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Influence of steam curing and nano silica on hydration and microstructure characteristics of high volume fly ash cement system

Junpeng Mei [a], Baoguo Ma [a], Hongbo Tan [a,*], Hainan Li [b], Xiaohai Liu [a], Wenbin Jiang [a], Ting Zhang [a], Yulin Guo [a]

[a] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, 430070 Wuhan, China
[b] Department of Construction Cost, Wuhan Textile University, 430200 Wuhan, China

HIGHLIGHTS

- In the presence of NS, steam curing is more effective to increase the strength.
- Under steam curing, NS has more remarkable nano effect.
- Synergistic effect of steam curing and NS on hydration of CHVFA was confirmed.

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ABSTRACT

In order to find a suitable way to improve the early strength of cement-high volume fly ash (CHVFA) system, nano silica (NS) was introduced. Two curing regimes with the same curing time was conducted: one is under standard curing (20 ± 2 °C, RH ≥ 95%) for 3 days, and the other is under steam curing (65 ± 2 °C, RH ≥ 95%) for 12 h and then standard curing for 60 h. The effect of NS and curing regimes on properties of CHVFA was systematically investigated. Pore structure, hydration products, and microstructure of interfacial transition zone (ITZ) were studied to reveal the mechanism behind the improvement in compressive strength. Results show that addition of NS can increase the strength of 3 days, regardless of the curing process. The reason for this increase is not only because of the accelerated hydrations of both cement and FA, but also due to the decrease in porosity and total pore volume as well as the improvement in the microstructure of ITZ. An interesting finding is that steaming curing can exert more efficient effect on increasing the strength in the presence of NS, which means that NS seems more effective to enhance the strength under steam curing, indicating an obvious synergistic effect between NS and steam curing in CHVFA system. Such results suggest effective way to improve the early strength of CHVFA paste, and the addition of NS can also promote the use of FA in precast concrete, with economic and environmental benefits.

1. Introduction

Fly ash (FA) is the inevitable by-product of coal-fired plants, and every 4 tons of coal consumption can produce 1 ton of FA. Only in 2015, FA output in China reached 620 million tons according to estimates, being the highest in the world [1]. This not only causes a great waste of resources and significant pollution for natural environment, but also takes up a large number of farmlands for storage, with negative effect on sustainable development of the industry. Therefore, effective utilization of FA will gain great economic and environmental benefits.

Application of FA as supplementary cementious materials (SCMs) in cement-based materials is one of the major ways for utilization of FA. As China is the largest cement producer for 32 years (about 2, 402, 950, 000 tons in 2016 alone) [2], the application of FA to partly replace the cement clinkers can result in significantly economic and environmental benefits, and this has been receiving more and more attention in industrial and research area. To be more precise, addition of FA not only reduces the consumption of natural resources, meeting the requirements of green concrete, but also has the various advantages for promoting the basic performance of the cement-based materials. Firstly, FA microspheres can benefit dispersing the cement particles as well as reduce the water cement ratio under the same fluidity demand [3]. Secondly, the calcium hydroxide consumption by FA can induce the hydration

* Corresponding author.
E-mail address: thbwhut@whut.edu.cn (H. Tan).

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of cement clinker, and mixing FA is also beneficial to disperse cement particles to increase the contact area between water and cement clinker, all of which would increase the hydration degree of cement [4]. Thirdly, the unhydrated FA, which means that the FA does not take part in the pozzolanic reaction, can be used as micro-aggregates to fill the pores among aggregate particles, further improving the density of concrete [5]. In addition, FA can delay the cement hydration, which lowers the concrete temperature rise caused by hydration heat to avoid generating cracks [6–9].

However, a widely accepted disadvantage of the cement high volume fly ash (CHVFA) system is the poor early strength, and because of this disadvantage, the use of fly ash is limited in most cases. Steam curing is one of the common ways to improve the early strength of CHVFA system, and the mechanism is related to the hydration and pore structure. Gonzalez-Corominas [10] studied the influence of steam curing on the pore structures and mechanical properties of FA concrete prepared with recycled aggregates, and it was found that steam curing was especially beneficial to the reduction of the porosity and the improvement in the splitting tensile strength of RAC in comparison to those concrete under room temperature curing. The study of Yazici [11] showed that steam curing increased the one-day strength values of high volume fly ash concrete (with 40%, 50% and 60% of FA) from about 10 to 20 MPa. Liu et al. [12] evaluated the compressive strength of steam-cured concrete containing ultrafine fly ash composite and proved that steam curing could significantly improve the hydration of FA.

The addition of nano materials, including nano-SiO_2 [13–15], nano-TiO_2 [16], carbon nanofibers [17] and so on, is another way to increase the early strength of CHVFA systems. Hou et al. [18–20] studied the effect of nano silica (NS) on compressive strength of cement-based materials containing different high volume fly ash. It was found that the addition of 2% NS in CHVFA mortars containing 40% and 50% fly ash increased the 7 days compressive strength by 5% and 7%, respectively. The study of Shaikh et al. [21] showed that 2% NS increased the compressive strength (i.e. 3 days) of concrete containing 60% fly ash by about 95%. Zhang et al. [22] evaluated the strength development of concretes with about 50% fly ash and the results indicated that the incorporation of 2% NS by mass of cementitious materials increased 3 days and 7 days compressive strengths of CHVFA concrete by 30% and 25%, respectively. The generally accepted reason for the improvement in strength is not only due to the good pozzolanic reactivity and crystal nucleus effect of NS to accelerate the hydration, but also because of its filling effect on modifying the microstructure and interface transition zone (ITZ) to make the paste much denser [13–15].

It is easy to find that the addition of NS and steaming curing can noticeably improve the early strength of cement-FA system. The improvement in the shortage of CHVFA system, namely very slow strength development at the early age, would be expected by these two measures. In this study, the influence of NS on the compressive strength of CHVFA system under two curing regime (standard curing and steam curing-strand curing) was investigated, and the governing mechanism was revealed in terms of pore structure, hydration products and microstructure of ITZ. Such results were expected to provide guidance on promoting the use of FA in precast concrete.

2. Experimental

2.1. Materials

Portland cement (PC) CEM I 42.5 was used in all mixes, and its specific gravity and surface area are 3.0 kg/m^3 and 345 m^2/g, respectively. Fly ash (FA) was used as supplementary cementious material (SCMs), in accordance with ASTM C618 [23]. Nano silica (nano-SiO_2, NS) with average particle size of 15 nm was used. A commercially available polycarboxylate superplasticizer (SP) with a solid content of 40.0% was added to ensure the same fluidity level with the same water/binder ratio. The chemical composition of PC and FA was characterized with XRF, and the results are shown in Table 1.

The particle size was tested with a Mastersizer 2000 laser particle size distribution instrument, and the results are shown in Fig. 1.The phase constitution and microstructure were studied with XRD, SEM and TEM, respectively, as shown in Figs. 2–4. XRD patterns indicate that the NS is amorphous material and is relatively less crystal than PC and FA. SEM images show that FA particles are perfectly spherical shape and PC particles are somewhat irregular. TEM image proves that the particle size of NS is about 15 nm.

Standard sand in accordance with ISO 679-2009 [24] was used as aggregates for mortars. The deionized water was used for all mixtures and experiments.

2.2. Mix proportion and sample preparation

The mix ratios of the pastes and mortars are shown in Table 2. Mortars were casted with a sand-binder ratio of 3.0 and a water-binder ratio of 0.5 by weight. Binder includes PC, FA and NS. The content of FA was fixed at about 40%, which is referred to as a high

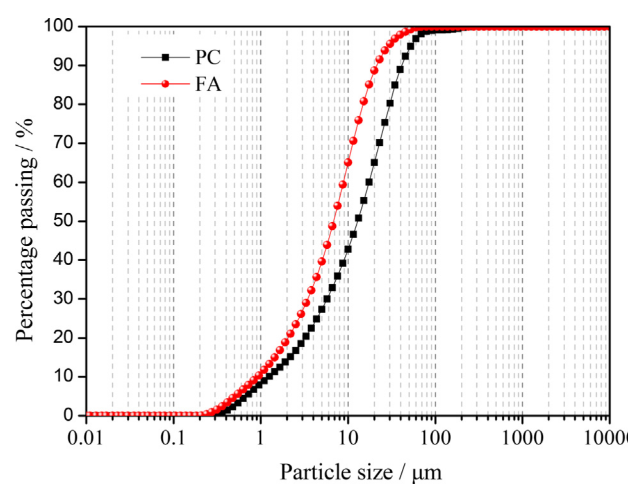

Fig. 1. Particle size distribution of PC and FA.

Table 1
Chemical composition of PC and FA.

Names of sample	Component (wt%)								
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Loss
PC	58.44	22.71	5.71	3.22	2.32	0.14	0.53	2.61	3.30
FA	8.55	49.17	25.52	4.45	0.94	0.59	2.12	1.73	4.59