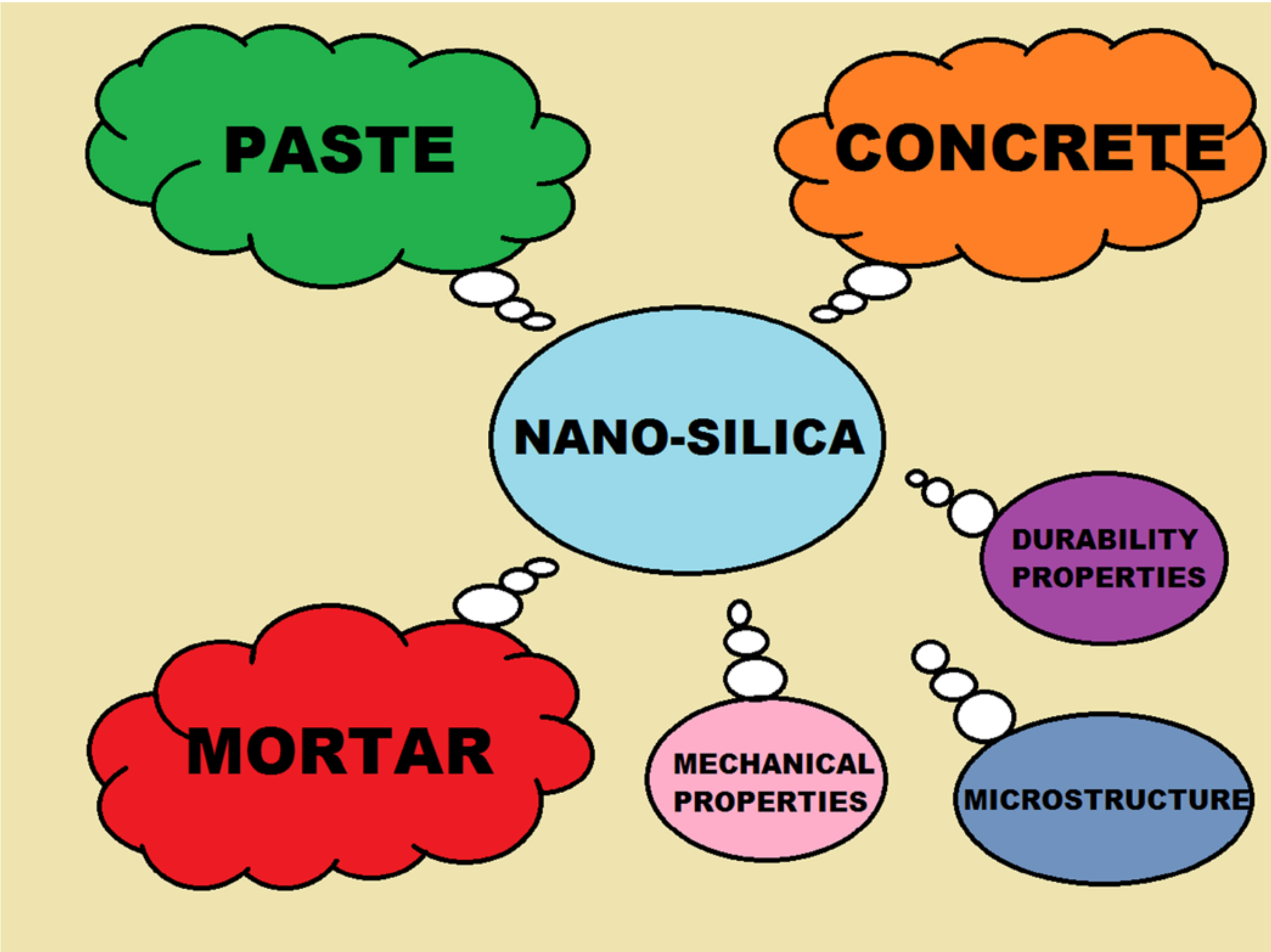
cogent engineering



CIVIL & ENVIRONMENTAL ENGINEERING | REVIEW ARTICLE

Use of nano-silica in cement based materials—A review

Paratibha Aggarwal, Rahul Pratap Singh and Yogesh Aggarwal

Cogent Engineering (2015), 2: 1078018

cogent engineering

CIVIL & ENVIRONMENTAL ENGINEERING | REVIEW ARTICLE

Use of nano-silica in cement based materials—A review

Paratibha Aggarwal[1]*, Rahul Pratap Singh[1] and Yogesh Aggarwal[1]

Received: 07 October 2014
Accepted: 26 July 2015
Published: 24 August 2015

*Corresponding author: Paratibha Aggarwal, Civil Engineering Department, National Institute of Technology, Kurukshetra, Kurukshetra, India
E-mail: paratibha@rediffmail.com

Reviewing editor:
Raja Rizwan Hussain, King Saud University, Saudi Arabia

Additional information is available at the end of the article

Abstract: The research nowadays is mainly focusing on the basic science of cementitious material at nano/atomic level. Further, researchers are continuing to improve the durability and sustainability of concrete and have realized significant increment in mechanical properties of cementitious materials by incorporating nano-silica. The review paper summarizes the effect of nano-silica addition on mechanical, durability and microstructure characteristics of paste, mortar and concrete. It provides the current development of application of nano-silica in paste, mortar and concrete. Finally, the future trend/potential and implication of nano-silica in cement-based materials is discussed.

Subjects: Concrete & Cement; Engineering & Technology; Nanoscience & Nanotechnology; Technology

Keywords: nanoparticles; concrete; durability; mechanical properties; microstructure; SEM; XRD

Paratibha Aggarwal

ABOUT THE AUTHORS

Paratibha Aggarwal is working as a professor in Civil Engineering Department of National Institute of Technology, Kurukshetra, India.

Rahul Pratap Singh is pursuing his PhD in Civil Engineering Department of National Institute of Technology, Kurukshetra, India.

Yogesh Aggarwal is working as an assistant professor in Civil Engineering Department of National Institute of Technology, Kurukshetra, India.

Their areas of interest include use of nano-silica in concrete, its study of mechanical and durability properties. High-performance concrete, self-compacting concrete, their performance and durability aspects incorporating industrial by-products. Cement is one of the most energy-consuming materials widely used globally. Efforts are being made mainly to use supplementary cementitious materials in mortars and concrete directed towards the reduction of carbon footprint. The present research work is one such effort towards attaining the above goal.

PUBLIC INTEREST STATEMENT

Concrete is one of most commonly used material on earth after water. Use of nano-materials, particularly nano-silica as supplementary cementitious material, in manufacturing of paste, mortar, and concrete offer the potential of producing materials with new and interesting properties, such as enhanced strength and durability properties. In this article, a review of use of nano-silica in paste, mortar and concrete is presented which provides an insight in the use of nano-silica in recent past. It also provides the current development of application of nano-silica with future trend/potential and implication of nano-silica in cement-based materials.

cogent oa

© 2015 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

1. Introduction

The importance of the cementitious materials in the construction industry is very significant; however, their variety of applications must not hide their complexity. They are indeed composite materials with multi-scale internal structures which have evolved over centuries. More specifically, the cement paste matrix is basically a porous material composed of calcium hydroxide (portlandite), aluminates and unhydrated cement (clinker) embedded into an amorphous nanostructured hydration product, the so-called C–S–H (calcium silicate hydrate) gel (Gaitero, Campillo, & Guerrero, 2008). This gel is the dominant 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 (Wiesner & Bottero, 2007). 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 wetted, 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 (Senff, Labrincha, Ferreira, Hotza, & Repette, 2009).

In recent years, the use of nanoparticles has received particular attention in many fields of applications to fabricate materials with new functionalities. When ultrafine particles are incorporated into Portland cement paste, mortar or concrete, materials with different characteristics from conventional materials were obtained (Lea, 1998; Li, Xiao, Yuan, & Ou, 2004; Neville, 1996). 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 (Collepardi et al., 2005). Nanoparticles 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 (Choolaei, Rashidi, Ardjmand, Yadegari, & Soltanian, 2012; Hou et al., 2013; Zapata, Portela, Suárez, & Carrasquillo, 2013). Previous researches (Björnström, Martinelli, Matic, Börjesson, & Panas, 2004; Lea, 1998; Qing, Zenan, Deyu, & Rongshen, 2007) indicate that the inclusion of nanoparticles 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 (Björnström et al., 2004). Nano-silica decreased the setting time of mortar when compared with silica fume (SF) (Qing et al., 2007) and reduced bleeding water and segregation, while improved the cohesiveness of the mixtures in the fresh state (Collepardi, Olagot, Skarp, & Troli, 2002). Nano-silica-added cement paste showed reduction in setting time (Lin, Lin, Chang, Luo, & Cai, 2008; Singh, Agarwal, Bhattacharyya, Sharma, & Ahalawat, 2011; Singh, Bhattacharyya, & Singh, 2012), 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 (Ltifi, Guefrech, Mounanga, & Khelidj, 2011; Senff et al., 2009). When combined with ultrafine fly ash, better performance is assured than that achieved by use of SF (Lea, 1998; Li, Xiao, & Ou, 2004; Li et al., 2004). Besides, the compressive strength of mortar or concrete with SF was improved when compared with formulations without addition (Jo, Kim, Tae, & Park, 2007; Li et al., 2004; Li, Zhang, & Ou, 2006). Nano-silica addition increased the quantity of C–S–H and C–A–H in the paste (Tobón, Payá, Borrachero, & Restrepo, 2012). Addition of nano-silica into cement paste and mortar demand more water to retain its workability (Quercia, Hüsken, & Brouwers, 2012). To avoid adverse effects on workability, Berra, Carassiti, Mangialardi, Paolini, and Sebastiani (2012) suggested delayed addition of water, stating that instead of adding all the mixing water at a time, certain amount of water should be added later on. Nano-silica samples showed lesser strength loss after being exposed to elevated temperatures (Lim, Mondal, & Cohn, 2012). Mortar containing high volume of fly ash showed higher residual strength after being exposed to 700°C, and dehydration of C–S–H produced calcium silicate, which acts as new binding material to retain residual strength (Rahel, Hamid, & Taha, 2012). The addition of nano-silica modified the porosity of the cement paste and increased the average chain length of silicate chains (Gaitero et al., 2008; Porro et al., 2005).

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 till date are reported with nanoparticles such as nano-silica (nano-SiO_2) and nano-titanium oxide (nano-TiO_2), nano-iron (nano-Fe_2O_3), nano-alumina (nano-Al_2O_3) (Li, 2004; Shekari & Razzaghi, 2011). 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 (Jo, Kim, & Lim, 2007). Even small additions (0.6 wt. % binder) of nS are very efficient and compare to much larger amounts of SF 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 (Pourjavadi, Fakoorpoor, Khaloo, & Hosseini, 2012). 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 (Hou et al., 2013; Mondal, Shah, Marks, & Gaitero, 2010).

2. Nano-material and cement composites

In the 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 as is clear from Table 1. 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 pore-filling effect.

2.1. 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. Mortar studies are used to explore the rheology and mechanical properties.

2.1.1. Fresh properties

Reduction in initial setting time (IST) and final setting time (FST) of pastes was observed on addition of nano-silica (Senff et al., 2009). Also, difference between the IST and FST decreased with increase in nano-silica content (Ltifi et al., 2011; Qing et al., 2007). With regard to the effect of nano-silica on the rheology behaviour of 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 (Senff, Hotza, Repette, Ferreira, & Labrincha, 2010; Senff et al., 2009). Berra et al. (2012) and Kawashima, Hou, Corr, and Shah (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. Therefore, there is a higher internal friction between solid particles (Ltifi et al., 2011).

Table 1. Summary of use of nano-silica in cementitious compositions

S. No.	Author	Concrete/mortar	Materials used for comparison	Nano material used	Size of particle (nm)	Fineness (m^2/g)	Water cement ratio	Additive or replacement	Properties
1	Senff et al. (2009)	Paste	–	nS 1.5%, 2%, 2.5%	9	300	0.35	Replacement	Flow table, rehological behaviour, XRD
2	Qing et al. (2007)	Paste 1:0.22:0.025	SF 2%, 3%, 5%	nS 1%, 2%, 3%, 5%	15	160	0.22	Additive	Compressive strength, bond strength, Setting time
3	Ltifi et al. (2011)	Paste, mortar	–	nS 3%, 10%	9	300	0.5	Replacement	Compressive strength, flexure strength
4	Senff et al. (2010)	Mortar	SF 0–20%	nS 0–7%	9	300	0.35–0.59	Additive	Rheological, compressive strength, water absorption
5	Berra et al. (2012)	Paste	–	nS 0.8%, 3.8%	10	345	0.5	Additive	Physical mechanical stability test
6	Kawashima et al. (2012)	Mortar	Fly ash	nS 2%, 5%	20–10		0.43–0.45	Additive	Compressive strength, rate of heat of hydration
7	Hou et al. (2013)	Mortar	–	nS 5%	10 nm		0.4	Additive	Hydration heat, morphology, CH content
8	Stefanidou (2012)	Paste	–	nS 0.5%, 1%, 2%, 5%	14	200	0.34–0.51	Additive	Flexural and compressive strength, microstructure
9	Li et al. (2004)	Mortar	Nano-Fe_2O_3 (3–10%) Silica fume (3–15%)	nS 3%, 5%, 10%	15 ± 5	15 ± 5	0.5	Replacement	Compressive and flexure strength, microstructure
10	Jo et al. (2007)	Mortar 1:2:45	SF 5%, 10%, 15%	nS 3%, 6%, 10%, 12%	40	60	0.5	Additive	Compressive strength, SEM, rate of heat of evolution
11	Zapata et al. (2013)	Mortar	SF	nS 1.5–6%	25	109	0.35, 0.4	Replacement	Compressive strength, SEM, XRD
12	Oltulu and Şahin (2013)	Mortar	Fly ash	nS 0.5%, 1.25%, 2.5%	12	200	0.4	Replacement	Compressive strength
13	Aly et al. (2012)	Mortar	Waste glass 20%, 40%	nS 3%	5	500	–	Replacement	Compressive, fracture, flexural and impact strength, DTA/TGA, SEM
14	Gaitero et al. (2008)	Paste	–	nS 20%, 40%, 45%, 90%	20, 30, 120, 1,400		0.4	Additive	Compressive strength, flexure strength
15	Zhang et al. (2012)	Concrete	SF	nS 0.5%, 1%, 2%	12 and 7	200.1 and 321.6	0.45	Replacement	Compressive strength, rate of heat of hydration, porosity
16	Zhang and Islam (2012)	Concrete	Fly ash, slag and SF	nS 1%, 2%	12	200.1	0.45	Replacement	Compressive strength, rate of heat of hydration, Setting time
17	Pourjavadi et al. (2012)	Concrete	SAP 0.1%, 0.3%	nS 0.5%, 1%	19	172	0.45	Replacement	Compressive strength, flexure strength
18	Li (2004)	Concrete	Fly Ash 50%	nS 4%	10 ± 5	640 ± 50	0.28	Replacement	Hydration heat, pore size
19	Naji Givi et al. (2010)	Concrete	–	nS 0.5%, 1%, 1.5%, 2%	15 and 80	160 ± 12 560 ± 32	0.4	Replacement	Compressive, flexure, and split tensile strength
20	Heidari and Tavakoli (2013)	Concrete	Ground ceramic powder 10–40%	nS 0.5%, 1%		200 ± 30	0.5	Replacement	XRD, compressive strength, water absorption

(*Continued*)

Table 1. (*Continued*)

S. No.	Author	Concrete/ mortar	Materials used for comparison	Nano material used	Size of particle (nm)	Fineness (m^2/g)	Water cement ratio	Additive or replacement	Properties
21	Zhang and Li (2011)	Concrete	Popypropylene fibre	nS 1%, 3%	10 ± 5	640 ± 50	0.42	Replacement	Compressive and flexure strength, pore structure, chloride permeability
22	Jalal et al. (2012)	Concrete	SF 2%, 10%	nS 2%, 10%	15 ± 3	165 ± 17	0.38	Replacement	Chloride penetration, water absorption, electrical resistivity
23	Ji (2005)	Concrete	Fly ash	nS	15 ± 5	160 ± 20	0.49–0.5	Replacement	Water permeability, SEM
24	Kong et al. (2012)	Mortar	–	nS 0.75%, 1%	100–200 and 200–400	142.9 and 157.8	0.3	Additive	Microstructure, compressive strength

Presence of nano-silica made cement paste thicker and accelerated the hydration process (Qing et al., 2007). Spherical morphology of fly ash helps increase the flowability of cementitious materials, whereas nanoparticles increase stiffness due to their higher specific surface area, thereby reducing fluidity of fly ash cement-blended nano-silica mortar with increase in the amount of nano-silica (Kawashima et al., 2012). The pozzolanic activity of nano-silica and CH adsorption of colloidal nano-silica (CNS) was investigated. It was observed that pozzolanic reaction of nano-silica was complete within 7 days of hydration (Hou et al., 2013).

2.1.2. Mechanical properties

With regard to the influence of nano-silica on the mechanical strength development of cementitious materials, the addition of nano-silica to Portland cement (PC) 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 (Berra et al., 2012; Qing et al., 2007; Stefanidou, 2012) along with bond strength (Qing et al., 2007) and flexural strength (Stefanidou, 2012). 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 was observed at the 3rd and 28th days (Qing et al., 2007), 7–11% at the 7th day (Berra et al., 2012) and an average increase of about 25% was observed on addition of 0.5–2% nano-silica (Stefanidou, 2012). The increase in gain of strength and optimum nano-silica content were observed to be 5% (Qing et al., 2007), 0.8% (Berra et al., 2012) and 0.5% (Stefanidou, 2012). The bond strength increase was observed between 16–43% at 7 days and 26–88% at 28 days (Qing et al., 2007). The flexural strength at the ages of 3 days was also observed to be maximum with 1–2% nano-silica content (Stefanidou, 2012).

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). 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 Ltifi et al. (2011), and 6.9–16.9% increase in compressive strength at 90 days was reported (Zapata et al., 2013). On addition of nano-silica to fly-ash concretes (Hou et al., 2013; Kawashima et al., 2012; Oltulu & Şahin, 2013), 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 (Kawashima et al., 2012) and 58–66% i.e. average of 63% increase on strength (Oltulu & Şahin, 2013). Also, flexural strength increase was reported as 28% at 7 days and 19.2–27% at 28 days (Li et al., 2004) and 42–55% at 28 days, along with fracture energy and impact strength increase at 28 days (Aly et al., 2012).

2.1.3. 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 (Senff et al., 2010) 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 (Kawashima et al., 2012). Hou et al. (2013) observed acceleration of cement hydration and maturation of gel structure in CNS added paste, 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.

2.2. Concrete with nano-silica

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

2.2.1. Fresh properties

Reduced setting times were observed by various researchers on incorporation of nano-silica in concrete which is same as observed for pastes and mortar (Zhang & Islam, 2012; Zhang, Islam, & Peethamparan, 2012). 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 (Pourjavadi et al., 2012).

2.2.2. Mechanical properties

Concrete strength is influenced by lots of factors like concrete ingredients, age, 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 et al. (2004) reported 3-day compressive strength increase by 81% and also at later stages, same trend was observed with 4% nano-silica in high volume fly ash concrete. Naji Givi, Abdul Rashid, Aziz, and Salleh (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 and 80 nm. Same results were obtained for split tensile and flexural strength. Pourjavadi et al. (2012) reported that negative effect of super absorbent polymer reduced compressive strength 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 and Islam (2012), Zhang et al. (2012) used 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 (2013) incorporated nano-silica in ground ceramic concrete and improvement in strength at early stage was observed.

2.2.3. 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 (Li, 2004; Zhang & Li, 2011; Zhang et al., 2012). Pore size distribution in concrete was refined and porosity lowered even at short time, curing on addition of 4% nano-silica (Li, 2004; Zhang & Li, 2011). Also, increasing nano-silica dosage decreased capillary porosity (Zhang et al., 2012). Water absorption capacity of nano-silica concretes decreased with incorporation of nano-silica (Jalal, Pouladkhan, Norouzi, & Choubdar, 2012; Zhang et al., 2012). Enhancement of resistance to chloride penetration of concretes with addition of nano-silica was reported (Jalal et al., 2012; Zhang & Li, 2011). Zhang and Islam (2012) studied 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.

3. Microstructure analysis

XRD and SEM observations have been reported by a number of researchers (Aly et al., 2012; Hou et al., 2013; Ji, 2005; Jo et al., 2007; Kong et al., 2012; Li et al., 2004; Pourjavadi et al., 2012; Qing et al., 2007; Senff et al., 2009; Stefanidou, 2012). Li et al. (2004) observed from SEM images that the nanoparticles 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 nanoparticles were uniformly dispersed. Ji (2005) also revealed through ESEM test that microstructure of concrete with nano-silica was more uniform and compact than that of the normal concrete. Qing et al. (2007) showed from XRD powder patterns of NS and SF 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 that is characteristic of amorphous SiO_2. The results showed that both NS and SF were in an amorphous state. SEM examination was performed to verify the mechanism predicted by compressive strength test (Jo et al., 2007) and nano-silica particles were found to influence hydration behaviour and lead to the differences in the microstructure of the hardened paste. 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. Qing et al. (2007) showed that NS can reduce the size of CH crystals at the interface more effectively than SF. Senff et al. (2009) also showed that nano-silica addition contributed to the increased production of CH at early stage compared to samples without nano-silica. Aly et al. (2012) showed through SEM micrographs show that the densest mortar structure was observed for the specimen with a hybrid combination of waste glass powder (WG) and colloidal nano-silica (CS). Stefanidou's (2012) observation recorded a denser structure in nano-modified samples. Also, Kong et al. (2012), through SEM observation, recorded an obvious microstructure improvement of the hardened cement paste (HCP) and the ITZ in mortar by adding nano-silica, regardless of its agglomerate size. 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. 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. Crystals of portlandite were reduced in size and quantity as a consequence of the pozzolanic reaction and crystal growth control by nano-silica.

4. 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 nanomaterials in cement.

Some of the outcomes from the literature reviewed can be summarized 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 nanoparticles were uniformly dispersed. The compressive strength is enhanced with nano-SiO_2 addition, especially at early stages, and the pozzolanic activity of nano-silica is much greater than that of SF. It was observed that nano-silica-blended concretes have higher strength as compared to non-blended concretes. Compressive strength is higher at all stages 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 stages. 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_2 significantly increases pozzolanic activity. Thus, nano-SiO_2 activates fly ash.

Nano-SiO_2 adsorbs 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 in an 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.

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.

(4) Optimization, fresh, mechanical, microstructural and durability properties of concrete 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.

Funding
The authors received no direct funding for this research.

Author details
Paratibha Aggarwal[1]
E-mail: paratibha@rediffmail.com
Rahul Pratap Singh[1]
E-mail: rahul9588@gmail.com
Yogesh Aggarwal[1]
E-mail: yogesh.24@rediffmail.com
[1] Civil Engineering Department, National Institute of Technology, Kurukshetra, Kurukshetra, India.

Citation information
Cite this article as: Use of nano-silica in cement based materials—A review, Paratibha Aggarwal, Rahul Pratap Singh & Yogesh Aggarwal, *Cogent Engineering* (2015), 2: 1078018.

Cover image
Source: Authors.

References

Aly, M., Hashmi, M. S. J., Olabi, A. G., Messeiry, M., Abadir, E. F., & Hussain, A. I. (2012). Effect of colloidal nano-silica on the mechanical and physical behaviour of waste-glass cement mortar. *Materials and Design, 33*, 127–135. http://dx.doi.org/10.1016/j.matdes.2011.07.008

Berra, M., Carassiti, F., Mangialardi, T., Paolini, A. E., & Sebastiani, M. (2012). Effects of nanosilica addition on workability and compressive strength of Portland cement pastes. *Construction and Building Materials, 35*, 666–675. http://dx.doi.org/10.1016/j.conbuildmat.2012.04.132

Björnström, J., Martinelli, A., Matic, A., Börjesson, L., & Panas, I. (2004). Accelerating effects of colloidal nano-silica for beneficial calcium–silicate–hydrate formation in cement. *Chemical Physics Letters, 392*, 242–248. http://dx.doi.org/10.1016/j.cplett.2004.05.071

Choolaei, M., Rashidi, A. M., Ardjmand, M., Yadegari, A., & Soltanian, H. (2012). The effect of nanosilica on the physical properties of oil well cement. *Materials Science and Engineering: A, 538*, 288–294. http://dx.doi.org/10.1016/j.msea.2012.01.045

Collepardi, M., Olagot, J. J. O., Skarp, U., & Troli, R. (2002, September 9–11). Influence of amorphous colloidal silica on the properties of self-compacting concretes. In *Challenges in concrete constructions–innovations and developments in concrete materials and constructions* (pp. 473–483). Dundee.

Collepardi, S., Borsoi, A., Olagot, J. J. O., Troli, R., Collepardi, M., & Cursio, A. Q. (2005, July 5–7). Influence of nano-sized mineral additions on performance of SCC. In *Proceedings of the 6th International Congress, Global Construction, Ultimate Concrete Opportunities*. Dundee.

Gaitero, J. J., Campillo, I., & Guerrero, A. (2008). Reduction of the calcium leaching rate of cement paste by addition of silica nanoparticles. *Cement and Concrete Research, 38*, 1112–1118. http://dx.doi.org/10.1016/j.cemconres.2008.03.021

Heidari, A., & Tavakoli, D. (2013). A study of the mechanical properties of ground ceramic powder concrete incorporating nano-SiO2 particles. *Construction and Building Materials, 38*, 255–264. http://dx.doi.org/10.1016/j.conbuildmat.2012.07.110

Hou, P., Kawashima, S., Kong, D., Corr, D. J., Qian, J., & Shah, S. P. (2013). Modification effects of colloidal nanoSiO_2 on cement hydration and its gel property. *Composites Part B: Engineering, 45*, 440–448. http://dx.doi.org/10.1016/j.compositesb.2012.05.056

Jalal, M., Pouladkhan, R. A., Norouzi, H., & Choubdar, G. (2012). Chloride penetration, water absorption and electrical resistivity of high performance concrete containing nano silica and silica fume. *Journal of American Science, 8*, 278–284.

Ji, T. (2005). Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO2. *Cement and Concrete Research, 35*, 1943–1947. http://dx.doi.org/10.1016/j.cemconres.2005.07.004

Jo, B. W., Kim, C. H., & Lim, J. H. (2007). Investigations on the development of powder concrete with nano-SiO_2 particles. *KSCE Journal of Civil Engineering, 11*, 37–42. http://dx.doi.org/10.1007/BF02823370

Jo, B. W., Kim, C. H., Tae, G. H., & Park, J. B. (2007). Characteristics of cement mortar with nano-SiO_2 particles. *Construction and Building Materials, 21*, 1351–1355. http://dx.doi.org/10.1016/j.conbuildmat.2005.12.020

Kawashima, S., Hou, P., Corr, D. J., & Shah, S. P. (2012). Modification of cement-based materials with nanoparticles. *Cement and Concrete Composites, 36*, 8–15.

Kong, D., Du, X., Wei, S., Zhang H., Yang, Y., Shah, S. P. (2012). Influence of nano-silica agglomeration on microstructure and properties of the hardened cement-based materials. *Construction and Building Materials, 37*, 707–715. http://dx.doi.org/10.1016/j.conbuildmat.2012.08.006

Lea, O. I. (1998). *Chemistry of cement and concrete* (4th ed.). London: Arnold.

Li, G. (2004). Properties of high-volume fly ash concrete incorporating nano-SiO_2. *Cement and Concrete Research, 34*, 1043–1049. http://dx.doi.org/10.1016/j.cemconres.2003.11.013

Li, H., Xiao, H. G., & Ou, J. (2004). A study on mechanical and pressure-sensitive properties of cement mortar with nanophase materials. *Cement and Concrete Research, 34*, 435–438. http://dx.doi.org/10.1016/j.cemconres.2003.08.025

Li, H., Xiao, H. G., Yuan, J., & Ou, J. (2004). Microstructure of cement mortar with nano particles. *Composites Part B: Engineering, 35*, 185–189. http://dx.doi.org/10.1016/S1359-8368(03)00052-0

Li, H., Zhang, M., & Ou, J. (2006). Abrasion resistance of concrete containing nano-particles for pavement. *Wear, 260*, 1262–1266. http://dx.doi.org/10.1016/j.wear.2005.08.006

Lim, S., Mondal, P., & Cohn, I. (2012). Effects of nanosilica on thermal degradation of cement paste. In *NICOM 4 – 4th International Symposium on Nanotechnology in Construction*. Greece.

Lin, D. F., Lin, K. L., Chang, W. C., Luo, H. L., & Cai, M. Q. (2008). Improvements of nano-SiO_2 on sludge/fly ash mortar. *Waste Management, 28*, 1081–1087. http://dx.doi.org/10.1016/j.wasman.2007.03.023

Ltifi, M., Guefrech, A., Mounanga, P., & Khelidj, A. (2011). Experimental study of the effect of addition of nano-silica on the behaviour of cement mortars Mounir. *Procedia Engineering, 10*, 900–905. http://dx.doi.org/10.1016/j.proeng.2011.04.148

Mondal, P., Shah, S. P., Marks, L. D., & Gaitero, J. J. (2010). Comparative study of the effects of microsilica and nanosilica in concrete. *Transport Research Recording*. doi:10.3141/2141-02.

Naji Givi, A. N., Abdul Rashid, S. A., Aziz, F. N. A., & Salleh, M. A. M. (2010). Experimental investigation of the size effects of SiO_2 nano-particleson the mechanical properties of binary blended concrete. *Composites Part B: Engineering, 41*, 673–677. http://dx.doi.org/10.1016/j.compositesb.2010.08.003

Neville, A. M. (1996). *Properties of concrete* (4th ed.). Harlow: ELBS with Addison Wesley Longman.

Oltulu, M., & Şahin, R. (2013). Effect of nano-SiO2, nano-Al2O3 and nano-Fe2O3 powders on compressive strengths and capillary water absorption of cement mortar containing fly ash: A comparative study. *Energy and Buildings, 58*, 292–301. http://dx.doi.org/10.1016/j.enbuild.2012.12.014

Porro, A., Dolado, J. S., Campillo, I., Erkizia, E., de Miguel, Y. R., Sáez de Ibarra, Y., & Ayuela, A. (2005). Effects of nanosilica additions on cement pastes. In R. K. Dhir, M. D. Newlands, & L. J. Csetenyi (Eds.), *Applications of nanotechnology in concrete design* (pp. 87–98). London: Thomas Telford.

Pourjavadi, A., Fakoorpoor, S. M., Khaloo, A., & Hosseini, P. (2012). Improving the performance of cement-based composites containing superabsorbent polymers by utilization of nano-SiO_2 particles. *Materials and Design, 42*, 94–101. http://dx.doi.org/10.1016/j.matdes.2012.05.030

Qing, Y., Zenan, Z., Deyu, K., & Rongshen, C. (2007). Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume. *Construction and Building Materials, 21*, 539–545. http://dx.doi.org/10.1016/j.conbuildmat.2005.09.001

Quercia, G., Hüsken, G., & Brouwers, H. J. H. (2012). Water demand of amorphous nano silica and its impact on the workability of cement paste. *Cement Concrete Research, 42*, 344–357. http://dx.doi.org/10.1016/j.cemconres.2011.10.008

Rahel, I., Hamid, R., & Taha, M. R. (2012). Fire resistance of high-volume fly ash mortars with nanosilica addition. *Construction and Building Material, 36*, 779–786.

Senff, L., Hotza, D., Repette, W. L., Ferreira, V. M., & Labrincha, J. A. (2010). Mortars with nano-SiO_2 and micro-SiO_2 investigated by experimental design. *Construction and Building Materials, 24*, 1432–1437. http://dx.doi.org/10.1016/j.conbuildmat.2010.01.012

Senff, L., Labrincha, J. A., Ferreira, V. M., Hotza, D., & Repette, W. L. (2009). Effect of nano-silica on rheology and fresh properties of cement pastes and mortars. *Construction and Building Materials, 23*, 2487–2491. http://dx.doi.org/10.1016/j.conbuildmat.2009.02.005

Shekari, A. H., & Razzaghi, M. S. (2011). Influence of nano particles on durability and mechanical properties of high performance concrete. *Procedia Engineering, 14*, 3036–3041. http://dx.doi.org/10.1016/j.proeng.2011.07.382

Singh, L. P., Agarwal, S. K., Bhattacharyya, S. K., Sharma, U., & Ahalawat, S. (2011). Preparation of silica nanoparticles and its beneficial role in cementitious materials. *Nanomaterial Nanotechnology, 1*, 44–51.

Singh, L. P., Bhattacharyya, S. K., Singh, & P. (2012). Granulometric synthesis and characterisation of dispersed nanosilica powder and its application in cementitious system. *Advances in Applied Ceramics, 111*, 220–227. http://dx.doi.org/10.1179/1743676112Y.0000000002

Stefanidou, M. (2012). Influence of nano-SiO_2 on the Portland cement pastes. *Composites Part B: Engineering, 43*, 2706–2710. http://dx.doi.org/10.1016/j.compositesb.2011.12.015

Tobón, J. I., Payá, J. J., Borrachero, M. V., & Restrepo, O. J. (2012). Mineralogical evolution of Portland cement blended with silica nanoparticles and its effect on mechanical strength. *Construction and Building Materials, 36*, 736–742. http://dx.doi.org/10.1016/j.conbuildmat.2012.06.043

Wiesner, M. R., & Bottero, J. Y. (2007). *Environmental nanotechnology: Applications and impacts of nanomaterials*. New York, NY: McGraw-Hill.

Zapata, L. E., Portela, G., Suárez, O. M., & Carrasquillo, O. (2013). Rheological performance and compressive strength of super plasticized cementitious mixtures with micro/nano-SiO_2 additions. *Construction and Building Materials, 41*, 708–716. http://dx.doi.org/10.1016/j.conbuildmat.2012.12.025

Zhang, M. H., & Islam, J. (2012). Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag. *Construction and Building Materials, 29*, 573–580. http://dx.doi.org/10.1016/j.conbuildmat.2011.11.013

Zhang, M. H., Islam, J., & 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, 34*, 650–662. http://dx.doi.org/10.1016/j.cemconcomp.2012.02.005

Zhang, M. H., & Li, H. (2011). Pore structure and chloride permeability of concrete containing nano-particles for pavement. *Construction and Building Materials, 25*, 608–616. http://dx.doi.org/10.1016/j.conbuildmat.2010.07.032

© 2015 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:
Share — copy and redistribute the material in any medium or format
Adapt — remix, transform, and build upon the material for any purpose, even commercially.
The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:
Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.
No additional restrictions
You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

***Cogent Engineering* (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group.**

Publishing with Cogent OA ensures:

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

Submit your manuscript to a Cogent OA journal at www.CogentOA.com