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Durability performances of concrete with nano-silica

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HIGHLIGHTS

- Nano-silica consumed calcium hydroxide during the pozzolanic reaction.
- The microstructures of paste at the ITZ were more compact and homogeneous.
- Capillary pores were refined by the addition of nano-silica.
- Compressive strength increased with the addition of nano-silica.
- Resistance to water and chloride ions was greatly improved, even at a dosage of 0.3%.

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ABSTRACT

This study investigated the durability properties of concrete containing nano-silica at dosages of 0.3% and 0.9%, respectively. Due to the nano-filler effect and the pozzolanic reaction, the microstructure became more homogeneous and less porous, especially at the interfacial transition zone (ITZ), which led to reduced permeability. Tests on the durability properties verified the beneficial effects of nano-silica. The channels for harmful agents through the cement composites were partially filled and blocked. The pore size distribution also indicated that the large capillary pores were refined by the nano-silica, due to the combined contribution of the nano-filler effect and the pozzolanic reaction.

1. Introduction

Concrete is the most commonly used manmade material, despite being vulnerable to the ingress of aggressive fluids/ions in a severe environment due to its porous microstructure. The durability issues of concrete have been particularly emphasized in lifeline structures and infrastructures. Recently, the use of nano-particles in cement-based materials has drawn intense interest because they can provide some unique properties at the nano-scale. For instance, nano-SiO_2, TiO_2, Al_2O_3, Fe_2O_3 was used as nano-filler in the cement matrix, the capillary pores were found to be smaller and the total porosity was also decreased [1–13]. Carbon nanotube or carbon nanofiber was able to arrest cracks at the nano-scale, thus improving the ductility of cement-based composites which were normally brittle in nature [14,15]. Graphene nanoplatelet has proved to be very efficient in lowering the permeability of cement-based materials to water and chloride ions, thanks to its 2-D morphology [16,17].

Compared to other nano-particles, nano-silica has a unique advantage in the potential pozzolanic reaction with cement hydration products. Due to its ultra fine particle size, nano-silica can possess a distinct pozzolanic reaction at a very early age. Therefore, one of the promising applications of nano-silica is to promote the hydration of cement blended with fly ash, slag or other pozzolanic materials [18,19]. According to previous studies, nano-silica distinctly increased the cement hydration and early age strength for blended cement [19], provided they were uniformly dispersed in the composites, otherwise, this benefit could be compromised by the agglomeration of nano-particles. To date, studies on the durability properties of cement-based materials with nano-silica are still limited, as most of the previous research deals mainly with the dispersion issue and the influence on the fresh state properties.

Ji first reported a clear reduction in the water penetration depth of about 45% by adding 3.8% nano-silica into the concrete mixture [3]. He observed a more uniform and compact microstructure

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(especially at the interfacial transition zone (ITZ)) in the nano-silica concrete and attributed this to the pozzolanic reaction, which occurred due to the addition of nano-silica. For the same reason, Gaitero et al. found the calcium leaching rate could be noticeably reduced from cement paste which had 6% nano-silica added [5]. Kong et al. also obtained a higher resistance for mortar to chloride penetration by means of adding up to 1% nano-silica [7]. Quercia et al. carried out a study on the durability of self-compacting concrete (SCC) incorporating nano-silica, in both colloidal and powder forms, at the same dosage of 3.8% [11]. All of the durability performances of SCC were enhanced due to nano-silica helping to increase the density microstructure, however there was no discussion regarding the influence of nano-silica dosage on durability. To date, no comprehensive study relating to the influence of nano-silica on the durability of ordinary concrete has been undertaken.

Hence, it is the objective of this study to examine the transport properties related to the durability performance of ordinary concrete containing nano-silica. In addition to strength, water permeability and sorptivity; chloride migration and diffusivity were determined for concrete at nano-silica dosages of 0%, 0.3% and 0.9%, respectively. Additionally, the influence of nano-silica on the microstructure of concrete was observed by measuring the pore size distribution, observing the microstructure and determining the chemical composition phase change. The effectiveness of using nano-silica to improve the impermeability and durability of concrete is also discussed.

2. Materials and methods

2.1. Materials

This study used Type I ordinary Portland cement (OPC) with the chemical composition listed in Table 1. Coarse aggregates of 9.5-mm granite aggregates with an oven-dry unit weight and specific gravity of 1650 kg/m^3 and 2.65 were used. The fineness modulus and specific gravity of sand used in this study were 2.80 and 2.65, respectively. Fig. 1 shows the particle size distribution of coarse aggregates, sand and cement. The study used a commercial nano-silica, in powder form, with an average primary particle size of 13 nm, corresponding to a surface area of 200 m^2/g. The morphology of the nano-silica is shown in Fig. 2. As displayed, despite the high surface area, most of the nano-scale particles agglomerated into clusters with micro-scale diameters. Hence, it was challenging to disperse and stabilize the nano-particles in the cementitious composites, therefore, combined surfactant and ultra-sonication were employed. Superplasticizer (SP), DARCEM 100, was used as the surfactant to achieve an aqueous solution for nano-silica and thus aid the suitable workability of the fresh concrete. This technique has proven effective in dispersing and stabilizing the nano-particles in an aqueous solution for cement-materials [8,17,18]. The mix proportions for the reference concrete and 0.3% and 0.9% nano-silica concrete are listed in Table 2.

2.2. Specimens

First, the specified amount of nano-silica was dissolved in 500 mL water with SP as the chemical surfactant. Prior to ultra-sonication, the aqueous solution was hand-mixed for 1 min. The sonication period was 10 min, at a power of 400 W in this study. During sonication an ice-bath was provided to the glass beaker to prevent overheating. Concrete was mixed in a Pan mixer. Coarse and fine aggregates and OPC were dry mixed in the mixer for 1 min before adding the mixing water. Finally, the nano-silica aqueous solution was added into the wet mixture. Additional SP was added into the concrete mixture to keep the consistency. The adjusted SP contents and obtained slumps are summarized in Table 2. All of the concrete specimens were compacted on a vibration table and kept in steel molds for 24 h. After demolding, the specimens were cured in water until reaching the age for each tested property.

Table 1
Chemical compositions of OPC.

Composition (%)	OPC
SiO_2	20.8
Al_2O_3	4.6
Fe_2O_3	2.8
CaO	65.4
MgO	1.3
SO_3	2.2
Na_2O	0.31
K_2O	0.44
TiO_2	–
Cr_2O_3	–

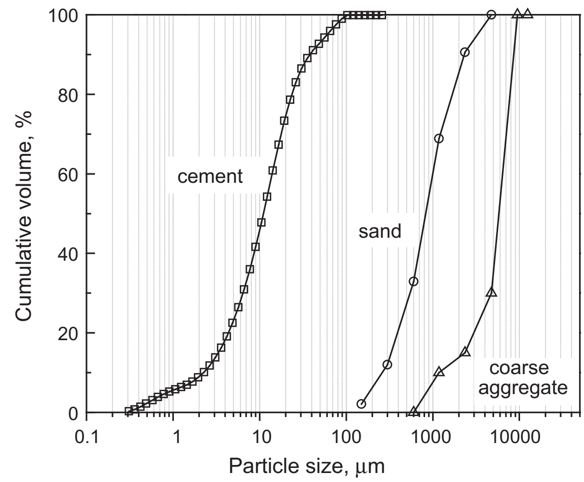
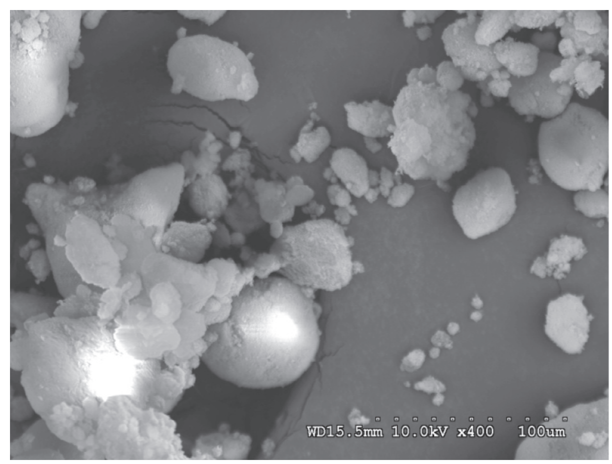
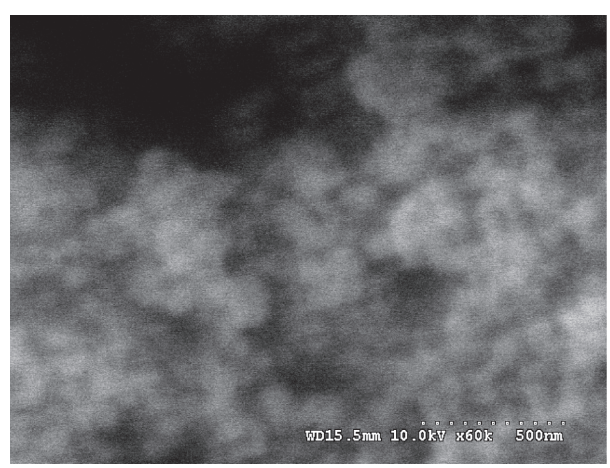


Fig. 1. Particle size distribution of coarse aggregates, sand and cement.



(a) Agglomeration of nano-particles as received



(b) High magnification of silica particles

Fig. 2. SEM image of nano-silica. (a) Agglomeration of nano-particles as received. (b) High magnification of silica particles.