



Original Research Article

Examining the Use of Nano-Silica Modified Self-Compacting Concrete in High-Rise Buildings

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ABSTRACT

The increasing height of modern structures requires concrete with superior workability, strength, and durability. This study evaluates the influence of nano-silica (NS) on the performance of self-compacting concrete (SCC) intended for high-rise building applications. Four SCC mixes containing 0%, 1%, 2%, and 3% nano-silica by weight of cement were prepared and tested for fresh properties, mechanical strength, durability, and time-dependent behavior following EFNARC and ASTM standards. Results show that incorporating nano-silica significantly improves SCC performance up to an optimum dosage of 2%. At this level, slump flow reached 705 mm, the L-box ratio improved to 0.90, and the 28-day compressive strength increased to 55.9 MPa, representing a 21% improvement compared with the control mix. Durability indicators also improved substantially, with chloride permeability reduced by 28%, freeze-thaw mass loss reduced by 34%, and water absorption reduced by 20%. Time-dependent properties, including drying shrinkage and creep were also reduced. However, increasing nano-silica to 3% resulted in marginal reductions in workability and strength, attributed to particle agglomeration and increased water demand. The findings demonstrate that nano-silica enhances SCC performance through accelerated hydration, formation of additional C-S-H gel, and refinement of pore structure. Statistical validation yielded a strong correlation between nano-silica dosage and performance parameters ($R^2 = 0.93$). The study concludes that 2% nano-silica provides the optimal balance between workability, mechanical performance, and durability, making nano-silica-modified SCC a promising material for high-rise construction.

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1. INTRODUCTION

Rapid urbanization has driven the global trend toward vertical construction, increasing the demand for advanced construction materials capable of sustaining higher structural loads and complex architectural

geometries (Okamura and Ouchi, 2003; Sanchez and Sobolev, 2010). Concrete used in high-rise buildings must simultaneously satisfy requirements for high flowability, structural strength, durability, and dimensional stability, particularly in heavily reinforced structural elements where conventional vibration becomes impractical (Okamura and Ouchi, 2003).

Self-compacting concrete (SCC), first introduced by Okamura and Ouchi (2003), was developed to overcome placement difficulties in congested reinforcement zones by allowing concrete to flow and consolidate under its own weight. SCC has since been widely adopted in high-rise construction due to its excellent filling ability, reduced labour requirements, and improved surface finish. However, maintaining an optimal balance between workability, strength development, and long-term durability remains a major challenge in SCC design (Güneyisi et al., 2013).

The high paste content typically required in SCC mixtures may increase porosity and shrinkage, potentially compromising durability and long-term structural performance (Georgy et al., 2017). These challenges are particularly significant in tall structures where cumulative deformation, chloride ingress, and environmental exposure can significantly influence service life (Güneyisi et al., 2013; Kong et al., 2012).

Recent advances in nanotechnology have introduced nano-materials as effective modifiers of cementitious composites. Among these materials, nano-silica (SiO_2 nanoparticles) has gained significant attention due to its high surface area and strong pozzolanic reactivity (Sanchez and Sobolev, 2010). Nano-silica accelerates cement hydration, consumes calcium hydroxide, and promotes the formation of additional calcium-silicate-hydrate (C-S-H) gel, resulting in a denser microstructure and improved mechanical performance (Qing et al., 2007; Zhang et al., 2012).

Du et al. (2014) and Jalal et al. (2015) reported improved compressive strength, permeability resistance, and microstructural densification in nano-silica modified concrete. Nevertheless, the effectiveness of nano-silica is strongly dosage dependent, as excessive nanoparticle content may lead to agglomeration and increased water demand, which negatively affects workability (Kong et al., 2012; Sadrmomtazi et al., 2016).

Despite growing research on nano-modified concrete, relatively few studies have investigated the integrated performance of nano-silica modified SCC within the specific context of high-rise structural applications, where pumpability, durability, and time-dependent deformation play critical roles.

Therefore, this study aims to systematically evaluate the effect of nano-silica on the fresh properties, mechanical performance, durability characteristics, and time-dependent behavior of SCC. By linking experimental results with hydration kinetics and microstructural evolution, the study seeks to identify an optimal nano-silica dosage that enhances both material performance and structural reliability in high-rise construction.

2. MATERIALS AND METHODS

2.1. Materials

The materials used include:

- i. Ordinary Portland Cement (ASTM C150)
- ii. Fine and coarse aggregates (ASTM C33)
- iii. Nano-silica particles
- iv. Polycarboxylate superplasticizer
- v. Potable mixing water

The water-cement ratio ranged from 0.35–0.40.

2.2. Experimental Design

A controlled laboratory experiment was conducted to evaluate SCC mixes containing 0%, 1%, 2%, and 3% nano-silica by weight of cement. Testing was conducted over 28 days, representing the standard age for structural concrete evaluation.

2.3. Fresh Concrete Testing

Fresh properties were evaluated using the Slump flow test, V-funnel test, and L-box test. These tests measure flowability, viscosity, and passing ability in accordance with EFNARC (2005) guidelines.

2.4. Mechanical Strength Testing

Mechanical properties evaluated include compressive strength (ASTM C39), flexural strength, and splitting tensile strength. The tests were conducted at 7 and 28 days.

2.5. Durability Testing

Durability indicators assessed include rapid chloride penetration (RCPT), freeze–thaw resistance, water absorption, and sulphate expansion.

3. RESULTS AND DISCUSSION

3.1. Fresh Properties

The fresh performance results presented in Table 1 indicate that nano-silica incorporation significantly influences the rheological behavior of SCC. Slump flow increased from 690 mm in the control mix to 705 mm at 2% nano-silica, demonstrating improved flowability and particle lubrication within the cementitious matrix. Similarly, the L-box ratio improved from 0.86 to 0.90, indicating enhanced passing ability through simulated reinforcement. The improvement in rheological behaviour can be attributed to the filler effect of nano-silica particles, which improves particle packing density and reduces inter-particle friction (Kong et al., 2012).

Table 1: Fresh properties and rheological behaviour of nano-silica modified SCC

Mix ID	NS (%)	Slump Flow (mm)	V-Funnel (s)	L-Box (h_2/h_1)	Segregation index (%)
M0	0	690	10.8	0.86	10.2
M1	1	700	9.9	0.88	9.1
M2	2	705	9.4	0.90	8.3
M3	3	680	10.6	0.87	9.6

As illustrated in Figure 1, workability improved progressively up to 2% nano-silica, beyond which slump flow decreased to 680 mm at 3% nano-silica. This reduction is attributed to increased surface area and nanoparticle agglomeration, which increases water demand and reduces flowability. Similar observations have been reported by Li et al. (2015) and Abd Elrahman and Hillemeier (2014).

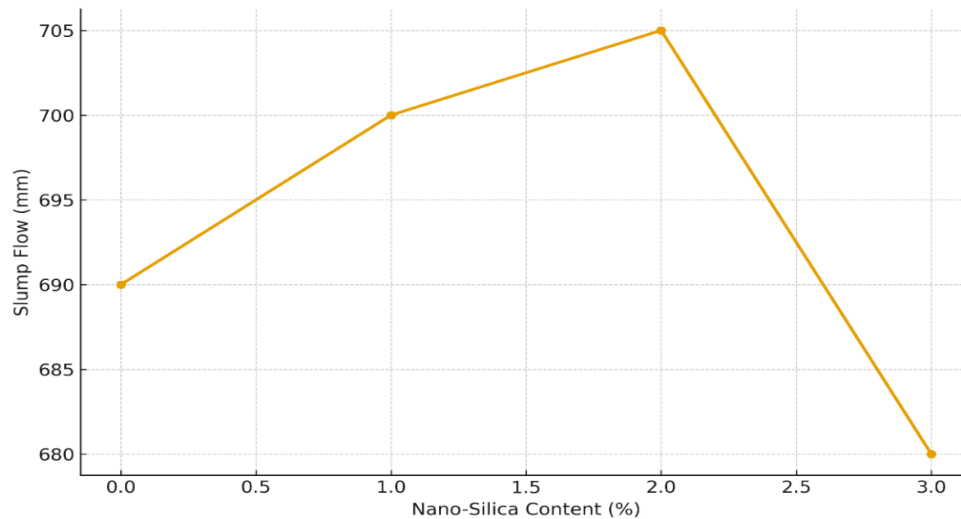


Figure 1: Variation of slump flow with nano-silica content

3.2. Mechanical Strength Development

Mechanical strength results presented in Table 2 demonstrate significant improvement with nano-silica addition. The 28-day compressive strength increased from 46.2 MPa (control) to 55.9 MPa at 2% nano-silica, representing a 21% increase, as illustrated in Figure 2. Similar improvements were observed for tensile strength and flexural strength. The strength enhancement is attributed to the pozzolanic reaction between nano-silica and calcium hydroxide, the nucleation effect accelerating hydration reactions, and the micro-filler effect refining pore structure. These mechanisms have also been reported by Qing et al. (2007) and Jalal et al. (2015).

Table 2: Mechanical strength development

Mix ID	NS (%)	fc,7days (MPa)	fc,28days (MPa)	ft,28days (MPa)	ff,28days (MPa)	Es (GPa)
M0	0	33.8	46.2	3.55	6.10	29.8
M1	1	38.9	51.8	3.92	6.55	31.1
M2	2	42.7	55.9	4.18	6.92	32.4
M3	3	41.5	54.6	4.10	6.80	32.0

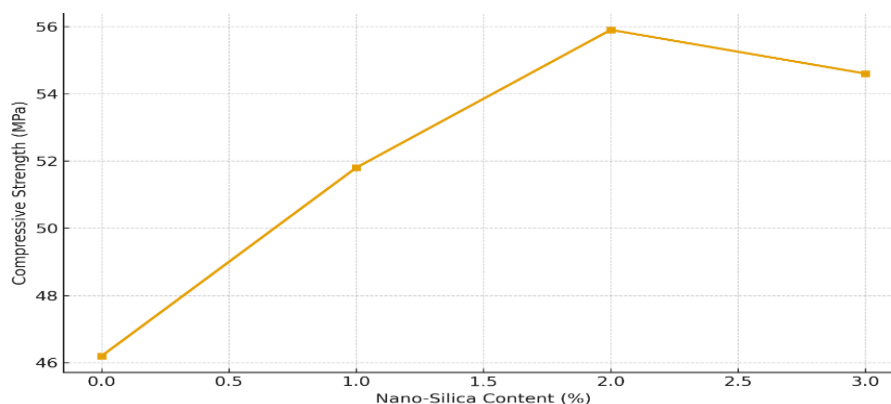


Figure 2: Compressive strength development with nano-silica content

At 3% nano-silica, a slight reduction in strength occurred due to nanoparticle agglomeration, which reduces effective dispersion in the cement matrix. The trend is consistent with the behavior shown in Figure 3.

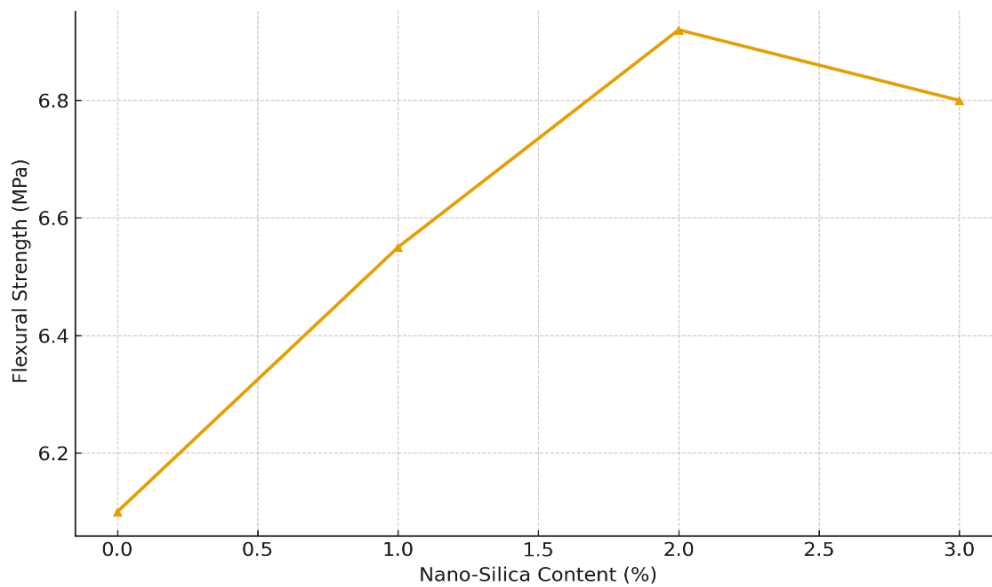


Figure 3: Flexural strength development with nano-silica content

3.3. Durability Performance

Durability results presented in Table 3 indicate substantial improvements with nano-silica incorporation. Rapid chloride penetration decreased from 2050 Coulombs in the control mix to 1480 Coulombs at 2% nano-silica, representing a 28% reduction in permeability. Similarly, water absorption decreased from 4.5% to 3.6%, freeze–thaw mass loss reduced from 1.24% to 0.82%, and dynamic modulus retention increased from 86% to 93%. These improvements are illustrated in Figure 4, which shows reduced freeze–thaw deterioration with increasing nano-silica content.

Table 3: Durability performance

Mix ID	NS (%)	RCPT (Coulombs)	Chloride depth (mm)	Water absorption (%)	Freeze-thaw mass loss (%)	Dynamic modulus retention (%)	Sulphate expansion (%)
M0	0	2050	13.2	4.5	1.24	86	0.072
M1	1	1720	10.6	4.0	0.96	90	0.060
M2	2	1480	9.0	3.6	0.82	93	0.053
M3	3	1520	9.4	3.7	0.85	92	0.055

The improved durability is attributed to microstructural densification and reduced pore connectivity, which restrict the penetration of aggressive agents (Du et al., 2014; Tufekcioglu et al., 2020).

3.4. Time-Dependent Behavior

Table 4 shows the influence of nano-silica on drying shrinkage and creep compliance. Drying shrinkage decreased from 610 microstrain in the control mix to 560 microstrain at 2% nano-silica, while creep compliance reduced from 1.72 to 1.60. These reductions are significant for high-rise structures where cumulative deformation can affect serviceability. The improvement is attributed to refinement of the interfacial transition zone and reduced capillary porosity, consistent with findings by Beigi et al. (2013). As shown in Figure 5, the minimum shrinkage occurred at 2% nano-silica, confirming the optimal dosage.

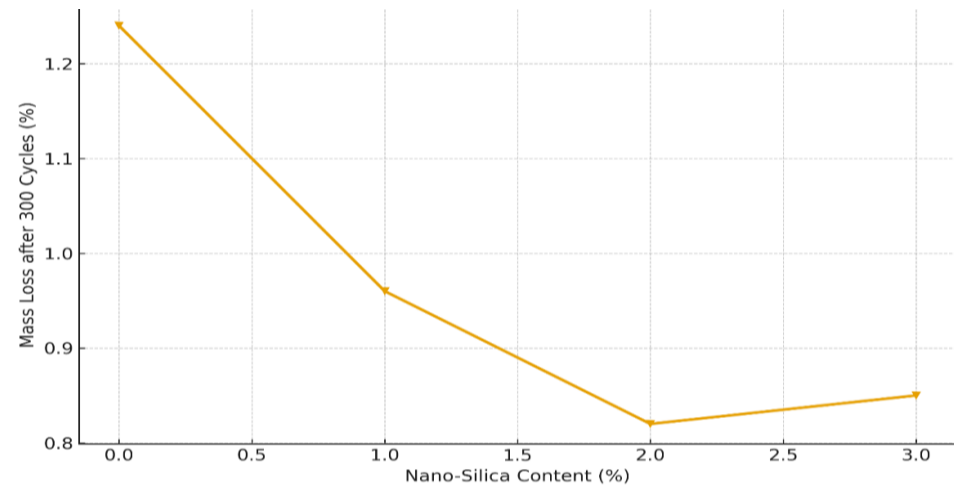


Figure 4: Freezing-thaw resistance versus nano-silica content

Table 4: Time-dependent behaviour

Mix ID	NS (%)	Shrinkage ($\mu\epsilon$, 28d)	Creep Compliance ($\times 10^{-6}$ MPa $^{-1}$)	Pump Pressure (MPa)
M0	0	610	1.72	3.2
M1	1	585	1.66	3.1
M2	2	560	1.60	3.0
M3	3	575	1.61	3.3

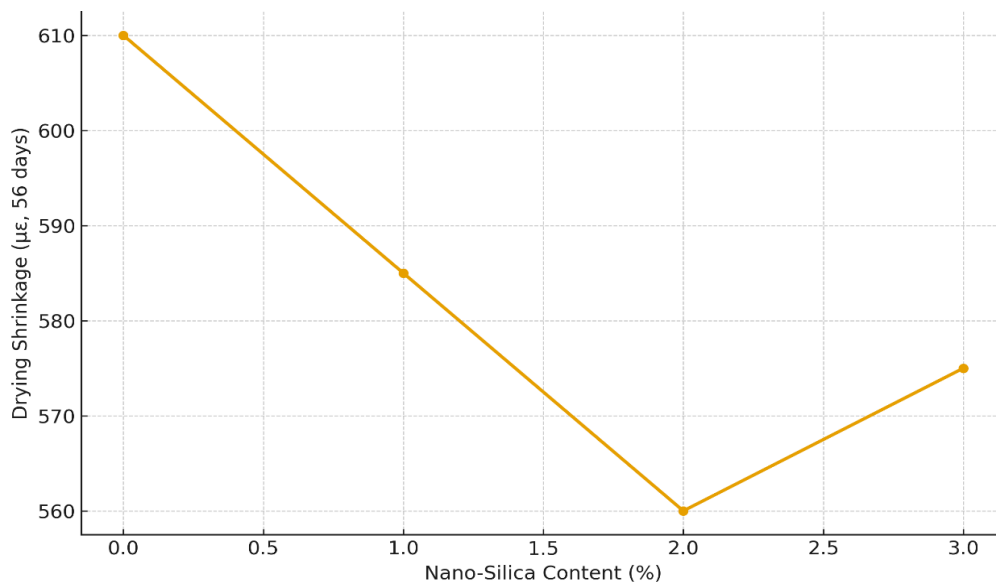


Figure 5: Drying shrinkage versus nano-silica content

4. CONCLUSION

This study investigated the influence of nano-silica on the performance of self-compacting concrete intended for high-rise structural applications. Experimental results demonstrate that nano-silica significantly enhances SCC performance by improving workability, mechanical strength, durability, and dimensional stability. Among the investigated mixtures, 2% nano-silica by weight of cement was identified as the optimal dosage, producing the highest compressive strength, improved durability

indicators, and reduced time-dependent deformation. The improved performance is attributed to accelerated hydration reactions, increased formation of C–S–H gel, and refinement of the pore structure. These microstructural improvements contribute to enhanced mechanical performance and reduced permeability.

The findings confirm that nano-silica modified SCC offers a high-performance and durable material suitable for high-rise construction, capable of improving long-term structural reliability and service life. Future research should focus on long-term durability evaluation beyond 28 days, field-scale validation in real high-rise construction projects, and hybrid nano-modified systems combining nano-silica with supplementary cementitious materials to further enhance SCC performance in large-scale infrastructure.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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