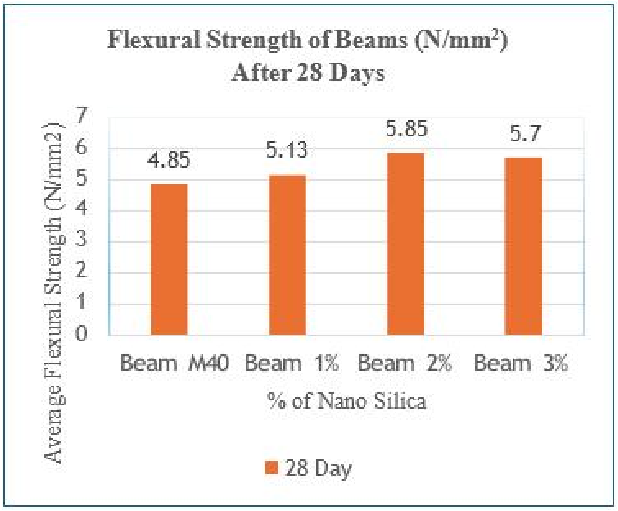

Graph 3 Flexural Strength Test

VI. CONCLUSIONS

• Based on the experimental investigation, it can be concluded that the incorporation of nano silica significantly improves the mechanical properties of M40 grade High-Performance Concrete. The addition of nano silica enhanced the compressive strength, split tensile strength, and flexural strength at all replacement levels when compared with conventional concrete.

• Among the different replacement percentages investigated, 2% nano silica exhibited the optimum performance by achieving the highest compressive strength of 44.35 MPa, split tensile strength of 5.10 MPa, and flexural strength of 5.85 MPa after 28 days of curing.

• The improvement in mechanical performance is mainly attributed to the micro-filling effect and high pozzolanic activity of nano silica, which promote the formation of additional calcium silicate hydrate (C–S–H) gel, resulting in a denser and more compact concrete microstructure.

• Although the use of 3% nano silica also improved the strength properties, the increase was slightly lower than that obtained with 2% replacement due to reduced workability and possible particle agglomeration.

• Therefore, 2% nano silica is recommended as the optimum dosage for producing high-strength and durable High-Performance Concrete suitable for high-rise buildings, bridges, industrial structures, pavements, and other modern infrastructure projects.

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