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Mechanical, rheological, durability and microstructural properties of high performance self-compacting concrete containing SiO_2 micro and nanoparticles

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ABSTRACT

In this paper, mechanical, rheological, durability and microstructural properties of high performance self compacting concrete (HPSCC) incorporating SiO_2 micro and nanoparticles have been investigated. For this purpose, a fraction of Portland cement was replaced by different amounts of microsilica, nanosilica and blend of micro and nanosilica as 10%, 2% and 10% + 2% respectively. Three different binder contents as 400, 450 and 500 kg/m^3 with a constant water to binder ratio (w/b = 0.38) were investigated. Rheological properties were determined through slump flow time and diameter, *V*-funnel flow time and *L*-box tests and mechanical characteristics were determined. Durability properties were evaluated by water absorption, capillary absorption, Cl ion percentage and resistivity tests. Microstructure of the concrete was also assessed via scanning electron microscopy (SEM). The results showed that the properties improved significantly for the specimens containing micro and nanosilica. Improvement of Cl ion percentage and resistivity results in the micro and nanosilica blended mixtures was also noticeable. From the microstructure point of view, the SEM micrographs showed more refined and packed pore structure of the concrete containing admixtures especially at longer ages which could lead to enhancement of strength and the durability properties of HPSCC specimens.

1. Introduction

High-performance concrete (HPC) has become an attractive option compared to normal-strength concrete (NSC). High-performance concrete (HPC) is a specialized concrete designed to provide several benefits in the construction of concrete structures. HPC offers high strength, better durability properties, and good construction. High strength is one of the important attributes of HPC. High strength concrete, according to American Concrete Institute Committee ACI 363 R [1], is the concrete which has specific compressive strength of 41 MPa or more at 28 days. The HPC offers significant economic and architectural advantages over NSC in similar situations, and is suited well for constructions that require high durability.

Self-compacting concrete (SCC) is considered as a concrete which can be placed and compacted under its own weight with little or no vibration without segregation or bleeding. It is used to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members. It has gained significant importance in recent years because of the advantages it offers [2–5].

Many researchers have used SCC containing admixtures to satisfy the great demand for fines needed for this type of concrete, thereby improving its mechanical, rheological and durability properties in comparison with normal vibrated concrete (NVC). Researchers have investigated the effects of different admixtures on SCC properties in recent years. Siddique [6] investigated the properties of SCC made with different amounts of fly ash. El-Dieb [7] studied mechanical and durability properties of ultra high strength-fiber reinforced concrete (UHS-FRC) with self compacting characteristics. According to Fava et al. [8], in SCCs with ground granulated blast furnace slag (GGBFS), strength increase can be achieved. Kulakowski et al. [9] reviewed the silica fume influence on reinforcement corrosion in concrete. The effect of metakaolin on transport properties of concrete were also investigated by Shekarchi et al. [10]. There are also some works on incorporating nanoparticles into concrete specimens to achieve improved physical and mechanical properties which most of them have focused on using SiO_2 nanoparticles in normal concrete [11], generally cement mortars and cement-based materials [12–15] and self compacting concrete [16].

By combining the characteristics and advantages of HPC and SCC, high performance self-compacting concrete (HPSCC) can be produced which possesses the advantages in both forms of fresh and hardened concrete, i.e. while presenting higher strength and durability, it has a good workability and rheological properties.

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HPSCC seems to be promising materials for many applications and structures. However, this would not be achieved without studying its performance before being widely adopted in construction. Also, the behavior of structural elements made with HPSCC needs better understanding, together with design provisions.

The aim of this study is to investigate mechanical, rheological and durability properties of high performance self compacting concrete incorporating SiO_2 micro and nanoparticles. With this respect, workability properties, strength enhancement, absorption characteristics, electrical resistivity, chloride ion percentage and microstructure of the HPSCC specimens have been assessed. The effect of different binder contents on the HPSCC mixtures has also been investigated.

2. Materials

An ASTM Type II Portland cement (PC) was used to produce the various HPSCC mixtures. In addition, SiO_2 micro and nanoparticles were used as admixtures which are hereafter called microsilica (MS) and nanosilica (NS) respectively. Table 1 summarizes physical properties and chemical composition of the cement and microsilica and Table 2 shows the properties of nanosilica used. The coarse aggregate used was limestone gravel with a nominal maximum size of 12.5 mm. As fine aggregate, a mixture of silica aggregate sand and crushed limestone (as filler) was used with a maximum size of 4.75 mm. The particle size gradation obtained through the sieve analysis and physical properties of the filler, fine and coarse aggregates are presented in Table 3. All aggregates in this research were used in dry form and the aggregates were a mixture of eight particle sizes of fine and coarse aggregates which the gradation curves can be seen in Fig. 1. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of between 1.06 and 1.08 was employed to achieve the desired workability in all concrete mixtures. Furthermore, viscosity modifying agent (VMA) was used for better consistency.

3. Mix design proportions

A total number of 12 concrete mixtures were designed with a constant water/binder (*w*/*b*) ratio of 0.38 and total binder content of 400, 450 and 500 kg/m^3. Concrete samples were prepared with 10% and 2% (by weight) replacement of Portland cement by micro and nanosilica respectively. The mixture proportions of concrete and binder paste are given in Table 4. The abbreviations used in the study for labeling the mixtures were adopted in such a way that they clearly show the main parameters and their amount. HPSCC stands for high performance self compacting concrete which is followed by the binder content. MS and NS denote microsilica and nanosilica respectively which are followed by their percentages.

4. Mixing procedure

Since the SP plays a very important role in the flowability of SCC mixes [17], a modified mixing procedure was adopted to take the benefit of action of adsorption of molecules of poly-carboxylic ether based SP on the cement particles for all mixes. HPSCC mixtures were prepared by mixing coarse aggregates, fine aggregates and powder materials (cement, micro and nanosilica) in a laboratory drum mixer. The powder material and the aggregates were mixed in dry form for 2 min. Then half of the water containing the whole amount of super plasticizer was poured and mixed for 3 min. After that, about 1 min rest was allowed and finally rest of the water containing VMA was added into the mixture and mixed for 1 min.

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

Chemical analysis (%)	Cement	Microsilica
Sio$_2$	20<	93.6
Al_2O_3	6<	1.3
Fe_2O_3	6<	0.9
CaO	<50	0.5
MgO	<5	1
SO_3	<3	0.4
K_2O	<1	1.52
Na_2O	<1	0.45
Loss of ignition	<3	3.1
Specific gravity	3.15	2.2
Blaine fineness (cm^2/g)	3260	21,090

Table 2
Properties of nanosilica.

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

Table 3
Sieve analysis and physical properties of the filler, fine and coarse aggregates.

Sieve size (mm)	Filler (%passing)	Fine aggregate (%passing)	Coarse aggregate (%passing)
12.5	100	100	97.9
9.5	100	100	79.3
4.75	100	98.38	13.2
2.36	100	76.45	0
1.18	100	46.65	0
0.6	100	39.32	0
0.3	100	15.26	0
0.15	90.9	3.62	0
0.075	33.7	0	0
Bulk density (kg/m^3)		1460	1450
Specific gravity (g/m^3)		2.619	2.6
Absorption (%)	8	2.72	0.4

5. Preparation of the specimens

Cubic molds of 150 × 150 × 150 mm dimensions and cylindrical molds of 100 × 200 mm dimensions were made for compressive and splitting tensile tests respectively. The molds for HPSCC were covered with polyethylene sheets and moistened for 48 h. Then the specimens were demoulded and cured in water at a temperature of 20 °C until the time of the test. The compressive and splitting tensile strengths of the concrete samples were determined at 3, 7, 28 and 90 days and the average of two trials was reported.

6. Testing of the specimens

When the mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow time and diameter, *V*-funnel flow time and *L*-box height ratio. Segregation was also visually checked during the slump flow test. From each concrete mixture, 150 × 150 × 150 mm cubes, 100 × 200 mm cylinders and 100 × 100 × 100 mm cubes were cast for the determination of compressive strength, split tensile strength and durability tests (absorption, capillary, specific electrical resistance and penetration Cl^- ion tests) respectively. All specimens were cast in one layer without any compaction. At the age of 48 h, the