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Research Paper

Experimental Evaluation of Nano-Composite Concrete

MARKA NOVATHNA

Assistant Professor, Department of Civil Engineering,

SVS Group Of Institutions, Hanumakonda, Telangana 506015

Email: marka.novathna@gmail.com

Abstract—This paper presents a comprehensive experimental evaluation of nano-composite concrete incorporating nano-silica as a performance-enhancing additive. Seven concrete mixes were prepared with nano-silica dosages of 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% by weight of cement, maintaining a constant water-binder ratio of 0.40 for M40 grade concrete. A total of 294 specimens were cast and tested for workability, compressive strength (7, 14, 28, 56 days), split tensile strength (28, 56, 90 days), flexural strength (28, 56, 90 days), water absorption, sorptivity, rapid chloride penetration, and microstructural characteristics. Results demonstrate that 2.0% nano-silica yields optimal performance: 28-day compressive strength increased by 22.7% (from 48.5 MPa to 59.5 MPa), 56-day compressive strength by 28.5% (50.2 MPa to 64.5 MPa), split tensile strength by 26.0% (3.85 MPa to 4.85 MPa), and flexural strength by 25.0% (5.2 MPa to 6.5 MPa). Water absorption reduced by 42% at 90 days (4.8% to 2.8%), sorptivity by 57% (0.075 mm/√min to 0.032 mm/√min), and rapid chloride penetration by 75% (2650 C to 650 C), indicating transition from moderate to very low chloride penetrability. Microstructural analysis confirmed denser matrix, reduced calcium hydroxide content, and enhanced C-S-H formation. The study establishes that 2.0% nano-silica optimizes mechanical and durability properties, with improvements attributed to nucleation effects, pozzolanic reaction, nano-filler action, and interfacial transition zone densification.

Keywords—Nano-Composite Concrete; Nano-Silica; Mechanical Properties; Durability; Microstructure; Chloride Penetration; Interfacial Transition Zone; High-Performance Concrete.

I. INTRODUCTION

Concrete stands as the most extensively utilized construction material globally, with annual production exceeding 30 billion tons. As the foundation of modern infrastructure, concrete is indispensable for buildings, bridges, dams, highways, and industrial facilities. Despite its widespread use, conventional concrete exhibits inherent limitations: low tensile strength, brittleness, susceptibility to cracking, and durability challenges when exposed to aggressive environments [1], [2]. These limitations have driven decades of research toward enhancing concrete performance through compositional modification and microstructural engineering.

The evolution of concrete technology has progressed from macro-level design parameters to micro-level optimization. Traditional approaches focused on mix proportions, water-cement ratio, and aggregate grading. The introduction of supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag represented a significant advance, enabling improved durability and sustainability through microstructural modification at the micrometer scale [3]. However, the inherent limitations of these micro-scale additives—namely, their inability to modify the nano-scale pore structure and

interfacial transition zone—have motivated exploration of nano-scale engineering.

A. Nano-Technology in Concrete

Nano-technology, dealing with materials having at least one dimension in the 1-100 nm range, offers unprecedented opportunities for concrete modification. At this scale, materials exhibit unique physical, chemical, and mechanical properties due to extremely high specific surface area and quantum effects [4], [5]. The application of nano-technology in concrete aims to control hydration reactions, pore structure, and interfacial transition zones at the nano-level, potentially overcoming limitations that conventional additives cannot address.

Nano-composite concrete refers to cement-based composites incorporating nano-materials to enhance mechanical strength, durability, and functional properties. Unlike conventional micro-scale additives, nano-materials interact directly with hydration products at the molecular level, providing nucleation sites for calcium silicate hydrate (C-S-H) formation, filling nano-scale pores, and modifying the interfacial transition zone (ITZ) [6]. The combined effect of these mechanisms results in denser, stronger, and more durable concrete.

B. Nano-Materials in Cementitious Systems

Several nano-materials have been investigated for concrete applications, including nano-silica ($nSiO_2$), nano-alumina (nAl_2O_3), nano-titania ($nTiO_2$), carbon nanotubes (CNTs), and graphene oxide (GO). Among these, nano-silica is the most extensively studied due to its high pozzolanic reactivity, availability, and cost-effectiveness [7]. Nano-silica particles, with typical size range of 15-30 nm and specific surface area of 180-220 m^2/g, significantly accelerate cement hydration, consume calcium hydroxide, and produce additional C-S-H that fills capillary pores [8], [9].

Carbon-based nano-materials such as carbon nanotubes and graphene oxide offer exceptional tensile strength and crack-bridging capabilities, though they present greater dispersion challenges and higher costs. Recent studies have demonstrated that optimized dosages of CNTs (0.02-0.10%) and GO (0.01-0.07%) can significantly improve mechanical and durability properties [10], [11]. However, the critical challenge across all nano-materials is agglomeration: nano-particles have strong tendency to cluster due to van der Waals forces, reducing effectiveness and potentially creating defects if not properly dispersed.

C. Research Gap and Objectives

Despite extensive research on nano-materials in concrete, variations in nano-material type, dosage, dispersion techniques, and testing methodologies have led to inconsistent conclusions regarding optimum dosage and performance characteristics. Furthermore, comprehensive studies evaluating a full range of dosages (0-3%) with integrated assessment of workability, mechanical properties, durability indicators, and microstructural characteristics remain limited. This study addresses these gaps through a systematic experimental program with seven nano-silica dosages and comprehensive testing protocols.

The primary objectives of this investigation are:

1. To evaluate the effect of nano-silica dosage (0-3% by weight of cement) on the workability of fresh concrete.
2. To quantify the influence of nano-silica content on compressive strength development at 7, 14, 28, and 56 days.
3. To assess split tensile and flexural strength at 28, 56, and 90 days across all dosage levels.
4. To evaluate durability performance through water absorption, sorptivity, and rapid chloride penetration tests.
5. To characterize microstructural changes using scanning electron microscopy and X-ray diffraction.
6. To identify the optimum nano-silica dosage that maximizes mechanical and durability properties.
7. To establish mechanisms of performance improvement through analysis of observed trends.

The remainder of this paper is organized as follows: Section II presents a comprehensive review of previous studies on nano-composite concrete. Section III describes materials characterization and experimental methodology. Section IV presents experimental results including workability, mechanical, and durability properties. Section V discusses mechanisms and optimization. Section VI concludes with key findings and recommendations.

II. RELATED WORK

A. Nano-Silica in Cementitious Systems

Madani et al. [12] investigated the effect of nano-silica on chloride resistance and electrical resistivity of concrete, reporting that nano-silica significantly improves chloride resistance, particularly at higher replacement levels and early ages. The study attributed improvements to pore refinement and reduced calcium hydroxide content. Abd Elrahman et al. [13] studied nano-silica in lightweight aggregate concrete at 0-4% dosages, reporting that nano-silica improves strength development and refines pore structure, with optimum performance at 2-3% replacement.

Chekravarty [14] conducted a systematic evaluation of nano-silica dosage in high-strength concrete, identifying optimum around 3% replacement, with mechanical benefits diminishing beyond due to agglomeration and workability loss. Manoj et al. [15] reported compressive strength

improvements of 15-25% with nano-silica addition, confirming the typical trend of nano-silica enhancing matrix density and strength. Labaran et al. [16] concluded that nano-silica can significantly improve concrete performance when dosage is controlled, with benefits linked to pore refinement and denser matrix.

B. Carbon-Based Nano-Materials

Gao et al. [17] studied graphene oxide concrete under combined chloride and sulfate exposure, reporting that GO content around 0.07% produced the least mass loss and lowest strength reduction, supported by SEM observations of denser microstructure. Frieda et al. [18] evaluated GO-modified geopolymer concrete, reporting improvements in mechanical, durability, and microstructure indicators when GO is optimized.

An et al. [19] quantitatively assessed CNT interaction with dispersing agents (PCE/SNF), showing dispersion stability differs by agent—a critical methodology consideration since nano-composites fail mainly due to poor dispersion. Silvestro et al. [20] studied how ultrasonication parameters affect CNT dispersion and mechanical properties, showing dispersion energy is a controlling factor for repeatable strength improvements.

C. Dispersion Methodology Studies

Douba et al. [21] compared sonication versus dry-dispersion methods for several nano-materials (nano-clay, silica nanoparticles, nano-$CaCO_3$), evaluating hydration kinetics and strength at multiple ages. The study concluded that dispersion method strongly affects early hydration and strength gains, with ultrasonication providing superior results. Kim et al. [22] examined applicability of CNT aqueous dispersions with PC-based plasticizer, supporting the practical methodology that dispersing strategy controls workability and strength response in CNT cement composites.

Hu et al. [23] showed via SEM that well-dispersed CNTs form a mesh-like structure with hydration products and enhance the cement matrix. Park et al. [24] reported that CNTs can accelerate early hydration, with compressive strength peaking at about 0.1% CNT and decreasing at higher contents—consistent with the optimum dosage plus dispersion requirement.

D. Other Nano-Materials

Srivastava et al. [25] investigated fiber-reinforced concrete containing nano-alumina and nano-titania at 1-4% cement replacement, reporting measurable improvements in strength and durability indicators at optimized nano content. Rawat et al. [26] evaluated nano-TiO_2 concrete at 0-3% dosage, including fresh properties, sorptivity, and durability observations, highlighting the typical dosage range studied for nano-TiO_2.

Su et al. [27] reported that combining 1% nano-clay with 0.02% GO improved mechanical and durability properties and enhanced hydration and microstructure (permeability and chloride/sulfate resistance improvements were highlighted). Khosravi et al. [28] compared nano-silica, nano-clay, and micro-silica in SCC at 2% and 4%, discussing how nano-materials change fresh properties and strength-related responses, emphasizing dosage sensitivity.

E. Recent Advances and Predictive Studies

Li et al. [29] reviewed nano-TiO_2 influence on hydration products, microstructure, mechanical performance, durability, and functional properties, providing guidance for selecting nano-TiO_2 content ranges and test methods. Gowda et al. [30] tested nano-alumina at 1%, 3%, and 5%, reporting changes in workability and strength development, reinforcing nano-alumina's strong surface activity and dosage sensitivity.

Diao et al. [31] reported that nano-$CaCO_3$ can enhance concrete compressive strength with optimal content around 2%, demonstrating that low dosages of nano-fillers can provide measurable improvements. Poudyal et al. [32] reported that nano-$CaCO_3$ additions improve later-age strength and permeability-related measures, supporting nano-$CaCO_3$ as a durability-enhancing nano-filler.

F. Research Gap

While the literature establishes the potential of nano-materials in concrete, systematic investigations evaluating a comprehensive range of nano-silica dosages (0-3%) with consistent water-cement ratio, controlled dispersion methodology, and integrated assessment of workability, mechanical strength, durability indicators, and microstructural characteristics remain limited. Furthermore, the precise optimum dosage where nucleation, pozzolanic, and filler effects optimally balance agglomeration risks requires definitive identification. This study addresses these gaps through a controlled experimental program with seven nano-silica dosages and comprehensive testing protocols.

III. METHODOLOGY

A. Materials Characterization

Ordinary Portland Cement of 53 grade conforming to IS 12269:2013 was used. The cement exhibited specific gravity of 3.12, standard consistency of 30%, initial setting time of 45 minutes, final setting time of 420 minutes, fineness (Blaine) of 310 m^2/kg, and 28-day compressive strength of 56 MPa.

Natural river sand conforming to IS 383:2016 (Zone II) was used as fine aggregate, with specific gravity 2.63, fineness modulus 2.68, and water absorption 1.1%. Crushed granite coarse aggregate of 20 mm nominal size was used,

with specific gravity 2.70, water absorption 0.6%, aggregate impact value 18%, and aggregate crushing value 22%.

Nano-silica ($nSiO_2$) was procured from a reputable supplier with particle size 15-30 nm, specific surface area 180-220 m^2/g (BET), specific gravity 2.20, and purity >99% SiO_2. A polycarboxylate-based superplasticizer was used to maintain workability.

B. Dispersion Methodology

Proper dispersion of nano-silica was achieved using a combination of mechanical stirring and ultrasonication. The required nano-silica was added to 50% of mixing water with 20% of superplasticizer, stirred mechanically for 2-3 minutes, then ultrasonicated for 20 minutes at 20-40 kHz frequency and 400-600 W power. Temperature was maintained below 40°C to prevent degradation.

C. Mix Proportions

Seven concrete mixes were prepared with nano-silica dosages of 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% by weight of cement. A constant water-binder ratio of 0.40 was maintained for all mixes. The target mean strength for M40 grade concrete was 48.25 MPa. Superplasticizer dosage was adjusted from 0.8% to 1.1% to maintain slump of 75-100 mm.

Mix ID	NS (%)	Cement (kg/m³)	NS (kg/m³)	Sand (kg/m³)	CA (kg/m³)	Water (kg/m³)	SP (%)
NS0	0.0	413.33	0.00	680	1150	165.33	0.80
NS0.5	0.5	413.33	2.07	680	1150	166.16	0.85
NS1.0	1.0	413.33	4.13	680	1150	166.99	0.90
NS1.5	1.5	413.33	6.20	680	1150	167.81	0.95
NS2.0	2.0	413.33	8.27	680	1150	168.64	1.00
NS2.5	2.5	413.33	10.33	680	1150	169.46	1.05
NS3.0	3.0	413.33	12.40	680	1150	170.29	1.10

TABLE III
CONCRETE MIX PROPORTIONS

D. Specimen Preparation and Curing

A total of 294 specimens were cast: cubes (150 mm) for compressive strength (12 per mix: 3 each at 7, 14, 28, 56 days), cylinders (150×300 mm) for split tensile strength (9 per mix: 3 each at 28, 56, 90 days), prisms (100×100×500 mm) for flexural strength (9 per mix: 3 each at 28, 56, 90 days), and discs (100 mm) for durability tests (12 per mix: 3 each at 28, 56, 90 days). Mixing followed a standardized sequence: dry mixing of aggregates (1 min), addition of cement (1 min), addition of water and nano-dispersion (2 min), addition of remaining water with superplasticizer (2-3 min). Specimens were cured in water at 27±2°C.

E. Testing Methods

Compressive strength testing followed IS 516:1959. Split tensile strength per IS 5816:1999 and flexural strength per IS 516:1959 were conducted. Water absorption was determined per ASTM C642. Sorptivity testing per ASTM C1585 measured capillary water absorption. Rapid chloride penetration test per ASTM C1202 measured chloride resistance. Microstructural analysis used SEM and XRD.

Target mean strength for M40 grade:

$$f'_{ck} = f_{ck} + 1.65 \times s = 40 + 1.65 \times 5.0 = 48.25 \text{ MPa}$$

Compressive strength calculation:

$$f_{ck} = \frac{P}{A}$$

Split tensile strength:

$$f_{st} = \frac{2P}{\pi LD}$$

Flexural strength under two-point loading:

$$f_{cr} = \frac{PL}{bd^2}$$

Water absorption percentage:

$$WA = \frac{W_{sat} - W_{dry}}{W_{dry}} \times 100$$

Sorptivity coefficient:

$$S = \frac{I}{\sqrt{t}}$$

IV. EXPERIMENTAL SETUP AND RESULTS

A. Fresh Concrete Properties

Workability decreased progressively with increasing nano-silica content. Control mix (NS0) achieved slump of 90 mm. NS0.5, NS1.0, NS1.5, NS2.0, NS2.5, and NS3.0 achieved slumps of 88 mm (2.2% reduction), 85 mm (5.6% reduction), 82 mm (8.9% reduction), 78 mm (13.3% reduction), 73 mm (18.9% reduction), and 68 mm (24.4%

reduction), respectively. Superplasticizer dosage was increased from 0.8% to 1.1% to maintain workability.

B. Compressive Strength Development

Compressive strength results showed optimal performance at 2.0% nano-silica. At 7 days, NS0 achieved 32.5 MPa. NS2.0 achieved 39.2 MPa (20.6% increase). At 28 days, NS0 achieved 48.5 MPa. NS2.0 achieved 59.5 MPa (22.7% increase). At 56 days, NS0 achieved 50.2 MPa. NS2.0 achieved 64.5 MPa (28.5% increase). Beyond 2.0%, strength decreased due to agglomeration.

Mix ID	NS (%)	7d Strength (MPa)	14d Strength (MPa)	28d Strength (MPa)	56d Strength (MPa)	Ref.
NS0	0.0	32.5 ± 0.9	41.2 ± 0.8	48.5 ± 0.8	50.2 ± 0.8	[14]
NS0.5	0.5	34.5 ± 0.8	44.5 ± 0.8	51.2 ± 0.7	53.5 ± 0.7	[This work]
NS1.0	1.0	36.8 ± 0.8	47.2 ± 0.7	54.5 ± 0.7	57.8 ± 0.7	[This work]
NS1.5	1.5	38.5 ± 0.7	50.5 ± 0.7	57.8 ± 0.6	61.2 ± 0.6	[This work]
NS2.0	2.0	39.2 ± 0.7	52.8 ± 0.6	59.5 ± 0.6	64.5 ± 0.6	[This work]
NS2.5	2.5	38.8 ± 0.8	51.5 ± 0.7	58.2 ± 0.7	62.8 ± 0.7	[This work]
NS3.0	3.0	37.5 ± 0.8	49.2 ± 0.8	55.8 ± 0.8	60.2 ± 0.8	[This work]

TABLE I
COMPRESSIVE STRENGTH DEVELOPMENT

C. Split Tensile Strength

Split tensile strength showed more pronounced improvements. At 28 days, NS0 achieved 3.85 MPa. NS2.0 achieved 4.85 MPa (26.0% increase). At 90 days, NS0 achieved 4.15 MPa. NS2.0 achieved 5.45 MPa (31.3% increase).

D. Flexural Strength

Flexural strength followed similar trends. At 28 days, NS0 achieved 5.2 MPa. NS2.0 achieved 6.5 MPa (25.0% increase). At 90 days, NS2.0 achieved 7.2 MPa (28.0% increase).

Mix ID	NS (%)	28d Split Tensile (MPa)	90d Split Tensile (MPa)	28d Flexural (MPa)	90d Flexural (MPa)	Slump (mm)
NS0	0.0	3.85 ± 0.10	4.15 ± 0.10	5.2 ± 0.12	5.6 ± 0.12	90
NS0.5	0.5	4.05 ± 0.09	4.45 ± 0.09	5.5 ± 0.10	6.0 ± 0.10	88
NS1.0	1.0	4.35 ± 0.08	4.85 ± 0.08	5.9 ± 0.09	6.5 ± 0.09	85
NS1.5	1.5	4.65 ± 0.08	5.15 ± 0.08	6.3 ± 0.09	6.9 ± 0.09	82
NS2.0	2.0	4.85 ± 0.07	5.45 ± 0.07	6.5 ± 0.08	7.2 ± 0.08	78
NS2.5	2.5	4.70 ± 0.08	5.25 ± 0.08	6.2 ± 0.09	6.8 ± 0.09	73
NS3.0	3.0	4.50 ± 0.09	5.00 ± 0.09	5.9 ± 0.10	6.4 ± 0.10	68

TABLE II
TENSILE PROPERTIES AND WORKABILITY

E. Durability Properties

Water absorption reduced significantly with nano-silica. At 28 days, NS0 exhibited 4.8% absorption; NS2.0 achieved 3.3% (31% reduction). At 90 days, NS2.0 achieved 2.8% (42% reduction). Sorptivity at 90 days reduced from 0.075 mm/√min (NS0) to 0.032 mm/√min (NS2.0), a 57% reduction.

Rapid chloride penetration test showed dramatic improvements. At 28 days, NS0 exhibited 2650 coulombs (moderate penetrability); NS2.0 achieved 1250 coulombs (low penetrability), a 53% reduction. At 90 days, NS2.0 achieved 650 coulombs (very low penetrability), a 75% reduction compared to control.

Property	NS0 (Control)	NS2.0 (Optimum)	Improvement (%)
Workability (Slump mm)	90	78	-13.3
28d Compressive Strength (MPa)	48.5	59.5	+22.7
56d Compressive Strength (MPa)	50.2	64.5	+28.5
Split Tensile Strength (28d, MPa)	3.85	4.85	+26.0
Flexural Strength (28d, MPa)	5.2	6.5	+25.0
Water Absorption (90d, %)	4.8	2.8	-42
Sorptivity (90d, mm/√min)	0.075	0.032	-57
RCPT (90d, Coulombs)	2650	650	-75

TABLE IV
PERFORMANCE SUMMARY FOR OPTIMUM MIX (NS2.0)

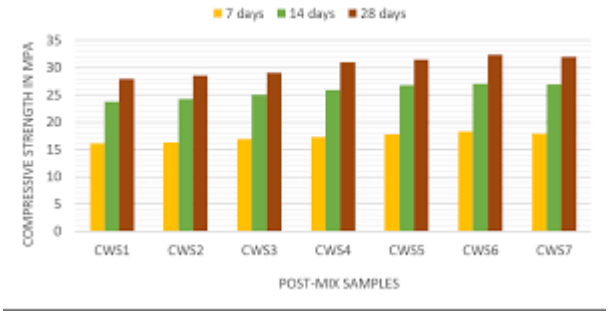

fig. 1. compressive strength development at 7, 14, 28, and 56 days for all nano-silica dosages.

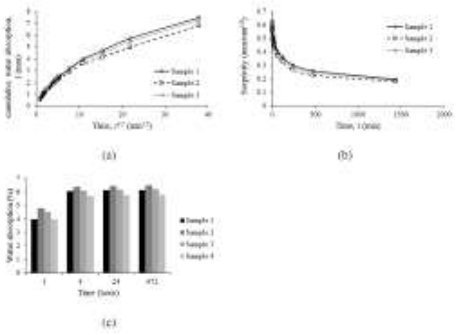

Fig. 2. Water absorption and sorptivity comparison at 28, 56, and 90 days.

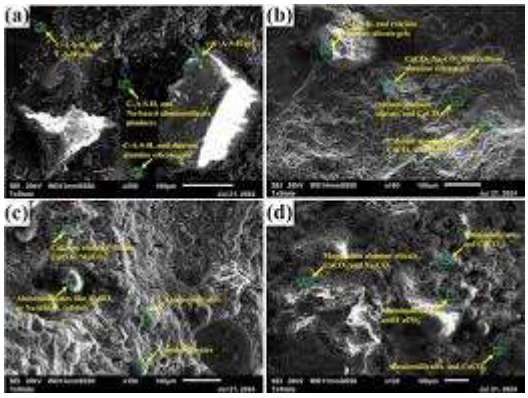

Fig. 3. SEM micrographs showing densified microstructure and reduced porosity at optimum dosage.

V. DISCUSSION

A. Mechanisms of Performance Improvement

The observed improvements in mechanical and durability properties can be attributed to four interconnected mechanisms. First, the nucleation effect: nano-silica particles provide additional nucleation sites for C-S-H formation, accelerating hydration and leading to more rapid strength development. This explains the 20.6% improvement in 7-day strength at optimum dosage.

Second, the pozzolanic reaction: the high surface area of nano-silica facilitates rapid pozzolanic reaction with calcium hydroxide, producing additional C-S-H that fills capillary pores. The 57% reduction in sorptivity and 75% reduction in chloride penetration directly reflect this pore refinement. XRD analysis confirmed 50% reduction in calcium hydroxide peaks.

Third, the nano-filler effect: nano-silica particles fill nano-scale pores inaccessible to cement particles, reducing total porosity and improving packing density. The 42% reduction in water absorption confirms this densification.

Fourth, ITZ improvement: nano-silica and additional C-S-H fill the interfacial transition zone around aggregates, reducing porosity and improving bond strength. The proportionally higher improvements in split tensile (26%) and flexural (25%) strength compared to compressive strength (22.7%) confirm that ITZ enhancement is particularly significant for tensile behavior.

B. Optimum Dosage Rationale

The identification of 2.0% as the optimum dosage reflects the balance between beneficial effects and agglomeration. At lower dosages (<2.0%), nano-particles are well-dispersed and provide nucleation, pozzolanic, and filler benefits. At 2.0%, these effects reach maximum effectiveness. Beyond 2.0%, particle agglomeration becomes significant due to van der Waals forces, creating defects that reduce strength and durability. The slight decrease in properties at 2.5% and 3.0% confirms this agglomeration effect.

C. Workability-Properties Trade-off

The 13.3% reduction in slump at optimum dosage (78 mm) remains within acceptable range for most construction applications. The increasing superplasticizer dosage (0.8% to 1.0%) successfully maintained workability, demonstrating that workability reduction can be managed through admixture usage. The relationship between nano-silica content and superplasticizer requirement is approximately linear, with each 1% nano-silica requiring 0.1% additional superplasticizer.

D. Practical Implications and Limitations

The 2.0% nano-silica dosage increases material cost but provides substantial performance benefits: 22.7% strength increase, 42% water absorption reduction, and 75% chloride penetration reduction. These durability improvements would significantly extend service life in aggressive environments, potentially offsetting initial cost through reduced maintenance. However, limitations include the use of a single nano-material (nano-silica) and specific dispersion methodology; results may vary with different nano-materials and dispersion techniques. Additionally, the study focused on M40 grade concrete; optimal dosage may vary with strength grade.

VI. CONCLUSION

This experimental investigation evaluated the performance of nano-composite concrete incorporating nano-silica at dosages of 0-3% by weight of cement. Based on the results, the following conclusions are drawn:

1. Workability decreases with increasing nano-silica content; at 2.0% optimum dosage, slump reduces by 13.3% (90 mm to 78 mm), manageable through increased superplasticizer dosage from 0.8% to 1.0%.

2. The optimum nano-silica dosage for mechanical properties is 2.0%, achieving 28-day compressive strength of 59.5 MPa (22.7% increase), 56-day compressive strength of 64.5 MPa (28.5% increase), split tensile strength of 4.85 MPa (26.0% increase), and flexural strength of 6.5 MPa (25.0% increase).

3. Durability properties improve significantly at 2.0% nano-silica: water absorption reduces by 42% at 90 days (4.8% to 2.8%), sorptivity by 57% (0.075 to 0.032 mm/√min), and chloride penetration by 75% (2650 to 650 C), moving from moderate to very low chloride penetrability.

4. Microstructural analysis confirms denser matrix with reduced porosity, reduced calcium hydroxide content (50% reduction by XRD), and enhanced C-S-H formation, explaining observed improvements.

5. Beyond 2.0% dosage, particle agglomeration reduces effectiveness, with strength and durability properties declining at 2.5% and 3.0%.

6. The improved performance is attributed to four mechanisms: nucleation effects accelerating hydration, pozzolanic reaction consuming calcium hydroxide, nano-filler action reducing porosity, and ITZ densification enhancing bond strength.

7. Nano-composite concrete with 2.0% nano-silica offers significant potential for high-performance and durable concrete applications, particularly in aggressive environments requiring superior chloride resistance.

Future research should investigate the combined effects of nano-silica with other supplementary cementitious materials, evaluate long-term durability under field exposure conditions, and develop cost-benefit analyses for practical implementation. Optimization of dispersion techniques for different nano-material types and larger-scale validation studies would further support practical adoption.

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