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A viscosity prediction model for cement paste with nano-SiO_2 particles

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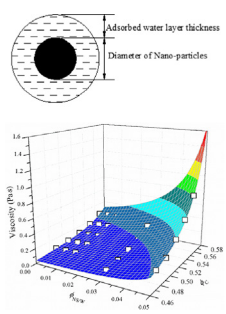
HIGHLIGHTS

- Effect of nano-SiO_2 particles dosage and W/C on the viscosity of cement paste is studied.
- An original viscosity model is proposed to predict the viscosity of nano-SiO_2 suspension.
- Relation of viscosity with nano-SiO_2 dosage and W/C is established about cement paste.
- Limitation of the proposed viscosity model is discussed.
- Adsorbed water layer thickness of nano-SiO_2 particles can be calculated by the model.

GRAPHICAL ABSTRACT



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ABSTRACT

The workability of cement paste with nano-SiO_2 (NS) particles depends on NS dosage and water to cement ratio (W/C). To characterize the workability of cement paste with hydrophilic NS particles, the viscosity of cement paste with different NS dosages and W/C is studied. An original viscosity prediction model is proposed to predict the minimum apparent viscosity of cement pastes with different NS dosages and W/C. In this viscosity prediction model, cement paste with NS can be taken as a suspension, i.e. cement particles is suspended in NS suspension. Therefore, the viscosity of cement paste with NS is composed of the viscosity of NS suspension and the relative viscosity of pure cement paste. The viscosity prediction models for NS suspension and pure cement paste are built up, respectively. The limitation of the viscosity prediction model of cement paste with NS is also discussed. Results show the proposed viscosity prediction model has high accuracy in predicting the viscosity of cement pastes with hydrophilic NS when NS volume fraction in NS suspension is less than 5.5%. The adsorbed water layer thickness of NS particles can be also calculated by the proposed model, and it is well in agreement with the mixing state results of NS suspension.

1. Introduction

The application of nanotechnology in cement-based materials has attracted much attention in recent years. Because of the unique properties of nanomaterials, it is being gradually accepted that the properties of cement-based material can be enhanced to a great extent in respects of strength gain, durability, and functional properties [1–5]. Among all the nanomaterials, nano-SiO_2 (NS) particle has been most widely investigated. The particle size of NS is often smaller than 100 nm. Due to the high fineness and activity, NS has the following reinforcement effect on cement-based materials: (1) NS inside the hydration products can prevent the crystal (such as calcium hydroxide (CH) and ettringite (AFt)) from forming big size due to nucleus effect [6]; (2) NS particles tend to physically fill the void space between the larger particles [7]; (3) the pozzolanic

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activity of NS can consume CH crystal, thus decreasing the orientation of CH crystal and reducing the size of CH in interfacial transition zone [8]. Because of these effects, it was reported in many studies that NS significantly improved the mechanical properties [9–19] and durability [3,20–27] of cement-based materials.

Although cement-based composite with NS is a promising construction material, there are two important issues to be considered regarding using NS. The first issue is NS dispersion. Because of the high fineness, NS particles have a strong tendency to form settlements or agglomerates when they contact with water [28]. Failing to achieve proper dispersion can cause a negative effect on the mechanical properties [12]. Therefore, intensive mechanical/ultrasonic dispersion and/or surface treatment were applied in the aforementioned studies. Another issue is the decrease in the workability of the cement-based materials with NS, also due to the high fineness and increased water demand of NS [29]. The workability of cement-based materials is degraded with the increasing NS dosage [30,31]. A poor workability can increase the difficulty of the forming of materials and further affect the mechanical properties [32]. However, most of the previous studies mainly focused on the effect of NS on the hardened properties as well as the corresponding mechanism, the effect of NS on the workability and rheological properties is seldom concerned. It is reported the workability of cement-based materials mainly depends on the rheological properties of cement paste [33,34], such as viscosity and yield stress. Superplasticizer with high water reducing ratio is preferred in cement paste with NS. With the effect of superplasticizer, cement paste is a less-flocculated suspension with very low yield stress. Therefore, this study will investigate the effect of NS on the viscosity of cement paste.

Cement paste with NS is essentially a suspension with cement and NS particles. The workability of cement paste depends on the NS dosage and water to cement ratio by weight (W/C). The workability of cement paste is degraded with the increasing NS dosage. To keep the same workability, W/C and superplasticizer dosage should be increased. However, the water reducing effect of superplasticizer increases little with superplasticizer dosage when superplasticizer dosage is above a critical dosage. Therefore, both of the NS dosage and W/C should be taken into account in study of the workability.

To reveal the effect of NS dosage on the workability of cement paste, this paper aims to give an original viscosity prediction model for cement paste with NS in consideration of both effects of NS dosages and W/C. To achieve the goal, the viscosity of cement paste with different NS dosage and W/C is firstly measured. Secondly, a methodology for predicting the viscosity of cement paste with nano-particles is proposed. Based on the methodology, a viscosity prediction model for cement paste with NS at different NS dosages and W/C is proposed. Finally, the mechanism of the effect of NS dosage is discussed in the basis of the viscosity prediction results. This work, to some extent, can provide a method to understand, design and control the workability of cement-based materials with NS particles and be also suitable for cement-based materials with other nano-particles.

2. Materials and experimental methods

2.1. Materials and specimens preparation

P.O 42.5R cement (from Dalian Onoda Cement Co. Ltd, China) was used throughout. The chemical compositions of cement are shown in Table 1. To disperse NS in water more easily, a hydrophilic NS (from Tokuyama Co., Japan) was used, with physical properties listed in Table 2. The morphology of the employed NS was observed by scanning electron microscope (SEM), which was shown in Fig. 1. A polycarboxylic acid based superplasticizer (water reducing ratio is 30%) was used in all mixtures, whose dosage was 1% of cement by weight. 1% of superplasticizer dosage is chosen because cement paste has minimum apparent viscosity in this condition [35].

To predict the viscosity of cement paste with different NS dosages and different W/C, cement pastes with different cement particles volume fractions (ϕ_C) and NS particles volume fractions (ϕ_{NS}) listed in Table 3 were fabricated in the test. In

Table 1
Chemical compositions of cement.

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TiO_2	Na_2O
Wt.%	65.0	21.2	5.16	3.39	2.43	1.32	0.63	0.78	0.07

Table 2
Physical parameters of NS.

Nano particle	Mean diameter (nm)	Specific surface area (m^2/g)	Density ($g.cm^{-3}$)	pH	Purity (%)
NS	12	200	2.2	4.5	≥99.8

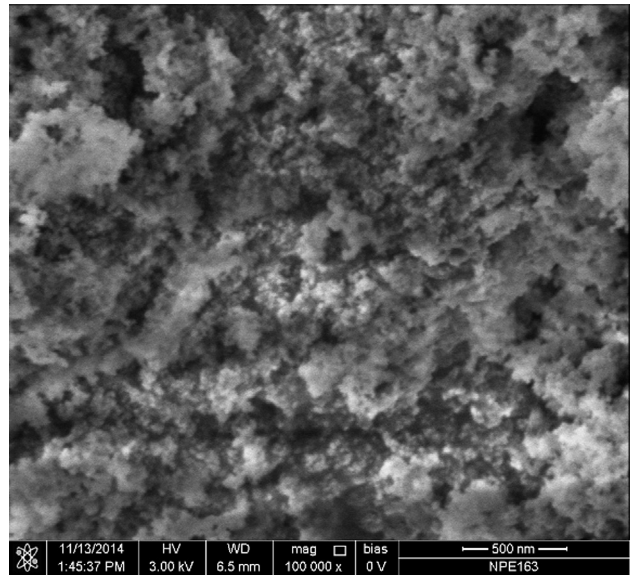

Fig. 1. SEM image of nano-SiO_2.

Table 3
Mix proportions of cement pastes.

Mix	$\phi_{NS}/(\phi_{NS}+\phi_W)$	ϕ_C	$\phi_{NS}+\phi_W$	C (g)	NS (g)	W (g)	SP (g)
N0C49	0	0.49	0.51	1519	0	510	15.2
N0C51	0	0.51	0.49	1581	0	490	15.8
N0C53	0	0.53	0.47	1643	0	470	16.4
N0C55	0	0.55	0.45	1705	0	450	17.1
N0C57	0	0.57	0.43	1767	0	430	17.7
N0.5C49	0.5%	0.49	0.51	1519	5.6	507.5	15.2
N0.5C51	0.5%	0.51	0.49	1581	5.4	487.6	15.8
N0.5C53	0.5%	0.53	0.47	1643	5.2	467.7	16.4
N0.5C55	0.5%	0.55	0.45	1705	5.0	447.8	17.1
N0.5C57	0.5%	0.57	0.43	1767	4.7	427.9	17.7
N1C49	1%	0.49	0.51	1519	11.2	504.9	15.2
N1C51	1%	0.51	0.49	1581	10.8	485.1	15.8
N1C53	1%	0.53	0.47	1643	10.3	465.3	16.4
N1C55	1%	0.55	0.45	1705	9.9	445.5	17.1
N1C57	1%	0.57	0.43	1767	9.5	425.7	17.7
N3C47	3%	0.47	0.53	1457	35.0	514.1	14.6
N3C49	3%	0.49	0.51	1519	33.7	494.7	15.2
N3C51	3%	0.51	0.49	1581	32.3	475.3	15.8
N3C53	3%	0.53	0.47	1643	31.0	455.9	16.4
N3C55	3%	0.55	0.45	1705	29.7	436.5	17.1
N5C47	5%	0.47	0.53	1457	58.3	503.5	14.6
N5C49	5%	0.49	0.51	1519	56.1	484.5	15.2
N5C51	5%	0.51	0.49	1581	53.9	465.5	15.8
N5C53	5%	0.53	0.47	1643	51.7	446.5	16.4
N5C55	5%	0.55	0.45	1705	49.5	427.5	17.1