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The effect of different water/binder ratio and nano-silica dosage on the fresh and hardened properties of self-compacting concrete

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HIGHLIGHTS

- Studying the effect of increasing w/b on properties of SCC with nano-silica.
- Different effect of nano-silica on hardened properties of low and high w/b SCC.
- Nano-silica dosage is critical for SCC fresh properties.

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ABSTRACT

This paper aims to study the effect of increasing water/binder ratio on the fresh and hardened properties of self-compacting concrete containing nano-silica with different dosages, focusing on the mixes with high w/b ratios that are produced in the field in places with hot weather. 12 mixes were designed with a total binder content of 350 kg/m^3, three different water/binder (w/b) ratios of 0.41, 0.45 and 0.5 and 0%, 0.25%, 0.5% and 0.75% (by weight) replacement of cement by nano-silica. Self-compacting concrete was examined concerning fresh state properties and hardened state properties (mechanical and durability properties). Also, the densification of the microstructure of hardened concrete was verified by SEM examinations. The results showed that the effect of a certain nano-silica dosage on compressive strength of concrete with high w/b is greater than that on concrete with low w/b. While concerning durability, the results proved that the influence of a certain nano-silica dosage on low w/b mixes is greater than that on high w/b mixes. Also, the results showed that for mixes with high w/b, the nano-silica cannot compensate the significant decrease in durability caused by increasing w/b but can compensate only the strength reduction and segregation.

1. Introduction

Concrete is a porous material; this makes it susceptible to the entrance of water or other liquids which cause durability problems. Many concrete structures built decades ago were often designed with little attention to durability issues, and have therefore suffered severe structural degradation [1]. Nanotechnology has become widely spread in the field of construction because it can improve construction materials performance since it can modify or cater the microstructures at nano- and micro-levels. As such, there is an increasing number of studies on using nanoparticles to enhance concrete properties among which nano-silica (NS) is quite outstanding. According to previous studies, it has been reported that the addition of NS decreases the permeability and increases the compressive strength of concrete because it has not only filler effect in which it fills the voids in the C-S-H gel, but also form nanostructured C-S-H gel material and thus improving the microstructure [2–14]. Also, NS possesses a special pozzolanic reaction due to its small particle size which provides larger surface area so accelerates the rate of hydration of cement thus increases the density of the internal transition zone between paste and aggregate [2–4,15].

One of the most significant problems in placing concrete is compaction especially in confined zones due to the shortage of skilled labour. Lack of compaction has a negative effect on durability, and, hence, causes poor durability performance of reinforced concrete. For this purpose, self-compacting concrete (SCC) was first developed in Japan in 1988 [16]. SCC is concrete that can flow under its weight and fill the formwork, even in the presence of

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dense reinforcement, without the need of any vibration, while maintaining homogeneity [17]. It is characterised by its filling ability, passing ability and segregation resistance [17]. The high flowability of SCC is achieved by using superplasticisers or high range water reducing admixtures, high amounts of fines, and, sometimes viscosity modifying agents (to decrease bleeding and segregation). According to Audenaert et al. [18], the presence of high amount of fines makes the pore structure of SCC different from that of ordinary concrete; therefore, the application of SCC might be slightly risky due to the lack of knowledge concerning its durability.

In hot weather such as in Egypt, if the rate of evaporation is greater than the rate of bleeding, plastic shrinkage occurs causing concrete cracking [19–21]. Therefore, in spite of using superplasticiser to achieve the desired flowability, there is still a need for high water/cement ratio, especially in hot weather. Yakoubi et al. [21] found that increasing W/C of SCC in hot weather may provide some protection at least in early age. He explained that by using high W/C, bleeding occurs which ensures the necessary moisture for hardening and it can be the natural self-cure of the surface, especially during the first hours. The influence of hot weather on the properties of fresh cement pastes was also reported by others [22,23].

Presently, only a few studies on the effect of NS on the durability of SCC are available [24–26]. Also, the effect of increasing w/b on SCC containing NS has not been previously reported.

The objective of this study is to investigate the effect of increasing water/binder ratio on the fresh and hardened properties of self-compacting concrete containing nano-silica with different dosages, focusing on the mixes with high w/b ratios that are produced in the field in places with hot weather such as Egypt. Self-compacting concrete was examined concerning fresh state properties and hardened state properties (mechanical and durability properties). Also, the densification of the microstructure of hardened concrete was verified by SEM examinations.

2. Materials and experimental procedure

2.1. Materials

This study used an ASTM type I Portland cement (CEM I/42.5 R) to produce SCC mixtures. Commercial nano-silica (NS) particles were used in powder form as a partial replacement for cement admixtures. Chemical analysis and physical properties of cement and NS are shown in Tables 1 and 2 respectively. Transmission electron microscopy (TEM) of NS particles is shown in Fig. 1; NS particles are represented by highly agglomerated clusters. Fig. 2 shows the XRD pattern which indicated that NS is a highly amorphous material. Crushed limestone was used as coarse aggregate with a nominal maximum size of 10 mm with bulk density and specific gravity of 1493 kg/m^3 and 2.67 respectively. The fine aggregate used was a mixture of limestone powder (as a filler) and sand with a maximum size of 4.75 mm. The bulk density and fineness modulus of sand used were 1636 kg/m^3 and 2.632 respectively. The particle size distribution of filler, coarse and fine aggregates is shown in Fig. 3. To obtain the required workability in all concrete mixes, an aqueous solution of modified polycarboxylates superplasticiser (SP) (meeting the requirements for superplasticisers according to ASTM C 494 [27] Types G and F) with a specific gravity 1.08 was used at a constant dosage 2% by weight of cement.

Table 1
Chemical composition of cement and nano-silica (NS).

Chemical analysis (%)	Cement	NS
SiO_2	22.74	90.9
Al_2O_3	3.22	0.29
Fe_2O_3	3.72	0.1
CaO	63.1	0.19
MgO	1.56	0.15
K_2O	0.62	–
Na_2O	0.39	1.1
SO_3	0.37	1.16
CL^-	1.88	–
Tio_2	–	0.29
In residue	0.33	–
Loss of ignition	1.9	5.71

Table 2
Physical properties of cement and nano-silica (NS).

Physical property	Cement	NS
Specific gravity	3.15	–
Soundness (mm)	7	–
Initial setting time (min)	70	–
Compressive strength (Mpa) (2days)	21.3	–
Compressive strength (Mpa) (28 days)	54.1	–
Diameter (nm)	–	7–25
Surface area (m^2/g)	0.323	240

2.2. Mix design proportions

In this study, twelve SCC mixes were designed with a total binder content of 350 kg/m^3 and three different water/binder (w/b) ratios of 0.41, 0.45 and 0.5 named series A, B and C respectively. Samples of each series were prepared with 0%, 0.25%, 0.5% and 0.75% (by weight) replacement of cement by NS. Table 3 shows the concrete mix designs for the samples.

2.3. Mixing procedure

SCC mixtures were prepared by mixing coarse aggregates, fine aggregates, and powder materials (cement and nano-silica) in a laboratory drum mixer. The powder materials and the aggregates were mixed in dry form for 2 min. Then the whole amount of superplasticiser dissolved in half of the water was poured and mixed for 3 min. After that, about 1 min rest was enabled and finally the rest of the water was added and mixed for 1 min [26,28].

2.4. Preparation of the specimens, curing and test methods

Once the mixing process was completed, tests were performed on the fresh concrete to determine the workability of SCC. The workability of SCC can be characterised by Filling ability (flowability), Passing ability and Segregation resistance. Self-compacting Concrete must meet the requirements of the three characteristics. In this study, fresh properties of SCC mixtures were examined through the slump flow test, V-funnel test, J-Ring test, and L-box test according to EFNARC [17] standards. The slump flow time (T_{500}), slump flow diameter (D) and V-funnel flow time were measured to represent the filling ability. During the slump flow test, segregation was checked by visual inspection. The passing ability was determined by J-Ring flow time (T_{500}j), J-Ring blocking step (BJ), and L-box height ratio.

Then all required specimens for hardened concrete tests were poured and cured according to EFNARC and The European Guidelines for Self-Compacting Concrete standards [17,29]. All specimens were cast in one layer without any compaction. Compressive strengths at 7 and 28 days and splitting tensile strengths at 28 days were determined on Ø100 × 200 mm cylindrical specimens from each mixture according to ASTM C 39 [30] and ASTM C 496 [31] respectively. The effect of NS on the durability of SCC was investigated by conducting many tests including; water penetration depth, abrasion resistance, water sorptivity, volume of permeable voids (VPV), water absorption and sulphate attack.