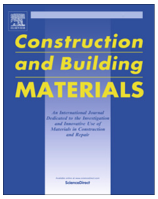
Construction and Building Materials 82 (2015) 114–122

Contents lists available at ScienceDirect

Construction and Building Materials

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



Effect of nano-silica on the mechanical and transport properties of lightweight concrete

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HIGHLIGHTS

- The effect of nano-silica on transport properties of LWC is firstly reported.
- Interfacial transition zone became more compact and denser with nano-silica.
- Nano-silica can increase compressive strength and lower porosity of LWC.
- Resistance to water and chloride ion were both improved at 1% nano-silica.
- Both pure cement and 60% slag cement LWC showed similar results.

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form 19 January 2015
Accepted 18 February 2015
Available online 6 March 2015

Keywords:
Durability
Interfacial transition zone
Microstructure
Lightweight aggregate
Pozzolanic reaction

ABSTRACT

This paper investigated the influence of nano-silica (NS) on the mechanical and transport properties of lightweight concrete (LWC). The resistance of LWC to water and chloride ions penetration was enhanced despite strength marginally increased. Water penetration depth, moisture sorptivity, chloride migration and diffusion coefficient was reduced by 23% and 49%, 23% and 10%, 5% and 0%, 22% and 12% compared to the two reference LWC mixes (pure cement and 60% slag blended cement), respectively with 1% NS. Such improvements were attributed to more compact microstructures because the micropore system was refined and the interface between aggregates and paste was enhanced.

1. Introduction

Portland cement, one of the largest commodities consumed globally, has great advantages to be cast to any desired shape, cheap and fire resisting. However, cement also has weakness like brittleness, volume instability and porous system. Recently, the tremendous potential of nanotechnology to improve the performance of traditional cement-based materials has drawn increasing efforts from researchers and engineers to explore the promising applications. The bulk engineering properties of cement composites might be able to be modified by using nano-particles such as higher strength and durability by nano-SiO_2 [1]. In addition, some smart properties which are desired for special purpose can be equipped for cement-based materials, for instance, self-cleaning and discoloration resistance by nano-TiO_2 to address air pollution problem [2], strain or damage sensing by carbon-based nano-materials in the area of structural health sensing [3,4], and higher ductility by carbon nanotube or nanofiber in the field of seismic resistance [5,6]. Among these nano-particles, nano-silica (NS) is the most used and studied [7–22].

Previous studies on the use of NS in cementitious materials show that NS can accelerate the cement hydration rate and its pozzolanic reaction can densify the microstructures (via turning calcium hydroxide into C-S-H gel and nano-filling) [7–9]. Therefore, the strength is improved and the strength gain rate could be greatly increased for cement mixture with high amount of pozzolanic materials. More recently, the durability properties for concrete with NS have also been documented. Quercia et al. [19] examined the influence of 3.8% colloidal NS on the durability performances of self-compacting concrete (SCC) and found that the pores are finer and less connected. In addition, the paste-aggregate interface is also modified and more tortuous for harmful agents. Therefore, the water resistance under pressure, chloride diffusion and

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http://dx.doi.org/10.1016/j.conbuildmat.2015.02.026
0950-0618/

migration coefficient can be reduced by 88.5%, 63.1% and 63.6%, respectively. Du et al. [23] reported the transport-properties related durability of normal-strength concrete added with powdered NS at dosage of 0.3% and 0.9%. Incorporating NS, the calcium hydroxide was rapidly consumed and at the same time paste pore systems were clearly refined, even at small NS addition of 0.3%. In addition to the reduction in water penetration depth and chloride migration and diffusion, the rate of water absorption was also much reduced, attributed to the less connected pores. Furthermore, some recent studies [20,21,24–26] explored the application of NS in high performance cementitious composites (HPCC). It is generally consistently reported that there exists a critical NS content beyond which the HPCC quality could not be further enhanced due to the fact that more air voids would be entrained in the system. Du and Pang [25] found that 1.5–2.0% colloidal NS could produce the best mechanical and durability performances.

Lightweight concrete (LWC) is a type of concrete with air-dry unit weight between 400 and 2000 kg/m^3. For structural LWC, the unit weight ranges 1400 and 2000 kg/m^3 compared to that of 2400 kg/m^3 for normal weight concrete [27–31]. With reduced self-weight, the buildings can have smaller cross-sectional structural components and thus more effective usable spaces. It was previously found that the ITZ thickness would decrease with higher absorption capacity of lightweight aggregate since less water can accumulate in the vicinity of the aggregate particle [32–34]. Beyond that, LWC with lightweight aggregates also has the advantage of internal curing which can prevent shrinkage cracking and reduce permeability [35]. Previous research [30,31] has shown that micro-silica (or silica fume) could obviously increase the LWC resistance against water and chloride-ion ingress. The bond at the paste-lightweight aggregate interface is improved because of both better packing (particles in micrometer level) and pozzolanic reaction (amorphous silica). Until now, no literature on the use of silica in nanometer scale in LWC is available, to the best knowledge of authors. Thus, this study aims to investigate the influence of colloidal NS on LWC, with a focus on the durability properties. In addition, the effects of NS will be compared for LWC with pure cement and those with slag cement.

2. Materials and methods

2.1. Materials

Expanded clay spheres were used as lightweight aggregate in this study, with particle size in the range of 4.75 to 9.50 mm. The bulk density and dry particle density are 650 and 1200 kg/m^3, respectively. The water absorption is 8.4% at 1 h and 13.0% at 24 h, respectively. The total porosity of lightweight aggregate is 57.2%, 25.8% of which is open while the rest is closed.

Natural sand with a fineness modulus of 2.80 and specific gravity of 2.65 was used as fine aggregates. CEM I 52.5N cement and slag was used in this study, with chemical compositions shown in Table 1. The specific gravity for cement and slag is 3.25 and 2.90, respectively, as determined by Automatic Density Analyzer ULTRAPYC 1200e. Laser scattering particle size analyzer, Malvern Mastersizer was used to determine the particle size distribution (PSD) of cement and slag. It was assumed that the irregular shape of cement and slag particles as sphere to calculate the surface area and size distribution. Cement and slag were dissolved in acetone and sonicated in ultrasonic bath for 2 min to achieve uniform dispersion. PSD for natural sand was determined by sieve analysis and shown in Fig. 1, together with cement and slag. The morphology of the slag is shown in Fig. 2, as observed by scanning electron microscope (SEM).

Colloidal nano-silica[1] used in this study contains 40% solids and has a density of 1.3 g/mL. The surface area of nano-silica is 220 m^2/g (provided by the product supplier) and correspondingly the average particle size is 12.4 nm. Fig. 3 shows the dispersion and morphology of mono-sized nano-silica particles in the as-received suspension, using a JEOL JEM2010 TEM at an operating acceleration voltage of 100 kV. Polycarboxylate-based superplasticizer was used to control the workability for LWC mixtures. It is commonly recognized that colloidal NS can achieve better dispersion than powdered NS and thus yielding better packing density (or lower porosity in another word) and better performances [10,11]. At the same time, the risk assessment for powdered NS is more severe compared to colloidal NS, which may cause unfriendly working conditions and heavy personal protective equipments for researchers. Thus, colloidal NS was used in this study, although its price is higher.

Table 1
Chemical compositions (% by mass) for cement and slag.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Cement	20.8	4.6	2.8	65.4	1.3	2.2	0.31	0.44
Slag	32.15	12.87	0.36	40.67	6.05	4.95	0.28	0.51

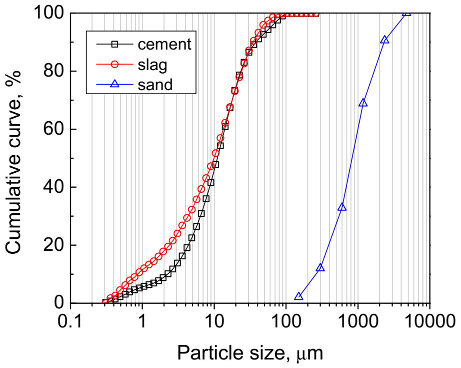

Fig. 1. Particle size distribution of raw materials.

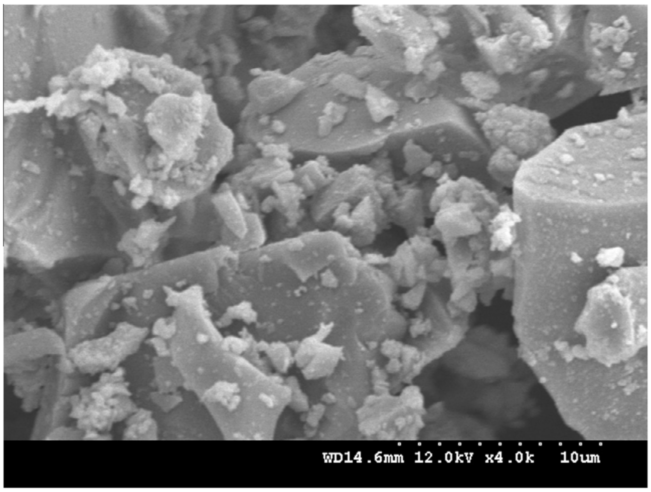

Fig. 2. SEM image of slag used in this study.

2.2. Mix proportions and casting

Table 2 summarizes the mix proportions for LWC with NS. Mix proportion for the reference LWC-C0 was modified based on a normal weight concrete mixture (selected according to ACI 211.1, based on the raw materials used), by replacing the normal-weight coarse aggregates by lightweight aggregates at the equivalent volume. Colloidal NS was added into the reference LWC at 1% and 2% by weight of the cement, respectively, as recommended by previous work [25]. At the same time, 60% of the cement was substituted by slag by weight in the other reference LWC-S0. Because slag has a slightly lower specific density, sand content was reduced correspondingly to maintain a unit volume, as shown in Table 2. Similarly, 1% and 2% NS was added into this reference LWC. The water-to-cementitious (*w/cm*) ratio was kept as 0.42 for all the concrete mixtures, for a target 28-day strength of 40 MPa, as suggested by ACI 211.1. It is noted that the water content in the NS aqueous suspension was calculated into the *w/cm* ratio. SP amount was adjusted to maintain the slump at 100 ± 25 mm for each LWC mix, for the application of beams, reinforced walls or building columns as recommended by ACI 211.1.

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[1] LUDOX® HS-40 colloidal silica, W.R. Grace & Co.-Conn.