International Journal of Concrete Technology
Vol. 1: Issue 1
www.journalspub.com

A Review on the Use of Nano-Silica in Cementitious Compositions

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Abstract
With the advent of nanotechnology, the material properties of the concrete industry, allows engineers and architects to use various materials in structural applications that were once impossible. Nowadays, the researchers are mainly focusing on the basic technology of cementitious material at nano/atomic level. The researchers are continuing to improve the durability and sustainability of concrete and have realised significant enhancement in mechanical properties of nano-silica incorporated cementitious materials. This review paper summarizes the effect of nano-silica addition on mechanical, durability and microstructure characteristics of cementitious compositions. It provides the current development of application of nano-silica in paste, mortar and concrete. Finally, the future potential and implication of nano-silica in cement based materials is discussed.

Keywords*: Nano-silica, mortar, mechanical properties, microstructure, concrete*

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INTRODUCTION

Nanotechnology is rapidly becoming the Industrial Revolution of 21st century. It will affect almost every aspect of one's life. In comparison to other technologies, at present nanotechnology is much less well-defined and well-structured. Nanotechnology is the engineering at nano-scale to produce materials with unique properties that cannot be achieved using traditional materials. The importance of the cementitious materials in the construction industry is now-a-days at its best. They are indeed composite materials with truly multi-scale internal structures that keep evolving over centuries. More specifically, the cement paste matrix is basically a porous material composed of calcium hydroxide (portlandite), aluminates and un-hydrated cement (clinker) embedded into an amorphous nano-structured hydration product, the so called C-S-H (calcium silicate hydrate) gel[1]. This gel is the most important hydration product of the cement paste, not only because it is the most abundant component (50–70% by volume), but also because of its exceptionally good mechanical properties.

Nanoparticles have a high surface area to volume ratio. In this way, nanoparticles with 4 nm diameter have more than 50% of its atoms at the surface and are thus very reactive[2]. The behaviour of such materials is mainly influenced by chemical reactions at the interface, and by the fact that they easily form agglomerates. When higher surface area is to be wet, it decreases free dispersant (water in aqueous systems) available in the mixture. Therefore, the use of nanoparticles in mortars and concretes significantly modify their behaviour not only in the fresh but also in the hardened conditions, as well as the physical / mechanical and microstructure development[3].

In recent years, the use of nano-particles has received particular attention in many fields of applications to fabricate materials with new functionalities. When ultra-fine particles are incorporated into Portland-cement paste, mortar or concrete, materials with different characteristics from conventional materials were obtained[4–6]. The performance of these cementitious based materials is strongly dependent on nano-sized solid particles, such as particles of calcium-silicate-hydrates (C-S-H), or nano-sized porosity at the interfacial transition zone between cement and aggregate particles. Typical properties affected by nano-sized particles or voids are strength, durability, shrinkage and steel-bond[7]. Nano-particles of SiO_2 (nano-silica) can fill the spaces between particles of gel of C-S-H, acting as a nano-filler. Furthermore, by the pozzolanic reaction with calcium hydroxide, the amount of C-S-H increases, resulting in higher densification of the matrix, thus improving the strength and durability of the material[8–10]. Previous researches[5, 11, 12] indicate that the inclusion of nano-particles modifies fresh and hardened state properties, even when compared with conventional mineral additions. Colloidal particles of amorphous silica appear to considerably impact the process of C_3S hydration[11]. Nano-silica decreased the setting time of mortar when compared with silica fume (SF)[12] and reduced bleeding water and segregation, while improved the cohesiveness of the mixtures in the fresh state[13]. Nano-silica added cement paste showed reduction in setting time[14–16], shortened duration of dormant and induction period of hydration, shortening of time to reach peak heat of hydration and increased production of calcium hydroxide at early ages[3, 17]. When combined with ultra-fine fly ash it assured better performance than that achieved by the use of silica fume alone[4, 5, 18]. Besides, the compressive strength of mortar or concrete with silica fume was improved when compared with formulations without addition[4, 19, 20, 45]. Nano-silica addition increased the quantity of C-S-H and C-A-H in the paste[21]. Addition of nano-silica into cement paste and mortar demand more water to retain its workability[22]. To avoid adverse effects on workability Berra *et al*.[23] suggested delayed addition of water stating that instead of adding all the mixing water at a time, certain amount of water should added later on. Nano-silica samples showed lesser strength loss after exposed to elevated temperatures[24]. Mortar containing high volume fly ash showed higher residual strength after exposed to 700ºC and dehydration of C-S-H produced calcium silicate which acts as new binding material to retain residual strength[25]. The addition of nano-silica modified the porosity of the cement paste and increased the average chain length of silicate chains[1, 26].

In particular, the developments in nano-science have had a great impact on concrete industry. Nano-materials have been used in concrete industry over the past decade. Few studies to date with nanoparticles have been with Nano-silica (nano-SiO_2) and Nano-titanium oxide (nano-TiO_2), Nano-iron (nano-Fe_2O_3), Nano-alumina (nano-Al_2O_3)[27, 28].

Additionally, a limited number of investigations are dealing with the manufacture of nano sized cement particles and the development of nano binders. Thus limiting the review of literature work to use of nano-silica in cementitious compositions, research has shown that incorporation of nanoparticles in cement matrix could improve durability and mechanical properties of cement based materials. Nano silica (NS) in particular has found wide usage in this field because of its high reactivity and very large specific surface area, which results in a high degree of pozzolanic activity. Nano silica further accelerates the dissolution of C_3S and formation of C-S-H with its activity being inversely proportional to the size, and also provides nucleation sites for C-S-H[29]. Even small additions (0.6 wt. % binder) of NS are very efficient as compare to much larger amounts of silica fume in terms of improvement in mechanical properties of cement based materials. This is especially pronounced at early ages and for concretes with regular strength grade[30]. From the nano indentation studies, it was observed that the nano-silica addition significantly alters the proportions of low stiffness and high stiffness C-S-H. By the pozzolanic reaction with calcium hydroxide, the amount of C-S-H increases, resulting in higher densification of the matrix, thus improving the strength and durability of the material. Nano-indentation results revealed that colloidal nano-silica modifies the gel structure to increase the high-stiffness C-S-H gel content. Nanoparticles increase the average chain length of C-S-H gel and thereby increasing the amount or the strength of the high stiffness C-S-H as the value of the compressive strength changes modifying the relative proportions of C-S-H phases promoting the formation of high stiffness phase over the low stiffness phase. Therefore, addition of nanosilica has a positive impact on durability[8, 31].

NANO MATERIAL AND CEMENTITIOUS COMPOSITIONS

In construction industry, extensive research is going on to improve the performance of various building materials and development of durable and sustainable concrete is one among them. With particular relevance to construction and the built environment, several nano-particulate materials (e.g. TiO_2, SiO_2, $CaCO_3$ and Silicate clay) have been widely used as fillers/additives in coatings/paints, adhesives, sealants and composites. Several semiconductors materials, such as TiO_2, ZnO, Fe_2O_3, WO_3 and CdSe, possess photocatalytic capacity. However, TiO_2 is the most used of all because of its low toxicity and stability. For example, nano clay and nanotubes/fibres are increasingly used as reinforcement in high performance composites. Dispersion/ slurry of amorphous nanosilica particles has also been produced as cement/concrete admixtures, which can be used to improve segregation resistance for fresh slurry and self-compacting concrete, or to enhance strength/durability performance of hardened concrete. Research has also demonstrated that bimetallic nanoparticles, such as Fe/Pd, Fe/Ag, or Zn/Pd, can serve as potent reductants and catalysts for a large variety of common environmental contaminants.

Among all the nano materials, nano-silica is the most widely used material in the cement and concrete to improve the performance, because of its pozzolanic reactivity besides the void filling effect.

PASTE AND MORTAR WITH NANO-SILICA

Various researchers have investigated the effect of nano-silica on pastes and mortars. Nano-silica incorporated cement pastes are studied to understand the hydration process and microstructure evolution. Basically this approach is used for the study of fundamental science behind cement hydration. Cement mortar is the second most widely studied substance with nano-silica. To study the effect of nano-silica on concrete first the studies have been carried out on mortar to get the evidences of the effect on various mechanical and durability properties. Mortar studies are used to explore the rheology and mechanical properties.

Fresh properties

Reduction in initial setting time (IST) and final setting time (FST) of pastes was observed on addition of nano-silica[3]. Also, difference between the IST and FST decreased with increase in nano-silica content[12, 17]. With regard to the effect of nano silica on the rheology behaviour on the cementitious mixes studies on cement paste and mortars, most of the researchers agree in indicating that the addition of nano-silica greatly increases the water demand of cementitious mixes as compared to the control ones. The plasticity loss of mortar with increased torque and yield stress in mixtures with nano-silica was more evident due to higher surface area[3, 32].Berra *et al.* 2012, Kawashima *et al.* 2012 worked on the rheology of cement pastes with various w/b ratios and suggested delayed addition of water by keeping certain amount of water to be added at a later stage. Also, addition of nano- silica into cement paste and mortar resulted in higher demand of water to retain its workability. Direct influence on water amount required in the mixture was observed when nano-silica was incorporated into the mortars in fresh state. This behaviour confirms the fact that additions of high surface area mineral particles to cement mixtures cause the need for higher amounts of water or chemical admixtures in order to keep the workability of the mixture. If the water content is kept constant, as in the actual conditions, an increase of nano-SiO_2 content will promote the packing of particles, decreasing the volume between them and decreasing the free water. The specific surface and the number of atoms in the surface increase rapidly. Therefore, there is a higher internal friction between solid particles[17]. When a material with high specific surface is added to cement or concrete, it acts as the micro-filler of the cement particles, which can reduce the amount of water that filled in the void of the blending materials. However, replacing cement with a high specific surface material would increase the wettable surface area and the amount of water adsorbed. Thus, the final water requirement will depend on which of the two above-mentioned factors will be superior. Presence of nano silica made cement paste thicker and accelerated the hydration process. The results show that the bond strength at the interface between aggregate and hardened cement paste (hcp) incorporating NS increases obviously[12]. For fly ash cement blended nano silica mortars greater reduction in fluidity with greater amount of nano silica was observed[33]. Investigated the pozzolanic activity of nano silica and CH adsorption of colloidal nano-silica (CNS)[8]. It was observed that pozzolanic reaction of nano silica was complete within 7 days of hydration. The strength gain continues however the strength enhancing effect gradually decreases over time. The greater CH consumption is seen when the amount of nano-silica increases which is due to the additional pozzolanic reaction by the colloidal nano-silica. Although it has been reported that nanoSiO_2 is beneficial for the hydration of fly ash in the early age, a lack of calcium hydroxide prohibits the hydration of fly ash in the later age and is likely a contributing factor to the reduced rate in long-term compressive strength gain of CNS-modified fly ash-cement mortar[27,45] Nano-SiO_2 consumes CH crystals, decreases the orientation of CH crystals, reduces the size of CH crystals at the interface and improves the interface structure more effectively.

Mechanical properties

With regard to the influence of nano-silica on the mechanical strength development of cementitious materials, the addition of nano-silica to Ordinary Portland Cement (OPC) pastes was found to increase the compressive strength to an extent that was dependent on the nano silica content, water-to-binder weight ratio (w/b), and curing time. Paste compressive strength was studied[12, 23, 34] along with bond strength[12] and flexural strength[34]. As a general observation, increase in paste strength was observed with increase in content of nano silica at early ages along with increase in pozzolanic activity. An increase of approximately 17–41% and 20–25% in compressive strength on comparing with control mix, at 3 day and 28 day[12], 7–11% at 7 day[23], and an average increase of about 25% was observed on addition of nano silica in various quantities respectively[34]. The increase in gain of strength and optimum nano-silica content were observed to be 5%[12], 0.8%[23], and 0.5%[34]. The bond strength increase was observed between 16–43% at 7 days and 26–88% at 28 days[12]. The flexural strength at the ages of 3 days was also observed to be maximum with 1–2% nano silica content[34].

Li *et al*. 2004 investigated cement mortars with nano-SiO_2 or nano-Fe_2O_3 to explore their super mechanical and smart potentials. Compressive strength increase in mortar mixes was observed 5.7–20.1% (7-days) and 13.8–26% (28-days)[4]. Jo *et al*. 2007, observed 53.67–63.9% (7 days) and 52.5–62.7% (28-days) increase in mortar mixes compressive strength and suggested the requirement of using higher content of nano-silica must be accompanied by adjustments to water and superplasticizer dosage in the mix in order to ensure that the specimens do not suffer excessive self-desiccation and cracking. Same results were observed by[17], and 6.9–16.9% increase in compressive strength at 90 days was reported[9]. On addition of nano-silica to fly-ash concretes[33, 8, 35] almost same results were observed with early age strength gain as high as 60%, which became equal at later stage to that of various mixes as shown in Figure 1[33] and 58–66% i.e. average of 63% increase on strength[35]. Also, flexural strength increase was reported as 28% at 7 days and 19.2–27% at 28 days[4] and 42–55% at 28 days, along with fracture energy and impact strength increase at 28 days[36].

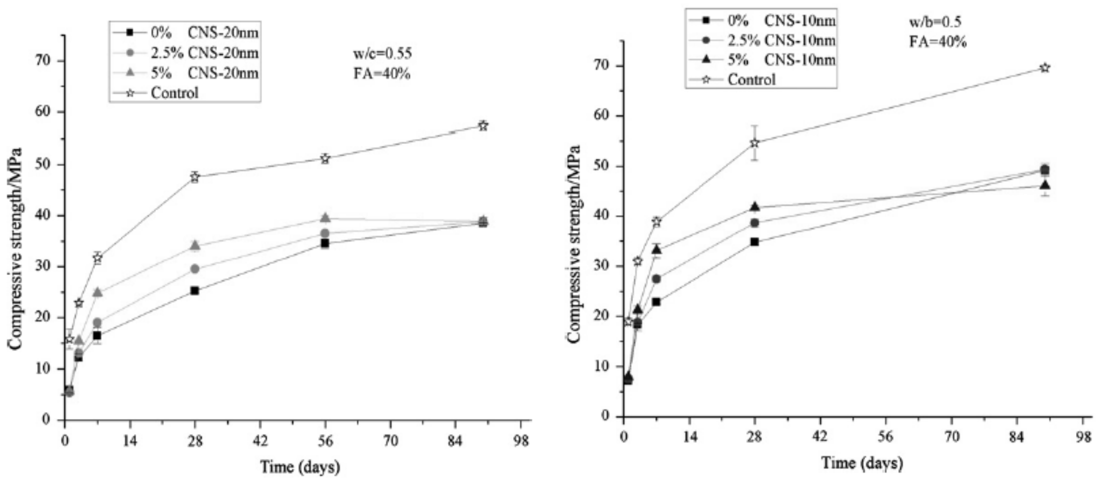

Fig. 1: *Effect of CNS on the Compressive Strength of Fly Ash Mortar*[33].

Durability properties

Jo *et al*. 2007 observed by examining the rate of heat of evolution that nano scale silica behaves not only as a filler to improve microstructure but also as an activator to promote pozzolanic reaction.

Gaitero *et al*. 2008 revealed reduced calcium leaching of nano silica added cement paste ascribing it to the densification of the paste, transforming of portlandite into C-S-H by means of pozzolanic reaction and modification of internal structure of C-S-H gel, all of which make the cement paste more stable and more strongly bonded. Higher values of water absorption and apparent porosity[32] were observed along with unrestrained shrinkage and weight loss of mortars with increase in nano-silica content (highest at 7% nano-silica wt%). For fly ash replaced cement based materials, CH generated by cement hydration is critical for later stage pozzolanic reaction. Nano silica addition has great influence on the CH content of fly ash-cement paste. Also depletion of $Ca(OH)_2$ was more severe when the nano silica dosage and fly ash replacement ratio are high[33]. Hou *et al.* 2013 observed acceleration of cement hydration and maturation of gel structure CNS added paste is achieved through an acceleration of the dissolution of cement particles and a preferred hydration and hydrates precipitation on CNS particle surface. Although, CNS can accelerate cement hydration to a great extent in the early age, the later hydration of cement is hindered. The new content of CNS-added paste experiences a higher rate of increase initially, but gradually becomes smaller than that of the control paste due to changes in the gel structure, making new content an unsuitable method for monitoring the hydration of CNS-added paste. However, nano-indentation results revealed that CNS modifies the gel structure to increase the high-stiffness C-S-H gel content.

CONCRETE WITH NANO-SILICA

Nano silica incorporation into cement concrete is the direct application approach of nanomaterials. Researchers have worked on the mechanical, durability properties and microstructure analysis of concrete with nano silica as discussed below.

Fresh properties

Reduced setting times were observed by various researchers on incorporation of nano silica in concrete which is same as observation as for pastes and mortar[37, 38]. Also, decrease in initial and final setting time was observed on incorporation of NS in various quantities, with increase in viscosity and yield stress reported[30].

Mechanical properties

Concrete strength is influenced by lots of factors like concrete ingredients, age, and ratio of water to cement materials etc. Nano silica incorporation into concrete resulted in higher compressive strength than that of normal concrete to a considerable level. Li 2004 reported 3 day compressive strength increase by 81% and also at later ages same trend was observed with 4% nano-silica in high volume fly ash concrete as shown in Figure 2. Givi *et al*. 2010 also reported higher compressive strength at all ages, for nano-silica blended concretes up to maximum limit of 2% with average particle size of 15 nm and 80 nm. Same results were obtained for split tensile and flexural strength. Pourjavadi *et al.* 2012 also reported that negative effect of super absorbent polymer could be offsetted by addition of nano-silica, but same results were not observed for flexural strength. An increase of about 23–38% and 7–14% at 7 days and 28 days respectively, in compressive strength of nano-silica concrete was reported, whereas low increase of 9.4% (average) was reported for flexural strength. Zhang *et al*. 2012, Zhang and Islam 2012 used Ground Granulated Blast Furnace Slag (GGBFS), fly ash and slag and increase in compressive strength was observed as 22% (3 days) and 18% (7 days) and 30% (3 days) and 25% (7 days) of concretes with GGBFS and fly ash and slag, respectively.

Heidari and Tavakoli in 2013 incorporated nano-silica in ground ceramic concrete and improvement in the early age strength was observed.

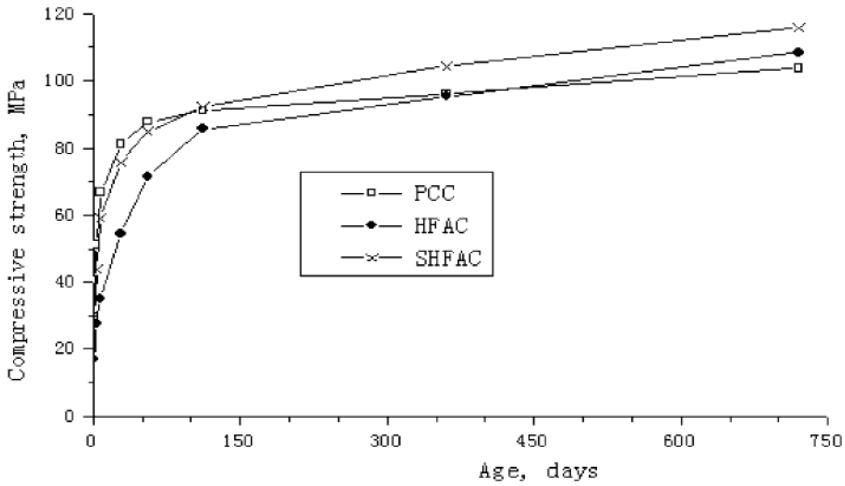

Fig. 2: *Development of the Compressive Strength Versus Time*[18].

Durability properties

Durability properties of concrete include aspects such as permeability, pore structure and particle size distribution, resistance to chloride penetration etc. Investigations on nano silica concrete for its permeability characteristics showed that the addition of nano silica in concrete resulted in reduction in water absorption, capillary absorption, rate of water absorption, and coefficient of water absorption and water permeability than normal concrete. The pore structure determines the transport properties of cement paste such as permeability and ion migration. Reduction in water absorption, capillary absorption, rate of water absorption and water permeability has been observed by various researchers[27, 41, 38]. Pore size distribution in concrete was refined and porosity lowered even at short time curing on addition of 4% nano-silica[27, 41]. Also increasing nano-silica dosage decreased capillary porosity[38]. Water absorption capacity of nano-silica concretes decreased with incorporation of nano-silica[38, 42]. Enhancement to resistance to chloride penetration of concretes with addition of nano silica was reported[41, 42]. Zhang *et al.* 2012studied the behaviour of high volume fly ash and slag concretes with nano silica addition and reported that the addition of nano silica reduced the length of dormant period during hydration and also accelerated the hydration. Chloride ion penetration was also reduced with the addition of nano silica into fly ash and slag concrete.

Microstructure Analysis

X-ray Diffraction (XRD) as shown in Figures 3 and 4 and Scanning electron microscope (SEM) observations as shown in Figures 5, 6 and 7 have been reported by various researcher[3, 4, 8, 12, 20, 30, 34, 36, 43, 44]. Li *et al.* 2004 observations of SEM revealed that the nano-particles were not only acting as a filler, but also as an activator to promote hydration process and to improve the microstructure of the cement paste if the nano-particles were uniformly dispersed as shown in Figure 5. Ji 2005, also revealed through environmental scanning electron microscope (ESEM) test that microstructure of concrete with nano silica was more uniform and compact than that of the normal concrete.

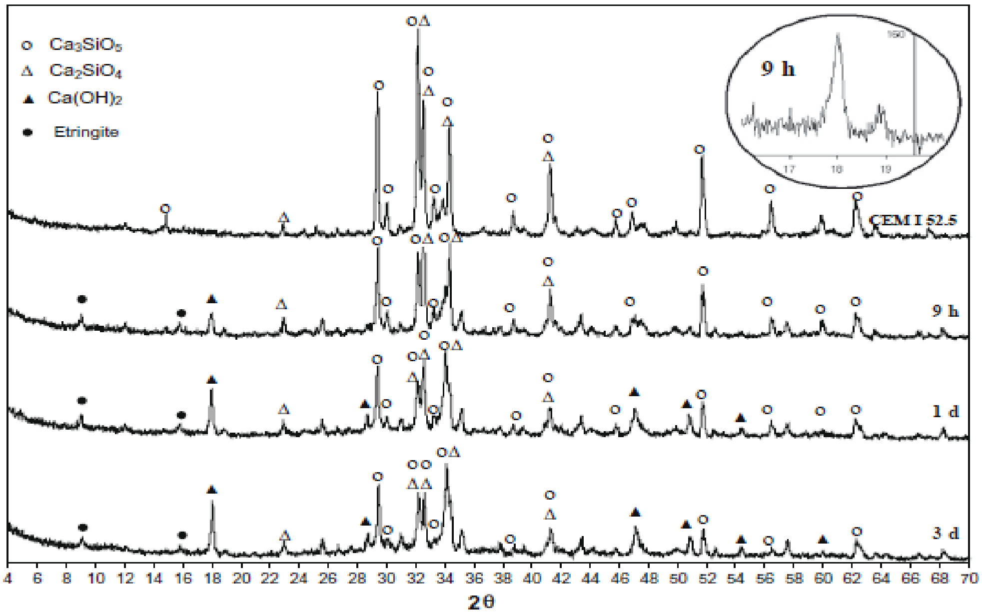

Fig. 3: *XRD of Cement Paste with NS*[3].

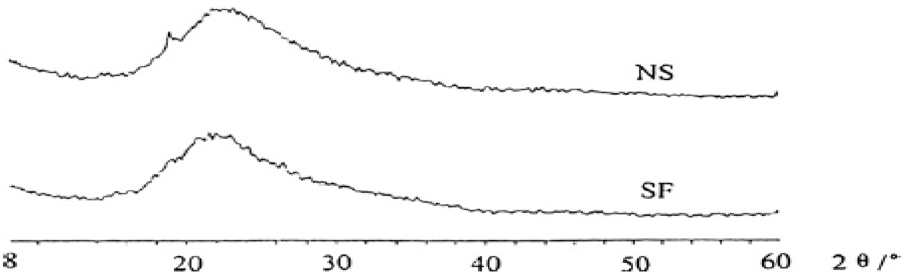

Fig. 4: *XRD Powder Pattern of Nano-SiO2 and Silica Fume*[12, 45].

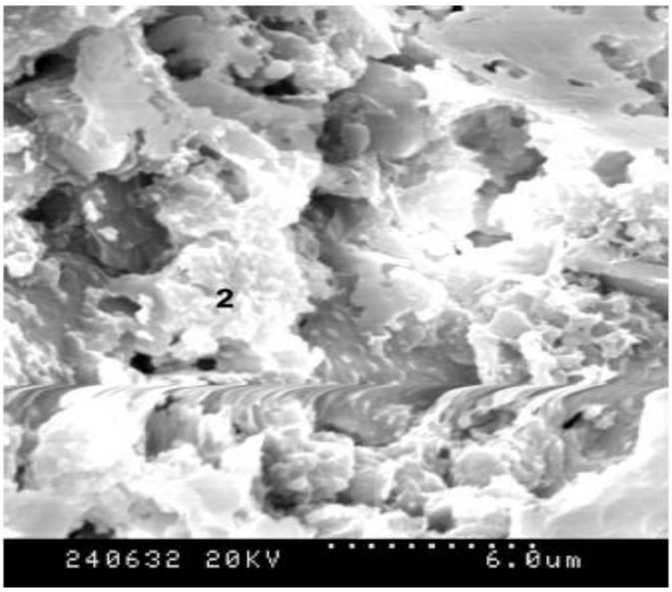

Fig. 5: *SEM Photograph of Nano-Silica Mortar Mixture*[18].

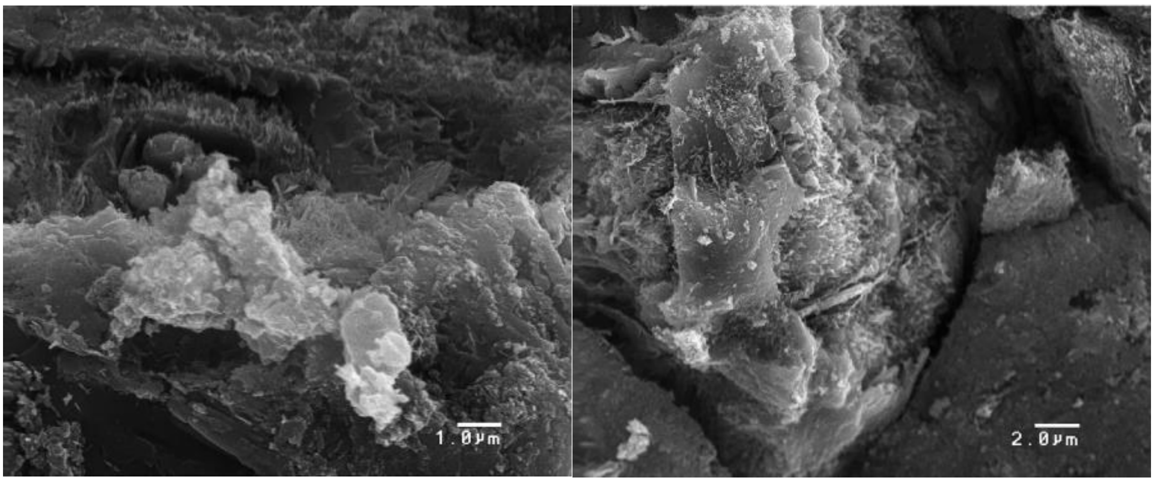

***Fig. 6:** SEM Micrographs of Paste Containing Nano-SiO$_2$ Particles (a) 10,000× and (b) 5000×*[20].

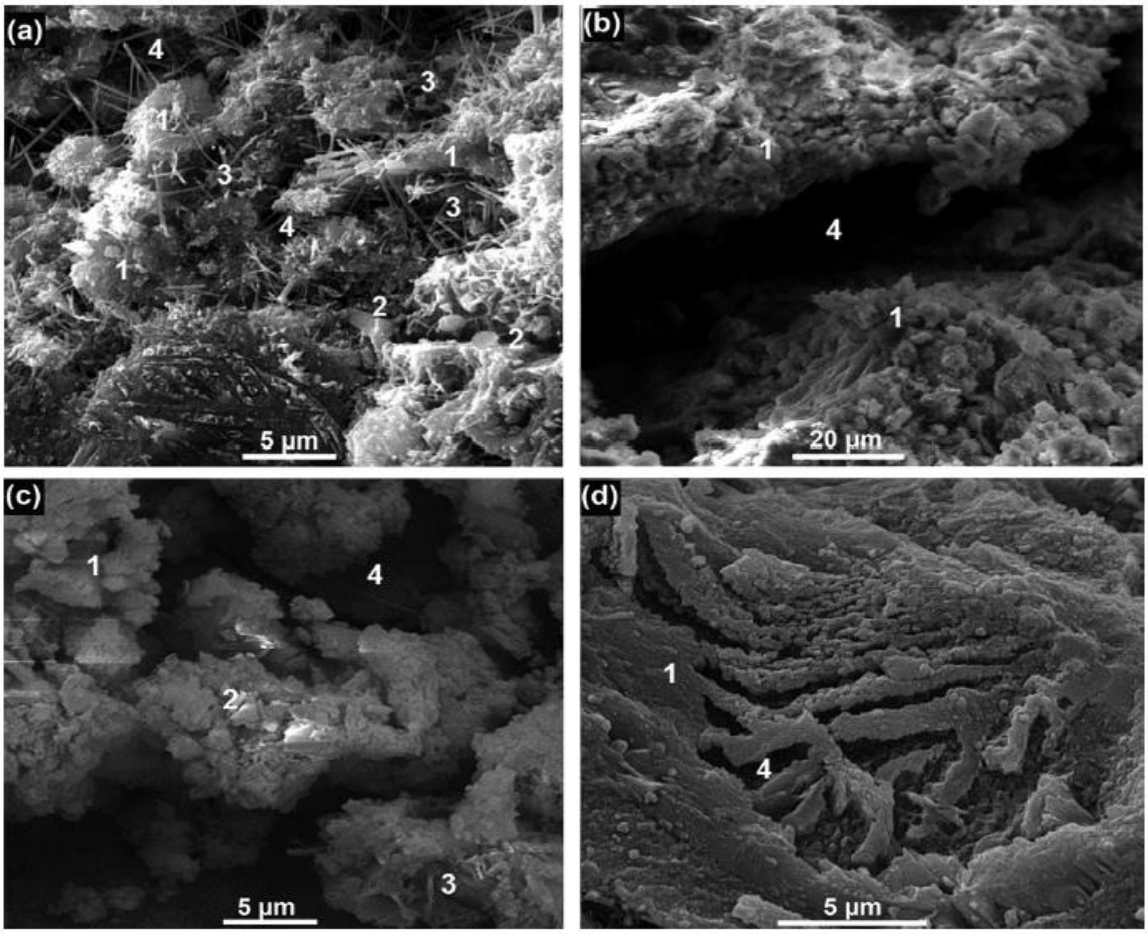

***Fig. 7 :** SEM Images of Paste Cured at Room Température for 28 days (a) 5µm Control Mix (b) 20µm 1% wt of NS (c) 5 µm 0.3% Superabsorbent Polymer (SAP) (d) 5µm 1% wt. NS and 0.3% SAP*[30].

Qing *et al*. 2007 showed from XRD powder patterns of NS and SF in Figure 4 that strong broad peaks of NS and SF were centred on 23° and 22° (2θ), respectively, which was in keeping with the strong broad peak of a characteristic of amorphous SiO_2. The results show that both NS and SF are in an amorphous state. SEM examination was performed to verify the mechanism predicted by compressive strength test[20] and addition of nano silica particles were found to influence hydration behaviour and lead to the differences in the microstructure of the hardened paste. C-S-H gel existed in isolation surrounded by and connected with many needle hydrates in case of control mix but the microstructure of the mixture containing nano-SiO_2 revealed a dense, compact formation of hydration products and a reduced number of $Ca(OH)_2$ crystals as shown in Figure 6, which was in accordance with the compressive strength values and hence is verified. Qing *et al*. 2007 showed that NS can reduce the size of CH crystals at the interface more effectively than SF. Senff 2009 also showed that nano-silica addition contributed to the increase production of CH at early age compared to samples without nano-silica and showed the XRD cement paste with NS in Figure 3. Pourjavadi *et al*. 2012 reported that the addition of 1% nano-silica reduced the porosity of hardened cement paste because of super pozzolanic performance and production of higher amounts of C-S-H gel. In addition, the microstructure was considerably improved due to the micro and nano filling effects as shown in Figure 7. Crystals of portlandite were reduced in size and quantity as a consequence of the pozzolanic reaction and crystal growth control by nano-silica. The microstructures were non-compact, with extensive presence of needle-like crystals of ettringite together with large crystals of Portlandite in case of control mix (a) as shown in the Figure 7. The addition of 1% NS reduced the porosity of the hardened cement paste because of super pozzolanic performance and production of higher amounts of C-S-H gel. In addition, the microstructure was considerably improved due to the micro and nano-filling effects. Crystals of Portlandite were reduced in size and quantity as a consequence of the pozzolanic reaction and crystal growth control by NS. These improvements in microstructure were reflected in macroscopic properties, especially the mechanical performance.

Aly *et al.* 2012 in Figure 8 showed through SEM micrographs show that the densest mortar structure was observed for the specimen with a hybrid combination of WG and CS. The addition of CS has great potential to accelerate the pozzolanic reaction. It seems that their nano-size allows them to react more readily with the CH, thereby increasing CSH conversion at 28 days of hydration. The hybrid combination of CS and WG was found to be a very effective method to use WG as a high-volume cement replacement, to achieve good performance and as an economic way to use CS. Stefandiou 2012 observation recorded a denser structure in nano modified samples. Also, through SEM observation recorded an obvious microstructure improvement of the HCP and the ITZ in mortar by adding nano-silica, regardless of its agglomerate size[44]. It was found that C-S-H gels from pozzolanic reaction of the agglomerates cannot function as binder. The gels from cement hydration did not penetrate into the pozzolanic gels.

CONCLUSIONS AND SUMMARY

The present paper reviews the current state of the field of nanotechnology in concrete and recent key advances. Current status of nano-silica opens up widely for research in cementitious compositions. Applications of nanotechnology have the potential to make breakthrough in materials technology. Nano-silica application in paste, mortar and concrete is a good way of enhancing their properties. It has been observed that optimum quantity of nano-silica to be used is still contradictory and it is for the researcher to decide the optimum quantity for his/her own material. Using nanotechnology in future will make it possible to design materials for their specific purpose of application. New developments have taken place in the nano-engineering and nano modification of concrete; however, current challenges need to be solved before the full potential of nanotechnology can be realized in concrete applications, including proper dispersion; compatibility of the nano-materials in cement; processing, manufacturing, safety and cost.

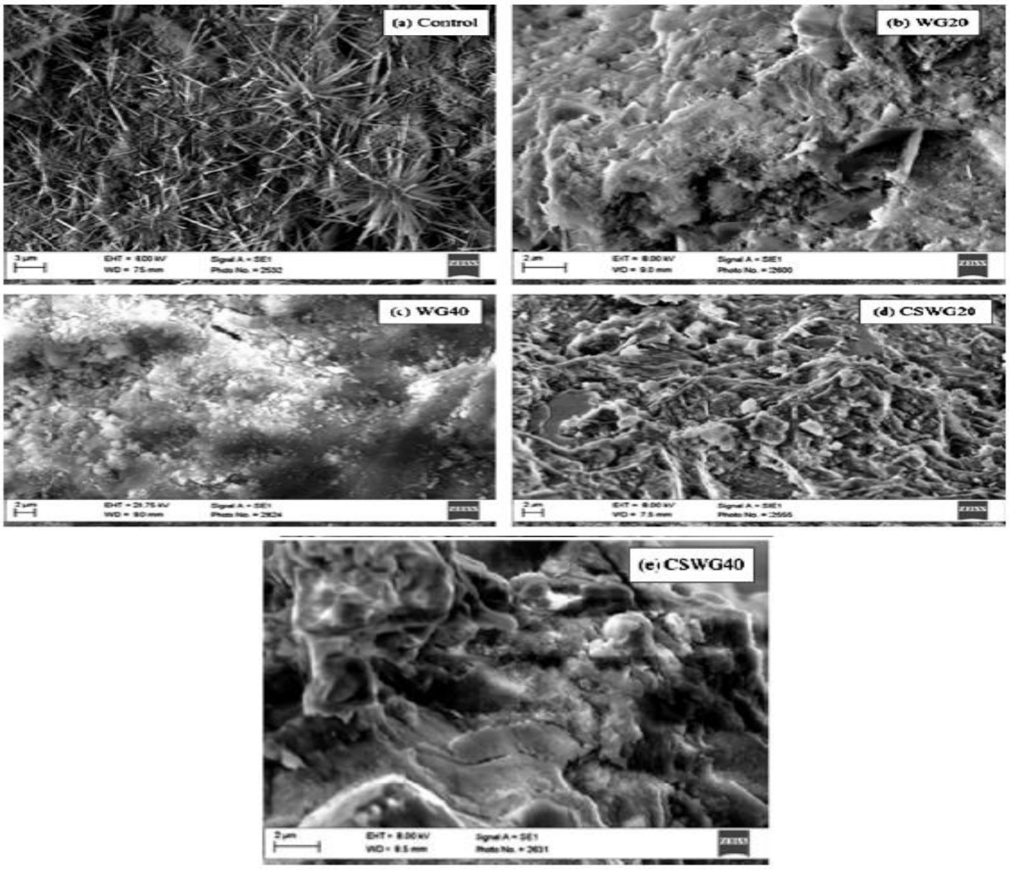

Fig. 8: *SEM Micrographs of: (a) Control Mix (b) WG20 i.e. 20% Ground Glass Powder (c) WG40 i.e. 40% Ground Glass Powder (d) CSWG20 i.e. 20% Ground Glass Powder and 3% Colloidal Nano-Silica (CS) (e) 40 i.e. 40% Ground Glass Powder and 3% Colloidal Nano-Silica*[36].

Some of the outcomes from the literature reviewed can be summarised as:

Direct influence on water amount required in the mixture was observed when nano-silica was incorporated into the mortars in fresh state. This behaviour confirms the fact that additions of high surface area mineral particles to cement mixtures cause the need for higher amounts of water or chemical admixtures in order to keep the workability of the mixture.

Compressive strengths increase with increase in nano-silica content which acts as activator to promote hydration and also to improve the microstructure of cement paste if nano particles were uniformly dispersed[17]. The compressive strength is enhanced with nano-SiO_2 addition, especially at early ages, and the pozzolanic activity of nano silica is much greater than that of silica fume. It was observed that nano silica blended concretes have higher strength as compared to non-blended concretes. Compressive strength is higher at all ages for nano-silica blended concretes.

Nano-Silica was observed to have no positive effect on the strength gain of fly ash replaced cement- based material at later ages. Flexural and split tensile strengths also improved by increasing the silica nano-particle content. Fly ash based cements have low initial pozzolanic activity, but the addition of a little nano-SiO_2significantly increases pozzolanic activity. Thus nano-SiO_2activates fly ash.

Nano-SiO_2 absorbs the $Ca(OH)_2$ crystals reducing the size and amount of the $Ca(OH)_2$ making the interfacial transition zone of aggregates and binding paste matrix denser. The nano-SiO_2 particles fill the voids of the C-S-H gel structure and act as nucleus to tightly bond with C-S-H gel particles, making binding paste matrix denser, resulting increase in long-term strength and durability of concrete. Nano-scale SiO_2 behaves not only as filler to improve mortar cement microstructure, but also as a promoter of pozzolanic reaction[45].

FUTURE POTENTIAL

Future research should address the following issues:

1. Physical state and dispersion of nano-silica into the concrete is a major issue requiring thorough study.
2. The optimum quantity of nano-silica for concrete or cement paste needs to be determined for certain percentage, which depends on the type of nano-silica i.e. colloidal, dry powder, etc and also, the average particle size of nano-silica. A relationship needs to be established between optimum quantity and characteristics of nano silica.
3. Most of the research works are limited to cement pastes and mortars, with only a few researchers having worked extensively on mechanical properties and permeability of the concrete incorporating nano-silica as is clear from the review paper. Durability properties still need to be investigated further on carbonation, corrosion resistance, acid resistance, sulphate resistance, etc.
4. Optimization, fresh, mechanical, microstructural and durability properties of concrete should be investigated along with mathematical modelling of concrete behaviour requires extensive research.

Additionally, introduction of these novel materials into the public sphere through civil infrastructure will necessitate an evaluation and understanding of the impact they may have on the environment and human health.

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