

EXPERIMENTAL STUDY ON WORKABILITY, MECHANICAL AND MICROSTRUCTURAL CHARACTERISTICS OF SELF-COMPACTING CONCRETE CONTAINING COLLOIDAL NANO SILICA

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Abstract

Self-compacting concrete (SCC) is voluminously utilized in building construction due to its distinct design. This work depicts the effect of colloidal nano-silica (NS) of size 5-40nm with an active nano solids content of 32% on SCC of grade 30 containing Ground Granulated Blast Furnace Slag (GGBFS) and Ordinary Portland Cement as binders in addition to NS. The liquid content of 68% in NS was added to the water content in the mix. The ratios of NS were evaluated at 0%, 0.5%, 1%, 1.5%, 2% and GGBFS as 20% by weight of binder in concrete. The water to binder ratio was 0.38 with a water and binder content of 201kg/m³ and 528.95 kg/m³ respectively. The optimum mix was 1.5% NS as per the slump and compressive strength at 28 days. The slump was reduced with a rise in NS beyond 1.5% due to the accumulation of NS particles causing the reduction in flowability. The density of SCC for all the mixes was satisfactory. The compressive strength of optimum SCC, M-1.5NS20G was increased by 11.71%, 8.58% and 17.45% at 7, 28 and 91 days respectively to that of the reference mix whereas its split tensile strength was risen by 43.40%, 23.11% and 9.51% and flexural strength was risen by 26.28%, 15.17% and 6.29% to that of the reference mix at aforementioned durations respectively. The microstructural studies on the optimum hardened SCC mix at 28 days revealed the presence of calcium silicate hydrate compounds of different crystalline structures and portlandite.

Keywords: Colloidal nano silica; Flowability; Ground granulated blast furnace slag; Self-compacting concrete

Introduction

Self-compacting concrete (SCC) is widely adopted within the construction industry. It was initially introduced in 1986 and the prototype was developed in 1988 in Japan. This innovative approach solved issues related to labour scarcity and achieving durable structures with optimal compaction without the need for vibration. Consequently, this method

effectively reduces voids in structural members and at congested reinforcement junctions (Okamura and Ouchi, 2003). The utilization of a superplasticizer, minimal aggregate content and a reduced water-to-powder ratio are essential in achieving self-compaction, high deformability, viscosity and preventing segregation during concrete flow

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through congested reinforcement areas (Okamura and Ouchi, 2003). The diminishment of particle gap leads to rise in collisions per unit of time, interparticle contact and internal stress within the deforming concrete, particularly, near obstacles (Okamura and Ouchi, 2003). The formation of clusters due to Brownian motion of small particles significantly influences the thickening of shear in SCC to increase viscosity and shear rate necessitating caution to prevent damage to mixers, conduits and pipes (Feys *et al.*, 2009). Maintaining a packing density of total aggregate between 50% and 60% is crucial to minimize the relation between particles and restrict concrete shear deformation (Okamura and Ouchi, 2003). As a result of transfer of pressure and decrease in shear deformation relying on the behaviour of solid particles within the mortar, it experiences normal stress between coarse aggregate particles (Ouchi and Edamatsu, 1999; Okamura and Ouchi, 2003). The integration of industrial waste materials like GGBFS and fly ash exhibits pozzolanic properties into SCC formulations which are essential to prohibit the disposal of the aforementioned materials onto land (Hoy *et al.*, 2024a, 2024b; Kantatham *et al.*, 2024). The strength enhancement of SCC is contingent upon the proportions of supplementary cementitious materials (SCM) in the concrete mix (Benaicha *et al.*, 2015). Initially, the lack of standard guidelines for self-compacting concrete mix design led construction companies to propose their own procedures. However, in 2005, international recognition was achieved with the proposal of guidelines for SCC (EFNARC, 2005) and subsequently, India has been adopting it since 2019 (Bureau of Indian Standards [BIS], 2019).

GGBFS, the ultimate residual product obtained from steel production, predominantly comprises calcium oxide and silica alongside minor proportions of alumina and magnesia. The revelation of GGBFS's hydraulic potential dates back to Emil Langen's findings in Germany in 1862 followed by its industrial inception in 1865 and led to the manufacture of Portland slag cement utilized in subterranean structures to resist harsh subsoil conditions (Higgins, 2010). The milling of GGBFS was conducted through two distinct methods: the wet process (The Trief cement process: Corrosion-resisting concrete in U.K., 1955) pioneered by Victor Trief in Belgium and the dry process which was later effectively implemented (Higgins, 2010). The hydraulic reactivity of GGBFS is contingent upon its chemical content, particularly, the basicity index determined by the quick lime-to-silica ratio exceeding 1.0. GGBFS induces variations in hydration products due to the emergence of C-S-H gel, consequently forming augmented pore volumes

within the cement matrix, elevated water absorption and diminished strength. The activated alumina further engages with portlandite and gypsum to yield Ettringite (Provis *et al.*, 2015). Notably, GGBFS exhibits a noteworthy water-reducing effect, curtailing the time-dependent slump flow loss and fluidity (Boukendakdji *et al.*, 2012). The workability is compromised for the expansive surface area and uneven texture of GGBFS. Through the application of superplasticizer (SP), the fresh mixture's performance was enhanced facilitating the steric repulsion for powder particle dispersion. SP's interaction with cement particles impeded initial hydration resulting in delayed setting and initial strength progression (Zhang and Kong, 2015). GGBFS fills voids within the aggregate to yield denser concrete and influence the strength development in SCC, contingent upon the water-to-cement ratio and GGBFS quantity wherein a rise in the former correlates with an increase in the latter across varying slag percentages (Dadsetan and Bai, 2017). Notably, the compression, split tension and flexural properties of concrete exhibit enhancement up to a 20% replacement threshold of GGBFS beyond which a decline was observed due to compromised flowability (Dadsetan and Bai, 2017) and a dilution effect fostering alkali-silica reactions owing to the significant unreactive silica content in GGBFS (Ahmad *et al.*, 2021). These reactions exert stress on the concrete leading to its expansion and crack formation (Ahmad *et al.*, 2021).

Colloidal nano silica (NS), derived from the Weber Stober method (Stöber *et al.*, 1968) comprises compact, amorphous hydroxylated silica particles ranging from 1 to 100 nm in aqueous solution and finds application within the realm of construction (Singh *et al.*, 2014). The extensive specific surface area of NS plays a pivotal role in a composite-cement binder (Wang *et al.*, 2018) and results in an increased water-cement ratio. A greater dosage of PCE based super-plasticizer is employed to improve flow characteristics, thereby reducing particle agglomeration and inadequate dispersion (Nazari and Riahi, 2010). PCE facilitates the dispersion of NS and enhances the compressive strength of mortar while reducing the porosity and detrimental voids in solidified cement paste (Qian and De Schutter, 2018). Well-dispersed nanoparticles cause an improvement in hydration leading to the consumption of portlandite and the generation of surplus C-S-H gel during pozzolanic reactions ultimately thickening the cementitious paste (Ltifi *et al.*, 2011) contrary to conventional concrete which depends primarily on cement for hydration, resulting in limited formation of C-S-H (Khaloo *et al.*, 2016). The early strength of concrete

is increased due to the nucleation effect of nano silica particles and reduces initial and final setting times (Zhang *et al.*, 2012). However, as curing time progresses, the effectiveness of NS in increasing later-stage compressive strength decreases (Khaloo *et al.*, 2016). The Interfacial Transition Zone (ITZ) is also enhanced through the packing of minute particles in all voids, thereby reducing permeability (Sharkawi *et al.*, 2018). An escalation in the quantity of NS leads to a decrease in slump due to the emergence of silanol groups and inadequate water content (Mukharjee and Barai, 2020). Incorporating up to 2% to 3% of NS as a substitute for cement in concrete enhanced its strength by leveraging its pozzolanic reactivity and filling capabilities (Nazari and Riahi, 2010; Amin and El-Hassan, 2015).

In consideration with the previous research studies on colloidal nano silica, it was noticed that the separate addition of NS solids content to binder materials and NS liquid content to the water and their influence on the workability and mechanical strengths of SCC had not been discussed. The objective of the current research work is to investigate workability properties, mechanical strength properties and microstructural analysis of the self-compacting concrete of grade 30 containing cement, GGBFS and colloidal nano silica (32% solids and 68% liquid) as cementitious materials and Auramix 300 plus as chemical admixture of PCE type.

Materials and Methods

Ordinary Portland Cement (OPC) 53 grade (Bureau of Indian Standards [BIS], 2015) with a specific gravity of 3.13, consistency of 29.50%, and compressive strength of 49 and 60 MPa at 7 and 28 days, respectively, was procured from KCP Limited. Ground granulated blast furnace slag (GGBFS) conforming to IS 16714:2018 (Bureau of Indian Standards [BIS], 2018) with a specific gravity of 2.90, consistency of 29%, and strength of 29 and 49 MPa at 7 and 28 days, respectively, was obtained from Visakhapatnam Steel Plant. The chemical characteristics of cement and GGBFS are shown in Table 1. Colloidal nano-silica designated as CemSyn XTX, with a specific gravity of 1.22 and silica as the main chemical constituent, was procured from Beechem Company located in Kanpur. The solid particles visible in the transmission electron microscopy (TEM) image (Figure 1) contain active nano-silica with liquid among them. Coarse aggregate conforming to IS 383:2016 (Bureau of Indian Standards [BIS], 2016) with a nominal size of 10 mm and specific gravity of 2.88, and river sand (Type II fine aggregate per

IS 383:2016; BIS, 2016) with a fineness modulus of 2.66 and specific gravity of 2.61, were utilized in the concrete mix. Auramix 300 Plus, a viscosity-modifying admixture with a specific gravity of 1.08, was procured from FOSROC and used as a chemical admixture in self-compacting concrete (SCC) per IS 10262:2019 (Bureau of Indian Standards [BIS], 2019). Potable water was used for concrete mixing.

Table 1. Comparative Overview of Inventory Classification Methods

Sl. No.	Characteristic	OPC 53*	GGBFS**
1	Lime Saturation Factor	0.92	-
2	Ratio of percentage of Alumina to that of Iron Oxide	1.24	-
3	Insoluble Residue (% by mass)	0.47	0.78
4	Magnesia (% by mass)	1.10	8.86
5	Sulphuric Anhydride (% by mass)	1.74	0.66
6	Total loss of ignition (%)	1.24	NIL
7	Chlorides (%)	0.002	0.012
8	Manganese Oxide (%)	-	0.72
9	Sulphide Sulphur (%)	-	0.78

Courtesy: *KCP Cement Limited, Andhra Pradesh, India. **Sri Vishnu Sai Saravana Enterprises, Autonagar, Visakhapatnam, India

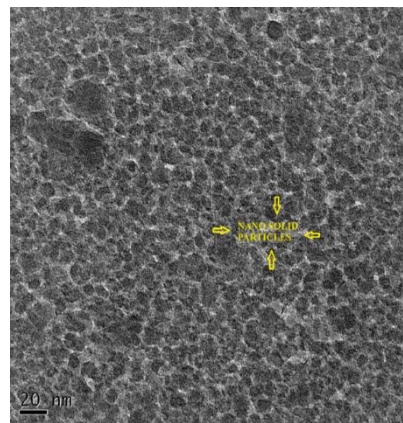


Figure 1. shows TEM image of colloidal nano silica

SCC Mix Design

In this research work, according to IS 10262:2019 (Bureau of Indian Standards [BIS], 2019), the standard deviation of M30 grade concrete was taken as 5 N/mm², yielding a mean target strength of 38.25 N/mm². The entrapped air content was taken as 1.5% of the concrete volume for a nominal maximum aggregate size of 10 mm. GGBFS was used at 20% replacement of cement, and colloidal nano-silica (NS) was incorporated at varying proportions of 0%, 0.5%, 1%, 1.5%, and 2%

by weight of binder (solids content). The liquid portion of colloidal NS was calculated separately and added to the mixing water. The remaining binder consisted of OPC. Based on trial mixes, a water-to-binder ratio of 0.38 was adopted, with binder and water contents of 528.95 kg/m³ and 201 kg/m³, respectively. The total powder content was 553 kg/m³. The fresh SCC is effected by GGBFS that depends on fineness and admixture proportion as it retains water at increased fineness to lower fluidity and slump flow (Dadsetan and Bai, 2017). The admixture was considered 0.5% for concrete containing 0% NS and 0.7% for the rest of the proportions of NS by weight of binder content. The fines required were then calculated as 24.05 kg/m³. The percentage of particles passing through 0.125 mm IS sieve was 3%. The total aggregate quantity was obtained in which fine aggregate lies within the

limits of 48% to 60%. Water to-powder ratio was within the limits. The mix design quantities are presented in Table 2. The constituents were mixed in the concrete mixer. The fresh concrete was tested for its workability after mixing as shown in Figure 2. The flow table was allowed to rotate and subjected to impact as shown in Figure 2(a). The concrete was spread horizontally throughout the circumference of the table considering a maximum distance between the far ends to be slump indicating the flowability or filling ability as shown in Figure 2(b). The concrete was allowed into the V-Funnel to find the viscosity by counting down the time taken (s) to pass through it as shown in Figure 2(c) and in the L-Box through the vertical duct to pass down and move in the horizontal portion to study the passing ability as shown in Figure 2(d) (IS 10262:2019) (BIS, 2019).

Table 2. Shows SCC Mix Design

Mix Notation/ Constituents	M-0NS 20G	M-0.5NS 20G	M-1NS 20G	M-1.5NS 20G	M-2NS 20G
Cement (kg/m ³)	423.16	422.31	421.47	420.62	419.77
GGBFS (kg/m ³)	105.79	105.79	105.79	105.79	105.79
NS (kg/m ³)	0	2.64	5.29	7.93	10.58
NS(Solids) (kg/m ³)	0	0.85	1.69	2.54	3.39
NS(Liquids) (kg/m ³)	0	1.79	3.60	5.39	7.19
Water (kg/m ³)	201	201	201	201	201
Fine Aggregate (kg/m ³)	801.75	801.75	801.75	801.75	801.75
Coarse Aggregate (kg/m ³)	871.75	863.47	858.00	852.54	847.07
Chemical Admixture (kg/m ³)	2.64	3.70	3.70	3.70	3.70
water-binder ratio	0.38	0.38	0.38	0.38	0.38



(a)



(b)



(c)



(d)

Figure 2. workability tests on SCC (a) flow table equipment, (b) slump flow, (c) viscosity test (d) passing ability test using L-Box

Preparation of Test Specimens

A total of 45 standard cube specimens of size 150mm × 150mm × 150mm were cast with the fresh concrete of the five different mixes. They were placed in ambient curing for a day at room temperature and then in water curing after demoulding for different durations of 7, 28, and 91 days (Bureau of Indian Standards, 2021). Three specimens of all five mixes were tested for compressive strength for the corresponding durations. The same procedure was repeated for 45 standard cylindrical specimens of size 150 mm diameter and 300 mm length to test for split tensile strength and 45 standard prism specimens of size 100 mm × 100 mm × 500 mm to test for flexural strength (Bureau of Indian Standards, 2021). The notations of the specimens were considered as M-0NS20G (reference mix), M-0.5NS20G, M-1NS20G, M-1.5NS20G and M-2NS20G and are mentioned in Table 3.

Workability Tests on SCC

The slump flow, viscosity and passing ability tests were conducted on flow table, V-funnel and L-

box as illustrated in Figure 2 and their values are mentioned in Table 4. The slump and viscosity of M-0NS20G are classified as SF1 and V2 whereas for M-0.5NS20G, M-1NS20G, M-1.5NS20G and M-2NS20G, are classified as SF2 and V1 respectively (BIS, 2019; EFNARC, 2005). The slump of M-2NS20G was observed to be less due to the accumulation of NS solid particles and water absorption. The horizontal flow of M-1.5NS20G was observed from the passing ability test (IS 10262:2019) and classified as PA2 (EFNARC, 2005). The viscosity of reference mix exceeded 8 seconds (BIS, 2019; EFNARC, 2005). A further increase beyond 2% NS led to a reduction in slump due to the emergence of silanol groups and insufficient water content (Mukharjee and Barai, 2020).

Compressive strength

The test was performed on specimens as depicted in Figure 3. The strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G was increased by 2.71%, 4.96%, 11.71% and M-2NS20G decreased by 8.12% to that of reference mix respectively at 7

Table 3. Shows SCC mix notations

M-0NS20G	SCC mix of grade 30 containing 0% colloidal nano silica and 20% ground granulated blast furnace slag
M-0.5NS20G	SCC mix of grade 30 containing 0.5% colloidal nano silica and 20% ground granulated blast furnace slag
M-1NS20G	SCC mix of grade 30 containing 1% colloidal nano silica and 20% ground granulated blast furnace slag
M-1.5NS20G	SCC mix of grade 30 containing 1.5% colloidal nano silica and 20% ground granulated blast furnace slag
M-2NS20G	SCC mix of grade 30 containing 2% colloidal nano silica and 20% ground granulated blast furnace slag

Table 4. Shows workability test values of SCC

Workability Tests	Mix Notation					Range of values as per IS 10262:2019	Range of values as per EFNARC 2005
	M-0NS 20G	M-0.5 NS 20G	M-1NS 20G	M-1.5NS 20G	M-2NS 20G		
Slump (mm)	650	720	720	730	690	SF1: 550 - 650 mm SF2: 660 - 750 mm SF3: 760 - 850 mm	SF1: 550 - 650 mm SF2: 660 - 750 mm SF3: 760 - 850 mm
Viscosity (s)	11	8	8	8	8	V1: ≤ 8 s V2: 8 - 25 s	V1: ≤ 8 s V2: 9 - 25 s
h ₁ (cm)	5	6.5	7	7.2	7	-	-
h ₂ (cm)	8	8.3	8	7.2	8	-	-
Passing Ability by L-box test	0.63	0.78	0.88	1.00	0.88	Minimum: 0.80 Horizontal flow: 1.00	PA1: ≥0.80 with 2 rebars PA2: ≥0.80 with 3 rebars



Figure 3. Shows compressive strength test on 300 T CTM

days. Similarly, the strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G and M-2NS20G was enhanced by 1.43%, 4.01%, 8.58% and 5.99% to that of reference mix at 28 days respectively. The strength of M-0.5NS20G and M-2NS20G was decreased by 0.82%, 1.10% and M-1NS20G and M-1.5NS20G increased by 3.05%, 17.45% to that of reference mix at 91 days respectively as illustrated in Figure 4. The strength of optimum mix, M-1.5NS20G was increased by 19.41% and 14.85% to that of self-compacting light weight concrete and normal blended concrete at 28 days respectively (Naniz and Mazloom, 2018; Raveendran and Krishnan, 2025). The growth in compressive strength was observed due to the generation of extra C-S-H gel from the reaction of nano silica with calcium hydroxide in lime solution (Najigivi *et al.*, 2013).

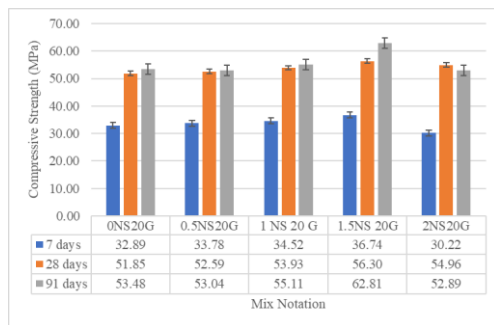


Figure 4. shows variation of compressive strength of SCC at 7, 28 and 91 days

Split Tensile Strength

The test was conducted on a specimen as depicted in Figure 5. The strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G, M-2NS20G was increased by 22.17%, 32.55%, 43.40% and 20.28% to that of reference mix at 7 days and 12.50%, 21.59%, 23.11% and 10.61% to that of reference mix at 28 days respectively. The strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G was increased by 3.17%, 4.61%, 9.51% and M-2NS20G reduced by 1.44% to that of reference mix at 91 days respectively as shown in Figure 6. The strength of optimum mix, M-1.5NS20G was reduced by 12.16% and 34.08% to that of self-compacting light weight concrete and normal blended concrete at 28 days respectively (Naniz and Mazloom, 2018; Raveendran and Krishnan, 2025). Owing to the intense reactivity of nano silica, calcium hydroxide produced during the early stages of cement hydration was quickly consumed resulting in greater strength in concrete containing nano silica with cementitious material. Since the extra nanoparticles in the mix replaced some of the cement, they didn't add to its strength and leached out excess silica and

weakened strength of cement due to their reaction with liberated lime during cement hydration. In addition to that, fragile regions were most likely caused by defects created during the dissemination of nanoparticles (Amin and El-Hassan, 2015; Khaloo *et al.*, 2016).



Figure 5. shows split tensile strength test using 300 T CTM

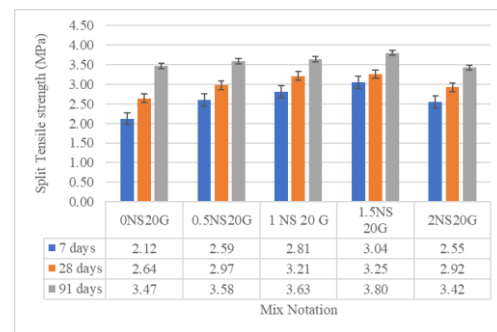


Figure 6. shows variation of split tensile strength of SCC at 7, 28 and 91 days



Figure 7. shows flexural strength test using 100 T UTM

Flexural strength

The test was conducted on specimen as depicted in Figure 7. The strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G was increased by 12.41%, 18.73%, 26.28% and M-2NS20G reduced by 4.14% to that of reference mix at 7 days.

Similarly, the strength of M-0.5NS20G, M-1NS20G, M-1.5NS20G, M-2NS20G was increased by 3.88%, 8.99%, 15.17% and 12.52% to that of reference mix at 28 days and 5.64%, 5.97%, 6.29% and 5% to that of reference mix at 91 days respectively as illustrated in Figure 8. The strength of optimum mix, M-1.5NS20G was reduced by 18.68% and increased by 24.14% at 28 days to that of self-compacting light weight concrete and normal blended concrete respectively (Naniz and Mazloom, 2018; Raveendran and Krishnan, 2025).

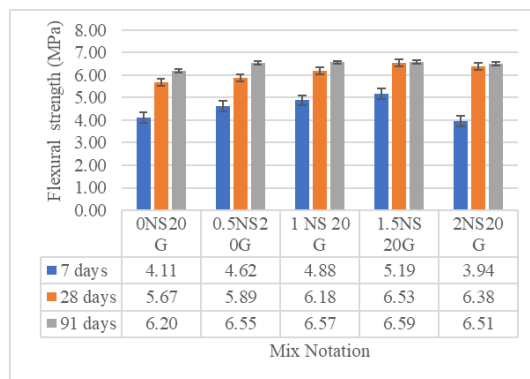


Figure 8. shows variation of flexural strength of SCC at 7, 28 and 91 days

The rise in strength was observed due to the quick usage of calcium hydroxide produced during cement hydration, at early ages, due to the strong reactivity of nano silica (Amin and El-Hassan, 2015).

Microstructural Studies on SCC

Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) tests were implemented on the optimum SCC mix, M-1.5NS20G at 28 days to study the compounds present in the concrete. The sample from the cube specimen was extracted and powdered using the impact testing equipment and then, it was sieved through 75 micron IS Sieve. The fine powder passed through the sieve was considered for the tests. The powder was compressed to a pill and dispersed in volatile solvent and placed on a mounting pin for the test. Scanning Electron Microscope (SEM) test is an instrument used to produce a magnified image to examine the internal structure of the material by ejecting electrons instead of light from an electron gun with much higher resolution due to the usage of electromagnets to control the degree of magnification to generate X-rays, backscattered and secondary electrons for image detection. As per the existing studies, C-S-H serves as the primary binding phase in cement and has an amorphous structure consisting of layered calcium silicate

sheets, with interlayer spaces occupied by calcium ions and water molecules to generate flexibility enabling it to assimilate varying compositions and water contents. These attributes are required for the binding properties of material as they allow C-S-H to bind aggregate particles together in concrete. As the Ca/Si ratio increases, the water content in the C-S-H structure also increases due to the formation of a more disordered and porous network due to higher calcium concentrations further leading to the formation of additional interlayer water and increased gel porosity whereas lower Ca/Si ratios result in a denser structure with reduced water retention. These changes directly impact mechanical strength and stiffness of concrete. The dynamic balance between water, calcium and silicate ensures that the C-S-H gel forms a cohesive and robust matrix capable of binding aggregate particles in concrete. When CNS was added, the uniformly dispersed nano-silica particles could provide nucleation points for the hydration reaction to generate the crystallization growth of the hydration products such as additional C-S-H gels due to high chemical reactivity and were responsible for refining the pores to develop a discontinuous pore structure. Simultaneously, large amounts of CH were consumed and the sizes were restricted during this process (Chen *et al.*, 2024). Regarding the current research work, Figure 9 illustrates the large prismatic crystals of calcium hydroxide and fiber-shaped Calcium-Silicate-Hydrate (C-S-H) which improved strength of concrete. In the structure of the C-S-H gel, nanoparticles can act like nucleus forming a strong bond with C-S-H gel particles (Beigi *et al.*, 2013). NS enhanced C-S-H gel formation and reduced calcium hydroxide to form a dense concrete structure (Ltifi *et al.*, 2011). Thus, stability of hydration products and mechanical properties of the concrete were improved (Beigi *et al.*, 2013).

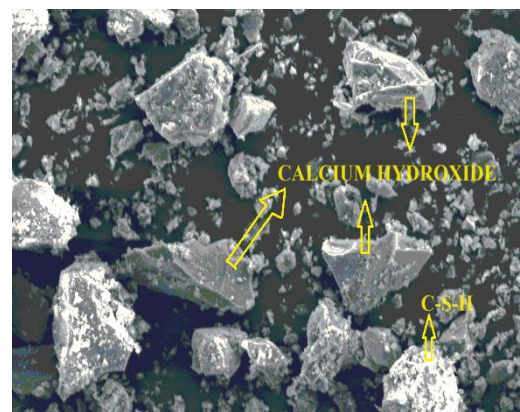


Figure 9. shows SEM image of 28 days hardened SCC, M-1.5NS20G

X-ray diffraction (Cullity and Stock, 2014) is a method to find compounds present in the sample by emitting X-rays from a X-ray tube that is placed on a goniometer along with sample, optics and detector. The powdered sample was placed on a glass slide in sample holder. The number of X-rays scattered by the peak position indicates the crystalline nature with Ettringite (Hexacalcium aluminate trisulfate hydrate), Calcite, Quartz, Yeelimite (Calcium sulfo aluminate) were identified as crystalline compounds with the parameters of the intensity (height of the peak), Full Width of Half Maximum (crystalline size) and detector angle (2θ) as shown in Figure 10. In general, the main origin of strength in the solid products of the hydrated cement paste is the existence of Vander Waals forces of attraction which cause the adhesion between two solid surfaces. The degree of the adhesive action depends on the extent and the nature of the surfaces involved. The crystals of C-S-H, Ettringite and hexagonal calcium aluminate hydrates contain extensive surface areas and adhesive capability. These hydration products of cement tend to adhere strongly to each other as well as low surface-area solids such as calcium hydroxide, anhydrous clinker grains, fine and coarse aggregate particles. Yeelimite forms the insoluble, fibrous mineral ettringite on hydration in the presence of calcium and sulfate ions which provides the strength in sulfoaluminate concretes, monosulfoaluminate, and aluminium hydroxide. Quartz and Calcite play vital role in concrete by enhancing its strength and workability (Mehta and Monteiro, 2014).

Conclusions

1. The slump of SCC was high at 1.5% NS as a binder beyond which NS solid particles assembled and lowered the flow due to water absorption and the additional amount of superplasticizer ($>0.7\%$ of binder material) must be added to sustain the workability of the mix beyond 1.5%NS.

2. The compressive strength of optimum SCC was risen by 11.71%, 8.58% and 17.45% at 7, 28 and 91 days respectively. The growth in compressive strength was observed due to liberation of extra C-S-H gel from the reaction of nano silica with calcium hydroxide in lime solution.

3. The split tensile strength of optimum SCC was increased by 43.40%, 23.11% and 9.51% to that of reference mix at 7, 28 and 91 days respectively. The rapid intake of calcium hydroxide generated during cement hydration at initial ages gives nano silica high reactivity and improved strength up to optimal mix. The mix's nano particles surpassed the optimal amount needed to react with released lime during cement hydration, leaching silica and reducing strength. In addition to that, defects during nano particle dissemination may have caused weak zones.

4. The flexural strength of optimum SCC was enhanced by 26.28%, 15.17% and 6.29% to that of reference mix at 7, 28 and 91days respectively. Strong nano silica reactivity caused calcium hydroxide to be consumed quickly during cement hydration at early ages to increase strength.

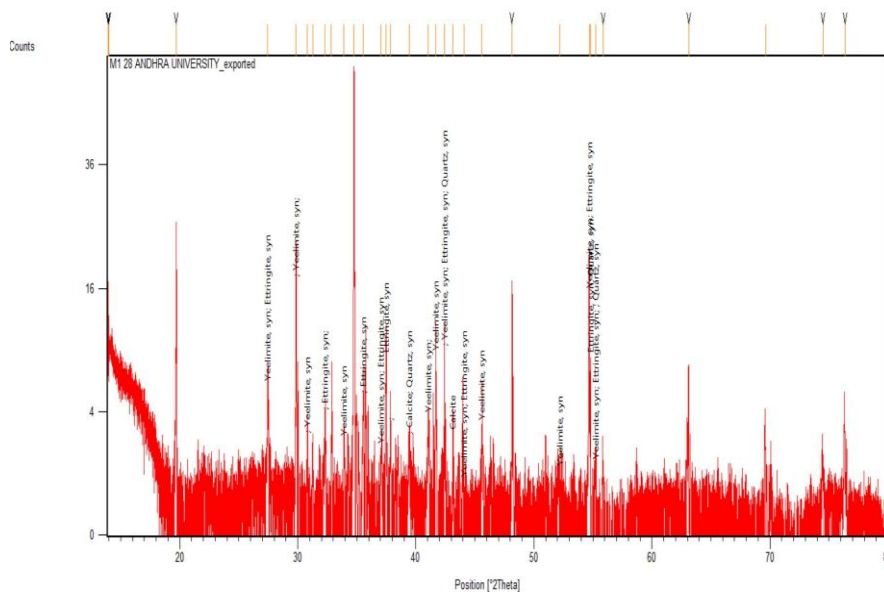


Figure 10. shows XRD pattern of 28 days hardened SCC, M-1.5NS20G

5. Since NS has a vast specific surface area, it binds cement and aggregate reducing initial and final setting time and increasing early age strength.

6. SEM and XRD pictures indicated calcium hydroxide and calcium silicate hydrate compounds with various crystalline structures. Strength was achieved predominantly due to these compounds. NS also improved C-S-H gel development and minimized calcium hydroxide, forming a compact concrete structure.

Scope for further study

1. The current research can be expanded by incorporating NS having a higher concentration of solid particles and other supplementary cementitious materials to investigate their impact on the characteristics of SCC.

2. The SCC presented in the research work can be practically used in building construction.

3. The structural behaviour of SCC beam column joints can be investigated.

Acknowledgement

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