Influence of SiO2 nanoparticles on the microstructure, mechanical properties, and thermal stability of Portland cement nanocomposites

A. Hakamy
Department of Physics, Umm Al-Qura University, Makkah, Saudi Arabia

ABSTRACT
In the context of the microstructure of nano-SiO2 cement nanocomposites, information regarding the tricalcium silicate (C3S) and dicalcium silicate (C2S) phases during the hydration reaction remains inadequate. Therefore, in this research, the effects of different SiO2 nanoparticles contents on the microstructures, mechanical performance, and thermal stability of cement nanocomposites were investigated. The X-ray diffraction (XRD) results highlighted that the incorporation of nano-SiO2 enhanced the microstructure of the nanocomposites by decreasing the Ca(OH)2, C3S, and C2S peaks, leading to a higher production of calcium silicate hydrate (CSH) products. Moreover, the intensity of the unhydrated gypsum phase increased with the increase in the nano-SiO2 contents, which was suggestive of the retardation effect of nano-SiO2 on the aluminate phases and aluminite reaction. Furthermore, the addition of nano-SiO2 considerably enhanced the flexural strength and thermal stability of the nanocomposites compared to the control composites. The optimum ratio of nano-SiO2 was 1 wt%.

1. Introduction
Nanomaterials represent a novel class of materials that exhibit unique advantages at the nanoscale level. Recently, nanomaterials have been exploited to manufacture novel materials and composites in the most branches of materials science such as metals, polymers, and ceramics with superior physical, chemical, and biological properties compared to common or bulk materials [1–6]. Moreover, in biomedical applications, the use of nanomaterials such as nanodiamonds and zinc and magnesium nanoparticles in several biomedical procedures such as drug delivery, tissue scaffold and surgical implant preparation, and bio-imaging and therapeutic applications has received considerable attention [7,8]. In the applications of metal composite materials, the metal substrate and metal alloys (such as magnesium and its alloys) can be protected against corrosion by implementing coating techniques involving nanocomposites (polymers or conductive polymers containing nanoparticles) [9,10]. Furthermore, microparticles are often used to reinforce the metallic matrix; for example, the addition of 7 wt% TiB2 micro-silicate particles to reinforce metallic aluminum matrix composites can considerably improve the mechanical properties of such metallic composites [11].

To improve the thermal, mechanical, optical, and biological properties of polymer composites and biomaterials, nanomaterials in various forms (nanoparticles, nanotubes, etc.) have been employed [12,13]. Moreover, different types of nanomaterials, such as (CaCO3, Fe2O3, TiO2, ZnO and Al2O3) nanoparticles, nanoclay, and carbon nanotubes, have been used to enhance the physical, mechanical, and thermal properties of ceramics and concrete composites [14–19]. In recent research, cement composites were incorporated with graphene oxide sheets as a nanofiller, synthetic CSH/polycarboxylate (PCE) nanocomposites, montmorillonite nanosheets modified with an organic surfactant, functionalized graphene nanoplatelets (GNP-COOH) containing 5% oxygen or hybrid graphene oxide-functionalized carbon nanotubes. These novel cement nanocomposites exhibited considerably enhanced flexural strength and compressive strength compared to those of pure composites [20–24].

Portland cement is a category of ceramic composite that consists of 86 wt% of two main crystalline compounds: tricalcium silicate (3CaO·SiO2) or (C3S) and dicalcium silicate (2CaO·SiO2) or (C2S). The reaction of C3S or C2S compounds with H2O to produce calcium silicate hydrate gel (C3S2H8) and calcium hydroxide crystals (Ca(OH)2) can be expressed as a hydration reaction [25,26]:

\[ 2C_3S + 6H_2O \rightarrow C_3S_2H_8 + 3CH \quad (1) \]
\[ 2C_2S + 4H_2O \rightarrow C_3S_2H_8 + CH \quad (2) \]

Here, CH represents Ca(OH)2, and C3S2H8 (CSH) products are porous amorphous microstructures.

In certain cases, Portland cement is partially replaced by pozzolans or pozzolanic materials (supplementary...
cementitious materials, SCM) to reduce environmental issues, as in general, concrete emits extremely high levels of CO₂ [27]. Such materials, which consist predominantly of micro-silica (micro-SiO₂), silica fume and fly ash as the pozzolanic materials, usually react chemically with the calcium hydroxide (CH) in cement composites or concrete to yield extra CSH products through a chemical pozzolanic reaction [28,29].

\[
Pozzolan + CH + H_2O \rightarrow C_3S_2H_8 \quad (3)
\]

Notably, nano-SiO₂ has emerged as a progressive pozzolan to enhance the microstructure and mechanical performance of cement composites and concrete [30–32]. The chemical reaction of SiO₂ nanoparticles with Ca(OH)₂ crystals to yield CSH gel can be expressed as a pozzolanic reaction [33].

\[
nano-SiO_2 + CH + H_2O \rightarrow C_3S_2H_8 \quad (4)
\]

In addition, nano-SiO₂ is principally useful as a filler to densify the cement composite and enhance the microstructure and mechanical properties compared to those of the control cement or concrete composites [34]. Biricik and Sarier [35] reported that cement composites containing nano-silica outperformed cement composites containing silica fume or fly ash. However, research regarding the C₃S and C₅S peaks in the hydration reaction for cement nanocomposites containing nano-SiO₂, as observed in X-ray diffraction (XRD) spectra, remains limited. Furthermore, the thermal stability has not been extensively examined through thermogravimetry analyses (TGA). Therefore, this study was aimed at clarifying the effects of the percentage content of nano-SiO₂ on the microstructure, mechanical properties, and thermal stability of nanocomposites.

2. Materials and methods

2.1. Materials

Nano-SiO₂ with an average size of 18–25 nm and 99% amorphous silicon dioxide content (Figure 1) was procured from Nanostructured and Amorphous Materials, Inc. (USA). Ordinary Portland cement type I (OPC) was used. The physical properties and chemical constitution of the OPC and nano-SiO₂ (NS) are summarized in Table 1.

2.2. Preparation of nanocomposites

Portland cement powder was partly replaced by nano-SiO₂ for 1%, 2%, and 3% weight percentages of cement (labeled 1NS, 2NS, and 3NS, respectively). Cement powders and NS were mixed as a dry binder for 10 min by using a Hobart mixer. The nanocomposites were prepared by via water to binder ratio of 0.48. According to ASTM C270 Standard [36], these nanocomposite pastes were mixed as wet mix for 5 min by using a Hobart mixer and subsequently case to the molds for a specific curing period. Details of the cement nanocomposites are listed in Table 2. For each mixture, five rectangular prism samples (7 × 2 × 1 cm³) were preserved in water for 28 d, after which, the samples were immediately dried and tested.

2.3. Characterization of nanocomposites

2.3.1. Investigation of the microstructures

XRD patterns of the nanocomposites and control composites were acquired using a D8 Advance Diffractometer (Bruker, Germany) with a Cu Ka (λ = 1.5406 Å) source. The scanning of 2-theta (2θ) from 7° to 70° was performed at a rate of 0.5°/min. Scanning electron microscope (SEM) images of the morphology and microstructure of each sample were obtained using the NEON 40ESB, ZEISS instrument (high-resolution imaging of 2.5 nm at 1 kV).

2.3.2. TGA

TGA was conducted using a TGA/differential scanning calorimetry analyzer (Mettler Toledo, 1 STAR) to evaluate the thermal stability of the mixtures. The tests were conducted in an argon atmosphere with a range of temperature from 35 to 1000 °C and the heating rate was 10 °C/min.

2.3.3. Sample porosity (P%)

Along with ASTM C20 Standard [37], the porosity value was determined using the Archimedes’ principle:

\[
P% = \frac{m_1 - m_2}{m_3 - m_1} \times 100 \quad (5)
\]

Table 1. Physical property and chemical constitution of cement and SiO₂ nanoparticles (NS)

| Property or Compositions | cement (Type I) | SiO₂ nanoparticles (NS) |
|-------------------------|-----------------|-------------------------|
| Specific surface area (m²/g) | 160 | 40% ≤ 7 µm |
| Particle size (nm) | 18-25 nm | 2.2-2.6 |
| Specific gravity | 3.17 | 2.2-2.6 |
| Chemical compound | wt% | wt% |
| SiO₂ | 21.10 | 99 |
| Fe₂O₃ | 3.10 | |
| Al₂O₃ | 5.24 | |
| CaO | 64.39 | |
| Na₂O | 0.23 | |
| SO₃ | 2.52 | |
| MgO | 1.10 | |
| LOI | 1.22 | |
| K₂O | 0.57 | |

Table 2. Mixture proportion of control composite and nanocomposites

| Type of mixtures | Cement (Type I) | Nano-SiO₂ (NS) | Water/ binder (cement + nano-SiO₂) |
|----------------|-----------------|-----------------|----------------------------------|
| C             | 100             | 0              | 0.48                             |
| 1NS           | 99              | 1              | 0.48                             |
| 2NS           | 98              | 2              | 0.48                             |
| 3NS           | 97              | 3              | 0.48                             |
$m_s$ is the saturated weight (weight of the sample saturated with water, measured in air), and $m_d$ is the dry weight. $m_i$ is the suspended weight (weight of the sample saturated with water, measured while suspended in water). All the weights were specified in grams (g).

2.3.4. Mechanical properties: flexural strength
A three-point bending flexural test (Figure 2) was implemented on a universal testing machine (LLOYD, 50 kN capacity) to measure the flexural strength. The test of five rectangular prism specimens ($7 \times 2 \times 1$ cm$^3$) of each type (control composites and nanocomposites) was estimated, and the displacement speed of 0.5 mm/min was used. The flexural strength can be evaluated as follows:

$$\sigma_F = \frac{3P_m S}{2BW^2} \quad (6)$$

where $P_m$, $S$, $B$, and $W$ denote the maximum force or load, span, width, and thickness of the specimen, respectively.

3. Results and discussion
3.1. The microstructural examination by XRD analysis
Figure 3(a–d) show the XRD patterns of the nanocomposites (1NS, 2NS, and 3NS) and control cement composite (C). The International Centre for Diffraction Data (ICDD) database for powder diffraction (patterns), file (PDF-4 2013), was considered to identify the phases. The XRD patterns exhibited three main phrases: (i) Portlandite (Ca(OH)$_2$; card no. PDF 00-044-1481), with two major $2\theta$ peaks corresponding to 18.01$^\circ$ and 34.10$^\circ$ and other small peaks at 28.67$^\circ$, 47.12$^\circ$, and 50.81$^\circ$; (ii) dicalcium silicate (C$_2$S; PDF 00-033-0302), with two main $2\theta$ peaks corresponding to 32.14$^\circ$ and 32.59$^\circ$; (iii) tricalcium silicate (C$_3$S; PDF 00-049-0442), with three main $2\theta$ peaks corresponding to 29.29$^\circ$, 32.12$^\circ$, and 32.46$^\circ$. A certain overlap could be between the peaks of the C$_2$S and C$_3$S phases, as shown in Figure 4(b).

The spectra presented in Figure 3 indicated that the incorporation of SiO$_2$ nanoparticles in the cement paste composites significantly modified the peak intensities.
of different phases of the nanocomposites compared to C, with the most notable change corresponding to 1NS. As shown in Figure 4(a), the reduction in the Ca(OH)$_2$ peaks indicated that nano-SiO$_2$ consumed additional CH through the pozzolanic reaction to form additional CSH products [38,39]. Moreover, as shown in Figure 4(b), the reduction in the C$_2$S and C$_3$S peaks indicated that the presence of SiO$_2$ nanoparticles accelerated the hydration reaction to produce more CSH products [40,41]. Thus, the microstructures of nanocomposites become denser than those of plain cement composites, as confirmed through the formation of additional CSH products. This enhancement indicated that nano-SiO$_2$ functions as a dispenser in the cement matrix, and the SiO$_2$ nanoparticles serve to promote the pozzolanic reaction.

Moreover, the XRD patterns indicated an increase in the intensity of gypsum peaks (2θ peaks corresponding to approximately 11.67°, as indicated in PDF Card 04-015-4421) with the increase in the SiO$_2$ nanoparticles content. Portland cement clinker contains tricalcium aluminate (C$_3$A) and gypsum (calcium sulfate hydrate CaSO$_4$·2H$_2$O). C$_3$A reacts with gypsum rapidly at the early age in the hydration reaction; however, the presence of SiO$_2$ NS likely delays this aluminate reaction, thereby reducing the consumption of gypsum. Thus, in the observed phenomenon, it was likely that a portion of gypsum had not reacted, and the aluminate reaction between C$_3$A and gypsum was still in progress [42,43]. This phenomenon has also been reported by other researchers. Hou et al. [44] studied the effect of 1 wt% nano-SiO$_2$ on the hydration process of C$_3$A-gypsum and C$_3$A-C$_3$S-gypsum systems and obtained similar results: The intensity of the gypsum peak, as observed in the XRD pattern for the C$_3$A-gypsum system with 1 wt% nano-SiO$_2$, was higher than that in the pattern for the C$_3$A-gypsum system without 1 wt% nano-SiO$_2$. Moreover, the authors derived a similar conclusion for C$_3$A-C$_3$S-gypsum systems containing 1 wt% nano-SiO$_2$: The mass fraction obtained through the quantitative XRD (QXRD) of gypsum was higher than that of the plain specimen after 12 d. The authors considered that the SiO$_2$ nanoparticles adsorbed on the surface of C$_3$A owing to the electrostatic interaction, which led to the retardation effect of the NS on the aluminate phases and aluminate reaction or hydration. However, the reaction between C$_3$A and either gypsum or water was still in progress at 28 d, and in later age, this reaction could likely enhance the microstructure and mechanical properties of the nanocomposite.

### 3.2. Sample porosity

The porosities of the C and nanocomposite samples are listed in Table 3. The addition of SiO$_2$ nanoparticles in the cement matrix significantly decreased the porosity of the nanocomposites compared to that of the C samples. The porosity of 1 NS nanocomposites was 23.6% smaller than that of the control paste. This enhancement highlighted that the microstructure of nanocomposites, especially those with 1 wt% nano-SiO$_2$, become more highly packed and compact. This enhancement could be attributed to the filling effect of NS [45–47].
However, the addition of more nano-SiO$_2$ led to an increased porosity, which indicated that the voids in the matrix grew due to the agglomerations of the high nano-SiO$_2$ contents. Oltulu and Sahin [48] reported that the incorporation of nano-SiO$_2$ in excess of the optimum ratio of 1.25 wt% could lead to an increase in the pore volume of nanocomposite mortars owing to the agglomeration of the NS.

### 3.3. Flexural strength

The flexural strengths of the samples are presented in Figure 5. The values for 1NS, 2NS, 3NS, and plain composites were 7.23, 6.64, 5.99, and 5.12 MPa, respectively. In particular, the flexural strengths of 1NS, 2NS, and 3NS were 41%, 30%, and 17% higher than that of the basic composite, respectively. This strength enhancement could be attributed to two factors, namely, the filler effect and pozzolanic reaction. In terms of the filler effect, the NS filled the voids in the porous CSH microstructures owing to their small size. Consequently, the CSH microstructure became denser. Furthermore, nano-SiO$_2$ likely supported the pozzolanic reaction, which increased the amount of CSH in the nanocomposites [49,50]. Notably, 1 wt% NS was the optimal ratio to achieve a high nanocomposite strength. Nazerigivi and Najigivi [51] conducted flexural strength tests and demonstrated that cement composites with 2% (15 nm) and 1.5% (80 nm) blends of nano-SiO$_2$ exhibited a higher strength in comparison with those of the other specimens. However, when the content of nanoparticles exceeded this critical optimal ratio, the porosity increased, which decreased the strength of the nanocomposites.
**Figure 5.** Flexural strengths at diverse contents of nano-SiO$_2$ (NS) for control composite (C) and nanocomposites (1NS, 2NS, 3NS) at 28 days.

**Figure 6.** (a-d). SEM photographs of (a) control composite (C), (b) 1NS, (c) 2NS, and (d) 3NS nanocomposites.
ratio, the strength reduced significantly owing to the agglomeration and low dispersion of the NS [52,53].

3.4. **SEM-based analysis of the sample morphology**

SEM micrographs of the nano-SiO$_2$ nanocomposites and control composite are shown in Figure 6(a–d). The comparative study for the SEM images of the specimens was focused on three factors, pertaining to the CSH gel, small pores mainly observed in the previous sections, and Ca(OH)$_2$ crystals. The microstructure of the control composite, as presented in Figure 6(a), had several pores as discussed in previous sections, few CSH products, and more Ca(OH)$_2$ crystals in comparison with those observed in the nanocomposite images. Furthermore, micro-cracking was observed. The addition of NS in the matrix of the composites improved the microstructure. As shown in Figure 6(b), the microstructure of 1NS nanocomposites was more compact with fewer voids and additional CSH gels because of the filler effect and pozzolanic activity. However, if the content of NS exceeded the critical or optimal ratio, agglomeration and low dispersion effects were observed in the microstructures of the nanocomposites [54,55]. For example, 3NS nanocomposites (Figure 6(b)) displayed more pores than 1NS nanocomposites.

3.5. **Examination of the thermal stability via TGA**

The thermal stability (weight loss (%)) of the nanocomposites and control composites was examined by performing a TGA. The TGA curves of the nanocomposites and control samples are displayed in Figure 7. The TGA curves of the samples exhibited three diverse decomposition stages or weight loss percentages. The first decomposition (35–230 °C) was attributed to the dehydration (loss of water) of CSH products. The second decomposition (400–510 °C) was related to the decomposition of Ca(OH)$_2$. The third decomposition (670–780 °C) corresponded to the decomposition of CaCO$_3$ [56–58]. Overall, the nanocomposites demonstrated a higher thermal stability than that of control composites from 35–1000 °C. This improvement could be attributed to the dense and compact microstructure of the nanocomposites owing to the effect of the fillers and pozzolanic activity, which led to the formation of additional CSH gel. Furthermore, 1NS nanocomposites displayed a higher thermal stability than that of the nanocomposites in all the decomposition stages. Notably, the agglomeration and low dispersion of nano-SiO$_2$ at high contents affected the thermal stability, as in the case of the 3NS nanocomposites.

4. **Conclusions**

Overall, the flexural strength and thermal stability of the nanocomposites were significantly enhanced with the incorporation of SiO$_2$ nanoparticles and nanocomposites with 1 wt% NS led to the highest strength and thermal stability. The XRD analysis and SEM images confirmed that the microstructures of the cement nanocomposites were denser compared to those of the control composites. The pozzolanic activity of nano-SiO$_2$ helped reduce the Ca(OH)$_2$, C$_3$S, and C$_2$S peaks, which led to the formation of further CSH products. Moreover, the filler effect of nano-SiO$_2$ helped reduce the number of pores in the microstructures of the nanocomposites. The agglomeration problem of nano-SiO$_2$ at higher contents requires further research. However, it was observed that the intensity of the unhydrated gypsum phase in the XRD patterns increased with an increase in the SiO$_2$ nanoparticle contents, which was suggestive of the retardation effect of
nano-SiO₂ on the aluminate phases and hydration. Nano-SiO₂ has prospective applications in building materials in the form of ceramic nanocomposites and fiber-reinforced concrete.

Acknowledgments

This study did not receive any funding or financial support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

A. Hakamy  http://orcid.org/0000-0003-0313-7064

References

[1] Contreras J, Rodríguez E. Nanostructured insulators – A review of nanotechnology concepts for outdoor ceramic insulators. Ceram Int. 2017;43:8545–8550.
[2] Kholiya K, Pandey K. High pressure compression behaviour of bulk and nanocrystalline SnO₂. J Taibah Univ Sci. 2019;13:592–596.
[3] Mathew J, Joy J, George C. Potential applications of nanotechnology in transportation: A review. J King Saud Univ Sci. 2019;31:586–594.
[4] Sharma G, Kumar A, Sharma S, et al. Novel development of nanoparticles to bimetallic nanoparticles and their composites: A review. J King Saud Univ Sci. 2019;31:257–269.
[5] Nadafan M, Tohidifar M. Evaluation of structural, optical and dielectric properties of MWNTBaTiO₃/silica ceramic nanocomposites. Ceram Int. 2020;46:12243–12248.
[6] Askari S, Ghashang M, Sohrabi G. Synthesis and mechanical properties of Bi₂O₃-Al₂O₃-B₂O₃ nanoparticles. J Compos Compd (JCC). 2020;2:171–174.
[7] Zamani Y, Zareein A, Bazli L, et al. Nanodiamond-containing composites for tissue scaffolds and surgical implants: A review. J Compos Compd (JCC). 2020;2:215–227.
[8] Niaazvand F, Cheshmi A, Zand M, et al. An overview of the development of composites containing Mg and Zn for drug delivery. J Compos Compd (JCC). 2020;2:193–204.
[9] Bazli L, Yusuf M, Farahani A, et al. Application of composite conducting polymers for improving the corrosion behavior of various substrates: A review. J Compos Compd (JCC). 2020;2:228–240.
[10] Ghazanfari H, Hasanzadeh S, Eskandarinezhad S, et al. Recent progress in materials used towards corrosion protection of Mg and its alloys. J Compos Compd (JCC). 2020;2:205–214.
[11] Jam F, Houri H, Ferdosi M. Characterization of TiB₂ reinforced aluminum matrix composite synthesized by in situ stir casting method. J Compos Compd (JCC). 2020;2:163–170.
[12] Khalil K, Bashal A, Khalafalla M, et al. Synthesis, structural, dielectric and optical properties of chitosan-MgO nanocomposite. J Taibah Univ Sci. 2020;14:975–983.
[13] Atif R, Shyha I. Mechanical IF. Thermal, and electrical properties of graphene-epoxy nanocomposites—A review. Polym. 2016;8:Article number.28.
[14] Hakamy A. Effect of CaCO₃ nanoparticles on the microstructure and fracture toughness of ceramic nanocomposites. J Taibah Univ Sci. 2020;14:1201–1207.
[15] Hakamy A, Shaikh F, Low L. Characteristics of nanoclay and calcined nanoclay-cement nanocomposites. Compos Part B. 2015;78:174–184.
[16] Ghafari E, Ghahari S, Feng Y, et al. Effect of Zinc oxide and Al-Zinc oxide nanoparticles on the rheological properties of cement paste. Compos Part B. 2016;105:160–166.
[17] Balata A, Mazu J. Effect of carbon nanoparticle reinforce-ment on mechanical and thermal properties of silicon carbide ceramics. Ceram Int. 2018;44:10273–10280.
[18] Joshtagani A, Balapour M, Mashhadian M, et al. Effects of nano-TiO₂, nano-Al₂O₃, and nano-Fe₂O₃ on rheology, mechanical and durability properties of self-consolidating concrete (SCC): An experimental study. Constr Build Mater. 2020;245:Article number 118444.
[19] Shafeek A, Khedir H, El-Dek S, et al. Influence of ZnO nanoparticle ratio and size on mechanical properties and whiteness of white Portland cement. Appl Nanosci. 2020;10:3603–3615.
[20] Birenboim M, Nadiv R, Alatawna A, et al. Reinforcement and workability aspects of graphene-oxide-reinforced cement nanocomposites. Compos Part B. 2019;161:68–76.
[21] Sun J, Dong H, Wu J, et al. Properties evolution of cement-metakaolin system with C-S-H/PCE nanocomposites. Constr Build Mater. 2021;282:Article number 122707.
[22] Oh J, Zhuge Y, Araby S, et al. Cement nanocomposites containing montmorillonite nanosheets modified with surfactants of various chain lengths. Cem Concr Compos. 2021;116:Article number 103894.
[23] Lavagna L, Massella D, Priola E, et al. Relationship between oxygen content of graphene and mechanical properties of cement-based composites. Cem Concr Compos. 2021;115:Article number 103851.
[24] Kothiyal NC, Kaur R. Synergistic effect of hybrid carbon nanomaterials as reinforcing phase on the physico-mechanical properties and pore structure refinement of cementitious nanocomposites. In: Reddy KR, Agnihotri AK, Yukselen-Aksoy Y, Dubey BK, Bansal A, editor. Sustainable environment and infrastructure. lecture notes in civil engineering, vol 90. Cham: Springer;2021. p. 83–94. doi:10.1007/978-3-030-51354-2_8.
[25] Papadakis V. Experimental investigation and theoretical modeling of silica fume activity in concrete. Cem Concr Res. 1999;29:79–86.
[26] Wang Y, Ying G, Hu J, et al. Analysis for Influence factors of cold recycling mixture compaction test. Appl Mech Mater. 2012;204:1633–1637.
[27] Roychand R, Silva S, Setunge S, et al. A quantitative study on the effect of nano SiO₂, nano Al₂O₃ and nano CaCO₃ on the physicochemical properties of very high volume fly ash cement composite. Eur J Environ Civ Eng. 2017;1:2116–7214.
[28] Pane I, Hansen W. Investigation of blended cement hydration by isothermal calorimetry and thermal analy-sis. Cem Concr Res. 2005;35:1155–1164.
[29] Qing Y, Zenan Z, Deyu K, et al. Influence of nano-SiO₂ addition on properties of hardened cement paste as compared with silica fume. Constr Build Mater. 2007;21:539–545.
[30] Ghafari E, Costa H, Julio E, et al. The effect of nanosilica addition on flowability, strength and transport properties of ultra-high performance concrete. Mater Design. 2014;59:1–9.
[31] Liu X, Feng P, Shu X, et al. Ran. effects of highly dispersed nano-SiO$_2$ on the microstructure development of cement pastes. Mater Struct. 2020;53:Article number 4.

[32] Hongjian D. Properties of ultra-lightweight cement composites with nano silica. Constr Build Mater. 2019;199:696–704.

[33] Zhang X, Yang H, Yang Q, et al. Effects of particle size of colloidal nanosilica on hydration of Portland cement at early age. Adv Mech Eng. 2019;11(2):1–9.

[34] Zhuang C, Chen Y. The effect of nano-SiO$_2$ on concrete properties: a review. Nanotech Rev. 2019;8:562–572.

[35] Biricik H, Sarier N. Comparative study of the Characteristics of nano silica. Silica Fume and Fly Ash–Incorporated Cement Mortars. Mater Res. 2014;17:570–582.

[36] ASTM C270. Standard specification for mortar for unit masonry. West Conshohocken: ASTM international; 2010.

[37] ASTM C20. Standard test methods for apparent porosity, water absorption, apparent specific gravity, and bulk density of burned refractory brick and shapes by boiling water. West Conshohocken: ASTM international; 2010.

[38] Kontoleontos F, Tsakiridis P, Marinos A, et al. Influence of colloidal nanosilica on ultrafine cement hydration: Physicochemical and microstructural characterization. Constr Build Mater. 2012;35:347–360.

[39] Wang L, Zheng D, Zhang S, et al. Effect of nano-SiO$_2$ on the Hydration and Microstructure of Portland cement. Nanomater. 2016;6:Article number 241.

[40] Land G, Stephan D. The influence of nano-silica on the hydration of ordinary Portland cement. J Mater Sci. 2012;47:1011–1017.

[41] Zhang A, Ge Y, Yang W, et al. Comparative study on the effects of nano-SiO$_2$, nano-Fe$_2$O$_3$ and nano-NiO on hydration and microscopic properties of white cement. Constr Build Mater. 2019;228:Article number 116767.

[42] Wang X, Hou P, Yu J, et al. The effects of silica fume on C$_3$A hydration. Constr Build Mater. 2020;250:Article number 118766.

[43] Zheng D, Monasterio M, Feng W, et al. Hydration Characteristics of tricalcium aluminate in the presence of nanosilica. Nanomater. 2021;11:Article number 199.

[44] Hou P, Wang X, Zhao P, et al. Physicochemical effects of nanosilica on C$_3$A/C$_3$S hydration. J Am Ceram Soc. 2020;103:6505–6518.

[45] Wang L, Zheng D, Zhang S, et al. Effect of nano-SiO$_2$ on the Hydration and Microstructure of Portland cement. Nanomater. 2016;6:Article number 241.

[46] Balapour M, Joshaghani A, Althoey F. Nano-SiO$_2$ contribution to mechanical, durability, fresh and microstructural characteristics of concrete: A review. Constr Build Mater. 2018;181:27–41.

[47] Emamian S, Eskandari-Naddaf H. Effect of porosity on predicting compressive and flexural strength of cement mortar containing micro and nano-silica by ANN and GEP. Constr Build Mater. 2019;218:8–27.

[48] Oltulu M, Sahin R. Pore structure analysis of hardened cement mortars containing silica fume and different nano-powders. Constr Build Mater. 2014;53:658–664.

[49] Gao X, Li Q, Xu S. Influence of hybrid fibers on flexural properties of ultra high toughness cementitious composites with nano-SiO$_2$. Key Eng Mater. 2015;645:411–415.

[50] Balapour M, Joshaghani A, Althoey F. Nano-SiO$_2$ contribution to mechanical, durability, fresh and microstructural characteristics of concrete: A review. Constr Build Mater. 2018;181:27–41.

[51] Nazerigivi A, Najigivi A. Study on mechanical properties of ternary blended concrete containing two different sizes of nano-SiO$_2$. Compos Part B. 2019;167:20–24.

[52] Long Z, Sun W, Xiao H, et al. Effects of nano-SiO$_2$ particles on the mechanical and microstructural properties of ultra-high performance cementitious composites. Cem Concr Compos. 2015;56:23–31.

[53] Kara I, Durmus O. Effect of nano silica on cement mortars containing micro silica. Chall J Conc Res Lett. 2019;10(2):42–49.

[54] Abdelaleem S, Heikal M, Morsi W. Hydration characteristic, thermal expansion and microstructure of cement containing nano-silica. Constr Build Mater. 2014;59:151–160.

[55] Isfahani F, Redaelli E, Lollini F, et al. Effects of nanosilica on compressive strength and durability properties of concrete with different water to binder ratios. Adv Mater Sci Eng. 2016; Article number 8453567.

[56] Singh L, Agarwal S, Bhattacharyya S, et al. Preparation of silica nanoparticles and its beneficial role in cementitious materials. Nanomater Nanotechno. 2011;1:44–51.

[57] Tsampali E, Tsardaka E, Pavlidou E, et al. Comparative study of the properties of cement pastes modified with nano-silica and nano-alumina. Solid State Phenom. 2019;286:133–144.

[58] Rojas D, Gomez P, Flores J. Effect of silica nanoparticles on the mechanical and physical properties of fiber cement boards. J Build Eng. 2020;31:Article number 101332.