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Influences of shear-mixing rate and fly ash on rheological behavior of cement pastes under continuous mixing

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HIGHLIGHTS

- The rheological behavior of cement paste under continuous mixing was investigated.
- High-rate shear mixing or adding fly ash slowed down the evolution of thixotropy.
- An effective way to hinder the evolution of flocculation structure was proposed.

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ABSTRACT

The shear rate experienced by the cement pastes inside fresh concrete depends on the placing operations and the nature of concrete, and it plays an important role in the evolution of rheological properties and stability of fresh concrete over time. In this study, the effects of continuous shear mixing and fly ash on thixotropy, apparent viscosity, and shear-thickening behavior of cement pastes were experimentally investigated. Various shear rates of 1 s^{-1}, 15 s^{-1} and 30 s^{-1} were selected to continuously shear the cement pastes. Results showed that the action of high-rate shear mixing slowed down the evolution of thixotropy, but the efficiency of reduction was gradually limited. Under the state of continuous shear mixing, the apparent viscosity of reference paste was significantly increased and the shear-thickening intensity at higher shear rate range was decreased. However, for the cement pastes containing fly ash, only slight increase in apparent viscosity was observed and the shear-thickening intensity also exhibited a slight increase behavior. It would be an effective way to hinder the evolution of flocculation structure by exerting a continuous shear mixing at an appropriate shearing rate and adding fly ash.

1. Introduction

As the main by-product of coal-fired power plants, the fly ash generation in China was gradually increasing in the past few years and was also in the primacy around the world [1]. The fly ash annual output in China was already higher than 600 million tons in 2015 [2]. If not managed effectively, such a large amount of fly ash generation would cause serious environment issues such as the pollution of air and water. In China, half of the utilization of fly ash was used in cement and concrete industry as cementitious material or pozzolanic additive, depending on the content of CaO. From the perspective of physical effect, fly ash particles with fine particle size and smooth surface could fill the voids and thus increase the distance between cement particles [3,4]. On the other hand, replacing cement with fly ash increases the volume of paste, which also shows a positive effect on the workability and bleeding resistance of fresh cement-based materials [5–7]. From the chemical point of view, the hydration process of cementitious system at early age could be delayed by the addition of fly ash and thus the chemical shrinkage and risk of cracking could be reduced [8–10]. The addition of fly ash reduces the early compressive strength. However, due to the calcium hydroxide produced by the cement hydration could react with the silica in fly ash, reducing the porosity and improving the microstructure, and thus the long-term mechanical properties and durability of cement-based materials could be enhanced [11,12]. Most importantly, the utilizations of fly ash as pozzolanic additive or supplementary material can obviously reduce the costs of cement and concrete and relieve the environmental burden. Therefore, the utilization of fly ash has great

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economic, technical and ecological benefits in cement and concrete industry.

The rheological properties play an important role in guiding mixture design and predicting the casting and forming process. The effects of types, content, particle size distribution or fineness of fly ash on the rheological behavior of cement and concrete have been reported by many researchers, which are reviewed in Ref. [3]. Besides, the mixing process, resting time and testing procedure could also exert significant influences on the rheological properties of fly ash cement-based materials. Ferraris et al. [13] stated that fly ash-cement binary paste prepared using low shear rate mixer showed higher yield stress compared to the control cement paste, while high shear rate mixer showed an opposite behavior. Bentz and Ferraris [14] found that the addition of 50% class F fly ash significantly reduced the initial peak stress at early time and increased the initial setting time derived from stress growth test by 1.8 times. Ferron et al. [15] pointed out that the flocs of fly ash-cement pastes were caused by orthokinetic aggregation under shearing conditions. Mehdipour et al. [16] believed that the reduction in inter-particle friction induced by the spherical fly ash particles was more evident than the inter-particle links originated by the high specific surface area. Furthermore, the casting temperature and time also have a great influence on the evolution of yield stress and plastic viscosity of mortar with or without fly ash, which can be found in Refs. [17–19].

It is well known that the application process of concrete includes mixing, transporting, pumping, casting and forming. During the above operation processes, shear stress is always applied to the fresh concrete. The applied shear rates are of great significance because of their effects on the construction quality, and also the properties of hardened concrete. Take the applied shear stress in transporting process as an example, higher shear stress (rate) results in higher flowability but higher risk of aggregate segregation, while a lower shear stress (rate) will lead to inadequacy of agitation, which could hardly hinder the formation of flocculating structure and thus reduce the flowability and workability during the casting process [20]. Thus, further research on the combined effects of shear mixing and elapsed time on rheological properties of cement pastes is needed to understand the changes in properties of fresh concrete during the placing and casting processes.

The shear rate experienced by the concrete depends on the process operations [21], and the shear rate applied to the cement paste inside concrete are much higher than that experienced by the concrete itself when considered as a homogeneous fluid [22]. Generally, the typical shear rate experienced by the cement paste in concrete during placing processes is about 10 or 20 s^{-1} [13,23]. In this study, the influences of continuous shear mixing over time and fly ash on rheological behavior of cement pastes were experimentally investigated. Several constant shear rates containing 1 s^{-1}, 15 s^{-1} and 30 s^{-1} were respectively applied to continuously shear mixing the cement pastes for 50 minutes. Afterwards, the influences of fly ash and shear-mixing rates on thixotropic area, apparent viscosity, rheological curves and shear-thickening behavior of cement pastes were discussed. This study will hopefully provide an effective approach to hinder the evolution of structure and maintain the excellent workability of fresh concrete during transporting.

2. Experimental program

2.1. Materials

In this study, P·I 42.5 Portland cement and low calcium fly ash were selected as the cementitious materials. The cement conformed to the Chinese Standards GB175-2007 [24]. The chemical compositions and physical properties of cement and fly ash are presented in Table 1. Fig. 1 shows the particle size distributions of cement and fly ash. The specific surface areas of cement and fly ash were 348 m^2/kg and 465 m^2/kg, respectively. A powder-type polycarboxylate superplasticizer was used.

2.2. Mix proportions

The water-to-cementitious (w/c) ratio of cement pastes was kept fixed at 0.3 and the superplasticizer dosage was 0.2%. The low water content and the addition of superplasticizer have a positive effect to reduce the risk of sedimentation and bleeding [25]. The replacement levels of fly ash were 0%, 25% and 50% by mass. The mixture proportions of cement pastes are presented in Table 2.

2.3. Testing procedure

2.3.1. Mixing method

The volume of each batch was about 300 ml. Water and superplasticizer were first added into the Hobart mixer before the well-

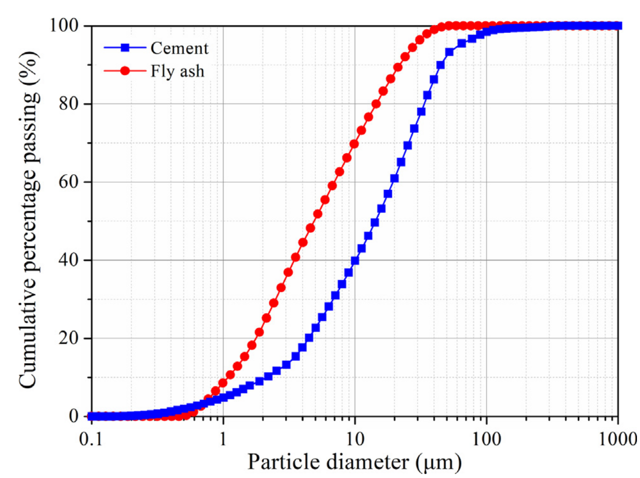

Fig. 1. Particle size distributions of Portland cement and fly ash.

Table 2
Mixture proportions of cement pastes (wt.%).

Mix.	w/c	Cement	Fly Ash	Superplasticizer
PC	0.3	100	0	0.2
FA25	0.3	75	25	0.2
FA50	0.3	50	50	0.2

Table 1
Chemical compositions and physical properties of cement and fly ash.

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	f-CaO	Loss	Density	Average particle size (μm)
Cement	20.76	4.58	3.27	62.13	3.13	2.80	0.76	1.86	3.15	16.49
Fly Ash	52.70	25.80	9.70	3.70	1.81	0.20	–	1.76	2.56	5.54