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Study of high volume circulating fluidized bed fly ash on rheological properties of the resulting cement paste

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HIGHLIGHTS

- Influence of high volume CFBFA on rheological properties of the cement paste was assessed.
- Cement paste with different fly ash dosages and types will present different fluid models.
- Adding CFBFA will reduce rheological properties of the cement paste.
- Adding ultrafine CFBFA can improve rheological properties of the cement paste.
- Cement particle size distribution can influence rheological properties of CFBFA cement paste obviously.

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ABSTRACT

This paper investigated the rheological properties of cement paste containing high volume circulating fluidized bed fly ash (CFBFA) using a rheometer. The effects of fly ash (type, content, particle size distribution and surface characteristics) on the rheological parameters of the cement paste were analyzed. The test results showed that the rheological properties of the paste system exhibited Bingham fluid characteristics when the replacement level of cement by CFBFA (d_{50} = 56 μm) was less than 50%. When the content reached to 70%, the rheological properties were exhibited the characteristics of revised-Bingham fluid model. In contrast, the cement with ultrafine CFBFA (d_{50} = 5 μm) exhibited the fluid characteristics that follow the Herschel-Bulkey model. The results also showed that the particle size distribution and the surface characteristics of fly ash were the important influencing factors on the rheological parameters, where particle size distribution played a decisive role. Results from the Rosin-Rammler fitting analysis showed that the use of CFBFA would increase the d_{50} value of paste particles and widen the particle size distribution. When the content of CFBFA was 50%, the yield stress and plastic viscosity of the paste system were increased by 76% and 169%, respectively, however the fluidity of the paste system was lowered. On the other hand, the use of ultrafine CFBFA would reduce d_{50} value and narrow the particle size distribution. Owing to the ultrafine particles of FA3, the thixotropy of the paste increased when the content of ultrafine CFBFA in the paste was low. When the content of ultrafine CFBFA was 50%, the yield stress and plastic viscosity of paste system were reduced by 45% and 54%, respectively, and the fluidity of system was improved.

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1. Introduction

Circulating fluidized bed fly ash (CFBFA) is a by-product of the coal combustion process in in the circulating fluidized bed boiler. Compared to the conventional pulverized coal-fired technology, circulating fluidized bed coal-fired technology is considered to be a new generation of efficient, clean and environmental friendly coal combustion technology. Due to the combustion conditions of circulating fluidized bed boiler are different from the traditional pulverized coal furnace and the combustion temperature is typically lower (850–900 °C), therefore, CFBFA is usually characterized with a coarse particle size, non-spherical, porous structure, high surface roughness and high loss on ignition [1,2]. Because of these characteristics, concrete mixed with CFBFA usually require high water content to maintain adequate consistency and fluidity. Compared to pulverized fuel ash (PFA), the ingredients of CFBFA are more complex. CFBFA usually contains a certain amount of burnt

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clay minerals and several sulfur capture minerals such as II-$CaSO_4$, f-CaO, etc. In the presence of these minerals, CFBFA is more reactive than PFA and can be used as fly ash to replace ordinary cement. As a supplementary cementitious material, CFBFA can lead to more ettringite formation at the early age and contribute to a faster strength development of the cement paste. However, it may lead to a volume expansion at a later stage [3–6].

The annual emissions of CFBFA in China are enormous, and about 80–150 million tons each year [7]. So it's a matter of urgency and national interest to explore the use of CFBFA in an effective way. One of the most promising ways is to introduce CFBFA as a sustainable alternative to cement for the production of concrete. The use of CFBFA can minimize the dependency on cementitious materials to produce concrete that would make a valuable contribution to achieve sustainability [8,9]. To the best knowledge of the authors, the studies on fluidity, hydration and hardening process of CFBFA-cement paste are limited, especially when the use of CFBFA is greater than usual, i. e. more than 30%.

It is known that cement-based materials exhibit different flow characteristics under different experimental conditions [10]. There are three rheological equations commonly used to understand the rheological properties of cement paste, namely, Bingham fluid model (BH:$\tau = \tau_0 + \eta\gamma$), Revised-Bingham fluid model (R-BH: $\tau = \tau_0 + \eta\gamma + c\gamma^2$) and Herschel-Bulkey fluid model (HB:$\tau = \tau_0 + \eta\gamma^n$) [11–15]. Yield stress (τ_0) indicates the minimum force to overcome the internal friction generated by the plastic flow. The smaller is the τ_0, the better is the workability of the paste. The plastic viscosity (η) indicates the strength of the internal friction between the particles. The higher viscosity means that the paste is less likely to flow. The thixotropic ring area (*As*) is the parcel area calculated from the upstream and downstream rheology curves, used to determine the impact of different types and contents of fly ash on the thixotropic behavior of cement paste. Many studies on altering the fluidity of cement paste with fly ash have been done and the following are the commonly accepted conclusions [16–20]. (1) The addition of fly ash could effectively increase the packing density and decrease the voids volume. Under the same water content, the flowability can be improved by the increase of excess free water that forming water films to coat the solid particles. (2) The addition of fly ash delays the hydration of cement. (3) The thixotropy of cement pastes with fly ash follows stress thinning behavior. (4) The rheological behavior of fresh cement pastes follows Bingham model and the paste containing fly ash does not change its rheological property. (5) Fly ash has a ball-bearing effect because of the spherical shape. However, these conclusions are based on the use of pulverized fuel ash in cement. Whether or not the use of CFBFA will show the similar conclusions is yet to be determined.

In this paper, the rheological properties of cement paste with high content of CFBFA were studied and the effects of fly ash types, contents, particle size distributions and surface characteristics were investigated.

2. Materials and methods

2.1. Materials

Ordinary Portland cement, complying with the requirements of China National Standard GB 175-2007 (Common Portland Cement), was used for all mixes investigated here. The initial and final setting time of cement was 139 min and 196 min respectively. Three types of fly ash were used in this research. FA1 was a type of ordinary PFA. FA2 and FA3 were supplied by a coal-fired power plant in Shanxi province. FA2 was the genuine CFBFA produced by the circulating fluidized bed boiler, and FA3 was an ultrafine CFBFA which was obtained by grinding FA2 with a jet mill. Their chemical composition and physical properties are shown in Tables 1 and 2, respectively.

From Table 1, it can be seen that both CFBFAs showed a significant difference in the chemical composition when compared to the ordinary fly ash (FA1). The difference is mainly due to different burning conditions and types of coal involved. Apparently, both FA2 and FA3 contained less SiO_2 and more Al_2O_3 contents, compared to FA1. More significantly, both CFBFAs contain more CaO and f-CaO contents. It can be expected that when FA2 and FA3 are used as supplementary cementitious materials, more $Ca(OH)_2$ can be formed in the mix so that numerous AFt can be formed and the early strength of cement paste is higher when compared to that of ordinary fly ash. However, the loss on ignition was higher than 7.5%, which suggested a high water requirement. Kanazu [21] found that the flow value of mortar containing fly ashes tended to decrease as unburned carbon content increased but the flow remained unchanged when the fly ash content was less than 1.5%. From Table 2, it can be seen that the specific surface area of the Portland cement particles is between 350–400 $m^2 \cdot kg^{-1}$, and the average diameter of particles was about 20 μm. FA2 had coarser particles and its average particle size was greater than 50 μm. FA1 had relatively smaller particles, and the d_{50} of FA1 was about 12 μm. The average particle size of FA3 was about 5 μm.

2.2. Mix proportions

Three different types of fly ash were used to replace 30, 50 and 70% of cement by weight and their effects on rheological properties of cement paste were revealed. The mix proportions and packing density are shown in Table 3. The water/cement (W/C) ratio was 0.35 and the amount of polycarboxylate superplasticizer was added to the mix at 0.2% by weight of cementitious materials. It should be noted that the packing density of the particle system was studied without the use of superplasticizer. From Table 3, it can be seem that the packing density reduced with the increase of fly ash replacement ratio. Among the three different fly ashes studied, the use of FA2 resulted in the greatest reduction in packing density.

2.3. Test on rheology and thixotropic properties

In this study, the rheological properties of cement paste was tested using a rheometer (Brookfield DV3T model) and a small sample adapter was used. Depending on the viscosity range of the cement paste, the rheological parameters of each system paste were determined by the most suitable fluid models. The Rosin-Rammler distribution function was applied to evaluate the particle size distribution data.

2.4. Morphology and particle size

The particle morphology and surface characteristics of cement and fly ash particles were studied using a tungsten filament scanning electron microscope (S3400N) supplied by Japan Hitachi. The particle size distribution of the materials was measured by laser diffraction-type particle analyzer (OMIC-LS-C(II)). These experiments were carried out at room temperature of 25 °C condition.

3. Results and discussion

3.1. The rheology curve and fitting results of fly ash-cement paste

The rheology curves of pure cement paste and fly ash-cement paste were fitted by the most suitable rheological models namely

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