Nano-Silica and its Role on Performance of Cement Concrete- A Review of Experimental Investigation

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Abstract. The researchers are generally focusing on the basic technology of cementitious materials at the nano level. In addition, the researchers are mainly aimed at enhancing the durability and strength of concrete and have found rapidly developing the mechanical and microstructural properties of cementitious materials with the introduction of nano-silica. The present paper reviewed and summarized the experimental research works carried out on the use of nano-silica in cement concrete mix as an additive or replacement of cement and its effects on rheology of the fresh concrete, and properties of hardened concrete such as strength, and durability. Thus, nano-silica is a promising material which can be used to improve the properties of the cement concrete.

1. Introduction
Notwithstanding the fact that the cement concrete is most destructive material to the environment of the planet earth, it is still being globally used as a common construction material for variety of structures. Engineers fail to develop a suitable material out of wastes or otherwise to substitute the cement concrete. Unfortunately, instead of developing an alternative to cement concrete, engineers have been working to improve its performance by using pozzolanic materials. The use of nano materials such nano-SiO₂ in the cement concrete is being investigated for last one and a half decades. It plays a significant role as an activator and enhance pozzolanic activities in presence of water and unburnt calcium hydroxide to improve the strength and durability of concrete by consuming the calcium hydroxide, and producing additional C-S-H gel in cement paste [1, 2]. When nanoparticles with higher surface areas get wet, it reduces the free dispersant water available in the concrete mix. Thus, the utilization of nanoparticles in concrete mortar considerably modify their response in fresh and hardened conditions as well as develop its microstructure [3]. In this study, the efforts have been made to critically review the role of nano-silica on the fresh and hardened properties of concrete as well as the microstructural development of the concrete.

2. Characteristic of nano-silica
Nano-silica is a white soft and fluffy powder containing amorphous SiO₂. Because of nano order of its particle size, it has high surface absorption. Nano-silica plays a significant role as a pozzolanic activator because of its large surface area, higher chemical purity, appreciable dispersion being amorphous. It
classified as hydrophilic and hydrophobic nano-silica with varying particle size. The hydrophilic nano-silica is used in cement concrete owing to its good dispersion in the water [1].

3. Setting time
This paper experimented to study the effectiveness of NS on the response of cement mortar. Cement was replaced by nano-silica with 3% and 5% by weight. Nano-silica increased the compressive strength of cement mortar. The effect of nano- SiO$_2$ was found different for consistency and setting time. It made the cement paste thicker and accelerated the hydration of cement. It was reported that the effective water to binder ratio reduced the amount of water present in the mix [4]. The aim of this paper was to measure the influence of nano-silica on the hydration and strength improvement of cement paste. Cement was replaced by nano-silica with 1.5, 3, and 5% by weight. It was found that the NS induced the accelerated hydration of cement. The addition of NS reduced the slump considerably. Nano-silica played an important role as a pozzolanic reactant, but the pore solution remained highly alkaline even at 5% of nano-silica content [5].

4. Workability of concrete
The author studied the effect of nano-silica on mechanical property, drying shrinkage, and flowability of ultra-high-performance concrete. Cement was substituted by NS with 2.5% and 5% by weight. The addition of nano-silica enhanced the crushing strength and drying shrinkage. Whereas, the workability of fresh ultra-high-performance concrete reduced considerably [6]. This paper studied the influence of nano- SiO$_2$ on the workability of concrete. Cement was substituted by nano-silica with 0.8% and 3.8% by weight. It was found that the addition of nano-silica decreased the workability of concrete and ascribed to more surface area of NS as compared to cement [7]. The presence of nano- SiO$_2$ negatively affected the workability of concrete. Nano- SiO$_2$ was substituted in place of cement with 1, 2, and 3% by weight. It was concluded that the higher dosage of NS considerably reduced the slump of concrete [8]. This experimental study investigated the role of nano-SiO$_2$ on the fresh and rheological characteristics of glass fiber reinforced self-consolidating concrete with 2 and 4% of cement replacement by nano-silica. It was reported that 2% and 4% of nano-SiO$_2$ with the addition of glass fiber caused to decrease the workability. Torque resistance enhanced with increasing nano-silica content [9].

5. Shrinkage and creep of concrete
This paper investigated the effect of nano-silica and micro-silica on drying shrinkage and creep of concrete. In separate experiments cement was substituted with nano and micro-silica with 3% and 7.5% by weight. The concrete with the NS showed higher shrinkage and creep than control concrete and the concrete containing the micro-silica [10]. This research work investigated the strength and shrinkage of powder-based nano-silica concrete. Cement was substituted by nano-silica with 0.5, 0.75, and 1% by weight of cement. The addition of nano- SiO$_2$ enhanced the bending tensile strength but led to a higher rate of shrinkage [11]. The influence of nano- SiO$_2$ together with fly ash on fresh property and shrinkage of mortar was studied. Cement was substituted with nano-silica by 0.5%, and 3% and fly ash was substituted in place of cement by 5%, and 20% by weight. Addition of NS significantly reduced the slump of the mortar, but dry shrinkage improved [12]. This research work was conducted to study the role of nano- SiO$_2$ on volume and chemical shrinkage of cement composite. Cement was replaced by NS with 0.3, 0.6, 0.9, and 1.2% by weight. The chemical shrinkage increased with increasing NS content. By considering 1.2% of NS content, the chemical shrinkage after 3 days and 28 days was found to be increased by 93.7%, and 57.5% respectively as shown in Figure 1. The volume shrinkage also increased with increasing nano-silica content as shown in Figure 2 [13]. The researcher measured the influence of nano- SiO$_2$ on water permeability, abrasion resistance, and drying shrinkage. Nano-silica of particle size of 12, 20, and 40nm were utilized in this research work. Cement was replaced by nano-silica with 9% by weight. Nano-silica of size 40nm with 9% by weight imparted the highest resistance to abrasion and water permeability and minimum shrinkage. Nano- SiO$_2$ with particle size of 12nm and 20nm together with silica fume experienced higher shrinkage as compared to 40nm size, and control concrete [14]. This research work carried out to investigate the influence of nano-SiO$_2$ on drying
shrinkage of concrete. Cement was substituted by nano-silica with 0.5, 0.75, and 1% by weight. It was reported that the addition of NS enhanced the 28 days drying shrinkage rate by 75.5, 127.1, and 163% respectively [15].

**Figure 1.** Chemical shrinkage of cement paste [13]  
**Figure 2.** Volume shrinkage of cement paste [13]

This experimental research work explored the effect of partial replacement of cement by nano-silica and palm oil fuel ash (POFA) on drying shrinkage of cement mortar. Cement was substituted by NS with 1%, and POFA with 10% and 30% by weight. It was found that POFA with a 30% replacement level enhanced water permeability by 138%, 158%, and 200% at the age of 3, 7, and 28 days. The replacement of POFA with 30% decreased the shrinkage but considerably reduced the compressive strength [16].

### 6. Compressive strength of concrete

The researcher studied high-performance concrete utilizing industrial waste namely, electric arc furnace slag and cement kiln dust together with nano-silica. Nano-silica with 5% by weight of cement was added to the concrete. It was reported that nano-SiO$_2$ improved the compressive and flexural strength and also improved the early age strength of concrete [17]. This experimented the influence of nano-silica as a substitution of cement on the crushing strength of concrete with varying percentages of 0.33, 0.67, and 1% by weight of cement. It was concluded that the optimum crushing strength was imparted by 1% of nano-silica content [18]. This research work reported the effect of nano-SiO$_2$ on various strengths of concrete. Nano-silica with varying percentages of 0.5, 1, and 1.5% by weight of cement was replaced. The concrete with 1.5% replacement level of nano- SiO$_2$, and with water to cement ratio of 0.55, the compressive strength of concrete enhanced by 41% as compared to control concrete. The influence of nano- SiO$_2$ on higher strength concrete was less than on lower strength concrete [19]. This paper studied glass fiber reinforced self-consolidating concrete with nano-silica for fracture and permeability. Cement was substituted by nano-silica with varying percentages of 0, 2, and 4% by weight. It was reported that the nano-silica ranging from 0 to 4% with 0.7% of glass fiber enhanced the compressive strength and permeability of self-consolidated concrete. Nano-silica of 4% together with glass fiber of 0.7% improved the compressive strength by 34% after 90 days with respect to control concrete. Concrete with nano-silica improved fracture energy and was attributed to the efficiency of the nano- SiO$_2$. The inclusion of nano- SiO$_2$ together with glass fiber exhibited higher ultimate load and large area under the load-displacement curve as shown in Figure 3a-Figure 3c [20]. The researcher studied the influence of nano- SiO$_2$ on the fresh and hardened state of cement paste. Cement was replaced with 0, 0.8, and 3.8% by nano- SiO$_2$. The addition of nano-silica decreased the workability but not significant increase of compressive strength was reported [21].
This paper reported the influence of nano-SiO$_2$ on crushing strength and water absorption of concrete. Cement was replaced by nano-silica with 1.5, 3, 5, and 7.5% by weight. The nano-silica increased the early age compressive strength of concrete. Nano-silica of 7.5% by cement weight enhanced the crushing strength by 18% after 3 days, and 42% after 91 days. Minimum water absorption was given by the concrete with 5% nano-SiO$_2$ content [22]. In this work influence of dosage and particle size of nano-SiO$_2$ on the crushing strength of cement mortar was considered. Replacement of cement with 3, 6, 9, and 12% of nano-silica by weight was considered in this work. Nano-silica with particle size of 12nm, 20nm, and 40nm was utilized. It was reported that the nano-SiO$_2$ of size 40nm imparted higher compressive strength to concrete than other particle sizes. The optimum replacement ratio was found as 9% by cement weight for all particle sizes of nano-silica [23]. This research work incorporated nano-silica together with recycled aggregate in concrete. Cement was substituted by nano-SiO$_2$ with 1% and 2% by weight. Natural coarse aggregate was substituted with 25% and 50% of RCA by weight. Crushing and splitting tensile strength were found after 7, 28, and 56 days. Nano-silica together with RCA improved the compressive strength after 56 days. The addition of nano-SiO$_2$ with RCA in concrete caused more reduction of the sorptivity at 28 days than 7 days [24]. The author of this paper reported the effect of nano-SiO$_2$ on the mechanical property of concrete. Cement was substituted by nano-SiO$_2$ with 1%, 3%, and 5% by weight. By incorporating 3% nano-SiO$_2$ and 10% polyethylene...
terephthalate waste by weight significantly increased the tensile, compressive, and flexural strength by 27, 30, and 9%, respectively [25]. In this study tests were conducted to investigate long-term effect on concrete with nano-silica as a partial replacement of cement with a fixed ratio of 5% by weight. The mechanical property of concrete was tested for crushing and splitting tensile strength after 28, 56, and 91 days. It was concluded that the nano- SiO$_2$ in concrete enhanced its compressive and splitting tensile strength considerably [26]. Authors investigated the influence of nano- SiO$_2$ on the fresh and hardened state of cement mortar by replacing cement with nano- SiO$_2$ by 1, 2, 3, 4, 5, and 6% by weight in this work. NS of size 0.2 to 0.3 microns was used. It was reported that the nano- SiO$_2$ of 5% by weight increased the strength of concrete. The workability of concrete reduced with the addition dosage of nano-silica content [27]. The aim of this research work was to scale the influence of nano-silica on the performance of cement concrete. Cement was substituted by nano-silica with 1, 2, 3, and 3.5% by weight. Cube and cylinder specimens were tested after 7, 14, and 28 days for compressive and splitting tensile strength. It was reported that the nano- SiO$_2$ with 3% by weight imparted higher strength to the concrete. Permeability of concrete decreased with increasing nano-silica content [28]. This work was done to measure the comparison of micro and nano- SiO$_2$ on the strength of concrete. Cement was substituted by micro silica with 5, 7.5, 10, and 15%. Whereas, nano-silica was substituted with 1, 1.5, 2, 2.5% by weight. Micro-silica of 7.5% together with nano-silica of 2% improved the compressive, splitting tensile, and flexural strength of M40 and M50 grade of concrete [29]. This paper reported the influence of NS and steel fiber on the mechanical performance of self-compacting concrete. Cement was substituted by nano- SiO$_2$ with 1, 2, 3, 4, 5, and 6% by weight. Cement replaced with 4% of nano-silica significantly enhanced the crushing, splitting tensile, and flexural strength of concrete. The addition of NS beyond 4% severely affected the workability of the concrete and made the NS particles stick to each other and formed balls like lumps called balling effect [30]. This paper studied the influence of nano- SiO$_2$ by replacing cement with 1%, and 2% by weight on the mechanical property of concrete. Also, the cement was substituted by fly ash with 30, 50, and 75% by weight. Nano-silica together with fly ash significantly improved the mechanical properties of concrete [31]. This paper presented the results of experiments conducted to explore the influence of nano-silica on the crushing strength of basalt cement pastes replacing it partially by nano-silica with 1, 2, 3, and 4% by weight. Cement was also replaced by basalt powder with 5, 10, 15, and 20% by weight. It was concluded that the replacement of OPC by basalt powder caused to decline crushing strength. The substitution of cement by basalt powder together with nano-silica by 3% increased the compressive strength at the age of 3 and 90 days by 31% and 18%, respectively [32]. This paper studied GGBS based self-consolidating geopolymer concrete utilizing nano-silica as replacement with 2% by weight of cement. Nano-silica with 2% by weight together with 16M concentration of alkaline solution imparted the highest compressive and tensile strength to the concrete after 90 days [33].

7. Splitting tensile strength

This research work scaled the influence of nano- SiO$_2$ on splitting tensile strength of concrete. Cement was replaced by NS with 1% and 2% by weight. It was found that the maximum splitting tensile strength of concrete enhanced by 17% after 28 days with 1% of nano-silica content [34]. This paper reported the influence of nano-silica on split tensile strength of concrete. Cement was substituted by nano-silica with 0.3, 0.6, 1, 2, 2.5, and 3% by weight. It was reported that splitting tensile strength increased by 29.82% with 2.5% of nano-silica content as compared to control concrete after 28 days [35]. The researcher experimentally studied the role NS and nano clay metakaolin on splitting tensile strength of cement mortar. Cement was substituted by nano- SiO$_2$ and nano clay metakaolin with 0.5, 1, 1.5, and 2% by weight. It was concluded that 1.5% of NS content, and 2% of NMK content imparted higher splitting tensile strength as compared to other mixes for 7, 28, 56, and 90 days [36]. This paper studied the influence of nano-SiO$_2$ on splitting tensile strength of RCA. Cement was replaced by 0.4, 0.8, and 1.2% by weight. Coarse aggregate was substituted by recycled coarse aggregate (RCA) with 50% and 100% by weight. It was reported that the additional quantities of nano-SiO$_2$ to RAC with 50% RCA and RAC with 100% RCA made to develop the splitting tensile strength of RACs equal to splitting tensile strength of control concrete with lower quantity of nano-SiO$_2$ [37]. This paper reported
the influence of nano-SiO$_2$ on the bond failure mechanism of concrete with steel reinforcement replacing cement partially by nano-silica with 1.5, 3, and 4.5% by weight. The Pull-out test was carried out on the cube specimens of size 150mm to study the bonding behaviour of concrete with nano-SiO$_2$. It was concluded that the addition of nano-silica enhanced the bond strength against pull-out and splitting due to improved mechanical behaviour of the concrete [38].

8. Flexural strength
This paper reported the influence of nano-silica on the flexural strength of concrete. Cement was substituted by nano-silica with 0.5, 0.75, 1, 1.25, and 1.5% by weight. It was inferred that the concrete with 0.75% of nano-silica content gave maximum flexural strength after 28 days [39]. This research work was conducted to investigate the influence of nano-SiO$_2$ on the flexural strength of concrete. Two types of NS namely type I (purity 89%) and type II (purity 99%) were utilized. Cement was replaced by both types of nano-SiO$_2$ with 1.5% and 3% by weight. It was deduced that 1.5% of nano-silica content increased the flexural strength by 14.81% for type I and 41.33% for type II [40]. This paper studied the role of NS on mechanical property of high-performance concrete, and the flexural response of beam made of this concrete. Cement was replaced by nano-SiO$_2$ with 1, 2, and 3% by weight. It was found that the ultimate load was maximum at 3% of nano-silica. Also, the mechanical properties of concrete enhanced containing 3% of nano-silica [41]. This paper reported the effect of nano-SiO$_2$ with the high dosage of fly ash on the mechanical properties of concrete. Cement by weight was substituted by nano-silica and fly ash with 4% and 50% respectively. It was found that the combination of nano-silica together with fly ash enhanced the short and long-term strength of concrete [42].

9. Durability of concrete
This paper investigated the effect of micro-SiO$_2$ and nano-SiO$_2$ on self-compacting concrete in acid environment. Cement was substituted by nano-SiO$_2$ with 0.3, 1, 2%, and micro-silica with 5, 6.7, 7, and 9% by weight. Little improvement of compressive strength of concrete with nano-SiO$_2$ and significant improvement of the strength by micro-silica was observed. However, a combination of micro and nano-silica improved the strength as well as resistance against sulfuric acid attack [43]. This research work studied the effect of nano-SiO$_2$ and heavyweight fine aggregate on cement mortar subjected to elevated temperature. Cement was substituted by nano-SiO$_2$ with 1, 2, 3, 4, and 5% by weight. The samples were exposed to an elevated temperature of 200, 400, 600, and 800°C. Nano-SiO$_2$ with 3% by weight significantly enhanced the thermal resistance and resistance against crack propagation of cement mortar in elevated temperature range of 200-400°C [44]. This experimental study reported the effect of nano-SiO$_2$ on mechanical properties and sorptivity of lightweight concrete replacing cement by nano-SiO$_2$ with 1, 2, 4, and 8% by weight. The addition of nano-SiO$_2$ effectively enhanced the flexural and crushing strength after 28 days. By the inclusion of nano-SiO$_2$, a more compact and refinement of air void structure of lightweight aggregate concrete was obtained [45]. This paper presented the experimental study conducted to find out the effect of nano-SiO$_2$ in concrete under sulfate attack. Cement was substituted by nano-silica with 2, 4, 6, and 8% by weight. The addition of nano-silica improved the early age strength of concrete. Not the compressive strength but sulfate attack resistance of the concrete was found significantly increased by 8% nano-SiO$_2$ as compared to the concrete that contains 6% nano-SiO$_2$ by weight [46]. In this research work cement was substituted by nano-SiO$_2$ with 2% by weight in concrete to study the durability and strength of concrete. The compressive and splitting tensile strength increased by 21.73% and 13.64% as compared to concrete without nano-SiO$_2$. The flexural strength improved by 27.37% as compared to control concrete. The concrete with nano-SiO$_2$ also enhanced the concrete resistance to alkali and sulfate attack considerably [47]. This paper studied the influence of metakaolin together with nano-SiO$_2$ on the mechanical properties of concrete. Cement was replaced by metakaolin with 5% and 10% by weight. Also, the nano-silica was substituted by 1% and 2% by weight of cement. Metakaolin; 10% and nano-SiO$_2$; 1% significantly contributed to enhance the strength of concrete [48]. In this research work the role of nano-SiO$_2$ on the mechanical properties, durability, and flowability of concrete was explored. Cement was replaced by nano-silica with 1, 2, 3, and 4% by weight. Compressive strength, splitting tensile and flexural strength were found.
after 28 days. The water adsorption test was also accomplished. Nano-silica of 3% by weight significantly improved the mechanical properties of concrete. It was concluded that the nano-silica increased the resistance to water absorption, however, decreased the flowability of concrete [49]. This paper studied the combined effect of cement replacement with fly ash, and alcofine, by 25, 10% along with CNS by 0.25, 1, 2, and 3% respectively with 0.43 w/c on the mechanical property of concrete. Colloidal nano-silica with 1% by weight improved the mechanical and water adsorption properties of concrete as compared to all other mixes [50]. This paper studied the influence of nano- SiO$_2$ on mechanical property, durability, and microstructure of lightweight concrete. Cement was substituted by nano-silica with 1, 2, 3, and 4% by weight. It was found that the replacement level of nano-silica beyond 1% considerably increase the 28 days compressive and flexural strength. Substituted nano-silica led to a more compacted and refined air-void structure of lightweight concrete [51]. This paper reported the performance of NS on self-consolidated glass mortar (SCGM) at a temperature of 200, 400, 600, and 800℃. Natural fine aggregate was substituted by glass powder with 10, 20, 30, 40, and 50% by weight. Cement was substituted by nano-silica with 3% by weight. By utilizing glass powder only, a significant decrease in compressive and flexural strength was observed. By incorporating 3% nano-silica this decrease of strengths was almost recovered. Also, it was reported that glass powder replacement greatly contributed to thermal response of the concrete [52].

10. Microstructural analysis of concrete

![Figure 4. Image from back scattered electron microscopy (BSEM) [53]](image)

![Figure 5. Image from back scattered electron microscopy (BSEM) [53]](image)

The authors investigated the effect of nano-SiO$_2$ on the performance of cement concrete by replacing its cement with 3% and 6% of nano-SiO$_2$ by weight. Fly ash of Class F was also in place of cement with 30% by weight. The incorporation of nano-silica together with class F fly ash by 6% and 30%
considerably improved the strength of concrete after 28 days. Back scattered scanning electron microscopy (BSEM) analysis exhibited densification in the interfacial transition zone (ITZ) in concrete with nano-SiO$_2$. More hydration has been reported in the concrete with class F fly ash and nano-SiO$_2$ at 28 days relative to the control mix containing only fly ash and recommended the additional dose of nano-SiO$_2$ to minimize the delay in microstructure development and durability improvement of the concrete as shown in Figure 4 and Figure 5 [53].

**Figure 6.** XRD pattern of selected mortar [54]  
**Figure 7.** XRD pattern of selected mortar [54]  
**Figure 8.** SEM image of control mix and nano-silica with cellulose fibers [55]

This paper studied the influence of nano-silica on the performance of polymer cement concrete. Cement was substituted by nano-silica with 1, 3, and 5% by weight. The addition of nano-SiO$_2$ catalysed the pozzolanic reaction thereby increasing the quantity of C-S-H gel, and caused to enhance the mechanical properties of the polymers and the same was confirmed by XRD analysis. The addition of NS decreased the peak of CH thereby revealing pozzolanic reaction required by CH to produce more C-S-H shown in Figure 6 and Figure 7 [54].
This paper reported the performance of cement composite reinforced with nano cellulose fiber and nano-silica. Cement was replaced by NS with 1, 1.5, 2% by weight. Nano cellulose fibers were added with varying percentage of 0.35, 0.55, and 0.75% by weight. Nano-silica considerably enhanced the crushing, and splitting tensile by 39% and 49% as compared to the control specimen. Higher reinforcement efficiency by modified transition zone between fiber and cementitious matrix under external normal forces had been noticed by SEM analysis. The SEM image are shown in Figure 8 and 9 [55].

This paper investigated the effect of NS as cement replacement on mechanical properties and microstructure of high-performance concrete (HPC) with 1, 2, 3, and 4% by weight. The addition of nano-SiO$_2$ improved the mechanical properties of concrete by reducing the number of pores thereby making the concrete denser at microstructure level [56].

11. Conclusions
In the present work, the influence and role of nano-SiO$_2$ on the fresh and hardened state of concrete was critically reviewed. Based on the previous experimental investigation, the following conclusion can be drawn:

- Utilization of nano-SiO$_2$ by partial replacement of cement, significantly increase the hydration of the cement matrix and influences the setting times of concrete.
- being a nanomaterial, it absorbs more water and affects the workability of concrete.
- Nano-silica plays a major role in the cement matrix, first, it improves the hydration of cement and react with calcium hydroxide (CH) to produce additional calcium silicate hydrate (C-S-H) gel and packs the pores available in cement paste thereby making the concrete more sound durable.
- NS of medium size that is of 40nm exhibits better pozzolanic activity, high and uniform dispersion of its particles, and packing capability (filling effect), also make the more compact, that gives the higher compressive strength to the concrete as compare to NS with the smaller particle size of 12 and 20nm which shows poor distribution and agglomeration of the particles.
- The NS in cement concrete plays a vital role in remarkably decrease the porosity of the cement matrix as confirmed by SEM analysis.

In addition to the aforesaid conclusions drawn from previous research work, authors are of the opinion that on the one hand nano-silica can be used to obtain very high strength/performance concrete and on the other hand nano-silica can be used to consume all kind of in disposable wastes menace to the society to develop alternative construction materials. The effect of steam curing at atmospheric pressure and autoclaving on concrete with nano-silica to be used for different applications need to be explored.
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