



Influence of Incorporation of Colloidal Nano-Silica on Behaviour of Concrete

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Abstract

The current research work is based upon the experimental study of the effect of the use of nano-sized particles of colloidal nano-silica (NS) on various properties of concrete. The concrete mixes are designed by substituting cement with 0.75%, 1.5% and 3% of colloidal NS. The analysis of experimental outcomes of this investigation illustrates that the compressive and tensile strength is enhanced with the increasing NS (%). Moreover, increase in density and decline in volume of voids and water absorption have been found due to the introduction of NS in concrete. Increase in mechanical properties and improved non-destructive test results indicates the qualitative improvement in concrete owing to the incorporation of NS. However, the inclusion of NS has no substantial impact on modulus of elasticity of concrete.

Keywords Colloidal nano-silica · Density · Volume of voids · Strength · Water absorption

1 Introduction

In recent decades, the vast use of concrete has made it an extensively utilised material for construction activity; because of various reasons like low cost, can be moulded to any desired shape, and easy accessibility of its raw materials. Previous studies reported that various pozzolanic materials could be utilised in concrete for enhancing the parameters (Mehta and Monteiro 2006). Among the various materials, SF is a key admixture, which significantly enhances the behaviour of concrete. Addition of SF improves 28-day compressive strength (CS), secant modulus and flexural strength (FS) of concrete (Khedr and Abou-Zeid 1994). Moreover, addition of SF in concrete reduced the chloride-ion diffusion, improved the corrosion resistance at later days and alkali silica expansion (Smith 2001). In the last two decades, the rapid advancements in the area of nanotechnology make it viable to produce novel materials with advanced

characteristics or improvements in the behaviour of existing products (Sanchez and Sobolev 2010; Zhang et al. 2011). Nanotechnology is very advantageous for analysis of the products generated during hydration at nano-scale, and up-gradation in the nature of these materials could be achieved by the incorporation of nano-materials to have substantial enhancement in the properties of cement-based products (Pacheco-Torgal and Jalali 2011). The usage of nano-particles in cementitious materials is increasing drastically as these are most efficient in transforming the nature of paste by reducing the voids of C–H–S by its filling effect, accelerating the hydration rate, and lessening the number of Ca(OH)₂ (Pacheco-Torgal et al. 2013). NS could be incorporated in cement-based materials considering its high surface area and reactivity (Li et al. 2004; Lin et al. 2008). Previous study confirmed that pozzolanic action of NS had higher SF throughout initial days of curing because the rate of reaction between Ca(OH)₂ and NS and the speed at which C–S–H gel was produced were considerably quicker than SF (Qing et al. 2006).

Compressive strength (CS), microstructure, the rate of heat of hydration and the residual quantity of Ca(OH)₂ of cement mortar containing NS and SF were examined (Jo et al. 2007). It was noticed that CS of mortar with NS was higher than SF-incorporated mortar. Further, NS improved the microstructure of cement mortar along with increase in pozzolanic action. Increase in the quantity of heat generated

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throughout setting and hardening process was detected, but reduction in the residual quantity of calcium hydroxide was observed. It was reported in previous studies that very small concentration of NS had an impact on the CS and FS of cement paste. However, the higher dosages of NS required more water in the fresh state and a decline in CS was reported (Stefanidou and Papayiann 2012). Scanning electron microscope (SEM) analysis of the paste with NS confirmed the densification of microstructure due to the filling of the empty spaces. When NS was added to the paste, the workability of the paste was reduced remarkably because of the immediate interactions of NS solution with the liquid phase of the cementitious mixes and development of gels having more water-holding ability (Berra et al. 2012). The examination of the impact of NS on fresh properties of pastes and mortars concluded that yield stress was enhanced considerably when NS was used; however, there was no substantial effect on the plastic viscosity (Senff et al. 2009). Moreover, the decrease in apparent density and an increase in air content were observed due to inclusion of NS.

The influence of NS in modifying the mechanical and micro-structural behaviour of mortar is well documented in previous studies. The investigation comprising usages of colloidal NS concluded that the cement paste became thicker and rate of hydration increased because of inclusion of NS. Increase in strength of mortar was detected with rising amount of NS (Ltifi et al. 2011; Mukharjee and Barai 2014). SEM analysis confirmed that the nano-particles of silica or iron could improve the microstructure of paste, but proper dispersion should be required while mixing (Li et al. 2004). It was also recommended in this study that the optimum use of nano-particles should be restricted to 10 per cent, and the combined use of different nano-particles should not be encouraged as its producing lesser strength than individual use.

The usage of nano-particles in concrete is also encouraged due to the development of strength and densification of microstructure. A significant effect on permeability and microstructure of concrete was reported with the inclusion of NS (Ji 2005). The uniform and compact microstructure of concrete with NS led to the reduction in water permeability. Previous investigations reported that the NS of particle size 9–12 nm were very effective in reducing the setting time and producing strength during early days of concrete containing higher amount of slag (Zhang et al. 2012). However, no substantial effect on setting time and early strength was detected when SF was used. The rate of hydration and reactivity of slag mortars containing NS was higher than that of SF. It was recommended that the ultrasonic technique for mixing of NS should be adopted than mechanical mixing to avoid segregation. The setting times of volume slag paste decreased, and early strength of high volume slag mortar was improved due to addition of NS. Total porosity remained unaffected

as medium porosity increased, but there was a decrease in large porosity with rising dosages of NS. The strength of concrete mix produced with NS of two varying sized particles (15 and 90 nm) was more than control concrete (Givi et al. 2010). However, the mechanical properties of concrete blended with 15 nm silica nano-particles were more than that of concrete containing NS of particle size 90 nm in the early days.

Nano-silica is available in dry powder or colloidal form. The workability of the concrete was dependent on the application technique of the NS (suspension, powder, or slurry), and the concentration of nano-particle had an effect on the workability of the cement paste as water has a bigger influence on the workability of the hydrating system containing NS with high surface area (Quercia et al. 2012). The colloidal NS, which is insoluble in water, constitutes small nano-particles of size varying between 1 and 500 nm. These nano-particles are made of amorphous silica as core with hydroxylated surface, which remain suspended in a fluid medium without setting due to their small size (Bjornstrom et al. 2004). Colloidal NS produced better behaviour than dry grained form because it is more dispersive and less segregated. Furthermore, the inclusion of colloidal NS affected the hydration process and the gel structures by reducing the number of C–S–H gel having low-stiffness and enhancing the high-stiffness C–S–H gel (Hou et al. 2013). The behaviour of concrete incorporating NS along with or without fly ash confirmed that the usage of NS enhanced strength and reduced porosity of concrete (Said et al. 2012). From the above context, it can be concluded that the investigations related to the study of effect of inclusion of NS on behaviour of concrete are less in the literature. Therefore, a comprehensive study of mechanical, non-destructive, micro-structural and some durability characteristics of concrete containing NS is conducted in this paper.

2 Experimental Program

2.1 Materials

Various tests were performed to find properties of Ordinary Portland Cement (OPC) of 43 Grade which was used for designing mixes and it conformed to Indian standards (IS 8112 1989). The outcome of results of standard experiments conducted on OPC is illustrated in Table 1. The colloidal NS utilised in this study was procured from market which had a suspension of fine amorphous, non-porous and typically spherical particles. The properties of NS have been determined by conducting several tests such as visual inspection for colour, distillation process for solid content, transmission electron microscopy for particle size, SiO₂ content from X-ray diffraction analysis, and the pH value of NS has

Table 1 Results of various recommended tests to access the properties of cement

Consistency	Setting time (min)		Specific gravity	Fineness (m ² /kg)	Mortar strength (MPa)		
	Initial	Final			3 days	7 days	28 days
32%	135	295	3.12	306	37.96	44.2	48.02

Table 2 Results of different standard tests carried out for characterising colloidal NS

Colour	Specific gravity	pH value	Solid content (%)	Particle size	SiO ₂ content (%)
White	1.12	10.11	39	8–20 nm	99.1

been determined using Digital pH meter. The outcomes of these tests are shown in Table 2. Transmission electron microscopy (TEM) analysis is a microscopic image analysis technique which is normally carried out for finding particle size, shape and their distribution. The TEM image of NS, obtained in bright field mode, is furnished in Fig. 1. From the TEM pictures, it was observed that the particle size ranged from 8 to 20 nm and these were spherical in nature

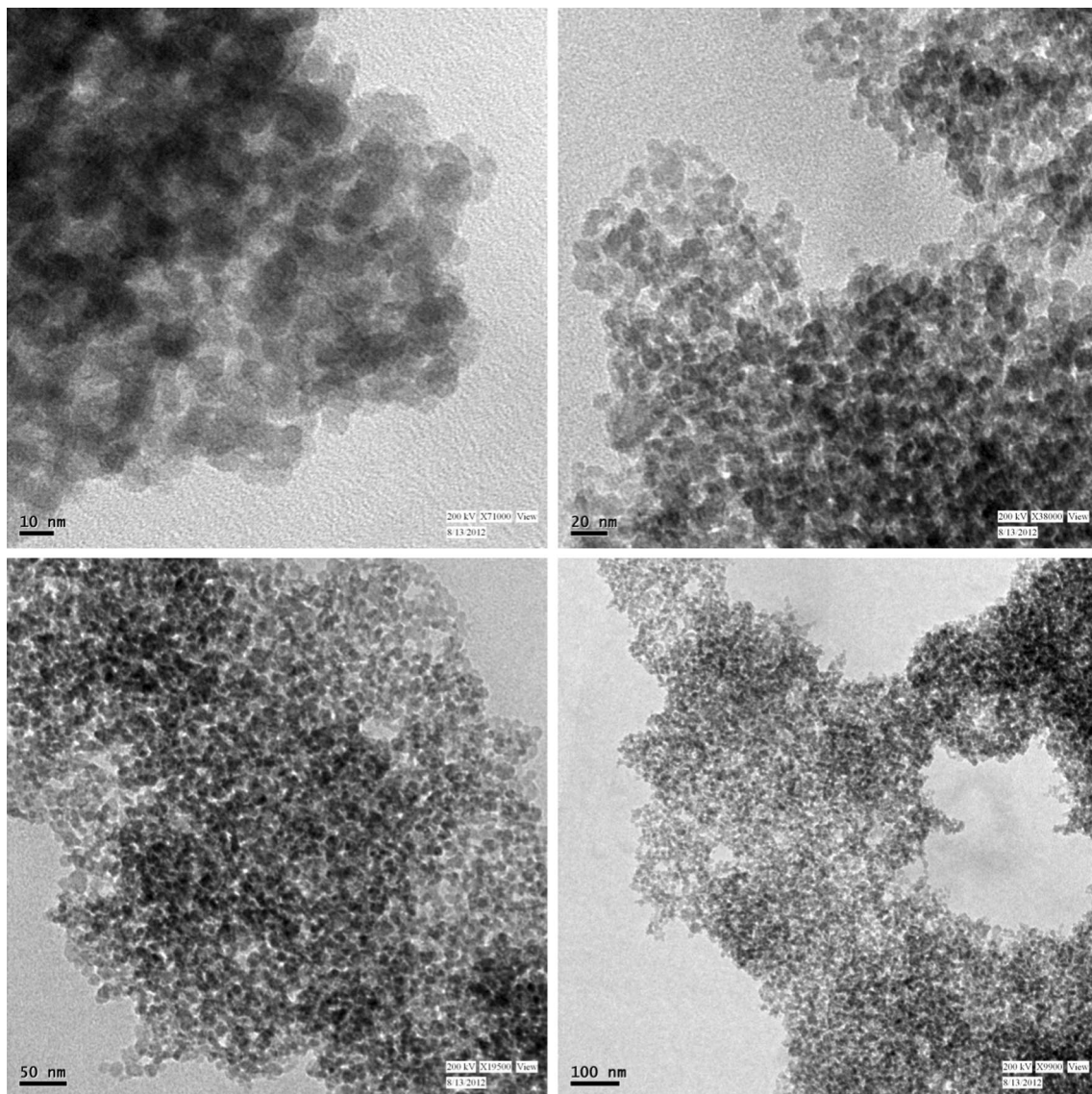
**Fig. 1** Transmission electron microscopic image of NS

Table 3 Results of various standard tests performed on aggregates

Property	Bulk density (kg/m ³)		Apparent specific gravity	Specific gravity	Impact value (%)	Los Angeles value (%)	Crushing value (%)
	Loose	Compact					
Fine aggregate	1525	1698	2.66	2.62	–	–	–
Coarse aggregate	1504	1654	2.81	2.72	15.35	19.72	15.11

and found to be in available in non-agglomerated form. The test results of aggregates utilised in making concrete are furnished in Table 3. The river sand conforming to zone II of IS 383 (1970) and 20-mm-crushed dolerite were utilised as natural aggregates.

2.2 Concrete Mixing and Specimen Preparation

The details of mix proportions of concrete mixed designed with different percentages of NS are furnished in Table 4. For all mixes, the water/binder ratio was 0.4 and varying quantities NS (0.75%, 1.5%, and 3%) were used in the mixes. The reference concrete (without NS) was made with aforementioned series of concrete to have a comparative study. The total water quantity of a particular mix was calculated while taking into account the quantity of water associated with it. Initially, colloidal NS was added to water and uniform dispersion of particles was achieved by continuous stirring. After this, aggregates and the cement were mixed for 2 min at a low-speed rotary mixture. Finally, mixture of nano-particles and water was added gently and mixed for 2 min. The fresh concrete was put into the designated moulds after completion of mixing and stored for duration of 24 h under controlled environment. After 24 h, the specimens were taken out of the mould and stored under water for curing purpose.

2.3 Testing of Specimens

The CS of 150-mm and 100-mm cubes, and cylinders 150 mm $\Phi \times$ 300 mm height using 3000 was found by using procedures of Bureau of Indian Standards (IS 516 1959). The development of CS with time was determined by calculating

Table 4 Quantity of various materials used for designing one cubic metre of concrete

Mix type	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Nano-silica (kg)	Water (kg)
NC 1	450.000	1180	640	–	180
NC 2	446.625	1180	640	3.375	180
NC 3	443.250	1180	640	6.750	180
NC 4	436.500	1180	640	13.500	180

7-, 28-, 90- and 365-day CS of the 150-mm cubes. Further, impact of specimen size with the inclusion of NS was found by performing the 28-day CS test of 100 mm cubes and cylinders. The cylindrical specimens of 150 mm $\Phi \times$ 300 mm height were utilised for finding 28-day split tensile strength (STS) of concrete following the procedure given in Indian standards (IS 5816 1999). Further, 100 \times 100 \times 500-mm-sized prisms were employed for finding 28-day FS using 100-kN universal testing machine BIS (IS 516 1959). The cylinder having dimensions of 150 mm $\Phi \times$ 300 mm height were employed for finding E values by following methods demonstrated in ASTM standards (ASTM C 469 2002). The UPV and RN of concrete were determined by following BIS codes (IS 1331: Part 1 and II 1992a, b). The density, WA and volume VV of were determined using 100-mm cubes following ASTM standards (ASTM C 642 2006). For each test, three numbers of specimens were prepared and mean of those values was considered. The standard deviations of each set of test results are not more than 5% of their corresponding mean values. To study the microstructure of concrete, backscattered scanning electron microscopy (BSEM) was performed using thin sections prepared from various concrete mixes. These sections were made by taking out 25 \times 50-mm-sized specimens from cylinders cured for 28 days. Then, vacuum impregnation of specimens was done with a low-viscosity epoxy coded as Epoxil-43 and hardener as Epoxil-MH43 in a 3:1 ratio; and coated specimens were kept for drying at room temperature for duration of 6 h. The aforementioned epoxy resin was useful in filling the voids and enhanced the contrast for distinguishing the pores and others (hydration products and anhydrous cement). In addition to epoxy coating, a thin layer carbon coating was done to avoid charging during BSEM. A powerful SEM having resolution of 3.0 nm (JEOL-JSM-6490) was employed in the present study for BSEM.

3 Results and Discussion

3.1 Fresh Concrete Properties

The outcome of the slump test conducted on concrete incorporating varying NS (%) illustrates that slump value of mixes reduced and this decrease is dependent upon the NS (%) (Fig. 2a). This degradation in workability of concrete

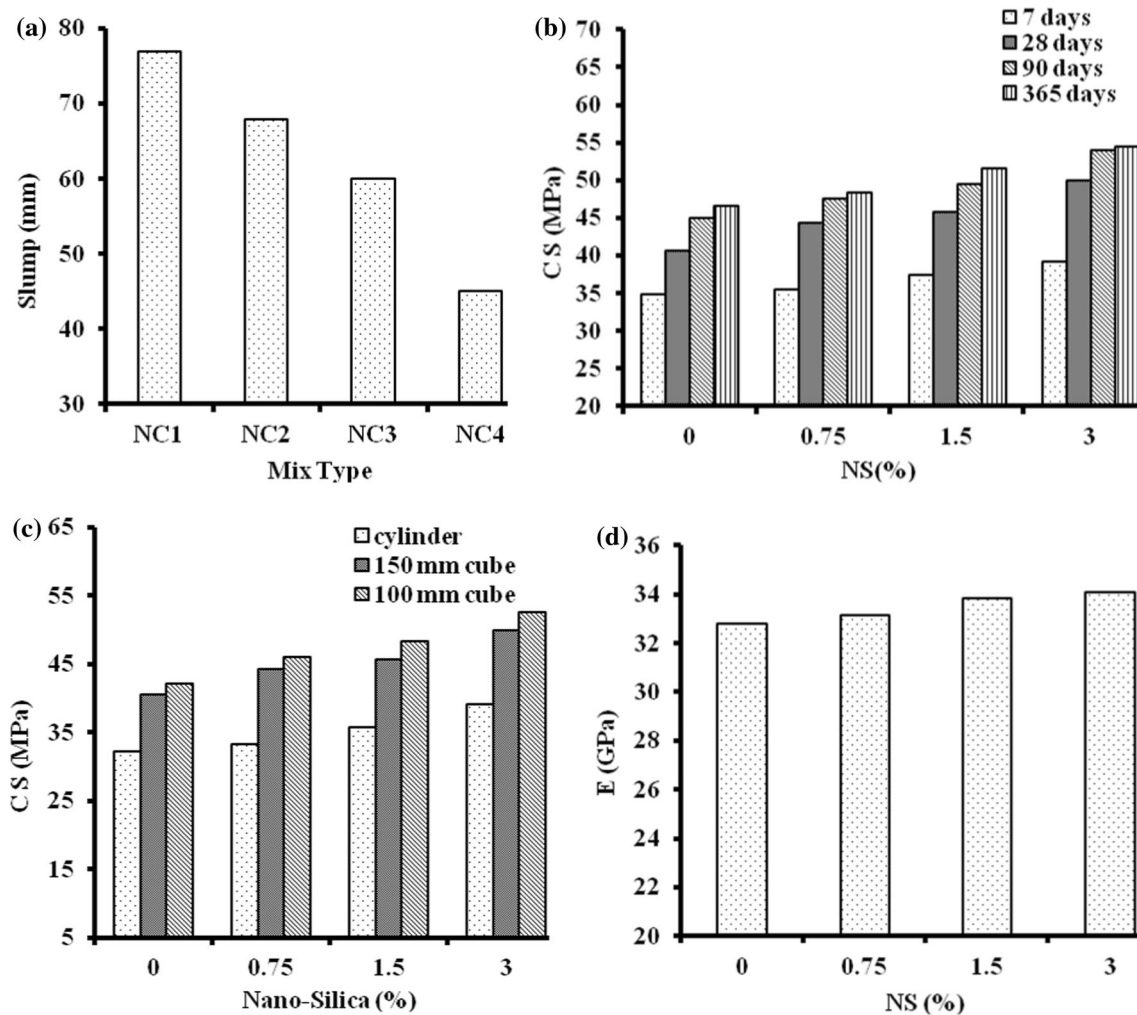


Fig. 2 Variation of: **a** slump; **b** CS with NS; **c** 28-day CS of cubes and cylinders; **d** E

with rise in NS (%) slump is because of the fact that NS attracts a fraction of mixing water. The high surface area and occurrence of unsaturated bonds in NS attract water towards their surface. Silanol groups (Si–OH) are developed because of attractive force between NS and water molecules and consequently formation of a chemical bonding between the water and these nano-particles. For this reason, the quantity of the water of the mix essential for improving the fluidity of the mix is considerably decreased. Hence, the viscosity of the concrete mix is improved with increasing NS content and workability of concrete with NS is reduced (Senff et al. 2009; Berra et al. 2012; Quercia et al. 2012).

3.2 Compressive Strength

Figure 2b illustrates the modification in CS (f_c) of concrete by the inclusion of varying NS (%). Higher value of CS during early days of curing observed as 7-day CS of concrete incorporating NS has more strength than reference

concrete. The development in CS during early days of curing with inclusion of NS is owing to the accelerated pozzolanic behaviour (Qing et al. 2006). Another reason for the up-gradation in strength is due to the inclusion of NS because of formation of a dense and compact microstructure (Ji 2005). The CS is enhanced in the order of 20% at 28 days with 3% NS as compared to reference concrete. Similar type of development of CS with the inclusion of NS has been reported by other researchers (Said et al. 2012). The CS of cubes after 90 and 365 days shows a similar trend in 28 days with the addition of NS. The change in CS between seven and 365 days is similar for each of the mixes designed in the present study. Higher value of CS of mixes after 7 days is owing to the type of cement used, since more than 80 per cent mortar strength is achieved in 7 days (Neville 2006). Figure 2c represents the variation of CS of cubical and cylindrical specimens of all the mixes of this study. For the reference concrete, the CS of the cylinders is 32.17 MPa, 100 mm cubes is

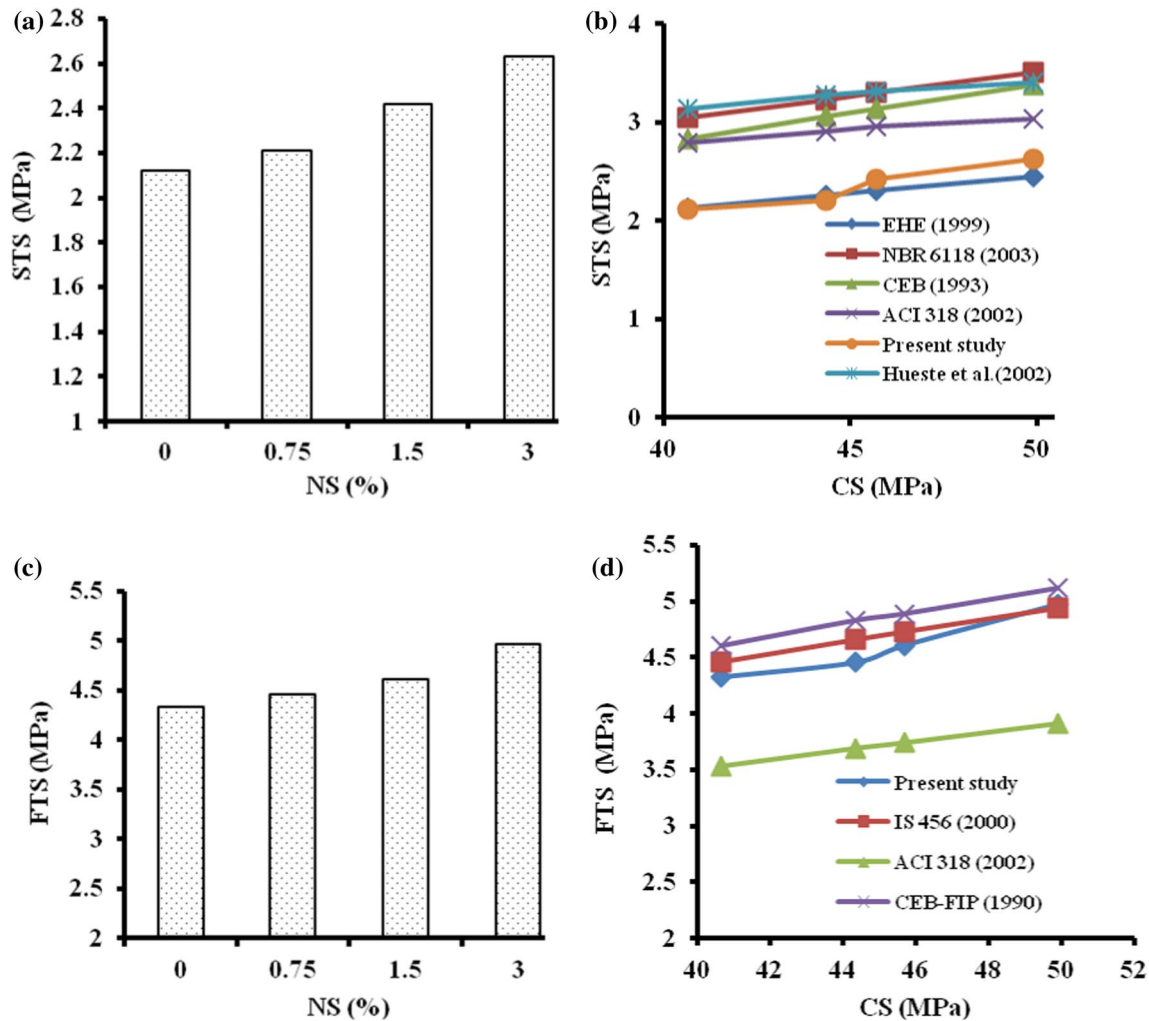


Fig. 3 a Variation of STS; b comparison of the present f_{sp} values with previous results; c variation of FTS; d comparison of the present f_i values with previous results

42.16 MPa and 150 mm cubes is 40.67 MPa, which illustrates that the CS of 150 mm cubes is maximum and that of cylinders is minimum. Similar type of variation in CS of cylinders and cubes is found for all the mixes of this study. This change in CS with varying specimen sizes is similar to normal concrete (phenomenon of size effect of specimens) (Neville 2006).

3.3 Modulus of Elasticity

The variation of modulus of elasticity (E) with varying NS (%) is illustrated in Fig. 2d, which shows that E value of reference mix changes from 32.763 to 34.06 GPa with the inclusion of 3% NS. But, this enhancement of E is not substantial as compared to strength of concrete, as the E value of concrete is not substantially influenced by the introduction of mineral admixtures (Corinaldesi and

Moriconi 2009). Primarily, the E value of concrete is mostly affected by the stiffness value of aggregates rather than the inclusion of admixtures with pozzolanic property (Neville 2006).

3.4 Tensile Strength

Figure 3a shows the changes in STS (f_{sp}) with variation of NS (%) of designed mixes which shows that there is a rising trend of STS with increasing NS (%). The relationship between CS (f_c) and STS (f_{sp}) is shown in Fig. 3b. The experimental outcomes of the current study are validated with the values anticipated using available formulations (Table 5). The cylinder strength after 28 days is termed as characteristics strength in all the relations shown in table. Therefore, the cube strength (as recommended by IS 456 for defining characteristic strength of concrete) found in the present study is converted to cylinder strength by using a

Table 5 Formulations to predict STS and FS from CS

STS		FS	
CEB-FIP (1990)	$f_{sp} = 1.56 \cdot \left(\frac{f_c - 8}{10} \right)^{\frac{2}{3}}$	CEB-FIP (1990)	$f_t = 0.81 \sqrt{f_c}$
EHE (1998)	$f_{sp} = 0.21 f_c^{\frac{2}{3}}$	IS:456 (2000)	$f_t = 0.70 \cdot \sqrt{f_c}$
ACI 318 (2002)	$f_{sp} = 0.56 \cdot \sqrt{f_c}$ $f_{sp} = 0.55 \cdot \sqrt{f_c}$	ACI 318 (2002)	$f_t = 0.62 \cdot \sqrt{f_c}$
Hueste et al. (2004) NBR 6118 (2003)	$f_{sp} = 0.3 \cdot f_c^{\frac{2}{3}}$		

correction factor of 0.8 (Neville 2006). It is observed that the experimental values obtained in this study are comparable to the STS values predicted using the formulation of Spanish code. However, higher values of f_{sp} are achieved by adopting the formulations provided by other standards. The difference in FS (f_t) with inclusion of NS is shown in Fig. 3c, and it is similar to STS of concrete. The FS of concrete with NS is more than the reference mix and improves with the up-gradation in the amount of NS. Figure 3d compares the present experimental values of FS with those predicted using standard formulations for predicting FS from CS (Table 5). Among all formulations listed in Table 5, the ACI 318 (2002) formulation utilises cylinder strength; however, all the other formulations use cube strength for predicting FS from CS. The comparative analysis shows that the values obtained from FS test are more than those anticipated using formulation of ACI 318 (2002), but lesser than those of CEB-FIP (1990). The present FS values are similar to the predicted values of the formulations of BIS (IS 456 2000). The up-gradation in the tensile strength of concrete with the inclusion of NS is because of the accelerated pozzolanic action and filling of pores by NS (Pacheco-Torgal et al. 2013). Interfacial transition zone (ITZ) has substantial influence on the tensile behaviour of concrete (Mehta and Monteiro 2006). The compactness and solidity of ITZ improve substantially with the inclusion of very fine particles of NS which leads to the improvement in tensile behaviour of concrete (Nazari and Shadi 2011).

3.5 Non-destructive Parameters

The ultrasonic pulse velocity (UPV) and rebound number (RN) values of concrete mixes with varying quantity of NS are illustrated in Fig. 4a, b, respectively. These parameters increase with increasing percentage of NS. UPV study confirms that concrete quality improves from good to excellent with the addition of NS. The RN test is useful in comparing one concrete against another, but it is an approximate prediction method for calculating the CS of concrete. The uniformity of mix and variation of quality of concrete due to the presence of voids can be compared in this test.

Figure 4c shows a second-degree curve could be suitable for relating the UPV and the CS of mixes. This relation is adopted to explain the nature of curve, which is comparable to the equation provided previously (Knaze and Beno 1984). Figure 4d shows the best-fit line that relates RN and the CS of concrete. There is no universal relation between these parameters, but many empirical relations have been suggested. The second-order equation adopted describes the relationship among CS and RN, and it is a similar type of relation as reported in the previous work (Knaze and Beno 1984).

3.6 WA, Density and VV

The change in WA of concrete with the introduction of NS is shown in Fig. 5a, which shows that the WA of reference mix (without NS) is 4.74%, which reduces to 3.21% because of the inclusion of 3% NS. Moreover, the WA of concrete declines with rising NS (%) (Li et al. 2004; Jo et al. 2007). This reduction in WA is because of the fact that the inclusion of NS minimises the quantity of voids of concrete; consequently, the water-absorbing capability of mixes diminishes. Figure 5b shows the changes in density of concrete with varying amounts of NS. It can be seen that the density of reference mix is 2389 kg/m³, and it changes to 2505 kg/m³ with the inclusion of 3% NS. The modification in density demonstrates that the mix turns out to be dense and minimisation due to the inclusion of nano-sized particles of NS (Qing et al. 2007). The VV of mixes with varying amounts of NS is furnished in Fig. 6c, which indicates that VV of concrete changes from 13.1 to 9.36% with the inclusion of 3% NS. This declination in the amount of VV is due to the filling of voids by NS (Stefanidou and Papayiann 2012). The relationship between CS and WA is presented in Fig. 6a, which indicates that quadratic curve is fitted to satisfy the relationship between the parameters. Moreover, a determination coefficient value of 0.9 signifies the presence of strong correlation between CS and WA. Figure 6b shows the relationship among CS and density of mixes which shows that the CS of concrete shows rising trend with the enhancement in the density, as the concrete possessing higher values of

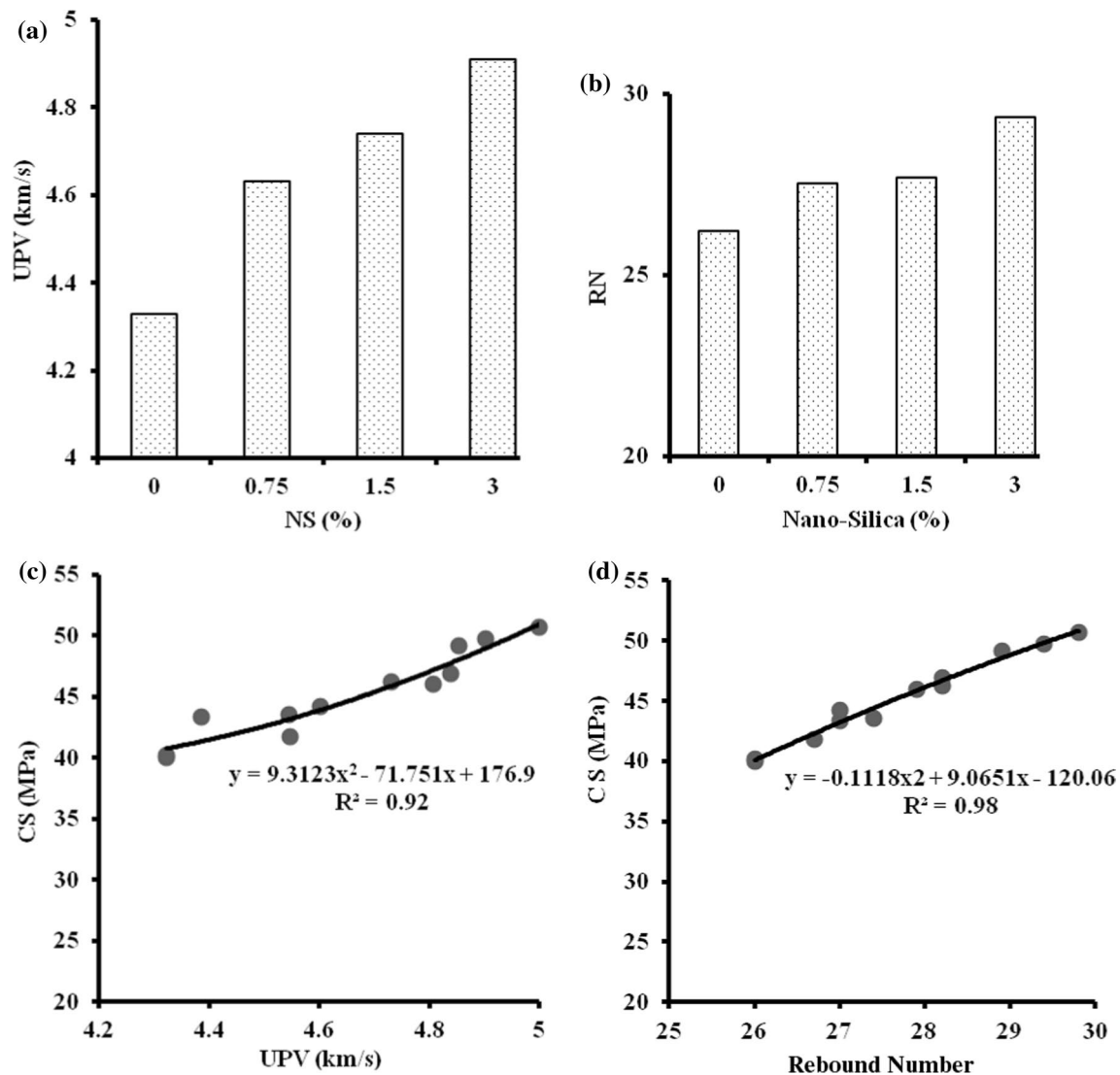


Fig. 4 a Variation of UPV; b relationship between CS and UPV; c variation of RN; d relationship between CS and RN

density has the sustainability to resist greater amount of loads. Moreover, the determination coefficient (0.88) shows that the fitted quadratic curve is appropriate for describing the relationship. The relationship developed among CS and the VV concludes that the best-fitted line among CS and VV is a curve (second degree), and it demonstrates that CS reduces with rise in VV (Fig. 6c). The determination coefficient for the relationship is equal to 0.92, which indicates the occurrence of a good correlation between VV and CS of concrete mixes.

3.7 Micro-Structural Analysis

Backscattered scanning electron microscopy (BSEM) has been performed on thin sections to examine the impact of inclusion of NS in concrete (Fig. 7). For image analysis, it

should be kept in mind that the residual cement is having highest brightness (white areas) and the pores are lowest resolution (dark areas) as epoxy resin will be inserted into the void are filled while samples are prepared (Diamond 2001). Figure 7a illustrates that the volume of un-hydrated cement and voids are substantially reduced with the introduction of NS in concrete, as a small number of areas with highest and lowest brightness are detected in the image. On the other hand, the occurrence of more voids and greater quantity of un-hydrated cement is found in the specimens without NS (Fig. 7b). This modification in microstructure concrete with NS is because of the fact that NS seals the voids present in concrete. Additionally, the inclusion of NS improves the pozzolanic reaction in the mixes and thereby decreases the amount of un-hydrated cement.

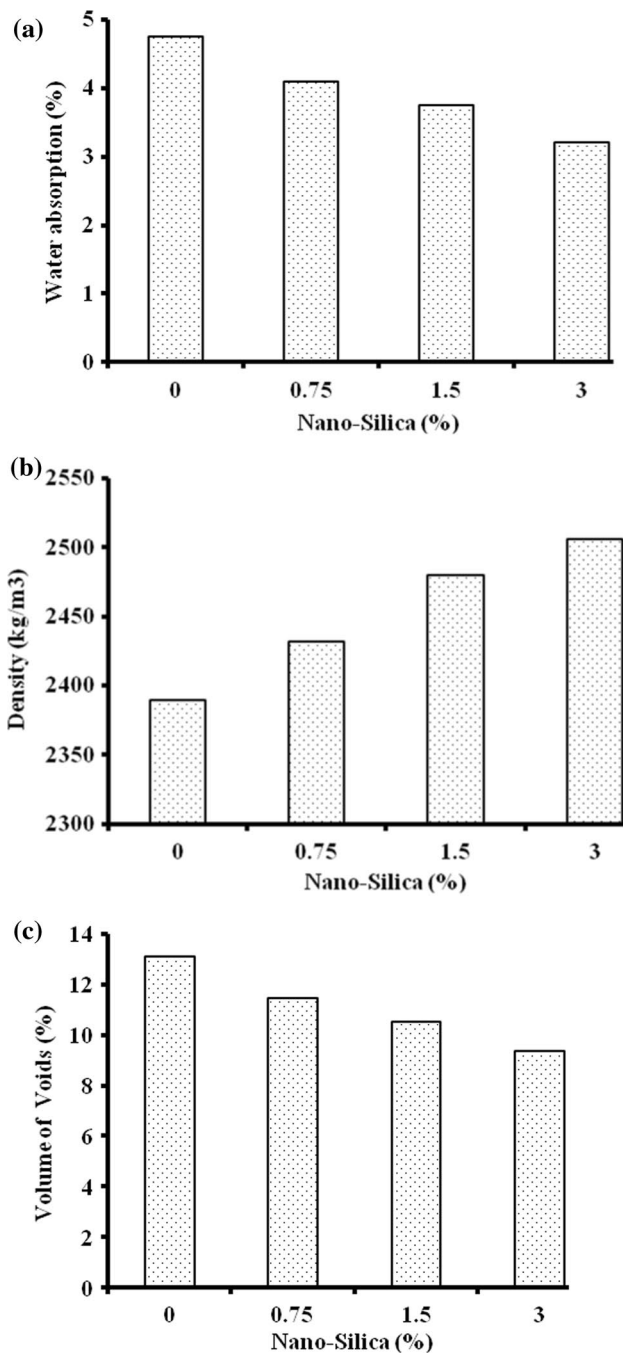


Fig. 5 Variation of: a water absorption; b density; c volume of voids

3.8 Statistical Analysis

To analyse the influence of the NS on the various parameters of NS-incorporated concrete, the design and analysis of a single factor (NS %) experiment with *a* (4) levels of the factor is performed according to the procedures given by Montgomery (2010). The above experimental work is conducted with *a* = 4 levels of the factor and *n* = 3 replicates. The analyses of variance (ANOVA) of the experimental outcomes of

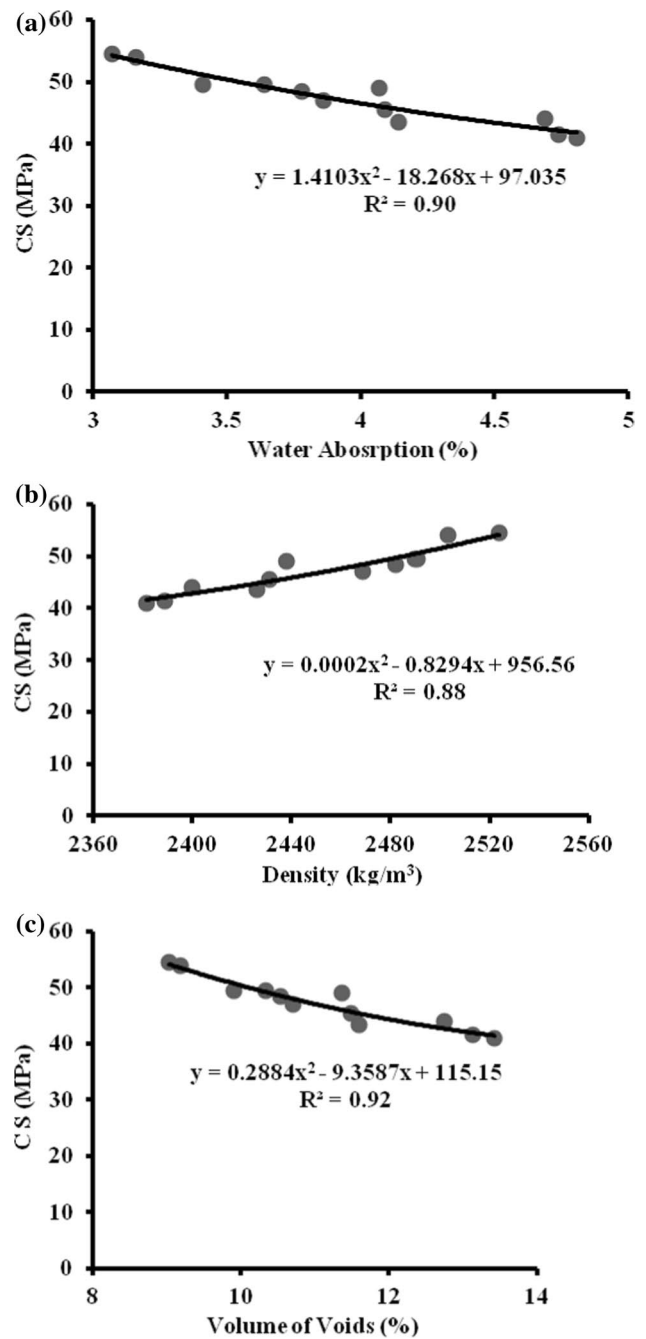


Fig. 6 Relationship between: a CS and WA; b CS and density; c CS and VV

various tests are carried out, and the resulting *F* values and *p* value are shown in Table 6. For every response, high *F* value and *p* value < 0.05 indicate that NS (%) considerably affects the responses. Correlations are developed between different parameters of concrete using regression analysis. The relation between different concrete parameters and percentage of NS is shown in Table 7. It is observed that the correlation equations are linear, and higher-order terms are absent in the

Fig. 7 BSEM image for **a** concrete with NS **b** reference concrete without NS

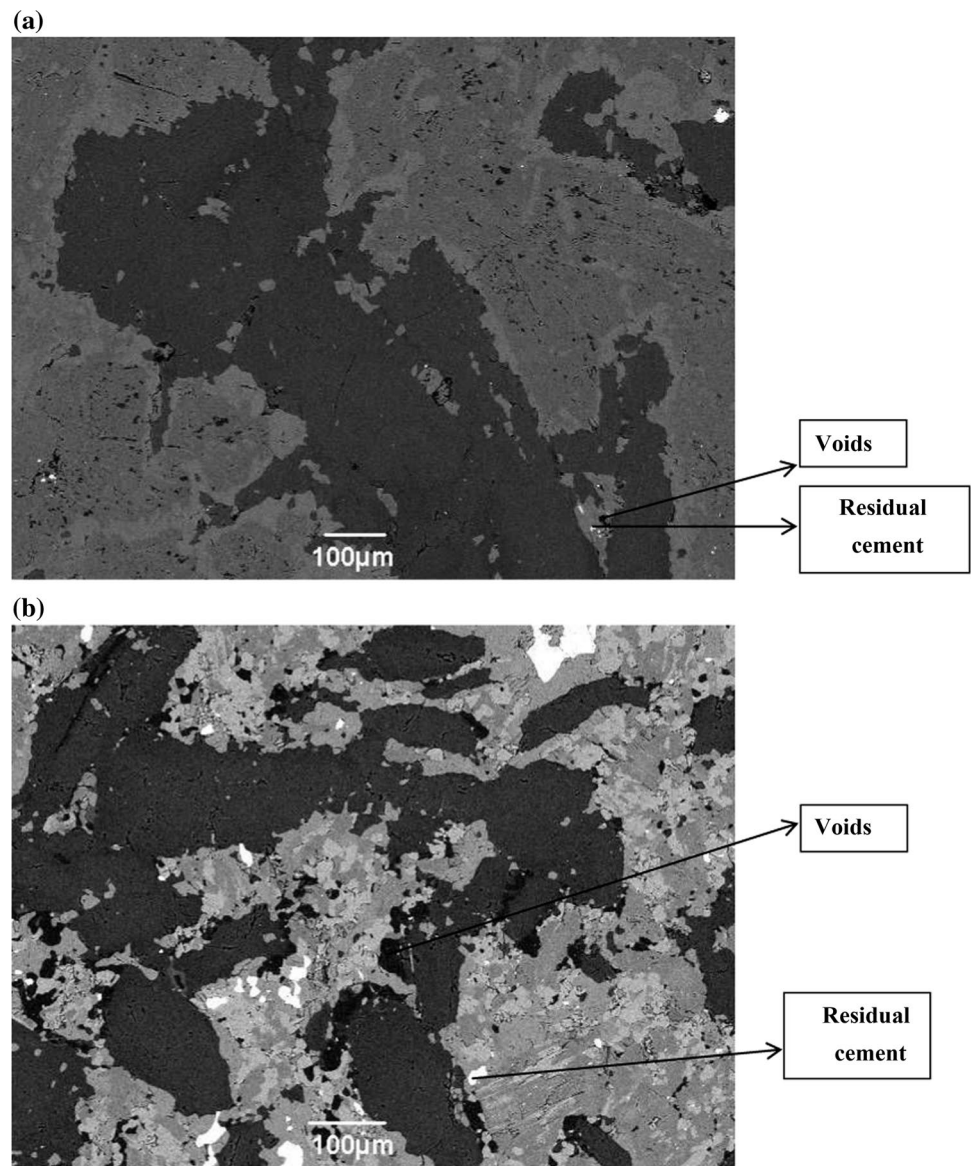


Table 6 Effect of NS (%) on various parameters of concrete

Response	<i>F</i> value	<i>p</i> value	SD	Mean	R^2	R^2 (adj)
7-day CS	23.88	0.0002	0.7	36.66	0.89	0.86
28-day CS	28.86	0.0001	1.22	45.15	0.91	0.88
STS	14.60	0.0013	0.1	2.35	0.84	0.78
FS	10.40	0.0039	0.15	4.59	0.79	0.71
E	1.02	0.4320	1.02	33.45	0.27	0.61
UPV	8.54	0.0071	0.13	4.66	0.76	0.67
RN	17.54	0.0007	0.53	27.71	0.86	0.81
WA	102.21	0.0000	0.11	3.96	0.97	0.96
DENSITY	59.13	0.0000	11.59	2452	0.95	0.94
VV	75.64	0.0000	0.31	11.08	0.96	0.95

Table 7 Relationship between various properties with NS percentage (P)

Regression equation	R^2
7-day CS = 34.7 + 1.51 * P	0.86
28-day CS = 41.3 + 2.92 * P	0.89
STS = 2.11 + 0.180 * P	0.84
FTS = 4.31 + 0.217 * P	0.79
E = 32.9 + 0.446 * P	0.27
UPV = 4.43 + 0.174 * P	0.74
RN = 26.42 + 0.982 * P	0.83
WA = 4.60 - 0.489 * P	0.93
DENSITY = 2402 + 38.3 * P	0.87
VV = 12.6 - 1.18 * P	0.89

regression equations. However, the influence of inclusion of NS has no substantial effect on the E value of concrete, p value > 0.05 . Therefore, the coefficient of determination (R^2) of the regression equation relating to E and P is found to be much less as the E value of concrete, predominantly related to the rigidity of coarse aggregates and inclusion of pozzolanic material, has no considerable effect on E value.

4 Conclusions

The impact of incorporation of colloidal NS as partial substitution of cement on the various parameters of concrete has been investigated in the current research. Based on the results obtained from various experiments and statistical analysis, the following meaningful conclusions can be drawn from this study:

- The present study introduces the utilisation of colloidal NS as a partial substitution of cement in designing concrete mixes; however, appropriate modification in the quantity of mixing water should be carried out bearing in mind the quantity of solid content of the colloidal NS.
- The outcome of the slump test illustrates that slump values of concrete mixes reduce with increasing NS (%) which is because of the soaking of a portion of mixing water by colloidal NS as the NS has high surface area and formation of silanol (Si–OH) groups.
- The up-gradation in CS of concrete during initial days of curing by inclusion of NS and this rise in strength are because of the higher pozzolanic activity of NS during this period. The improvement in 28-day CS with rising NS (%) is because of the formation of C–H–S gel, filling of voids in it, and strengthening in the bond between mortar and aggregates.

- The improvement in tensile parameters of mixes by the inclusion of NS owes to the fact that the particles of NS improve the mortar matrix by lessening the voids and developing stronger interface between two phases of concrete.
- The modulus of elasticity of concrete is increased marginally with the introduction of NS, which is not substantial with reference to the control mix as it may be noted that the introduction of pozzolanic materials has no considerable impact on elastic parameters of concrete. The modulus of elasticity of concrete is generally influenced by the nature of coarse aggregate used designing mixes.
- Non-destructive tests are usually carried out to predict the quality of specimens without physical breaking of specimens. In this study, substantial improvement in RN and UPV is detected by the inclusion of NS, which indicated enhancement in the quality of concrete.
- The WA, density and VV of concrete are determined to examine the influence of NS on water-retaining capacity and amount of voids of concrete. The outcomes of experimental study illustrate that WA and VV reduce with rise in added quantity of NS, but density improves with rising NS (%). The primary reason behind this is the decrease in the free water in concrete and subsequently, significant reduction in quantity of voids.
- BSEM analysis shows significant reduction in the quantity of residual cement and voids in NS-incorporated mixes, which confirms the improvement in concrete behaviour. The microstructure of concrete containing NS is found to be compact and uniform with regard to control concrete.
- Statistical analysis has been carried out by performing ANOVA test to verify the significance of the addition of NS on the mechanical and non-destructive parameters of concrete. Moreover, findings of analysis confirm that the introduction of NS considerably influences the different parameters of concrete, which indicates the usefulness of inclusion of NS. However, incorporation of colloidal NS has no major impact on elastic modulus, which could be seen from regression analysis and ANOVA table.

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