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Research Article

Influence of ultrafine blast furnace slag and nano silica on the engineering characteristics of self-compacting concrete

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Abstract

Self-compacting concrete (SCC) mix design conventionally requires a high binder content to achieve the required flowability and segregation resistance, thereby increasing the risk of shrinkage at both early and later ages. The present study explores the synergistic effect of incorporating nanosilica (NS) and ultrafine blast furnace slag (UFBFS) on the fresh and hardened properties of M60 grade SCC, including durability and shrinkage performance, by optimizing the binder content without compromising SCC performance requirements. Preliminary experimental investigations revealed that UFBFS enhances workability and strength properties, while NS increases paste viscosity and uniformity. The results of the experiments showed that a 5–8% replacement of the UFBFS-to-OPC ratio could be considered optimal for enhancing compressive strength. Integrating UFBFS and NS allowed for optimizing the binder content at 565 kg/m^3 while meeting SCC flow requirements, reducing it from 600 kg/m^3. The modified SCC demonstrated a 28-day compressive strength of 70 MPa and exhibited better durability, such as high resistance to water penetration, low water absorption, and low chloride permeability. The drying shrinkage was reduced by 38% in the modified SCC, and cracking due to plastic shrinkage was avoided in the modified SCC. The work clearly illustrates how UFBFS and NS can be used to prepare a durable SCC at lower binder content and with good shrinkage resistance.

1. Introduction

The application of self-compacting concrete (SCC) is considered a solution for the construction of reinforced concrete structures (RCC) that pose casting difficulties [1]. Difficulties can be due to 1) the unique shape of the structural element, 2) rebar congestion, 3) limited access for placing concrete effectively, and 4) the need for a higher number of resources in the form of skilled manpower and equipment required for placing and compaction [2, 3]. In some situations, the project execution team may encounter multiple difficulties, especially a shortage of skilled manpower required for casting [4]. It could be a challenge for the execution team to cast such RCC Structures without any blemishes while meeting the time-bound execution plan [5, 6]. Experience across various parts of the world shows that the preference for speedy construction can lead to improper casting of RCC elements, thereby adversely affecting the durability of RCC structures. Criticalities, as mentioned above, add to the challenge of achieving durability in time-bound project execution. Hence, a concrete mix with the flowing ability of a fluid was considered to address these difficulties [7, 8]. Okamura first conceptualized a fluid-like concrete material in 1986 in Japan, where a shortage of skilled labour made durable construction a challenge, leading to the development of self-compacting concrete. Ozawa and Maekawa conducted studies on the development of self-compacting concrete with appropriate workability and other hardened concrete properties at the University of Tokyo. Subsequently, a prototype SCC application was

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made in 1988 [9]. The approach was to make fresh concrete fluid enough to remove entrapped air to the maximum extent possible, thereby eliminating the need for manual compaction.

While a flowing concrete mix containing varying aggregate sizes is required to pass through rebars and fill the formwork, it is expected to remain uniform without segregation. Hence, SCC is designed to meet requirements such as flowing ability, passing ability, segregation resistance, and optimal viscosity [10, 11]. Dependence on a higher binder content to make a fresh SCC mix robust has been the conventional approach since the earliest days of SCC. Okamura and Ouchi state that limiting the coarse aggregate content in SCC to levels lower than those in normal concrete is essential to reduce the energy required for the flow of fresh concrete. The concept is to increase the space between aggregate particles to reduce the internal stress caused by collisions and contacts between aggregates. A reduction in coarse aggregates and an increase in fines could provide a better-flowing medium, helping the SCC mix remain uniform whilst flowing to fill and occupy the structure, even in the presence of congested rebars, and to take shape without requiring any external compaction. Reduction in coarse aggregates has thus become an invariable feature of an SCC mix [12]. However, reducing the aggregate/binder ratio compared with normal concrete would increase the concrete's shrinkage probability at both early and later ages [13]. Although the mechanical properties of the SCC are superior to those of the conventional concrete, the shrinkage of SCC is significantly higher [14]. Farhad Aslani and Shami Nejadi quote based on other researchers that “because the SCC has a higher paste volume (or higher sand to aggregate ratio) to achieve high workability and high early strength, several researchers have claimed larger shrinkage of the SCC for precast, prestressed concrete, resulting in larger prestress losses” [15].

Various research into chemical admixtures led to the development of a viscosity-modifying agent (VMA). As the name implies, VMA increases the viscosity of the liquid medium, i.e., the slurry, making it more viscous [16]. VMA is found to be highly effective in underwater concrete, enhancing its anti-washout properties [17]. A fresh mix with higher workability yet remains very viscous enough to resist washing out when placed underwater is possible with the addition of VMA [18]. This principle has been extended to SCC as well. An increase in slurry viscosity is found to moderately counter segregation in the SCC mix. Meera et al. concluded from an experimental study that the use of VMA in SCC mix enhanced the uniformity and robustness of the fresh concrete mix [19]. The incorporation of VMA into the SCC mix has also reduced binder content [20]. The reason is that the role of the increased binder content in making the slurry more viscous is now partially offset by VMA. The industry worldwide has started using liquid-based VMA in SCC, the last ingredient in the batching sequence added to the concrete mixer. As far as India is concerned, its availability is limited due to import dependency and a lack of manufacturers. Apart from a lack of availability, SCC mixes with VMA have been reported to yield mixed results, including an adverse impact on strength and durability. After reviewing various research works on the different behavior of VMA, Beata Lazniewska-Piekarczyk reported that “due to the controversial data dealing with the relationship between the viscosity-modifying agents and strength of concrete, the experiments should be performed to find how the type of VMA alters mechanical properties”. Based on the experimental findings, it was concluded that the VMA type also significantly affects the air content in high-performance self-compacting concrete (HPSCC) [21]. Hence, an alternative solution is required in the Indian context. Attempts are also being made worldwide to optimize the binder content in SCC using suitable alternative materials that are finer than cement and locally available. Research has been conducted on the use of fine limestone powder, along with other supplementary cementitious materials (SCM) such as fly ash or GGBS, to improve the deformability and stability of fresh SCC [22, 23].

In India, ultrafine blast furnace slag (UFBFS) has been used for more than a decade, especially in high-grade applications [24]. It is considered an alternative to micro silica. Micro silica has been used in India for more than 25 years and is imported, originally from Europe and later mainly from China. Micro silica fineness is known to be extremely high, i.e., more than 12,000 m^2/kg, and can reach 25,000 m^2/kg. Micro silica’s fineness contributes to a reduction in bleeding and segregation to some extent when added to concrete [25]. The addition of micro silica also increases admixture demand due to its extreme fineness, as concluded by Roncero J et al. in their study of cement pastes [26]. The main purpose of incorporating micro silica is to enhance concrete's mechanical properties. It has been found that compressive strength, split tensile strength, and static modulus of elasticity increased with the addition of microsilica [27]. However, as reported by Yun K K et al., the probability of plastic shrinkage increases with the addition of microsilica due to its extreme fineness, leading to an increase in capillary pressure [28]. Another important challenge is its densified form. Densification is required, as handling silica fume is impractical due to its very low bulk density [29]. Thus, densification becomes necessary to pack, transport, and store MS without requiring a much greater volume. It is important to note that densified microsilica should be fully de-densified during the mixing process in the concrete mixer. In regular concrete mixing, substantial amounts of micro silica agglomerates are almost always retained in the concrete. Sidney Diamond and Sadananda Sahu state that "thus the assumption that the densification process is somehow 'reversible' is not generally warranted. The sizes of undispersed agglomerates remaining in concrete after mixing often exceed those of Portland cement particles, thereby limiting the potential benefits of the fine particle filler effect. Large undispersed grains always appear to undergo chemical reactions in concrete, but such reactions may induce alkali silica reaction (ASR) damage only under especially unfavourable circumstances [30]. In such a condition, MS could be counterproductive.

UFBFS is understood to have contributed to the mechanical properties of concrete, similar to micro silica. The amorphous nature and high fineness of UFBFS are found to be the factors behind the enhancement of concrete strength and durability. Ground granulated blast furnace slag (GGBS) is produced by grinding granular slag aggregates that are made by the controlled quenching of molten slag, which is released as a by-product during steel manufacturing [31]. When these granular slag aggregates, which are amorphous in nature, are ground much finer, they become UFBFS. While the fineness of GGBS is around 4,000 m^2/kg, that of UFBFS exceeds 10,000 m^2/kg. Its high fineness is found to contribute to the secondary reaction with calcium hydroxide and the formation of secondary calcium silicate hydrate (C-S-H) gel [32]. As in the case of microsilica, UFBFS is found to have a higher pozzolanic reactivity index and can therefore replace a higher percentage of OPC. The advantage of UFBFS is that it is produced in India. It is also important to note that densification is not required for UFBFS. The product is used in its "as produced" form. Based on these facts, UFBFS is a suitable alternative to microsilica as a tertiary binder to optimize OPC content [33].

Another material under consideration in various research on concrete is nanosilica (NS), among other nanoparticles. The influence of NS on both fresh and hardened properties has been analyzed and presented by many researchers. Niewiadomski et al have mentioned that "based on the studies conducted, it can be concluded that the addition of nanoparticles improves the microstructure of self-compacting concrete. Analysis of the porosity results proved that concretes modified with the addition of nanoparticles are characterized by lower porosity" [34]. On the mechanical and rheological properties of SCC with nanoparticles, Faez A et al have shared that "the increase in nanoparticles increases the homogeneity and consistency of concrete. Due to their higher effective surface area and greater water absorption, Al_2O_3 Nano Particles increase Yield Stress and reduce flowability [35]. In the study by Quercia et al., it was reported that nanosilica significantly increases the water demand of cement paste, resulting in reduced workability [36]. It can be inferred that adding NS increases the viscosity of the concrete mix. Dispersion of NS, like other nanoparticles, has been a topic of particular interest, as agglomeration can occur in slurry media due to their extreme fineness. The use of a poly carboxylate ether (PCE)-based superplasticizer is found to be effective for dispersing nanoparticles. Du et al., in their review, citing various studies, noted that the use of superplasticizers helps overcome the difficulty of dispersing nanoparticles in cement-based materials [37]. Khan et al. have highlighted the beneficial effect of PCE-based admixture in effectively dispersing NS [38]. Since the PCE-based superplasticizer is used in the SCC mix to impart flowability, the challenge of NS dispersion can be addressed [39]

Recent studies have reported the individual effects of ultrafine blast furnace slag (UFBFS) and nanosilica (NS) on concrete properties. The high fineness and pozzolanic reactivity of UFBFS have been proven to enhance strength and durability. At the same time, the NS is known to influence the rheological behaviour and refinement of the cementitious matrix. However, the existing literature mainly focuses on the individual application of these materials or on conventional concrete systems. Very few studies have investigated the application of UFBFS in combination with nanosilica in self-compacting concrete, especially to optimize binder content while minimizing shrinkage potential without compromising fresh and hardened concrete performance. The availability of the two aforementioned finer materials, one ultra-fine and the other of nano-scale, provides a good opportunity to consider them in designing a uniform and robust SCC mix with reduced binder content as an alternative to the conventional approach of using higher binder content. Hence, the current research aims to study the combined effect of UFBFS and NS on the fresh and mechanical properties of SCC, its durability, and its shrinkage potential, to formulate a reliable SCC with an optimized binder content and lower shrinkage. The research objectives of the present study are:

- To investigate the integrated effect of UFBFS and nanosilica on the fresh properties of SCC.
- To evaluate the effect of UFBFS and NS on the mechanical and durability features of SCC
- To examine the influence of UFBFS and NS on the plastic and drying shrinkage behaviour of SCC.
- To develop a robust SCC mix with optimized binder content and improved shrinkage resistance.

2. Materials

2.1. Aggregates

Coarse aggregates (CA) with 20 mm and 12.5 mm as nominal maximum size (NMS) are chosen for the initial experimental works to evaluate the efficiency of UFBFS, whereas CA with 12.5 mm as NMS are chosen for experimental works on SCC. Coarse and fine aggregates belong to the granite type of rock. Particle size distribution is given in Figs. 1 and 2.

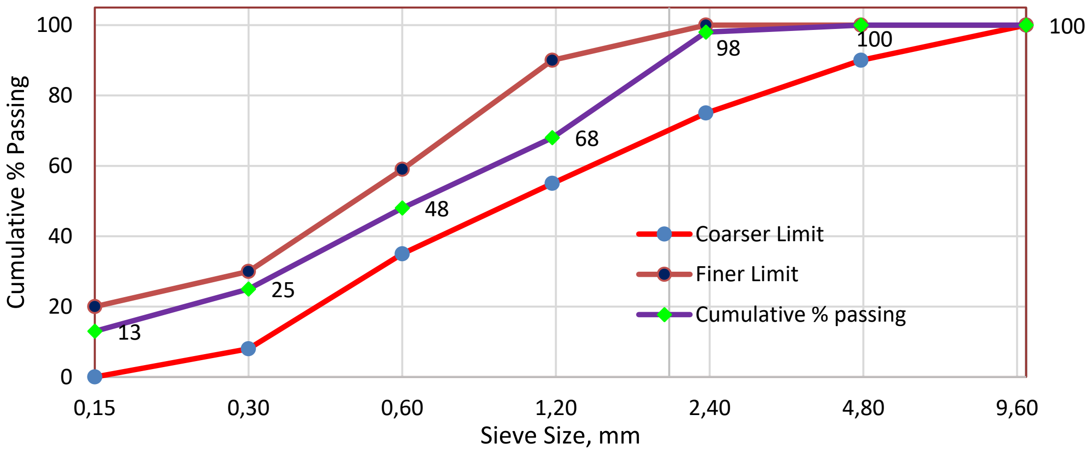


Fig. 1. Particle size distribution of crushed sand stone

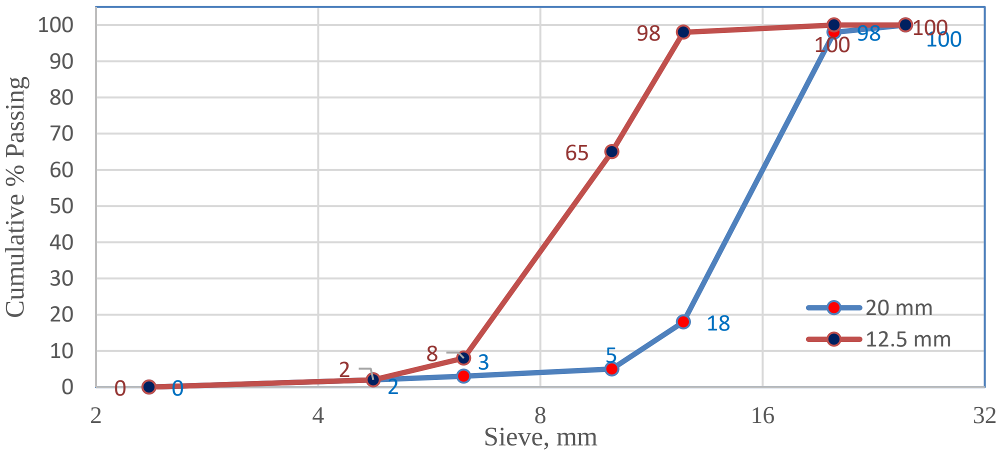


Fig. 2. Particle size distribution of coarse aggregates used in this study

The crusher unit located at Walaja, near Chennai, has been identified as the source of CA, with a three-stage crushing process comprising a vertical shaft impact (VSI) crusher installed as the third-stage crusher. Fine Aggregates (FA) used in the experiments are the product of crushed stone aggregates processed through a VSI Crusher, which provides better particle shape. The same crusher unit from which CA is sourced is also used to procure crushed stone sand (CSS).

2.2. Ordinary Portland cement

Ordinary Portland Cement (OPC) of 53 Grade is chosen for the experimental work. OPC from a single source, i.e., the UltraTech Cement factory located near Chennai, has been ensured throughout the study period. The sample has been tested for its Physical and Chemical Properties; these are presented in Tables 1 and 2.

Table 1. Physical properties of binders used in the study

Physical Properties		OPC	Fly ash	UFBFS	NS
Blaine's Permeability, m^2/kg		274	326		
Fineness (BET Method), m^2/kg				2730	202,000
Average Particle size, um in %				1.5	0.017
Retention on 45 microns			29 %		
Normal Consistency		27.0 %			
Setting Time	Initial Setting Time (min)	90			
	Final Setting Time (min)_	225			
Specific	Le-Chatelier Flask	3.15	2.10	2.90	2.4
Soundness	Le-Chatelier (mm)	0.15			
Compressive Strength	72 hours (MPa)	32.9			
	168 hours (MPa)	43.2			
	672 hours (MPa)	57.8			
28-day Compressive Strength w.r.t. OPC			85%	127%	

Table 2. Chemical properties of the binders employed in the study

Chemical Properties	OPC	Fly ash	UFBFS	NS
Aluminum oxide, percent by mass	4.9			
Ferric oxide, percent by mass	4.9			
Insoluble residue percent by mass	3.0		0.11	
Magnesium oxide (MgO), in %	1.8		7	
Manganese oxide (MnO), in %			0.35	
Sulphate (SO_3), in %	2.8	0.19	0.26	
Sulphide Sulphur			0.3	
Total loss on ignition percent by mass	2.8	0.19	0.11	0.66
Silica, percent by mass	20.4	64.2		99.9
Calcium oxide, percent by mass	59.7	2.11		
Total chloride content, percent by mass	0.010	0.011	0.015	0.010
Equivalent Sodium Oxide, percent by mass		0.26		
Glass Content, in %			96	
$CaO-0.7SO_3/2.8SiO_2+1.2Al_2O_3+0.65Fe_2O_3$	0.90			
Silicon dioxide (SiO_2) + Aluminum oxide (Al_2O_3) +Iron oxide (Fe_2O_3) in % by mass		95.8		
$(CaO+MgO+1/3Al_2O_3)/(SiO_2+2/3Al_2O_3)$, in %			1.12	
$(CaO+MgO+Al_2O_3)/(SiO_2)$, in %			1.8	

2.3. Fly Ash

Fly ash collected from the electrostatic precipitator is used in the experimental studies. The thermal power plant located in North Chennai is identified for this study, and the fly ash available at this source belongs to 'Type F'. The physical and chemical property test results of the fly ash employed in this study are presented in Tables 1 & 2, respectively.

2.4. Ultrafine Blast Furnace Slag (UFBFS)

UFBFS particles are finely ground blast furnace slag with a D (0.95) less than 10 microns. The UFBFS used is Alccofine, a product of Gujarat Ambuja Limited, and is governed by IS 16715:2018 (amended 2019). Its properties (physical & chemical) are presented in Tables 1 and 2, respectively.

2.5. Nano Silica

Nanosilica with particle sizes ranging from 15 to 80 nm and containing more than 90% of silicon dioxide (SiO2) is sourced for the experimental study. The properties of the nanosilica, as given in Tables 1 & 2, indicate that NS is highly reactive. Nanosilica was incorporated as the final ingredient during mixing to enhance the uniformity of the fresh SCC mix. Sonication was not employed in this present work. The adopted procedure was based on Marsh Cone flow test findings, which showed that flow time increased with increasing NS addition. The images of SCC trial mixes, shown before and after the addition of NS, show a fresh SCC mix becoming uniform and cohesive after NS is added.

2.6. Superplasticizer

A PCE-based superplasticizer admixture is selected for the trial mixes in this experimental study. High-range water-reducing (HRWR) CONXL PCE 2635 from Chemcon TecSys, Chennai, is used in the trial mixes, which are Type 'G' as per ASTM C494 standards.

3. Mix Design Methodology

Methods as per IS 10262:2019 and IS 9103:1999 are used for proportioning normal concrete mixes. "European Guidelines for self-compacting concrete: 2005" is referred to for the design and evaluation of SCC mix. Preliminary trial mixes are planned to study the behaviour of NS and UFBFS, as well as their interactions. A slurry-based trial is planned to assess the effect of NS on the cement slurry. A concrete trial mix is initially conducted to determine the water-reduction efficiency and dosage of the selected superplasticizer.

Table 3. Mix design criteria

Description	Nominal mix	SCC mix
Grade mix	M60	M60
Target mean strength	60+1.65×5 = 71.25 MPa	60+1.65×5 = 71.25 MPa
Maximum Water to Binder Ratio	0.31	0.31
Nominal Maximum Size of coarse aggregates	20mm	12.5 mm
Assumed Air content	1%	1.5%
Workability Test	Slump Test (200+/-25mm)	Flow (600-700mm), T500, V-Flow & J-Ring Flow

Table 4. Fresh concrete property requirements of SCC

Fresh Concrete Properties	Test Method	Requirement
Flowing Ability	Slump Flow	600 +/- 50mm
Viscosity	T500	< 6 seconds
Viscosity	V-Flow	< 26 seconds
Passing Ability / Segregation resistance	J-Ring Flow	Difference between Slump Flow and J-Ring Flow < 50mm

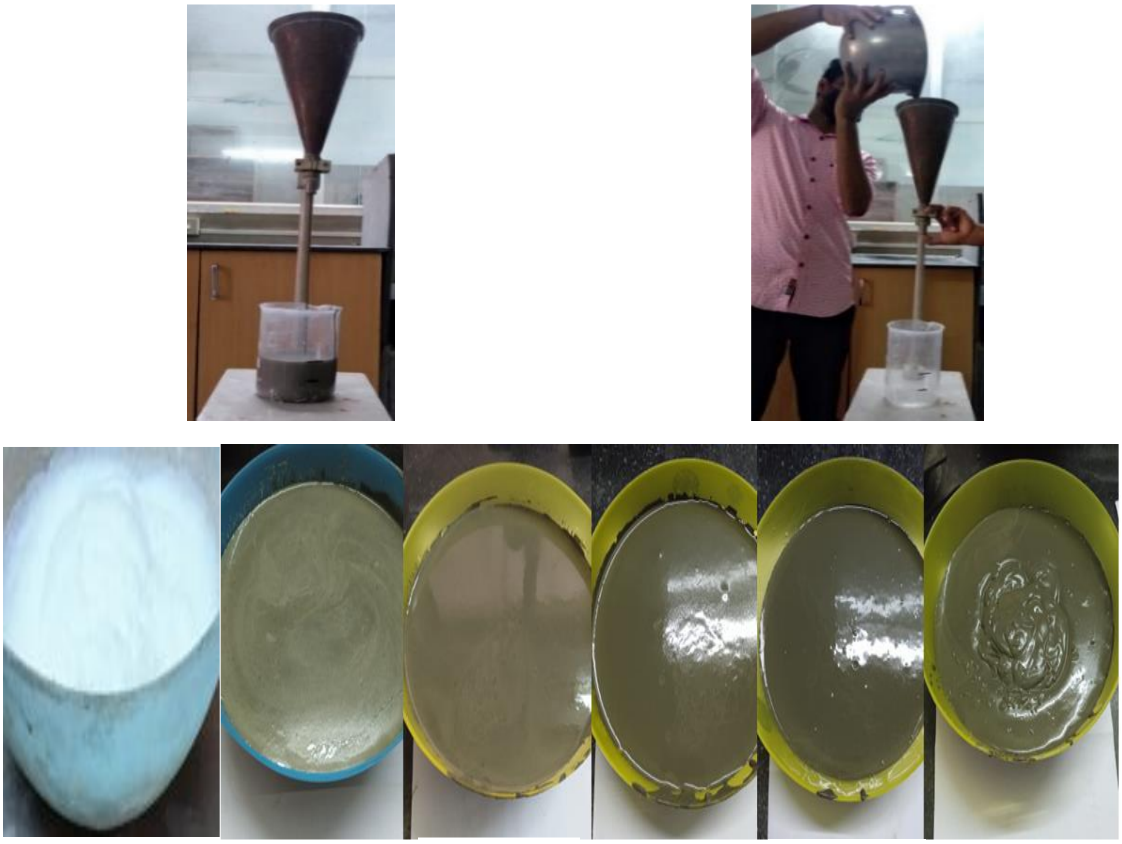
A set of trial mixes for the M60 grade is planned to assess the effect of UFBFS on concrete compressive strength and to evaluate its potential to reduce OPC content in the mix. Trial mixes for the main objective of proportioning M60 grade SCC with UFBFS and NS are planned to be conducted subsequently. Details of the mix design criteria are provided in Table 3, and the fresh concrete properties of the SCC considered in the experiments are provided in Table 4. After verifying fresh concrete properties, samples are taken, and specimens are cast to measure the hardened concrete properties of the mixes for comparison and evaluation.

4. Experimental Works on NS and UFBFS

4.1. Marsh Cone Test

To understand the influence of nanosilica on workability (flowability), a Marsh cone test was conducted on a cement slurry. The Marsh cone test is used to measure the fluidity/rheology of one or more combinations of cementitious materials and superplasticizer [40]. It helps to establish cement-admixture compatibility to achieve an optimal superplasticizer dosage. The same method was used to determine the rheology of slurry with OPC and NS, measured as the time taken for a half-litre slurry to flow through the Marsh Cone. In the Marsh cone test, the flow duration of slurry mixes having varying NS percentage was determined. To evaluate the influence of NS in cement slurry, slurry mixes containing 0%, 0.25%, 0.5%, 0.75%, and 1.00% NS with respect to OPC content were prepared, with OPC content, water content, and SP dosage held constant. It is evident from Figs. 3 & 4, with an increase in the percentage of NS in the slurry, the slurry flow duration increased as the slurry became increasingly stiffer.

Many researchers have found that NS increases water demand in cement paste or concrete mixes owing to its very high surface area. In other words, it alters the viscosity of the mix [41, 42]. The Marsh cone test of the cement slurry indicates that increasing the NS dosage reduces the slurry's flowability. Hence, it can be concluded that the addition of NS to the slurry medium of a concrete mix would increase the yield stress, thereby preventing segregation in the flowing concrete [43].



0% NS 0.25%NS 0.50%NS 0.75%NS 1.0% NS

Fig. 3. Marsh Cone test, image of NS and images of slurry with varying % of NS

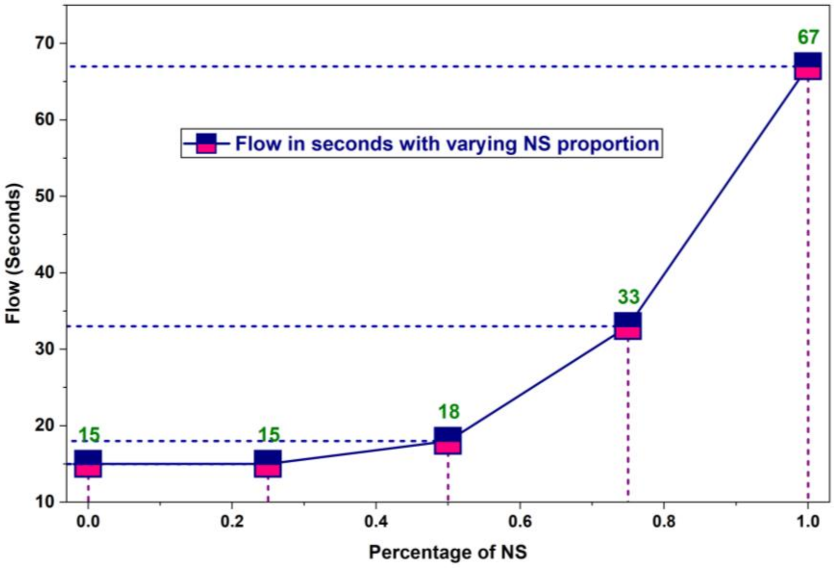
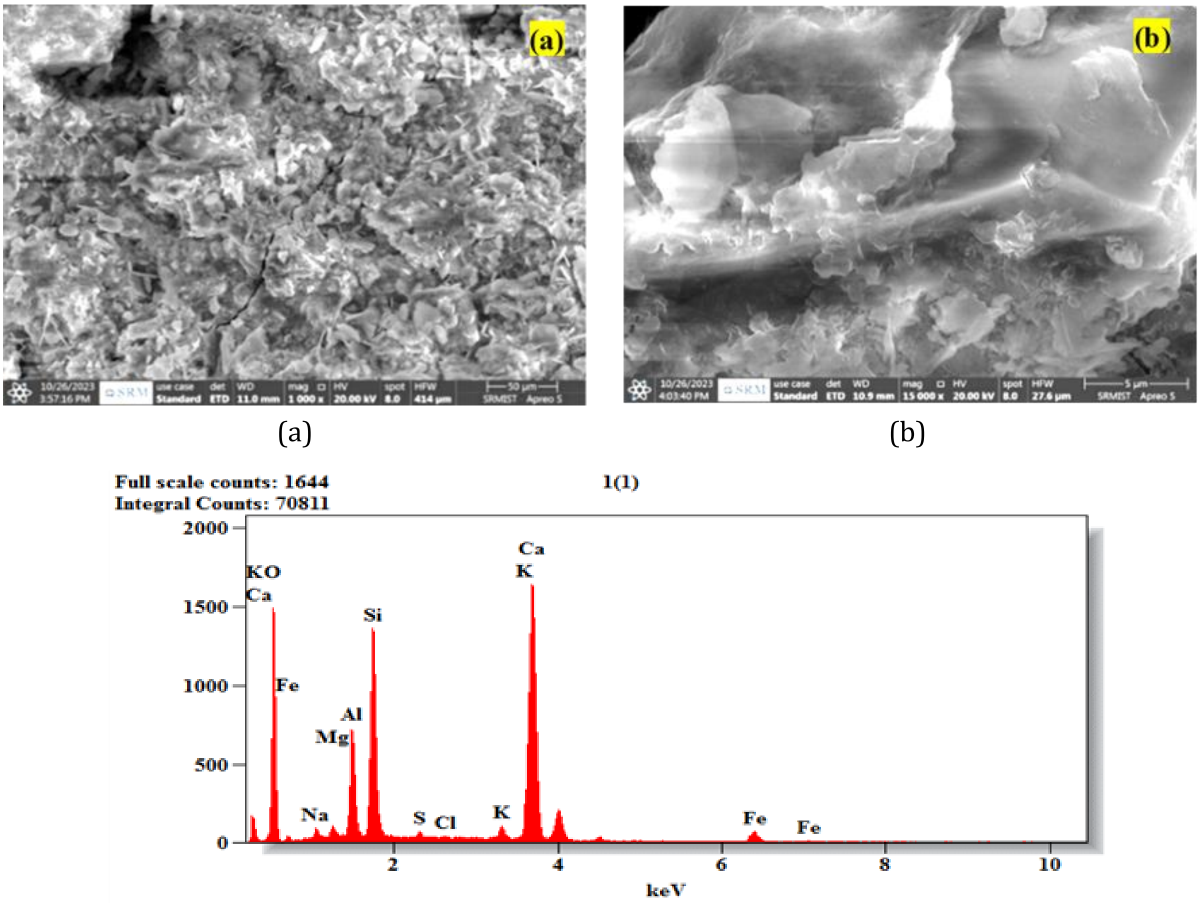


Fig. 4. Increase in flow duration with increase in NS proportion

4.2. SEM-EDX and XRF Analysis

Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) was performed on two paste samples: one containing pure OPC and the other containing a combination of OPC and NS. These paste specimens were cured for 28 days, and images were taken from their thin sections. SEM images in Figs. 5 and 6, when compared, show dispersion of NS Particles in the paste containing NS.



(a) (b)

(c)

Fig. 5. Hydrated paste with OPC a) image 50 μm scale, b) image at 5 μm and c) EDX image

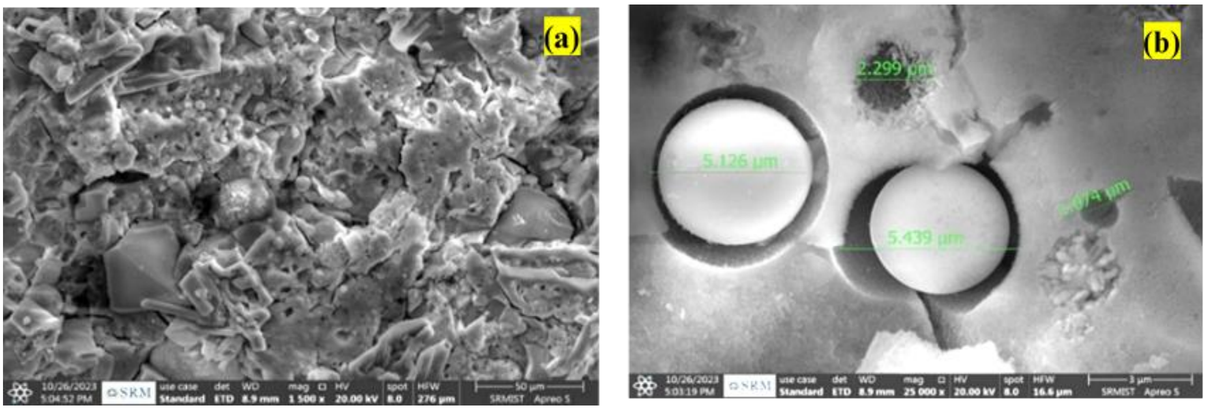
EDX data of the paste combining OPC and NS, as reported in Table 6, also indicate a relatively higher Si content (15.15%) and a lower Ca content (4.93%) in the vicinity of NS. In contrast, paste with pure OPC contains a higher Ca content (24.7%), as shown in Table 5. Particle size (5.1 µm) of NS in Fig. 6 (b) indicates that there is agglomeration of NS particles. The possible reason is explained by Lavergne F et al., who reported that flocculation of NS occurs due to the presence of Ca ions in the pore solution, which adsorb to the NS surface [42]. However, it is observed that, despite flocculation of NS, the slurry becomes more viscous, which is of particular importance to the current research.

Table 5. EDX data of the slurry with OPC

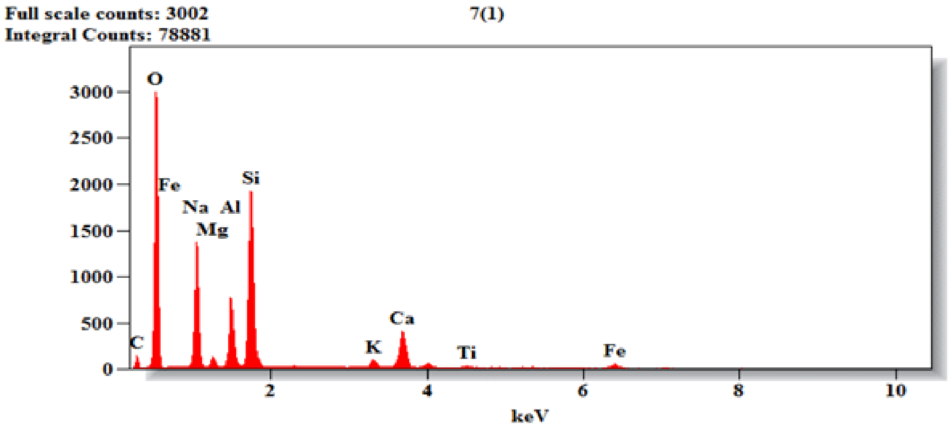
Element	Net counts	Weight (%)	Atom (%)	Atom error (%)	Formula
O	8125	52.66	70.29	± 0.80	O
Na	445	0.94	0.88	± 0.07	Na
Mg	463	0.65	0.57	± 0.05	Mg
Al	5369	5.68	4.50	± 0.11	Al
Si	11903	11.88	9.04	± 0.11	Si
S	329	0.29	0.20	± 0.03	S
Cl	32	0.03	0.02	± 0.02	Cl
K	830	0.89	0.48	± 0.03	K
Ca	20563	24.70	13.16	± 0.14	Ca
Fe	784	2.27	0.87	± 0.10	Fe
Total		100.00	100.00		

Table 6. EDX data of slurry with OPC and NS

Element	Net counts	Weight (%)	Atom (%)	Atom error (%)	Formula
C	748	3.96	6.36	± 0.29	C
O	16841	52.54	63.31	± 0.48	O
Na	9638	14.30	11.99	± 0.15	Na
Mg	579	0.74	0.59	± 0.09	Mg
Al	5627	5.32	3.80	± 0.10	Al
Si	17382	15.15	10.40	± 0.10	Si
K	854	0.79	0.39	± 0.02	K
Ca	4920	4.93	2.37	± 0.06	Ca
Ti	190	0.27	0.11	± 0.02	Ti
Fe	862	2.00	0.69	± 0.04	Fe
Total		100.00	100.00		



(a) (b)



(c)

Fig. 6. Hydrated paste with OPC & NS a) image 50 µm scale, b) image at 3 µm shows NS in agglomerated condition, and c) EDX image

4.2. Concrete Trial Mixes with UFBFS

Trial mixes were conducted to determine the dosage of superplasticizer (CONXL PCE 2635) to achieve an initial slump value of about 230 mm. From the trial mix M60-ADMX, as shown in Table 7, the chosen SP at a dosage of 3.2 kg/cum imparts the required workability, resulting in a slump value of 225 mm. In the next step, comparative trial mixes were conducted to determine the optimal UFBFS dosage based on concrete compressive strength. Five M60 Grade mix designs with varying content of UFBFS, i.e., @ 0 kg (M60-UF0), 15 kg (M60-UF15), 20 kg (M60-UF20), 30 kg (M60-UF30) and 40 kg (M60-UF40) were proportioned. The total binder content was kept constant at 570 kg/cum, and with an increase in UFBFS content, the amount of OPC in the mixes was reduced by the same amount, as shown in Table 7. Trial mixes were conducted to measure the workability of the mixes, as shown in Fig. 7, and the corresponding slump values are presented in Table 8. Compressive strength values for the mixes were recorded and presented in Table 8, and the results were analyzed as shown in Fig. 8. UFBFS was used in its “as produced” form along with other binders, namely OPC and fly ash.


M60-UF0 M60-UF15 M60-UF20 M60-UF30 M60-UF40 M60-F0C M60-UF25

Fig. 7. Slump test conducted on varying UFBFS %, and its influence on workability

Cube compressive strength test results show that increases in values are significant for mixes with UFBFS quantities ranging from 20 kg/cum to 30 kg/cum, with 20 kg/cum corresponding to a 5.4% UFBFS-to-OPC ratio and 30 kg/cum corresponding to an 8.3% UFBFS-to-OPC ratio. From 8.30% to 11.40%, the strength increase is marginal. Hence, the optimal replacement efficiency of UFBFS can be considered to fall between 5% and 8%. Another set of trial mixes was conducted for confirmatory purposes. Since optimal strength gain was found to fall between the mixes containing 20 kg and 30 kg UFBFS, a mix containing 25 kg UFBFS per cum was selected. Confirmatory trial mixes were conducted with a nil UFBFS mix (M60-UF0C) and the mix with 25 kg UFBFS (M60-UF25) as given in Table 7. Slump test values and compressive strength test values for these mixes are also shown in Table 8.

As confirmed by Ahmad S et al. [44] in their experimental work on UFBFS, the current study found that slump values increase marginally with increasing UFBFS percentage. An increase in compressive strength is also observed with increasing UFBFS content up to an 8% UFBFS-to-OPC ratio. The contribution of UFBFS to strength gain is highly associated with earlier experimental findings [44, 45]. Due to their extreme fineness, UFBFS particles disperse well and become so effective that their replacement ratio to OPC exceeds 1.0 at an optimal UFBFS/OPC ratio. Based on the trial mixes conducted, it can be concluded that incorporating UFBFS positively influences both the fresh concrete properties and the compressive strength.

Table 7. Mix proportion used for initial experimental works on UFBFS efficiency

Material	Initial	Trial Mixes with varying UFBFS %					Confirmatory Trial Mixes	
	M60-ADMX	M60-UF0	M60-UF15	M60-UF20	M60-UF30	M60-UF40	M60-UF0C	M60-UF25
OPC	390	390	375	370	360	350	390	350
Fly Ash	180	180	180	180	180	180	180	180
UFBFS	0	0	15	20	30	40	0	25
20mm	455	455	455	454	454	454	455	461
12.5mm	453	453	453	453	453	452	453	459
CS Sand	725	725	725	724	724	724	725	735
Water	174	174	174	174	174	174	174	170
Total	2377	2377	2377	2375	2375	2374	2377	2380
PCE 2635	3.2	3.25	3.15	3.00	2.80	2.70	3.2	2.9
W/B	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Binder Content	570 kg	570 kg	570 kg	570 kg	570 kg	570 kg	570 kg	555 kg
% UFBFS/OPC	0.0%	0.0%	4.0%	5.4%	8.3%	11.4%	0.0%	7.1%

Table 8. Slump values and compressive strength values improve with an increase in UFBFS

Properties	Initial	Trial Mixes with varying UFBFS%					Confirmatory Trial Mixes	
	M60-ADMX	M60-UF0	M60-UF15	M60-UF20	M60-UF30	M60-UF40	M60-UF0C	M60-UF25
% UFBFS/OPC	0.0%	0.0%	4.0%	5.4%	8.3%	11.4%	0.0%	7.1%
Workability test, slump measurement in mm								
Initial slump	225	230	230	225	245	240	230	225
Cube compressive strength test results in MPa								
7 day	54.2	57.2	54.2	55.7	53.3	55.2	52.7	55.6
28 day	69.6	69.0	70.6	72.1	72.8	73.1	68.4	71.5
Increase in 28-day strength over reference mix, %	---	Ref. mix	2.3	4.5	5.5	5.9	Ref. mix	4.5

A second set of trial mixes was conducted for confirmatory purposes to optimize OPC content and measure the influence of UFBFS on compressive strength; the results also show similar findings. In the comparison between a mix without UFBFS (M60-UF0C) and a mix with 25kg/cum UFBFS (M60-UF25), the mix with UFBFS (M60-UF25) showed enhanced workability even when the superplasticizer dosage was reduced by 10%. Strength gain of mix M60-UF25 with 25 kg/cum of UFBFS is calculated to be 4.5% over the reference mix M60-UF0C, even with the reduction of 40kg/cum of OPC. With increased compressive strength in the M60-UF25 mix, it is shown that optimizing OPC and total binder content is possible with the incorporation of UFBFS. This approach serves as the basis for reducing OPC content and increasing aggregate content (to compensate for the mix volume) in the modified SCC mix design that is being experimentally investigated.

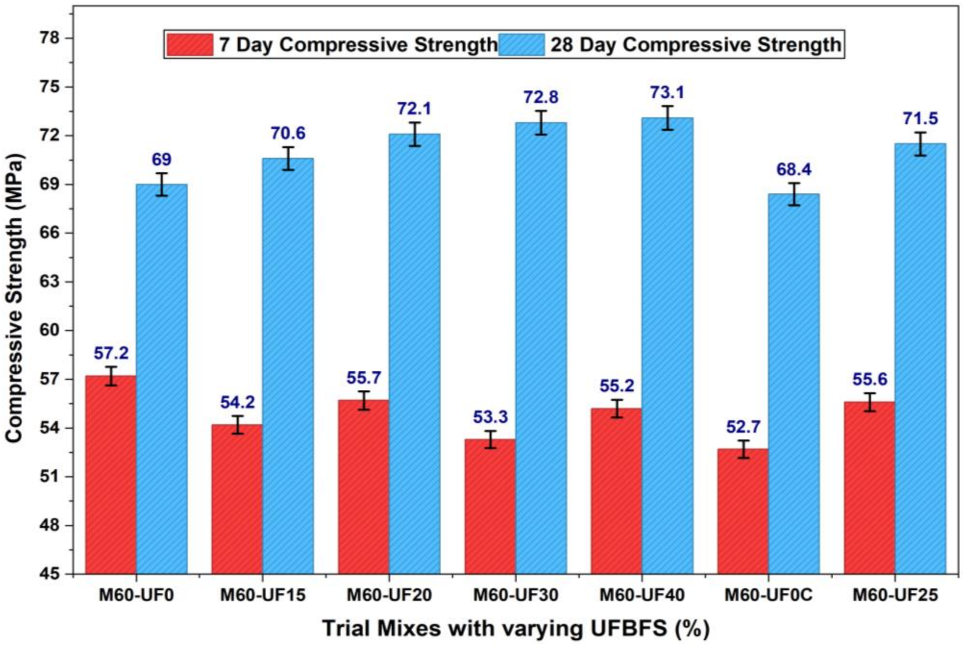


Fig. 8. Influence of UFBFS on 7 & 28 day compressive strength results

5. Experimental Investigations on the Application of UFBFS and NS in M60 SCC

Initial experimental studies conducted so far in this research work, using NS and UFBFS, have provided insight into the influence of these two materials on the behaviour of cement slurry and concrete mix, particularly on fresh slurry/concrete properties. While NS increases the viscosity of the cement slurry, UFBFS enhances the workability of the concrete mix [46]. NS, thus, is expected to play a role in making SCC robust in the fresh stage by controlling bleeding and preventing segregation. UFBFS, by enhancing workability, helps reduce water content and superplasticizer dosage. The ability of UFBFS to replace OPC at a ratio greater than 1:1 in terms of compressive strength performance is considered another important factor in reducing binder content and, consequently, meeting the objective of mitigating the probability of shrinkage in SCC mixes. Hence, the incorporation of NS & UFBFS into SCC mixes was found to be efficient, as it supports the aim to optimize binder and aggregate contents by reducing the former and increasing the latter, thereby reducing shrinkage risk. In this experimental work, the conventional self-compacting concrete (SCC-Conv) mix is designed with a combination of OPC and fly ash as binders, whereas the modified self-compacting concrete (SCC-Mod) is designed with a combination of OPC, fly ash, and UFBFS as binders, with NS as the rheology-modifying additive. A PCE-based HRWR superplasticizer was used to achieve the required flow [47].

5.1. Trial Mixes Comparison on Conventional SCC and Modified SCC with UFBFS And NS

A conventional SCC mix with an OPC and fly ash combination of 390+180 kg/cum (SCC-Conv1) was evaluated first. In the initial trial mix, slight segregation, in the form of aggregate settling, was observed (Fig. 10(a)). Hence, this mix was discarded, and no further testing was performed. To enhance uniformity, the binder content was increased to 400+200 kg/cum, as conventionally done, and a trial mix (SCC-Conv2) was conducted. An increase in total binder content improved the uniformity of the SCC-Conv2 mix, as shown in Fig. 10 (b). The SCC-Conv2 mix met the required flow properties, as shown in Figs. 10(c), 10(d), and 10(e). After finalizing the conventional SCC mix design, a modified SCC (SCC-Mod) mix was developed to reduce the total binder content by combining OPC, fly ash, UFBFS, and NS. While designing Modified SCC, the quantities of 30 kg of OPC and 30 kg of fly ash were reduced. OPC was reduced based on the initial trial mixes, indicating that UFBFS offers greater OPC replacement potential, whereas 30 fly ash was reduced, as the dependency on higher binder content is expected to be reduced with the addition of NS [3]. Fig. 9

shows the reduction in binder content and paste content in the SCC-Mod mix. Mix designs of SCC (Conv1), SCC (Conv2) and SCC (Mod) are given in Table 9.

Table 9. SCC mix designs, conventional and modified

Material	SCC-Conv 1	SCC-Conv 2	SCC-Mod
OPC	390	400	370
Fly ash	180	200	170
UFBFS	0	0	25
12.5mm	821	795	827
CS Sand	803	777	809
Water	167	174	165
Total density	2361	2346	2366
PCE 2635	5.1	5.1	4.8
Nanosilica	0	0	1.2
UFBFS / OPC ratio	0	0	6.8%
W/B ratio	0.29	0.29	0.29
Total binder content by weight, kg	570	600	565
Paste content by volume, litres	376.5	396.2	372.1

Table 10. Fresh concrete properties test results

Properties Tested	SCC-Conv2	SCC-Mod
Fresh Concrete Properties		
Slump Flow Initial	660 mm	650 mm
T500, initial	4.5 sec	4.8 sec
V-Flow initial	12 sec	11 sec
J-Ring Flow, initial	620 mm	620 mm
Slump Flow, 1 hour	650 mm	650 mm
T500, 1 hour	4.8 sec	5.0 sec
V-Flow, 1 hour	13 sec	13 sec
J-Ring Flow, 1 hour	620 mm	620 mm

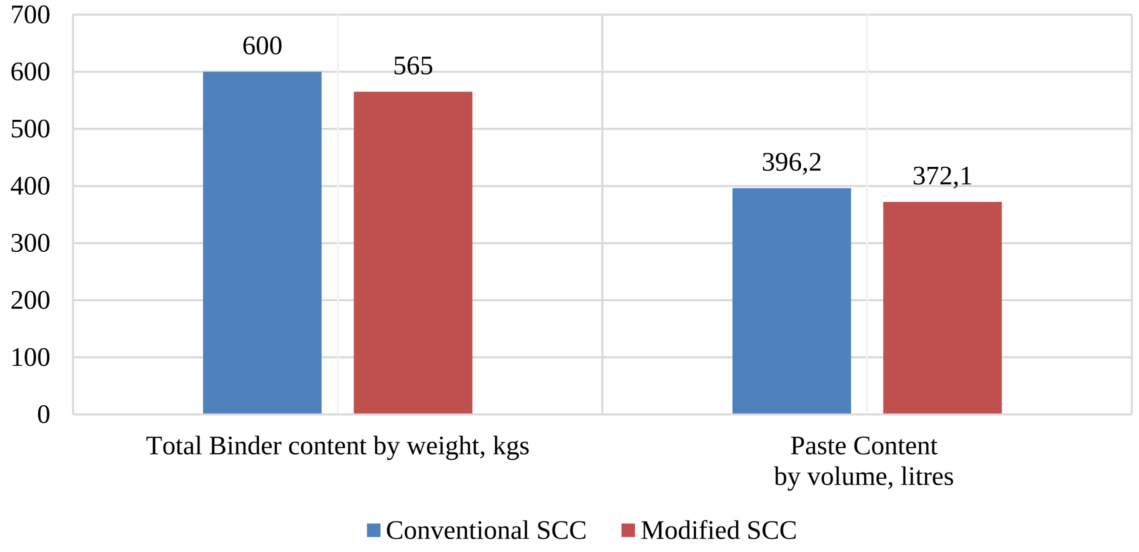


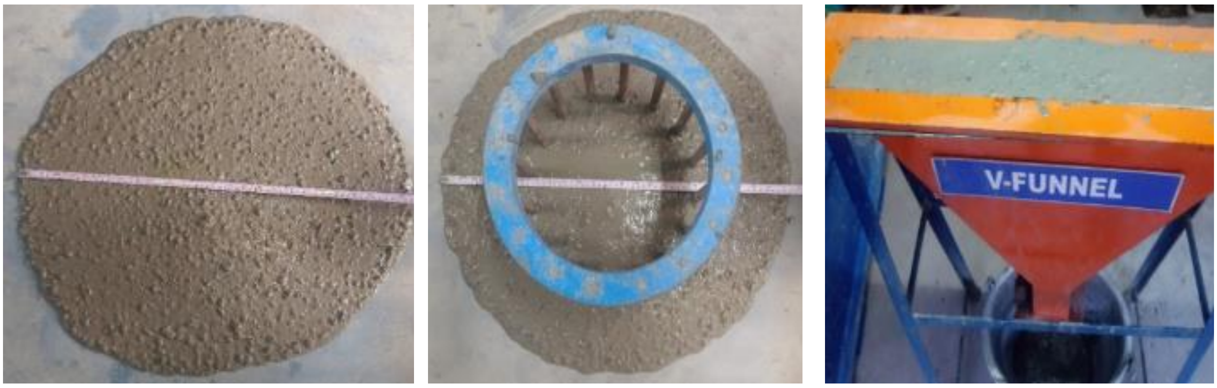
Fig. 9. Reduction in binder and paste contents in Modified SCC mix

The properties of the Modified SCC mix were measured and recorded, as shown in Fig. 11 and Table 10. Samples for testing hardened concrete properties, such as compressive strength, flexural strength, water penetration resistance, rapid chloride penetration resistance, and water absorption, were cast and tested as shown in Fig. 12. Test results for hardened concrete properties are shown in Table 11. As conventionally practiced, a total binder content of 600 kg/cum is required to achieve uniformity in the SCC M60 mix and to meet the required SCC flow properties. With the incorporation of UFBFS and NS, the modified SCC mix with reduced binder content of 565 kg/cum, is able to meet SCC flow requirements. The ability of NS to impart more viscosity in the flowable SCC mix and to make it more uniform is evident from the trial mix.

SCC-Conv1Mix (390+180) SCC-Conv2 Mix (400+200)

(a) 12.5 mm settling (b) Improved uniformity

Flow Tests on SCC-Conv2

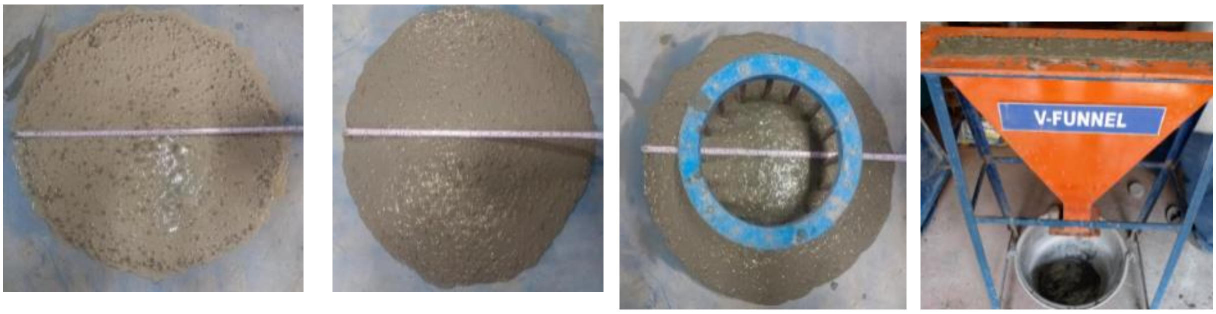


(c) Slum Flow (d) J-Ring Flow (e) V-Flow

Fig. 10. Behaviour of SCC mixes: CC-Conv1 (390+180 kg/m^3 binder content) showing segregation and SCC-Conv2 (400+200 kg/m^3 binder content) exhibiting uniformity

Mix in the mixer machine

(a) SCC-Mod before the addition of NS (b) SCC-Mod after the addition of NS



Flow Tests – SCC-Mod with NS

(c) Before the addition of NS

(d) After the addition of NS

(e) J-Ring Flow

(f) V-Flow

Fig. 11. SCC modified mix proportion comprising 370 kg/m3 OPC + 170 kg/m3 fly ash +25 kg/m3 UFBFS + 1.2 kg/m3 NS exhibiting improved uniformity and fresh flow properties

5.2. Test Results of Hardened Concrete Properties

Compressive strength and Flexural strength properties of SCC-Mod mix are comparable to those of SCC-Conv2. However, a significant improvement in the durability properties of the SCC-Mod mix has been observed compared to the SCC-Conv2 mix. Water penetration resistance increased by 34%, chloride penetration resistance increased by 40% at 28-day age and by 67% at 56-day age, and water absorption reduced by 12%. As reported in other studies, the addition of UFBFS has enhanced concrete durability [48].

Table 11. Hardened concrete properties test results

	Cube compressive strength	
7 days	52.7 MPa	56.3 MPa
28 days	69.2 MPa	70.3 MPa
	Beam flexural strength	
7 days	4.7 MPa	4.9 MPa
28 days	6.9 MPa	6.8 MPa
	Water Penetration test results	
28 days	5.0 mm	3.3 mm
	RCPT evaluation	
28 days	1341 coulombs	796 coulombs
56 days	986 coulombs	329 coulombs
	Water absorption	
28 days	5.0 %	4.4 %

Compressive Strength

Flexural

Water Penetration

RCPT

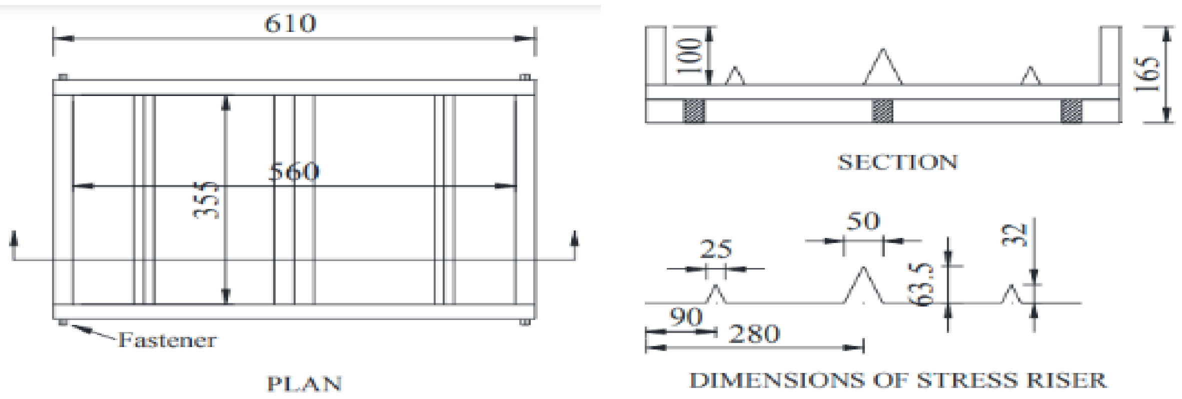
Water Absorption

Fig. 12. Tests conducted on the strength and durability properties of SCC mixes

5.3. Plastic Shrinkage Investigation on Conventional SCC and Modified SCC Mixes

A plastic shrinkage study was conducted by casting both SCC-Conv2 and SCC-Mod mixes in a mould with stress risers to induce cracking. The mould set-up was as per ASTM C1579, as shown in Fig.

13. To maintain temperature and humidity, a humidity chamber was used. Temperature was maintained at 40 ± 2 °C, and Humidity at 40 ± 5% for both test samples. Both SCC-Conv2 and SCC-Mod mixes, as per the designs given in Table 9, were mixed in a laboratory pan mixer and were placed into the mould. Compaction was done with a stainless-steel tamping bar. The surface was finished with a trowel, and the test specimens were placed inside the humidity chamber immediately after finishing. Observations were made every 30 minutes.



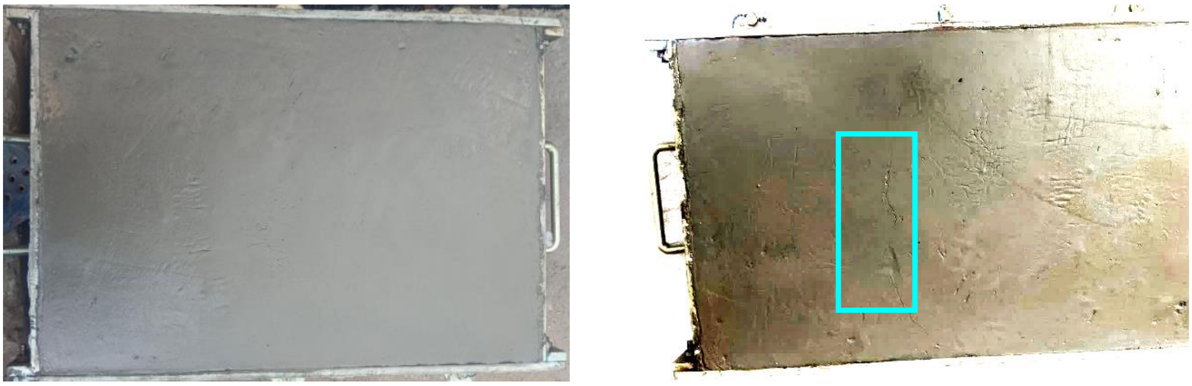
(a) Mould with Stress Raisers

(b) Mould used for the study

Fig. 13. Plastic shrinkage mould used in the study

In the specimen cast with SCC-Conv2, a plastic shrinkage crack was observed at 2 hours after casting, as shown in Fig. 14(a). It was observed that the crack propagated slowly. The final appearance of the crack was observed at 12 hours, by which time the concrete had become hard enough to resist the plastic shrinkage crack, as shown in Fig. 14 (d). SCC-Mod observed for 12 hours until the mix hardened, as seen in Fig. 15, did not exhibit any early-age cracking, as the mix was able to withstand the stress induced by the stress risers.

It has been well documented by many researchers, including Jamali A et al. [49], that capillary pressure, with the formation of a meniscus between finer particles, is one of the main reasons for Plastic Shrinkage and subsequent cracking, as concrete is weak in the plastic state. As found in studies on SCC mixes by Birdu Y et al. [50] and Rozie et al. [51], mixes with a higher binder content tend to exhibit greater shrinkage. The reason is that a higher binder content makes capillary pores smaller, thereby reducing the meniscus radius and increasing capillary pressure, leading to greater shrinkage. An increase in aggregate content in Modified SCC (SCC-Mod) enhances resistance to shrinkage. A current experimental study on plastic shrinkage also shows that a Modified SCC (SCC-Mod) mix with reduced binder content and increased aggregate content resists cracking at early ages. In contrast, a Conventional SCC (SCC-Con) mix cracks at early ages. The addition of nanosilica is found to modify viscosity and contribute to early strength gain in the paste medium. These two properties are considered important factors in mitigating plastic shrinkage behaviour [52, 53]. The addition of UFBFS and NS to the SCC-Mod mix has resulted in improved resistance to early-age shrinkage.



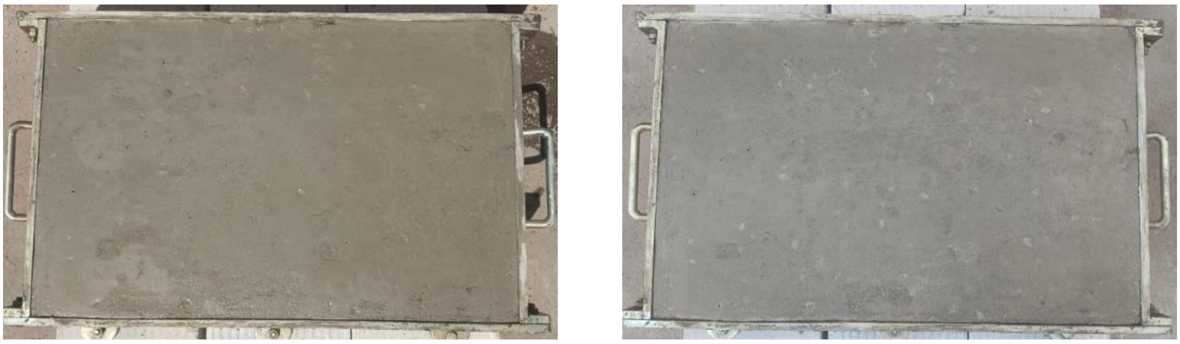
(a) Immediately after casting

(b) Initiation of cracks at 2 hours

(c) After 6 hours

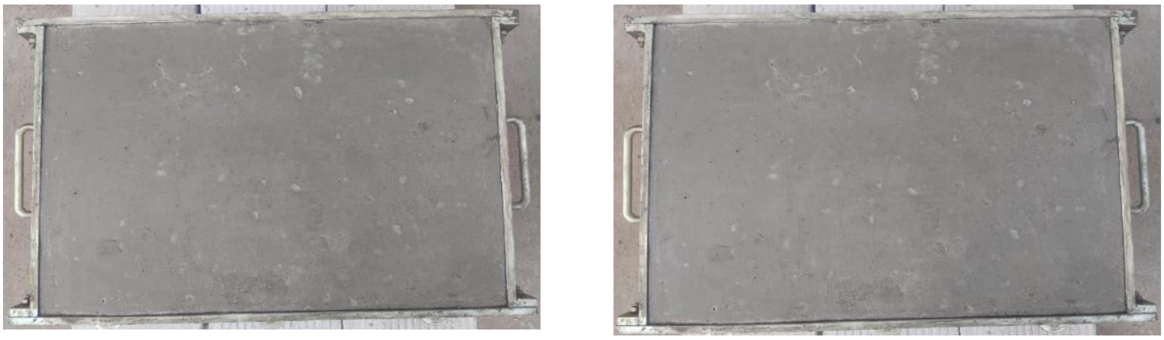
(d) Appearance of Full Crack after 12 hours

Fig. 14. Initiation and propagation of PSC till concrete hardens



(a) Immediately after casting

(b) After 2 hours



(c) At 6th Hour

(d) No Crack after 2 hours

Fig. 15. SCC-Mod mix resisting PSC

5.4. Drying Shrinkage Investigations on Conventional and Modified SCC Mixes

A Drying Shrinkage study was conducted to compare SCC-Conv2 Mix and SCC-Mod Mix as per ASTM C157. Three prism specimens with dimensions of 75 mm x 75 mm x 285 mm were cast as shown in Fig. 16 (a) for each mix and cured for 14 days before being dried in a humidity chamber. A length comparator was used to measure changes in length over a 28-day drying period. The test setup is shown in Fig. 16 (b). Periodic length change values recorded through the 28-day test period are presented in Table 12 and Fig. 17.

(a) Specimens cast in the mould

(b) Length comparator

Fig. 16. Drying shrinkage assessment by measuring length change

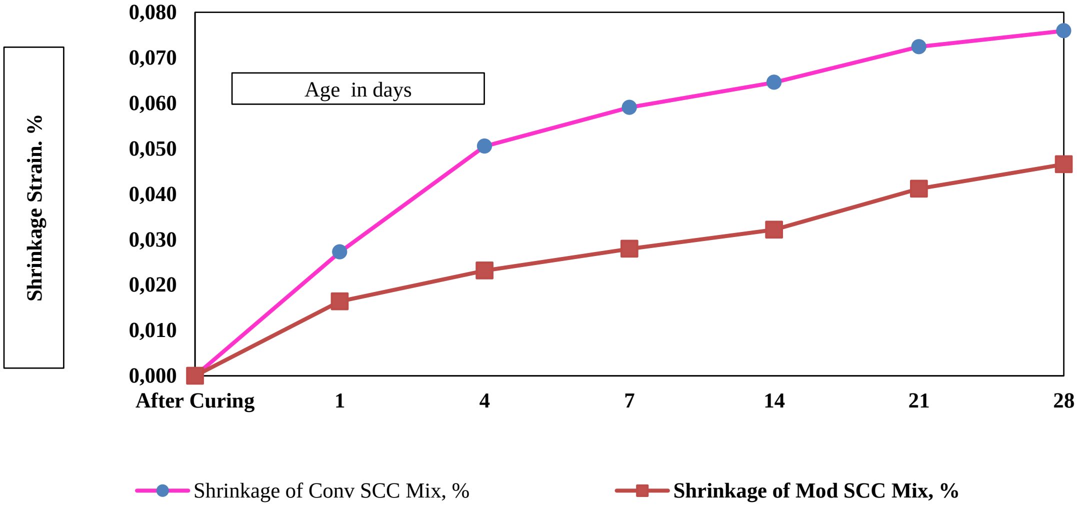


Fig. 17. Length change values over 28 days drying

Table 12. Length change values over 28 days of drying

Age of Testing, day	After Curing	Period of Drying					
		1day	4day	7day	14day	21day	28day
Shrinkage of SCC-Conv2 Mix (%)	0.000	0.027	0.051	0.059	0.065	0.072	0.076
Shrinkage of SCC-Mod Mix (%)	0.000	0.016	0.023	0.028	0.032	0.041	0.047

Drying shrinkage of modified SCC with reduced paste content is lower than that of conventional SCC. It must be noted that a reduction in free water associated with a reduction in binder content results in a reduction in gel-pore water. Drying shrinkage, a result of the loss of gel-pore water as discussed by Mastali et al. [54], is thus reduced in SCC-Mod. An increase in aggregate content in the

SCC-Mod mix, compensating for the reduction in paste content, also contributes to reduced drying shrinkage.

5. Results and Discussions

- Conventional SCC (SCC-Conv) mix requires a higher binder content to prevent segregation in the fresh state and to achieve uniformity.
- A modified approach is required to optimize binder content and reduce SCC's shrinkage probability. Incorporating UFBFS and nanosilica is considered in this research work following an analysis of their potential through initial experimental work.
- It is evident that the addition of UFBFS increases workability, helping reduce the superplasticizer dosage by 10% and the water content by 4kg/cum, despite an increase in total aggregate content in the modified SCC mix (SCC-Mod).
- The ability of nanosilica to enhance the viscosity of the paste medium when added as the last ingredient is evident from experiments conducted on both the slurry and the SCC mix. Similar findings have been reported by many researchers.
- It has been experimentally found that the addition of nanosilica imparts greater uniformity in the SCC-Mod mix, demonstrating flowability similar to that of SCC-Conv, even when the total binder content is reduced by 35kg/cum compared with SCC-Conv.
- The SCC-Mod mix that incorporates UFBFS and nanosilica shows compressive and flexural strengths similar to those of SCC-Conv, despite reduced binder and paste content.
- In durability tests, a 41% reduction in RCPT value at 28 days of age is observed in the SCC-Mod mix, which increases to 67% at 56 days of age. A 12% reduction in porosity at 28 days of age is also observed in the SCC-Mod mix. Water penetration resistance of SCC-Mod has increased by 34%.
- Plastic shrinkage behaviour of the conventional mix is more evident, with a crack emanating from the stress-inducing central section where a raiser is located. The crack initiated as early as 2 hours and propagated into a longer, wider crack within 12 hours after casting. The modified SCC mix resisted cracking, and the specimen remained uncracked until the concrete hardened.
- Drying shrinkage tests show that the Modified SCC mix, with an increased aggregate-to-paste ratio, exhibited 38% less shrinkage than the conventional SCC mix, a significant difference.

6. Conclusions

The primary objective of developing a self-compacting concrete (SCC) mix with reduced shrinkage probability was achieved in this study. Results from the experiments demonstrated that incorporating UFBFS and nanosilica (NS) reduced the total binder from 600 kg/m^3 to 565 kg/m^3, meeting the flow requirements and fresh properties of SCC. The modified SCC mix achieved a similar 28-day compressive strength of around 70 MPa and an equivalent flexural strength compared with conventional SCC. Durability performance increased significantly, with a 41% decrease in RCPT value at 28 days, followed by a 67% decrease at 56 days. An increase of 12% in water penetration resistance and a decrease of 34% in water absorption were also observed at 28 days of age. The modified SCC mix also did not exhibit the plastic shrinkage cracks observed with the conventional SCC mix, and its drying shrinkage was reduced by about 38% compared with the conventional SCC mix. The outcome shows that while UFBFS contributes to increased strength, NS primarily serves as a rheology modifier to achieve a uniform, stable mix, and the addition of these two finer materials enhances the durability and shrinkage resistance of SCC. From these experimental findings, it can be inferred that the combined use of UFBFS and NS could be an effective approach for producing a durable SCC mix with an optimized binder quantity and enhanced shrinkage resistance.

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