



# Influence of different types of nano-SiO<sub>2</sub> particles on properties of high-performance concrete



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## HIGHLIGHTS

- Effect of different sizes of nano-SiO<sub>2</sub> particles on HPC properties was investigated.
- By decreasing w/b ratio, coarser nano-SiO<sub>2</sub> improved mechanical properties of HPC more than finer type.
- Finer nano-SiO<sub>2</sub> showed higher pozzolanic activity than coarser nanoparticles.
- Probability of nano-SiO<sub>2</sub> agglomeration was increased by using finer type.
- Coarser type of nano-SiO<sub>2</sub> led to a finer pore structure compared to finer particles.

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## ABSTRACT

The aim of this study was to evaluate the effects of applying low replacement ratios (0.75% and 1.50% of the binder weight) of nano-SiO<sub>2</sub> particles with different specific surface areas (200 and 380 m<sup>2</sup>/g) on the properties of high-performance concrete (HPC). Mechanical (compressive and splitting tensile strengths), electrical resistivity, non-destructive (ultrasonic pulse velocity), and microstructural (mercury intrusion porosimetry, X-ray diffraction, and scanning electron microscopy) tests were conducted to investigate the macroscopic and microscopic effects of nano-SiO<sub>2</sub> particles on HPC characteristics.

The results indicated that the performance of nano-SiO<sub>2</sub> particles significantly depended on their specific surface areas and the water to binder (w/b) ratio of the mixtures. By decreasing the HPC w/b ratio from 0.35 to 0.25, nano-SiO<sub>2</sub> particles with lower specific surface area performed better than finer one (higher specific surface area). Microstructural investigations demonstrated that the decrease in efficiency of nano-SiO<sub>2</sub> particles with higher specific surface area at lower w/b ratio correlates to the formation of nanoparticles agglomerates, particularly at the higher replacement ratio of nanosilica (1.5%). However, the influence on the compressive and splitting tensile strengths and electrical resistivity varied due to differences in performance of nano-SiO<sub>2</sub> particles affected the mechanical and durability properties.

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## 1. Introduction

In recent years, improving the durability of cement-based products has become a key factor to improve the lifespan of concrete structures [1]. Indeed, durability enhancement of cement-based materials can extend the service life of concrete structures, particularly infrastructures and special structures, such as sewage systems, highway bridges, tunnels, and marine structures, which are important for every society.

Increasing the service life of concrete structures can delay the demolition and reconstruction of these structures. As a result, in a specific period, less debris can be produced by demolition and

fewer construction materials will be consumed for reconstruction. In fact, less construction waste will be generated and fewer raw materials will be required for production of construction materials.

High-performance concrete (HPC) is designed with high workability, high strength, and high durability [2]. The design of HPC is based on selecting low water to binder ratios (usually between 0.25 and 0.35), limiting maximum aggregate size, and the application of highly reactive pozzolanic materials, such as blast furnace slag, silica fume, and fly ash [3,4].

Nanoparticles have been widely recognized as the most important products of nanotechnology [5]. These particles have significant effects on the properties of different products according to their fine dimensions, physical and chemical properties. Among the different nanoparticles available in the market, nano-SiO<sub>2</sub> particles significantly affect the properties of cement-based composites

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because of their high purity (greater than 99%), and high specific surface areas [6,7]. Numerous researchers have investigated the effects of nano-SiO<sub>2</sub> particles on the performance of cement-based materials, such as cement paste, mortar, and concrete [5–9]. According to previous research [5–10], nano-SiO<sub>2</sub> particles enhance the mechanical performance and durability properties of cement-based materials and thicken cementitious fresh mixtures. However, the application of large amounts of nano-SiO<sub>2</sub> particles (more than 5% cement replacement) can lead to detrimental effects on the mechanical and durability properties of cement-based materials [11,12]. This can be attributed to the high specific surface areas of nano-SiO<sub>2</sub> particles, increasing the probability of nanoparticle agglomeration and consequently causing poor dispersion of nano-SiO<sub>2</sub> particles in the cement-based matrices [13,14]. The high specific surface areas of nano-SiO<sub>2</sub> particles can affect the fresh properties of cement-based mixtures because of the absorption of water molecules at their surface [8,9]. Nano-SiO<sub>2</sub> particles thicken fresh mixtures, increasing the probability of air bubbles entraining during mixture casting and inhibiting proper compaction of specimens [6,7,11]. Increasing the specific surface area of nano-SiO<sub>2</sub> particles by decreasing their dimensions can intensify the agglomeration of these particles because of the increasing particle surface energy [12]. By increasing the specific surface area of the nano-SiO<sub>2</sub> particles and/or the incremental addition of these nanoparticles, the dispersion of nano-SiO<sub>2</sub> particles becomes more difficult [15,16]. Therefore, special dispersion methods, such as ultrasound mixing may be required, significantly increasing the fabrication costs of cement-based specimens [16,17].

To avoid the application of special mixing procedures and to develop HPC mixtures using conventional mixing methods, the utilization of low replacement ratios of nano-SiO<sub>2</sub> particles (0.75% and 1.50%) was considered in this study. Furthermore, based on the high specific surface areas of nano-SiO<sub>2</sub> particles (200 and 380 m<sup>2</sup>/g) utilized and low water to binder ratios (0.25, 0.30, and 0.35) of the concrete mixtures, it is reasonable to apply such low nanosilica dosages.

Because of the importance of HPC application for concrete infrastructures, nano-SiO<sub>2</sub> particles can be utilized as a highly reactive pozzolanic material in the HPC matrix. However, there is limited published research on fabricating HPC by incorporating nano-SiO<sub>2</sub> particles [18,19]. According to Baomin et al. [18], nano-SiO<sub>2</sub> can develop the microstructure of HPC and consequently improve the freezing resistance of specimens. Pacheco-Torgal et al. [19] stated that further investigations are required to discover which nanoparticles are the most effective for developing high durability mixtures, such as HPC.

Considering the previously presented information related to the importance of HPC production and the use of nano-SiO<sub>2</sub> particles in concrete, the aim of this study is to assess the feasibility of the application of low replacement ratios of nano-SiO<sub>2</sub> particles (0.75% and 1.50%) with different specific surface areas (200 and 380 m<sup>2</sup>/g) in the production of HPC mixtures. To determine the properties of HPC incorporating nano-SiO<sub>2</sub> particles, different tests were conducted. The compressive and splitting tensile strengths were obtained to evaluate the mechanical performance of the nano-reinforced HPC specimens. To investigate the effects of nano-SiO<sub>2</sub> particles on the pore structure of the HPC matrices and their conductivity, mercury intrusion porosimetry (MIP) and electrical resistivity tests, respectively, were performed. In addition, to develop a regression model for predicting compressive strength with a non-destructive test, the ultrasonic pulse velocity (UPV) through the concrete specimens was determined. X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests were conducted on high-performance cement paste and concrete fragments to explain the primary behaviors of nano-SiO<sub>2</sub> particles that affect the mechanical and durability properties of the HPC specimens.

## 2. Experimental plan

### 2.1. Materials

The binder included cement and nano-SiO<sub>2</sub> particles (pyrogenic type) with different specific surface areas. The cement used was Type II Portland cement that meets the requirements of ASTM C 150 [20].

The pyrogenic nanosilicas are generally produced through reaction of silicon tetrachloride, hydrogen and oxygen in high temperature furnaces [21–23]. They can be produced with different specific surface areas ranging from about 50 m<sup>2</sup>/g to 400 m<sup>2</sup>/g [23]. In the production process of these materials, the particles fuse together and form primary aggregates with dimensions up to a hundred nanometers. The primary aggregates also bind together and form agglomerates up to about a few hundred micrometers in length [21–24]. Therefore, the main product has particles with dimensions of micrometers containing millions of SiO<sub>2</sub> nanoparticles. The physical and chemical properties of the cement and pyrogenic nanosilicas are listed in Tables 1 and 2, respectively.

A polycarboxylate-based superplasticizer (with 40 ± 1% solid content, pH of 7 ± 1, and specific gravity of 1.12 ± 0.05 at 20.4 °C) was employed to aid the dispersion of the nanoparticles and achieve good flowability in the HPC mixtures. Coarse aggregate with a maximum size of 19 mm, a specific gravity of 2.73, and water absorption of 1.61% was used. The fine aggregate was natural river sand with a specific gravity of 2.63, absorption of 2.59%, and fineness modulus of 3.17. Both the coarse and fine aggregates met the requirements of ASTM C 33 [25]. Potable water was used for the preparation of the HPC mixtures.

### 2.2. Mixing and testing procedures

The binder content (550 kg/m<sup>3</sup>) was kept constant for all of the HPC mixtures. In addition, the ratio of coarse aggregate to fine aggregate was maintained at 1.5. Three water to binder ratios (0.25, 0.30, and 0.35) were selected for use in fabricating the HPC mixtures. Portland cement was partially replaced with pyrogenic nanosilicas at the two addition ratios of 0.75% and 1.50% by weight. To achieve a constant slump level (26 ± 1 cm), a superplasticizer was used at different dosages for all mixtures. Table 3 presents the mix proportions of the HPC mixtures.

To fabricate homogenous and uniform HPC mixtures, the following procedure was employed:

- Coarse and fine aggregates in a saturated surface dry (SSD) condition were added to the pan type mixer and were mixed together for one min.
- Cement was added to the mixer and the ingredients were mixed together for 30 s.
- Slurry of pyrogenic nanosilica (if applicable) was added into the mixer and the mixture was mixed for approximately two min.
- The remaining mixing water (in the mixtures containing nanosilica) or the entire quantity of water (in the control mixtures) incorporated with the superplasticizer were added to the mixer and mixing was continued for four min.

To improve the performance of pyrogenic nanosilicas in the HPC matrix, a pre-dispersion method was used. At each w/b ratio, nanosilica slurry, in the form of a colloidal dispersion with 10% solid content, was prepared by mechanical mixing using a high-shear mixer rotating at 1500 rpm. The water required for preparing the nanosilica slurry was a portion of the mixing water. The main reason for pre-dispersion was efficient de-agglomeration of the nano-SiO<sub>2</sub> particles before using them to fabricate HPC mixtures.

Immediately after mixing, a portion of the fresh mixture was used for measuring slump and slump flow of the fresh HPC mixtures according to ASTM C 143 [26] and ASTM C 1611 [27], respectively. The remaining fresh mixture was then poured into oiled molds to form 100 mm cubes for compressive strength and electrical resistivity tests and ultrasonic pulse velocity measurement. Cylinders of

**Table 1**  
Chemical composition and physical properties of cement.

Chemical composition	Percent (wt%)
CaO	63.0
SiO <sub>2</sub>	20.4
Al <sub>2</sub> O <sub>3</sub>	4.9
Fe <sub>2</sub> O <sub>3</sub>	3.9
MgO	1.7
SO <sub>3</sub>	2.0
Na <sub>2</sub> O + K <sub>2</sub> O	0.9
Loss on ignition (LOI)	1.5
<i>Physical properties</i>	
Specific gravity	3.12
Blaine fineness (m <sup>2</sup> /kg)	295
Average particle size (μm)	26

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