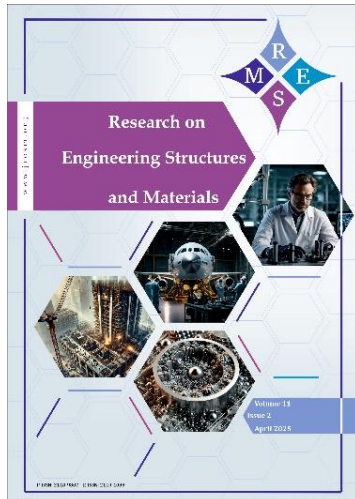




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Performance evaluation of modified self-compacting concrete incorporating UFBFS and nano-silica across varying aggregate densities and strength grades

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Abstract

Self-Compacting Concrete (SCC) mixes typically require higher binder content to address segregation that could hinder passing ability and increase the shrinkage probability; therefore, a modified approach is required to address these challenges. Building upon previous findings on M60 grade SCC designed with ultrafine blast-furnace slag (UFBFS) and nano-silica (NS), this study expands the scope of the modified SCC mix design approach to M50 and M70 SCC mixes, using granite-type aggregates as done in the earlier study. The experiment was extended to M50, M60, and M70 SCC mixes with basalt-type aggregates, using the same binder contents of 520 kg/m³, 565 kg/m³, and 610 kg/m³, respectively. Verified for flow properties, all the mixes achieved slump flow values between 650mm and 680mm, T₅₀₀ less than 6 seconds, a slump to J-ring flow difference less than 50mm, and a V-flow duration of 11 seconds or less. The 28-day compressive strength and flexural strength results for M50, M60, and M70 grade SCC fell in the ranges of 59.0 MPa to 83.4 MPa and 5.5 MPa to 9.20 MPa, respectively. Durability tests at 28 days showed water penetration of less than 10 mm and water absorption of less than 5.5%, and at 56 days, rapid chloride penetration results were less than 800 coulombs. This modified SCC mix design approach could be used across a wider region of India.

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1. Introduction

The ability of self-compacting concrete (SCC) to flow and fill formwork is considered both a material and a solution in time-bound construction projects. The major difference between a normal concrete and an SCC is the conversion of a plastic mass into a flowable material. However, such a conversion has its own challenges, such as resisting bleeding and segregation within a flowable mass, and maintaining homogeneity throughout manufacturing, transportation, and placement. Hence, SCC mixes are invariably designed with various filler materials, such as supplementary cementitious materials (SCMs), lime powder, and marble powder to achieve flowability with uniformity [1–7]. Construction of modern day high-rise residential apartments with a tunnel-housing system involves casting RCC slabs along with a series of interconnected, thin walls with cutouts for doors, windows, electrical/plumbing service requirements, and architectural projections. Other applications where SCC is required include critical structures such as shear wall structures, columns with heavy reinforcement, composite columns with hollow sections, and encased pre-engineered building (PEB) structural members, etc., where both placing and compaction of concrete are difficult. To overcome the casting challenges in these structures, designing and applying SCC mixes with flowability, optimal viscosity and cohesiveness is essential [8]. Equally essential is optimizing the binder content in SCC mixes so that heat of hydration and

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probability of shrinkage, especially at early age, could be limited and durability of the structure is enhanced.

In 1986, Okamura first proposed the idea of SCC to augment durable construction practices. In 1988, Ozawa and Maekawa at the University of Tokyo developed unique methods to design and validate fresh concrete properties for SCC. To demonstrate the functioning of SCC, a prototype application was carried out in 1988. In a pioneering effort, Ozawa et al. developed a deformable (flowable) mix containing lower amounts of coarse aggregate and higher proportions of powder materials, combining OPC, slag, and fly ash. Their experimental work found that, to achieve a flowable mix without segregation, a paste content sufficient to provide adequate viscosity was necessary. Their recommendation was to limit the coarse aggregate content to 50% by solid volume, with the remaining volume occupied by mortar with sufficient deformability to enable the fresh mix to flow without segregation [9].

To design and qualify an SCC mix, fresh concrete properties such as flowability, passing ability, segregation resistance, and viscosity are used as criteria [10]. Okamura and Ouchi noted that a highly viscous paste is required to prevent blockage of coarse aggregates as they flow through obstacles. They mentioned when concrete is deformed, paste with a high viscosity also prevents localized increases in internal stress due to the approach of coarse aggregate particles. High deformability can be achieved only by employing a superplasticizer, while keeping the water-powder ratio very low [11]. To achieve the fresh concrete properties, designing an SCC mix with higher binder content, more than that required in a normal mix, tends to be the concept as it increases the quantity of the paste medium to transport the aggregates with uniformity [12, 13].

However, designing an SCC mix using a powder-based approach is not an efficient approach, as increasing the binder content to achieve uniformity and prevent segregation requires numerous permutations and combinations. The investigation by Miao Lv et al. on various powder-based SCC mix designs concluded that “it might require lots of experiments and waste of material to obtain the SCC mix proportion with satisfying performance” [14]. Their approach, too, was to recommend only a modified powder-based mix design, with rigorous experimental analysis. A powder-based mix design approach increases the shrinkage behavior at both early and later ages of concrete. Various researchers have reported an increased probability of cracking in SCC mixes with higher paste content [15–17]. Hilmioglu et al., reported that cracking in SCC occurred at lower stresses than in normal concrete [18]. A powder-based SCC mix design approach could: increase the probability of shrinkage at both early and long-term ages, require a high number of trial mixes with varying permutations and combinations, rely on additional resources for bulk materials, and increase carbon footprint.

An alternative approach in designing SCC mix is to incorporate a viscosity-modifying agent (VMA) without requiring a much higher binder content. Khayat, K.H et al in 1997 tried VMA in high slump concrete mixes and concluded that “incorporation of a viscosity-modifying admixture is shown to significantly enhance the resistance to bleeding, settlement, and segregation [19]”. Although fillers such as limestone powder were also used to prevent segregation in SCC, their effectiveness is limited. Garcia L et al., reported that additional limestone fines reduced the mix's robustness during the T_{500} and V-Flow tests. They also reported that the mix cohesiveness, as measured by segregation resistance, improved when VMA replaced limestone fines [20]. An experimental observation by Gettu R et al., demonstrated that the robustness of the SCC mix improved with the addition of VMA [21]. However, reports indicated that VMA could adversely affect the hardened properties of concrete. J. Golaszewski reported that a viscosity-enhancing agent (VEA), another term for VMA, might affect compressive strength and recommended that the evaluation of SCC mixes not be limited to rheological properties alone [22]. Wojciech K et al., concluded that VMA use negatively affected the air permeability of concrete. Furthermore, the strength of CEM III concrete decreased with increasing VMA content [23]. Beata Lazniewska Piekarczyk mentioned that “superplasticizers (SPs) and VMAs from different sources cannot be used interchangeably, even if they appear to have a similar chemical composition” [24]. VMA availability in India is limited to very few suppliers, and its production is import-dependent. Apart from receiving the material on time, ensuring the compatibility between superplasticizers and VMAs from different

manufacturers is a major challenge. Moreover, issues such as the air-entraining tendency of VMA, which reduces the strength and durability of concrete, and its retarding effect, which results in delayed setting/hardening of concrete, are considered adverse impacts of VMA on SCC mixes, especially at higher dosages.

When designing SCC mixes, replacing OPC partially with fly ash is essential to achieve an economical mix and reduce the heat of hydration [25, 26]. Partial replacement of OPC is achieved through the addition of one of the two Supplementary Cementitious Materials (SCMs), namely, fly ash and ground granulated blast furnace slag (GGBS). It is also essential to reduce the total binder content, which is a combination of OPC and an SCM, to reduce the probability of concrete shrinkage. The reduction of OPC can be achieved by incorporating micro silica (MS) or ultrafine blast furnace slag (UFBFS). While MS, a by-product of the silicon and ferrosilicon industries, is imported into India, UFBFS is produced by grinding blast furnace slag (BFS), a by-product of the steel manufacturing process. UFBFS is produced and supplied in India either directly by steel manufacturers or by dedicated manufacturers.

Both MS and UFBFS have higher OPC replacement potential due to their higher pozzolanic index. MS, with its higher percentage of reactive silica (SiO_2) exceeding 85% and BET fineness of more than 15,000 m^2/kg , can replace OPC at a ratio of more than 1:1. Its ability to enhance mechanical properties such as compressive strength has been published through various research works, including that of Smarzewski, P [27]. Similarly, UFBFS with higher fineness, in excess of 1500 m^2/kg (BET method), and with reactive compounds in the form of calcium (CaO), silica (SiO_2) and alumina (Al_2O_3) can contribute to the strength with more than 100% efficiency when it replaces OPC in 5% to 10% range. Various studies indicated the beneficial effects of UFBFS on properties such as strength and durability [28–31].

Among MS and UFBFS, the latter can be considered more suitable in the Indian context. The reason is that MS, apart from its limited availability stemming from import dependence, can undergo partial de-densification of its densified particles during mixing, which can have a negative impact, as reported by Diamond S et al. [32]. In terms of influence on workability, while micro silica reduces the workability [33], ultra-fine slag enhances the workability [34], making UFBFS addition advantageous. Positive effect of UFBFS on workability could be attributed to its smooth surface texture derived from the parent granulated slag. MS supplied in bags poses a burden and a health hazard during storage and handling. UFBFS is supplied through bulk carriers directly from the manufacturing units. It can be stored in a silo and used in 'as produced form' through a batching system, a process that removes the dependence on manual storage and addition.

The reduction in binder content, including OPC, is compensated for by an increase in aggregate content to achieve the mix's design yield. Aggregates, especially coarse aggregates, are inert and act as internal restraints that mitigate shrinkage in concrete mixes [35]. However, this could increase friction among aggregate particles in the mix, leading to segregation. Though VMA is found to address these challenges, limitations of VMA in the form of technical challenges as mentioned above, coupled with a lack of VMA manufacturers to ensure quality and consistent supply of VMA in India, necessitate an alternate methodology. Such a methodology shall aid in designing an SCC mix as a uniform, flowing concrete mass with adequate viscosity and optimal binder content.

Nano-silica (NS), a novel material, has attracted the attention of many researchers in the fields of medicine and engineering due to its nanoscale efficacy. Its role in modifying the rheology of the cement slurry is significant in SCC mixes that require robustness and adequate yield stress. Kontoleon et al. reported that the yield stress increased considerably when NS was incorporated into the paste; on the other hand, changes in plastic viscosity were less pronounced [36]. [Click or tap here to enter text.](#), indicating ability of NS in making the paste medium viscous. The experimental investigations of G. Quercia et al. confirmed that the addition of nano-silica reduced the workability, indicating an increase in the mix's yield stress [37]. Xiuzhi Zhang et al. observed that the viscosity of SCC increased with increasing NS (less than 0.3%), but the yield stress values changed little [38]. The dispersion of NS with particle sizes less than 40 nm in fresh concrete mixes requires attention. While discussing the dispersion of NS in concrete mix, Kaffayatullah Khan et al., highlighted that poly carboxylate ether (PCE) based admixture is capable of NS dispersion in concrete mix [39].

Farid Alvansaz et al. concluded that the loss of workability in concrete mix with the addition of NS was addressed with superplasticizers [40]. Dispersion of NS ensures that larger nanoparticle agglomerates do not compromise the intended performance of the SCC mix. PCE-based superplasticizing admixture, which has become mandatory in SCC mixes, plays an additional role as a dispersing agent through its steric hindrance behavior and thus, dispersion of NS is addressed.

A previous study by the authors compared conventional powder-based M60-grade SCC with modified M60-grade SCC incorporating UFBFS and NS. The experimental findings indicated that, despite a reduction in total binder and paste contents compared with conventional SCC, the modified SCC achieved uniformity and met all flow criteria. The compressive strength results of modified SCC were comparable to those of the conventional SCC, and it even performed better in shrinkage mitigation and durability enhancement [41]. This study showed that while UFBFS was useful in reducing a higher quantity of OPC, NS, when used as the final ingredient, enhanced the uniformity and cohesiveness of M60 SCC mix that exhibited segregation due to reduced binder content, at an appropriate dosage. The learnings indicate the likelihood of adopting this modified approach in SCC mixes with varying grades, binder contents, and aggregate densities. In India, SCC has become a necessity in infrastructure projects, and in the construction of both commercial buildings and high-rise residential apartments. The types of rocks used to manufacture concrete aggregates in India can be broadly divided into 'granite' in the southern part and 'basalt' in the northern part. The properties of aggregates in these two types of rocks, such as relative density, shape, size, texture, particle distribution, strength, and brittleness, vary from one another. Among these, the higher relative density values of the aggregates would increase aggregate content and fresh concrete density, thus making SCC mix susceptible to segregation. If the modified approach to SCC mix design that validated the performance of M60 SCC with granite-type aggregates could contribute to similar performances in other grades of SCC mix and for other types (basalt) of aggregates, it could be considered as a unique solution for designing SCC mixes for the wider area of the country. Hence, the authors aim to provide an alternative method for the industry by examining and validating the modified SCC mix design approach for a wider range of SCC mixes through this experimental study. There are three objectives set in this experimental research work.

- The first objective is to incorporate UFBFS and NS into the design and evaluation of SCC mixes for two other grades, namely M50 and M70, with granite-type aggregates. The design of these two SCC mixes is based on the modified M60 SCC mix design approach.
- The second objective is to evaluate the performance of UFBFS and NS-based modified M50, M60 and M70 grade SCC mixes with basalt-type aggregates. The binder content and its combination are kept the same as in the mixes designed with granite-type aggregates.
- The third objective, inherent to the modified SCC mix design approach, is to simplify the mix design procedure, which helps in adopting SCC mixes without a large number of trials and difficult algorithms. The potential efficiency of NS in enhancing the uniformity of the SCC mix is considered a key contributor to this simplification objective.

The experimental work has been formulated with the following scope: designing SCC mixes using a modified approach incorporating UFBFS and NS, with NS added last. Validating the SCC mix designs by measuring the fresh concrete properties (Slump Flow, T_{500} and V-Flow tests as per EFNARC 2005, and J-Ring Flow and Visual stability index (VSI) as per ASTM C1621 and ASTM C1611), hardened concrete properties (compressive and flexural strength) and durability properties (rapid chloride penetration test, water penetration resistance and water absorption). The objectives of the present research work, as mentioned above, are to arrive at M50, M60, and M70 SCC mix designs with optimal binder content for two types of aggregates through a modified approach. The ability of the three mixes in meeting fresh concrete requirements and the strength and durability requirements is considered validation for such a modified approach.

2. Materials

2.1 Aggregates

Granite-type aggregates, both coarse and fine, were sourced from the crusher unit at Walaja, near Chennai, Tamil Nadu. Basalt-type aggregates, both coarse and fine aggregates, were sourced from

the crusher unit located near Indore in Madhya Pradesh. Both crushers consisted of a three-stage crushing process, with a vertical shaft impact (VSI) crusher being the third-stage crusher. Nominal maximum size (NMS) for both types of coarse aggregates was 12.5 mm. Crushed stone sand (CSS) was considered 100% of fine aggregates in experiments with granite-type aggregates. A combination of river sand (RS) and crushed stone sand at a 50:50 volumetric ratio was considered in experiments with basalt-type aggregates to achieve particle size distribution as per the Zone II requirement of IS 383. Particle size distributions of all aggregates are given in Table 1 and in Figs. 1 and 2. Impact value, crushing value, flakiness indices, elongation indices, relative density and water absorption values for both granite-type and basalt-type aggregates are given in Table 2. Fig. 3 shows the differences in appearance between granite-type and basalt-type CSS, with the latter being darker in color. Fig. 4 shows samples of coarse and fine aggregates from both sources used in the experiments.

Table 1. Particle size distribution of coarse and fine aggregates

S.I. No	Sieve Size	Granite-type, Chennai Cumulative passing (%)		Basalt-type, Indore Cumulative passing (%)			
		12.5 mm	CS sand	12.5 mm	CS sand	River sand	Combined CSS & RS
1.	20 mm	100	-	100	-	-	-
2.	12.5 mm	98	-	98	-	-	-
3.	10 mm	65	-	36	-	-	-
4.	6.30 mm	8	-	10	-	-	-
5.	4.75 mm	2	100	1	100	98	99
6.	2.36 mm	-	98	-	78	96	87
7.	1.18 mm	-	68	-	37	92	65
8.	0.60 mm	-	48	-	21	75	48
9.	0.30 mm	-	26	-	9	13	11
10.	0.15 mm	-	13	-	5	2	3
Fineness modulus of fine aggregates (IS 2386: Part I)			2.47	-	3.50	2.24	2.87

Table 2. Relative density and water absorption values of coarse and fine aggregates

Properties of aggregates	Granite-type, Chennai		Basalt-type, Indore		
	12.5 mm	CS sand	12.5 mm	CS sand	R sand
Relative density, SSD (IS 2386: Part III)	2.70	2.64	2.88	2.77	2.67
Water absorption (IS 2386: Part III)	0.50%	1.52%	1.42%	2.48%	1.35%
Flakiness Index (IS 2386: Part I)	8.40%	-	8.80%	-	-
Elongation Index (IS 2386: Part I)	11.20%	-	14.50 %	-	-
Impact value (IS 2386: Part IV)	23%	-	10.90 %	-	-
Crushing value (IS 2386: Part IV)	27%	-	17.20 %	-	-
Los Angeles Abrasion value (IS 2386: Part IV)	29%	-	26%	-	-

Note: In trial mix design calculations, water absorption values were used to adjust water and aggregate contents, depending on the moist/dry condition of the aggregates, to maintain free water to binder ratio and calculated aggregate contents of the mixes.

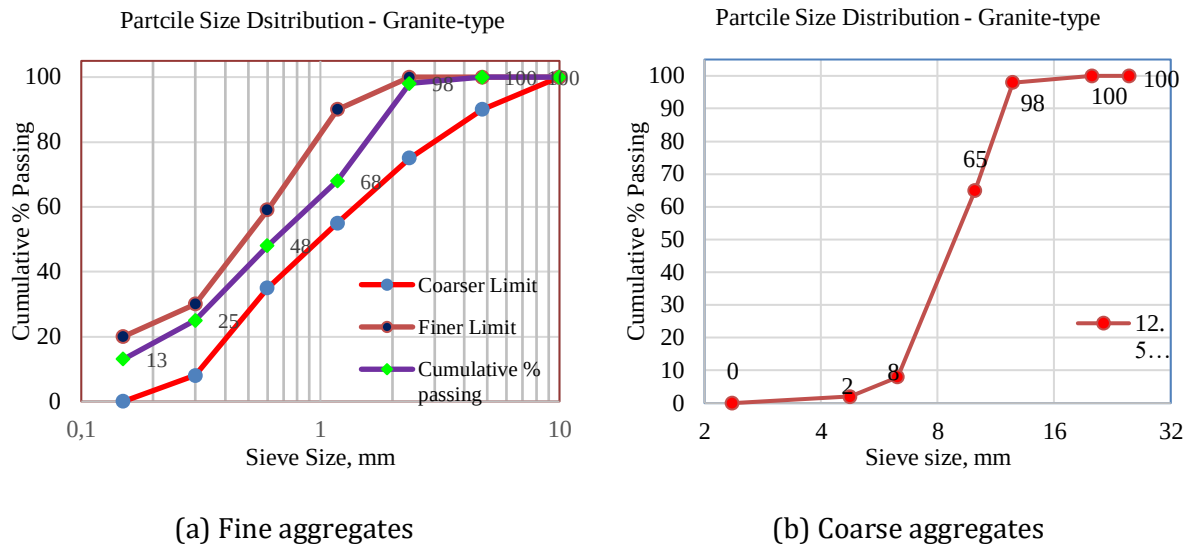


Fig. 1. Particle size distribution of granite-type aggregates

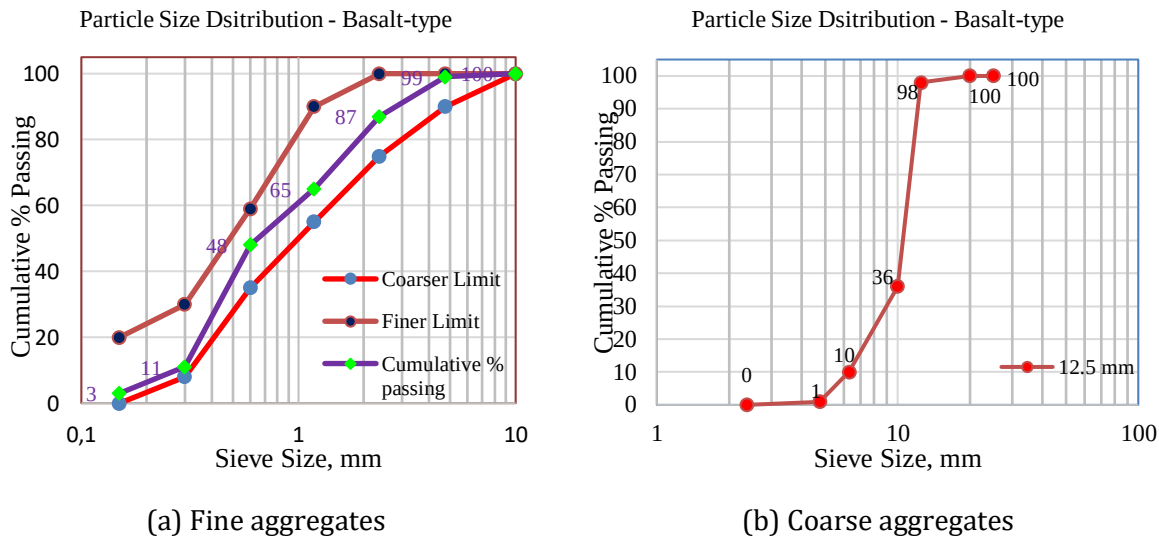
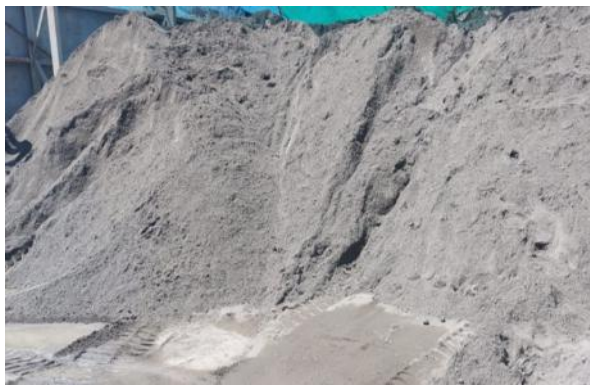


Fig. 2. Particle size distribution of basalt-type aggregates



(a) Granite-type CSS, (Chennai source)

(b) Basalt-type CSS (Indore source)

Fig. 3. Granite-type and basalt-type (CSS) images in the stock yard, distinguishing the difference



(a) Granite-type 12.5mm & CSS, Chennai source



(b) Basalt-type 12.5mm, CSS and RS, Indore source

Fig. 4. Images of aggregate samples used in the trial mixes

2.2 Binder Materials, NS and Superplasticizer

The binder materials used to develop simplified SCC consisted of Ordinary Portland Cement (OPC) grade 53, class F fly ash, and ultrafine blast-furnace slag (UFBFS), commercially available as Alccofine 1208. For the consistency of properties, OPC procured from a single source, "UltraTech Cement" from Chennai, was used throughout the experimental program. The North Chennai Thermal Power Plant (NCTPP) was the source of Class F fly ash, which was collected from the electrostatic precipitator (ESP). The UFBFS material chosen was Alccofine (by Gujarat Ambuja Limited), finely ground blast-furnace slag with BET fineness of 2730 m²/kg, meeting the requirements as per IS 16715:2018 (amended 2019). Nano-silica (NS) was supplied by ASTRRA Chemicals, Chennai, in powder form with BET fineness of 202 m²/g and silicon dioxide (SiO₂) content 99.90%. The physical and chemical characteristics of the binder materials used in this present study are summarized in Table 3. A high-range water reducing admixture (HRWR), CONXL PCE 2635, a polycarboxylate ether (PCE) based superplasticizer, was sourced from Chemcon TecSys, Chennai, and was employed as the admixture for SCC trial mixes. The solids content, relative density, and pH of the CONXL PCE 2635 superplasticizer were measured at 40%, 1.10, and 6.1, respectively.

Table 3. Physical and chemical characteristics of constituent binding materials

Property	OPC	Fly ash	UFBFS	NS
Specific gravity (IS 2386 – Part III)	3.15	2.10	2.90	2.40
Blaine fineness (IS4031- Part II)	274 m ² /kg	326 m ² /kg	-	-
BET fineness (IS 15388/IS 16175)	-	-	2,730 m ² /kg	202 m ² /g
Average particle size	-	-	4.30 μm	0.017 μm
SiO ₂	20.40 %	64.20 %	32.30%	99.90 %
Al ₂ O ₃	4.90 %	26.64%	20.60%	-
Fe ₂ O ₃	4.90 %	4.96%	-	-
CaO	59.70 %	2.11 %	34.20%	-
SO ₃	2.80 %	0.19 %	0.26 %	-
MgO	1.80%	-	7%	-
MnO	-	-	0.35%	-
Chloride content	0.011%	-	0.015%	-
Equivalent Na ₂ O	0.41%	0.83%	0.48%	-
Loss on ignition	2.80 %	0.20 %	0.11 %	0.66 %

3. Mix Proportion Details of the SCC Mix

The SCC mixes were proportioned and tested in accordance with the European Guidelines for SCC mixes-2005 [10]. The mix design criteria adopted for the present investigation and its corresponding fresh property requirement are summarized in Tables 4 and 5, respectively. The mix proportions used in this investigation were obtained from the authors' earlier study [41], in which the simultaneous use of UFBFS and NS was employed to optimize the binder content to meet the fresh properties requirements of SCC. To meet the desired strength requirements, three SCC grades (M50, M60, and M70) were proportioned by selecting appropriate binder and free-water contents. The water binder ratio of M50, M60 and M70 grades was considered as 0.33, 0.29 and 0.25, respectively. The coarse and fine aggregates were kept at the same solid volume ratio (50:50), while the binder system comprised ordinary Portland cement (OPC), Class F fly ash, and UFBFS. The purpose of adding NS was to enhance the cohesiveness and stability of fresh SCC, and mixing was performed using a laboratory mixer; no sonication of NS was employed.

Table 4. SCC mix design parameters

Description	SCC mix		
Grade mix	M50	M60	M70
Target mean strength	$50+1.65 \times 5 = 58.25$ MPa	$60+1.65 \times 5 = 68.25$ MPa	$70+1.65 \times 6 = 79.50$ MPa
Maximum Water to Binder Ratio	0.33	0.29	0.25
Nominal Maximum Size of coarse		12.5 mm	
Assumed Air content		1.5%	
Workability Test	Flow (600-700mm), T500, V-Flow, J-Ring Flow & VSI		

Table 5. Fresh concrete property requirements for SCC

Fresh Concrete Properties	Test Method	Requirement
Flowing Ability (EFNARC)	Slump Flow	650 +/- 50mm
Viscosity (EFNARC)	T500	< 6 seconds
Viscosity (EFNARC)	V-Flow	< 12 seconds
Passing Ability / Segregation resistance (ASTM C1621)	J-Ring Flow	Difference between Slump Flow and J-Ring Flow < 50mm
Segregation Resistance (ASTM C1611)	VSI	0

3.1 Mixing Process

In the trial mix process, aggregates were placed in the pan mixer first, followed by the addition of UFBFS, OPC and Fly ash in sequence. Dry mixing was performed for 2 minutes, followed by another 2 minutes of mixing after adding the total water. PCE admixture was then added, and mixing was continued for 4 minutes to achieve the mix's workability/flowability. NS was added manually as the final ingredient, and mixing was continued for 2 minutes; this duration was sufficient to disperse NS and enhance the uniformity of the mix. Visual inspection before the addition of NS showed segregation in all the mixes, invariably. Visual inspection was performed after adding NS to ensure the flowable mix was uniform. The appearance of coarse aggregates on the surface of the fresh mix, with no bleeding after mixing NS, was considered a requirement for a uniform and cohesive mix. Appropriate moisture correction for fine aggregates and water absorption correction for coarse aggregates were carried out based on the moisture test results. Since the maximum water-to-binder ratio was 0.33, the entire mix water was added to make the mix as wet as possible, ensuring effective dispersion of the PCE admixture. Trial mixes for each grade were prepared in batches of 40 liters to ensure adequate volume and better uniformity for fresh concrete property tests and sampling for hardened concrete property tests.

4. Experimental Investigation

The modified SCC mix design approach used in the present study was developed from the authors' previous research on M60 SCC with granite-type aggregate. In that study, the combined

incorporation of NS and UFBFS aided in optimizing the binder content. The performances of that modified M60 SCC mix, in terms of fresh, mechanical, durability, and shrinkage properties, were measured to be satisfactory. Results showed that NS increased cohesiveness in the fresh mix, while UFBFS replaced a higher amount of OPC content without reducing hardened properties. The positive results from the modified mix design approach demonstrated its feasibility and functioned as a basis for the present study. This method has yet to be applied to SCC with basalt-type aggregate, however. Compared with granite-type aggregates, basalt-type aggregates have higher relative densities, which lead to higher fresh concrete density and a greater tendency towards segregation. The first phase of the present study is to extend the modified approach to M50 and M70 grade mixes designed with granite-type aggregates. The second phase is to evaluate the modified SCC mix design method for three grades of SCC: M50, M60, and M70, using basalt-type aggregate. Prior to the SCC mix study, paste studies were conducted with and without NS to gain insight into the role of NS in early-age strength development.

4.1 Influence of NS on Setting Time and Early Strength of Paste

In the present study, an experiment was conducted to measure the setting time pattern and compressive strength at 12 and 24 hours age for paste samples with and without NS. The purpose is to identify the early setting and hardening patterns of paste with NS compared with paste without NS, factors that are considered mitigating early-age cracking of concrete. Two pastes, one with pure OPC (0% NS) and another with a combination of OPC and 0.25% NS by weight of OPC, were prepared for both tests. The Vicat apparatus test set up shown in Fig. 5 was used to verify the normal consistency and setting times. Cube specimens measuring 50 mm × 50 mm × 50 mm were cast to determine compressive strength.

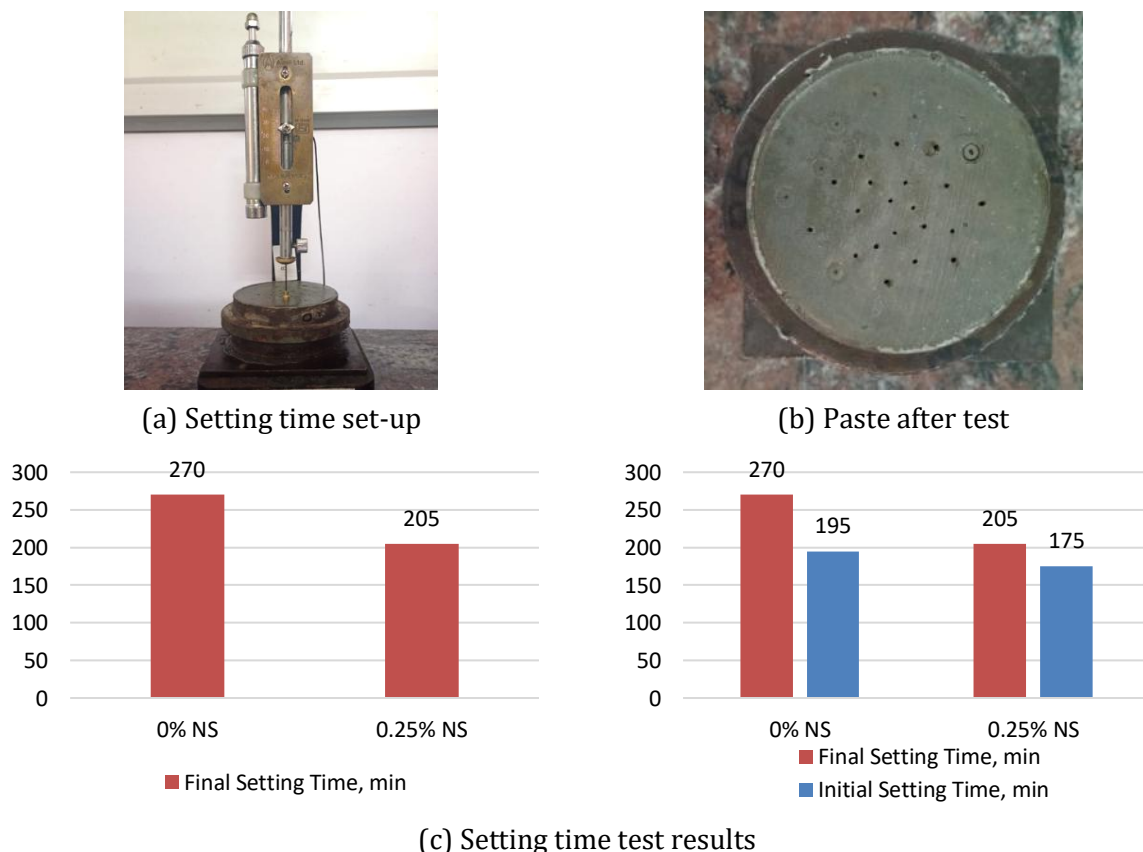


Fig. 5. Setting time test on pastes with and without NS

Pure OPC Paste was mixed in a 5-liter capacity laboratory digital paddle mixer. Initial mixing was done for 60 seconds at lower rpm followed by 60 seconds mixing at higher rpm. For the paste with 0.25% NS, after mixing of pure OPC paste for 120 seconds at lower and higher rpm, NS was added into the paste and was mixed at higher rpm for 60 seconds. Uniform mix was obtained for both the pastes with and without Nano-Silica. Both the sets of specimens in the mold

were kept inside the humidity chamber with top surface covered, at the temperature of $27 \pm 2^\circ\text{C}$ and at humidity of $95 \pm 5\%$. Specimens were removed from the molds just before testing. Water-to-cement ratio was maintained at 0.29 for both samples. The initial setting time and final setting time tests of pastes containing 0% NS and 0.25% are shown in Fig. 5 (c), and the corresponding cube compressive strength results are presented in Table 6.

Setting time tests conducted on both pure OPC paste and paste with 0.25% NS indicated that the paste with 0.25% NS reached the final setting 65 minutes earlier. Compressive strength tests conducted on these two paste samples showed that the paste with 0.25% NS achieved higher strength at 12 and 24 hours, with 35.60% increase at 12 hours, a significant difference, as shown in Fig. 6. The paste with 0.25% NS exhibited enhanced viscosity and rigidity, reaching setting time earlier and achieving higher strength in the early hours compared with pure OPC paste. Lavergne F et al., investigation showed that paste with NS promoted hydration and contributed to early strength [42]. As reported by Sun et al that, “nano-silica with small particle size provides more nucleation sites to form calcium silicate hydrate (C-S-H) seeds and to promote the hydration of C_3S and the formation of C-S-H [43]”. An experimental investigation by Paktiawal A and Alam M concluded that the utilization of nano- SiO_2 by partial replacement of cement significantly increased the hydration of the cement matrix and influenced the setting times of concrete [44]. Early setting time and early strength achievement of paste with NS are very similar to the findings of the above-mentioned research works. Early age strength gain in paste with the addition of NS is anticipated to enhance potential resistance against early age shrinkage cracking. It must be noted that the paste study was conducted with 100% OPC to isolate the pure nucleation effect of NS on OPC; pozzolanic synergy in the concrete matrix was investigated through concrete trial mixes in subsequent stages.

Table 6. Compressive strength results at the end of 12 hours and 24 hours

Compressive strength	0% NS	0.25 % NS	Strength gain of 0.25% NS
@ 12 hours	13.20 MPa	17.90 MPa	35.60%
Standard deviation	1.80 MPa	1.90 MPa	
@ 24 hours	30.20 MPa	34.40 MPa	13.90%
Standard deviation	1.90 MPa	1.60 MPa	

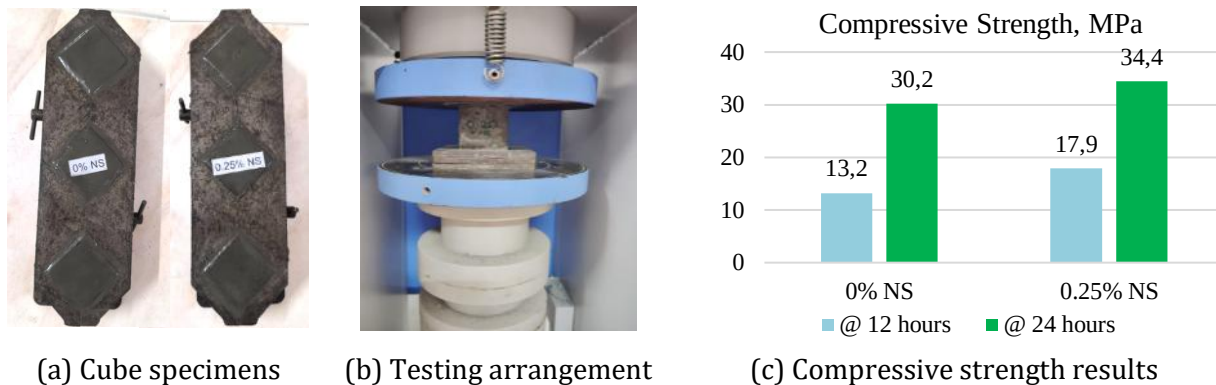


Fig. 6. Early age compressive strength outcomes from paste studies with and without NS

4.2 Design and Validation of M50 and M70 SCC Mixes with a Modified Approach Using Granite-Type Aggregates

Since the test results for both fresh and hardened concrete properties of M60 SCC (G) Mod, designed using the modified M60 SCC mix design approach in the earlier study, were satisfactory, the same approach was extended to design and validate M50 and M70 grade SCC mixes with granite-type aggregates. Binder contents were decreased and increased with respect to M60SCC (G) Mod in M50 and M70 SCC mixes, respectively, to meet the strength requirements.

Both these mixes are identified as M50 SCC (G) Mod and M70 SCC (G) Mod, where ‘G’ denotes granite-type aggregates. The volume of fine aggregates was maintained at 50% of the total aggregate content in both mixes. The mix proportions for M60, M50 and M70 modified SCC mixes

with granite-type aggregates are presented in Table 7. Flow tests conducted for both mixes are shown in Fig. 7 and Fig. 8. The test results for fresh and durability concrete properties of modified SCC mixes prepared using granite-type aggregates are presented in Table 8 and Table 9, respectively. The compressive strength and flexural strength progression of modified SCC mixes (M50 SCC (G) Mod, M60 SCC (G) Mod, and M70 SCC (G) Mod) at the age of 7 and 28 days, are presented in Figs. 9 and 10, respectively.

Table 7. M60, M50 and M70 modified SCC mix designs with granite-type aggregates

Type of materials	*M60 SCC(G) Mod	M50 SCC(G) Mod	M70 SCC(G) Mod
OPC	370	330	410
Fly ash	170	170	170
UFBFS	25	20	30
12.5 mm	827	840	821
CS Sand	809	821	803
Water	165	170	155
Total	2366	2351	2389
CONXL PCE 2635	4.8	4.40	5.30
Nano-Silica	1.2	1.40	1.0
UFBFS / OPC	6.80%	6.10%	7.30%
W/B ratio	0.29	0.33	0.25
Total binder content by weight, kg	565	520	610
Paste content by volume, liters	372.10	362.70	376.60
NS/OPC	0.32%	0.42%	0.24%

*Mix design of M60 SCC (G) Mod obtained from earlier study

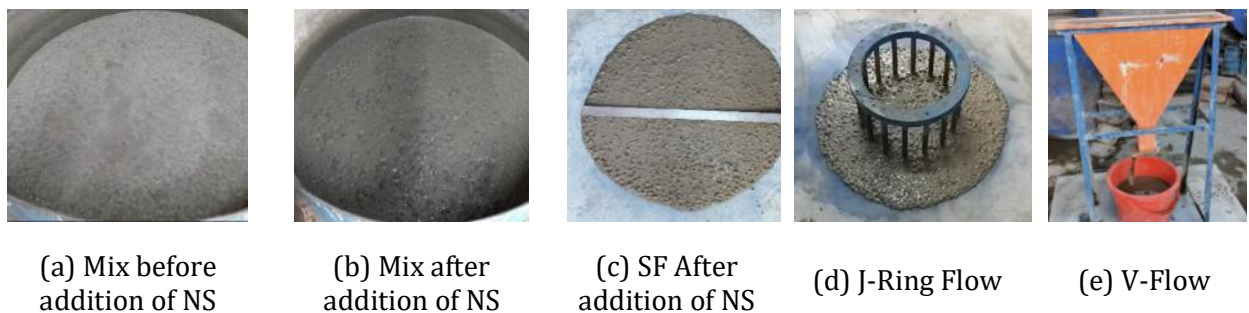


Fig. 7. Fresh concrete properties testing on M50 SCC (G) Mod

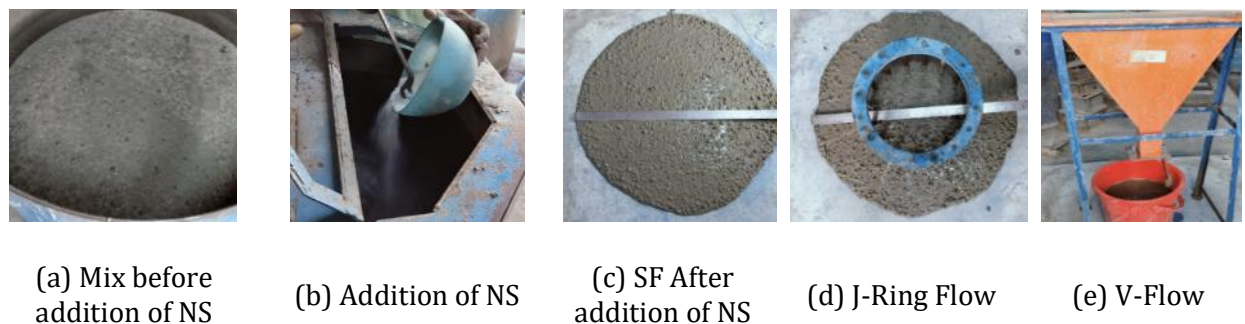


Fig. 8. Fresh concrete properties testing on M70 SCC (G) Mod

Both M50 SCC (G) Mod and M70 SCC (G) Mod became uniform and cohesive after the addition of NS as shown in Fig. 7 and Fig. 8. The dosage of NS required for M50 is measured at 1.4 kg/m³, and for M70 at 1.0 kg/m³. M50 SCC (G) Mod requires a higher NS dosage owing to its relatively lower binder content. It is evident that an appropriate dosage of NS made the M50 SCC (G) Mod mix more robust, despite its relatively low binder content. Compressive strength increment in the three grades of SCC mixes from 7 days to 28 days is noted to be between 70% to 80%, and flexural strength increment is between 70 and 75% in the same period. The reduction in RCPT coulomb

values from 28-day to 56-day age is between 49% and 59% for these three mixes (including M60 SCC (G) Mod evaluated in the earlier study), indicating increased resistance to rapid chloride penetration with age. The results of other durability tests, such as water penetration (WP) and water absorption (WA) at 28 days, are satisfactory, with WP less than 10 mm and WA not more than 5% in all three mixes.

Table 8. Fresh properties of modified SCC mixes prepared from granite-type aggregates

Tested properties	*M60 SCC (G)	M50 SCC (G) Mod	M70 SCC (G)
Fresh concrete properties			
Slump flow	650 mm	675 mm	670 mm
T500	4.80 seconds	4.20 seconds	4.90 seconds
V-Flow	11.0 seconds	7.0 seconds	9.0 seconds
J-Ring flow	620 mm	650 mm	670 mm
VSI	0	0	0

*Data of M60 SCC (G) Mod obtained from earlier study

Table 9. Durability properties of modified SCC mixes prepared from granite-type aggregates

Tested properties	*M60 SCC (G) Mod	M50 SCC (G) Mod	M70 SCC (G)Mod
RCPT test results			
RCPT @ 28 days	796 Coulombs	1252 Coulombs	629 Coulombs
RCPT @ 56 days	329 Coulombs	644 Coulombs	301 Coulombs
Gain in strength and reduction in RCPT			
7/28 days compressive	80%	71%	79%
7/28 Flexural strength ratio	72%	71%	75%
RCPT reduction (28 to 56	58.67%	48.56%	52.15%
Water penetration test results			
Water penetration (28 days)	3.3 mm	7 mm	3 mm
Water absorption test results			
Water Absorption (28 days)	4.4%	5%	3.9%

*Data of M60 SCC (G) Mod obtained from earlier study

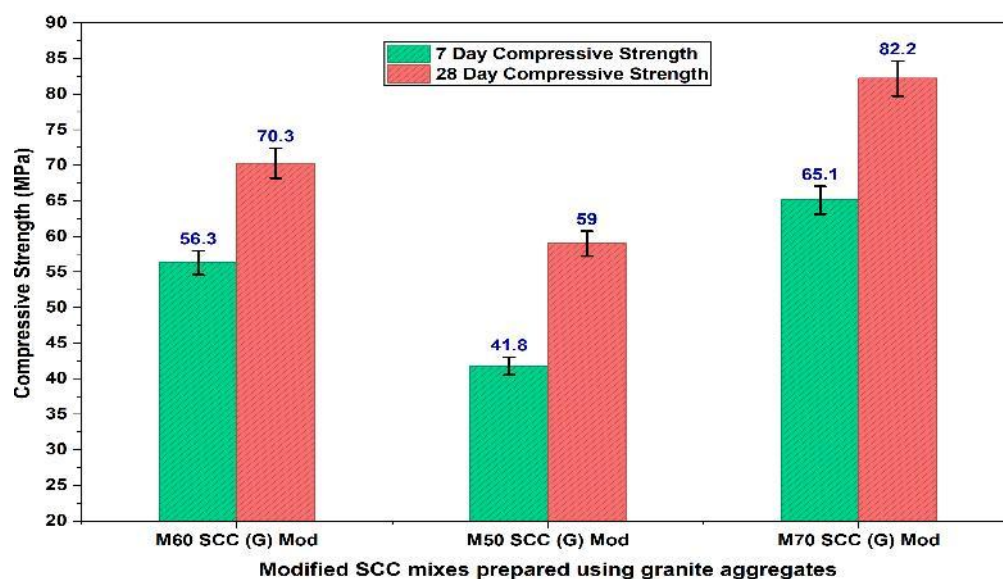


Fig. 9. Cube compressive strength results of modified SCC mixes prepared from granite-type aggregates

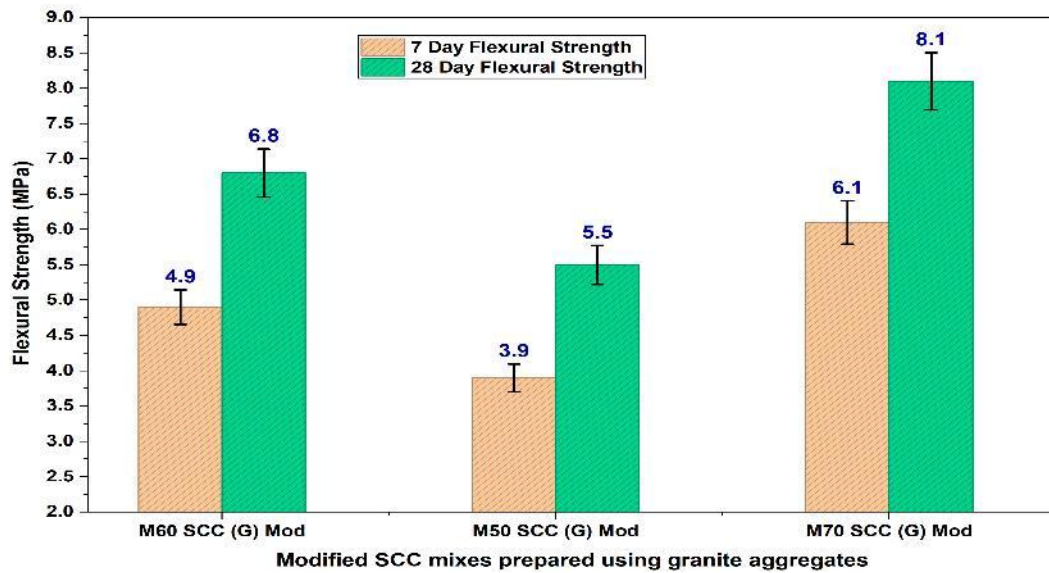


Fig. 10. Beam flexural strength results of modified SCC mixes prepared from granite-type aggregates

4.3 Experimental Investigations on the Modified M50, M60, and M70 SCC Mixes Using Basalt-Type Aggregates

In this phase of the experimental study, the modified approach incorporating UFBFS and NS was adopted to design M50, M60, and M70 grade SCC mixes using basalt-type aggregates. These mixes are identified as M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod, in which 'B' denotes basalt-type aggregates. Higher relative density values of basalt-type aggregates increased the design density of these SCC mixes compared with SCC mixes designed with granite-type aggregates. With increased aggregate content, which increases the aggregate surface area, these SCC mixes are more likely to segregate when the binder content is optimized.

Table 10. M50, M60, and M70 modified SCC mix designs with basalt-type aggregates

Type of materials	M50 SCC(B) Mod	M60 SCC(B) Mod	M70 SCC(B) Mod
OPC	330	370	410
Fly ash	170	170	170
UFBFS	20	25	30
12.5 mm	896	883	876
CS Sand	431	424	421
Water	170	165	155
Total	2432	2446	2468
CONXL PCE 2635	4.70	5.20	5.60
Nano silica	1.60	1.40	1.10
UFBFS / OPC	6.10%	7.30%	7.30%
W/B ratio	0.33	0.29	0.25
Total binder content by weight, kg	520	565	610
Paste content by volume, liters	362.70	372.10	376.60
NS/OPC	0.48%	0.38%	0.27%

The experimental study showed that it was possible to produce an M50 grade SCC mix with the lowest binder content among the three validated grades (M50, M60, and M70), and that the addition of NS made it uniform and cohesive. Hence, similar performance could be expected in SCC mixes with basalt-type aggregates. While designing M50 SCC (B) Mod, M60 SCC (B) Mod, and M70 SCC (B) Mod mixes using the modified approach, the binder and free water contents were kept identical to those of modified SCC mixes of similar grades with granite-type aggregates. The volumetric proportion of coarse to fine aggregates was maintained at 50:50 in these mixes as well.

Table 10 presents the mix-proportion details for the M50, M60 and M70 modified SCC mixes prepared with basalt-type aggregates. Figs. 11 to 13 illustrate visual representations of fresh property measurements for the M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod mixes, respectively. Tables 11 and 12 present the fresh and durability properties of modified SCC mixes containing basalt-type aggregates. Figs. 14 and 15 illustrate the progression of compressive strength and flexural strength results of modified SCC mixes (M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod) at the age of 7 and 28 days, prepared using basalt-type aggregates.

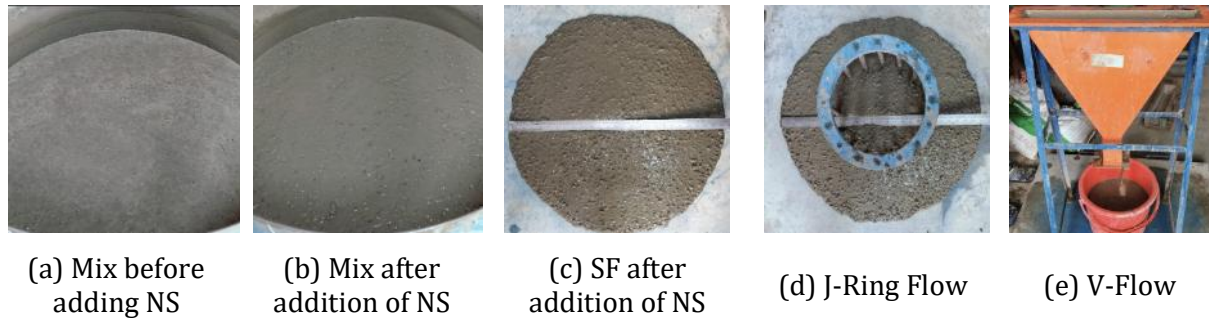


Fig. 11. Fresh concrete properties Tests done on M50 SCC(B) Mod

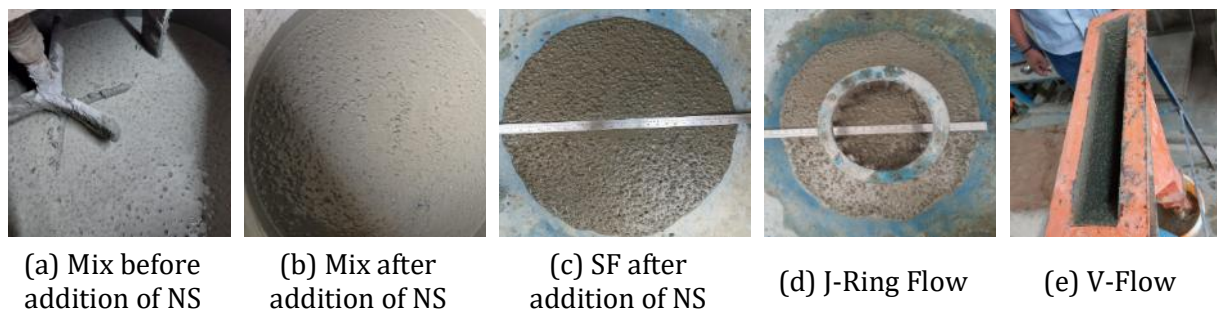


Fig. 12. Fresh concrete properties testing on M60 SCC (B) Mod SCC mix

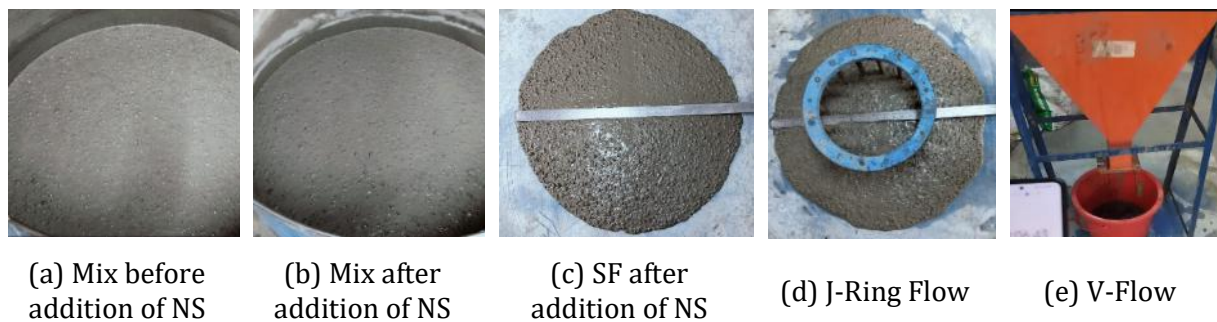


Fig. 13. Fresh concrete properties testing on M70 SCC (B) Mod SCC mix

Table 11. Fresh properties of modified SCC mixes containing basalt-type aggregates

Tested properties	M50 SCC (B) Mod	M60 SCC (B) Mod	M70 SCC (B)
Fresh concrete properties			
Slump flow	670 mm	680 mm	680 mm
T500	3.5 seconds	4.5 seconds	5.0 seconds
V-Flow	6.0 seconds	6.0 seconds	8.0 seconds
J-Ring flow	650 mm	660 mm	640 mm
VSI	0	0	0

Table 12. Durability properties of modified SCC mixes containing basalt-type aggregates

Tested properties	M50 SCC (B) Mod	M60 SCC (B) Mod	M70 SCC (B)
RCPT test results			
RCPT @ 28 days	1546 Coulombs	1438 Coulombs	927 Coulombs
RCPT @ 56 days	743 Coulombs	586 Coulombs	445 Coulombs
Water absorption test			
Water absorption @ 28 days	5.40%	5.0%	4.80%
Water penetration test results			
Water penetration (28 days)	9 mm	8 mm	5 mm
Gain in strength and reduction in RCPT			
7/28 days compressive	76%	75%	75%
7/28 days Flexural strength	72%	80%	73%
RCPT reduction (28 to 56 days)	51.90%	59.20%	52.0%

In the trial mixes conducted to validate M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod mixes, the quantity of NS required to be added to make the mixes uniform is found to be higher in comparison with similar grades of SCC mixes having granite-type aggregates. The increase in density of M50, M60, and M70 modified SCC mixes with basalt-type aggregates is 81 kg/m³, 80 kg/m³, and 79 kg/m³, respectively, compared with similar grades of modified SCC mixes with granite-type aggregates.

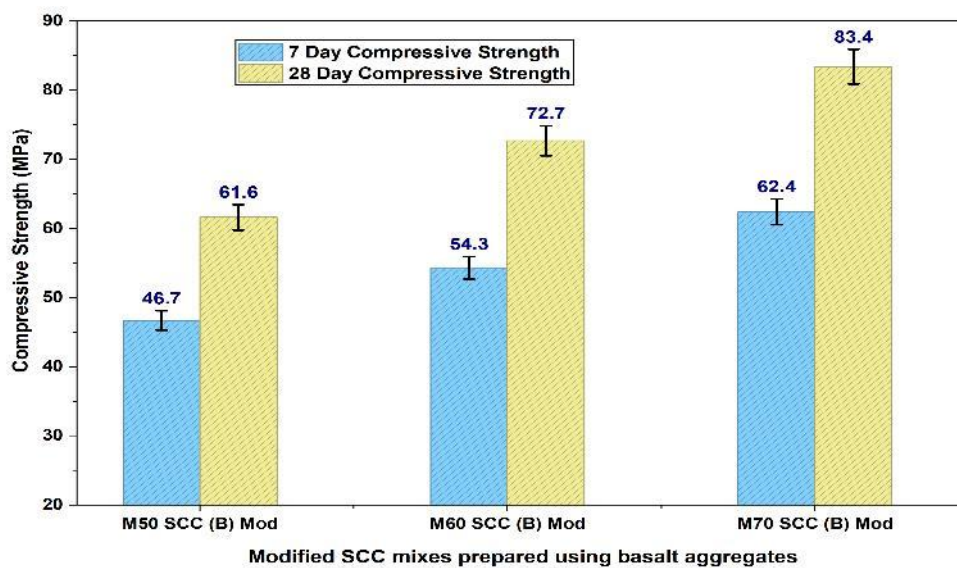


Fig. 14. Cube compressive strength results of modified SCC mixes prepared from basalt-type aggregates

This is due to the higher relative density of basalt-type aggregates compared to granite-type aggregates, i.e., 2.70 & 2.64 vs 2.88, 2.77 & 2.67. According to Okamura and his team, reducing coarse aggregate content and increasing paste content are required to reduce internal stress caused by coarse aggregates in the deformable mix, thereby preventing segregation and blocking issues [9, 11]. Hence, the conventional approach would be to offset an increase in aggregate quantity, partially or fully, by maintaining a higher slurry or paste medium to ensure a uniform, free-from-segregation, and flowable mix. However, in this experiment, a slight increase in the NS dosage is found to be sufficient to make the slurry or paste medium viscous and robust enough to make SCC mixes with basalt-type aggregates cohesive and to meet the flow requirements. It is more evident that the modified approach replaces the conventional approach of relying on higher binder content. Compressive strength increment in the three grades of SCC mixes with basalt-type aggregates from 7 day to 28 day is around 75%, and flexural strength increment is between 70% and 80% over the same period. The reduction in RCPT coulomb values from 28 days to 56 days is

between 50% and 60% for these three mixes, indicating enhanced resistance to chloride penetration with age. The 28 day age tests show that water penetration is less than 10 mm and water absorption is less than 5.5% in all three mixes. The durability properties of the three mixes of M50, M60 and M70 grades are found to be excellent.

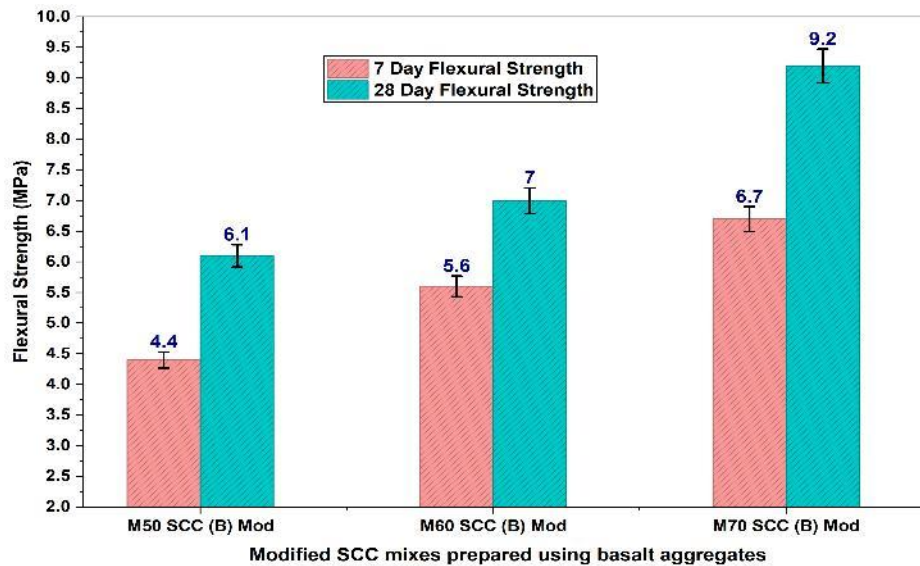


Fig. 15. Beam flexural strength results of modified SCC mixes prepared from basalt-type aggregates

5. Proposed Simplified Mix Design Methodology

Designing an SCC mix usually requires conducting a series of trial mixes and repeatedly fine-tuning the mix ingredients, especially the binder content, to meet the required flow properties. Previous experimental research by the authors on M60-grade SCC mix with granite-type aggregates, comparing conventional and modified approaches, demonstrated the combined role of UFBFS and NS in reducing the binder content while meeting fresh concrete properties satisfactorily [41]. The modified M60 SCC mix exhibited early-age cracking resistance and reduced drying shrinkage behavior, thereby addressing the cracking issue associated with a typical conventional SCC mix [41]. In the present study, a similar approach has been adopted to design and validate M50 and M70 SCC mixes with granite-type aggregates. These two modified mixes, apart from meeting the flow requirement, also meet the strength and durability requirements. In the next stage, M50, M60 and M70 mixes with basalt-type aggregates are designed using a modified approach incorporating UFBFS and NS. When designing SCC mixes with both granite-type and basalt-type aggregates, the same modified mix design approach is adopted. The only difference in SCC mixes with basalt-type aggregates is an increase in aggregate content, attributable to their higher relative density.

It is found that a marginal increase in NS dosage enhanced the viscosity of the slurry medium, thereby keeping the relatively heavier coarse aggregate particles as an integral part of the mix and ensuring uniformity and flowability of the SCC mixes. Many studies on the addition of NS to concrete mixes, including SCC, have reported its role in enhancing mechanical and durability properties [45–47]. While reporting the influence of NS on the rheology of the mixes, the research works stated that the addition of NS caused workability and flow losses, and an increase in thixotropy and yield stress. Such an effect on the rheology of concrete mixes holds true when the NS dosage exceeds 0.50%, as evidenced by the authors' Marsh-Cone test in their previous study [41]. However, in the previous study and in the current study conducted by the authors, the NS dosages used to enhance the uniformity and cohesiveness of M50, M60 and M70 grade SCC mixes were less than 0.5%. At such a low dosage, NS was found to make the mixes sufficiently viscous to prevent segregation while maintaining their fresh-concrete properties and meeting the required SCC flow criteria. This novel approach also helped in “simplifying the SCC mix design methods,” as illustrated in the flowchart in Fig. 16.

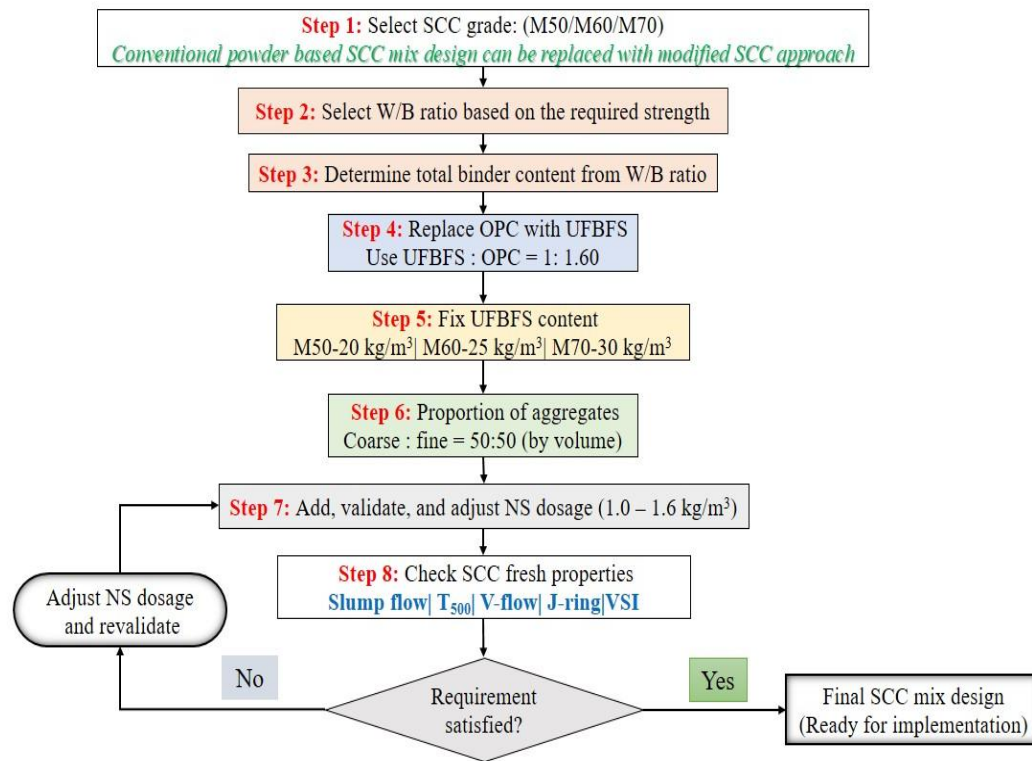


Fig. 16. Step-by-step procedure involved in developing a simplified SCC mix design approach

Validation of the performance of all six mix designs in both fresh and hardened states showed that the modified approach simplified the SCC mix design. The resultant simplification is presented as follows;

- Conventional powder-based SCC mix designs can be replaced with modified SCC mix designs.
- Binder contents are determined solely by the water-to-binder ratio needed to achieve the specified strength.
- The preliminary study conducted by the authors on M60 mixes showed that 25 kg/m³ UFBFS could replace 40kg/m³ OPC while achieving a 4.5% higher compressive strength. The pozzolanic efficiency of UFBFS relative to OPC was found to be 1:1.6 [41]. Incorporating UFBFS in the current experimental study helps to maintain optimal OPC content.
- UFBFS are added at dosages of 20 kg, 25 kg, and 30 kg per cubic meter in M50, M60, and M70 SCC mixes, respectively, to ensure effective incorporation during manufacturing.
- Coarse and fine aggregates are proportioned at a 50:50 volume ratio.
- NS is the last ingredient added to the fresh mix to convert the slurry medium robust enough to carry aggregates, ensuring a uniform mix with SCC flow properties.
- The NS dosage observed during validation of SCC mixes ranges from 1 kg/m³ to 1.6 kg/m³. Adjusting NS to meet the requirements of flowable SCC mixes is a simpler, more effective step and the final step in SCC mix design formulation and validation.
- As far as NS addition in the batching plant is concerned, it can be added either in the central mixer or in the transit mixer as the final ingredient, as is usually done for fibers or additives such as waterproofing compounds. With the enhanced batching control mechanism in the modern-day batching plants, an auto-dispensing arrangement can also be implemented, as is done for UFBFS.

6. Results and Discussions

6.1 Effect of NS Incorporation on Setting Time and Early Strength of Cement Paste

An earlier experimental study conducted by the authors demonstrated that a modified mix design approach for M60 SCC mix, incorporating UFBFS and NS, was effective in mitigating early-age shrinkage and cracking behavior. In that study, the role of NS in contributing to early strength gain required to resist cracking was inferred from the research findings [39, 40]. A reduction in total binder content and the role of NS in providing stiffness at an early age could have helped to mitigate early-age shrinkage. In the present experimental work, a preliminary study was conducted on OPC paste containing 0% and 0.25% NS. The paste with 0.25% NS achieved an earlier setting time by 65 minutes and a higher 12-hour strength by 35.60%. As concluded by other researchers, while a reduction in total binder content is essential to mitigate the probability of shrinkage in SCC mixes, the benefit of NS in promoting hydration and early strength gain is an additional factor that offers potential resistance to early-age plastic/autogenous cracking by accelerating structural buildup [43, 44].

6.2 Fresh, Mechanical and Durability Assessment of Modified SCC Mixes with Granite-Type Aggregates

Building on the earlier experimental study comparing the conventional and modified SCC mix design approaches, the current study has expanded its scope to include M50 and M70 SCC mix grades. Similar to M60 SCC (G) Mod, M50 and M70 SCC mixes are also designed with granite-type aggregates. The total binder content for M50 SCC (G) Mod is 520 kg/m³, and for M70 SCC (G) Mod it is 610 kg/m³, considered based on the strength requirements. In the trial mixes conducted to validate both these mixes, segregation is noticed before the addition of NS. The addition of NS at 1.4 kg/m³ (0.42 NS/OPC) to M50 SCC (G) Mod and at 1.0 kg/m³ (0.24% NS/OPC) to M70 SCC (G) Mod makes both mixes uniform and cohesive. Flow tests conducted are found to meet the SCC criteria. The 28-day compressive strengths of M50 SCC (G) Mod and M70 SCC (G) Mod mixes are measured as 59.0 MPa and 82.2 MPa, respectively, indicating their potential to meet the characteristic strength requirement. Water penetration depth of M50 SCC (G) Mod and M70 SCC (G) Mod is limited to 7.0 mm and 3.0 mm, respectively, at the 28-day age test, and the rapid chloride penetration test results at 56 days of age are 644 coulombs and 301 coulombs, respectively. Water absorption values obtained at 28 days of age for M50 SCC (G) Mod and M70 SCC (G) Mod are 5.0% and 3.9%, respectively.

6.3 Fresh, Mechanical and Durability Assessment of Modified SCC Mixes with Basalt-Type Aggregates

The modified approach to designing SCC mixes is extended to mixes with basalt-type aggregates, which have a higher relative density than granite-type aggregates. M50, M60, and M70 SCC mixes are designed for experimental validation. The total binder contents are kept the same as that of SCC mixes with granite-type aggregates, which means that M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod mixes with basalt-type aggregates have total aggregate content increased by 81 kg/m³, 80 kg/m³, and 79 kg/m³, respectively. The trial mixes showed that adding NS as the final ingredient at dosages of 1.6 kg/m³ (0.48% NS/OPC), 1.4 kg/m³ (0.38% NS/OPC), and 1.1 kg/m³ (0.27% NS/OPC), respectively, allowed all three SCC mixes to achieve uniformity.

Flow tests conducted on these three mixes indicate that they meet the requirements of fresh concrete properties of SCC. The 28-day compressive strength of M50 SCC (B) Mod, M60 SCC (B) Mod and M70 SCC (B) Mod SCC mixes are found to be 61.6 MPa, 72.7 MPa and 83.40 MPa, respectively, exceeding target mean strength requirements. Water penetration resistance values for these three mixes at 28 days of age are 9.0 mm, 8.0 mm, and 5.0 mm, respectively, and rapid chloride penetration test results at 56 days of age are 743, 586, and 445 coulombs, respectively. Water absorption test results at 28 days of age are 5.4%, 5.0%, and 4.8%, respectively.

Various studies have reported the role of fly ash, UFBFS and NS in pore refinement and in improving impermeability through the pozzolanic reaction, which converts calcium hydroxide (CH) into

secondary C-S-H. Fly ash and NS also eliminate bleeding and make the interfacial transition zone (ITZ) strongly bound to the aggregate phase, enhancing the strength potential of concrete. While the secondary reaction of NS is observed at an early age due to its much higher fineness and reactivity, the reaction of fly ash is said to continue for a prolonged period beyond 28 days. Thus, all three of these ingredients contribute to the enhanced durability of concrete. This is evident in the increased RCPT values from 28 to 56 days of age.

In M50, M60 & M70 modified SCC mixes with granite-type aggregates, the NS/OPC dosages used are 0.42%, 0.32% and 0.24%, respectively. In mixes with basalt-type aggregates, the dosages in terms of NS/OPC for M50, M60 & M70 are 0.48%, 0.38% and 0.27%, respectively. Although an increase in the relative density of aggregates commonly requires a higher binder content to reduce friction between relatively high quantities of aggregates, a marginal increase in NS can nullify that dependence on a higher binder content. As reported by other researchers, NS, due to its large surface area and adsorption characteristic enhances plastic viscosity and yield stress (moderately) even at lower dosage [36-38]. The observation in this study also indicates that NS plays a crucial role in making the paste/slurry medium viscous and in contributing to an SCC mix that is uniform, cohesive, and free of segregation, with an optimal binder content.

It is also observed that the demand for NS, as measured by the NS-to-OPC ratio, decreases as the concrete grade increases. Increased binder content (610 kg/m³), and paste content (376.6 litres) in M70 SCC, increase the matrix's plastic viscosity and intrinsically lower the additional NS requirement for segregation resistance. With the water-to-binder ratio maintained at 0.33, 0.29, and 0.25 for the M50, M60, and M70 mixes, respectively, both strength and durability test results are found to be satisfactory. Reductions in OPC and total binder can be achieved by modifying the SCC mix design with the incorporation of UFBFS and NS. The modified approach to SCC mix designs undertaken in this experimental research has also simplified the process. With binder content kept optimal in the modified approach to meet the water-to-binder ratio requirements, as in normal concrete mix design, the challenge of making SCC free from segregation and achieving its flow properties is addressed by adding NS. Incorporation of NS as the final ingredient is an important factor in simplifying SCC mix designs.

7. Conclusions

- The main objective of the experimental study was to design SCC mixes using a modified approach, as an alternative to powder-based SCC mix design. The modified method adopted in this research work incorporated UFBFS and NS to design M50, M60, and M70 SCC mixes with optimal binder content to meet the water-to-binder ratio requirements, rather than increasing binder content to enhance the uniformity of the SCC mixes when segregation is encountered. Two sets of experiments were considered: one with granite-type aggregates, which possessed lower relative density values, and another with basalt-type aggregates, which possessed higher relative density values. Binder content and its individual components, namely OPC, UFBFS and fly ash, were kept constant for both sets of SCC mixes.
- The experimental work conducted on M50, M60 and M70 grade modified SCC mixes with both granite-type and basalt-type aggregates included testing of fresh concrete properties, namely slump flow, T₅₀₀, V-flow, J-ring flow, and VSI, to validate the performance requirements.
- The 28-day cube compressive strength results for granite-type aggregate-based mixes were measured at 59.0 MPa for M50 SCC, 70.3 MPa for M60 SCC and 82.2 MPa for M70 SCC. For M50, M60 and M70 SCC mixes with basalt-type aggregates, the cube compressive strength results were 61.6 MPa, 72.7 MPa and 83.4 MPa, respectively. These results indicate that the designed mixes with optimal binder content met the intended strength requirements.
- In durability tests conducted, RCPT values of all six mixes at 56 days were less than 1000 coulombs, thus falling in the category of "very low chloride penetrability" as per ASTM C1202. Water penetration at 28 days was limited to less than 10mm in all six mixes, with the M50 basalt-type-based SCC mix exhibiting a maximum value of 9mm. Water absorption values at 28 days of age were found to fall within the ranges of 3.9% to 5.0% for granite-type aggregate-based SCC mixes and 4.8% to 5.4% for basalt-type aggregate-based SCC mixes.

- Fresh concrete densities of SCC mixes with basalt-type aggregates were comparatively higher due to increased aggregate content. In experimental work aimed at achieving a robust, uniform and cohesive mix to obtain a VSI index of “0”, it was found that mixes with basalt-type aggregates required slightly more NS than similar mixes with granite-type aggregates. In M50, M60 & M70 modified SCC mixes with granite-type aggregates, the NS dosages were 1.4 kg/m³, 1.2 kg/m³ and 1.0 kg/m³, corresponding to 0.42%, 0.32% and 0.24% NS/OPC, respectively. Similarly, for mixes with basalt-type aggregates, the corresponding NS dosages were 1.6 kg/m³, 1.4 kg/m³ and 1.1 kg/m³, corresponding to 0.48%, 0.38% and 0.27% NS/OPC, respectively.
- All the trial mixes exhibited segregation before addition of NS and became cohesive achieving VSI index of “0” after the addition of NS. In the modified approach, NS must be added as the final ingredient to achieve a homogeneous, robust SCC mix and, more importantly, to determine an appropriate dosage. This experimental study recommends a novel approach of varying NS dosage for SCC mixes with varying grades, aggregate content, or aggregate density, rather than fixing the NS dosage and assessing its impact on SCC properties. The objective of this experimental research was to provide a modified approach, as an alternative to the conventional binder/powder-based SCC mix design, with an optimal binder content to minimize the potential risk of shrinkage and to fulfil the requirements for fresh and hardened SCC parameters. This objective was achieved.
- The modified approach, validated in the experimental studies, was also shown to be a simplified design method for SCC mixes containing either granite or basalt-type aggregates. Thus, this approach could be found useful in a broader area across India.

7.1 Future Scope of the Study

SEM/EDS and TGA microstructural studies will be carried out to gain an understanding of the development of the cementitious matrix. Drying shrinkage on different grades of modified SCC mixes will be conducted. Future studies on SCC mixes having coarse aggregates higher than 50% in solid volume and in M40 grade will be taken up for experimental investigation using the modified SCC mix design approach. To evaluate the feasibility of applying the proposed approach in practice, casting into site-scale structural elements will also be carried out.

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