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REVIEW PAPER

Influence of Nano Silica on Fresh and Hardened Properties of Cement-based Materials – A Review

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Abstract
In field, the research has been extended to the usage of Nano material in concrete and thereby enhancing the performance of the structure. It has been identified that incorporating a trifling amount of Nano material in concrete can modify the properties of cement at Nano level which makes the concrete much sustainable. Among the various Nano materials, Nano Silica has gained the attention in contemporary days because it offers high SSA and good pozzolanic reactivity even better than the other conventional mineral admixtures. Due to its high SSA, Nano Silica extended its advantages as a better filler, which makes the concrete less porous and thus enhances the durability. Early-age strength gain is due to the accelerated Nano Silica – Cement hydration which ends up in the formation of complex microstructural C-S–H gel. Accelerated hydration is the result of high pozzolanic reactivity of Nano Silica. For the better rheological properties, concrete with Nano Silica requires the higher dosage of super plasticizers to promote the rolling effect of Nano particles and also to avoid the agglomeration of Nano particles in concrete even at high water-cement ratio (0.45) when paralleled with conventional one. Moreover, dispersion type, particle size distribution and densification of concrete with Nano Silica particles plays a vital role in enhancing the strength parameters of the concrete. This review paper presents the study on how Nano Silica in concrete at different dosages can alter the properties of the concrete.

Keywords Nano Silica · High specific surface area · Pozzolanic Reactivity · Filler effect · Mechanical properties · Durability studies

Nomenclatures

OPC	Ordinary Portland Cement
SCM	Supplementary Cementitious Material
CNTs	Carbon Nano Tubes
NS	Nano Silica
SEM	Scanning Electron Microscope
CO_2	Carbon dioxide
C-S–H	Calcium Silicate Hydrate
ITZ	Interfacial Transition Zone
W/C	Water-to-Cement
W/B	Water-to-Binder
Ca/Si	Calcium-Silica Ratio
nm	Nano meter
μm	Micro meter
rpm	Revolution Per Minute
min	Minutes
˚C	Degree Celsius
SCC	Self-Compacting Concrete
HPC	High Performance Concrete
PCE	Poly Carboxylate Ether
TOC	Total Organic Carbon
$mSiO_2$	Mesoporous Silica
TEOS	Tetraethyl Orthosilicate
$mSiO_2/TiO_2$	Mesoporous titania-silica
SiO_2	Silicon dioxide
Al_2O_3	Aluminum oxide
Fe_2O_3	Ferric Oxide
MgO	Magnesium Oxide
CaO	Calcium Oxide
SO_3	Sulphur Trioxide
K_2O	Potassium oxide
Na_2O	Sodium oxide

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TiO_2	Titanium oxide
P_2O_5	Phosphorous pentoxide
SSA	Specific Surface Area
SF	Silica Fume
FA	Fly Ash
UFFA	Ultra-Fine Fly Ash
MK	Metakaolin
NCW	Nano Ceramic Waste
GP	Glass Powder
GO	Graphene Oxide
NC	Dry Calcium Carbonate
GF	Glass Fiber
HVFA	High-Volume Fly Ash
HPSCC	High Performance Self-Compacting Concrete
MPC	Magnesium Phosphate Cement
GGBFS	Ground Granulated Blast Furnace Slag
UHPC	Ultra-high-Performance Concrete
RAC	Recycled Aggregate Concrete
SCLC	Self-Compacting Light Weight Aggregate
C_3S	Tricalcium Silicate
C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
$Ca(OH)_2$	Calcium Hydroxide
PCA	Poly Carboxylate Water-Reducing Admixture
HSC	High Strength Concrete
PP	Polypropylene
LWC	Light Weight Concrete
LWA	Light Weight Aggregate
HSLWC	High strength lightweight concrete
ULWC	Ultra-Light Weight Concrete
ULCC	Ultra-Light weight Cement Composites
OWC	Oil Well Cement
HVS	High Volume Slag
HVS-FA	High Volume Slag Fly Ash
BFS	Blast Furnace Slag
Cement L	Low C_3A Cement
Cement H	High C_3A Cement
PCM	Printable Cement Mortar
CAC	Calcium Aluminate Cement
HVFAC	High-Volume Fly Ash High-Strength Concrete
MP	Macro polymeric Fibre
PVA	Poly-Vinyl Alcohol
UPV	Ultra-sonic pulse velocity
SEM	Scanning Electron Microscopy

1 Introduction

In construction field, one of the most frequently pronounced substance is concrete, which meets the production of about 27.3 billion tons annually by 2015 [1]. Generally concrete is comprised of cement, water and aggregates (Fine and Coarse aggregates) in a measured quantity. It is used globally in a massive amount when compared with the other building materials like steel, wood, plastic etc., An enormous consumption of concrete results in increased demand for the cement thereby increasing its production. However, it's low compressive–to-tensile strength, high brittleness and reduced flowability in addition to that; its exposure to the aggressive environment increases the global concern over lifespan [2].

In spite of the different grades of OPC, it is commonly used in widespread [3–13]. Cementitious composite materials made from Portland cement find its far-reaching applications in construction domain. In this modern era, the industrial growth and technological development put forth the requirement for colossal infrastructure. This results in the production of cement in the huge quantities. An immense production of cement has numerous environmental effects due to the emission of hazardous pollutants like particulates and greenhouse gases. According to the assessment, cement clinker production is considered as the major source for the emission of greenhouse gases (Carbon dioxide. Methane, Nitrous oxide [14, 15]) in construction industry contributing 8% of global emissions [8]. One of the major effects from cement manufacturing is emission of greenhouse gases [16] which can be immensely reduced by Carbon dioxide sequestration [17], Catalytic Conversion [14] Amine scrubbing [15], and also by inculcating the supplementary materials or alkali activated cementitious materials [18, 19] with pozzolanic nature and there by reduces the utilization of cement partially [16]. In recent times, some researchers developed the aggregates from industrial by-products and agricultural waste which is incorporated to cement-based materials to attain the sustainability [18]. By incorporating the SCM's from agricultural waste (E.g: Bagasse ash) reduces the disposal issues in environment [20]. However, the demand for cement manufacturing rises with the advancement in infrastructure which paves the way for excessive greenhouse gas emission. The prime concern also includes strength, durability and maintenance cost of the construction material [8]. The percentage emission of CO_2 in stages of life cycle (2005–2012) is shown in Fig. 1 [17].

The emerging new technique must enhance the control and cutoff the emission of greenhouse gases and energy used for the cement production and also by adding the SCM like Pozzolans for the sustainable development [8]. The volcanic ash [8], Silica fume [8], bottom ash [8], Bagasse Ash

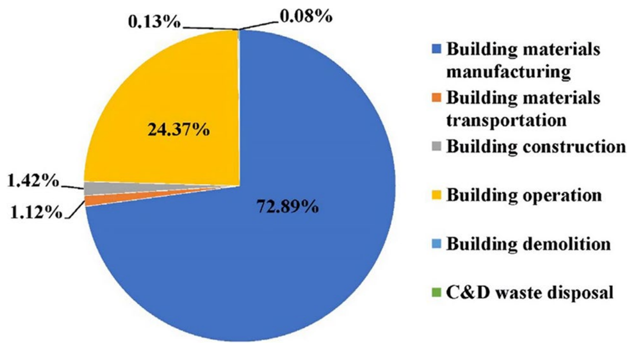


Fig. 1 Percentage emission of CO_2 in stages of life cycle (2005–2012) [17]

[20–22], Rice husk ash [21–23], Corn cab ash [21] etc., are the types of conventional Pozzolans. Cementitious Material chosen for the sustainable construction practices must possess better pore structure and high strength by binding the materials. By proportionating the cement with materials having smaller sized particles can influence the physical and chemical properties ending in betterment of pore structures. It has been proven that incorporation of Nano-sized cementitious material has its impacts on the performance of the structure due to its high volume to the surface area.

1.1 Nanotechnology

Nanotechnology is a branch of science that deals with manipulating the dimension of material at Nano level for improvising its characteristics and performance in a wide range of applications. This cutting-edge technology involves engineering material at its atomic or molecular level whose dimension will be lesser than 100 nm [6]. Embodiment of Nano sized particles in concrete technology shows a positive effect on development of sustainable concrete which in turn reduces the greenhouse gas emission [1, 3]. The report of RILEM Technical Committee 197- Nanotechnology in Construction Materials (TC 197-NCM) [24] reveals the fact that the incorporation of Nanoparticles augments the durability and mechanical properties of the cementitious composite materials. The handling of cementitious composite at Nano size is embarked in this technology driven world [25]. The advancement in this field allows concrete technologists to extend their scope of work in cement-based materials. Since the quantity of Nano particle is required in substantial amount to bring about strength and better performance thus reducing the usage of alkali or alkali Silicate. Higher Vander Waals force is experienced in Nano Silica on their surface which easily leads to the formation of aggregate/agglomerates.

Homogenous densified compact microstructure has been achieved by using the finer Nano size particles because of its high pozzolanic activity as well as by the filler action [1, 8, 26]. Due to invading of ultra-fine Nano particles in the voids of cement matrix leads to the pore refinement, pore volume reduction and cutting off the capillary pore mechanism, the physicochemical and mechanical properties of the cement concrete structure have been improved significantly [8]. Subsequently, the cement concrete structure has improved resistance for the chemical attack and decreased water permeability capacity of the cement matrix [8]. The integration of Nano particles in cement mortar produces the dense micro structure owing to form the compact cement mortar and develops better mechanical behavior [8]. The other commonly used Nano materials are Titanium oxide (TiO_2) [27], Aluminium oxide (Al_2O_3) [27], Ferrous oxide (Fe_2O_3) [27], Zinc oxide (ZnO) [27], Nano clay [28], Nano iron [28] and CNTs [27]. The Particle size and SSA related to concrete materials [1] is shown in Fig. 2.

1.2 Nano Silica

NS particle has gained the interest among the various Nano materials due to its early age reactivity. It has earned more benefits in concrete and glass industries [21]. Around 46% of the researchers have used the powdered form. Moreover, Nano Silica (NS) might be pyrogenic NS, precipitated NS or NS gel [29]. In aqueous suspension, colloidal NS is comprised of amorphous hydroxylated Silica particles of size ranging between 1–500 nm [8]. The SEM image of NS is shown in Fig. 3. To improve the mechanical and durability performance of the cement concrete structures, NS can be used as an additive [30]. Replacing the cement with NS to a particular extent can reduce the CO_2 footprint and make the concrete cost effective [1]. Due to its early age reactivity, NS in cement concrete reacts with calcium hydroxide to form C-S–H gel which fills up the pores and thereby improving the early strength. Moreover, with the better filling effect and particle size distribution, NS reduces the porosity of the concrete when compared with other conventional mineral admixtures [1]. High SSA of the NS demands high W/C ratio or increased dosage of super plasticizers for the better flow properties and also to avoid the agglomeration of the particles. The agglomeration of Silica Nano particles might occur only in powdered form whereas the NS hydrosols may be monodispersed or become stabilized as small aggregates [29]. The Role of NS is shown in Fig. 4 [29]. The filling effect of NS agglomerates is shown in Fig. 5 [31].

In concrete environment, NS facilitate the nucleation site for the formation of C-S–H gel [33] and also for the other hydration products, which could fill up the concrete pores accounting for the closing of cracks [8]. Furthermore, Initial and final setting time of cement mortars have also lessened due to extensive reaction of NS [8, 27]. Even a small amount (0.25%) of synthesized NS might improve the compressive

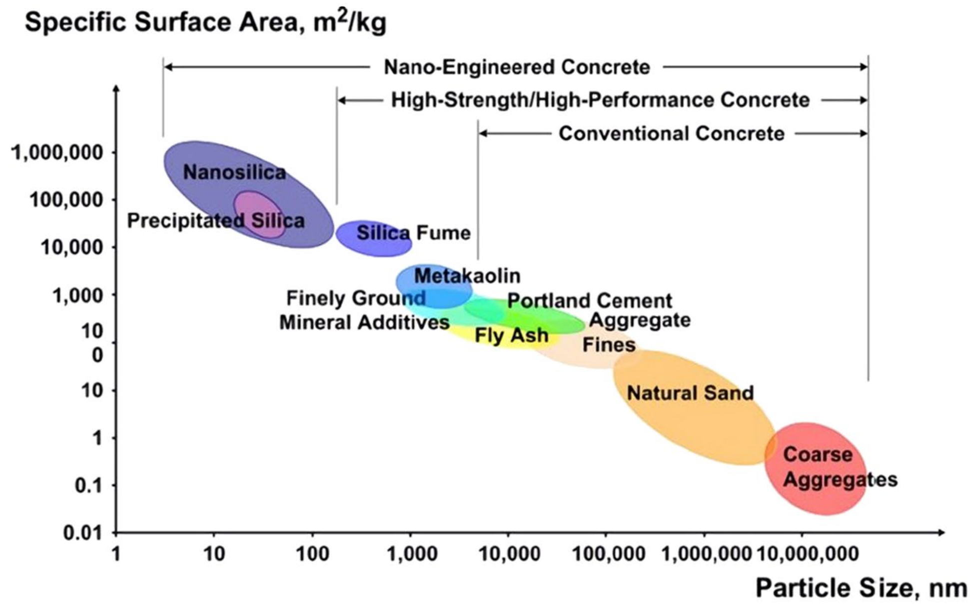


Fig. 2 Particle size and SSA related to concrete material [1]

strength of cement matrix [3]. Kong et al. [29] stated that mechanical properties, rate of hydration and durability are greatly influenced by agglomeration of various forms of NS. The above-mentioned properties are not only affected by the pre-mentioned factors but also by the nature, concentration, particle size of the binder and additive particles, application technique and water/binder ratio [8]. The advantages, disadvantages and applications of NS are shown in the Table 1. This review paper presents the study on how NS in cementitious environment at different dosages can alter the properties of the mix.

1.3 Objective

The main objective is to provide the entire review on influence of NS and the combined effect with SCM in cement concrete mix at all aspects. This review article is attempted to communicate the following problems during investigation.

- Does the replacement percentage of cement with NS and/or SCM enhance the properties of the proposed mix?

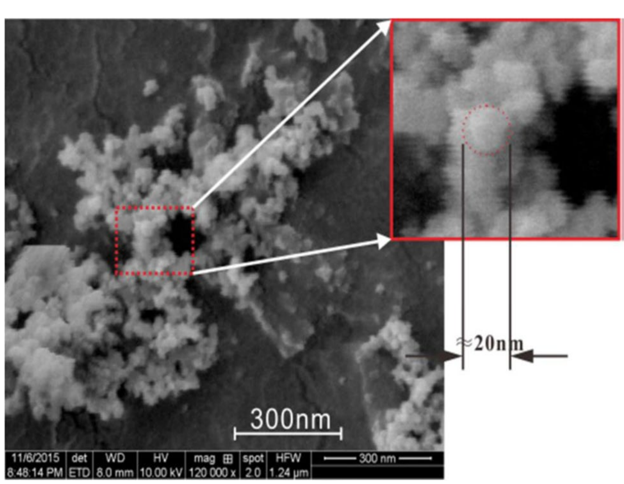


Fig. 3 SEM image of NS [32]

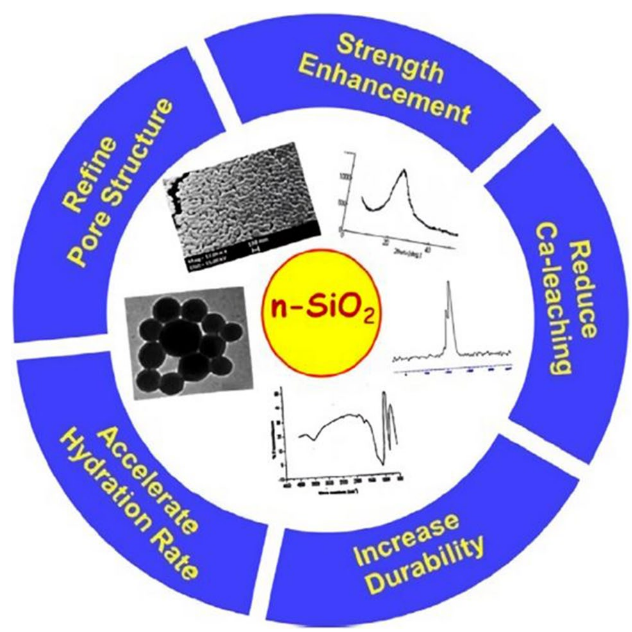


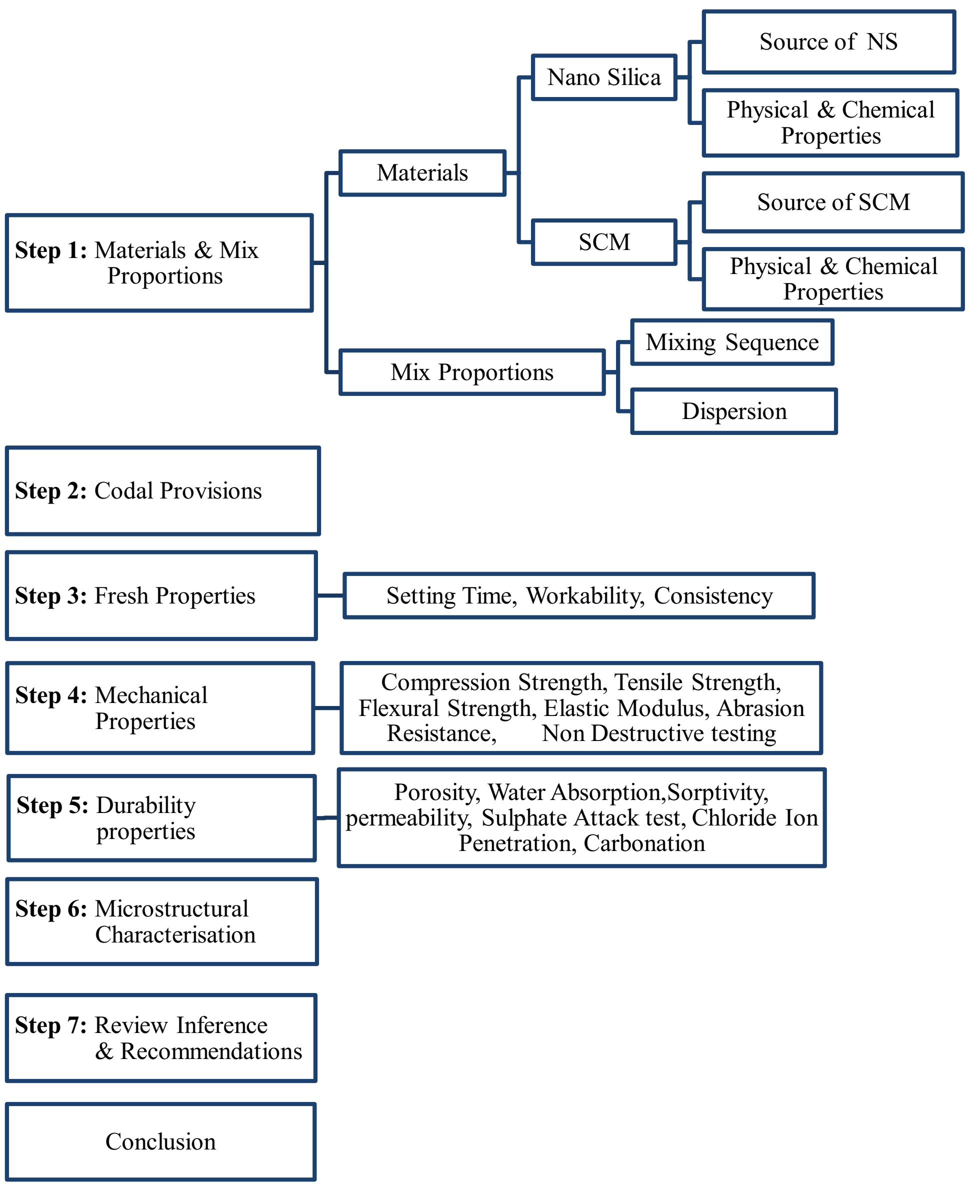
Fig. 4 Role of NS [29]

- How does the mixing sequences and size of NS particles and SCM influences the fresh and hardened state properties of the cement concrete mix?
- Does the NS require dispersion medium and different type of dispersion methods for better dispersion?
- Does the type of cement and its blends influence the properties of the concrete?
- How does the water to binder ratio and type of super plasticizer dosage influences the rheological properties?
- What are the different types of tests and its corresponding codal provisions that have been adopted by the researchers?

1.4 Methodology of the Review Article

1.5 Research Significance

The need for incorporating the NS in construction industry is increasing day by day to increase the sustainability in economical manner. There is n' number of investigations done focusing on fresh and hardened properties of NS incorporated cement-based composites. So, the present review article focuses on how the size, form, replacement level, dispersion, type of mix and mixing sequences of NS influences the properties of different types of mortar and concrete. The fresh and hardened properties of the NS incorporated mix is discussed with justification. Markedly, the review would pave the way to select the NS based on their place of application, with promising colossal development.



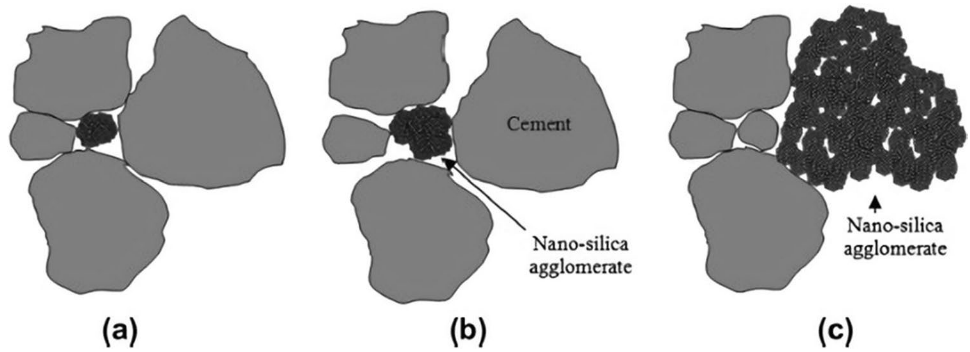


Fig. 5 Filling effect of NS agglomerates [31]

2 Materials and Mix Proportions

The various types of NS and SCM are the major constituents of this review article. Hence, study on the source and the properties of the materials become necessary which in turn, helps in material selection.

2.1 Sources of Nano Silica

NS can be synthesized either by top down (scale reduction) or bottom up (atomic or molecular scale) process [29], Sol–gel process [35], Silica Vaporization [35], biological and precipitation method [35]. Moreover, other methods include electro dialysis or neutralization of sodium silicate, electrolysis or direct oxidation of silicon, milling or peptization of silica gel, hydrolysis, silicon compound condensation, ion exchange etc. [29].

2.1.1 Synthesis of Nano Silica gel

Researchers M. Kooshafar and H. Madani [6] synthesized the NS gel by sol–gel process. In this process, sodium silicate was diluted with water to obtain the concentration of about 7 – 10%. Then few drops of sulphuric acid were added to the diluted solution. This attributed to the interconnection of NS particles or the formation of NS gel. After this, the alkaline solution was used to wash the obtained gel at 70–80˚C. In the next step, the gel was washed with distilled water, until the soluble salts were removed. Finally, the NS gel was oven dried at 110˚C for 24 h followed by milling to attain the suitable particle size.

2.1.2 Synthesis of Nano Silica Core–Shell Particles

Sarita Rai and Shivani Tiwari [38] studied and revealed the synthesis of silica-titania core shell but the synthesis of $mSiO_2/TiO_2$ core–shell procedure was not clearly discussed. Furthermore, Gu et al. [39] synthesized novel core–shell method for Nano particles. It was developed by grafting the NS with polycarboxylate super plasticizer. In this method, the surface modified PCE was achieved by free radical copolymerization between Acrylic acid ($C_3H_4O_2$), Triethoxy vinylsilane ($H_2C{=}CHSi(OC_2H_5)_3$) VETO and TPEG. The entire procedure was carried out in a water bath at 40˚C. Then, the varying mass of surface modified PCE were subsequently added to 150 g of colloidal NS. Meanwhile, the stirring was continued for 3.5 h at 300 rpm. To remove the unreacted monomers and PCE, the solution was dialyzed through polyrthersulfone ultrafiltration membrane for 2 days. The carbon concentration of the solution was examined by TOC Analyzer (MultiN/C 3100) and it remained constant. In addition to this, by increasing the core–shell ratio, better dispersion can be achieved due to the stability of these particles in concrete pore solution. The formation of $mSiO_2/TiO_2$ core–shell Nano Composite is shown in Fig. 6. The Chemical reaction of PCE with Si–OH groups of NS is shown in Fig. 7.

Table 1 Advantages, disadvantages and applications of NS

Advantages	Disadvantages	Applications
• Makes concrete less porous [34] • Enhances the bond between aggregates and cement matrix • Accelerates the setting time • Increased availability of nucleation sites • Densified microstructure • Reduces water permeability	• At higher concentrations, NS increases the cracking potential • Requires good dispersion and mixing sequences [34] • Requires more water to maintain workability • Requires increased dosage of super plasticizer at low W/B ratio • Material and Transportation costs are high [34]	• Anti-bleeding agent in SCC and HPC concrete [35] • Additives in eco-concrete [35] • Rock-Matching grouting mortars [35] • Gypsum particle boards [35] • Roller Compacted Road Pavements [36] • Engineering Cementitious Composite [37]

2.1.3 Physical and Chemical Properties of Nano Silica

The distribution level of NS adopted for the experimental purpose plays a significant role in altering the microstructure at Nano level. For better understanding in research, it is necessary to study the physical and chemical properties of the materials used. Hence the physical properties of NS used by the researchers are shown in Table 2. The chemical composition of different types of NS are shown in Table 3.

2.2 Supplementary Cementitious Materials

The majorly used SCMs are SF [6, 9, 40, 53, 60, 61, 66, 73], FA, UFFA [58], MK, NCW, GP, GO, Chromium Oxide and NC. Ternary and quaternary blends with NS, MS and FA can replace the cement by 32% and thereby reduce the disposal issues of industrial waste products [74].

Fig. 6 Formation of $mSiO_2/TiO_2$ core–shell Nano Composite [38]

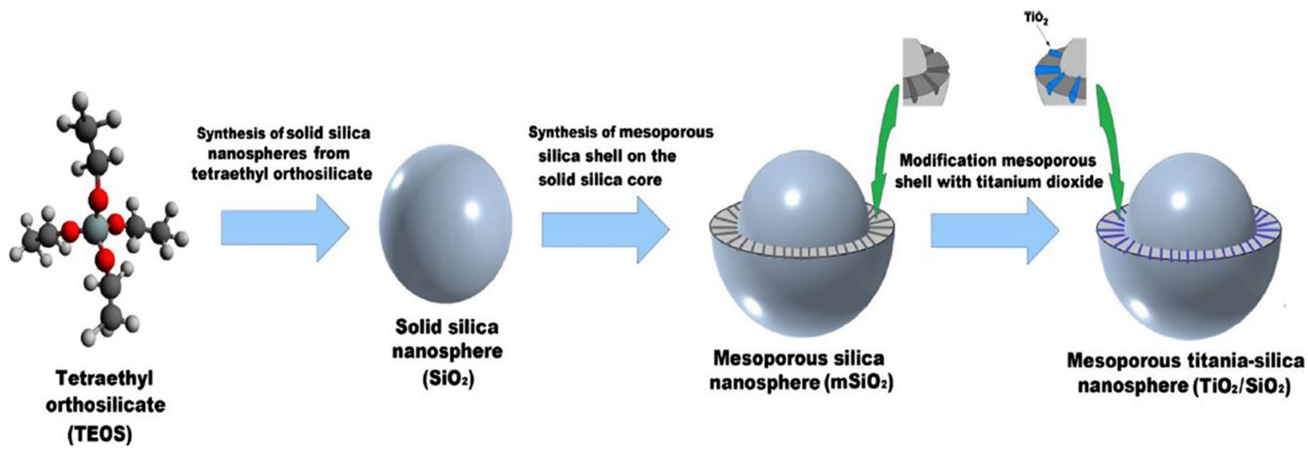


Fig. 7 Chemical reaction of PCE with Si–OH groups of NS, Gu et al. [39]

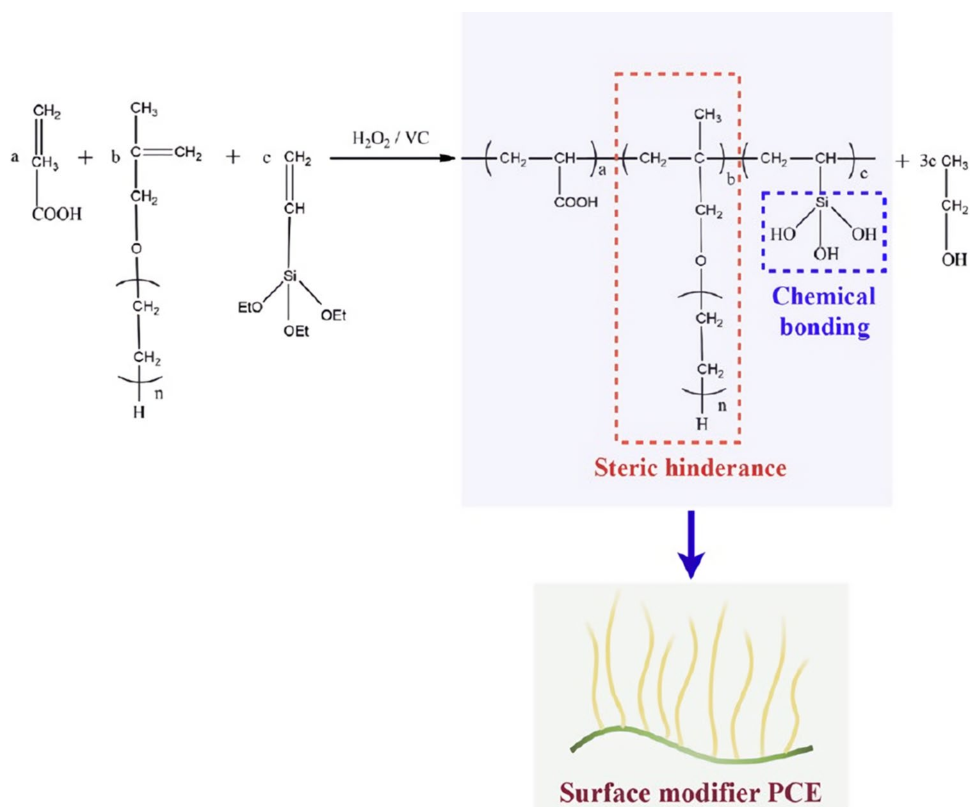


Table 2 Physical properties of different types of NS

Type	Size (nm)	SSA (m^2/g)	Reference
Powder	20	-	[25]
Powder	15–20	640	[4, 40]
Powder	5–20	-	[5]
Colloidal	10	954.3	[41]
Colloidal	50	187.4	
Powder	20	-	[42]
Powder	-	200	[43]
Powder	15	-	[44]
Colloidal	10-140	-	[45]
Powder	9–11	300	[46]
-	14	150	[24]
Powder	15	-	[47]
Sol & Gel	30–60	-	[6]
-	10–140	300	[32]
Powder	7–40	-	[7]
-	27	80	[9]
Powder	10–20	-	[10]
Colloidal	35	-	[16]
Powder	30–70	175–225	[48]
Powder	7–40	300	[49]
Powder	7–25	240	[50]
Powder	4	188	[51]
Powder	25	160	[52]
-	30	150	[53]
-	7–40	300	[13]
Powder	21	-	[54]
Colloidal	20	140	[55]
Colloidal	13.9	-	[39]
Powder	5–20	-	[56]
Powder	10,20,30	220,90,50	[57]
Colloidal	20	-	[58]
Powder	-	116	[10]
-	3 -200	-	[59]
-	12	200.1	[60]
Powder	15 ± 3	165 ± 17	[61]
Colloidal	8–20	-	[62][88]
Colloidal	-	50	[63]
Powder	-	56	
-	14	150 ± 15	[64]
Powder	7–24	-	[65]
-	20–30	193	[66]
Powder	15 ± 3	165 ± 17	[67][76]
Powder	15	200	[68]
Colloidal	12.4	220	[69]
Powder	10–150	120 -230	[26]
-	10 ± 5	640 ± 50	[70]
Colloidal	5–20	-	[71]
Powder	20–30	125	[72]

2.2.1 Source of SCM's

Most of the investigators used SF and FA as SCM than the other above-mentioned ones. The SCM's like MS [8, 21, 42, 75], SF [6, 9], UFFA [58], MK [9], NC [52], Chromium Oxide [76] and Slag [32, 69] are sourced commercially whereas some of the investigators synthesized the SCM's are as follows:

i. MS: By-product of ferrosilicon industries [75].
ii. MK: Synthesized by thermal activation of kaolin clay with high purity [77].
iii. NCW: By grinding the ceramic waste in Tabin Crusher followed by the milling process with the grinding speed of 400 rpm upto12hrs [54].
iv. GP: Bottles were collected from dump yard and washed to remove the dust, paper labels and other particles from the surface. Then, bottles were broken into tiny pieces followed by grinding until they were pulverized to attain the practice size of 63 µm [78]
v. Perlite Powder: The perlite stone is oven dried at 105˚C for 24 h to remove its cohesiveness and then ball milled at a speed of 30 rpm [79].

2.2.2 Physical and Chemical Properties of SCM's

The combined effect of NS and SCM plays a vital role in influencing the strength as well as the rheological properties of the mix. Hence it is necessary to understand the physical and chemical properties of SCM. The physical and chemical properties of various types of SCM used by various investigators are shown in Table 4. The average particle size of NS and SCM are shown in Fig. 8.

2.3 Mix Proportions

In order to study the performance of NS, researchers have replaced the cement content with NS at different substitution level in concrete or cement mortar mix. The summary of the percentage of NS replacement and W/S ratio adopted by the various investigators are shown in Fig. 9. The percentage of SCM with cement replacement and W/S adopted by various investigators are shown in Fig. 10.

2.3.1 Mixing Sequences of Nano Silica

The main aim of studying the mixing sequences is to reduce the flocculation of Nano particles was observed from the investigations of Niloufar Zabihiet al. [89]. In the same context, Nano material must be well dispersed either in water or super plasticizer and water used for the admixture. Better dispersion can be achieved by stirring the suspension at high speed for 1–3 min [54]. Furthermore, findings of other

Table 3 Chemical composition of different types of NS

Type	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	K_2O	Na_2O	TiO_2	P_2O_5	Reference
Powder	99.65	0.01	0.012	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.02	< 0.01	[54]
Powder	90.9	0.29	0.1	0.15	0.19	1.16	-	1.1	0.29	-	[50]
Powder	99.5	0.002	0.001	0.001	0.002	-	-	-	-	-	[4]
-	-	0.79	-	0.02	-	0.59	0.08	-	-	-	[9]
Powder	95	1.08	0.45	1.06	0.2	0.31	0.12	0.68	0.18	0.12	[65]
-	≥ 98	0.076	0.293	0.05	0.392	0.185	0.08	0.328	0.064	0.129	[66]
-	> 99.5	< 0.1	< 0.1	0	0	-	-	< 0.2	-	-	[64]

The other researchers incorporated NS content with ≤ 99.9% purity

Table 4 Physical and chemical properties of SCM

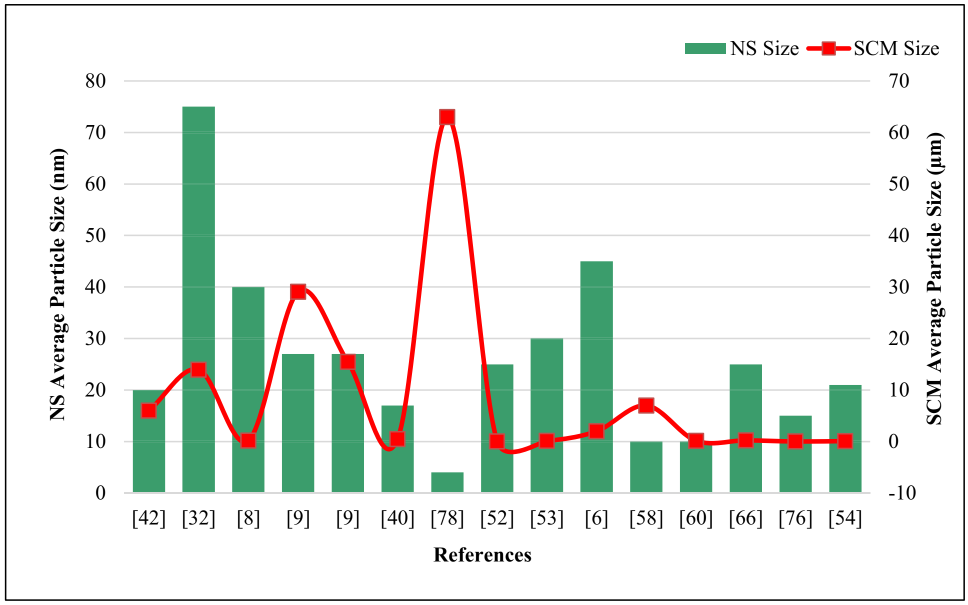
Physical Properties			Chemical Properties								Reference
Type	Particle size	SSA (m^2/g)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	K_2O	Na_2O	
Blast furnace slag	13.96 µm	10–140	32.31	16.36	0.29	10.41	35.53	2.74	-	-	[32]
MK	29.07 µm	27	57.43	32.58	2.08	1.51	0.02	-	-	1.81	[9]
SF	15.45 µm	27	92.54	0.12	0.14	1.19	0.98	-	0.46	0.41	[9]
MK	1.5 µm	-	52.40	44.90	0.41	-	-	-	0.12	0.16	[77]
GP	63 µm	4	71.09	3.52	1.77	1.56	10.59	0.03	0.89	10.46	[78]
class-F FA	-	35	58.25	16.60	4.63	-	10.23	0.84	-	-	[16]
NC	15–40 nm	25	-	-	0.02	0.5	97.8	-	-	-	[52]
SF	120 nm	30	93	0.4	0.8	0.6	-	0.4	-	-	[53]
SF	2 µm	30–60	94.66	0.31	0.6	0.78	0.36	0.23	0.2	0.22	[6]
FA	-	-	55.27	26.69	8.14	0.39	1.61	0.25	1.76	0.13	[30]
FA	-	-	42.52	32.62	9.35	0.73	8.63	1.21	2.16	0.59	[73]
SF	-	-	93.90	-	0.59	0.27	1.85	-	0.86	0.17	[73]
SF	150 nm	7–12	95.9	0.3	0.3	0.4	0.2	1.5	0.6	0.05	[60]
SF	-	15	93.6	1.3	0.9	1	0.5	0.4	1.52	0.45	[61]
FA	-	-	52	30	3.5	5	6.5	1.6	1.27	0.58	[61]
FA	-	-	57.2	24.4	7.1	-	2.24	0.29	3.37	0.38	[64]
SF	229 nm	20–30	93	1.7	1.2	1	0.3	-	1.1	0.6	[66]
Slag		-	32.15	12.87	0.369	6.05	40.67	4.95	0.51	0.28	[69]
class-F FA	- B	-	56.2	20.17	6.69	1.92	4.24	0.49	1.89	0.58	[24]
NCW	84 nm	21	68.6	17	0.8	2.5	1.7	0.12	-	-	[54]
MS	150 nm	22	99.88	0.04	0.04	-	0.001	-	-	0.003	[75]

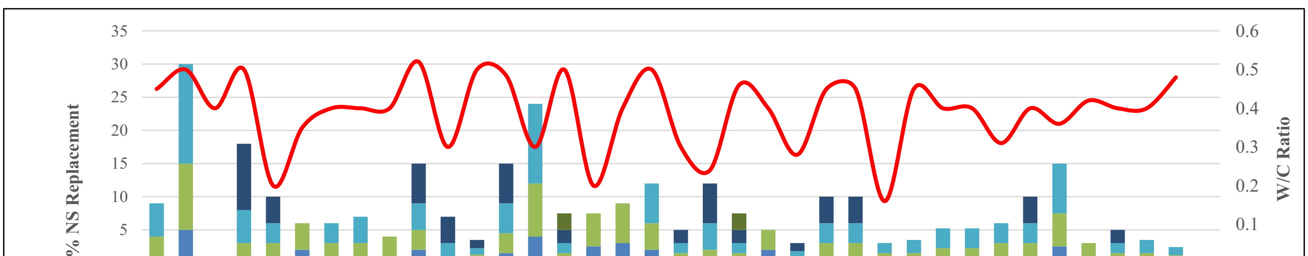
researchers [5, 6, 13, 25, 32, 43, 44, 46, 47, 49, 52, 86, 90, 91] have revealed that sonication of Nano particle leads to prominent effect in dispersion. The sonication time followed by various investigators are shown in Fig. 11.

2.4 Dispersion of Nano Silica

As evident from the study, mostly NS particles are characterized by their large SSA. This attribute the agglomeration of NS particles at poor dispersion. Hence to avoid the agglomeration, it is necessary to understand the mixing sequence of Nano particles. Moreover, enhanced dispersion increases seeding effect and thereby increasing the nucleation sites [10]. At the same time, from the study of Ehsan Ghafari et al. [80] revealed that, dry NS particles may disperse in air due to its low density. To overcome this, Nano particles are first dissolved in water or super plasticizer and then added to the cement matrix. The Well dispersed Nano SiO_2 at PCE is shown in Fig. 12. The steps involved in dispersing the NS in Super plasticizers [90] are as follows:

Fig. 8 Average particle size of NS and SCM





	[41]	[42]	[43]	[44]	[80]	[24]	[47]	[81]	[82]	[83]	[7]	[8]	[40]	[12]	[29]	[78]	[16]	[84]
															2.5			
				10	4					6	4	1.25	6		2			
	5	15	0.15	5	3		3	4		4	2	1	4.5	12	1.5			6
	3	10	0.1	2	2	4	2	2	3	3	1	0.75	3	8	1	5	6	4
Percenatge	1	5	0.5	1	1	2	1	1	1	2	0	0.5	1.5	4	0.5	2.5	3	2
W/S ratio	0.45	0.5	0.4	0.5	0.2	0.35	0.4	0.4	0.4	0.52	0.3	0.5	0.49	0.3	0.5	0.2	0.4	0.5

	[85]	[86]	[87]	[52]	[13]	[54]	[57]	[73]	[60]	[62]	[88]	[66]	[67]	[68]	[69]	[76]	[71]	[72]
			2.5															
	2	6	2		1.2	4	4						4			2		
	1.5	4	1.5		0.9	3	3	1.5	2	3	3	3	3	7.5		1.5	2	1.2
	1	2	1	3	0.6	2	2	1	1	1.5	1.5	2	2	5	2	1	1	0.8
Percenatge	0.5	0	0.5	2	0.3	1	1	0.5	0.5	0.75	0.75	1	1	2.5	1	0.5	0.5	0.4
W/S ratio	0.3	0.24	0.46	0.4	0.28	0.45	0.45	0.16	0.45	0.4	0.4	0.31	0.4	0.36	0.42	0.4	0.4	0.48

Fig. 9 Percentage NS replacement and W/S ratio

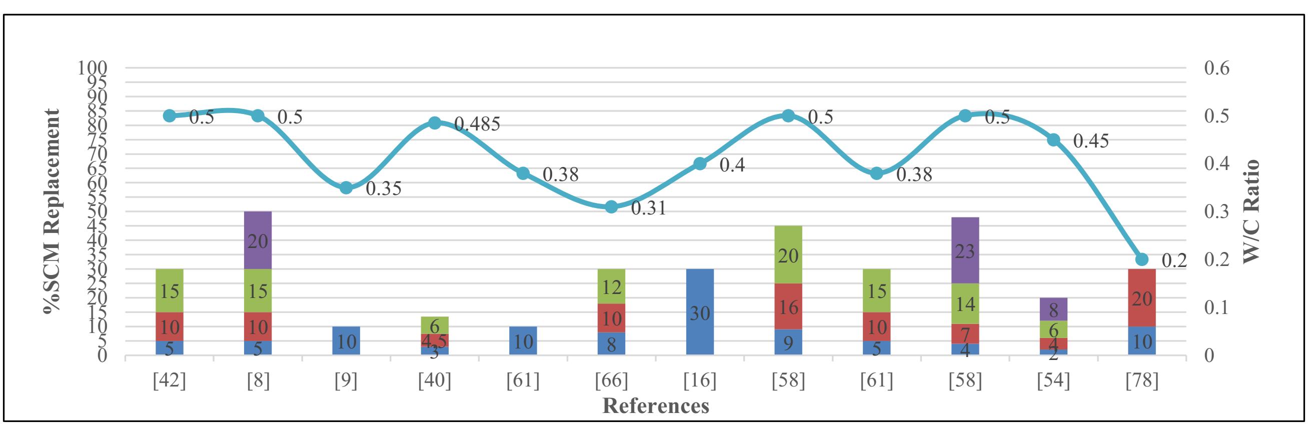


Fig. 10 Percentage SCM replacement and W/S ratio

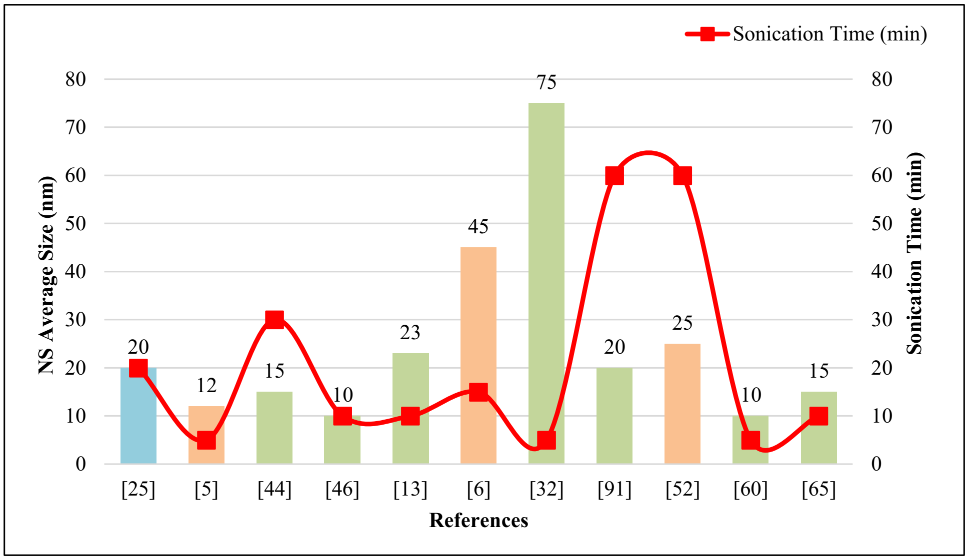


Fig. 11 Sonication time followed by various investigators

Step 1**:** (Synthesized branched polymers + NS) to be dissolved in distilled water.
Step 2: The suspension prepared was transferred to the test tube once it got neutralized.
Step 3: Then the solution is sonicated for 30 min and also it can be used for Dynamic Light Scattering (DLS)

3 Codal Specification

Researches followed the codal provisions for specimen preparation and testing. The codal specification followed by the researchers is summarized in Table 5.

4 Effects of Nano Silica and SCM on Fresh Properties of Cement Mortar and Concrete

The NS particles in proposed mix shows their effect on fresh properties of concrete/cement paste such as consistency, setting time, workability, etc.

4.1 Setting Time

The researchers Mohammad Kooshafar et al. [6] & Rishav Garg et al. [8] reveal that, NS gel in Portland cement mortar effectively accelerates the initial and final setting times than

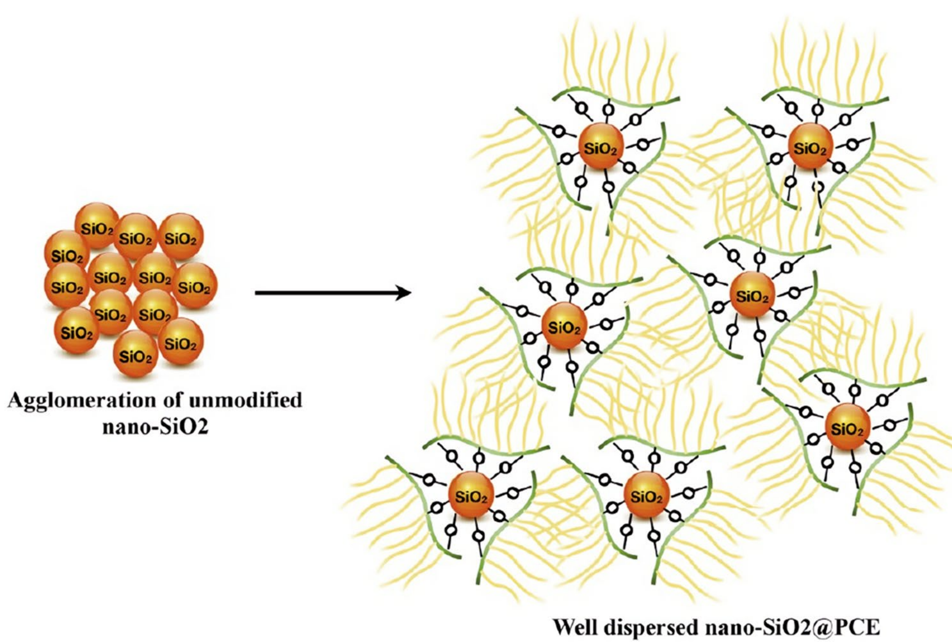


Fig. 12 Well dispersed NS in PCE, Gu et al. [39]

Table 5 Codal specifications

Property	Codal Specification	References
Setting Time	ASTMC191 [92]	[6]
	IS4031-2019 Part 5 [93]	[8]
	IS4031 [93]	[58]
	ASTMC230 [94]	[6, 89]
	IS5512-1983 [95]	[8]
	ASTMC1437 [96]	[25][42][47][60][73][78][80]
	EN1015-3 [97]	[58]
	EN445-2007 [98]	[82]
	GB/T50080-2016 [99]	[5][56]
	ASTMC1611 [100]	[10]
Consistency	IS4031-2019 Part 4&5 [93]	[8]
Compressive Strength	ASTMC39 [101]	[2][16][24][26][50][66][67][76][113]
	ASTMC109 [102]	[4][6][10][25][40][42][47][55][60][73][81][84]
	EN197-1:2011 [103]	[77]
	ASTM C349-14 [104]	[7]
	EN 196–1 [105]	[80][83]
	EN1015-11 [106]	[43]
	IS 2250–1981 [107]	[8]
	GB/T17671 [108]	[46][86][91]
	ASTMC 192 [109]	[54]
	IS 516 1959 [110]	[62][88]
	EN12390-3: 2009 [111]	[42][63][71][72] [82][87][134]
Tensile Strength	ASTMC 496 [112]	[16][42][50][61][66][67][113][130]
	EN1015-11 [106]	[43]
	IS 5816–1999 [114]	[8][62]
	BS-EN 12,390–6 [111]	[63][72]
Flexural Strength	IS 516 1959 [110]	[54][62]
Elastic Modulus	ASTMC 469 [115]	[51][62][66]
	ISO 1920–10 [116]	[87]
Abrasion Resistance	DN 52,108 [117]	[50]
	ASTM C 1138 [118]	[76]
Porosity	ASTMD4404-84 [119]	[68][77]
	ASTMC 642 [120]	[50][55][66][67][72][130]
	ASTM 1202 [121]	[63]
Water Absorption	ASTMC1585 [122]	[6][56][84]
	ASTM C1403-15 [123]	[42]
	BS-EN12390-8 [111]	[63]
Sorptivity	ASTMC1585 [122]	[7][24][47][50][55][80][82][113][130]
Permeability	RILEM,116-PCD [124]	[24][80][113]
	ASTM C1012 [125]	[26][30]
Chloride Attack	CEN/TS 12,390–11 [126]	[77]
	NT BUILD 492 [127]	[6][63][79]
	ASTMC1202 [121]	[16][40][55][58][60][130]
	GB/T 50,082 [128]	[5]
Carbonation	GB/T 50,082–2009 [128]	[56]
	RILEM CPC-18 [129]	[30]

the other forms of NS. In the same context, it is identified from the investigations done by Satheesh Kumar et al. [29] i.e., increasing NS content in cement mortar decreases the setting time. This is attributed to filler effect of Ultra-fine NS particles which increases the cement mortar thickness at the time of hydration [29]. Moreover, there is a substantial decline in initial and final setting time of Binary, Ternary and Quaternary blends of Portland cement mortar due to the accelerated pozzolanic reactivity along with the rapid hydration process [58]. Similarly, initial and final setting time of activated alkali material can be reduced by incorporating the highly reactive NS as an accelerator [86].

Furthermore, Zhang et al. [60] reveals that incorporating 2% of NS in Slag based concrete and HVFA accelerates the setting time. Correspondingly, the same effect in HPSCC and UHPC is observed [61]. In contrast to the above statements, NS mixing sequences with PCE might increase the setting time is mentioned by Pengkun Hou et al. [49].

4.2 Workability

The NS increases the Portland cement matrix stiffness by better packing as a result of its filler effect and there by decreases the flow was observed from the study done by Rishav Garg et al. [8]. In accordance with the above statement, the filler effect and homogeneity in NS incorporated cement mortar reduces the workability [29]. Additionally, Niloufar Zabihiet al. [89] revealed that even 0.5% cement replacement by Colloidal NS could decrease the flowability. Remarkably, attributed to the addition of super plasticizer to enhance the water demand for flowability [9, 12, 46, 89]. Along with this, NS possess the dominant effect on flowability than the GO consequently in need of super plasticizers which is affirmed from the observations done by Michael Newell et al. [82]. At same time, that the smaller size of NS in MPC increases the water demand was noticed from the study done by Y. Liu et al. [86].

The workability of Geopolymer mortar reduced significantly when NS dosage exceeds 5%. This is due to the fact that, NS at high dosage possess high packing density with poor dispersion and thereby reduce the free water content [42]. Furthermore, Partha Sarathy Deb et al. [47] revealed that, 3% NS in GGBFS blended FA geo polymer mortar the flow reduced to 64% and for OPC blended fly ash geo polymer mortar flow reduced to 50%. In UHPC, NS content is limited up to 3% for standard slump flow [80]. Moreover, it is ascribed from the investigations done by Mohammad A. Mosaberpanah et al. [78] that the absence of interaction among waste GP and NS on the UHPC workability. The investigations done by Nandhini et.al., revealed that incorporation of NS in SCC reduces the slump of the mix by increasing the cohesiveness [130]. The incorporation of 2%NS might not affect the workability of HPSCC [61]. For SCC with 10% MS and 2% NS confirms the better workability than the other combinations [131].

Markedly, ternary mix requires higher super plasticizer dosage than the Binary one [9]. On the other hand, from the study of K.Snehal et al. [58] it is observed that ternary and quaternary also shows reduced workability due to the ball bearing effect of UFFA and FA. The NS sol exhibits greater influence in flowability than the powdered NS due to its rapid flocculation [6, 85]. Nevertheless, better dispersion, higher dosage of NS has its impact on flowability was noticed from the investigations of Zhiyu Luo et al. [25]. It is observed that, decreased W/C ratio increases the super plasticizer dosage for the better dispersion and to achieve the desired slump values [5, 56]. Besides, Yogiraj Sargam et al. [10] affirmed that, even 0.01% of surfactants (sodium dodecyl sulfate, Tritons, Tweens) dosage also decreased the flowability of cement paste.

Thus, increasing the NS content, slump gets decreased. This is attributed to a part of water in the mix moves towards surface of NS particles with unsaturated bonds to form the silanol (Si–OH) bonds and thereby increased the water demand need for flowability [62]. Along with this, the study on NS incorporated RAC possess the low slump values due the absorption of water by recycled aggregates and NS particles [88].

4.3 Consistency

The consistency of the mix with MS and 1% of NS increases water demand due to the improved binder particle interaction resulted in increased consistency [8]. For instance, the concrete with NS possesses the air content at higher level due to larger SSA of Nano particles resulted in high viscosity [63]. Moreover, increased consistency of the SCC resulting in increased viscosity with decreased flowability. Because of large SSA of NS, segregation and bleeding was also absent [50]. Similar trend was absorbed in the study done by Erhan Güneyisi et al. [64] in SCLC incorporated with NS increased the consistency and thereby decreased the density of fresh paste. Along with the above statements, Pawel Sikora et al. [83] revealed that the fresh properties of Printable Mortars could be altered by adding NS to the mortar. This is attributed to the increased activity of NS in binder phase of mortar.

5 Effects of Nano Silica and SCM on Mechanical Properties of Cement Mortar And Concrete

5.1 Compressive Strength

One of the prominent characteristics that influences the life of concrete is compressive strength, which rules the serviceability of the structure [24]. Compressive strength of the concrete can be improved by incorporating the NS even at early ages, because of its high pozzolanic activity and smaller particle size. The mechanism behind this early strength is due to the formation of C-S–H gel which could fill up the pores and at 28 days NS increases the bond strength of mortar – aggregate, was revealed by Mukharjee et al. [60, 62]. Based on the particle size, NS with 15 nm possess the better early strength than the NS with 80 nm particles, but on later ages (90 days) larger size Nano particles of NS acquires desired strength [1]. Belkowitz et al. [1] noticed that elastic modulus and compressive strength can be enhanced 20% better by the larger NS particles than the smaller ones. However, 4% NS at pH 7 increases the strength by 12.45% at 90 days was observed from the investigations done by Mahdi Mahdikhani et al. [84]. The following equation gives the primary and secondary C-S–H formation.

Hydration Reaction:

$$C_2S \text{ or } C_3S + H_2O \rightarrow \text{Primary CSH} + Ca(OH)_2$$

Pozzolanic Reaction:

$$Ca(OH)_2 + (SiO_2) + H_2O \rightarrow \text{SecondaryCSH}$$

Mohammad Kooshafa et al. [6] revealed that, delayed pozzolanic reactions of SF increases the strength than the NS on later ages. In accordance with previous statement, L.G. Li et al. [5] noticed that, combined effect of NS (1%) and SF (5%) increases the strength up to 73.3 MPa at 0.45 W/C. At same time, combining 6% NWC with 3% NS (3%) also enhances the strength due to its pozzolanic reaction with $Ca(OH)_2$ (hydration by product) to form the secondary C-S–H [54]. The RAC requires lesser amount of NS (0.5,1 & 1.5%) for better bonding as well as to increase strength was observed from the study done by Erdem et al. [71].

Addition of 3% NS gradually increases the strength in RAC was revealed by Mukharjee et al. [88]. From the study of Jibang Wang et al. [13] it is observed that, Portland cement concrete with 1.2% NS increases the strength by 11.4 MPa in 28 days at 0.28 w/c. The strength gain is due to the formation of $Ca(OH)_2$ as a by-product of cement hydration which in turn increases the concrete density by sealing the pores. Furthermore, Shuai Bai et al. [91] revealed that NS modified cement paste possess better strength than that of the plain cement paste at freezing condition.

According to the investigations done by Yemmcy Calcina Flores [51] it is observed that combined effect of SF and NS heterogeneously increases the particle –to –particle packing which leads to the accelerated formation of nucleation sites. In other words, chemical reaction causes the physical effect by packing up the pores was stated from the observations done by Abreu et al. [59]. Hence reduced strength is due to the replacement of cement with coarse sized Quartz wherein there is a lesser influence of filler effect. Moreover, the beneficial effects can only be evident from the combined ultra-sonication of PCE and NS was interpreted from the investigation performed by Pengkun Hou et al. [49].

From the observations of Deyu Konga et al. [85] it is inferred that incorporation of colloidal NS increases the strength by the formation of open pores in mortar which retains the free water for the prolonged cement hydration. The core shell effect of NS and titania (TiO_2) acts as the seeding agent for the nucleation sites and thereby escalates the compressive strength was depicted from the study of Sarita Rai et al. [38]. Ahmed Mohammed [48] worked on the concept stating that enhancement of strength in cementitious paste depends on the curing period and W/C ratio. Apparently, it is revealed from the reaction occurred between type of cement used and dosage of NS added. On altering the 0–6% of NS in cement mix, positive effect on strength at optimum dosage of 4%.is observed [84].

A.M.Said et al. [16] revealed that adding 30% of Class F FA with NS enhances the strength at initial stages. With the W/C ratio of 0.5, the rate of strength development gives an affirmative trend till the NS addition reaches 4% and then reversal of trend was observed. This reversal effect is due to the reduction in homogeneity of cement mixture and pozzolanic characteristic of NS [29, 38]. Yogiraj Sargam et al. [10] studies showed that 0.8% nonionic surfactant triton TX405 increases the strength of the mix by 54% at 28-days and at the same time TX405 with 0.8% anionic surfactant PCE increases strength up to 50.61 MPa at 28 days. The combined effect of surfactants offers a better dispersion for NS particles which results in the peak rate of heat evolution in cement-NS. This also adds benefit by providing additional sites for nucleation.

However, hydrophilic silica incorporated with cement concrete generates the homogeneity in the mix, while the hydrophobic silica fails to generate bond due to its repelling nature which results in strength drop [11]. The Strength of the concrete gets decreased due to the mono dispersion of NS sol and colloidal NS due to its poor dispersion [3, 6]. Whereas Heng Chen et al. [7] et al. experimented that incorporating the hydrophobic NS to investigate the influence of PCA in concrete strength attainment. The amount of PCA (0.78) incorporated sample increased the fluidity of

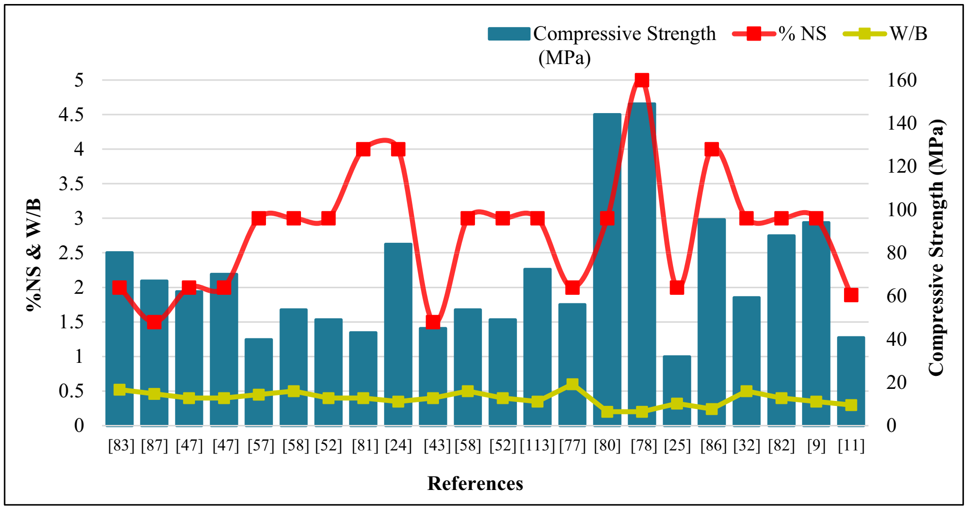


Fig. 13 Compressive strength of various cement concrete with different NS dosage

the hydrating cement paste. In other words, cohesive cement matrix traps the air voids than the cohesion less one which directly influences the strength of the cement matrix [6].

Moreover, Daniel Da Silva Andrade et al. [9] worked on ternary mixtures (Cement + NS + MK) and reveals that the hydration rate increased at 28 and 91 days which results in strength increases up to 30%. Furthermore, Rishav Garg et al. [8] done research work on incorporating MS and NS in Portland cement to achieve the better strength at optimum dosage. Incorporating 10% MS & 1% NS shows the desired results, on exceeding the negative effect on strength is observed it is due to the loss in homogeneity of the cement mixture which is caused by the friction of the MS particles. It has been proven that carbonated silica enhances the strength than the uncarbonated one was revealed by Taha M. Jassam [11] et al. The type of curing adopted for concrete with NS also influences the strength was noticed from the observations done by aforementioned author.

Nazari et al. [76] observed that the samples curing in lime solution requires only 2% of NS and water cured samples requires 1% NS which might be fixed as an optimum replacement of cement. Due to the rapid decalcification and deterioration of C-S–H gel, NS in Low & Moderate tricalcium aluminate cement doesn't meet the expected line of strength results at later ages [4]. Taher A. Tawfik [23, 54] noted that NS up to 3% replacement with cement can strengthen the mix; beyond the optimum dosage decrease in strength is observed due to leaching of unreacted silica which doesn't contribute for the strength development. By confirming to the prementioned fact, up to 3% dosage of NS increases the strength of dolomite concrete and upon 4% addition strength of the concrete gets reduced was revealed by S.A. El-Ghany Abo El-Enein et al. [65]. In contrast to the above one, NS on 8% replacement could bring the positive effect on strength development with 0.3 W/C was noticed from the investigations of Madhuwanthi Rupasinghe [12].

Belkowitz et al. revealed that, lowest dosage of NS with particle size of 5 nm increase in strength up to 20% but with higher dosage of the same reduces the strength by 14%. High dosage of NS causes the agglomeration which in turn reduces the strength because of open pores. In HSC, with 0.2% PP and 3%NS contributes the 13.5% increase in strength when compared to reference mix was noticed from the study done by Fallah et al. [66]. The colloidal NS shows the superior performance in enhancing the strength of SCC at all the ages than the powdered NS [63]. Therefore, the SCC with NS possess the increased rate of evaporation even at low dosages by increasing the open pores which is filled by the pozzolanic reaction products and thereby increases the strength [132].

At W/B of 0.25,0.37 & 0.5 with NS ($\leq$ 5%) enhances the strength at high rate [64]. Moreover M. Jalal et al. [61] worked on HPSCC and revealed that NS improve the strength by the accelerated hydration. By confirming the previous statement, Massana et al. [68] experimented that up to 7.5% of adding NS increased the strength in HPSCC around 13% (28 days). For LWC, prolonged curing decreases the strength offered by the NS particles was noticed from the investigation done by Du et al. [69]. Even on lesser replacement level NS enhances the early strength of concrete by refining the pores through its pozzolanic reaction was observed from the study of N.V. Makarova et al. [133].

In UHPC, it can be witnessed that reduced flexural to compressive strength ratio when dosage of NS exceeds 1% and vice versa was revealed by W.Li et al. [73]. On imparting 50% & 100% Recycled Aggregate with NS dosage of 0.4, 0.8, 1.2% enhances the strength by 10, 18 and 22% as well as 6, 13 and 16% respectively [72]. The compressive strength of various type of cement concrete with different NS dosage at 28 days is shown in Fig. 13. The effects of NS and SCM on Compressive strength in special types of cement mortar and concrete are summarized in Table 6.

Table 6 Effects of NS and SCM in special cement mortar and concrete

Type of Cement concrete	Size and type of NS	Remarks	References
OWC	10 nm, 20 nm,40 nm Powder	The samples composed of 40 nm performs better than that the samples of 10 and 20 nm	Mtaki Thomas Maagi et al. 2020 [57]
ULCC	20 nm Colloidal	NS with optimum dosage of 2% at 0.32 W/C gives 27.8Mpa at the age of 28 days	Hongjian Du et al. 2019 [55]
HVS & HVS-FA	25 nm Powder	The addition of 3% NS in HVSFA enhances better when compared with 1% NC. But in HVS, 1% NC enhances better than NS incorporation	Anwar Hosan et al. 2020 [52]
HSLWC	14 nm	At 3% addition of NS to the mix, increases the strength of control mix by 12.91% while it is found 4.77%, 6.90%, 3.81% and 3.31% for 0%, 10%, 20%, 30% and 40% of various replacement levels respectively	Nihat Atmaca et al. 2017 [113]
SCC	35 nm, 17 nm, 5 nm Colloidal	FA80/S35/1.5% mix gives the compressive strength of 67 MPa at 28 days	Muhammed Yasin Durgun et al. 2018 [87]
SCC	7–25 nm Powder	The 28 days strength of B- 0.25% and C-0.5% are 29.2 MPa and 29.9 MPa respectively which is close to reference SCC A-0% (i.e., 29 MPa). The influence of NS on compressive strength of weak concrete is greater than that on concrete with lower w/b as it increases compressive strength by 26.9%, 32.7% and 48.8% for w/b of 0.41, 0.45 and 0.5 respectively by 0.75% replacement of cement	Nadine Hani et al. 2018 [50]
MPC	25 nm Powder	The compressive strength, the group NS0, NS2, NS4, and NS6 were 84.3 MPa, 89.6 MPa, 95.3 MPa, and 79.5 MPa	Yuantao Liu et al. 2020 [86]
UHPC	23-30 nm	For the lowest level of NS and waste glass powder, compressive strength is found as 124 MPa from control mix at minimum of 28 days while strength of 149 MPa observed from mix no. 4(5% ns + 20% GP) for highest level of NS and waste glass powder at maximum of 28 days	Mohammad A. Mosaberpanah et al. 2018 [78]
BFS	i) Colloidal ii)AEROSIL 200 iii)AEROSIL OX50	Mixtures METOX, OX50, METAOX and its combinations have provided prominent results on strength of BFS based cement	Ramiro Garcia et al. 2020 [77]
Cement L & Cement H	15-20 nm Powder	For cement L, adding bigger amount of 6% NS in the mix L6NS, it results in weaker mortars while testing is done at period of 6 months and 1 year in contrast to the control and both MS-containing mixtures	Nader Ghafoori et al. 2018 [40]
BFS	7-40 nm	At early ages, combination of 30% BFS and 3% NS possess the desired results in strength attainment but later on ages the growth rate of strength is lower than that of 3% NS	Mingle Liu et al. 2016 [32]

Table 6 (continued)

Type of Cement concrete	Size and type of NS	Remarks	References
PCM	10-140 nm Colloidal	After 28 days, casted mortars with 2% & 3% of NS increases the strength by 17% and 10% than the control mix. At same time printed cube mortars with pre mentioned NS dosage increase its growth rate by 18% and 8% respectively	Pawel Sikora et al. 2021 [83]
Portland Cement	12 nm Colloidal	At 0.018% of GO increase the strength by 25.8% comparatively higher than the reference mix	Michael Newell et al. 2019 [82]
CAC	Powder	After 28 days of warm water exposure, the strength of the N0, N1, N2, and N4 was 33, 22, 34, and 43 MPa respectively	H.M. Son et al. 2018 [81]
FA + Geo Ploymer	15 nm Powder	*i) Acid Exposure:* samples with 2% NS incorporated OPC blended Geopolymer mortar decreases the strength from 11.5 MPa (FA-PC-NS0) to 6.5 MPa (FA-PC-NS2) ii) For 2% NS incorporated GGBFS mortar reduces the strength from 7.5 MPa (FA-S-NS0) to 4.0 MPa (FA-S-NS2)	Partha Sarathi Deb et al. 2016 [47]
SCC	14 nm Powder	Addition of NS (0 -4%) along with glass fiber (0—1.5%) to SCC enhances the strength	Yahya R. Atewi et al. 2020 [24]
UHPC	15 nm Powder	By adding 3 (wt.%) NS enhances the strength by 24% at 7 days, which is 40% greater higher than the control mix	Ehsan Ghafari et al. 2014 [80]
Cement + GGBS	9-11 nm Powder	Replacing the cement with 30,50 & 70% of GGBS enhances the strength by 42%,63% & 81% in presence of 3% of NS	Xia Liu et al. 2021 [46]
LWC & ULWC	10–140 nm Colloidal	i)Adding NS up to 5% in ULWAC increases the strength gain. Moreover, such remarkable increase was not observed in 1%NS ii) In LWA, 1% NS alone increases the strength, on exceeding this limit, reversal effect was observed	Pawel Sikora et al. 2020 [45]
HVFA mortar	1-500 nm	The Samples with (0.5–1.5) % of NS could enhance strength by 48%—56% at 28 days	Jing Yu et al. 2020 [43]
FA + Geo Polymer	20 nm Powder	For the Geo-0 min sample, the strength is about 28.32 MPa whereas, Nanoparticles under sonification for the duration of 20 min and 120 min results in increased strength of about 3.88% and 13.59% respectively. The equivalent strength of 32.17 and 31.83 MPa is observed for Geo-120 min and Geo-180 min respectively, which specifies that increased sonification period of one hour doesn't influence strength to greater extent	Zhiyu Luo et al. 2021 [25]

Table 7 Effects of NS and SCM in on tensile strength in Special cement mortar and concrete

Type of Cement concrete	Size & type of NS	Inference	References
HPSCC	15 ± 3 nm Powder	Incorporating 2% NS with 10%SF in HPSCC with binder content of 500 kg/m^3 enhanced the tensile strength by 33% at 28 days	Jalal et al. 2015 [61]
RAC	8–20 nm Colloidal	Adding 3%NS in RAC could enhance the tensile strength even up to strength values of control mix due to NS's pozzolanic and filler effect	Mukharjee et al. 2014 [88]
RAC	20–30 nm Powder	For RAC containing 1.2% NS and 100% recycled aggregate, 3.58 MPa is the observed maximum tensile strength	Younis et al. 2018 [72]
SCC	Powder & Colloidal	The colloidal and powdered NS in SCC enhances the tensile Strength up to 4.92 N/mm^2 and 5.48 N/mm^2 respectively which is greater than the reference mix	Quercia et al. 2014 [63]
SCC	14 nm Powder	Incorporating 4% NS could increase the tensile strength by 34% at 90 days	Yahya R. Atewi et al. 2019 [24]
HSLWC	14 nm	Even at 3% addition of NS in HSLWC, decreased tensile strength was observed due the limitations of LWA	Nihat Atmaca et al. 2017 [113]
HSC	20–30 nm Powder	The splitting tensile strength of HSC ranges between 7.24 MPa to 7.34 MPa due to the incorporation of 1.25% MP Fibers and 3%NS	Fallah et al. 2017 [66]
FA based Geopolymer mortar	20 nm Powder	The reduced tensile strength was observed in the mix containing 30% FA and 5% NS. This is due to the incomplete pozzolanic reaction of FA which hinders the C-S–H growth due to the presence of aluminium and silicon ions	Mostafa Seifan et al. 2020 [42]

5.2 Split Tensile Strength

5.2.1 Portland Cement Mortar and Concrete

The preliminary studies on NS incorporated concrete possess increased tensile strength than the other plain concrete and conventional mineral admixed concrete. As revealed by Rishav Garg et al. [8], increasing split tensile strength with increase in NS and MS dosage ranging between 0.5% to 1.0% and 5.0% to 15% respectively, with furthermore strength reduction at later ages. Nevertheless, tensile strength of Portland cement concrete increased markedly by incorporating NS up to 6% [16]. Moreover, incorporating optimum dosage of 3% NS and 6% of NCW increases the split tensile strength by 18.2% and 13.6% respectively, on exceeding the optimum level of Nano particles tensile strength decreases [54]. The increased strength is due to the fact that, rapid consumption of Calcium Hydroxide by highly reactive Nano particles on early stage of hydration and the strength reduction is due to silica leaching.

5.2.2 Special Cement Mortar and Concrete

In FA based Geo Polymer mortar, tensile strength was not improved even on adding 10% NS compared to 5%NS was noticed from the study done by Mostafa Seifan et al. [42]. At same time, increased FA content in mortar decreases the strength. This is attributed to the incomplete pozzolanic reaction of FA which hinders the C-S–H growth due to the presence of aluminium and silicon ions. For SCC the incorporation of 4% NS and 1.5% GF increased tensile strength up to 34%. This is due to the incorporation of NS enhances the better ITZ as the result of densified stiff C-S–H gel [24]. Similarly, increase in tensile strength is due to strong IT'Z up to 3%NS addition only as a result of reduced voids [62]. The concrete tensile strength is increased by adding NS which enhances the bond strength among aggregate and hardened paste was affirmed form the study by Quercia et al. [63].

Nevertheless, NS doesn't influence the tensile strength of SCC in particular due to its round shape in spite of its dosage [50]. In contrast to the above statement, incorporating 10%SF and 2% NS in HPSCC markedly enhances the strength [61]. For GGBS based SCC, up to 3% NS alone increases the tensile strength, on exceeding reversal effect was observed from the investigations of Ali Nazari et al. [67]. Besides this, Saber Fallah et al. [66] revealed that adding 3% NS and 1.25% MP fiber enhances the strength by 29% whereas 3% NS increases the strength by 16%. Furthermore, HSLWC follows the compressive strength pattern [113].

From the study of Mukharjee et al. [88] and Khaleel H.Younis et al. [72], RAC incorporated with NS (1.2% & 3%) enhances the tensile strength almost near to the strength of control mix. This attributed to the strong densified ITZ formed by the NS particles. For SCC with NS at 1%, 2% and 3% increases the strength up to 9.88%, 21.36%, and 5.63% at 28 days. The increase in the strength is due to enhanced particle packing density [130]. The effects of NS and SCM on tensile strength of Special cement mortar and concrete are summarized in Table 7. The optimum tensile strength of various type of

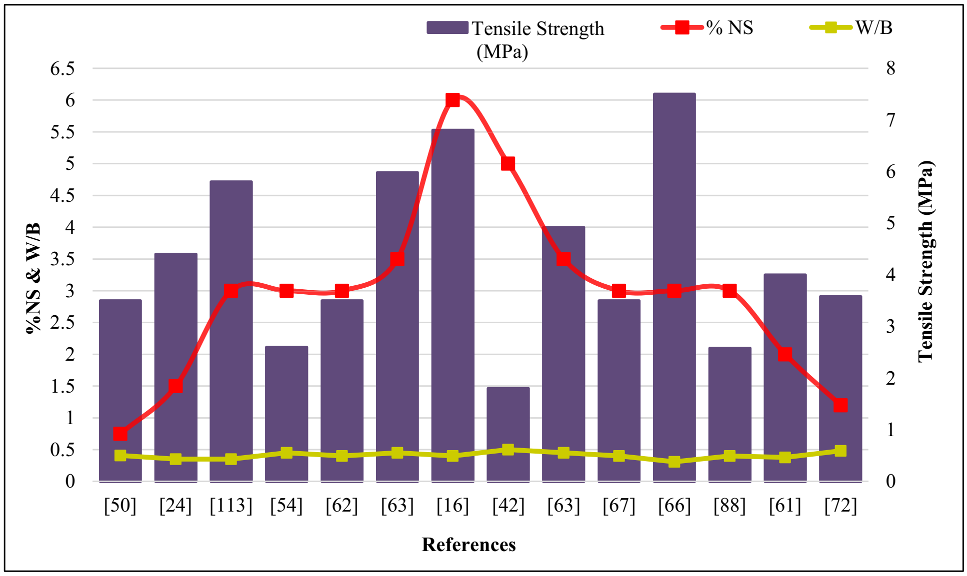


Fig. 14 Tensile strength of various cement concrete with different NS dosage

cement concrete with different NS dosage at 28 days is shown in Fig. 14.

5.3 Flexural Strength

5.3.1 Portland Cement Mortar and Concrete

From the research work carried out by Taher A. Tawfik et al. [54] it is observed that addition of NS and NWC increase the flexural strength of mortar, but their dosage is limited to 3% and 6% respectively. As such improved strength is due to the pozzolanic activity of NS produce the Calcium-Silicate-Alumina-hydrates along with the 1.0 Ca/Si ratio and thereby increases the reactivity between cement hydrates and ceramic particles (Li et al., 2020). Furthermore, Qian Huang [41] reveals that filler effect of NS increases erosion resistance of the mortar therefore strength loss also reduced.

5.3.2 Special Cement Mortar and Concrete

From the research work by Jing yuet al. [43] reveals that the incorporating 0.5–1.5% NS alone in HVFA mortar increases the flexural strength to 22–34%. At same time, adding 0.2–1.0 vol% PVA fibers in plain HVFA mortar enhances the strength ranging between 29–51%. This is attributed to the enhanced post peak behavior of PVA fiber in addition, NS exhibits the inelastic failure mode. By increasing the dosage of GF in SCC enhance the flexural strength [24]. In the same context, that 10% SF and 2% NS increases the flexural strength of HPSCC up to 59% at 28 days [61]. The flexural strength of various type of cement concrete with different NS dosage at 28 days is shown in Fig. 15.

Additionally, flexural strength of Concrete ULWA concrete is lower than the parallel LWA concrete as result of low density and high porosity [45]. Moreover, at early days NS increased the flexural strength of GGBS incorporated cement mortar although the GGBS dosage limited to 30%. This is because

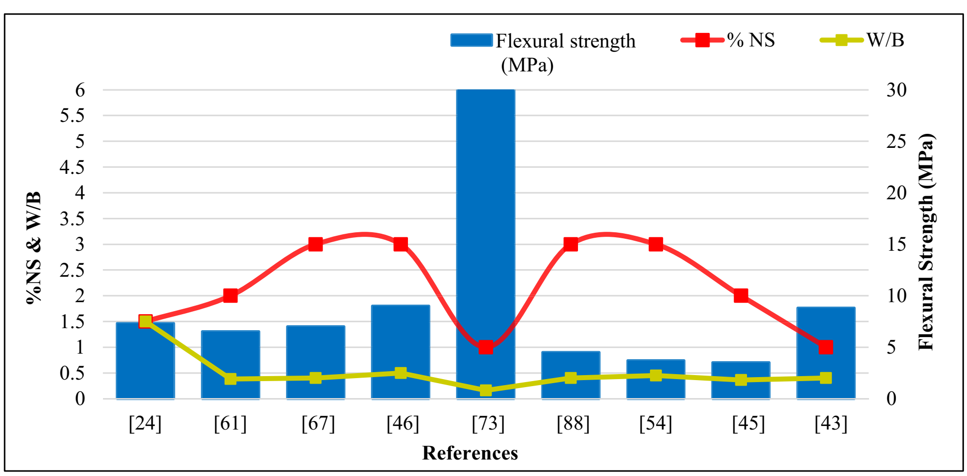


Fig. 15 Flexural strength of various type of cement concrete with different NS dosage

Table 8 Effects of NS and SCM on porosity of special cement mortar and concrete

Type of Cement concrete	Size & type of NS	Inference	Author
LWC & ULWC	10–140 nm Colloidal	In both types of concrete, NS produces the impermeable microstructure and thus enhances the transport properties of the NS modified mix	Pawel Sikora et al. 2020 [45]
LWC	12.4 nm Colloidal	Incorporating 1% NS to the mix, reduces the porosity, on exceeding the reversal effects was observed. This is due to the increased viscosity which entraps the air voids on mixing and thereby increases the porosity of the hardened cement concrete	Du et al. 2015 [69]
ULCC	20 nm Colloidal	The Nano filling effect of NS reduces the water accessible porosity by producing the additional hydrates through its pozzolanic reaction with calcium hydroxide	Hongjian Du et al. 2019 [55]
UHPC	15 nm Powder	The addition of NS enhances the microstructures of the ITZ between binding paste and aggregates and thereby refines the voids of the concrete mix	Ehsan Ghafari et al. 2014 [80]
PCM	10-140 nm Colloidal	The mortar with 4% and 6% NS marginally increased the porosity but it alters the pore structure and its tortuosity considerably	Pawel Sikora et al. 2021 [83]
BFS	7-40 nm	By adding, 30% BFS and 3%NS, reduces the harmful pores and thereby increases the harmless and less harmful pores in the cement mix	Mingle Liu et al. 2016 [32]
BFS	i) Colloidal Nano silica ii) AEROSIL 200, OX50	From critical diameter analysis, NS reduces the porosity of the cement mix from the early ages	Ramiro Garcia et al. 2020 [77]
Cement L	15-20 nm Powder	The agglomeration of NS particles in the cement mix, increases the capillary macro pores volume and also increases the pore diameter which results in increased permeability	Nader Ghafoori et al. 2018 [40]
Cement H	15-20 nm Powder	The NS modified mortar exhibits the significant reduction in gel pores and increased volume of capillary macro pores	
SCC	35 nm, 17 nm, 5 nm Colloidal	Regardless the mixtures containing colloidal NS and FA or not, the critical pore width was reduced over curing in all samples	Muhammed Yasin Durgun, et al. 2018 [87]
SCC	15 ± 3 nm Powder	The NS incorporated concrete mix possess increased mesopore content and also improved pore structure	Ali Nazari et al. 2011 [67]
GGBS	7 nm & 12 nm	By adding 2% NS to the mortar reduces the large capillary pores as well as the decreased threshold and critical pore diameter	Zhang et al. 2012 [60]
HVFAC	10 ± 5 nm	The FA content in HVFAC increases the pore size and total porosity, which can be markedly reduced by incorporating the NS to the mix	Gengying Li et al. 2004 [70]

of NS influenced the GGBS cement mortar process of hydration as well as the hardening [46]. Furthermore, adding 3%NS with GGBS based SCC increases the flexural strength due the accelerated hydration process [1, 67].

For the combined curing conditions (Heat Curing- 2 days and Standard Curing -26 days), UHPC with 1% NS at different W/B ratio of 0.16 and 0.17 increases the tensile strength up to 41% and 35% [73]. Furthermore, Mukharjee et al. [88] revealed that, adding 3% NS in RAC increases the flexural strength by 15%.

5.4 Elastic Modulus of Cement Concrete

Based on the investigations done by Yahya R. Atewi et al. [24], it is noticed that Incorporating GF and NS in SCC enhances the static elastic modulus comparatively higher than the control mix. Hence GF highly influences the elastic modulus than the NS contribution. In accordance with the above statement, increased elastic modulus of colloidal NS incorporated SCC is due to the enhanced stiffness as a result of improved microstructural development of ITZ [87]. Whereas, addition of Quartz, SF and NS in Portland cement paste did not show substantial differences in elastic modulus regardless its particle size [51]. Nevertheless, HSC reaches the maximum value of elastic modulus while adding 2% NS [66]. Moreover 3% NS shows slight increment in elastic modulus of concrete [62]. For RAC, elastic modulus increases with increase in NS content as a result of improved micro structure [71].

5.5 Abrasion Resistance of Cement Concrete

Nadine Hani et al. [50] reported that, regardless the NS dosage and W/B, NS reduced the loss of specimen thickness and thereby increases the resistance. This is enhancement is attributed to the C-S–H gel fills the pores and makes the concrete denser. For lime water and plain water cured samples also NS increases the abrasion resistance, irrespective of its dosage [76].

5.6 Non-Destructive Testing on Nano Silica Cement Composites

In Non-destructive Testing methods, UPV is a notable indicator of mechanical strength parameters of concrete (Ashrafian et al., 2018). Taher A. Tawfik et al. [54] revealed that UPV shows the progressive growth with increase in NS and NWC content till 3% and 6% correspondingly, after then UPV gets reduced. Furthermore, the quality of concrete, increased with increase in NS content observed from UPV and Rebound Number (RN) [62].

6 Effects of Nano Silica and SCM on Durability Properties of Cement Mortar and Concrete

6.1 Porosity

6.1.1 Portland Cement Mortar and Concrete

The pore connectivity and total porosity of the mix was majorly reduced by finer one than the coarser NS [41]. Similarly, NS with small SSA (Coarser) were highly prevented fill the pores, however NS with high SSA exhibits the dense microstructure and markedly less pores were observed from the research work of Alhawat et al. [134]. Additionally, NS with micron-scale agglomerates or flocs reduces the macro pores beyond 5 μm effectively than the micro pores, which is noticed from the investigation done by Deyu Kong et al. [85]. On incorporating 4% NS to the Portland cement pastes highly reduces the porosity than its lower dosages of 1% and 2%. This can be attributed to the 4% NS could progressively increase the C-S–H formation through pozzolanic reaction when compared to its lower-level replacements [7]. Moreover, the mechanism behind the reconstruction of week pore structure is pozzolanic and filler effect of NS is revealed by Shuai Bai et al. [91]. Furthermore, SF and NS blends enhances the pore refinement effectively rather than NS added alone [51]. Likewise, the combinations of NS, SF and MK refines the pore structure and thereby improves the durability performance of the mix [9]. The effects of NS and SCM on porosity in special cement mortar and concrete is summarized in Table 8.

6.2 Water Absorption, Sorptivity, Water Permeability

6.2.1 Portland Cement Mortar and Concrete

The NS aqueous solution enhanced the resistance to permeability whereas powder form of NS possesses negative progression. In other words, poor dispersion of NS results in agglomeration even before its pozzolanic reaction with cement particles and thereby reduction in acting as a filler [4]. At same time, NS gel also improves the resistance against capillary water absorption effectively even at the 1% and 3% replacement levels [6]. The water accessible porosity and absorption coefficient of NS incorporated printable mortars reduced up to 12% and 39% as a result of densified microstructure was revealed by Pawel Sikora et al. [83]. The water absorption potential of the Portland cement concrete was decreased with increased NS content in the mix due to the reduction of voids [62]. In accordance with the above statement, as a Nano filler, NS could fill up the pores and thereby decrease the permeability and porosity of the concrete [84]. Hence, the permeability of the hardened cement paste is reduced by the adding the NS, which is directly related to its threshold pore radius [7]. Moreover, combined effect of NS and MS effectively reduces the sorptivity than they are incorporated alone in the mix [56]. In addition to the above statement, NS and GO contents of 2.2% and 0.018% could reduce the sorptivity coefficient up to 22% [82]. The effects of NS and SCM in special cement mortar and concrete is shown in Table 9.

Table 9 Effects of NS and SCM in special cement mortar and concrete

Type of Cement concrete	Size & type of NS	Inference	References
FA based Geopolymer	20 nm Powder	The FA content in the mortar decreases the resistance to water permeability and thereby increases the water absorption of the mortar in spite of 5% NS dosage. This is due to the poor dispersion of NS particles and compaction of FA in mortar	Mostafa Seifan et al. 2020 [42]
FA based Geopolymer	15 nm Powder	The NS reduces porosity of the specimen and thereby reduces the sorptivity. This is attributed to the increased particle packing density and geopolymerisation of NS	Partha Sarathy Deb et al. 2016 [47]
LWC	12.4 nm Colloidal	For slag based LWC and pure cement, optimum dosage of NS is about 1% and 2% respectively, on exceeding NS dosage results in insufficient mix densification	Du et al. 2015 [69]
LWC & ULWC	10-140 nm Colloidal	In both the mixes, NS enhances the impermeability of the microstructure at its optimum dosage than the SF modified mix	Pawel Sikora et al. 2020 [45]
ULCC	20 nm Colloidal	i) Incorporating 1% colloidal NS decreased the sorptivity by 30% at 0.32 W/B ratio where as 2% and 3% NS decreased the sorptivity by 22% for 0.24 W/B ratio ii) For 0.32 and 0.24 W/B, water penetration depth was reduced to 23%, 43% and 42% by incorporating 1%, 2% and 3% NS respectively	Hongjian Du et al. 2019 [55]
HSLWC	14 nm	i) The NS modified mix refines pore structure by increasing the hydration process and there by decreases the water absorption, sorptivity values and gas permeability as well	Nihat Atmaca et al. 2017 [113]
UHPC	15 ± 5 nm	Incorporation of NS to the mix reduces the connection between the capillary pores which in turn reduces the sorptivity, water absorption and gas permeability of the modified mix	Ehsan Ghafari et al. 2014 [80]
SCC	14 nm	By Increasing the NS and GF content, decreases the sorptivity coefficient and gas permeability of the mix as a result of enhanced pozzolanic activity and void filling capacity of NS	Yahya R. Atewi et al. 2019 [24]
SCC	7-25 nm Powder	Especially for low W/B ratio, incorporating 0.75% NS reduces the voids volume and total absorption of the mix by 13% and 16.2% respectively	Nadine Hani et al. 2018 [50]
HPSCC	15 ± 3 nm Powder	The combined effect of 10%SF and 2% NS resulted in enhanced packing and pore refinement which in turn reduces the water absorption of the specimen	Jalal et al. 2015 [61]
SCC	15 ± 3 nm Powder	At early ages of curing, NS increased the formation of hydration products and thereby decreases the water absorption of the samples	Nazari et al. 2011 [67]
HSC	20-30 nm	By adding 3% NS to the HSC mix with PP and MP fibers results in reduced water absorption	Saber Fallah et al. 2017 [66]
RAC	23-30 nm Powder	For both 100% and 50% recycled aggregate content, 0.8% of NS could effectively reduce the water absorption when compared with 0.4% NS2	Younis et al. 2018 [72]
RAC	5-20 nm Colloidal	Improved pore structure could be achieved by adding NS to the mix which resulted in reduced water absorption	Erdem et al. 2018 [71]

6.3 Sulphate Attack Test

6.3.1 Portland Cement Mortar and Concrete

From the investigation of Quian Huang et al. [41], revealed that, incorporation of increased NS content increased the Sulphate resistance of cement mortar. This is due to the pore refinement and reduction in pore connectivity by NS and there by restricts the entry of Sulphate ions which in turn reduces the sulphate attack deterioration in the specimen. In contrast, the replacement of moderate tricalcium aluminate cement by 6% NS shows the improved expansion which is twice that of the expansion observed in 1.5%/ NS [4]. Additionally, the combined effects of NS and SF at low

W/C reduces the strength loss of the specimen after sulphate attack [5].

6.3.2 Special Cement Mortar and Concrete

According to study of Nader Ghafoori et al. [40] it is noted that, for high SSA and Cement H NS improved the sulphate resistance due to its pozzolanic activity of the NS agglomerates which reduces the availability of calcium ions for the reaction with sulphate. For low SSA and Low C_3A the reversal effect was observed, because the NS agglomerates increases the pore diameter and capillary macro pores volume which in turn increases the permeability of the mortar. Regardless the NS dosage and W/B ratio, NS enhances the sulphate resistance of the SCC mix [50]. For SCC with 3% NS shows the reduced strength loss of 2.71% by forming the densified honeycomb [130].

6.4 Chloride Ion Penetration

6.4.1 Portland Cement Mortar and Concrete

The depth of chloride ion penetration in the specimen is reduced up to 43.8% and 39.1% after immersion of 28 and 180 days when 2% NS incorporated in the mix [85]. Additionally, at 1% and 3% NS gel incorporation enhances the chloride resistance effectively when compared with SF whereas SF at higher dosage of 5% and 7% improves the resistance [6]. It is noticed from the study of A.M.Said et al. [16] that increasing the NS dosage decreases the charges passed and the depth of penetration in the specimen. This is due to the addition of NS even at small dosages decreases the concrete conductivity and refines the pore structure which prevents the entry of chloride ion in the cement matrix. Furthermore, the combined effect of NS and SF on enhances

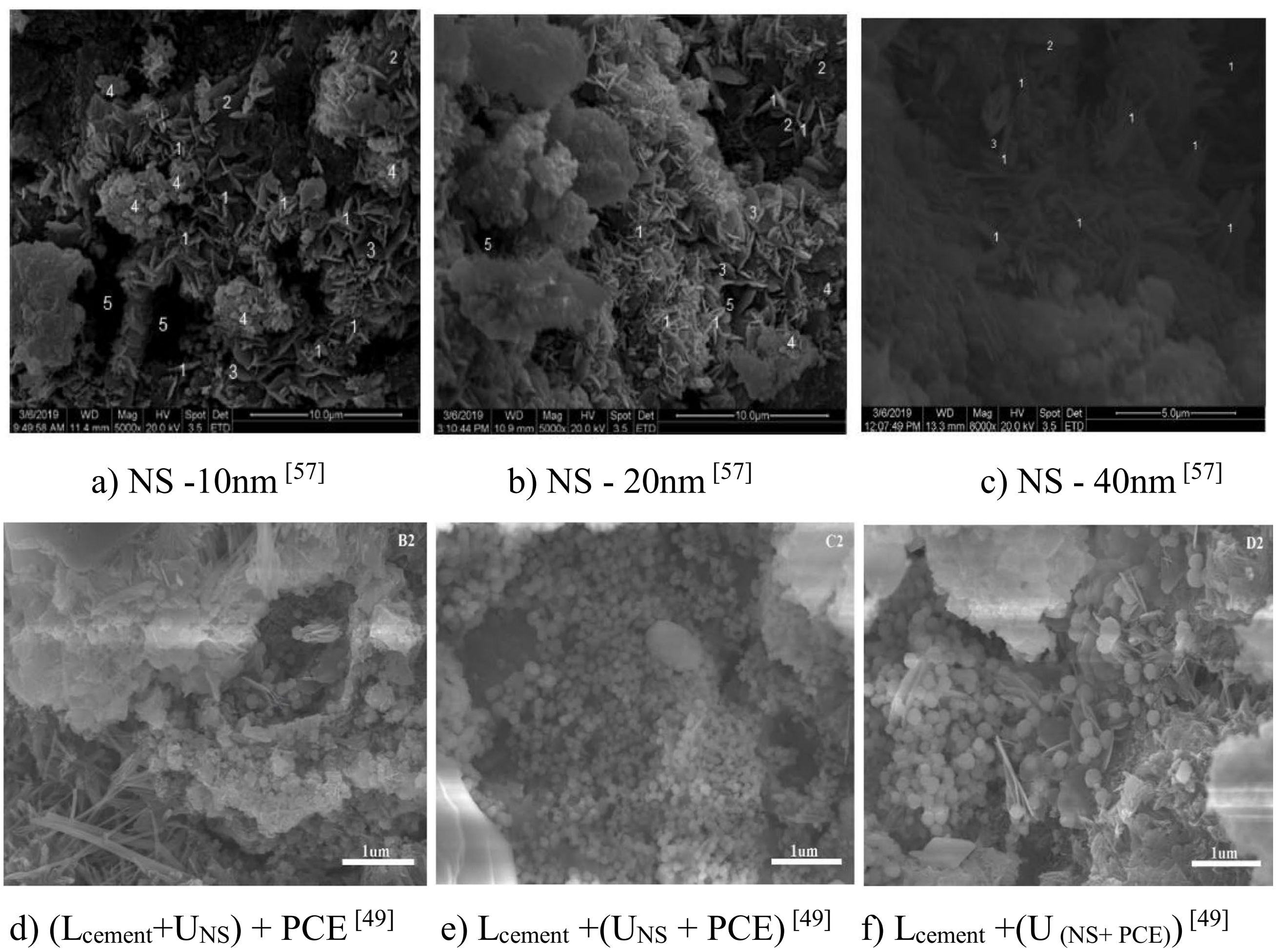


Fig. 16 SEM image of NS and its effects in cement concrete. **a** NS -10 nm [57]. **b** NS—20 nm [57]. **c** NS—40 nm [57]. **d** (L_{cement} + U_{NS}) + PCE [49]. **e** L_{cement} + (U_{NS} + PCE) [49]. **f** L_{cement} + ($U_{(NS+ PCE)}$) [49]

the chloride resistance of concrete which is observed to be superior than they are added individually. For higher W/C ratio lower will be the chloride resistance [5]. Moreover, the mortar with 3% colloidal NS prominently reduces the charges passing through the specimen [58].

6.4.2 Special Cement Mortar and Concrete

The reduction of chloride ion penetration in SCC composite increases with increase in NS dosage and GF Volume fractions [24]. Likewise, combined effect of NS and SF in HPSCC could reduce the chloride ion penetration

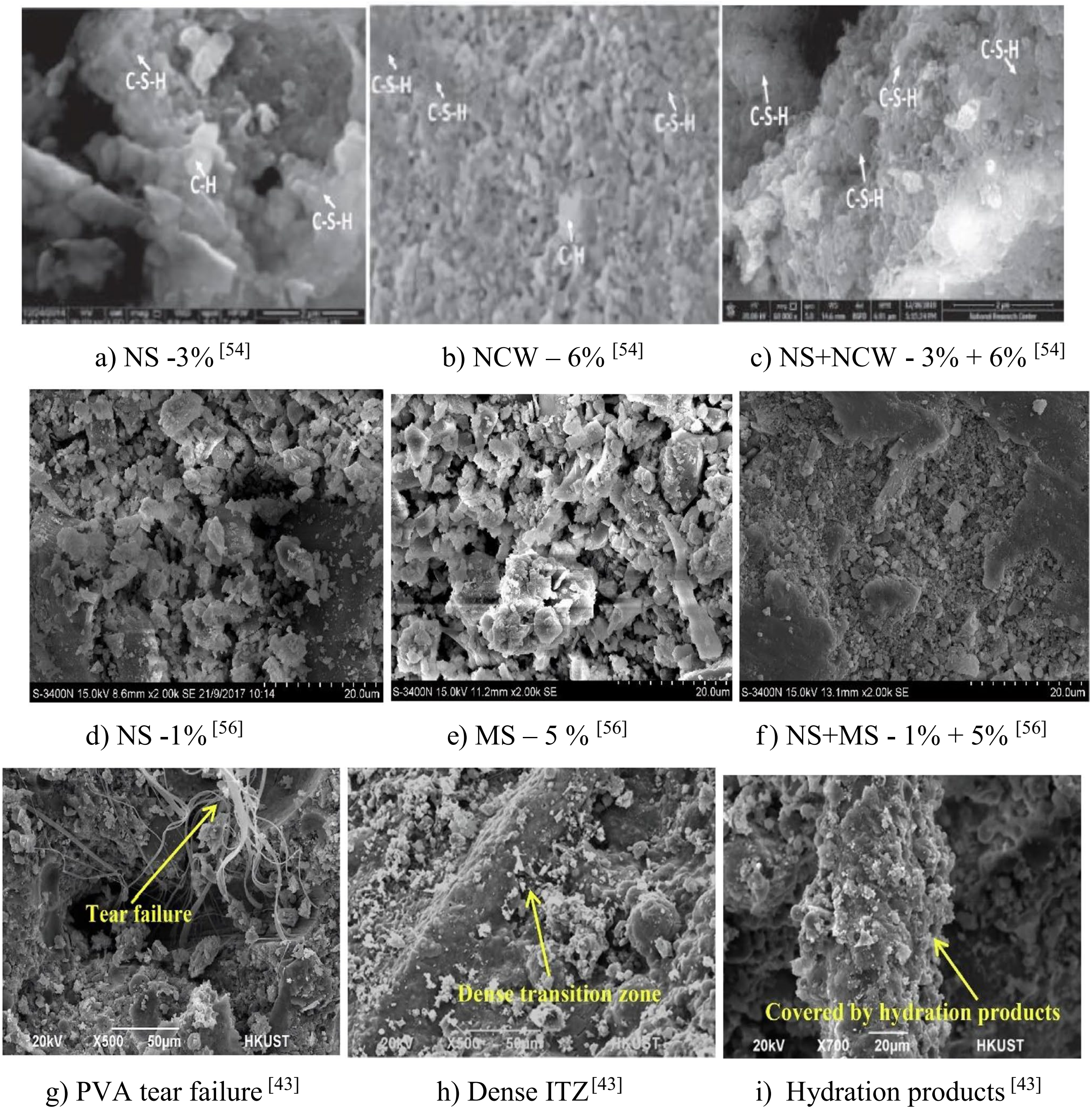


Fig. 17. SEM image on effects of NS and SCM's in cement concrete mix. **a** NS - 3% [54]. **b** NCW – 6% [54]. **c** NS+NCW—3%+6% [54]. **d** NS -1% [56]. **e** MS – 5% [56]. **f** NS+MS—1%+5% [56]. **g** PVA tear failure [43]. **h** Dense ITZ [43]. **i** Hydration products [43]

considerably [61]. The electrical conductivity of the of ULCC composites was reduced to 49% and 34% for the W/B ratio of 0.24 and 0.32 respectively by incorporating 3% colloidal NS were revealed by Hongjian Du et al. [55]. Markedly, 2% NS in LWC also reduces the entry of chloride ion by the formation of C-S–H gel [69]. From the investigations done by Ramiro Garcia et al. [77] it is observed that, Nano and micro blends in BFS based cement possess the durable performances at early ages as same as that of the durable performance of control mix at 28 days. Moreover, Nandini et al. revealed that, NS in SCC mix enhances the resistance to penetration of chloride ion by increasing the network of calcium silicate hydrate gel [130].

6.5 Carbonation

The depth of carbonation was reduced to 8.6 mm by the combined effect of 5% MS and 1% NS with W/C ratio of 0.45 whereas increased W/C possess increased carbonation depth was revealed by Leo Gu. Li et al. [56]. Moreover, incorporation of 3% NS in FA cement concrete mix reduces the carbonation depth by 73% at 180 days when compared with reference mix. This attributed to the formation of stable hydration products during pozzolanic reactivity and thereby resists the entry of aggressive ions, which enhances the durability of the mix [30].

7 Microstructural Characteristics of Nano Silica Cement Composites

Incorporation of SCM in cement mortar/concrete alters the microstructure and its properties [135]. Hence the microstructural characteristics of NS, SCM and fibers in different types cement concrete are analyzed by SEM are explained below.

Fig. 18 Replacement percentage of NS

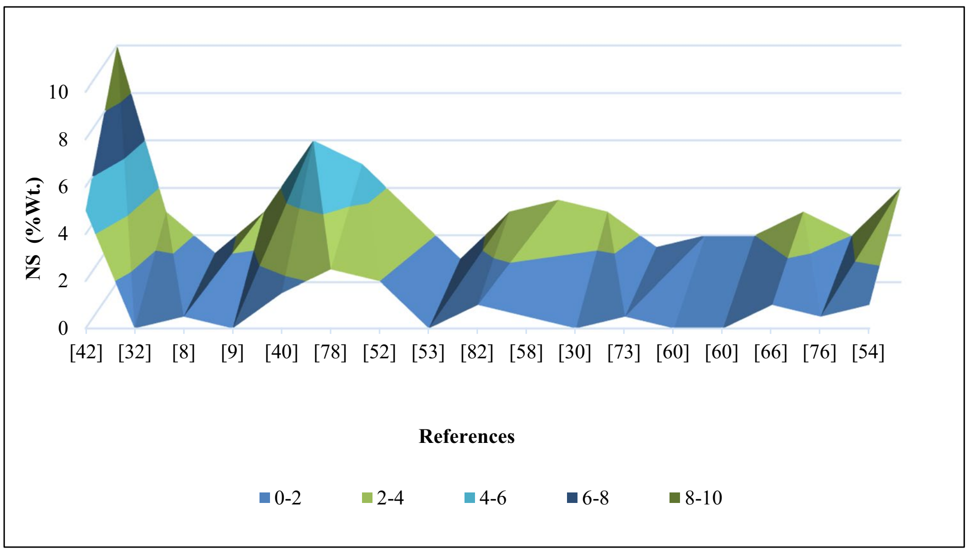


Fig. 19 Replacement percentage of SCM

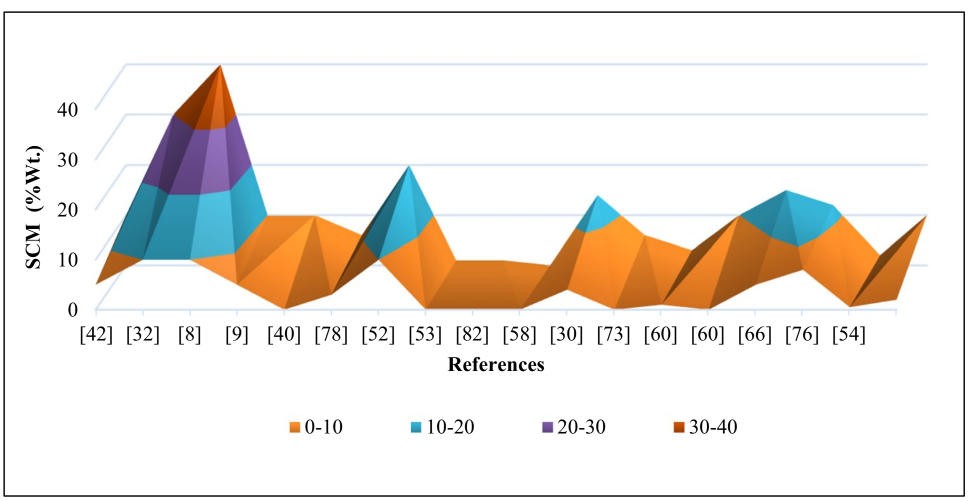


Table 10 Summary of the review inference

Title	Inference
Replacement percentage	a) From Fig. 18 and 19, it is observed that replacement percentage of NS is lower than that of the SCM in spite of its type and particle size b) The particle size of SCM incorporated with NS is always greater than the particle size of NS in spite of its form is observed from Fig. 8 c) The replacement percentage of NS ranges between 0.5% to 15% with W/B between 0.16 to 0.6 in spite of the cement type is observed from Fig. 9
Mixing Sequences	a) Most of the researchers follows the sequence of mixing all the dry ingredients together and then followed by the water/super plasticizers. Mixing the ingredients may be either by manually or mechanical mixer b) The other mixing sequence adopted are NS + Deionised water/water, here the water used for dispersion is the part of water from the W/B ratio c) Sonication timing rages between 5 to 60 min, but there is no evidence for uniform dispersion. It is based only on visual observations
Dispersion	a) From Fig. 11, it is observed that sonication time for NS dispersion is independent of its particle size. The sonication time followed by researchers doesn't have evident to recommend b) NS could be either dispersed in water, ionic or non-ionic surfactants, super plasticizers used c) The type of dispersion medium chosen depends on the type of NS nature (Hydrophobic or Hydrophilic) d) Well dispersed NS particles increases pozzolanic reactivity, ion adsorption and the nucleation sites
Fresh Property	a) The super plasticizer helps to maintain the desired flowability/consistency and also to avoid the agglomeration/flocculation of the NS/SCM particles in cement concrete mix b) Most of the researches used the polycarboxylate based super plasticizers c) Setting time and workability of the mix gets decreased on higher dosage of NS (> 5%) /NS + SCM by leaving the unhydrated cement particles at low W/B ratio. This leads to the formation of voids and the strength loss
Mechanical Property	a) NS greatly increases the early strength but on later ages the rate of strength attainment is reduced due to the immature pozzolanic action which may overcome by incorporating the other SCM b) The ratio of compressive –to-tensile strength is low for NS incorporated samples which implies that, NS doesn't offer much for tensile and flexural properties c) NS greatly increases the compressive strength and abrasion resistance by filling up the pores by hydration products
Durability Property	a) At good dispersion, NS/ NS + SCM's reduces the porosity by breakdown the macro pores to micro level which becomes harmless pores on optimum dosage b) By reducing voids in cement paste reduces the transport property of the cement concrete mix
Microstructure	a) From SEM observations, it is observed that the NS/NS + SCM's improves the compactness of microstructure and thereby increases the strength of the mix b) NS with greater particle size possess the better filling effect than the smaller ones c) NS with other SCM's possess the low flocs than NS used alone in the cement concrete mix

7.1 Effects of Nano Silica in Cement Concrete

From the study of Jibang Wang et al. [13] it is affirmed that even 1.2% NS accelerates the degree of hydration and thereby makes links of gel products closer which results in densified microstructure. The higher W/C ratio results in weak ITZ where the reversal effect is observed in microstructure [50]. Moreover, incorporating 1.89% aerogel exhibits the packed and dense microstructure was observed from the study of Taha M.Jassam et al.[11]. Though Silica Sol at lower W/C ratio increases the microstructure compactness by enhanced water retaining ability is noticed from the observations done by Deyu Kong et al. [85]. Furthermore, K.Snehal et al. [58], reveals that, low atomic ratio of Ca/Si is observed for all the binary, ternary and quaternary blends which implies the formation of compact microstructure. The quaternary blends show the least Ca/Si ratio when compared to other blends. M.T.Maagi et al.[57] studied the influence of NS particle size in microstructure and it is noticed that, 40 nm (c) NS particles possess greater filling effect than the 10 nm (a) and 20 nm (b) particles. Whereas Pengkun Hou et al. [49], studied effects in mixing sequences of NS with PCE and reveals that in cement-based materials PCE should be added subsequently the NS addition which results in better dispersion. By adding the non-ionic surfactant triton TX405 with PCE to the mix deagglomerates the NS particles and thereby increases the compressive strength by 33% than the other surfactants [10]. The SEM image of NS and its effects in cement concrete mix is shown in Fig. 16.

7.2 Effects of Nano silica and SCM in cement concrete

On incorporating colloidal NS and Flyash enhance the densification of ITZ between hardened cement paste and aggregates was noticed from the study by Muhammed Yasin Durgun, et al. [87]. Taher A. Tawfik et al. [54] revealed that, the combined effect of 6% NCW and 3% NS increases the compactness of the microstructure than they are incorporated individually at all curing ages. Moreover, adding 1% NS and 5% MS together densify the microstructure by considerably increasing the small crystals in hardened cement paste was affirmed from the investigations done by Leo Gu. Li et al. [56]. It is observed that, in HVS and HVS-FA concrete ITZ found to be with fewer voids and cracks on adding 1% NC and 3% NS from the study of Anwar Hosan et al. [52]. Furthermore, by adding PVA fibers to the cement matrix with NS enhances the load transfer by covering the fibres with hydration products [43]. The SEM image shows the effects of NS and SCM's in cement concrete mix is shown in Fig. 17.

8 Review Inference and Recommendations

8.1 Review Inference

The following affirmations are inferred from the theoretical and graphical representations of average particle size of NS and SCM, Replacement percentage of NS and SCM's with cement, sonication, compressive strength, tensile strength and flexural strength observed from the research work of various researchers. The different replacement percentages of NS and SCM are shown in Fig. 18 and 19 respectively. The inference from the reviewed articles is summarized in Table 10.

8.2 Recommendations for Future Work

The following recommendations are made from the research work done by various investigators.

i. *Type of NS:* Both powder and colloidal form are recommended.
ii. *Source:* Either it can be synthesized or sourced commercially.
iii. *Particle size:* NS with particle size greater than 20 nm is recommended. The particle size of SCM should be greater than the size of NS particles.
iv. *Percentage of Replacement:* NS ranging between 0.5% to 4% is recommended.
v. *Water-to-Binder ratio:* Ranging between 0.2 to 0.45 is recommended.
vi. *Dispersion medium:*

   a) For Hydrophobic NS, surfactants and polymers are recommended.
   b) For Hydrophilic NS, water and SP are recommended.

vii. *Mixing Sequences:* First NS must be dispersed in water/SP/surfactants/polymers and then added to the dry mix is recommended.
viii. *Type of Curing:* Both standard and moist curing is recommended, but the temperature should be maintained same throughout the entire curing period.

Note: To increase the flexural strength fibers with good tenacity can be added.

9 Conclusion

The various types of NS and its synthesis, dispersion types, mixing sequences and their influence on the properties of the concrete are reviewed comprehensively. The salient conclusions are summarized based on the review of the research works.

1. Based on NS type, particle size, dosage level, method of dispersion, type of dispersant used, water-cement ratio adopted, mixing sequences followed could shows the effect on concrete strength.
2. High SSA of NS resulted in either agglomeration caused by insufficient dispersion or effective dispersion leads to increase the availability of nucleation sites and thereby increases the formation of C-S–H gel as a result of pozzolanic reaction. It depends on the type of dispersant and the method of dispersion adopted.
3. Optimum replacement dosage of NS ranges between 2 to 3% in spite of the type of cement used.
4. To maintain the rolling effect of NS and make concrete workable, it requires the high dosage of plasticizers as well as the increased w/c ratio.
5. NS superiorly increases the compressive strength whereas other ductile properties are increased markedly. Hence NS can blend with fibres to increase the ductile properties.
6. The significant improvement in the durability properties of NS modified concrete at its optimum dosage is evidently witnessed. The enhancement in durability performance is attributed to the hydration products formed in pozzolanic reaction is highly stable and prevents the entry of deleterious agents which causes deterioration.

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Code Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent of Publication Not applicable.

Conflicts of Interest The authors declare that they have no conflict of interest.

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