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INVESTIGATION OF MECHANICAL PROPERTIES OF CONCRETE BY USING NANO MATERIALS

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Abstract: Concrete is the most widely consumed construction material worldwide, but it suffers from limitations such as brittleness, low tensile strength, and high porosity in the interfacial transition zone (ITZ). These drawbacks reduce durability and restrict the performance of reinforced concrete structures under aggressive environments. Nanotechnology has emerged as a potential solution, with nano-silica (NS) gaining significant attention due to its pozzolanic reactivity and micro-filler effect. This study investigates the influence of nano-silica on the mechanical properties of M30 grade concrete. Ordinary Portland Cement (OPC) 43 grade was partially replaced with NS at 0%, 0.5%, 1.0%, 1.5%, and 2.0% by weight of cement. Experimental work included testing for slump (workability), compressive strength, split tensile strength, and flexural strength at curing ages of 7, 28, and 90 days.

The results indicated that the addition of nano-silica decreased slump values due to higher water demand, but acceptable workability was maintained using a PCE-based superplasticizer. Compressive strength improved significantly, with a maximum gain of 16% at 1.5% NS replacement after 28 days. Similarly, split tensile and flexural strengths improved by approximately 12–15% at 1.5% NS. However, beyond 1.5%, the performance slightly declined due to particle agglomeration and reduced workability. Microstructural observations confirmed that NS refined the ITZ and reduced porosity, contributing to improved durability.

The study concludes that an optimum NS dosage of 1.5% replacement of cement enhances the strength properties of M30 grade concrete, making it a promising material for high-performance and durable construction applications.

Key Words **- Nano-silica, Mechanical properties, High-performance concrete, Compressive strength, Flexural strength, Tensile strength**

1 INTRODUCTION

Concrete is one of the most versatile and widely used construction materials in the world, second only to water in terms of consumption. It provides structural strength, durability, and adaptability at a relatively low cost. Despite its extensive use, concrete suffers from inherent weaknesses such as low tensile and flexural strength, shrinkage, creep, and susceptibility to environmental degradation. One of the most significant weaknesses is the porous and weak interfacial transition zone (ITZ) that develops between the aggregate and the cement paste. This zone acts as a path for crack initiation and propagation, ultimately reducing structural life.

To improve performance, supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast-furnace slag (GGBS) have been used successfully. These materials improve durability and long-term strength by refining the microstructure. However, they primarily act at the microscale and do not fully address nanoscale porosity or ITZ refinement. The need for a material that enhances both micro- and nanoscale properties has led researchers to nanotechnology.

Nanotechnology involves manipulating materials at dimensions ranging from 1–100 nanometers, where unique physicochemical properties emerge. Nano-silica (NS), one of the most widely studied nanomaterials in concrete, is highly reactive due to its ultrafine particle size and large surface area. It functions in two ways: (1) chemically, it reacts with calcium hydroxide (a weak hydration product) to form additional calcium silicate hydrate (C–S–H), which is the primary strength-giving phase in cement paste, and (2) physically, it acts as a filler, reducing voids and densifying the ITZ.

Previous research (Jo et al., 2007; Qing et al., 2007; Sanchez & Sobolev, 2010) has consistently reported strength and durability improvements with nano-silica. However, optimum dosage varies, with most studies recommending between 1–2%. Excess NS can reduce workability and cause agglomeration, resulting in strength reduction.

This research investigates the influence of nano-silica on the mechanical properties of M30 grade concrete, focusing on compressive, split tensile, and flexural strengths, as well as workability. By systematically replacing cement with nano-silica at varying dosages, this study aims to identify the optimum percentage for enhancing performance, thus contributing to the development of high-performance concrete.

2 LITERATURE REVIEW

2.1 Conventional Concrete and Its Limitations

Concrete is the most extensively used construction material worldwide, owing to its versatility, ease of production, and cost-effectiveness. Its strength in compression and ability to be molded into various shapes make it the backbone of infrastructure such as buildings, bridges, dams, and pavements. Despite its widespread use, conventional concrete exhibits several shortcomings that affect its overall structural performance and service life.

One of the primary weaknesses of concrete lies in its low tensile strength and brittle behavior. Although concrete can withstand high compressive forces, its tensile and flexural capacities are only about 8–12% and 12–15% of compressive strength, respectively. This imbalance often results in cracking under tensile stress, which is why reinforcement is necessary in structural applications. However, cracks act as points of weakness that allow ingress in water and harmful agents.

Another limitation is its porous microstructure. The cement paste, particularly the interfacial transition zone (ITZ) around aggregates, is more porous and less dense than the bulk matrix. This weak zone facilitates the development of microcracks, reduces load transfer efficiency, and accelerates deterioration. Furthermore, shrinkage and creep contribute to long-term deformations, which can compromise dimensional stability and serviceability.

Durability is another major concern. In aggressive environments, conventional concrete is susceptible to chloride penetration, sulphate attack, alkali-silica reaction (ASR), and carbonation. These processes weaken the material and, in reinforced concrete, cause steel corrosion, leading to spalling and reduced service life. The lack of resistance to freeze-thaw cycles further limits the application of ordinary concrete in cold climates.

Over the years, supplementary cementitious materials such as fly ash, silica fume, and GGBS have been used to address some of these problems. While they improve durability and long-term strength, their performance is inconsistent due to variations in raw material quality and slower reactivity at early ages. Thus, there is a need for advanced materials capable of refining the microstructure at the nanoscale.

The emergence of nano-silica provides an opportunity to overcome these limitations by densifying the ITZ, accelerating hydration, reducing porosity, and improving mechanical as well as durability properties. This makes it a promising candidate for producing high-performance concrete.

2.2 Role of Nanotechnology in Construction

Nanotechnology has emerged as a transformative field across industries, and in civil engineering it holds tremendous potential to improve the performance of construction materials. By manipulating matter at the nanoscale (1–100 nanometers), it is possible to enhance the physical, chemical, and mechanical properties of traditional materials such as cement, concrete, steel, and asphalt.

In the context of concrete, nanotechnology addresses the microstructural weaknesses that conventional materials cannot. Concrete's performance largely depends on the hydration of cement and the formation of calcium silicate hydrate (C–S–H), which binds aggregates together. However, the process generates calcium hydroxide (CH), which is relatively weak and contributes little to strength. Nanomaterials such as nano-silica act as highly reactive pozzolans, consuming CH and producing additional C–S–H gel, thereby improving strength and durability.

Another critical contribution of nanotechnology is the filler effect. Due to their extremely small particle sizes, nanomaterials fill the micro voids within the cement matrix and interfacial transition zone (ITZ), resulting in a denser and more refined microstructure. This reduces permeability, minimizes crack propagation, and improves durability. Additionally, nanoparticles act as nucleation sites, accelerating hydration and leading to higher early-age strength.

Different nanomaterials have been studied in construction:

- Nano-silica: Improves strength, durability, and reduces permeability.
- Nano-alumina: Accelerates setting time and increases early-age strength.
- Carbon nanotubes (CNTs): Provide exceptional tensile reinforcement, though dispersion is challenging.
- Nano-titanium dioxide (TiO_2): Adds self-cleaning and photocatalytic properties.
- Graphene oxide: Improves tensile capacity and crack resistance.

While the benefits are evident, challenges remain. Dispersion of nanoparticles in cementitious systems is difficult due to agglomeration, and specialized mixing techniques or superplasticizers are often required. Moreover, nanomaterials are currently expensive compared to traditional SCMs, raising cost-effectiveness concerns for large-scale applications.

Nevertheless, the potential of nanotechnology in construction is undeniable. By improving the mechanical properties, durability, and sustainability of concrete, it offers solutions to some of the biggest challenges in modern infrastructure development.

Nano Materials	Role in Concrete	Challenges
Nano-silica	Pozzolanic reaction, filler effect, improves strength	Workability reduction, dispersion issues
Nano-alumina	Accelerates hydration, increases early strength	Agglomeration tendency
Carbon nanotubes	Enhance tensile strength & crack resistance	High cost, poor dispersion

Nano-TiO2	Self-cleaning, photocatalytic	Expensive
Graphene oxide	Improves toughness and tensile properties	Limited availability

2.3 Properties of Nano Silica

Nano-silica is one of the most widely studied nanomaterials in cement and concrete technology because of its distinctive physical and chemical properties. It is a highly reactive amorphous form of silica (SiO_2) with particle sizes typically ranging from 10 to 100 nanometers. The extremely small particle size gives nano-silica a very large surface area (greater than 200 m^2/g), which enhances its reactivity compared to traditional silica fume or micro-silica.

Chemically, nano-silica reacts with calcium hydroxide (CH), a weak byproduct of cement hydration, to produce additional calcium silicate hydrate (C–S–H) gel. This gel is responsible for the strength and durability of concrete. By reducing the quantity of CH and increasing C–S–H, nano-silica contributes to a denser and stronger cement matrix.

Physically, nano-silica acts as a micro-filler. Due to its very fine size, it fills voids within the cement paste and especially in the interfacial transition zone (ITZ), which is the weakest area of conventional concrete. This filler effect refines the pore structure, decreases permeability, and enhances durability.

However, the use of nano-silica also presents challenges. Because of its ultrafine size and high surface energy, nanoparticles tend to agglomerate if not properly dispersed. This can reduce effectiveness and create weak points. Additionally, nano-silica increases the water demand of concrete, reducing workability unless compensated with superplasticizers.

Properties	Typical Values
Particle Size	10-100 nm
Surface Area	>200 m2/g
Density	2.2 g/cm3
Appearance	White amorphous powder

2.4 Previous Research Studies

Several researchers worldwide have studied the incorporation of nano-silica into cement and concrete. Their findings consistently indicate that nano-silica improves both fresh and hardened properties, though the optimum dosage varies.

- Jo et al. (2007): Reported a 20% increase in compressive strength at 28 days with 2% nano-silica replacement. They concluded that nano-silica accelerates hydration and densifies the microstructure.
- Qing et al. (2007): Found that 1.5% nano-silica provided significant improvements in ITZ density and reduced porosity, which enhanced durability.
- Sanchez & Sobolev (2010): Conducted a comprehensive review and concluded that nanotechnology improves not just strength but also sustainability of concrete.
- Said et al. (2012): Reported that nano-silica addition reduced shrinkage and improved bond strength between paste and aggregates.
- Patel & Shah (2018): In the Indian context, they determined that 1.5% was the most effective dosage for mechanical strength and cost balance.

2.5 Identified Research Gap

Although numerous studies have explored the effect of nano-silica on concrete properties, certain areas remain under-researched. First, large-scale field studies are limited. Most available research is laboratory-based, which does not fully replicate the variability of real construction conditions. Secondly, standard dosage guidelines are not available. While most studies recommend an optimum between 1% and 2%, results vary depending on cement type, aggregate characteristics, and mixing procedures.

Another gap is the long-term durability performance of nano-silica modified concrete. While short-term mechanical improvements are well-documented, there is insufficient data on resistance to chloride penetration, sulphate attack, carbonation, and freeze-thaw cycles. Similarly, the economic aspect of using nano-silica on an industrial scale remains unclear, as production costs are higher than traditional SCMs.

Dispersion techniques also present a challenge. Nano-silica tends to agglomerate, which reduces effectiveness and can even create weak zones if not properly mixed. Research on advanced dispersion methods and admixture combinations is therefore essential.

In summary, while nano-silica clearly enhances strength and microstructure, research gaps remain in field-scale application, durability assessment, standardized guidelines, and cost-effectiveness. These gaps justify the present research, which focuses on identifying optimum dosage for M30 grade concrete in practical conditions.

2.6 Summary

The literature review highlights that conventional concrete, while strong in compression, suffers from significant drawbacks such as low tensile strength, porous ITZ, shrinkage, creep, and vulnerability to chemical attacks. SCMs like fly ash and silica fume improve performance but only at the microscale.

Nanotechnology, particularly nano silica, addresses these shortcomings at the nanoscale by acting as both a pozzolanic material and micro-filler. Previous studies consistently report strength and durability improvements with nano-silica, with most identifying 1.5% replacement as the optimum dosage. However, challenges remain in terms of reduced workability, lack of standard dosage guidelines, dispersion difficulties, and limited durability data.

The review concludes that nano-silica has great potential as a supplementary cementitious material, but further systematic investigation is required, especially under local material and environmental conditions. This sets the foundation for the present study, which investigates the mechanical properties of nano-silica blended concrete for M30 grade applications.

3 MATERIALS AND METHODS

The experimental program was designed to study the effect of nano-silica on the mechanical properties of M30 grade concrete. The materials used were carefully selected and tested for quality.

- Cement: Ordinary Portland Cement (OPC) 43 Grade, conforming to IS 8112, with specific gravity 3.15.
- Fine Aggregate: River sand conforming to Zone II of IS 383, specific gravity 2.64, water absorption 1.2%.
- Coarse Aggregate: Crushed angular granite aggregates of maximum size 20 mm, specific gravity 2.70, water absorption 0.5%.
- Water: Potable water free from impurities.
- Nano-Silica: Amorphous nano-silica powder with particle size 10–80 nm, surface area >200 m²/g, purity 99%.
- Superplasticizer: Polycarboxylate ether (PCE)-based admixture as per IS 9103 to maintain workability.

Mix Design: The mix proportions for M30 grade were determined using IS 10262:2019 guidelines. A water-cement ratio of 0.45 was adopted. Cement was partially replaced with NS at dosages of 0%, 0.5%, 1.0%, 1.5%, and 2.0% by weight.

Specimen Preparation: Concrete was mixed in a tilting drum mixer, cast into oiled mould, and compacted using a table vibrator. After 24 hours, specimens were demolded and cured in water at 27±2°C until testing. Specimens included 150 mm cubes (compressive strength), 150 × 300 mm cylinders (split tensile strength), and 100 × 100 × 500 mm beams (flexural strength).

Testing Methods:

- Slump test as per IS 1199 for workability.
- Compressive strength test as per IS 516 on cubes at 7, 28, and 90 days.
- Split tensile strength as per IS 5816 on cylinders.
- Flexural strength as per IS 516 using third-point loading on beams.

This methodology ensured reliable and reproducible results for evaluating the effect of NS on mechanical properties.

4 RESULT AND DISCUSSION

4.1 WORKABILITY (SLUMP TEST)

The slump test results indicated a gradual reduction in workability with increasing NS content. The control mix (M0) had a slump of 80 mm, while mixes with 0.5%, 1.0%, 1.5%, and 2.0% NS showed slumps of 75 mm, 70 mm, 65 mm, and 60 mm respectively. The reduction is due to the extremely high surface area of NS, which increases water demand. With superplasticizer dosage adjustment, acceptable workability was maintained.

Key Interpretation: NS negatively affects workability, but with admixtures, it is manageable.

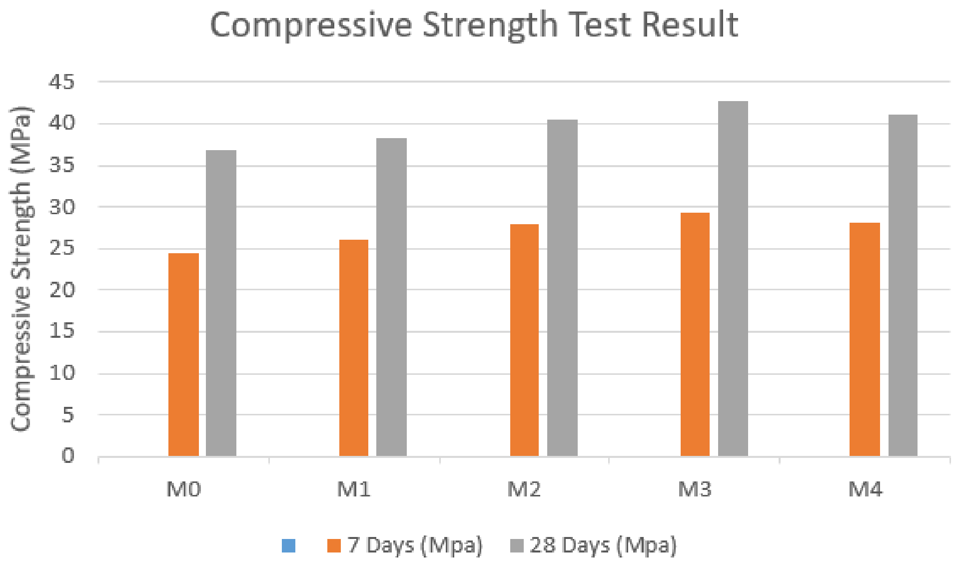
Mix ID	Nano - Silica (%)	Slump (mm)
M0	0	80
M1	0.5	75
M2	1	70
M3	1.5	65
M4	2	60

4.2 COMPRESSIVE STRENGTH

The compressive strength test revealed significant improvement up to 1.5% NS. At 28 days, strength increased from 36.8 MPa (control) to 42.8 MPa (1.5% NS). At 90 days, the control reached 42.5 MPa, while 1.5% NS reached 48.7 MPa. At 2.0% NS, strength dropped slightly to 46.8 MPa, indicating overdosage causes agglomeration.

Table: Compressive Strength (MPa)

Mix ID	Nano - Silica (%)	7 Days (Mpa)	28 Days (Mpa)	90 Days (Mpa)
M0	0	24.5	36.8	42.5
M1	0.5	26.1	38.2	44.1
M2	1	27.8	40.5	46.2
M3	1.5	29.3	42.8	48.7
M4	2	28	41	46.8



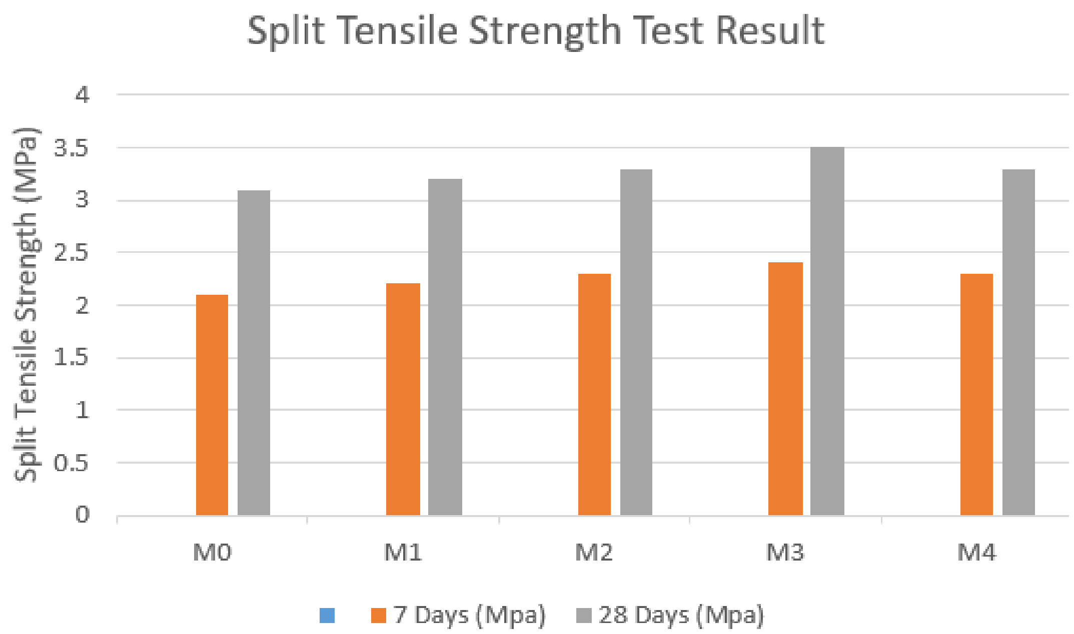
Key Interpretation: Optimum compressive strength occurs at 1.5% NS.

4.3 SPLIT TENSILE STRENGTH

At 28 days, tensile strength increased from 3.1 MPa (control) to 3.5 MPa (1.5% NS), and at 90 days from 3.5 MPa to 4.0 MPa. Improvement is due to ITZ densification, which prevents microcrack propagation. Beyond 1.5%, tensile strength reduced slightly due to poor dispersion.

Key Interpretation: NS enhances crack resistance and bonding in ITZ.

Mix ID	Nano - Silica (%)	7 Days (Mpa)	28 Days (Mpa)	90 Days (Mpa)
M0	0	2.1	3.1	3.5
M1	0.5	2.2	3.2	3.7
M2	1	2.3	3.3	3.8
M3	1.5	2.4	3.5	4
M4	2	2.3	3.3	3.7

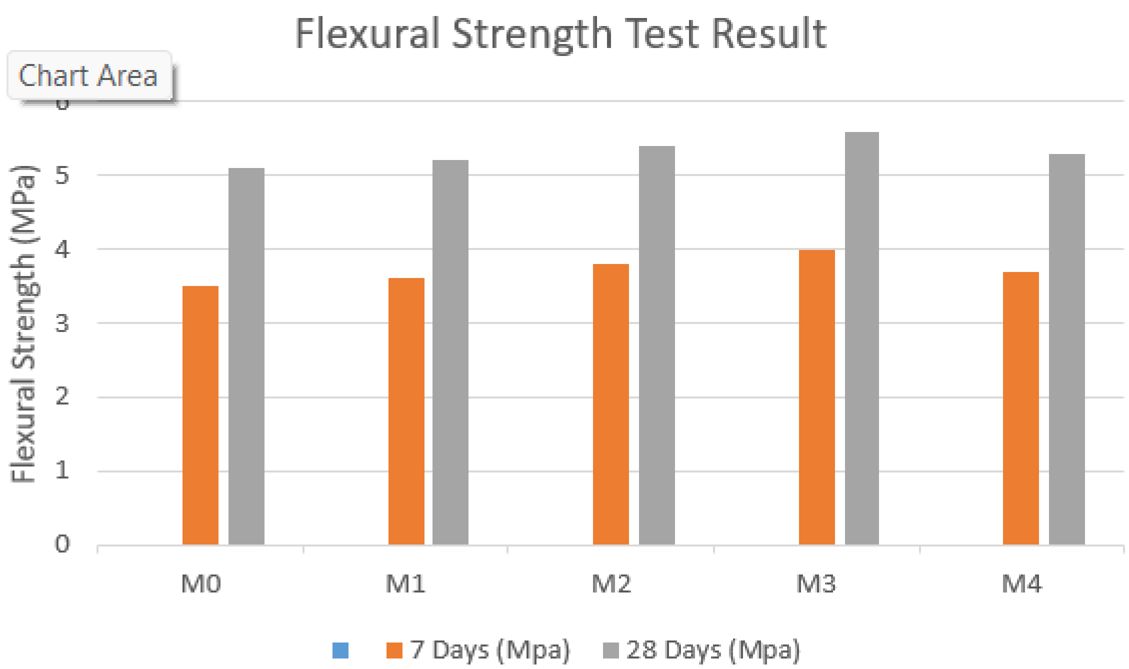


4.4 FLEXURAL STRENGTH

Flexural strength followed a similar trend. At 28 days, strength improved from 5.1 MPa (control) to 5.6 MPa (1.5% NS). At 90 days, strength increased from 5.7 MPa to 6.2 MPa. Flexural performance indicates better load transfer and crack resistance.

Key Interpretation: Flexural properties improve with NS, optimum at 1.5%.

Mix ID	Nano - Silica (%)	7 Days (Mpa)	28 Days (Mpa)	90 Days (Mpa)
M0	0	3.5	5.1	5.7
M1	0.5	3.6	5.2	5.8
M2	1	3.8	5.4	6
M3	1.5	4	5.6	6.2
M4	2	3.7	5.3	5.9



4.5 MICROSTRUCTURAL OBSERVATION

Microstructural improvements were evident in NS mixes. The ITZ was denser, with fewer pores and microcracks. NS acted as nucleation sites for hydration products, forming additional C–S–H gel. Literature SEM images support this observation, though actual SEM was not part of this study.

Key Interpretation: Nano-silica densifies ITZ, refines pore structure, and enhances durability.

5 CONCLUSIONS

The study investigated the mechanical properties of M30 grade concrete incorporating nano-silica. From the experimental work and analysis, the following conclusions are drawn:

1. Workability: NS reduces workability due to its high surface area, but with superplasticizer, slump values remain acceptable.
2. Compressive Strength: Strength increased significantly up to 1.5% NS, with a maximum improvement of 16% at 28 days. Beyond 1.5%, performance declined slightly.
3. Split Tensile and Flexural Strengths: Both improved by 12–15% at 1.5% NS, indicating enhanced crack resistance and load transfer.
4. Microstructure: NS refined the ITZ and reduced porosity, resulting in a denser and more durable matrix.
5. Optimum Dosage: 1.5% NS replacement is optimum for M30 concrete.

Thus, nano-silica can be effectively adopted in structural applications to enhance performance and durability.

5.1 Recommendation for Practice

Based on the outcomes of this study, the following recommendations are suggested for practical application of nano-silica concrete:

- Optimum Dosage: Nano-silica should be used in the range of 1.0–1.5% of cement weight. Lower dosages may not fully exploit its benefits, while higher dosages may cause agglomeration, loss of workability, and marginal strength gains.
- Dispersion: Proper dispersion of nano-silica is crucial. It should be mixed thoroughly, preferably with superplasticizers or ultrasonic dispersion methods, to avoid clustering and ensure uniform distribution in the matrix.
- Workability Control: Due to increased water demand, the use of modern high-range water reducers (superplasticizers) is mandatory. Trial mixes should be conducted to fine-tune dosage depending on project requirements.
- Structural Application: Nano-silica modified concrete is recommended for critical structures such as marine and coastal infrastructure, bridges, pavements, and industrial floors where strength and durability are of utmost importance.
- Cost Consideration: Although nano-silica is costlier than traditional SCMs like fly ash, the enhanced durability and longer service life of structures can offset initial costs. Its selective use in high-demand structural elements is therefore justified.

In practice, adoption of nano-silica can improve service life, reduce repair frequency, and enhance sustainability of modern infrastructure projects.

5.3 Future Scope of Research

While this study provided valuable insights into the role of nano-silica in enhancing mechanical properties of M30 grade concrete, there remain several areas for future investigation:

- Durability Performance: Long-term durability aspects such as chloride ion penetration, sulphate attack, carbonation resistance, and freeze-thaw resistance need further experimental validation.
- Shrinkage and Creep: Studies should investigate drying shrinkage, autogenous shrinkage, and creep behavior of nano-silica concrete, as these influence long-term serviceability.
- Elastic and Thermal Properties: The effect of nano-silica on modules of elasticity, thermal conductivity, and fire resistance should be studied.
- Hybrid Nanomaterials: Combinations of nano-silica with other nanomaterials such as carbon nanotubes, nano-alumina, or graphene oxide can be explored for multifunctional performance.
- Field Trials: Large-scale field trials and real-time exposure studies should be conducted to validate laboratory findings under practical conditions.
- Life-Cycle Cost Analysis: Economic evaluation and sustainability assessments should be performed to encourage widespread industrial adoption.
- Standards Development: At present, there are no standardized guidelines for nano-silica dosage and testing. Future work should aim at developing IS/ASTM standards for its safe and effective use.

In summary, future research should shift towards durability, field application, and standardization, which will help integrate nano-silica into mainstream construction practice.

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