

A Comprehensive Study on the Role of Nano-Silica in Enhancing the Mechanical and Durability Properties of Concrete

Alok Raj¹, Narendra Dudhe²

¹M.E. Scholar, Department of Civil Engineering, RNTU, Bhopal, M.P., India

²Associate Professor, Department of Civil Engineering, RNTU, Bhopal, M.P., India

Abstract—Concrete's exceptional compressive strength, adaptability, and worldwide availability make it the most widely used building material. Despite its extensive use, the environmental impact of Portland cement has increased along with its rising demand as a binder in concrete. Cement production consumes approximately 1.5 kilowatt-hours of energy per kilogram and emits roughly 1 kilogram of carbon dioxide, accounting for around 7% of global carbon dioxide emissions. A significant challenge in modern construction is increasing concrete strength without compromising sustainability. One potential solution is to add Nano-silica, which can enhance microstructure density, exhibit strong pozzolanic reactivity, and consist of microscopic particles, as a partial replacement for cement. This thesis examines the effects of adding Nano-silica to M 30 grade concrete at rates from 0 to 5 percent. The mechanical and durability properties of the material are assessed with the addition. The experimental analysis includes tests for compressive strength, split tensile strength, flexural strength, water absorption, and durability against acid attack, sulfate attack, and chloride penetration. Following standard procedures, concrete samples were cured for 7, 14, and 28 days before testing. Notable improvements in all mechanical properties were observed with the incorporation of Nano-silica. It was found that the compressive strength of M30-grade concrete increased by 13%. 13.95% and M 40 grade concrete by 16. 16.82% after 28 days of curing with 3% Nano-silica, by weight, replacing part of the cement in the control mix. “The flexural strength was boosted by about 27 percent, and the split tensile strength by 16 percent. 16.10 percent. These benefits are attributed to the pozzolanic interaction between Nano-silica and calcium hydroxide, which enhances the formation of calcium silicate hydrate (C-S-H), strengthens the interfacial transition zone (ITZ), and improves particle packing. The addition of Nano-silica between 2% and 3% of the cement weight was found to be optimal, providing the

right balance between strength increase, durability, and workability. Increased dosages resulted in particle agglomeration, causing slightly lower performance. Based on the findings, Nano-silica may improve concrete's performance and lessen the environmental impact of building materials, making it a more sustainable and effective alternative to cement. To meet future demands for infrastructure, the study provides valuable insights into creating sustainable, long-lasting, and high-performance concrete.

Index Terms—Nano Silica, Building Material, Compressive Strength, Nanomaterials, Nanotubes, Nanostructured materials. Polycarboxylate Ether (PCE), Flexible Strength, Split Tensile Strength
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I. INTRODUCTION

The widespread use of concrete as a building material globally is one of its most notable features. Cement, water, aggregates (such as sand and gravel), and sometimes other admixtures make up this adaptable and long-lasting substance. Buildings, roads, bridges, dams, and many different types of contemporary infrastructure rely heavily on concrete. Due to its strength, durability, and adaptability, it is widely used in construction worldwide. It has been an essential part of the contemporary world's infrastructure, helping to sustain highways, bridges, and buildings [1]. Researchers and engineers have sought new methods to enhance concrete's qualities as building needs evolve and sustainability becomes a greater concern. The demand for Portland cement is high, as the amount of concrete produced each year is growing

at a rate of more than one cubic meter per person. However, one of the principal sources of energy consumption and carbon dioxide emissions is the production of Portland cement. Cement has many admirable structural qualities, but it often falls short of expectations in terms of longevity. As a result, improving concrete's sustainability requires replacing a significant amount of cement with by-product elements [2].

Constant technological advancements in the twenty-first century have had a profound impact on the building sector, transforming the way various types of buildings are conceived and constructed. Societal reforms, which affect people's financial situations, living standards, and leisure activities, are driven by scientific and industrial advancements in developed countries. Moreover, between 2018 and 2050, the demand for concrete is expected to rise by 12–23% in emerging nations (IEA, 2018). However, the manufacture of regular Portland cement causes environmental harm and has significant consequences on a global scale. [3]

II. NANO-MATERIALS

Developing new materials with enhanced properties, functionality, and durability for diverse applications remains a significant challenge in materials research. The scientific and technological communities are highly interested in Nanomaterial research and development due to the numerous potential applications of these materials. [4] Thanks to their exceptional mechanical strength and durability, enhanced chemical properties, increased surface-to-volume ratio, and surface free energy, Nanostructured materials are becoming increasingly important. [5] Nanomaterials hold great promise across nearly every industry, including medical, nuclear, electrical, automotive, artistic, culinary, storage, and biological sectors. Their unique physicochemical characteristics, compared to those of bulk materials, have recently attracted significant attention. [6] The higher surface-to-volume ratio allows for a broader range of applications for these Nanomaterials. Additionally, many industries are utilizing tiny molecules to expand and improve their applications. The healthcare and agricultural sectors are two key areas that are seeing a growing focus on potential uses for Nanoparticles. [7] Using Nano-fertilizers, which contain essential

macro- and micro-nutrients, can significantly increase crop yields. Due to their exciting potential across various fields of science and technology, a thorough understanding of Nanomaterials is crucial today. Due to their unique features, Nanomaterials such as Nano silica, Nano iron, and Nano molybdenum have been extensively studied for their impact on environmentally friendly solutions. [8]

III. ADVANTAGES OF NANOMATERIALS

Due to their small size (typically less than 100 Nanometers), high surface area-to-volume ratio, and distinctive physical, chemical, and mechanical properties, Nanomaterials offer numerous applications and benefits. Due to these advantages, they are highly valued in various industries, including construction, healthcare, electronics, and energy. [9]

- **Enhanced Mechanical Strength:** Nanomaterials, including carbon Nanotubes, Nano-silica, and Nano-alumina, significantly enhance the mechanical strength, toughness, and longevity of materials such as polymers, composites, and concrete.
- **Increased Sturdiness:** The incorporation of Nanomaterials into building materials enhances their resistance to cracking, shrinking, and chemical attacks, resulting in longer-lasting buildings in service.
- **High Surface Area:** Catalysis, energy storage, and sensor applications benefit from their large surface area, which boosts chemical reactivity.
- **Lightweight with High Performance:** Nanomaterials can replace heavier conventional materials without compromising strength, making them ideal for aerospace, automotive, and portable electronics.
- **Self-Cleaning and Anti-Bacterial Properties:** Nanoparticles, such as titanium dioxide (TiO₂), exhibit photocatalytic properties, enabling self-cleaning surfaces and sterilization effects.
- **Energy Efficiency:** Nanomaterials enhance energy conversion efficiency and storage capacity in fuel cells, solar cells, and batteries.
- **Improved Thermal and Electrical Properties:** In electronics and thermal systems, Nanomaterials provide superior conductivity and heat resistance.

- **Targeted Drug Delivery and Medical Applications:** In the biomedical field, Nanomaterials allow for precise drug delivery, early disease detection, and the development of advanced imaging techniques.
- **Environmental Remediation:** Nano-adsorbents and catalysts are used for removing contaminants from water and air, making Nanomaterials beneficial for environmental cleanup.

IV. SELECTION OF NANO MATERIAL

Nanomaterials are considered one of the most promising alternatives to conventional materials due to their superior performance at the Nanoscale, which enables improvements that are often unattainable with traditional materials. They are ideal for cutting-edge, long-term applications in various industries due to their exceptional mechanical, chemical, and physical properties. [10]

- **Exceptional Strength-to-Weight Ratio:** Nanomaterials, such as carbon Nanotubes and Nano-silica, are ideal for high-performance applications in the construction, aerospace, and automotive industries, as they significantly enhance mechanical strength while maintaining a lightweight profile.
- **Enhanced Durability and Lifespan:** In construction materials like concrete, Nanomaterials strengthen resistance to wear, corrosion, chemical attacks, and environmental degradation, resulting in longer-lasting and more resilient structures.
- **Eco-friendly and Sustainable:** Many Nanomaterials enhance efficiency and reduce the need for large quantities of raw materials. They also improve energy efficiency in products such as solar cells and batteries, thereby supporting sustainable development.
- **Multifunctionality:** Nanomaterials can simultaneously offer multiple benefits, such as strength enhancement, antimicrobial effects, self-cleaning ability, and thermal resistance, which eliminates the need for numerous additives or treatments.
- **Higher Efficiency at Lower Dosage:** Due to their high reactivity and surface area, even a small amount of Nanomaterial can lead to significant

improvements in performance, making them cost-effective over time.

- **Intelligent Material Behavior:** Certain Nanomaterials respond to external stimuli, such as temperature, pH, or light, enabling the development of intelligent systems in fields like biomedical engineering, sensors, and innovative coatings.
- **Improved Energy Performance:** Nanomaterials are key components in next-generation energy technologies, including supercapacitors, fuel cells, and thermal insulators, which contribute to energy savings and support renewable energy solutions.
- **Versatility Across Industries:** From construction and medicine to electronics and environmental remediation, Nanomaterials are being adapted for numerous innovative uses due to their customizable and scalable properties

V. OBJECTIVES OF THE RESEARCH

The objective of the research is to determine the influence on the mechanical and durability properties of concrete that arises when Nano-silica is used as a partial replacement for cement. The goal of this study is to find the optimal Nano-silica dose that enhances concrete performance without compromising its workability or structural integrity. The purposes which are intended to be achieved through the research are as follows:

- To determine how the addition of Nano-silica to concrete influences its compressive strength at 7, 14, and 28 days of curing.
- The second objective is to assess how Nano-silica impacts the flexural and split tensile strengths, as well as the overall tensile behavior of concrete.
- To evaluate how different concentrations of Nano-silica affect the water absorption rates of concrete mixes, to assess the material's porosity and permeability.
- To identify the optimal Nano-silica percentage (ranging from 0% to 5%) that maximizes mechanical strength and durability.

VI. LITERATURE REVIEW

Nanoparticles and other particles of a microscopic size are the subject of this investigation. The toughness qualities of cement can be enhanced by adding Nanoparticles and smaller particles as reactants. The following text provides an overview of the benefits, drawbacks, mix percentage, and overall use of Nano silica in concrete. This evaluation study demonstrates how the combined use of NS affects the strength characteristics of cement.

Vikram Singh Kashyap et al. (2023). This involves experiments conducted on incorporating Nano silica into concrete, including the Use of Nano silica to enhance its strength with different concentrations: 1%, 2% & 3% of Nano silica. “The 43-grade ordinary Portland cement (OPC) was used to test the concrete, which contained Nano silica with a proportion of 5 percent to the compressive strength, the split tensile strength, the flexural strength, the water absorption, the carbonation, and the acid attack with a water cement ratio of 0.4. The results revealed that, with the replacement of Nano silica with cement, the compressive strength of concrete has been enhanced, particularly at higher concentrations. An increase in flexural strength was observed with 3% Nano silica during the early stage of curing; however, it decreased over time. Additionally, without altering the volume of concrete, Nano-silica reduced the voids and pores. In the Split tensile strength test, a decrease is observed when Nano-silica is used in mixtures with concentrations higher than 2% in place of cement. This occurs when the Nano-silica particles become mainly fillers rather than contributing to the hydration process. There was no significant difference in the concrete mixes with and without Nano silica after the first thirty days of the carbonation test. Adding 2% Nano silica causes a shift in the pore structure and densifies it. At a higher concentration of Nano silica than the control mix, there is an improvement in the acid resistance, weight change, and compressive strength of concrete. The research concluded that the addition of various concentrations of Nano-silica to concrete altered and enhanced the properties of the concrete. [11]

Fadi Althoey et al. (2023). Concrete is a significant building material; however, the production of Portland cement emits large volumes of carbon dioxide into the atmosphere, as detailed in this study. Recent studies

have focused on fortifying concrete at the Nano level by incorporating Nano-silica (NS), which enhances strength and longevity while suppressing specific properties. “When a reaction occurs between Nano-silica and calcium hydroxide, this causes the formation of the C-S-H gel that enhances the microstructure and raises the density of the matrix in the concrete. The mechanical and durability properties improve due to the strengthened bond between the aggregate and binder caused by this densification.” The physical and mechanical properties of concrete are significantly improved by the addition of 2-4 percent Nano-silica, according to research. The reason is that Nano-silica fills the pores and fine-tunes the pore structure, thereby accelerating the hydration process. However, the advantages of NS can diminish at higher dosages due to complex interactions within the cement material. Additionally, Nano-silica can synergize with waste pozzolanic materials to further enhance the properties of concrete. Despite these advantages, challenges like maintaining workability with high-surface-area Nano materials hinder its commercial application, necessitating ongoing research to optimize its use in construction. [12]

Changjiang Liu et al. (2021). This research article examines the impact of incorporating Nano silica into concrete to improve its properties. The concept of concrete was examined about cementitious materials and concrete-reducing admixtures to achieve carbon peaking and neutralization, with a 20% reduction in cement content. “With an increase in Nano silica, the mechanical properties of concrete will be enhanced. The compressive strength of the concrete was 22.58 MPa and 31.82 MPa at 3, 7, and 28 days, respectively, when the dosage of NS was 2.0%, 2.5% and 2.5%, respectively.” It was 15.6, 11.9, and 6.6 percent less in the control groups. On days 3, 7, and 28, the maximum strength of the concrete in flexure was found to be 3.2 MPa, 4.4 MPa, and 6 MPa at dosage levels of 1.5%, 2.5%, and 2.0% of NS, respectively. In comparison to the control group, these figures showed increments of 10.3%, 18.9%, and 11.1%. Moreover, at 3, 7, and 28 days, the splitting tensile strength of concrete due to the addition of NS doses of 1.5%, 2.5% and 2.5% was 1.5 MPa, 2.6 MPa, and 3.8 MPa, respectively. To summarize this piece, it is hypothesized that the concrete slump is significantly decreased when the amount of Nano-silica (NS) is

elevated to 3% (approximately the weight of cementitious materials) compared to when the dosage of Nano-silica (NS) is 0.25%. Changes in the Portland cement (PC) content are required to mitigate this effect and improve workability. [13]

R. Rashmi et al. (2021). The above work is conducted for both experimental and analytical studies, in which the structural behavior of the RC beam is strengthened with varying percentages of Nano-silica along with various ratios of M-sand. Ordinary Portland cement grade 43 and concrete grades M40 and M50 were used in the mix design and non-linear finite element analysis, with the aid of ABAQUS, to verify the results. "As a partial replacement of cement, the percentage of Nano silica occupied 1-5% and the percentage of M-sand replaced 25-100%. Therefore, to enhance the mechanical properties and strength properties of the concrete (strength and durability), a small quantity of Nano silica can be introduced as a substitute for cement." This will accelerate the initial stages of pozzolanic reactions and hydration. All of the beams failed in flexure, and the first break was discovered in the mid-span tension zone of the beam, as indicated by the test results. When compared to conventional beams, Nano concrete beams exhibit superior flexural properties. The primary reason for flexural failure is caused by steel yielding and the subsequent crushing of the concrete. Nano silica percentage determines the failure load in Nano concrete beams, improving crack performance with fewer and narrower cracks. The overall flexural qualities of concrete are enhanced by adopting M-sand and Nano-silica, which increases the flexural ultimate load. Analytical simulations demonstrate that the model accurately predicts bending, crack patterns, and concrete damage, consistent with experimental findings. Overall, Nano concrete performs better than conventional concrete, as evidenced by a 52% increase in ultimate load for the M40 grade and a 48% increase for the M50 grade. [14]

Vivek et al. (2021) conducted a study on the properties of HPC containing 1%, 2%, 3%, and 4% fly ash and Nano-silica. The mechanical qualities of the concrete were shown to improve at all curing ages, according to the research. Increased hydration reactions and the pore-refinement effect caused by Nano-silica were shown to be responsible for this improvement. [15]

Yonggui et al. (2020) investigated the effect of varying Nano-silica replacement ratios on the structural performance of recycled concrete mixes. Their revelations indicated that the compressive strength declined with the value of the proportion of Nano-silica replacements. Moreover, they have found out that the strength of recycled concrete manufactured with the use of Nano-silica rather than cement was significantly affected by increased manufacturing temperatures. Gas pressure that emerged due to the evaporation of adsorbed and capillary water compromised the interior microstructure of the concrete within the temperature range of 25 to 200 °C. [16]

Mustakim et al. (2021) concluded that the rapid alkali activation technique for geopolymers concrete, combined with the addition of 1.5% Nano-silica and silica fume, improved the microstructure of the geopolymer concrete and resulted in outstanding compressive strength. [17]

Abna and Mazloom (2022) observed the influence of these additives (polypropylene, micro- and Nano-silica) on the fracture strength of concrete. The findings revealed an increase in the fractural strength and fracture energy of the concrete samples when polypropylene fibers were added to the concrete. We established that the best concentration of these ingredients was 5 % micro-silica, 0.75 % Nano-silica, and 0.1 % polypropylene, about the fractural energy and severe fracture strength." The values of the fracture strength of Nano-silica-modified concrete, presented in Figure 3, were not overlooked in the research. [18]

The work prepared by researchers Rajput and Pimplikar (2022), which contained more Nano-silica, resulted in a decrease in the amount of water absorbed by M30 and M40 grade concretes. The rate of water absorption of M30 concrete was 5.15 percent, 30.15 percent, and 35.66 percent, respectively, compared to the control mix, when the concentration of Nano-silica increased to 1 percent, 2 percent, and 3 percent, respectively. The percentage of water absorption of M40 concrete decreased by 1.47 percent, 30.40 percent, and 59.99 percent with the addition of Nano-silica in 1 percent, 2 percent, and 3 percent, respectively. The effect of Adding Nano-Silica to cement composites was an improvement in the pore structure, a reduction in water absorption, and an increase in durability. [19]

Athira and Shanmugapriya (2022) examined the potential utilization of pastes produced with calcined red mud and colloidal Nano-silica (CNS) prepared at different water-to-binder ratios. They found that the introduction of 1.5 percent CNS into red mud cement paste decreased water absorption across all water-to-binder ratios, suggesting the possibility of making cement products more durable by using CNS instead of Nano-silica addition to cement-based products. [20]

VII. MATERIAL AND METHODOLOGY

A. MATERIALS:

Some of the primary materials used in this study are Nano-silica, fine and coarse aggregates, ordinary drinking water, and 43/53-grade Ordinary Portland Cement (OPC). Silica Nano was partially replaced by cement as a means of enhancing the mechanical properties and microstructure of concrete. Powdered Nano-silica from an approved source was used; the average particle size was less than 100 nm. No further treatment was applied to any of the materials; all comply with the applicable IS regulations.

- CEMENT

All plaster, mortar, and concrete use ordinary Portland cement (OPC), which is a blend of oxides of silicon, calcium, and aluminum based on an IS 1489 (Part 1) - 1991 formula. To produce Portland cement and related items, clay and limestone undergo temperatures varying between 1300 and 1400 degrees Celsius. The remaining products are called clinker, which is then ground together with sulphate, usually gypsum, forming the final commodity. The fastest and most widely used type of Portland cement is ordinary Portland cement (OPC), which is sold in shops in a variety of gray shades. Additionally, white Portland cement can be purchased in most hardware stores. Due to its caustic or highly alkaline nature (pH > 13), Portland cement can cause chemical burns if not properly managed. Irritation might be an unpleasant side effect of using Portland cement powder. Portland cement contains chromium and silica, two hazardous chemicals that, when inhaled over an extended period, can lead to silicosis, lung cancer, asthma, and other related health issues. The high energy costs of mining, manufacturing, and exporting Portland cement are just one of the many environmental challenges associated with cement production. Other pollutants include dioxin, NO₂,

SO₂, particulates, and greenhouse gases such as carbon dioxide, which are released into the air. [21] [22]

- SAND (FINE AGGREGATE)

After hard stone is crushed, fine aggregates are collected, as seen in Figures and Figure. Squished sand has a size less than 4.75 mm. It is sourced from the area around the Bhopal construction site in Madhya Pradesh. The range of the fine total is from 150 µm to 600 µm. [23]

COARSE AGGREGATE:

The filler material used in solid blends is of a larger size. In concrete terms, they serve no use whatsoever. The surface zone of coarse aggregates does not precisely equal the fine totals. Crushed rock or stone, dolomite totals, and the gradual erosion of rocks are significant sources of coarse totals. Bhopal was the local source for the coarse aggregates used in Figures 3.7 and 3.8. Use a range of 10 mm to 20 mm for the coarse total. [24]

- NANO SILICA:

Nano silica is used to partially replace cement in concrete mixes, making it one of the most widely used Nanomaterials in the field of civil engineering. Nano silica (also known as silica Nanoparticles) can be one of the most effective new Nanomaterials in civil engineering. With its microscopic particles at the Nanoscale level, Nano silica exhibits unique properties, making it a valuable additive in concrete and other construction materials. This paper examines the impact of Nano silica on enhancing concrete performance, focusing on its ability to improve strength, durability, environmental footprint, and overall sustainability. As we explore Nano silica, its potential to revolutionize traditional construction practices becomes clear, marking a significant step forward in the pursuit of advanced and environmentally friendly building solutions. Incorporating Nano silica into concrete enhances its resistance to abrasion, strengthens its microstructure, and reduces permeability. The addition of Nano silica improves the overall durability of the construction. Additionally, it enhances the workability and flowability of the concrete mix. Furthermore, it strengthens the bond between steel and concrete. Nano silica in concrete has been the subject of

ongoing research. The mix design and intended application are among the many criteria that determine the optimal dosage and unique features of Nano silica. Alongside expanding our understanding of material behavior, work on Nano-silica in reinforced concrete mixes continues. [25] Table No. 1 presents the properties of Nano silica as follows:

Table 1 Physical Properties of Nano Material [25]

Test Item	Standard Requirements
Specific Surface Area (m ² /g)	200 ± 20
pH Value	3.7 – 4.5
Loss on Drying @ 105°C (%)	< 1.5
Loss on Ignition @ 1000°C (%)	< 2.0
Sieve Residue (5 µm) (%)	< 0.04
Tamped Density (g/L)	40 – 60
SiO ₂ Content (%)	> 99.8
Carbon Content (%)	< 0.15
Chloride Content (%)	< 0.0202
Al ₂ O ₃ (%)	< 0.03
TiO ₂ (%)	< 0.02
Fe ₂ O ₃ (%)	< 0.003
Specific Gravity	2.2 – 2.4 (Generalized)
Particle Size	-

Table 2: Chemical Properties of Nano Silica [26]

Property	Description
Chemical Formula	SiO ₂
Surface Groups	Silanol (Si–OH), Siloxane (Si–O–Si)
Reactivity	High (especially in alkaline medium)
Solubility	Insoluble in water; reacts with strong bases.
Surface Area	High (50–600 m ² /g depending on synthesis)
Thermal Stability	Up to ~1000°C (amorphous type)
Modification Capability	High (via silane chemistry)

- POLYCARBOXYLATE ETHER (PCE)

Polycarboxylate Ether (PCE) is a new-generation superplasticizer (high-range water reducer) used to improve the workability, fluidity, and strength of concrete. It is particularly effective in producing self-compacting, high-performance, and high-strength concrete, especially in mixes containing mineral additives such as Nano-silica, fly ash, or slag. Key Properties of Polycarboxylate Ether (PCE) are as follows: Table 3 represents the properties of Polycarboxylate Ether (PCE) [27]

Table 3 Properties of Polycarboxylate Ether (PCE)

Property	Description
Appearance	Light yellow to brown liquid
Solid Content	Typically, 30–50%
pH	4–6
Specific Gravity	1.05–1.10
Chloride Content	Nil (safe for reinforced concrete)
Shelf Life	6–12 months in sealed containers

Polycarboxylate Ether (PCE) offers significant advantages in concrete by providing high water reduction (up to 35%), which enhances strength and durability. It ensures excellent slump retention, making the mix workable for extended periods without requiring additional water. PCE enhances the dispersion of cement and fine particles, such as Nano-silica, resulting in improved compaction, reduced porosity, and a smoother surface finish. It is especially beneficial in high-performance and self-compacting concrete, and its compatibility with supplementary materials, such as fly ash or silica fume, makes it ideal for sustainable, cost-effective construction. [27]

B. METHODOLOGY:

This study aimed to investigate the impact of Nano-silica on the mechanical and durability properties of M30 grade concrete, which can be achieved by partially replacing the cement with Nano-silica. The methodology adopted involved systematic planning, material selection, proportioning of the mix,

specimen preparation, and testing under standard laboratory conditions. The following steps outline the experimental procedure: Figure 1 represents the methodology chart.

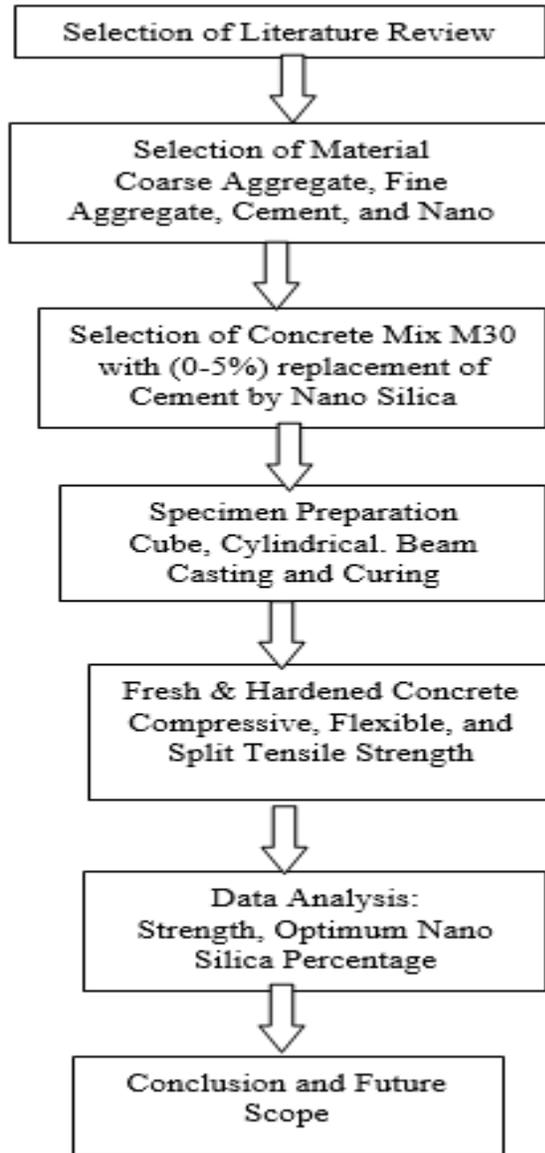


Figure 1: Methodology Chart

C. MIX DESIGN;

Mix design is the process of determining which components to use in the concrete and how much of each to use to produce concrete that meets the job's specifications at the lowest feasible cost. To achieve the appropriate performance qualities of concrete, the proportioning of its elements is a crucial step in concrete technology. In this experimental study, the

impact of Nano-silica inclusion in concrete mixtures, with percentages of the cement weight of 0% and 5%, was increased in increments until it reached 5% of the cement weight. The properties of M30-grade concrete were tested. Throughout the design of the control mix (0% NS), a stable water-to-binder ratio of 0.40 has been maintained, comprising 400 kg/m³ of cement, 650 kg/m³ of fine aggregate, 1200 kg/m³ of coarse aggregate, and 160 kg/m³ of water. In addition to Nano-silica, a progressive cement replacement was performed with the total binder content kept constant at 400 kg/m³. To be more specific, the cement was reduced to 396, 392, 388, 384, and 380 kg/m³ in terms of a 1%, 2%, 3%, and 5% Nano-silica substitution. The proportional Nano-silica volumes were 4, 8, 12, 16, and 20 kg/m³. The Nano-silica in the mix increases the water content due to its large surface area. A superplasticizer (referred to as an HRWR) was employed to ensure that the amount of water used remained constant, while maintaining a certain level of workability. This admixture is based on polycarboxylate ether. The dosage of superplasticizer used varied depending on the Nano-silica content, starting with 1.0 percent of the control mix and increasing to 1.5 percent of the mixture, equivalent to 5 percent of the binder weight by Nano-silica. This resulted in superplasticizer dosages of 4.0, 4.4, 4.8, 5.2, 5.6, and 6.0 kg/m³ for the 0%, 1%, 2%, 3%, 4%, and 5% mixes, respectively. This systematic adjustment ensured consistent workability and mix performance while facilitating the investigation into the influence of Nano-silica on concrete's fresh and hardened properties. Table 3 presents the mix design of M30 concrete. [28] [29]

Table 3 Mix Design of M30 Concrete with Nano Silica

Nano-Silica %	Cement (kg/m ³)	Nano-Silica (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	SP Dosage (% of binder)	SP (kg/m ³)
0%	400	0	650	1200	160	1.0 %	4.0
1%	396	4	650	1200	160	1.1 %	4.4
2%	392	8	650	1200	160	1.2 %	4.8
3%	388	12	650	1200	160	1.3	5.2

						%	
4%	384	16	650	1200	160	1.4 %	5.6
5%	380	20	650	1200	160	1.5 %	6.0

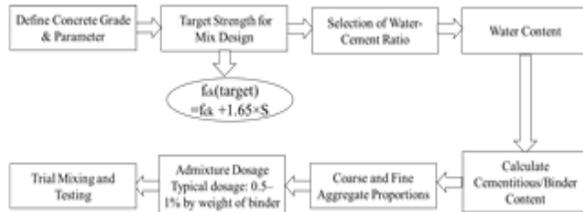


Figure 2 Step-by-Step Concrete Mix Design (with Nano Silica)

VIII. PARTICLE SIZE DISTRIBUTION

The term "gradation of sand" refers to the distribution of particle sizes within a specific sand sample. The strength, longevity, and quality of mortar and concrete mixtures are greatly affected by it. Properly graded sand provides better compaction, reduces voids, and ensures more effective packing of particles, resulting in enhanced strength and workability of the mix. Table 4 represents the particle size distribution. [30]

Table 4 Particle Size Distribution

Sieve Diameter (mm)	Cumulative Passing (%) - Lower Limit	Sand (Actual)	Cumulative Passing (%) - Upper Limit
0.15	5	10	18
0.25	10	20	35
0.5	22	40	60
1.0	40	60	80
2.0	60	80	95
4.75	85	95	100
10.0	100	100	100

IX. RESULTS & DISCUSSION

The findings and interpretations of the study's many experimental tests are presented in this chapter. Cement, fine and coarse aggregates, Nano-silica, and other materials will be examined for their physical, mechanical, and durability properties. To determine the quality and applicability of the materials, each test result is compared to relevant standards and recommendations. Strength, microstructural, and

durability evaluations also provide light on how Nano-silica affects concrete's performance. The discussion highlights the significance of observed trends, correlates the experimental findings with theoretical expectations, and supports the conclusions drawn from the study.

A. COMPRESSIVE STRENGTH:

One of the most important ways to measure concrete's mechanical performance is by testing its compressive strength. An important metric of structural capacity and material quality, it determines how well concrete can resist axial loads. The compressive strength of concrete samples with Nano-silica contents ranging from 0 to 5 percent was measured at 7-, 14-, and 28-days following curing. Understanding how Nano-silica affects both the short-term and long-term phases of strength growth was the driving force behind this experiment. The findings provide light on how Nano-hydration silica's filling qualities and pozzolanic activity influence the final bearing capacity, matrix densification, and hydration process of concrete. Table 5 presents the compressive strength of concrete with Nano-silica. [31]

Table 5: Compressive Strength

Nano-Silica (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0% (Control)	26.4	31.2	38.0
1%	27.8	33.0	40.5
2%	29.1	34.7	42.6
3%	30.0	35.9	44.1
4%	30.4	36.6	45.0
5%	30.2	36.3	44.5

The addition of Nano-silica to concrete was found to have a significant impact on its compressive strength, a crucial factor in evaluating its structural performance. The concrete strength was measured in a compressive manner at 7, 14, and 28 days after it had been cured in different concentrations of Nano-silica (concentration of Nano-silica ranged between 0 percent and 5 percent). As the Nano-silica concentration increases up to 4%, the strength consistently improves, according to the data. By contrast, the control mixes devoid of Nano-silica reached 26.4 MPa after 7 days, 31.2 MPa after 14 days, and 38.0 MPa after 28 days. On the other hand,

at the same ages, the mixture with 4% Nano-silica showed the greatest compressive strengths of 30.4 MPa, 36.6 MPa, and 45.0 MPa, respectively. It is through the pozzolanic reaction between Nano-silica and calcium hydroxide during the hydration process that the production of additional calcium silicate hydrate (C-S-H) gel occurs, leading to an increase in the density and microstructure of the concrete. Additionally, the micro-pores of the cement paste are filled with Nano-silica, which has a minimal particle size, thereby reducing porosity and enhancing the ITZ (interfacial transition zone) between the cement paste and aggregates. The results indicate that 5 percent Nano-silica remains superior to the control at 4 percent, although not as powerful. This is probably because the increased surface area needs more water, which makes the mixture less workable and causes it to disperse improperly. Based on these results, it appears that 4% Nano-silica is the optimal concentration for optimizing compressive strength, beyond which the advantages may level off or even decrease slightly. Generally, the addition of Nano-silica to concrete extensively enhances the compression strength of concrete. It offers a possible solution for developing concrete with high performance, lasting longer with superior mechanical properties. The graph in Figure 3 represents compressive strength.

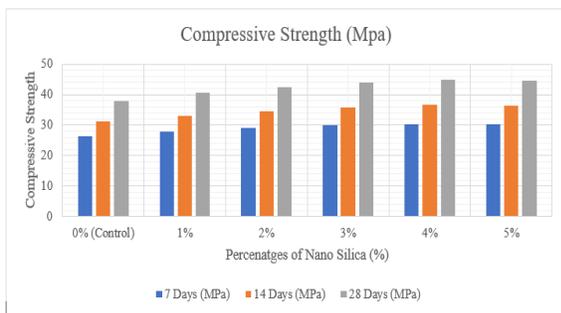


Figure 3: Compressive Strength of Concrete with Nano Silica

B. FLEXIBLE STRENGTH:

To determine how well concrete holds its shape when bent or flexed, engineers perform a flexural strength test. To determine how Nano-silica affects the development of flexural strength, this research evaluated concrete specimens at 7, 14, and 28 days with varying percentages of Nano-silica (ranging from

0% to 5%). It is expected that the inclusion of Nano-silica will increase flexural strength, as the microstructure is improved, particularly in the interface transition zone (ITZ) between aggregates and the paste, and reinforcement of cement matrix bonding. With the help of this test, the optimal level of Nano-silica that can be used to enhance the capacity of concrete to resist tensile stresses and fracture extension might be identified. Table 6 presents the flexural strength of concrete with Nano-silica. [31]

Table 6: Flexible Strength

Nano-Silica (%)	7 Days	14 Days	28 Days
0% (Control)	3.50	4.10	4.80
1%	3.65	4.25	5.00
2%	3.75	4.40	5.20
3%	3.90	4.55	5.40
4%	4.00	4.60	5.50
5%	3.95	4.55	5.40

The flexural strength of the concrete increased dramatically with the addition of Nano-silica, and the effect remained constant during the curing process. The control mix (mix not containing Nano-silica) flexural strengths were stated at 3.50 and 4.10 when the mix was subjected to 7 days and 14 days, respectively, and it reached 4.80 after 28 days. The ultimate strength also improved progressively with the increase in nano-silica. The ultimate strengths achieved were 4.00 MPa, 4.60 MPa, and 5.50 MPa at 4% replacement at the end of 7, 14, and 28 days, respectively. As a consequence of the silica filler's impact and due to the high pozzolanic activity of Nano-silica, the microstructure of the concrete skeleton is enhanced, resulting in increased formation of calcium silicate hydrate (C-S-H) gel. Additionally, Nano-silica enhances the ITZ, which in turn increases fracture resistance when subjected to flexural stress. Particle agglomeration and increased water consumption, which may lead to microstructural flaws, likely contributed to a slight decrease in strength at a 5% replacement level. In conclusion, the findings indicate that Nano-silica enhances the flexural strength of concrete, with a dose of 4% yielding the most effective results. Figure 4 represents the graph of flexible strength.

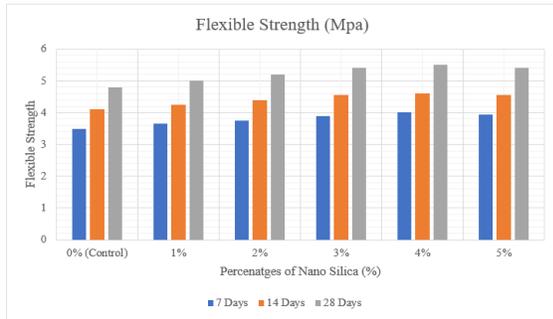


Figure 4: Flexible Strength of Concrete with Nano Silica

C. SPLIT TENSILE STRENGTH

One of the significant properties that influences the reaction of concrete to cracking and design collapse is its tensile strength; the tensile strength of concrete is calculated by conducting a split tensile strength test. Given that the strength of concrete is inversely proportional to the weight bearing on it, this test can be used to measure the material's endurance against indirect tensile stresses. Concrete specimens with varying levels of Nano-silica (0-5%) were observed at 7, 14, and 28 days of curing to establish the impact of Nano-silica on the improvement of tensile strength. In this test, cylindrical specimens are subjected to compressive loads through their diameters to determine whether they can withstand such loads without breaking under tension. The addition of Nano-silica to the mix is believed to enhance tensile strength by reinforcing the connection between aggregate and cement paste, improving the porous structure, and increasing the density of the matrix. For concrete to maintain its structural integrity and longevity, it is necessary to assess its fracture resistance and ductility, two properties that may be measured using this test. Table 7 represents the split tensile strength of concrete with Nano silica. [32]

Table 7 Split Tensile Strength

Nano-Silica (%)	7 Days	14 Days	28 Days
0% (Control)	2.25	2.60	3.00
1%	2.35	2.75	3.20
2%	2.45	2.85	3.40
3%	2.55	3.00	3.55
4%	2.60	3.05	3.60
5%	2.58	3.00	3.50

The addition of Nano-silica enhanced the tensile behavior of concrete, facilitated by a consistent rise in the split tensile resistance of the material. At 7, 14, and 28 days, the non-Nano silica control mix had strengths of 2.25 MPa, 2.60 MPa, and 3.00 MPa, respectively. A linear correlation was found between the increase in tensile strength and the Nano-silica concentration, reaching values of 2.60 MPa (after 7 days), 3.05 MPa (after 14 days), and 3.60 MPa (after 28 days) with simultaneous 4% replacement. Nano-silica is highly pozzolanic, causing the breakdown of calcium hydroxide into more C-S-H gel, thereby making the area more compact and cohesive. That is why it enhances the material. The other two significant functions of ultra-fine particles of Nano-silica are filling micro-gaps and increasing the binding of the cement paste and aggregate. This is particularly true in the zones of interfacial transitions (ITZ), which are a critical zone in terms of the distribution of tensile stresses. At 5% Nano-silica, however, strength drops somewhat at all curing ages, suggesting that there may be a saturation threshold beyond which adding too much Nano-silica causes poor dispersion or higher water consumption, which in turn affects the mix's homogeneity. In general, the findings indicate that to maximize split tensile strength, the ideal Nano-silica concentration is approximately 4%. Any more than this, the benefits become negligible or even harmful.

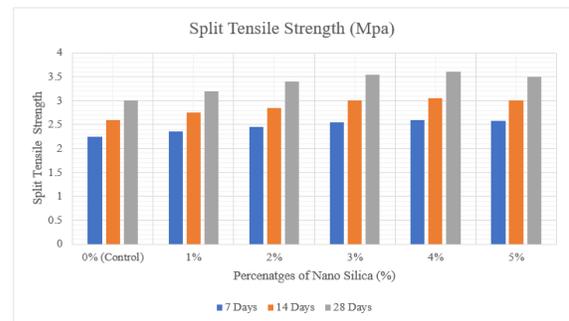


Figure 5: Split Tensile Strength of Concrete with Nano Silica

D. WATER ABSORPTION TEST

The concrete's porosity and permeability, which impact its resilience to harsh environmental conditions, were assessed by the water absorption test. When evaluating the durability of a building that will be subject to moisture, freeze-thaw cycles, or

chemical assaults over time, this test is essential for determining how much water can infiltrate the concrete matrix. This research investigated the water absorption capacity of concrete at 7, 14, and 28 days of curing with varying Nano-silica concentrations, ranging from 0% to 5%. Table 8 presents the water absorption test results for concrete with Nano-silica.

Table 8 Water Absorption Test

Nano-Silica (%)	7 Days (%)	14 Days (%)	28 Days (%)
0% (Control)	3.10	2.95	2.80
1%	2.80	2.65	2.50
2%	2.55	2.35	2.20
3%	2.30	2.10	1.95
4%	2.20	2.00	1.85
5%	2.25	2.10	1.90

The results of the water absorption test indicate that permeability reduces with an increase in curing age and Nano-silica concentration. The control mix (0% Nano-silica) displayed the highest values of water absorption properties at 7, 14, and 28 days, at 3.10%, 2.95%, and 2.80%, respectively, indicating a more porous microstructure. Water absorption was also notably reduced in all age groups when Nano-silica was added. This is achieved through the pozzolanic reaction between Nano-silica and calcium hydroxide, resulting in a greater amount of calcium silicate hydrate (C-S-H) gel. This gel serves a dual purpose: it seals tiny holes in the matrix and helps create a denser, more refined pore structure, both of which significantly reduce water infiltration. The most effective performance was recorded at 4% Nano-silica, with the water absorption dropping to 2.20%, 2.00%, and 1.85% at 7, 14, and 28 days, respectively. This indicates that Nano-silica not only enhances the early-age densification of concrete but also continues to improve durability with time. Interestingly, a slight increase in water absorption was noted at 5% Nano-silica, suggesting that excessive Nano-silica may lead to issues such as particle agglomeration, poor dispersion, or increased water demand, which can affect the overall compactness of the matrix. These findings confirm that 4% Nano-silica is the optimal replacement level for achieving minimum water absorption and maximum durability benefits. These findings suggest that Nano-silica could be a valuable

addition to enhance the long-term performance and high-performance properties of concrete by improving the pore structure of the material.

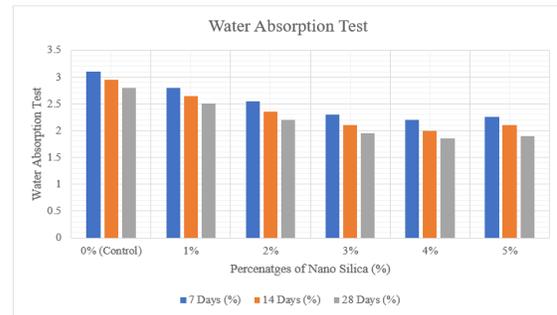


Figure 6 Water Absorption Test of Concrete with Nano Silica

E. DISCUSSION

Using a range of replacement levels (from 0% to 5% by weight of cement), this experimental investigation thoroughly assessed the impact of Nano-silica on the mechanical and durability performance of concrete. The results demonstrated that Nano-silica significantly enhances concrete performance, with an optimal dosage found at 4%. Beyond this dosage, the improvements tend to stabilize or slightly decline due to factors such as agglomeration or increased water demand. At 28 days, the control mix's compressive strength was 38.0 MPa, whereas the blend with 4% Nano-silica reached 45.0 MPa, representing an improvement of approximately 18.4%. At 28 days, the flexural strength of the 4% Nano-silica mix was 5.50 MPa, a 14.6% increase over the control mix, while the control mix recorded 4.80 MPa. The two mixes followed a similar trajectory. Further, a lot of enhancements were made in split tensile strength, which rose to 3.60 MPa (4% Nano-silica), an upsurge of 20% against 3.00 MPa (control). The pozzolanic activity of Nano-silica results in the increase of calcium silicate hydrate (C-S-H), which leads to the appearance of a Nano-filling effect and a denser, stronger matrix. The water absorption test provided further evidence to support the results. At 7, 14, and 28 days, the water absorption values of the control mix were 3.10%, 2.95%, and 2.80%, respectively. The 4 percent Nano-silica blend, however, had registered a 34 percent reduction at 28 days relative to the control, with results of 2.20 percent, 2.00 percent, and 1.85 percent, respectively. This decline in

absorption level is directly linked to the addition of Nano-silica, which increases the impermeability and compactness of the concrete matrix.

X. IMPACT ON THE ENVIRONMENT

The addition of Nano-silica to M30 grade concrete enhances the mix's mechanical and durability properties while also contributing to sustainable building practices and offering significant environmental benefits. Reducing the use of cement—a substance with a large carbon footprint due to its energy-intensive manufacturing processes—is one of the most noticeable effects. This work helps reduce CO₂ emissions associated with concrete manufacturing by substituting Nano-silica for up to 4% of the cement. Nano-silica, primarily when derived as a by-product from industrial processes (e.g., silica fume), serves as a value-added waste utilization strategy, reducing landfill disposal and minimizing environmental degradation. Its use leads to reduced permeability and improved durability, thereby extending the service life of concrete structures and decreasing the frequency of repairs and reconstructions, which in turn lowers the lifecycle environmental impact of infrastructure. Moreover, enhanced resistance to chemical attacks (acid, sulphate, and chloride) significantly reduces deterioration in aggressive environments, helping to protect embedded steel reinforcement and reduce corrosion-related resource consumption. Lower water absorption also means less susceptibility to freeze-thaw damage and moisture-driven deterioration, conserving materials and energy over the structure's lifespan. However, it is also essential to consider that Nano-silica production, particularly synthetic Nano-silica, may involve high energy input and environmental concerns if not properly regulated. Therefore, sourcing Nano-silica from industrial waste or eco-friendly processes is encouraged to maximize sustainability benefits.

XI. CONCLUSION

Ultimately, Nano-silica is an excellent cementitious ingredient for creating long-lasting, high-performance M30 concrete. This makes it a great choice for modern building techniques, especially in areas that are chemically aggressive or prone to dampness. This

project aimed to investigate the effect of replacing part of the cement in M30 grade concrete with Nano-silica on the mechanical and durability properties of the material. According to the trial results, adding Nano-silica to M30 concrete produced a stronger and more rigid material. The most notable results were observed at a 4% replacement of cement by weight. The compressive strength of the control mix was 38.0 MPa after 28 days; however, with 4 percent Nano-silica, it increased by approximately 18.4 percent (45.0 MPa). Flexural strength also increased to 5.50 MPa, compared to 4.80 MPa in the control, and split tensile strength rose to 3.60 MPa from 3.00 MPa. Therefore, this concrete can resist cracks more effectively and bear a greater weight. These improvements are mainly due to Nano-filling and the pozzolanic reaction of Nano-silica. Another way Nano-silica helps lower the carbon footprint of concrete production is by partially replacing cement, a material that significantly contributes to CO₂ emissions. It promotes the reuse of waste materials and supports circular economy principles when derived from industrial by-products. A longer lifespan and reduced maintenance also lead to less resource consumption and environmental impact over time, as shown by the improved durability of Nano-silica concrete, which exhibits less weight loss and strength decline when exposed to acid, sulfate, and chloride. Additionally, reduced water absorption and permeability help protect embedded steel reinforcement from corrosion, further extending the structure's life. These benefits collectively contribute to a lower environmental impact over its lifecycle, making Nano-silica-modified concrete a sustainable choice aligned with modern green building practices and global environmental goals.

XII. FUTURE SCOPE

Although this research has demonstrated that adding Nano-silica to M30 concrete enhances its mechanical and durability properties, several questions remain unanswered. Research in the future may concentrate on:

- To evaluate the long-term performance of concrete enhanced with Nano-silica, it should undergo extended durability testing in real-world environments (including carbonation, sea exposure, and freeze-thaw cycles).

- To investigate the microstructural alterations and pozzolanic reactions generated by Nano-silica, advanced characterization methods may be used, for example, Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Thermogravimetric Analysis (TGA).
- To close the gap found between lab results and the ability to apply this in practice, it is helpful to consider the effectiveness of Nano-silica in full-scale concrete elements and real situations in the field.
- Evaluating the viability and sustainability of Nano-silica in commercial buildings would need thorough economic research and environmental life cycle assessment (LCA).
- To create more environmentally friendly and efficient concrete mixes, researchers should look at how Nano-silica interacts with other pozzolanic or waste elements. These may include fly ash, slag, or rice husk ash.
- Future studies may examine the performance of Nano-silica in high-strength, self-compacting, geopolymer, or fibre-reinforced concrete for use in specialized structural applications.
- Incorporating artificial intelligence (AI) and machine learning (ML) techniques can assist in predicting optimal mix designs and performance outcomes, reducing trial-and-error experimentation.

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