Construction and Building Materials 68 (2014) 402–408

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Performance of nano-Silica modified high strength concrete at elevated temperatures

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## HIGHLIGHTS

- We studied effect of elevated temperature on HSC modified with nano-Silica (nS).
- We studied compressive($f'_c$ > 80 MPa) and tensile strengths, spalling and mass loss.
- nS used in HSC can improve its mechanical properties at elevated temperature.
- The presence of nS improved the tensile strength to prevent crack extension.
- The addition of nS was more effective than SF for increasing residual strengths.

## ARTICLE INFO

*Article history:*
Received 29 March 2014
Received in revised form 15 June 2014
Accepted 17 June 2014

*Keywords:*
Nano-Silica
Silica fume
High strength concrete
Elevated temperature

## ABSTRACT

This research studied effect of elevated temperature on of high strength concrete (HSC) modified with nano-Silica (nS) and on its compressive and tensile strengths, spalling, and mass loss ($f'_c$ > 80 MPa). This research studied the effect of elevated temperature on the compressive and tensile strength, spalling, and mass loss of HSC modified with nS. Six sample mixtures contained varying amounts of nS and two samples did not contain nS are considered in the experimental program. The mechanical properties of the modified HSC were measured by heating 150 × 300 mm sample cylinders of concrete to 400, 600 and 800 °C at a rate of 20 °C/min. The obtained results demonstrate that nS efficiently used in HSC can improve its mechanical properties at elevated temperature. The results show that the presence of nS increased residual compressive and tensile strengths, and spalling and mass loss are decreased as penetrability increased.



## 1. Introduction

### 1.1. General effects of nano-Silica

Different effects are produced by the addition of nano-Silica (nS) or Silica Fume (SF) powder to concrete. Adding micro-silica decreases the amount of cement required an effect that is more pronounced for nS [1–5]. The main mechanism of this working principle is the high surface area of nS, which acts as a nucleation site for the precipitation of CSH gel [5]. Bjornstrom et al. [6] assert that it is unclear whether the more rapid hydration of cement in the presence of nS is caused by its chemical reactivity upon dissolution (pozzolanic activity) or increased surface activity. Viscosity test results have shown that cement paste and mortar with nS require more water to maintain the workability of the mixtures; moreover, nS exhibits a stronger tendency for adsorption of ionic species in the aqueous medium, thus, the formation of agglomerates is expected. In the latter case, a dispersing additive or plasticizer is required to minimize this effect [5].

At high nS concentrations, autogenous shrinkage occurs as self-desiccation increases, resulting in higher cracking potential. To avoid this effect, researchers have added high concentrations of superplasticizer and water and applied appropriate curing methods [5–7]. The superplasticizer was applied at 2.6–4.2% of binder mass depending on the ratio of nS.

Microstructural analysis of concrete using electronic microscope techniques (SEM, ESEM, TEM) has revealed that the microstructure of nS concrete is more uniform and compact than normal concrete. Particles of nS fill the voids of the CSH gel structure and function as nuclei to tightly bond with CSH gel particles. This means that the application of nS decreases the calcium leaching rate of cement paste and increases its durability [3–11]. SEM has shown that nano-$Fe_2O_3$ and nS particles fill the pores and

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http://dx.doi.org/10.1016/j.conbuildmat.2014.06.026
0950-0618/

decrease the content of $Ca(OH)_2$ in the hydration products. These effects improve the mechanical properties of mortars with nanoparticles [12–13].

Jo et al. [14] studied the characteristics of cement mortar with nS particles and showed that nano-scale $SiO_2$ behaved as a filler to improve the microstructure and as an activator to promote the pozzolanic reaction. Ji [15] studied water permeability resistance and the microstructure of concrete with nS. The water permeability tests revealed that, for concretes having similar 28-day strength, the incorporation of nS improved resistance to water penetration.

The most-often reported effect of nS is its impact on the mechanical properties of concrete and mortars. The addition of nS increases the density, decreases porosity, and increases the bond between the cement matrix and aggregates [3,5,8,16,17]. The presence of nS also produces concrete that exhibits higher compressive and flexural strength [13,18–20]. For example, Li et al. [13] studied the mechanical properties of cement mortars with nano-$Fe_2O_3$ and nS. Their study demonstrated an increase in compressive and flexural strength for mortars containing nanoparticles. It has also been determined that an increase in nS increases the strength of mortars over the strength of mortars with silica fume [12–13].

### 1.2. Thermal properties of nano-Silica

No research has focused thus far on the effect of nS on the performance of HSC at elevated temperatures. Sobolev et al. [21] studied the thermal properties of nS products. They employed thermal treatment to 800 °C to remove the functional groups from synthesized nS particles. The treatment did not trigger the formation of a crystalline structure; however, it affected the surface area and porosity of the products. It was observed that the surface area of particles treated at 400 °C increased from 27,000 $m^2$/kg (initial area of particles dried at 70 °C) to 510,000 $m^2$/kg. On the other hand, treatment at 600 °C and, especially, at 800 °C resulted in products with decreased surface area (482,000 $m^2$/kg and 80,000 $m^2$/kg, respectively). The pore size steadily increased as temperature increased, reaching 5 nm for specimens treated at 800 °C.

Nanoparticles such as silicon dioxide have been found to be highly effective additives for polymers and concrete; which has led to the development of high-performance self-compacting concrete with improved workability and strength. The application of an effective superplasticizer helps disperse agglomerates and, for certain nS products, improves the strength of Portland cement mortars at all ages of hardening to a 90-day compressive strength of up to 144.8 MPa. It can be concluded that high-temperature treatment ($\geqslant$400 °C) of nS adversely affects the performance of these additives and must be avoided. Ultrasonification is effective for restoring the performance of thermally-treated nS; however, it is not a highly effective disagglomeration method for standard nanoparticles dried at 70 °C [12,21].

Previous studies have shown that the behavioral difference between HSC with and without SF is its effect on normal compressive strength; while the relative strength of heated specimens with SF is not significantly affected, it affects the spalling ratio significantly [1].

This study investigated the effects of nS on the properties of HSC at elevated temperatures. Specimens containing nS were compared to specimens without nS for spalling, residual compressive strength and mass loss.

## 2. Materials

The cement employed was ordinary Portland cement with silica fume powder and liquid nS particles. Their pertinent chemical and physical properties, as provided by the manufacturer, are shown in Table 1. The fine aggregate was natural river sand with a fineness modulus of 3.0. Crushed siliceous gravel with a maximum nominal size of 10 mm was used.

## 3. Testing

The mix proportions of eight high strength concrete mixes are shown in Table 2. These were determined based on previous research [1,22] to achieve optimum strength and performance at a maximum temperature of 800 °C.

Five parameters were examined: water to binder ratio, crass, fine ratio, silica fume and nS. Testing was performed on six mixtures with nS (M2, M3, M4, M6, M7 and M8) and two without nS (M1 and M5). All specimens were stored in the laboratory at a room temperature of 25 ± 3 °C. For each test, all results are an average of three measurements.

Concrete cylinder specimens (150 × 300 mm) from each mix batch were selected after 28 d of water curing. Their weights and densities were measured and recorded under saturated surface-dry conditions. The cylinders were then stored at room temperature until they reached a constant dry weight. Three representative concrete cylinder specimens from each batch were then chosen.

The mechanical properties of the HSC were measured by heating the cylinders at 20 °C/min to temperatures of 400, 600 and 800 °C. This was maintained for 1 h and the cylinders were then gradually cooled to room temperature for 24 h before the residual strength tests were conducted.

Time–temperature curve of the furnace is approximately fitted with the standard curve recommended by ISO Fire 834 [23]. The heating rate of the experimental curve was slightly less than the ISO recommendation, which was a limitation imposed by available equipment. It is likely that this had only a minimal effect on the results, since the duration of exposure at the maximum temperature was 1 h.

The mixtures used 3% nS, 1.5%, 3% and 4.5% cement, and 0%, 33.3%, 100% and 300% SF. The total mass for nS and SF was held constant in M1–M4 at 30 kg/$m^3$ and in M5–M8 at 60 kg/$m^3$. The ratio of water to binder, coarse aggregate, and fine aggregate were held constant to maximize the effect of nS.

Each concrete batch included three cylinders that were cured normally as a control when measuring the ultimate compressive strength of unheated concrete. The compressive strength of the heated specimens was compared with the unheated control cylinders to establish the effect of heating on strength, spalling and mass loss.

## 4. Test results and discussion

There was no visible effect on the surface of specimens heated to 400 °C. Large cracks and partial spalling of specimens was observed at 600 °C. The aggregates decomposed and lost their integrity at 800 °C. The properties of concrete after exposure to fire can be assessed by observing the color change of the concrete. Table 3 shows the performance and spalling of the specimens at 400, 600, and 800 °C.

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

| Item | Chemical composition (%) | | Chemical (%) |
|---|---|---|---|
| | Portland cement Type1 | SF | nS |
| $S_iO_2$ | 22 | 95.0 | 99.89 |
| $AL_2O_3$ | 6.6 | 0.9 | 0 |
| $Fe_2O_3$ | 2.8 | 0.6 | 0 |
| CaO | 60.1 | 0.3 | 0 |
| MgO | 3.3 | 0.9 | 0 |
| $SO_3$ | 2.1 | 0.5 | 0 |
| LOI | 2.6 | 2.1 | 0.11 |
| Specific gravity | 3.15 | 2.33 | |
| Mean size of particles | 13 μm | 0.1 μm | 45 nm |
| SSA ($m^2$/g) | 0.38 | 20 | 60 |