Construction and Building Materials 153 (2017) 506–513

Contents lists available at ScienceDirect

Construction and Building Materials

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

Studies on enhanced thermally stable high strength concrete incorporating silica nanoparticles

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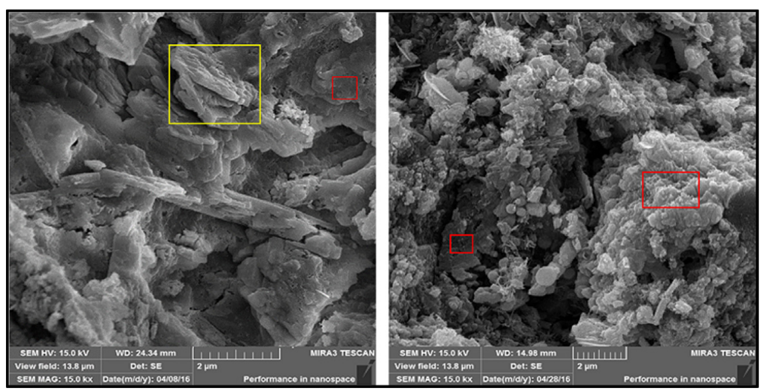
HIGHLIGHTS

- Thermal degradation in SNPs-HSC specimens is delayed as compared to the control HSC specimens.
- Microstructural changes revealed that SNPs-HSC specimens have a stable microstructure up to a temperature of 400 °C.
- The strength of SNPs-HSC specimens has increased significantly up to 400 °C unlike the control HSC specimens.
- The elastic modulus of SNPs-HSC specimens was higher than that of control HSC specimens even up to 600 °C.

GRAPHICAL ABSTRACT

Surface textural and morphological presentation of control HSC and SNPs specimens after exposure to 400 °C.



ARTICLE INFO

Article history:
Received 23 January 2017
Received in revised form 28 June 2017
Accepted 4 July 2017

Keywords:
High strength concrete
Time-temperature studies
SNPs
Microstructure

ABSTRACT

The performance of silica nanoparticles incorporated high strength concrete (SNPs-HSC) has been evaluated under elevated temperature conditions by exposing up to 800 °C, followed by cooling to ambient temperature before performing experiments. Time-temperature studies revealed that incorporation of silica nanoparticles (SNPs) in concrete mix delays the heat transfer by 11%, 18%, 22% and 15% at 200 °C, 400 °C, 600 °C and 800 °C respectively thereby, decreasing the rate of degradation as compared to the conventional high strength concrete (HSC). A reduction in weight loss was observed in SNPs-HSC specimens after exposure to 200 °C, 600 °C, and 800 °C; whereas at 400 °C the weight loss quantity was ~3.5% higher than the control HSC specimens due to the evaporation of water from calcium silicate hydrate (C-S-H) gel. On exposure up to 400 °C for 2 h, the compressive strength and split-tensile strength increased by 40% and 13% respectively, for SNPs-HSC specimens, whereas in control HSC specimen's strength didn't increase after 200 °C. A higher residual compressive (7%) and split-tensile strength (8%) was found to be in SNPs-HSC specimens exposed to 800 °C for 2 h as compared to the control HSC specimens. The stress-strain curves revealed that SNPs-HSC specimens exhibits brittle failure up to 600 °C whereas in control HSC brittle failure was observed only up to 400 °C. Microstructural studies performed on the samples taken from the core of the 400 °C exposed SNPs-HSC revealed the formation of higher C-S-H content and lower amount of calcium hydroxide (CH) leading to their enhanced mechanical and thermal stability.

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.057
0950-0618/

1. Introduction

Recently, high strength concrete is becoming a material of choice owing to its wide range of applications in high-rise buildings, bridges, shells of a nuclear reactor, etc. Its use enables a reduction in the size of compression elements and the quantity of reinforcement required. Conventionally, HSC is produced by reducing the amount of water and by incorporating the several additives namely silica fume, fibres, reactive powders, etc., leading to the decrease in porosity, but this makes it more brittle and less fire resistant [1,2]. Apart from this, the mechanical properties of concrete such as compressive strength, stiffness, modulus of elasticity, etc. are significantly reduced during fire exposures and one of the major drawbacks of HSC when exposed to elevated temperature is explosive spalling, which is responsible for the sudden failure of the structure [3,4]. The residual mechanical properties of concrete post-fire exposure are of great importance in determining the load bearing capacity of structural members required for retrofitting and restoration of the concrete structures.

Researchers have evaluated the residual mechanical properties of HSC exposed to elevated temperature and reported a decrease of 14–25% in compressive strength when exposed to 100 °C [1,4], whereas an improvement of 2–5% in strength has been reported at 200 °C [1,4,5] but according to Li et al. [6] there was a gradual decrease in strength up to this temperature. According to Chang et al. [7], a decrease of only 1–10% in compressive strength was observed up to 400 °C, while most of the studies revealed that the major loss of compressive strength occurred in the range of 400–800 °C. A significant decrease of 45–70% in the strength was observed as the exposure temperature was elevated to 600 °C [1,4,6,7]. However, Bastami et al. [8], have observed a much higher strength decrement of 64–82% after exposure to 800 °C and that too in specimens which are free of silica fume. In addition to the compressive strength, the tensile strength of concrete plays a significant role in concrete structures, because it results in the cracking of concrete on the application of tensile stress [9]. However, limited studies are available on the splitting tensile strength of the HSC at elevated temperature. According to Li et al. [6] and Chang et al. [7], a major loss of 20–80% in split-tensile strength was observed in the temperature range of 400–800 °C. However, according to Khaliq and Kodur [9], split-tensile strength decreases at a faster rate, i.e. around 40% up to 300 °C, then becomes steady up to 500 °C. In the temperature range of 500–800 °C, there was a significant reduction in the strength and finally, after exposure to 800 °C, the residual split-tensile strength was around 8% of the original strength [9]. Similarly, strain corresponding to peak stress was nearly constant up to 400 °C but beyond 400 °C, strain change was significant [1,10,11]. Apart from mechanical properties, thermal properties of concrete play a major role in understanding the behaviour of structural elements exposed to elevated temperatures. The type of aggregates used has a significant influence on the thermal properties of HSC at elevated temperature as the use of carbonate aggregate increases the fire resistance of HSC [12–14].

Various supplementary cementitious materials have been explored to enhance the strength and durability of cement-based materials. The addition of silica fume and finely ground granulated blast furnace slag in cement mortar results in high thermal resistance within the temperature range of 100–700 °C [15]. However, in recent times, the SNPs are being explored to produce HSC other than silica fume [16] because it accelerates the rate of hydration, resulting in the improvement of mechanical strength, durability properties and leads to the denser microstructure [17–20]. The addition of SNPs results in the decrease of the amount of calcium hydroxide (the weakest element in hydrated cement) and initiates the formation of additional C-S-H gel [21]. It increases the average length of the silicate chains in C-S-H gel and makes it more polymerized [22]. Further, the type of SNPs also affects the strength properties of mortar as experimental results of Porro et al. [23] and Campillo et al. [24] show that colloidal silica is more effective than agglomerated silica. Sobolev et al. [25] have observed a strength enhancement of 20% and 12% at 1 and 28 days in SNPs incorporated mortars as compared to reference cement mortars. On the one hand, SNPs reduces the capillary porosity while on the other hand, it increases the gel porosity, thus, the overall decrease in porosity of concrete is reported. Because of these advantages, SNPs are becoming the material of choice, however, the nano-engineered concrete, thus formed may behave differently when exposed to elevated temperature. Recent results on mortar specimens incorporating 7.5% SNPs showed a strength increment of 20% as compared with the control specimens when exposed to 400 °C [26], however, at the higher temperature severe reduction in strength occurred. Paste specimens incorporating 5% SNPs showed a strength increment of 20% and 17% when exposed to 400 °C and 500 °C, respectively [27]. Mortar specimens incorporating 7.5% SNPs and 37.5% fly ash showed 30% higher residual strength as compared to control specimens after exposure to 700 °C [28]. Concrete specimens incorporating 5% SNPs showed very less spalling but it showed maximum loss in compressive strength i.e. around 79% after exposure to 800 °C [29].

Keeping in view the above facts, in the present study, we have focused on the effect of elevated temperature and exposure duration on the mechanical properties and microstructure of SNPs incorporated HSC. To the author's knowledge, there are limited studies available on the residual mechanical properties of concrete incorporating SNPs after exposure to elevated temperature.

2. Materials

The present studies were carried out with OPC 43 grade cement conforming to IS 8112:1989 and its chemical composition is given in Table 1. River sand with a fineness modulus of 2.72 was used as fine aggregate and a siliceous crushed angular aggregate of maximum 12.5 mm size was used as coarse aggregate. The properties of coarse aggregate are given in Table 2. SNPs used throughout the experimental work was amorphous and dispersed powder with an average particle size of 30–70 nm as shown in Scanning Electron Microscope (SEM) micrographs (Fig. 1). A modified polycarboxylic ether based superplasticizer (Glenium 51) of BASF, India was used in the concrete mix to achieve the desired workability confirming to IS 9130:1999. Tap water was used for casting and curing of specimens, which was free from the deleterious material as per IS 456:2000.

3. Experimental methods

3.1. Mix Proportions and casting

A HSC, incorporating 3% SNPs were cast with a water/binder ratio of 0.29. Incorporation of 3% SNPs was selected for the concrete mix as the same gives the maximum compressive strength for a varying dosage (0–5%) of SNPs. The details of weight based mix proportion of HSC mixes are given in Table 3. For each mix of HSC, three specimens were prepared and tested for each of five test temperatures: ambient, 200 °C, 400 °C, 600 °C and 800 °C having an exposure duration of 0, 1, and 2 h. The casting of concrete mixes was carried out as per IS 10086:1982. After casting, the specimens were demoulded after one day and were cured in water at a temperature of 27 ± 2 °C for 28 days as per IS 516:1959.

3.2. Methods

After curing, the moist concrete specimens were air dried for two days prior to testing. The surface dried concrete specimens were placed in a muffle furnace and subjected to the desired temperatures of 200 °C, 400 °C, 600 °C and 800 °C at a heating rate of 10 °C/min in accordance with the standard fire curve (ISO-834). Three different temperatures were recorded for the specimens