

Influence of nano silica on mechanical properties of high strength concrete

*Mohd Moonis Zaheer¹ Syed Danish Hasan² and Amman Ahmad³

^{1,2,3}*Department of Civil Engineering, Z.H.College of Engg. and Tech., Aligarh Muslim University, Aligarh, India*

ABSTRACT

This article presents the effect of incorporating nano-silica particles to produce high strength concrete. Nano-silica particles were replaced with cement at the rates of 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, and 4% by weight, and test specimens without nano-silica were also prepared. All mixtures had a constant water-to-binder ratio of 0.33 and were cured under full immersion condition. Various mechanical properties like compressive, flexural and split tensile strengths were determined after 28 days of curing. The fractured surfaces of the specimens were then examined using a scanning electron microscope (SEM). Study showed that the optimum content of nano-silica replacement with cement for improving the mechanical properties of concrete was 3%. The incorporation of nano-silica particles improved the stated properties apart from enhancing the elastic modulus, toughness, and ultrasonic pulse velocity of concrete. SEM micrographs illustrate the widespread distribution of cement paste containing nano-silica particles with a more compact microstructure and fewer pores, resulting in improved strength in the concrete composites.

1. INTRODUCTION

Due to significant infrastructure development in the recent past, the requirement of concrete is also considerably increasing. This high demand for concrete is causing the consumption of its ingredients, particularly cement, to increase substantially. Cement industry plays a significant role in air pollution due to CO₂ emissions (Huntzinger and Eatmon, 2009; Turner and Collins, 2013; Katare and Madurwar, 2017). Therefore, construction industries are searching for suitable additives for partial replacement of cement to produce concrete with improved performance in terms of fresh, hardened, and durability properties. Amongst several additives, nano-silica addition in concrete is finding considerable interest by the research community owing to its quick pozzolanic reactivity (Zhang and Li, 2011; Shaikh *et al.*, 2014; Yeşilmen *et al.*, 2015; Nazerigivi *et al.*, 2017; Snehal *et al.*, 2020). It is reported that the application of nanotechnology in concrete by incorporating nano-silica significantly improved the

*¹ Corresponding author, E-mail: mooniszaheer@rediffmail.com, Tel: +91-8126994199

² E-mail: sdhasan.amu@gmail.com, Tel: +91- 9557914410

³ E-mail: ammanahmad1992@gmail.com.

*The 2020 World Congress on
The 2020 Structures Congress (Structures20)
25-28, August, 2020, GECE, Seoul, Korea*

performance of concrete (Du *et al.*, 2014; Han *et al.*, 2017; Mahdikhani *et al.*, 2018). Further, high performance and high strength concrete could be effectively produced by nano-silica addition with a larger service life for lifetime structures like bridges, the foundation for offshore structures, containment structures, etc. (Said *et al.*, 2012). Nano-silica particles are capable of filling the voids between the particles of C-S-H gel. This process enhances the pozzolanic reactivity, which would result in the densification of microstructure, causing improved mechanical and durability properties of concrete (Zhang and Li, 2011; Zhang *et al.*, 2012). Recent advances in nano-silica application in concrete were presented in a review paper by Barbhuiya *et al.*, (2020). In this paper, attention was paid to investigate the effect of nano-silica substitution on the fresh, mechanical, and durability properties of nano-modified concrete. Recently, other nanomaterials like nano-TiO₂, Al₂O₃, Fe₂O₃, carbon nanotubes (CNTs) and others were also used by researchers as nanofiller in the cementitious composites for improving the microstructure (Kong *et al.*, 2012; Said *et al.*, 2012; Oltulu and Şahin, 2014; Yu, Spiesz and Brouwers, 2014; Zaheer, 2019; Zaheer *et al.*, 2019), but these particles were found to be expensive, limiting large scale application.

Incorporation of nano-silica in concrete resulted in a denser and compact microstructure (Said *et al.*, 2012). The nano-silica admixed concrete resulted in higher mechanical strength than that of normal concrete to a considerable level (Zhang and Li, 2011; Said *et al.*, 2012). An increase in tensile and flexural strength is also reported in nano-silica concrete (Riahi and Nazari, 2011). A critical review of the beneficial role of nano-silica in cementitious materials can be found in a review paper by Singh *et al.* (2013). Characteristics of sustainable concrete by incorporating recycled aggregate and colloidal nano-silica was investigated by Mukharjee and Barai (2015) and showed that the negative effect of recycled aggregate concrete could be mitigated with the addition of 3% nano-silica. In a recent study by the same authors, Mukharjee and Barai (2019) carried out a performance assessment of nano-silica added recycled aggregate concrete (RAC). Analysis of variance has been conducted on the experimental results and showed that recycled coarse aggregate and nano-silica percentages have a significant effect on the response quantities. In another study, the improvement of compressive and flexural strength of concrete with the incorporation of nano-silica was reported by Shekari and Razzaghi (2011). Experimental investigation on the effect of nano-silica on the compressive strength of lightweight aggregate concrete (LWAC) was performed by Wang *et al.* (2018). LWAC with different nano-silica dosage (1%, 2%, 3%) were used to assess the effect of nano-silica on LWAC. Results showed that the incorporation of 3% nano-silica increased the compressive strength significantly. Janković *et al.* (2016) investigated the effect of nano-silica and barite aggregate on the properties of ultra-high performance concrete. They showed that by increasing the nano-silica content up to 2%, mechanical properties were increased. Further, by increasing the nano-silica content between 2-5%, mechanical strength was found to decrease. Technical and economic aspects of using nano-silica particles for construction purposes were studied by Rad (2018) and found that for 1-ton concrete production, the price increases by about 1\$. In contrast, the beneficial effect on compressive strength was about 3.5 times as compared to the control concrete.

To author's knowledge, investigations on the strength properties of high strength concrete with nano-silica are still limited, as past studies were mainly focused on dispersion issues and its influence on normal strength concrete. This present work consists of producing a high strength concrete by identifying the optimal level of nano-silica replacement with cement for the desired improvement in the mechanical properties. Experiments were performed at the hardened states to evaluate the compressive strength, strength development, flexural strength, splitting tensile strength, modulus of elasticity, and stress-strain characteristics of different concrete mixtures. The study also included toughness and ultrasonic pulse velocity (UPV) tests to study the feasibility of using this nanomaterial in the production of high strength concrete.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

JK 43 grade Indian Portland cement was used, which meets IS 8112-2013 (Standard Specification for Portland Cement) criteria. The cement has a specific gravity of 3.15. The composition and properties of the Portland cement are listed in Table 1. Locally procured natural sand conforming to Indian standard specifications, IS 383-1970 was used for all mixtures. The natural sand had a fineness modulus of 2.97, specific gravity of 2.65, a bulk density of 1.4 kg/m³, and water absorption of 1%. Natural crushed stone with two gradations, viz; 20 mm and 10 mm maximum size having a specific gravity of 2.68 and 2.67, respectively, was used in nano-silica mixtures. The nano-silica used was delivered from the ASTRAA chemicals, Chennai, Tamil Nadu, India. The main composition and properties of nano-silica are shown in Table 2. The nano-silica used was in a dry powder form with a purity of 99.88% and a particle size of 17-20 nm. For achieving constant workability, a high range water reducer admixture (HRWRA) and complying with IS 9103:1999 Standards, was used at different dosages to maintain a slump of 100-120 mm in different mixes. The specific gravity and pH of HRWRA were 1.105, and 5.75, respectively.

Table 1. Properties of ordinary Portland cement.

Ingredients	CaO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	MgO	SO ₃	LOI
Quantity (%)	62.5	2.9	4.5	19.2	3.2	2.5	3.5

Table 2. Properties of dry nano-silica particles.

Nano particle	Colour	Particle size (nm)	Specific surface area (m ² /g)	Purity (%)	pH value	Specific gravity
Nano silica	White	17-20	202	99.88	4.12	1.31

2.2. Mixtures design and tests procedure

In this study, a total of 8 nano-silica mixtures were tested. Cement replacement levels of 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, and 4% by dry nano-silica powder were chosen for various mixes. All mixtures contained a total cement content of 428 kg/m³, coarse to a fine aggregate ratio of 1.45, and a water-to-binder ratio of 0.33 to obtain successful mixes. The amount of HRWRA was adjusted for each mixture to obtain a slump between 100 and 120 mm. Higher amounts of HRWRA were needed for the larger replacement levels of nano-silica. The required quantity of nano-silica was initially mixed in a measured quantity of water in a 1000 ml flask and is sonicated for 20 minutes in a bath sonicator, as shown in Fig. 1. The mixture proportions of all tested mixtures are shown in Table 3.



Fig.1. Bath sonicator.

The compressive strength was measured using cube samples (150 mm × 150 mm × 150 mm) according to IS 516:1959, at a loading rate of 400 kg/min (BIS:516-1959, 1959). The split tensile strength was measured using cylinder samples (150 mm × 300 mm) as per BIS:5816, 1999, and flexural strength was measured on prism samples (100 mm × 100 mm × 500 mm) under third-point loading, according to BIS:516-1959, 1959. Prism sample after flexural failure is shown in Fig. 2. Table vibrator was employed for proper compaction of mixes in the molds. After 24 hours of casting, specimens were un moulded and placed in a curing tank at a temperature of 23 ± 2 °C and with a relative humidity of more than 95%. Before the testing, specimens were dried for 24 h at room temperature. The compressive strength at different curing ages (7 and 28 days) and flexural and split tensile strength at 28 days were determined. All mixtures are designated according to the percentages of cement replacement (0.5 to 4%). For example, a mixture with a 1% nano-silica replacement would be designated as NS1.0. After the tests, small crushed concrete fragments were picked from select concrete mixtures and stored in ethanol to prevent hydration. Then, the samples were first put up in an oven at 80 °C for 24 h. It was then allowed to cool for 24 h before the fragments were gold-coated by a layer of approximately 20 μm using an automated sequence sputter coating machine as shown in Fig. 3(a). In addition, JSM-5610 as shown in Fig. 3(b) was adopted to study the microstructure of the composites. The ultrasonic pulse velocity (UPV) test was carried out according to the provisions of IS 13311 (Part 1), 1992.



Fig. 2. Prism showing crack pattern after flexural testing.

Table 3. Proportions of mixtures per cubic meter of concrete.

Mix	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Nano-silica (kg)	HRWRA (litre)	Water (litre)
Control	428.0	775	1128	0.00	4.28	141
NS0.5	425.5	773	1125	2.50	4.32	141
NS1.0	423.5	771	1122	4.50	4.46	141
NS1.5	421.5	769	1120	6.50	4.61	141
NS2.0	419.0	767	1117	9.00	4.76	141
NS2.5	417.0	766	1114	11.0	4.93	141
NS3.0	415.0	764	1112	13.0	5.17	141
NS3.5	413.0	762	1109	15.0	5.32	141
NS4.0	410.5	760	1107	17.5	5.51	141

In all the specimens, the w/c ratio is kept as 0.33.



Fig.3. Set-up for microstructural characterization (a) Gold etching machine, (b) SEM analyzer.

Table 4. Results of nano-silica concrete tests.

Mix (nano-silica %)	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)	Elastic modulus (GPa)	Split Tensile strength (MPa)	Flexural strength (MPa)
Control	42.77	55.55	33.07	3.54	5.90
NS 0.5	44.41	56.49	33.97	3.68	6.25
NS 1.0	46.60	57.60	34.77	3.96	6.75
NS 1.5	47.95	58.21	35.69	4.11	7.00
NS 2.0	49.65	58.88	36.49	4.25	7.75
NS 2.5	50.75	59.27	37.16	4.39	8.25
NS 3.0	51.85	59.63	37.85	4.53	8.50
NS 3.5	42.08	53.65	32.59	3.43	5.85
NS 4.0	36.60	49.05	32.29	3.29	5.60

3. RESULTS AND DISCUSSION

3.1. Compressive strength

Based on compression testing results in Table 4, the compressive strength was generally increased when nano-silica particles were replaced by cement in a small amount. For instance, partial replacement of cement with 0.5 to 3.0% by nano-silica resulted in an increase in compressive strength by 1.7, 3.7, 4.8, 6.0, 6.7, and 7.3%, respectively compared to control concrete at 28 days. However, when nanoparticles were added in a large amount, i.e., 3.5% and 4%, the compressive strength of concrete was found to be lower as compared to control concrete (Table 4). The control concrete had a 28 day compressive strength of 55.55 MPa, and the 3.5% nano-silica replacement showed a 3.42% decrease in that compressive strength, as shown in Fig. 4. It is noticeable from Fig. 4 that the compressive strength shows a high increase in strength from 3.8 to 21.2% at 7 days, indicating quick hydration of cement at an early age. The increase in strength is attributed to the transformation of calcium hydrate (C-H) into calcium silicate hydrate (C-S-H) due to a pozzolanic reaction. Furthermore, in all specimens, reduction in strength was observed by increasing nano-silica content above 3% as compared to the control specimen, which may be due to improper mixing, which leads to the agglomeration of nano-silica particles. The same observation was made by Kong *et al.* (2012) and Oltulu and Şahin (2014).

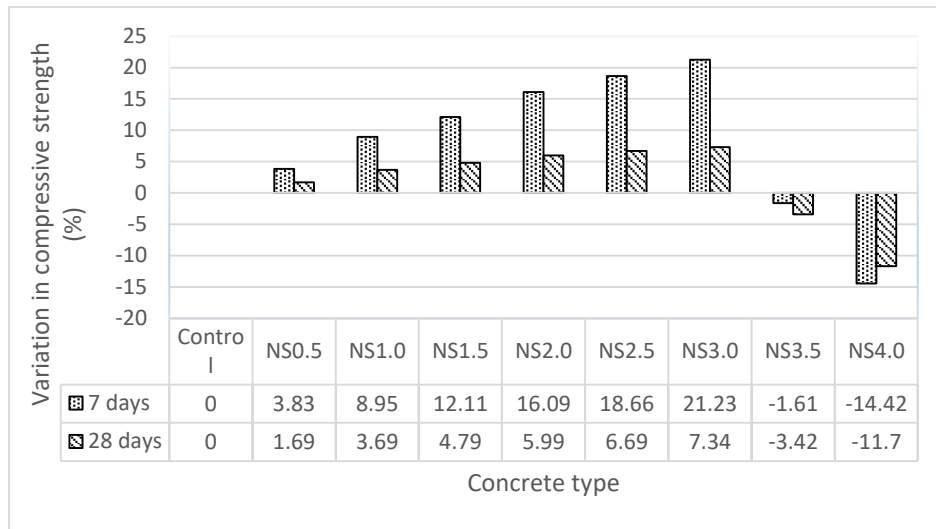


Fig. 4. Variations of compressive strength test results.

3.2. Strength development

Fig. 5 shows the compressive strength development of nano-silica mixes. The Strength of concrete at 7 and 28 days are respectively denoted by f_c and f_c^{28} . The figure shows that a mixture containing 3% nano-silica replacement had the highest strength development at 7 days (93%) when compared to the control mix. This result confirms that the addition of nano-silica significantly improves the strength gained by nano-silica admixed concrete. This finding were found to be similar to that obtained from a study on silica-breccia in mortar and concrete (Hassan *et al.*, 2014).

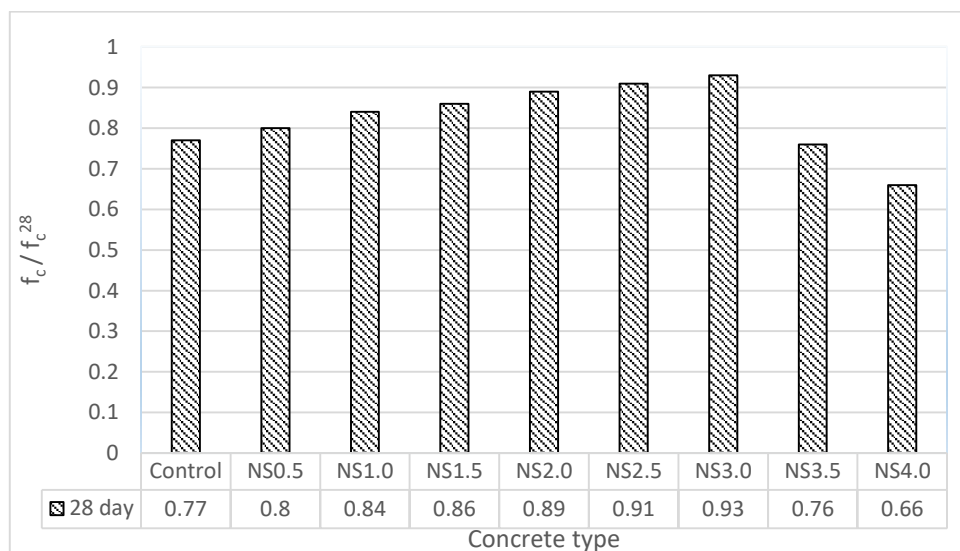


Fig. 5. Compressive strength development at 7 days of the tested nano-silica concrete mixtures.

3.3. Splitting tensile test

This test was performed on a cylindrical specimen with dimensions of 150 mm × 300 mm. The splitting tensile strength T is calculated by the following relation (BIS:5816, 1999):

$$T = 2P/\pi ld$$

where P denotes the failure load, l and d represent the length and diameter of the cylindrical specimen, respectively.

Fig. 6 illustrates the effects of different nano-silica contents on the split tensile strength. As can be seen, increasing the nano-silica content in the mix increases the split tensile strength except for specimens in which nano-silica content is more than 3%. Replacing 0.5%, 1%, 1.5%, 2%, 2.5% and 3% of cement with nano-silica increased the split tensile strength by 4%, 12%, 16%, 20%, 24% and 28%, while 3.5% and 4% nano-silica content led to 3% and 7% decrease in the split tensile strength compared to the control concrete. Hence, the stated outcomes clearly show that optimum tensile results were obtained at 3% nano-silica replacement.

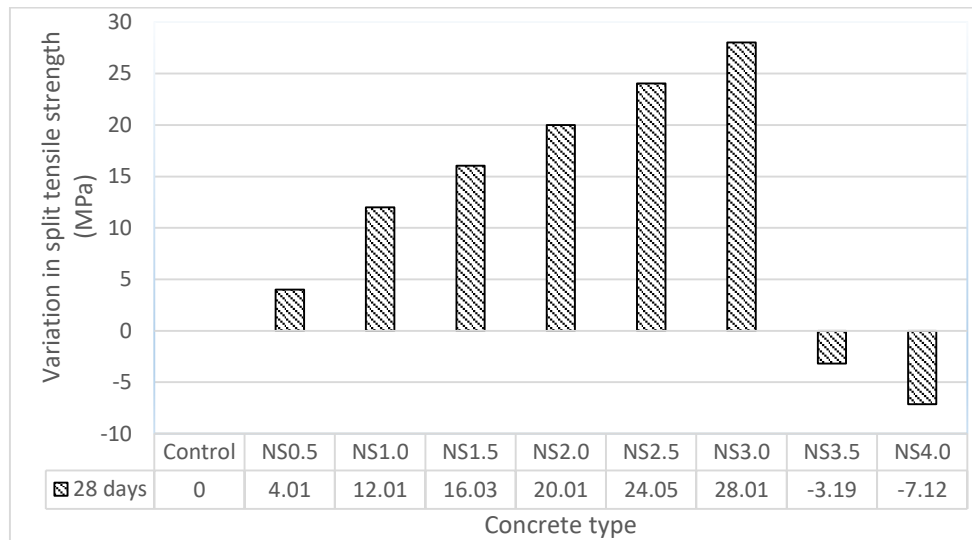


Fig. 6. Variations of split tensile strength test results.

3.4. Flexural strength test

This test evaluated the behavior of the material under flexure, which may cause deformation or cracking of the composite matrix. The most common type of this test includes center-point loading and third-point loading test. Normally, third-point loading is adopted to ensure pure flexural failure.

As shown in Fig. 7, flexural strength of specimens increased by nano-silica content up to 3% followed by a decrease in strength. The increase in flexural strength is of the order of 44% at 3% nano-silica replacement. The addition of 3.5% nano-silica led to a slight drop in flexural strength by 0.85%. When the concentration of nano-silica is larger, the agglomeration of nanoparticles, which creates weak zones in concrete increases (Zhang and Li, 2011) and leads to a decrease in flexural strength.

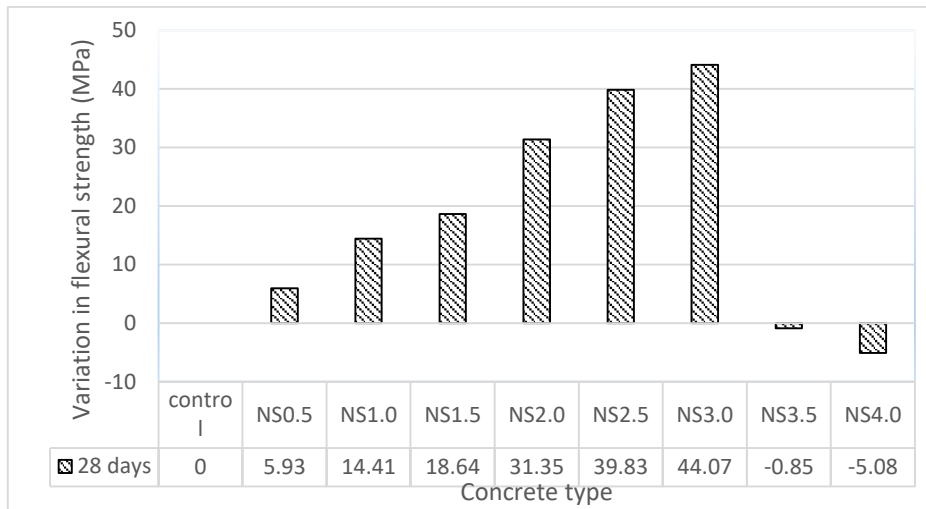


Fig. 7. Variations of flexural strength test results.

3.5. Stress-strain curves

The stress-strain curves for a few nano-silica flexural specimens are plotted in Fig. 8, reinforced with 0%, 2.5%, 3.0%, and 4.0% nano-silica particles. Based on the observation, practically a linear behavior is noticed, which can be correlated to the elastic behavior of the composite matrix. Further, the substitution of nano-silica particles increases stress transfer efficiency at the matrix interface. The substantial stress enhancement after the substitution of nano-silica can be due to improvement of the interfacial interaction in the nano-silica concrete mixes. Concrete mixes with nano-silica show more elastic behavior than the control counterparts, which may be attributed to lesser voids, and therefore denser microstructure could be obtained. The distinctive properties of nano-silica may be responsible for a clear improvement in the stress-strain characteristics. Nano-silica particles make crack initiation and propagation within the cement matrix more challenging. This crack arresting mechanism is likely to cause crack-tip deflection, which causes a drop in the brittleness of nano-silica specimens (Alomayri, 2019)

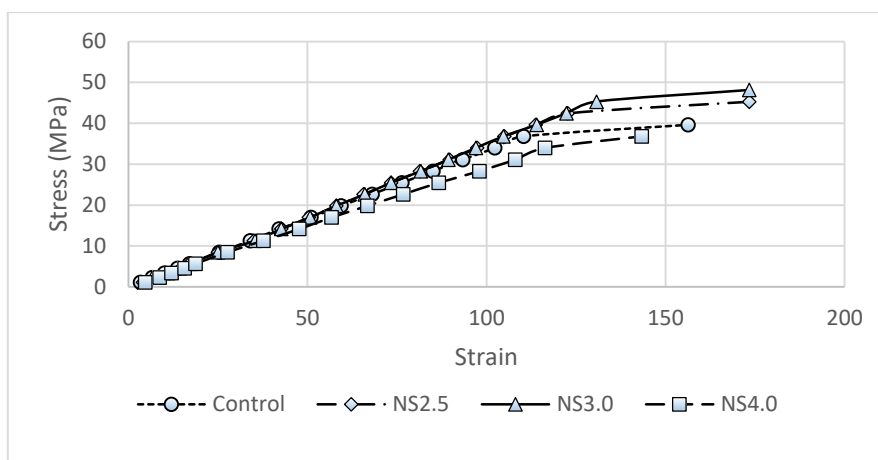


Fig. 8. Stress-strain curves of nano-silica concrete specimens.

3.6. Modulus of elasticity

Modulus of elasticity refers to a value for the resistance of a material to deformation on bending (Alomayri, 2019). The average elastic modulus results determined from three samples of each mix are presented in Table 3. It shows that with increasing concentration of nano-silica, the modulus of elasticity of concrete was increased compared to the control concrete. For instance, at 28 days and for the NS 0.5 till NS 3.0 mix, the modulus of elasticity was increased from 33.07 to 37.85 MPa; In other words, the elastic modulus increased by 2.73 and 14.45% for NS 0.5 and NS 3.0 when compared to the control specimen. As per Fig. 9, the elastic modulus of concrete is generally found to be greater for a higher concentration of nano-silica (3.0%). The mechanism of improvement in elastic modulus is similar to the strength improvement mechanism described earlier. The nano-silica particles react with $\text{Ca}(\text{OH})_2$ resulting in matrix densification, thus improving the microstructure. Therefore, under flexural testing, a steeper stress-strain slope was obtained for NS 3.0 composites (Fig. 8) due to the lesser deformation of the denser matrix.

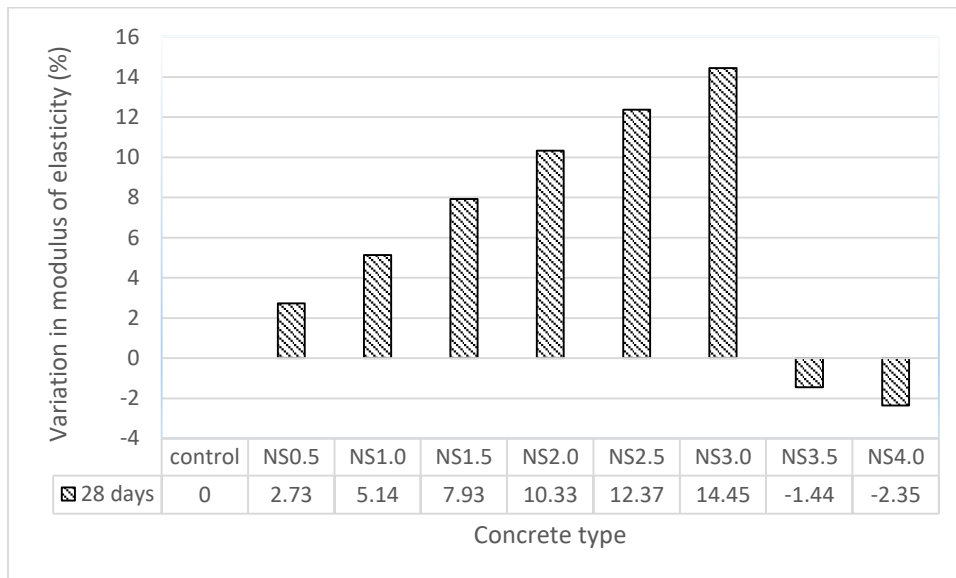


Fig. 9. Variations of modulus of elasticity test results.

3.7. Toughness

The toughness is calculated using MATLAB by simply integrating the area enclosed by the stress-strain diagram. In general, the toughness shows the same tendency: a beneficial effect upto 3% nano-silica content and an adverse effect at higher contents, as presented in Fig. 10. The maximum improvement was shown by the 3% nano-silica specimens with a substantial increase of 67% when compared to the control specimens. Beyond 3% nano-silica concentration, a significant decrease in toughness values, lesser than the control ones, was observed.

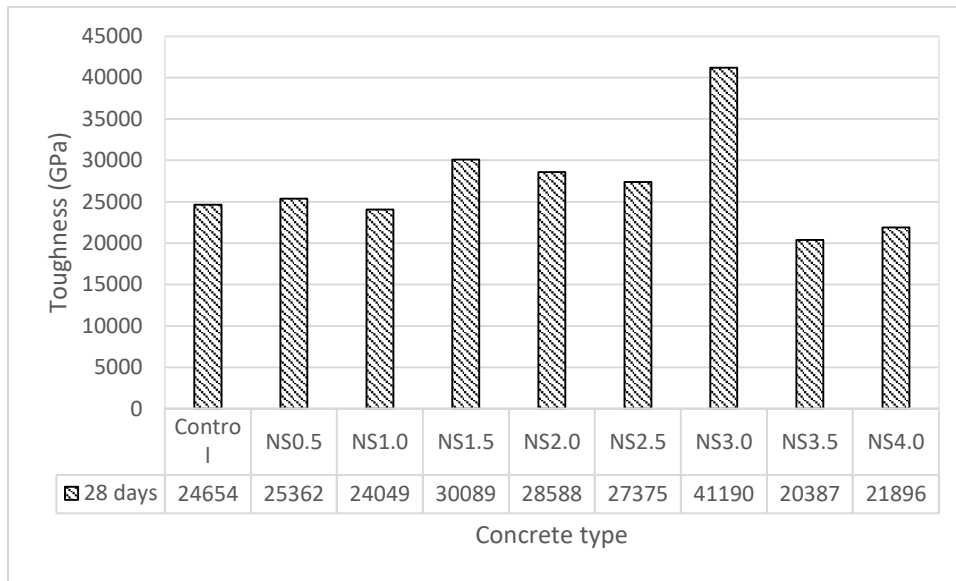


Fig. 10. The results of the toughness of nano-silica concrete.

Deviation in the outcomes of a few mixes was observed even though each mix was prepared using the design mix proportions. Uniform dispersion of nano-silica particles by sonication technique did not assure its uniform distribution within the cementitious matrix; causing stress-strain variations in the flexural specimens non-uniform, leading to variable toughness of the samples.

3.8. Ultrasonic pulse test

The ultrasonic pulse velocity (UPV) test was performed as per the provisions of IS 13311 (Part 1), 1992. This test gives the strength and quality of concrete by measuring the velocity of an ultrasonic pulse to travel through a specimen of a specified dimension. The density and elastic properties of concrete essentially affect the UPV variations. Emitting and receiving transducers are placed on opposite sides of the specimen, and the UPV is determined by using the following relation (Zareei *et al.* 2018).

$$\text{Pulse velocity} = \frac{\text{width of the specimen}}{\text{Travel time by pulse to pass through the sample}}$$

The principle used for deciding good quality concrete in terms of density, homogeneity, and uniformity is based on obtaining higher ultrasonic velocities by an ultrasonic concrete tester (Devi and Khan, 2020). The UPV results revealed that the addition of nano-silica caused an improvement in the pulse velocity, as shown in Fig. 11. Ultrasonic pulse velocity passing through a solid material significantly influenced by the density and elastic properties of the material (Panzera *et al.*, 2008). Higher the UPV is estimated (more than 4.5 km/s), the denser is the material. A velocity of less than 3 km/s shows doubtful/poor quality concrete. The results of the UPV are shown in Fig. 11.

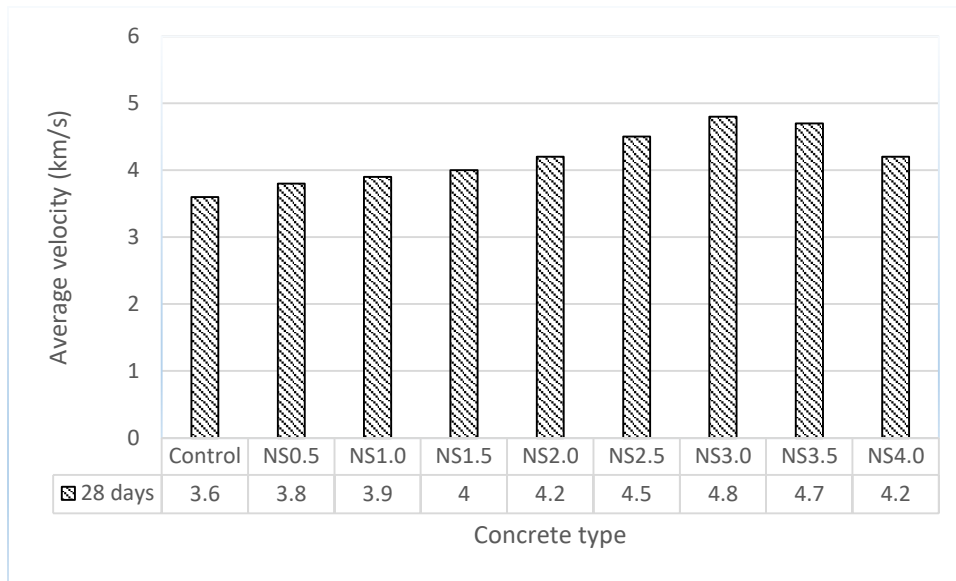


Fig. 11. The UPV test results of nano-silica concrete at 28 days.

3.9. SEM micrographs

Fig. 12 (a-d) show the microstructure of concrete with and without nano-silica. It was observed that in micrograph for control specimen (Fig. 12(a)) C-S-H gel found in the form of 'stand-alone' clusters, lapped and connected together by several needle hydrates. Further, deposited $\text{Ca}(\text{OH})_2$ crystals were spread among the cementitious matrix, and little connection was observed between the hydration products.

The Figs. 12 (b-d) show the SEM micrographs of mixes NS 1.0, NS 2.0, and NS 3.0, which are of higher strength than control counterparts. In the SEM images of these mixes, the texture of hydrated products was observed to be more uniform and compact. Large size crystals of $\text{Ca}(\text{OH})_2$ were not seen. Although the pattern of the cementitious matrix in these three mixes showed few differences, their microstructures were generally dense and compact. In principle, such microstructures were consistent with the corresponding improvement in strengths, as listed in Table 4.

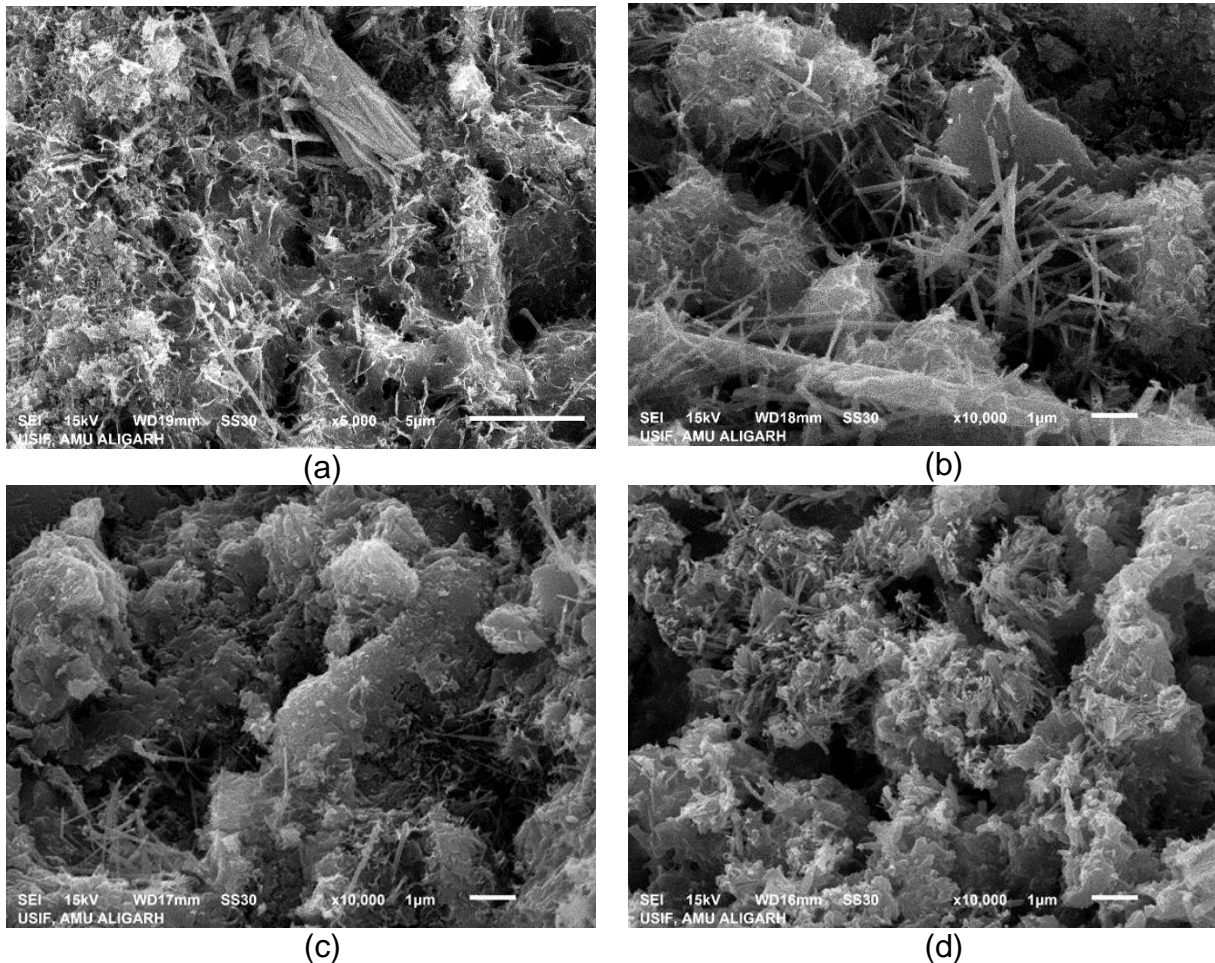


Fig. 12 SEM micrographs (a) 0% (b) 1% (c) 2% and (d) 3% nano silica specimens at different magnifications

The mechanism of strength enhancement with nano-silica particles due to improvement in the microstructure of the resulting concrete can be illustrated as follows. When a small quantity of nano-silica was uniformly dispersed in the matrix, the hydrated products will surround the nano-silica particles due to their enormous surface energy and grow to form conglomeration containing the nano-silica particles as 'nucleus.' The nano-silica particles placed as a nucleus will further support and accelerate hydration reaction due to their high activity. While considering uniform dispersion of nano-silica particles, a better microstructure could be obtained with uniformly distributed conglomeration. The binding force between centropiasm (fine and coarse aggregates) and transmitter (cementitious gel) has a significant effect on the strength of concrete as reported by (Li *et al.*, 2004). Numerous nano-silica particles distributing in the matrix as 'sub-centropiasm' can strongly bond with the hydrated products around the interfacial transition zone (ITZ) between the nanoparticle and hydration products. Alternatively, the nano-silica particles among the hydration products will eventually inhibit the crystals from growing, like $\text{Ca}(\text{OH})_2$ and calcium sulphoaluminate hydrate (AFm), and such fine crystals are mainly responsible for the

strength of concrete (Li *et al.*, 2004). However, when the nano-silica particles are not uniformly dispersed, due to excessive nano-silica content, the aggregating nano-silica particles will create weak zones in the form of voids and pores. Accordingly, the homogeneous microstructure could not be formed, and lesser strength will be predicted.

4. CONCLUSIONS

The paper investigated the effects of partial replacement of cement with nano-silica on the mechanical properties of high strength concrete. A comprehensive experimental programme was carried out wherein mechanical properties, as well as stress-strain characteristics of concrete containing various amounts of nano-silica, were examined. Mechanical tests, including compressive strength, split tensile strength, flexural strength, and ultrasonic pulse velocity test, were conducted. Based on the experimental findings, the following conclusions were drawn:

1. In general, replacement of cement with nano-silica improved the mechanical properties of high strength concrete upto a certain level of substitution.

2. The compressive and flexural strength results showed that upto 3% nano-silica concentration, the respective properties were improved by 7.34% and 44%, respectively.

3. The replacement of 3% nano-silica with cement in high strength concrete led to an increase in the split tensile strength by 28%.

4. Stress-strain results showed that the composite material behaves linearly right upto the collapse load. In specimens with NS0.5 and NS3.0 mix after 28 days, the elastic modulus increased by 2.73% and 14.45%, respectively.

5. Ultrasonic pulse velocity results indicated that all samples were of good to excellent quality with velocities above 4 km/s were reported consistently.

6. An increase in mechanical properties upto 3% nano-silica is possibly due to the filler effect of nano-silica particles in densifying the concrete microstructure. Further increase in nano-silica content showed degradation, and accordingly, the optimum content of nano-silica replacement with cement was determined as 3% for high strength concrete.

7. The SEM observation revealed that the nano-silica particles were not only acting as filler but also as an activator to promote hydration and to improve the microstructure of the cementitious matrix, provided they were uniformly dispersed.

5. REFERENCES

- Alomayri, T. (2019), "Experimental study of the microstructural and mechanical properties of geopolymer paste with nano material (Al_2O_3)."
Journal of Building Engineering, Vol. **25**, 100788.
- Barbhuiya, G. H., Moiz, M. A., Hasan, S. D. and Zaheer, M. M. (2020), "Effects of the nanosilica addition on cement concrete: A review."
Materials Today: Proceedings of the 3rd International Conference on Innovative Technologies for Clean and Sustainable Development, Chandigarh, India.

*The 2020 World Congress on
The 2020 Structures Congress (Structures20)
25-28, August, 2020, GECE, Seoul, Korea*

- BIS:516-1959 (1959), "Indian Standard Methods of Tests for Strength of Concrete." Bureau of Indian Standards, New Delhi, India.
- BIS:5816 (1999), "Indian Standard Splitting tensile strength of concrete- method of test." *Bureau of Indian Standards, New Delhi*, 5816, 1–14.
- Devi, S. C. and Khan, R. A. (2020), "Effect of graphene oxide on mechanical and durability performance of concrete." *Journal of Building Engineering*. Vol. **27**, 101007.
- Du, H., Du, S. and Liu, X. (2014), "Durability performances of concrete with nano-silica." *Construction and Building Materials*, Vol. **73**, 705–712.
- Han, B. *et al.* (2017), "Nano-core effect in nano-engineered cementitious composites." *Composites Part A: Applied Science and Manufacturing*, Vol. **95**, 100–109.
- Hassan, A. A. A., Abouhussien, A. A. and Mayo, J. (2014), "The use of silica-breccia as a supplementary cementing material in mortar and concrete." *Construction and Building Materials*. Vol. **51**, 321–328.
- Huntzinger, D. N. and Eatmon, T. D. (2009), "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies." *Journal of Cleaner Production*. Vol. **17**(7), 668–675.
- IS 13311 (Part 1) (1992), "Method of Non-destructive testing of concret, Part 1: Ultrasonic pulse velocity." *Bureau of Indian Satandards*, 1–7.
- Janković, K. *et al.* (2016), "The influence of nano-silica and barite aggregate on properties of ultra high performance concrete." *Construction and Building Mat.*, Vol. **126**, 147–156.
- Katare, V. D. and Madurwar, M. V. (2017), "Experimental characterization of sugarcane biomass ash – A review." *Construction and Building Materials*, Vol. **152**, 1–15.
- Kong, D. *et al.* (2012), "Influence of nano-silica agglomeration on microstructure and properties of the hardened cement-based materials." *Construction and Building Materials*, Vol. **37**, 707–715.
- Li, H., Xiou, H., Yuan, J. and Ou, J. (2004), "Microstructure of cement mortar with nano-particles." *Composites Part B: Engineering*, Vol. **35**(2), 185–189.
- Mahdikhani, M., Bamshad, O. and Fallah Shirvani, M. (2018), "Mechanical properties and durability of concrete specimens containing nano silica in sulfuric acid rain condition." *Construction and Building Materials*, Vol. **167**, 929–935.
- Mukharjee, B. B. and Barai, S. V. (2019), "Performance assessment of nano-Silica incorporated recycled aggregate concrete." *Advances in Concrete Construction*, Vol. **8**(4), 321–333.
- Mukharjee, B. B. and Barai, S. V (2015), "Characteristics of sustainable concrete incorporating recycled coarse aggregates and colloidal nano-silica." *Advances in concrete construction*, Vol. **3**(3), 187–202.
- Nazerigivi, A. *et al.* (2017), "Influence of nano-silica on the failure mechanism of concrete specimens." *Computers and Concrete*, Vol. **19**(4), 429–434.
- Oltulu, M. and Şahin, R. (2014), "Pore structure analysis of hardened cement mortars containing silica fume and different nano-powders." *Construction and Building Materials*, Vol. **53**, 658–664.
- Panzer, T. H. *et al.* (2008), "Correlation between structure and pulse velocity of cementitious composites." *Advances in Cement Research*, Vol. **20**(3), 101–108.
- Rad, S. S. (2018), "Technical and economical assessment of applying silica nanoparticles for construction of concrete structures." *Computers and Concrete*, Vol.

*The 2020 World Congress on
The 2020 Structures Congress (Structures20)
25-28, August, 2020, GECE, Seoul, Korea*

22(1), 117–122.

Riahi, S. and Nazari, A. (2011), "Compressive strength and abrasion resistance of concrete containing SiO₂ and CuO nanoparticles in different curing media." *Science China Technological Sciences*, Vol. **54**(9), 2349–2357.

Said, A. M. *et al.* (2012), "Properties of concrete incorporating nano-silica." *Construction and Building Materials*, Vol. **36**, 838–844.

Shaikh, F. U. A., Supit, S. W. M. and Sarker, P. K. (2014), "A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes." *Materials and Design*, Vol. **60**, 433–442.

Shekari, A. H. and Razzaghi, M. S. (2011), "Influence of nano particles on durability and mechanical properties of high performance concrete." *Procedia Engineering*. Vol. **14**, 3036–3041.

Singh, L. P. *et al.* (2013), "Beneficial role of nanosilica in cement based materials - A review." *Construction and Building Materials*, Vol. **47**, 1069–1077.

Snehal, K., Das, B. B. and Akanksha, M. (2020), "Early age, hydration, mechanical and microstructure properties of nano-silica blended cementitious composites." *Construction and Building Materials*, Vol. **233**, 117212.

Standards, I. (1999), "Specification for Concrete Admixtures." *Bureau of Indian Standards, New Dehli*, 1–22.

Turner, L. K. and Collins, F. G. (2013), "Carbon dioxide equivalent (CO₂-e) emissions: A comparison between geopolymers and OPC cement concrete." *Construction and Building Materials*, Vol. **43**, 125–130.

Wang, X. F. *et al.* (2018), "Effect of nano-SiO₂ on strength, shrinkage and cracking sensitivity of lightweight aggregate concrete." *Construction and Building Materials*, Vol. **175**, 115–125.

Yeşilmen, S. *et al.* (2015), "Nano-modification to improve the ductility of cementitious composites", *Cement and Concrete Research*, Vol. **76**, 170–179.

Yu, R., Spiesz, P. and Brouwers, H. J. H. (2014), "Effect of nano-silica on the hydration and microstructure development of Ultra-High Performance Concrete (UHPC) with a low binder amount." *Construction and Building Materials*, Vol. **65**, 140–150.

Zaheer, M. M. (2019), "Experimental study of multi-walled carbon nano-tubes in cement mortar for structural use." *Jordan Journal of Civil Engineering*, Vol. **13**(4), 521–537.

Zaheer, M. M., Shamsuddin, M. and Sharma, R. (2019), "Effect of diameter of MWCNT reinforcements on the mechanical properties of cement composites." Vol. **8**(3), 207–215.

Zareei, S. A., Ameri, F. and Bahrami, N. (2018), "Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash." *Construction and Building Materials*, Vol. **184**, 258–268.

Zhang, M. H., Islam, J. and Peethamparan, S. (2012) 'Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag', *Cement and Concrete Composites*. Elsevier Ltd, 34(5), pp. 650–662.

Zhang, M. H. and Li, H. (2011) 'Pore structure and chloride permeability of concrete containing nano-particles for pavement', *Construction and Building Materials*. Elsevier Ltd, 25(2), pp. 608–616.