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Effects of mineral admixtures on shear thickening of cement paste

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HIGHLIGHTS

- Influence of FA, LP and SL on shear thickening of cement paste are investigated.
- γ_{crit}, τ_{crit}, η_{min} and rheological index (n) are put forward to describe and compare shear thickening.
- The addition of FA, LP and SL into cement paste make paste take on shear thickening easily.
- Intensity sequence of shear thickening of mineral admixture to cement paste are SL, FA and LP.

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ABSTRACT

Rheological behaviors are the essential workability characteristics of fresh concrete. Generally speaking, paste volume in self-compacting concrete (SCC) are no less than 340 L/m^3. Therefore, rheology of paste could be mainly responsible for rheology of SCC. Mineral admixtures are important for modern concrete, taking great influence on concrete rheology. In this paper, an experiment was designed to investigate the shear thickening behaviors of cement paste replaced by fly ash (FA), slag (SL) and limestone powder (LP), respectively.

Results show that plastic viscosity of paste discussed in this paper prominently decrease first and then increase with the shear rate increasing. Therefore, there exist critical shear rate (γ_{crit}), critical shear stress (τ_{crit}) and minimum plastic viscosity (η_{min}) in rheological curves at the beginning of shear thickening taking place. The addition of FA, SL and LP into cement paste not only decrease the γ_{crit}, τ_{crit} and η_{min}, resulting in cement paste easy to exhibit shear thickening, but also increase the rheological index (n), leading to shear thickening intensity augmenting. γ_{crit} of cement paste with addition 30% SL drops to10 s^{-1}, displaying shear thickening response taking place easily compared to cement paste with the same FA and LP contents. Rheological index (n) of cement paste with SL is also larger than cement paste with FA and LP at the same mineral admixtures contents. The shear thickening intensity sequence of cement paste under the effects of mineral admixtures are SL, FA and LP, respectively.

1. Introduction

Due to the characteristics of higher fluidity and segregation resistance of fresh concrete, lower porosity, higher strength and durability of hardened concrete, self-compacting concrete (SCC) is believed as a milestone achievement in modern concrete technology[1]. Mineral admixtures materials are indispensable compositions for modern concrete, especially for SCC. These mineral admixtures materials come from wastes and by-products of industry including fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF) et al. Replacement part of cement with mineral admixtures materials is an effective way of improving SCC properties and reducing carbon footprint of concrete production [2–4]. Rheological properties are the essential workability characteristic of SCC, which is very important for fresh SCC [5,6].

Shear thickening is an important aspect of concrete rheology, referring to the growth of plastic viscosity with shear rate increasing. Shear thickening is hard to avoid for SCC, but shear thickening is strongly unwanted in the process of mixing or pouring concrete for it can interfere with product quality and may even lead to damaging processing equipment. In some cases, the process of producing, mixing, transporting and pumping concrete would result in shear rate changing, giving rise to an obvious change of rheological behaviors and leading to shear thickening taking place in fresh SCC [7–9]. Generally speaking, paste volume in SCC are no less than 340 L per m^3 [10,11], and paste mainly take on lubricating and

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packing effects among aggregate. Therefore, rheological properties of paste play a key role in workability of SCC. Now, a large number of FA, SL and LP are used in SCC widely, resulting in rheological properties of SCC being susceptible. Replacement of cement with mineral admixtures will change the rheological behaviors of SCC greatly, including shear thickening [12]. Martin Cyr et al. pointed out [13] that the intensity of the shear thickening depended on the nature of mineral admixtures. It could be amplified (metakaolin), unchanged (quartz, fly ashes) or reduced (silica fumes). Yahia A carried out experiment and found [14,15] the addition of 8% silica fume particles reduced the shear thickening response. Diamantonis N et al. showed [16] that limestone (40%) could improve the rheological behavior of cement paste, and the synergy of limestone (20%) and fly ash (20%) could lead to higher packing density. Studies showed that there were a shear thinning stage and shear thickening stage in rheological curves of fly ash-cement paste. And replacement cement with FA makes paste strengthen shear thickening intensity [17,18]. The shear-thickening behavior observed with cement-based materials could be explained by either an order-disorder transition theory or cluster theory [19,20]. Barnes H A [21] studied shear thickening deeply and proposed that the severity of shear thickening depended on the particle concentration in proportion to the maximum packing fraction. The intensity of shear thickening continuously decreased as the mixture became more and more polydisperse. Shear thickening took place only when the suspensions were deflocculated. Particles that present irregular shape tend more easily to show a shear thickening behavior.

All these studies above are useful for people to understand rheological properties of SCC. Practically, because of the different of shape, size, chemical compositions and physical structure, mineral admixtures will take on different effects on shear thickening of cement paste. As results, comparing and evaluating the effects of mineral admixtures on cement paste are necessary. In SCC, the addition of FA, SL and LP are more than other mixture admixtures. Therefore, the objectives of this study were to experimentally study the effects of FA, SL and LP on shear thickening of cement-based materials and put forward parameters to judge and compare, mainly aimed at comparing and evaluating the shear thickening behaviors of cement paste under such mineral admixtures. The significance of this study is to distinguish the roles of different mineral admixtures on rheological behaviors of cement-based materials and provide useful information for SCC design and preparation.

2. Materials and method

2.1. Materials and admixtures proportion

Ordinary Portland cement P.O 42.5 (C) satisfied Chinese standards GB 175 was prepared [22]. Qualified and densified FA, SL and LP were used. Fig. 1(a)~(d) displayed the tested results of particle size distribution of C, FA, SL and LP. The chemical and physical properties of C, FA, SL and LP were given in Table 1. In order to disperse the cementitious materials and reduce agglomeration, a polycarboxylate-based superplasticizer with solid content 25.4% and specific gravity 1.09 was used. Mixing water (W) was deionized.

In this study, five mineral admixtures contents, namely 0, 20%, 30%, 40% and 50%, each expressed as a percentage by mass of the total cementitious materials, were adopted for the design of the paste samples, respectively. Water to binder ratio was kept constantly in 0.28 for all, and a dosage of 0.4% (mass fraction) superplasticizer was added into all paste so that the experimental conditions could be same.

2.2. Rheology test

2.2.1. Rheological curves

A room with ambient temperature (25 ± 2) °C and relative humidity (70 ± 5)% was used to carry out this test. Co-axial cylinder rotary viscosimeter produced by ANTON PAAR Company with Rheolab QC type was used to determine the rheological curves of different paste. In order to keep mixing uniformity, electric mixer of one-phase was used to mix paste. First, water and superplasticizer were mixed together by electric mixer with 500 rpm over a time span of 1 min. Second, cement and mineral admixtures were added into the admixtures of water and superplasticizer with 1500 rpm over a time span of 2 min. After being mixed samples were immediately loaded to co-axial cylinder rotary viscosimeter for testing. The rheological curves were tested at 2 min after mixing. The shearing rate was then increased gradually from 1 S^{-1} to 300 S^{-1}. Rheological equation and related rheological parameters were calculated according to mathematic fitting.

2.3. Methods for data analysis

The shear-stress and shear-rate data came from experiment and the rheological parameters were fitted through Herschel-Bulkley (H-B) model. This model can be expressed by Eq. (1)

$$\gamma = 0,\ \tau < \tau_0$$

$$\tau = \tau_0 + \eta\gamma^n,\ \tau \geqslant \tau_0 \tag{1}$$

where τ is shear stress (Pa); τ_0 is yield stress (Pa); η is plastic viscosity coefficient (Pa·s); γ is shear rate (S^{-1}); n is rheological index. When τ_0 is equal to 0 and n is equal to 1, the fluid is called Newtonian fluid. When τ_0 is not equal to 0 and n is equal to1, the fluid is called Bingham fluid. When n is more than 1, the fluid is called dilatant fluid. Namely, shear thickening takes place. In shear thickening stage, the larger the rheological index (n) is, the stronger the intensity of shear thickening is.

2.4. Particle size distribution test

Particle size distribution of cement, fly ash, limestone powder and slag were taken by auto laser particle size analyzer produced by Jinan Runzhi Science and Technology Ltd. Specific surface area of cement and other mineral admixtures were tested through BET method.

3. Results

3.1. Effect of mineral admixtures on rheological curves

Studies of rheological behaviors of cement paste addition of FA, SL and LP can provide useful information for understanding mechanism of controlling shear thickening response with different mineral admixtures concentration. Fig. 2(a)~(c) show the curves of shear rate *vs.* plastic viscosity under the influence of FA, LP and SL. Fig. 3(a)~(c) are the curves of shear rate *vs.* shear stress with the addition of FA, LP and SL.

Fig. 2(a)~(c) present that no matter what kind of mineral admixtures, with the growth of shear rate, the plastic viscosity decreases obviously first and then increases gradually. In other words, shear thinning takes place first and then shear thickening happens. At the beginning of shear thinning transforming to shear thickening, being points *A*,*B*,*C*,*D* and *E* presented in Fig. 2(a), points