Composites: Part B 42 (2011) 570–578

Contents lists available at ScienceDirect

Composites: Part B

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

The effects of SiO_2 nanoparticles on physical and mechanical properties of high strength compacting concrete

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ARTICLE INFO

Article history:
Received 11 August 2010
Received in revised form 23 September 2010
Accepted 29 September 2010
Available online 8 October 2010

Keywords:
A. Ceramic-matrix composites (CMCs)
B. Mechanical properties
B. Strength
D. Thermal analysis

ABSTRACT

In this work, compressive, flexural and split tensile strengths together with coefficient of water absorption of high strength self compacting concrete containing different amount of SiO_2 nanoparticles have been investigated. Strength and water permeability of the specimens have been improved by adding SiO_2 nanoparticles in the cement paste up to 4.0 wt.%. SiO_2 nanoparticle could accelerate C–S–H gel formation as a result of increased crystalline $Ca(OH)_2$ amount especially at the early age of hydration and increase the strength of the specimens. In addition, SiO_2 nanoparticles are able to act as nanofillers and recover the pore structure of the specimens by decreasing harmful pores. Several empirical relations have been presented to predict flexural and split tensile strength of the specimens by means of compressive strength at a certain age of curing. Accelerated peak appearance in conduction calorimetry tests, more weight loss in thermogravimetric analysis and more rapid appearance of peaks related to hydrated products in X-ray diffraction results, all also indicate that SiO_2 nanoparticles up to 4 wt.% could improve the mechanical and physical properties of the specimens.

1. Introduction

Advancements in concrete technology have resulted in the development of a new type of concrete, which is known as self compacting high performance concrete (SCHPC). The qualities of SCHPC are based on the concept of self compacting high performance concretes. Self compacting concrete (SCC) is a fluid concrete that spreads through congested reinforcement, fills every corner of the formwork, and is consolidated under its weight [1]. SCC necessitates excellent filling ability, good passing ability, and adequate segregation resistance. But it does not include high strength and good durability as significant performance criteria. On the other hand, high performance concrete (HPC) has been defined as a concrete that is appropriately designed, mixed, placed, consolidated, and cured to provide high strength and low convey properties or good durability [2]. HPC exhibits good segregation resistance, but does not provide excellent filling and passing ability, and therefore needs external means such as rodding or vibration for suitable consolidation. Hence, a concrete that fulfills the performance criteria of both SCC and HPC can be referred to as SCHPC. An SCHPC is that concrete which offers excellent performance with respect to filling ability, passing capability, segregation resistance, strength, transport properties and durability.

Nearly all research has used SCC which includes active additions to satisfy the great demand for fines needed for this type of concrete, thereby improving their mechanical properties in comparison with NVC. Köning et al. [3] and Hauke [4] registered strength increase in SCCs made with different amount of fly ash. According to Fava et al. [5], in SCCs with granulated blast furnace slag, this increase is also evident. On the other hand, when limestone filler is used, Fava et al. [5] and Daoud et al. [6] achieved a tensile strength in SCC lower than the other normal types of concrete.

Besides strength assessments, permeability of concrete is defined as the movement of liquid and/or gas through a mass of concrete under a constant pressure gradient. It is an inherent property of concrete that chiefly depends upon the geometric arrangement and characteristics of the constituent materials. The permeability of concrete is mainly controlled by the solidity and porosity of the hydrated paste present in bulk paste matrix and interfacial transition zone. In the hydrated paste, the capillary and gel pores can be distinguished. The gel pores are very small. Although they constitute a network of open pores, the permeability of this network is very low. Conversely, the capillary pores are relatively large spaces existing between the cement grains. It is the capillary porosity that greatly affects the permeability of concrete [7]. The permeability of SCHPC is typically lower than that of ordinary concrete. Some researches have shown that SCHPC results in very low water and gas permeability [8,9]. This is mostly attributed to the superior flow properties, dense microstructure and refined pore.

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1359-8368/$ - see front matter
doi:10.1016/j.compositesb.2010.09.025

Table 1
Properties of Portland cement (wt.%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Loss on ignition
Cement	21.89	5.3	3.34	53.27	6.45	3.67	0.18	0.98	3.21

Specific gravity: 1.7 g/cm^3.

Good flow properties result in superb packing condition due to better consolidation, and thus contribute to reduce the permeability of concrete.

Since strength assessments and water permeability of concrete are joined together to affect the final performance of concrete, considering mechanical properties in terms of various types of strengths together with physical properties of concrete specimens seems essential. Hence, in this work, both physical and mechanical properties of concrete have been studied.

As authors knowledge, there are few works on incorporating nanoparticles about SCCs to achieve improved physical and mechanical properties. Only, there are several reports on incorporation of nanoparticles in NVCs which most of them have focused on using SiO_2 nanoparticles [10–19] and TiO_2 nanoparticles [20,21]. There are a few studies on incorporating nano-Fe_2O_3 [22], nano-Al_2O_3 [23], and nanoclay particles [24,25]. Additionally, a limited number of investigations are dealing with the manufacture of nanosized cement particles and the development of nanobinders [26]. Previously, a series of works [27–34] has been conducted on cementitious composites by adding different nanoparticles evaluating the mechanical properties of the composites. Nanoparticles can act as heterogeneous nuclei for cement pastes, further accelerating cement hydration because of their high reactivity, as nano-reinforcement, and as nano-filler, densifying the microstructure, thereby, leading to a reduced porosity. The most significant issue for all nanoparticles is that of effective dispersion.

Though it is particularly significant at high loads, even low loads experience problems with self-aggregation, which reduces the benefits of their small size and creates un-reacted pockets leads to a potential for concentration of stresses in the material. SiO_2 nanoparticles have been found to improve concrete strength [11,18,35], to increase resistance to water permeability [36], and to help control the leaching of calcium [37], which is closely associated with various types of concrete degradation. SiO_2 nanoparticles, in addition, have been shown to promote the hydration reactions of C_3S as a result of the large and highly reactive surface of the nanoparticles [19,38]. SiO_2 nanoparticles have been found to be more efficient in enhancing strength than silica fume [39,40]. Adding 10% SiO_2 nanoparticles with dispersing agents has been observed to increase the compressive strength of cementitious composites at 28 days by as much as 26%, compared to only a 10% increase with adding 15% silica fume [19]. Even the addition of small amounts of SiO_2 nanoparticles has been observed to increase the strength results in improving the 28 day compressive strength by 10% and flexural strength by 25% [11]. However, these results depend on the production route and conditions of synthesis of SiO_2 nanoparticles (e.g., molar ratios of the reagents, the type of reaction media, and duration of the reaction for the sol–gel method) and that dispersion of SiO_2 nanoparticles in the paste plays an important role. SiO_2 nanoparticles not only behaved as nanofiller to improve the microstructure but also as an activator to accelerate pozzolanic reactions [39].

The aim of this study is incorporating SiO_2 nanoparticles into SCCs to study compressive strength and water permeability of self compacting high strength concrete. In addition, pore structure, thermal properties and microstructure of the concrete specimens have been evaluated. Several specimens with a constant amount of polycarboxylate superplasticizer (PC) have been prepared and their physical and mechanical properties have been considered when, instead of cement, SiO_2 nanoparticles were partially added to the cement paste.

2. Materials and methods

Ordinary Portland Cement (OPC) conforming to ASTM C150 [41] standard was used as received. The chemical and physical properties of the cement are shown in Table 1. The particle size distribution pattern of the used OPC has been illustrated in Fig. 1.

SiO_2 nanoparticles with average particle size of 15 nm and 45 m^2/g Blaine fineness producing from Suzhou Fuer Import & Export Trade Co., Ltd. was used as received. The properties of SiO_2 nanoparticles are shown in Table 2. Scanning electron micrographs (SEM) and powder X-ray diffraction (XRD) diagrams of SiO_2 nanoparticles are shown in Figs. 2 and 3.

Crushed limestone aggregates were used to produce self-compacting concretes, with gravel 4/12 and two types of sand: one coarse 0/4, for fine aggregates and the other fine 0/2, with a very high fines content (particle size <0.063 mm) of 19.2%, the main function of which was to provide a greater volume of fine materials to improve the stability of the fresh concrete.

A polycarboxylate with a polyethylene condensate defoamed based admixture (Glenium C303 SCC) was used. Table 3 shows some of the physical and chemical properties of polycarboxylate admixture used in this study.

Totally, two series of mixtures were prepared in the laboratory trials. C0-SCC series mixtures were prepared by cement, fine and ultra-fine crushed limestone aggregates with 19.2% by weight of ultra-fine ones and 1.0% by weight of polycarboxylate admixture replaced by water. N-SCC series were prepared with different contents of SiO_2 nanoparticles with average particle size of 15 nm. The mixtures were prepared with the cement replacement by SiO_2 nanoparticles from 1.0 to 5.0 wt.% and 1.0 wt.% polycarboxylate admixture. The superplasticizer was dissolved in water, and then the nano-SiO_2 was added and stirred at a high speed for 3 min.

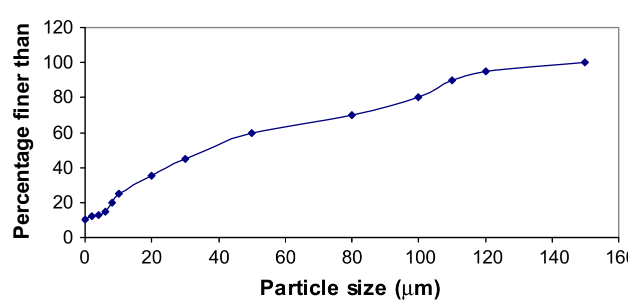

Fig. 1. Particles distribution pattern of ordinary Portland cement.

Table 2
The properties of nano-SiO_2.

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Purity (%)
15 ± 3	165 ± 17	<0.15	>99.9