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Rheological and Strength Properties of Nano Silica and Nano Metakaolin in Self-compacting Concrete

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Abstract

Self-compacting concrete (SCC) is a variant of special concrete renowned for its remarkable strength and endurance attributes. However, there are notable differences in the mix proportioning and testing procedures employed to determine the flow characteristics of this specific concrete in comparison to normal concrete. SCC is a variant of concrete that demonstrates remarkable workability, showcasing elevated levels of strength and performance attributes. The material possesses a distinctive characteristic of exhibiting smooth flow under its own gravitational force, even when traversing through tight or constricted sections, without encountering problems such as separation and exudation. It is achieved by decreasing the proportion of aggregate to cementitious materials, increasing the amount of paste, and using various admixtures and superplasticizers that enhance viscosity. Nano silica (NS) and nano metakaolin (NMK) are employed as partial substitutes for cement in varying proportions (0 to 12%). The current research findings indicate that including NS and NMK in SCC results in advantageous enhancements in both the rheological and strength characteristics.

Keywords

Nano silica, Nano metakaolin, Self-compacting concrete, Admixtures

Introduction

Nowadays, the prominent concern revolves around the phenomena of global warming and the consequential environmental degradation. It was manufacturing one metric ton of cement results in the emits of an equivalent quantity of carbon dioxide, a highly potent greenhouse gas that contributes to the phenomenon of global warming. 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.

SCC is a distinctive variant of concrete that possesses a fluid consistency, allowing it to flow smoothly without the need for external vibration or compaction when placement within the formwork. Since the early 1980s, the utilization of SCC has been widely adopted globally owing to its advantageous production characteristics. This particular type of concrete indicates a significant advancement in the field of concrete technology. It is characterized by its advanced properties and exceptional performance, which have had a substantial impact on both the economic and environmental aspects of the building sector during the past twenty years. This specific variant of concrete signifies a notable progression in the field of concrete technology. The construction sector has experienced significant advancements and notable achievements over the past two decades, mostly attributed to the remarkable performance and sophisticated properties exhibited by this particular entity. These attributes have had a deep influence on both the economic and environmental dimensions of the industry [1].

Silica fume (SF) is composed of fine particles that possess a specific surface area approximately six times greater than that of cement due to their significantly smaller size in comparison to cement particles. Therefore, it has been shown that the incorporation of SF into concrete leads to a reduction in the size of the microscopic voids. It exhibits pozzolanic properties due to its inherent reactivity, akin to that of volcanic ash. The incorporation of SF in concrete has garnered significant recognition due to its ability to improve strength properties [2].

Metakaolin has unique properties compared to other supplementary cementitious materials mostly due to its peculiar manufacturing process [3]. Uysal [4] evaluated the flow properties and resistance to segregation of mineral admixtures. The aim was to get a better understanding of how these admixtures operate and evolve when incorporated into SCC. The inclusion of admixtures greatly increased the fluidity. The researchers performed a comparative examination of the rheological behavior of SCC containing MK and SF. The study's results revealed a favorable association between the proportion of MK and both the viscosity and the yield stress. Nevertheless, a noticeable enhancement in the yield value was seen with the rise in the proportion of SF.

The results also indicated a considerable relationship between the diameter of the yield stress, and the slump flow along with a connection between the viscosity and the duration of the slump flow [5]. As stated by Siddique [6], the quantity of fly ash (FA) generated annually in India surpasses 88 million tons, with a utilization rate varying between 10% and 15%. The hardened properties of SCC are influenced by mineral admixtures in varying ways. Notably, the use of particular quantities of marble powder has been found to result in the highest compressive strength. In conclusion, it has been determined that the utilization of mineral admixtures presents a viable approach for decreasing the cost of concrete [7, 8].

The presence of FA led to a drop in both the penetrability and average pore size of the cementitious adhesive, in contrast to the paste utilizing unclassified FA. The inclusion of finer FA at various replacement amounts led to a decrease in overall porosity and capillary pores, accompanied by an increase in gel pore size [9]. The researchers looked into the effects of adding more cementitious components to ternary mixtures on the various characteristics of SCC and the results indicated a substantial enhancement in strength [10].

The study findings indicate that the concrete mixture containing 25% FA had improved levels of compressive strength and modulus of rigidity compared to the concrete mixture incorporating 50% FA and conventional concrete. The researchers evaluated the impact of different fillers on the flowability and strength characteristics of SCC [11]. The observed data suggests that the characteristics and composition of additives have a substantial effect on the behavior of fresh concrete. The study shown that the incorporation of pozzolanic fillers enhances the material's capacity to withstand segregation and bleeding [12]. Tang et al. [13] demonstrated that SF and NS exhibited a favorable pozzolanic influence and underwent an additional hydration reaction with calcium hydroxide, leading to an enhanced formation of C-S-H. Over the last two decades, nanomaterials have been employed in the construction sector, particularly in the manufacturing of concrete products. Research has shown that adding nanomaterials to concrete has a beneficial effect on its qualities [14]. The intent of this study is to incorporate NS and NMK into SCC in order to enhancement its strength and durability properties.

Materials and Method

Materials and properties

Cement

The utilization of ordinary Portland cement (OPC) 43 grade is in accordance with the specifications given in IS 8112 [15]. During the course of the experiment, a singular batch of Ultratech cement is employed. The evaluation of various qualities of cement is conducted in accordance with the Indian standard (IS) code. The fineness and specific gravity were measured to be 8% and 3.15, respectively. The periods for the initial and final setting durations were determined to be 75 and 215 min, respectively.

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 [16]. The control concrete was limited to an acceptable coarse aggregate (CA) 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.

NS and NMK

NS, a white powdery substance, possesses several advantages due to its small molecular size. These include an extensive surface area, excellent surface adsorption, and effective dispersion [17]. The specific gravity of NS was obtained at 2.12. NMK is an exemplary pozzolanic substance that is utilized in conjunction with OPC to enrich the mechanical properties and long-term performance of concrete. The determined specific gravity of NMK was recorded as 2.35. Table 1 presents the chemical properties of the binding components.

Super plasticizer (SP)

Conplast SP430 is used as SP conforming to IS 9103:1999 [18]. It disperses fine particles inside the concrete mixture, en-

Table 1: Chemical characteristics of binding materials.

Compound	(% by weight)		
	NMK	NS	OPC
SiO_2	61.45	90.46	20.58
Al_2O_3	28.95	1.13	5.36
Fe_2O_3	2.68	0.86	3.84

hancing 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.

Experimental program

Mix proportions of SCC

The mix ratio for SCC is determined by the trial-and-error approach, following the guidelines outlined in the EFNARC 2005 regulations [19]. Table 2 and table 3 illustrate the identification of each mix and the corresponding concrete mix proportions. The mixes are designated as SSC1 to SSC6. A total of six varieties of trail mixes are provided. NS and NMK are mixed in a proportion of 12%. The percentage of NS was augmented by 2%, whereas the percentage of NMK was reduced by 2%.

Fresh properties of SCC

In order to evaluate the passing ability, segregation resistance and filling ability of fresh SCC mixes, laboratory tests were conducted following the EFNARC 2005 requirements. Table 4 displays the fresh state parameters of SCC mixes. This investigation involved conducting tests to assess the fresh qualities of SCC mixes. A total of six different mixtures were conducted and evaluated, with each mixture including 0% replacements of mineral admixtures in comparison to the SCC controlled mix. Test setup for fresh-state characteristics of SCC mixture is represented in figure 1.

The investigation of the findings listed in table 4 shows that the addition of mineral admixtures diminishes the workability of concrete; furthermore, the extent of admixture substitution is directly proportional to this effect. There exists a direct relationship between the incorporation of micro silica and the corresponding increase in water consumption. The combination of mineral admixtures in concrete leads to an augmentation in its adhesive properties [17]. The findings indicate that all combinations satisfy the criteria for SCC as per the established specifications.

Table 2: Mix identification.

Designation	Mix combination
SSC1	Conventional mix
SSC2	NS2% + NMK10%
SSC3	NS4% + NMK8%
SSC4	NS6% + NMK6%
SSC5	NS8% + NMK4%
SSC6	NS10% + NMK2%

Table 4: Workability test results.

Mix ID	L-box (h_1/h_2)	Slump diameter (mm)	V-funnel (sec)
SCC1	0.94	705	10.24
SCC2	0.92	692	8.15
SCC3	0.9	684	8.94
SCC4	0.89	670	9.54
SCC5	0.86	657	10.26
SCC6	0.74	636	13.97

Figure 1: Test arrangement for fresh state properties of SCC mix. **(a)** Measurement of slump flow, **(b)** Test arrangement for L-box test, and **(c)** Test arrangement for V-funnel test.

Results and Discussion

Mechanical properties of SCC

Different mechanical strength parameters, including split tensile strength, compressive strength, and flexural strength, are assessed after different curing durations. The test findings of SCC are depicted in figure 2, figure 3, and figure 4.

Test findings on compressive strength test

The range of observed compressive strength for different combinations of SCC is illustrated in figure 2. The values observed over a period of 28 days ranged from 29.79 N/mm^2 to 34.52 N/mm^2. The compressive strength exhibited an upward trend as the proportion of SF increase reaching its peak at 15%. However, above this threshold, the strength at all ages experienced a decline. The blend identified as ID SCC5 (NS8% + NMK4%) demonstrated superior strength compared to all other mixtures. The CC mixture exhibited a

Table 3: Mix design proportions for SCC per cubic meter.

Mix ID	Cement (kg)	FA (kg)	CA (kg)	NS (kg)	NMK (kg)	Water (L)	SP (%)
SCC1	524.31	788.77	773.06	0	0	199.24	1.2
SCC2	419.45	788.77	773.06	10.48	52.43	199.24	1.2
SCC3	419.45	788.77	773.06	20.97	41.94	199.24	1.2
SCC4	419.45	788.77	773.06	31.45	31.45	199.24	1.2
SCC5	419.45	788.77	773.06	41.94	20.97	199.24	1.2
SCC6	419.45	788.77	773.06	52.43	10.48	199.24	1.2

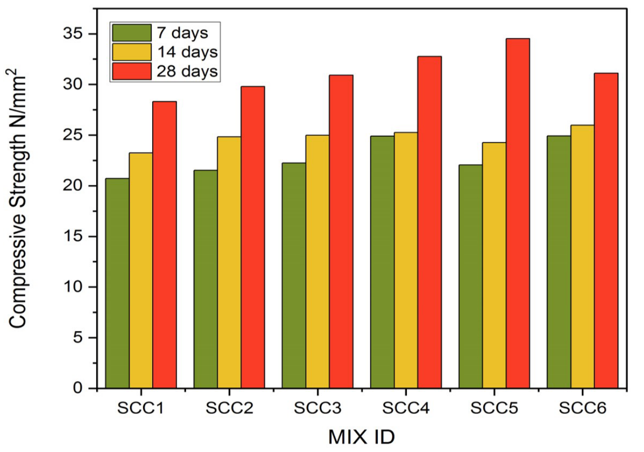

Figure 2: Test findings of compressive strength for various SCC mixes.

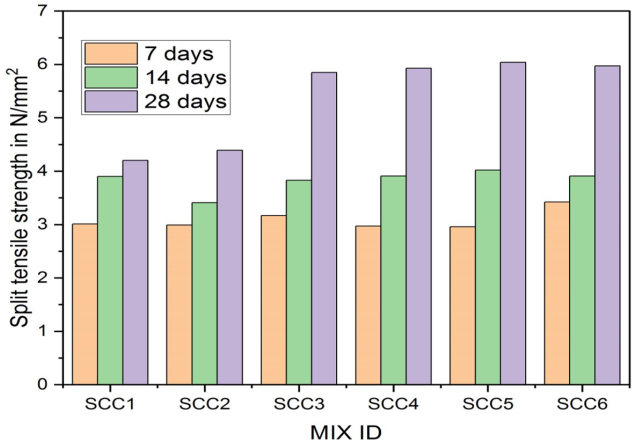

Figure 3: Test findings of split tensile strength for various SCC mixes.

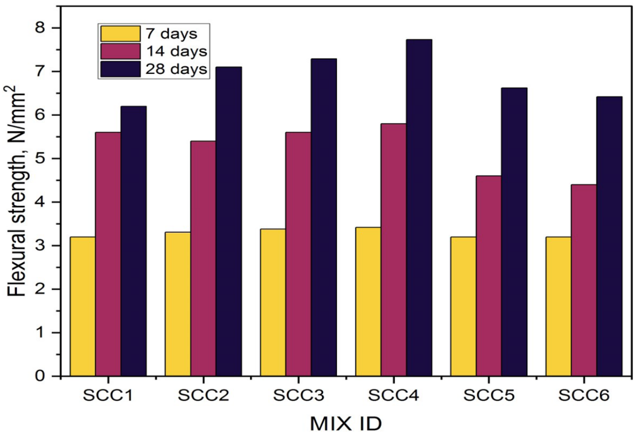

Figure 4: Test findings of flexural strength for various SCC mixes.

compressive strength of 28.32 N/mm² after the completion of the 28-day curing interval. The SSC5 mixture showed a significant increase of 21.89% when compared to that of CC. The enhanced particle packing capacity of concrete can be ascribed to the pore-filling mechanism facilitated by the inclusion of micro silica.

Test findings on split tensile strength

Figure 3 displays the tensile strength of different SCC blends. The SCC5 mixture exhibited an increase in tensile strength from 4.2 MPa for the control SCC to 6.04 MPa. Nevertheless, the strength declined subsequent to the introduction of 8% NS and 4% NMK, respectively. As the unreacted silica particles agglomerated after the adding of more NMK and NS, the workability and strength of the material decreased. As NS particles filled the voids in the cementitious system, the strength of combinational mixtures containing 8% NS and 4% NMK increased significantly.

Test findings on flexural strength

The findings pertaining to the flexural strength of SCC are illustrated in figure 4. The SCC of M_{25} grade demonstrated flexural strengths of 3.21 MPa and 6.20 MPa after 7 and 28 days accordingly. The incorporation of a 6% volume fraction of NS, along with an additional 24.67% increase, resulted in an enhancement of the flexure strength. The addition of NMK to the composition of the SCC led to a significant improvement in its flexural strength, with an approximate increase of 4%. However, adding more NMK contributed to a drop in strength due to an accumulation of unreacted NMK particles, which hindered the pozzolanic reactivity. Based on the experimental findings, it can be shown that the most favorable combination of materials, comprising 6% NS and 4% NMK resulted in flexural strengths of 3.42 MPa and 7.73 MPa at the end of 7 and 28 days, respectively.

Water absorption (WB) on SCC mixes

The experiment involved conducting WB tests on cubical specimens measuring 150 mm in size as per ASTM C642 [20]. Figure 5 exhibits the outcomes of the WB tests conducted on different SCC mixes after a curing interval of 28 days. The WB rate of the conventional mixture was recorded as 5.2%. The WB values of the SCC mixes exhibited a range of 3.91% to 4.95%. The WB values of the SSC6 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 the adhesive strength and diminishes water penetration into concrete [21, 22].

Microstructural properties of SCC concrete mix

The SCC5 blend exhibited excellent mechanical strength properties. Therefore, these blends have been selected for microstructural analysis.

Scanning electron microscope (SEM) analysis of SCC mix

The SEM examination of the SCC mix ID SCC5 is depicted in figure 6. The analysis of the sample reveals the presence of hydrated products evenly distributed throughout the entire area. However, in certain areas of the sample, a crystalline structure is observed, indicating the presence of inert silica or unhydrated products. These unhydrated products can be transformed into an amorphous state through secondary hydration [23]. The sample exhibits a minimal number of pores, which enhances the stability of the concrete. The NS

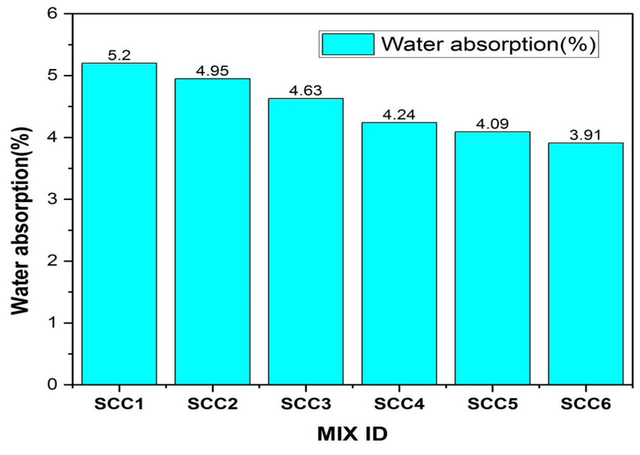

Figure 5: WB of SCC mixes.

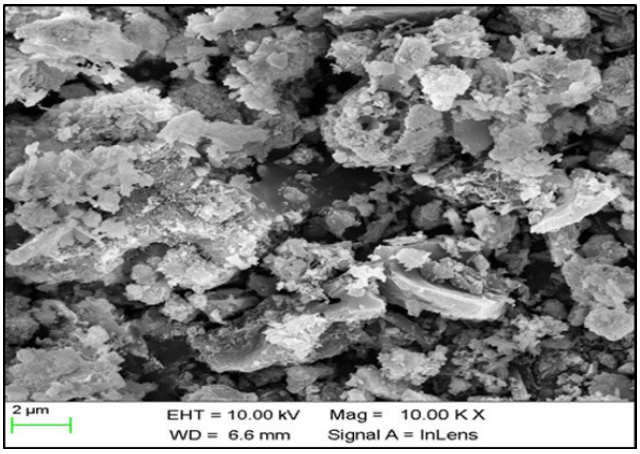

Figure 6: SEM photograph for SCC5 concrete blend.

and NMK particles have the ability to fill the gaps between particles of cementitious substance in the morphology. Additionally, they have the ability to occupy the empty spaces within the interfacial transition zone and other minuscule voids.

Energy dispersive X-ray spectroscopy (EDX) analysis

The elemental structure of the sample is determined through the utilization of EDX spectroscopy, as illustrated in figure 7. Calcium and silica are identified as the predominant substances, while the presence of hazardous substances such as carbon and iron are found to be negligible. This signifies that the concrete specimen possesses sufficient strength to endure additional chemical attacks.

Conclusions

The subsequent inferences were drawn from the experimental investigation performed.

- This study intends to examine the feasibility of including nanomaterials to enhance the strength of SCC.
- The investigation of rheological parameters indicates that the addition of mineral admixtures decreases the slump flow and passing ability of the concrete mixture, while concurrently increasing its viscosity.

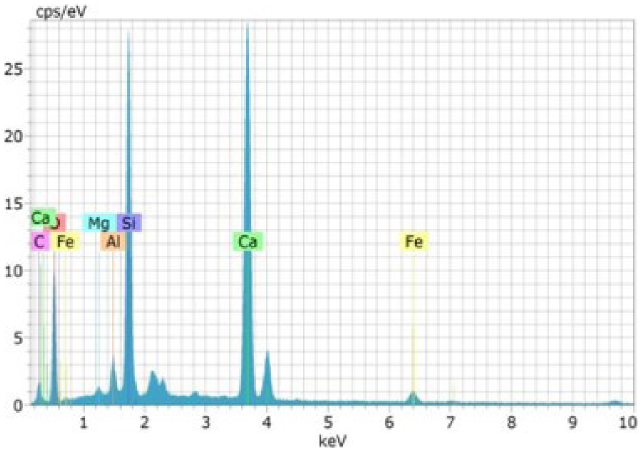

Figure 7: EDX analysis for SCC5 concrete blend.

- The application of NMK as a partial substitution for OPC results in a substantial enhancement in its resistance to water permeability owing to its comparatively reduced loss on ignition value in comparison to OPC.
- The decrease in workability of the combination can be ascribed to the intensified rigidity of the mixture resulting from the enhanced fineness caused by the inclusion of mineral admixtures.
- Based on the comparative analysis conducted on the hardened properties of concrete, it was deduced that increasing the weight of cement replacement resulted in greater strength.
- The mixture that exhibited the greatest mechanical strength properties consisted of 8% NS and 4% NMK.
- The SEM study determined that the NS and NMK particles had exhibited the capacity to occupy the voids between the particles of the cementitious material in the microscopic structure.
- The findings of the current research suggest that the addition of NS, NMK, or a mixture of both in SCC leads to favorable improvements in both the workability and strength properties.

Acknowledgements

None.

Conflict of Interest

None.

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