Research Article

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Influence of Nano-SiO_2 and Nano-TiO_2 on Self-Compacting Concrete: A Study of Rheology and Strength Improvement

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ABSTRACT

Self-Compacting Concrete (SCC), known as advanced concrete, flows and consolidates under its own weight, even in confined or congested spaces, without mechanical vibration. This study examines the impact of using nanoparticles, namely Nano-Silica (N-SiO_2) and Nano-Titanium Dioxide (N-TiO_2), as a partial replacement for cement in SCC. Six mix variations were created with different quantities of N-SiO_2 and N-TiO_2, and their fresh and hardened characteristics were tested. Fresh-state tests, such as slump flow, V-funnel, and L-box, proved the good workability and passing ability of all mixtures, which met EFNARC 2005 requirements. The combination of 6% N-SiO_2 and 4% N-TiO_2 performed best in terms of mechanical strength. SEM studies demonstrated that the optimized mix had better particle packing, fewer voids, and a greater density. Water absorption tests revealed enhanced durability and lower permeability. The findings indicated that the use of nanoparticles enhances the flowability, strength, and durability of nano-modified SCC.

Keywords: Nano silica (N-SiO_2); Nano titanium dioxide (N-TiO_2); Self-Compacting Concrete (SCC); Admixtures.

1. INTRODUCTION

Nowadays, the prominent concern revolves around the phenomena of global warming and the consequential environmental degradation. one metric tonne of cement, which results in the emission of an equivalent quantity of carbon dioxide (CO_2), a highly potent greenhouse gas that contributes to the phenomenon of global warming (Praveen *et al.* 2023). One potential strategy for mitigating this environmental issue involves the reduction of cement consumption or manufacture. Since cement is a fundamental constituent utilized in the building sector, it becomes imperative to identify a suitable alternative material for its substitution (Mosaberpanah *et al.* 2020).

SCC is a unique type of concrete characterized by its fluid fluidity, enabling it to flow effortlessly without requiring external vibration or compaction during installation in the formwork (Safiuddin *et al.* 2011; Jalal *et al.* 2013; Joshaghani *et al.* 2020). Since the early 1980s, the global use of SCC has been prevalent due to its beneficial manufacturing attributes. This specific form of concrete signifies a notable progression in concrete technology. It is distinguished by its superior qualities and outstanding performance, which have significantly influenced both the economic and environmental dimensions of the construction industry during the past two decades. This particular kind of concrete represents a significant advancement in concrete technology. The construction sector has seen substantial developments and outstanding accomplishments in the previous two decades, mostly due to the exceptional performance and advanced characteristics of this business. These features have profoundly impacted both the economic and environmental aspects of the sector (Hossain *et al.* 2010; Vejmelková *et al.* 2011; Uysal *et al.* 2011)

The advancement of nanotechnology has led to the significant utilization of nanomaterials in our lives. The utilization of nanomaterials to enhance concrete has garnered significant attention (Nazari *et al.* 2010; Hanus *et al.* 2013). Recently, the incorporation of nano-materials, including nano aluminium oxide, nano-silica and nano-TiO_2 has attracted interest in the enhancement of SCC characteristics (Chinthakunta *et al.* 2021). Nano-silica (N-SiO_2) is highly reactive in the cement matrix, filling micro-voids, reducing porosity, and facilitating the formation of additional calcium silicate hydrate (C-S-H). This is essential for increasing the compressive strength and durability of concrete as a result of its extremely fine particle size (Althoey *et al.* 2023). Research indicates that the pozzolanic reaction of N-SiO_2 with calcium hydroxide fortifies the internal structure of concrete, resulting in improved performance (Li *et al.*

2006; Nazari *et al.* 2011; Zhang *et al.* 2011; Riahi *et al.* 2011; Singh *et al.* 2013; Chithra *et al.* 2016). N-SiO_2 concrete exhibits lower water absorption, capillary absorption, and water permeability comparable to traditional concrete (Sanchez *et al.* 2010; Zhang *et al.* 2011).

Nano-titanium dioxide (N-TiO_2) is a potential addition that offers distinct benefits. Addition to adding to SCC's strength and durability, N-TiO_2 enhances the strength and durability of concrete/mortar while also providing photocatalytic qualities (Paz *et al.* 1995; Wang *et al.* 1998; Ichiura *et al.* 2003; Furumura *et al.* 2006; Chen *et al.* 2009). The wide application of photocatalytic materials in building and construction materials is made possible by developments in their research. The strong binding capacity of cementitious materials has attracted interest as an efficient support medium for N-TiO_2 since it firmly immobilizes the nano-powders inside their matrix. Hardened cement pastes or mortar's porous structure allows for the incorporation of TiO_2 particles and promotes photo-oxidation processes. TiO_2-based photocatalytic cementitious materials have several applications, including self-cleaning surfaces, self-disinfection, and air pollution mitigation (Yuranova *et al.* 2007; Maggos *et al.* 2007; Rawat *et al.* 2022).

Previous research has indicated that N-TiO_2 can react with hydration products to produce gel-like materials, hence improving the early strength of concrete. This suggests that it performs similarly to N-SiO_2 (Yang *et al.* 2015; Mohseni *et al.* 2015). This research aims to develop SCC mixtures using various concentrations of nano-silica (N-SiO_2) and nano-titanium dioxide (N-TiO_2) to assess the synergistic impacts of these modified nanomaterials on strength and durability properties.

1.1 Novelty of the Research

This work investigates the unique incorporation of nano-silica (SiO_2) and nano-titanium (TiO_2) into SCC to improve its rheological and mechanical characteristics. This research explores the dual effects of nanoparticles, utilizing their high specific surface area and pozzolanic reactivity, in contrast to conventional SCC enhancement approaches. The study investigates the connection between nano-SiO_2 and nano-TiO_2 in enhancing flowability, passing ability, and segregation resistance. This study gives a thorough assessment, filling gaps in current research and enhancing sustainable construction techniques

2. MATERIALS AND METHODOLOGY

2.1 Cement

The utilization of Ordinary Portland Cement (OPC) 53 grade is in accordance with the specifications given in BIS 12269. During the course of the experiment, a singular batch of ultra-tech cement is employed. The evaluation of various properties of cement is conducted in accordance with the Indian standard code. The fineness and specific gravity were measured to be 8% and 3.16, respectively. The periods for the initial and final setting durations were determined to be 87 and 242 minutes, respectively.

2.2 Aggregates

The grading of SCC is a crucial aspect that contributes to its overall significance. The fine aggregate utilized in SCC must possess a suitable grading to achieve the lowest possible voids ratio. Additionally, it should be devoid of any harmful substances such as clay, silt, and chloride contaminants. The present study utilizes river sand that is readily accessible within the local area. The river sand's specific gravity was ascertained to be 2.62, and its grade has been validated as zone II in accordance with the guidelines specified in IS 383. The control concrete was limited to an acceptable coarse aggregate size of 20 mm, whereas the SCC had a maximum aggregate size of 12.5 mm. The specific gravity was determined to be 2.67.

2.3 Nano Silica (N- SiO_2)

N-SiO_2 a highly reactive form of silica that enhances the performance of cementitious materials. It reacts with calcium hydroxide generated during cement hydration, forming supplementary calcium silicate hydrate (C-S-H), which strengthens and compacts the concrete. Its micro size enables it to occupy micro-voids within the cement matrix, hence decreasing porosity and improving the durability and overall efficacy of concrete. A Sample of N-SiO_2 is depicted in Fig.1(a).

2.4 Nano Titanium Dioxide (N-Tio_2)

It is a nanomaterial composed of titanium dioxide (N-TiO_2) particles. It possesses distinctive photocatalytic capabilities that facilitate the degradation of contaminants and maintain surface cleanliness upon exposure to light and it enhances durability and compressive strength of concrete. Table 1 presents the properties of the nanomaterials. A Sample of N-SiO_2 is depicted in Fig.1(b).

Table 1. Characteristics of nanomaterials

Properties	N-SiO_2	N-Tio_2
Specific gravity	2.12	2.26
Size (µm)	15	25
Colour/ form	White/ powder	White/ powder
Chemical Composition % by weight		
SiO_2	94.24	-
Al_2O_3	0.6	-
Fe_2O_3	0.15	
TiO_2	-	97.30

2.5 Super Plasticiser

Conplast SP430 is used as a super plasticiser conforming to IS: 9103:1999. It disperses fine particles inside the concrete mixture, enhancing the efficiency of the water content in the concrete. A substantial increase in strength can be attained due to the considerable decrease in water content.

3. RESULTS AND DISCUSSIONS

3.1 Mix Proportions of SCC

The SCC mix proportions for M_{25} grade concrete were established using a trial-and-error approach in accordance with EFNARC 2005 recommendations.

Fig. 1(a): Sample of N-SiO_2

Fig. 1(b): Sample of N-TiO_2

Table 2. Mix identification

Designation	Mix Combination
NM0	Conventional Mix
NM1	N-SiO_2 (0%) + NTiO_2 (10%)
NM2	N-SiO_2 (2%) + NTiO_2 (8%)
NM3	N-SiO_2 (4%) + NTiO_2 (6%)
NM4	N-SiO_2 (6%) + NTiO_2 (4%)
NM5	N-SiO_2 (8%) + NTiO_2 (2%)
NM6	N-SiO_2 (10%) + NTiO_2 (0%)

Tables 2 and 3 outline the mix classifications along with their respective proportions. The mixtures are designated NM0 to NM6, comprising a conventional mix (NM0) and six different forms in which N-SiO_2 and N-TiO_2 are utilized as partial substitutes for cement by weight.

Fig. 2(a): L-box test

3.2 Fresh properties of SCC

Laboratory tests were performed to assess the passing ability, segregation resistance, and filling capacity of fresh SCC mixes in accordance with EFNARC 2005 recommendations. Table 4 displays the fresh state parameters of SCC mixes. This investigation involved conducting tests to assess the fresh qualities of SCC mixes. Test setup for fresh-state characteristics of SCC mixture is represented in Fig 2(a) and 2(b).

The outcomes of the workability assessments indicated that an increase in the proportions of Nano addition in the mixture led to a reduction in the flowability of the concrete. The slump diameter varied from 707 mm for the conventional mix (NM0) to 650 mm for the mix with the greatest NS content (NM6), demonstrating diminished flowability with higher NS content. The L-Box test (h1/h2) indicated values from 0.95 for the usual mix (NM0) to 0.85 for the mix with the highest NS concentration, demonstrating a reduction in passing capacity. The V-Funnel test revealed a duration of 10.32 seconds for NM0 and 14.50 seconds for NM6, demonstrating that the mixture required more time to flow as the quantities of NS and NTiO2 rose. This indicates that the incorporation of these nanomaterials enhances strength but concurrently reduces the workability of the concrete (Ghafari *et al.* 2014).

Table 3. Mix design proportions for SCC per cubic metre

Mix ID	Cement kg	FA kg	CA kg	N-SiO_2 Kg	N-Tio_2 Kg	Water lit	SP %
NM0	524.31	788.77	773.06	0	0	199.24	1.2
NM1	419.45	788.77	773.06	0	41.94	199.24	1.2
NM2	419.45	788.77	773.06	8.38	33.55	199.24	1.2
NM3	419.45	788.77	773.06	16.77	25.16	199.24	1.2
NM4	419.45	788.77	773.06	25.16	16.77	199.24	1.2
NM5	419.45	788.77	773.06	33.55	8.38	199.24	1.2
NM6	419.45	788.77	773.06	41.94	0	199.24	1.2

Fig. 2(b): V-Funnel test

Table 4. Workability test results

Mix ID	L-BOX (h1/h2)	SLUMP DIA (mm)	V-FUNNEL (sec)
NM0	0.95	707	10.32
NM1	0.93	690	9.80
NM2	0.91	675	9.50
NM3	0.90	660	9.10
NM4	0.88	640	8.80
NM5	0.85	620	8.40
NM6	0.82	600	8.00

3.3 Mechanical Properties of SCC

Different mechanical strength parameters, including split tensile strength, compressive strength, and flexural strength, are assessed after different curing durations.

3.3.1 Test Findings on Compressive Strength Test

The range of observed compressive strength for different combinations of SCC is illustrated in Fig.3. After 28 days of testing, the nanoengineered concrete exhibited compressive strength values ranging from 33.4 to 37.5 MPa. The strength results indicate that incorporating N-SiO_2 and N-TiO_2 enhances concrete strength up to NM4. However, beyond NM4, a slight decrease in strength was observed, possibly due to excessive NS causing agglomeration and poor dispersion. This suggests that an optimal ratio of N-Sio2 and N-TiO_2 promotes hydration and densifies the microstructure, resulting in improved strength. These observations are consistent with previous studies that emphasize the significance of appropriate nanomaterial proportions in enhancing concrete performance. N-SiO_2 and N-TiO_2 improve mechanical strength by filling micro-pores, improving the microstructure, and increasing pozzolanic processes that form more C-S-H gel, resulting in better bonding between cement particles. The mixture with 6% N-SiO_2 and 4% N-TiO_2 exhibited the maximum mechanical strength due to the optimal balance of pozzolanic activity and microstructure refinement. The observed strength reduction in NM5 and NM6 may be attributed to excess NS, potentially leading to agglomeration and uneven distribution within the mixture, thereby diminishing its effectiveness. These findings align with earlier research, underscoring the importance of optimal nano-material dosage for maximizing performance (Singh *et al.* 2019; Kumar *et al.* 2019).

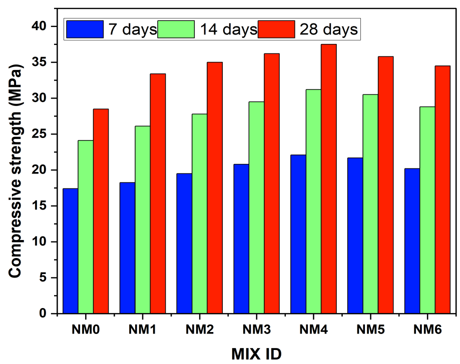

Fig. 3: Test findings of compressive strength for various SCC mixes

3.3.2 Test findings on Split Tensile Strength

Fig 4 displays the tensile strength of different SCC blends. The tensile strength of SCC mixes exhibited an increase with the incorporation of N-SiO_2 and N-TiO_2, attained a maximum at the mix NM4 (2.80 MPa at 7 days, 3.60 MPa at 14 days, and 4.20 MPa at 28 days). This enhancement can be attributed to the pozzolanic reaction of NS and the filler effect, which improves the bond between particles and reduces voids in the concrete (Varghese *et al.* 2019). However, mixes beyond NM4 demonstrated a decline in tensile strength, potentially due to excessive N-SiO_2, which resulted in agglomeration and impeded uniform distribution. These findings underscore the critical importance of balanced proportions of N-SiO_2 and N-TiO_2 in optimizing tensile strength.

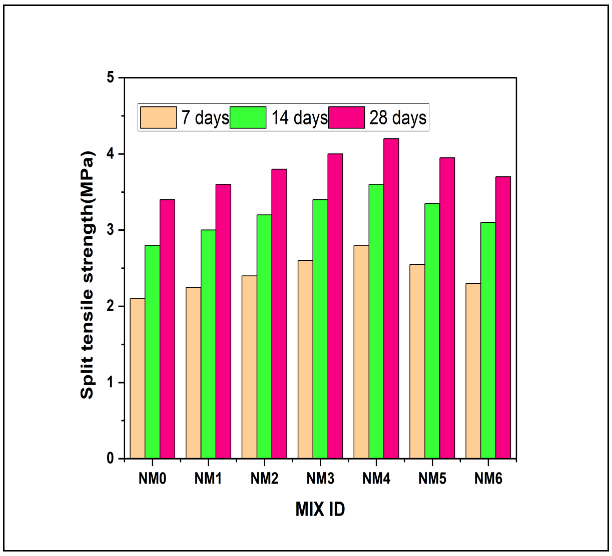

Fig. 4: Test findings of Split Tensile Strength for Various SCC Mixes

3.3.3 Test Findings on Flexural Strength

The findings pertaining to the flexural strength of SCC are illustrated in Fig 5. The results regarding the flexural strength of SCC are depicted in Figure 4. The SCC of M25 grade exhibited flexural strengths of 3.60 MPa and 5.48 MPa after 7 and 28 days, respectively. The incorporation of N-Tio$_2$ into the SCC composition resulted in a notable enhancement of its flexural strength, with an approximate rise of 4%. Nevertheless, increasing the quantity of N-TiO_2 resulted in a decrease in strength due to the aggregation of unreacted N-SiO_2 particles, which impeded the pozzolanic reactivity. The experimental results indicate that the optimal material combination of 6% N-SiO_2 and 4% N-TiO_2 yielded flexural strengths of 4.20 MPa and 7.75 MPa after 7 and 28 days, respectively.

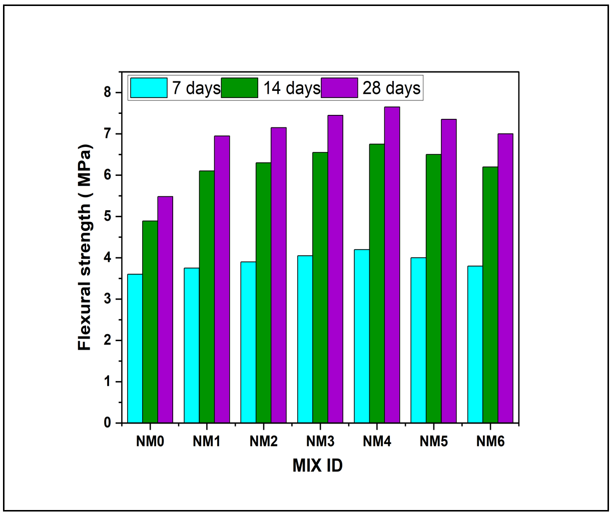

Fig. 5: Test findings of flexural strength for various SCC mixes

3.4 Water Absorption (WB) on SCC mixes

The experiment involved conducting water absorption tests on cubical specimens measuring 150 mm in size as per ASTM C642. Fig.6 exhibits the outcomes of the WB tests conducted on different SCC mixes after a curing interval of 28 days. The water absorption rate of the conventional mixture was recorded as 4.9%. The WB values of the SCC mixes exhibited a range of 3.68% to 3.85%. The WB values of the NM4 mixture were found to be the lowest among the other specimens. The results obtained from the WB tests indicate that the amalgamation of NS improves adhesive strength and diminishes water penetration into concrete (Massana *et al.* 2018).

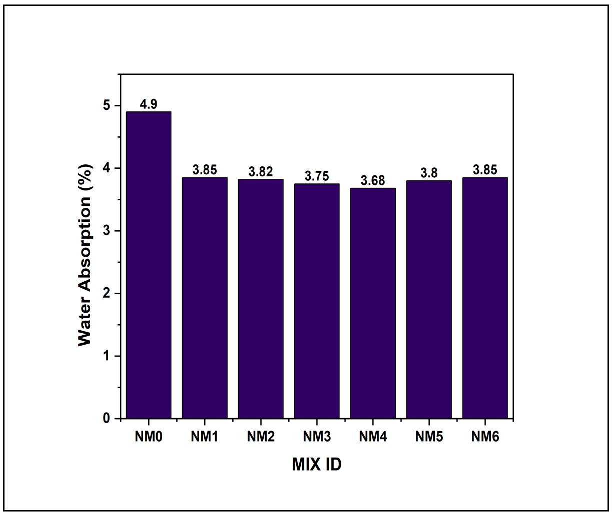

Fig. 6: Water absorption of SCC mixes

3.5 SEM analysis of SCC Mix

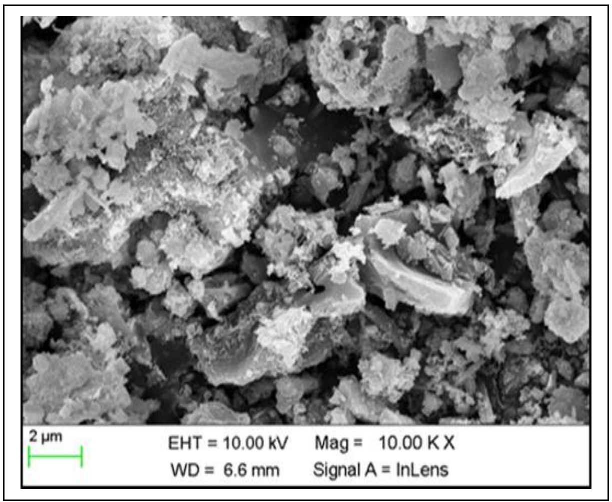

Fig. 7a: SEM photograph for NM4 concrete blend

Fig. 7b: SEM photograph for conventional mix

The SEM analysis of the conventional mix (NM4) is illustrated in Fig.7(a). The particle sizes of N-SiO_2 and N-TiO_2 used in this study are 15–20 nm and 20–25 nm, respectively. The reactivity of the ultrafine particles is enhanced, enabling them to effectively occupy micro-pores, refine the microstructure, and improve the overall strength and durability of the mix.

The sample analysis indicates the uniform distribution of hydrated products across the entire area. In specific regions of the sample, a crystalline structure is evident, suggesting the presence of inert silica or unhydrated substances. These anhydrous products can be converted into an amorphous state with subsequent hydration. The sample displays a limited quantity of pores, hence augmenting the stability of the concrete. The N-Sio2 and N-Tio2 particles can occupy the interstices between particles of cementitious material in the morphology. Moreover, they can infiltrate the vacant areas within the interfacial transition zone (ITZ) and other minute voids. The SEM analysis of the SCC mix ID NM4 is illustrated in Fig. 7(b). The SEM picture of the NM0 (Conventional mix) exhibits a dense morphology with both crystalline and amorphous phases. The irregularly shaped particles signify unhydrated cement grains and hydration products. Small voids and micro-cracks are evident, suggesting possible porosity that could impact strength and durability.

4. CONCLUSION

The subsequent inferences were drawn from the experimental investigation performed;

a. This study demonstrates that the incorporation of N-SiO_2 and N-TiO_2 nanoparticles in SCC significantly enhances its fresh and hardened properties. The examination of rheological characteristics reveals that the incorporation of nano additions reduces the slump flow and passing ability of the concrete mixture, while simultaneously enhancing its viscosity.

b. The NM4 mix attained superior compressive, split tensile, and flexural strengths, attributable to the nanoparticles' capacity to refine the microstructure and augment the concrete's overall strength.

c. Water absorption studies indicated that NM4 had lower values than other mixes, signifying enhanced density and less permeability, hence augmenting the concrete's endurance.

d. The mixture that exhibited the greatest mechanical strength properties consisted of 6% (N-SiO_2) and 4% (N-TiO_2)

e. SEM study showed a dense, compact microstructure in the NM4 mix, with fewer voids and a consistent dispersion of hydration products.

f. These characteristics point to a well-optimized matrix aided by the nanoparticles.

The study found that using N-SiO_2 and N-TiO_2 as partial cement replacements results in high-performance SCC with enhanced durability, mechanical strength, and microstructural integrity.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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