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Role of nano-SiO_2 in improving the microstructure and impermeability of concrete with different aggregate gradations

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HIGHLIGHTS

- When Fuller exponent is 0.4-1.0, the impermeability of concrete is the strongest.
- When Fuller exponent is 0.4-1.0, the role of nano-SiO_2 becomes much important.
- Different aggregate gradations can induce diverse types of defects in concrete.
- The real-time monitoring water sorptivity test method is used in this study.

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ABSTRACT

Permeability is a significant and key property of concrete, and aggregate gradation is one factor that can affect the properties of concrete. Therefore, the aim of this study is to explore the improvement characteristics of nano-SiO_2 on the microstructure and impermeability of concrete with different aggregate gradations. Two innovative test procedures have been applied in this research to obtain the parameters related to permeability: water permeability and real-time monitoring of water sorptivity. In addition, kernel density estimation and step function fitting are used to statistically characterize and quantify the microstructure features of samples. The results reveal that different aggregate gradations induce diverse types of defects. When the Fuller exponent (q) ranges from approximately 0.4–1.0, the microstructure of concrete is the densest and the impermeability is the strongest, in the meantime, the roles of nano-SiO_2 become much clearer in weakening the connectivity of microdefects and improving the impermeability of concrete.

1. Introduction

Permeability is the most important property of concrete and is strongly related to durability. Some species such as chloride ions, SO_2, CO_2, and sulfates are soluble in water, which in turn can ingress into concrete, as well as other external forces can damage to concrete and other building materials, which greatly influences service life of construction and building materials and has been identified as a global problem [1–4].

Many researchers have been studying issues related to the permeability of concrete [5–9]. Permeability is mainly determined by the microstructural characteristics of concrete, including pore size, microcracks, and interconnections. Therefore, the addition of admixtures and minerals (to change the microstructure of concrete) will lead to good impermeability [10–13]. Nanoengineering (or nanomodification) of cement is a fast-moving embryonic field, so materials on the nanometre scale are selected as new cement additives [14–21]. Past research has revealed that concrete containing nano-TiO_2 displays superior impermeability than does pure concrete by resisting the coupled effects of chloride diffusion and scouring [21]. Nano-SiO_2 added at a certain concentration not only improves the strength of high-strength concrete (HSC) but also acts as a cement replacement material [22]. Nano-silica can also reduce permeability of concrete by its nano-filler effect and the pozzolanic reaction, especially by making the interfacial transition zone (ITZ) more homogeneous and less porous [23]. Further, nano-Fe_3O_4, nano-ZrO_2, and nano-Al_2O_3 can effectively improve both the durability and mechanical properties of concrete [24].

Aggregate gradation (and other aggregate properties) can affect the properties of concrete, including durability and mechanical

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performance [25–29]. Moreover, good aggregate gradation results in low porosity and high properties of concrete [30]. Different aggregate gradations can impart different advantages to concrete but can also induce diverse types of defects. However, there are almost no related reports of effect of nano-SiO_2 on microstructure and impermeability of concrete with different aggregate gradations.

Therefore, the aim of this study is to explore the role of nano-SiO_2 in improving the microstructure and impermeability of concrete with different aggregate gradations. Water permeability tests and real-time monitoring of water sorptivity were carried out to obtain the parameters related to permeability. Moreover, kernel density estimation (and step function fitting) were used to statistically characterize and quantify the microstructure features of the samples.

2. Experimental procedure

Portland cement (PO42.5) was used as the cementitious material. Nano-SiO_2 (with the grain diameter, specific surface area, pH, purity of approximately 20 nm, 640 ± 60 m^2/g, 6–8 and 99.5% respectively.) was used as the modifier for concrete, and the nano-SiO_2-to-cementitious material ratio was 1.5%. Quartz with irregular edge shown in Fig. 1 was chosen as the aggregate and sizes of quartz were 4–8, 2–4, 1–2, 0.38–0.83, 0.18–0.38, and 0.12–0.18 mm. The water to cement ratio (W/C) used in this study was 0.35. A polycarboxylate superplasticizer with a solid content of approximately 40% was used as the additive. The mixture proportions of all materials are shown in Table 1. The contents of the different sized aggregates were determined using Eq. (1) [31], and shown in Fig. 2. The Fuller exponent q was chosen as 0.3, 0.4, 1.0, and 3.0 in the reference concrete (denoted as RC 0.3, RC 0.4, RC 1.0, and RC 3.0, respectively) and nano-concrete (denoted as NC 0.3, NC 0.4, NC 1.0, and NC 3.0, respectively).

$$P_i = 100\left(\frac{D_i}{D_{max}}\right)^q. \quad (1)$$

Here, P_i is the total percentage of particles passing through (or finer than) the sieve;

D_{max} is the maximum size of the aggregates;
D_i is the diameter of the current sieve;
q is the exponent of the equation.

After all the materials were prepared, cement, aggregate, and nano-SiO_2 were first mixed together for 5 min. Second, the superplasticizer was mixed uniformly with water, and then, this mixture was added to the dry mix and mixed for a further 5 min. Finally, the concrete mixture was poured into a mould (100 × 100 × 100 mm) and compacted on a swing table for 30 s.

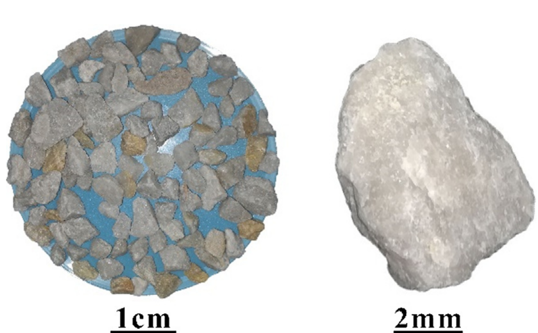

Fig. 1. The shape and surface of quartz.

Table 1
Mixture proportions (kg/m^3).

No.	Cement	Nano-SiO_2	Water	Superplasticizer	Aggregate	q
RC0.3	558	0.0	195	7.81	1581	0.3
RC0.4	558	0.0	195	7.81	1581	0.4
RC1.0	558	0.0	195	7.81	1581	1.0
RC3.0	558	0.0	195	7.81	1581	3.0
NC0.3	549	8.4	195	8.92	1581	0.3
NC0.4	549	8.4	195	8.92	1581	0.4
NC1.0	549	8.4	195	8.92	1581	1.0
NC3.0	549	8.4	195	8.92	1581	3.0

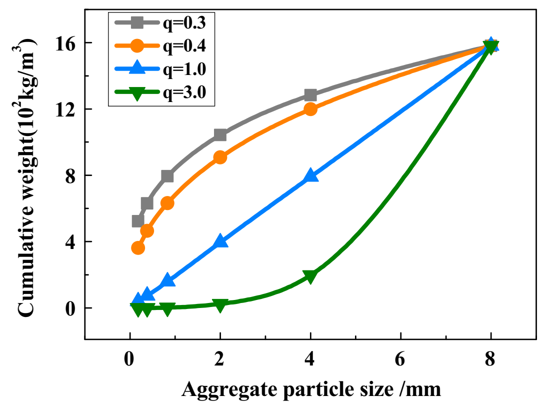

Fig. 2. Weight of aggregates with different sizes.

After 24 h of casting, the samples were removed from the moulds and cured under standard conditions (20 ± 2 °C, RH > 90%). On the day before testing, the samples were drilled and cut to sizes of approximately 100 mm diameter and 15 mm height.

3. Test method

3.1. Water permeability and water absorption

Water permeability and water absorption are important properties related to the permeability of concrete. Further, these parameters are beneficial for effectively analysing and evaluating the permeability and durability of concrete.

The water permeability test (WPT), which was conducted during the curing time in water, is regarded as innovative. The key to this program is to insert the sample into the WPT setup (Fig. 3 [32]) before the curing time (up to 28 days); then, WPT is performed on the sample surface. Therefore, this program can measure the water permeability in real time and guarantee accurate determination of the water permeability coefficient at a particular time. Based on the ASTM: C1585-13 standard [33], the water sorptivity test (WST) was performed using a real-time monitoring test device, as shown in Fig. 4.

The detailed WPT was conducted according to the previous literature [32]. The coefficient of water permeability (K_{wpt}) was calculated according to Eq. (2) [34], and water absorption I was calculated using Eq. (3) [33] and Eq. (4).

$$K_{wpt} = \frac{l}{ah} \cdot \frac{dQ}{dt} \quad (2)$$

$$I = \frac{m_t}{ad} \quad (3)$$