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Relationship among particle characteristic, water film thickness and flowability of fresh paste containing different mineral admixtures

Huan Ye [a], Xiaojian Gao [a,b,*], Rui Wang [a], Hui Wang [a]

[a] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[b] Key Lab of Structure Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin 150090, China

HIGHLIGHTS

- Packing density increases linearly with the lower *n* value of Rosin–Rammler model.
- Mineral admixture increases the threshold solid volume fraction for paste to flow.
- The relative flow diameter (*RFD*) and *WFT* value is described by *RFD* = b/(*WFT* + a) + c.

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ABSTRACT

This paper aims to study the influences of particle characteristic on flowability of cement paste containing different mineral admixtures. Fly ash (FA), ground granulated blast furnace slag (GGBS) and limestone powder (LS) were added by 10–30% of cement weight to prepare binary system. SEM observation, particle size distribution and packing density were carried out for every single and binary cementitious system. Fresh pastes of every cementitious system were prepared with variable solid volume fractions, and slump flow and flow times (T150, T200 and T250) were recorded in the mini-slump test to evaluate the rheological performance. The results show that the packing density of cementitious system is increased significantly by addition of LS due to the wider particle size distribution and decreased by addition of GGBS due to the irregular shape. FA has a little increasing effect on the packing density due to its finer and sphere particles. For different cementitious systems with similar particle shape, the closer to the Fuller distribution the particle size distribution, the higher the packing density is. The packing density of solid particles increases linearly with the lower *n* value of Rosin–Rammler distribution and the particle shape has little influence on this tendency. A flowable paste containing mineral admixture can be prepared with the higher threshold solid volume fraction and lower water film thickness (*WFT*) value. For every cementitious system, the relationship between the relative flow diameter (*RFD*) and *WFT* value can be described by the equation of *RFD* = b/(*WFT* + a) + c, and the relationship between flow time (*T*) and *WFT* accords with the equation of *T* = 1/(d + e * *WFT*).

1. Introduction

With the addition of chemical and mineral admixtures, high-fluidity concretes such as pumping and self-compacting concretes have been widely used all over the world. The rheological behavior of fresh mixture becomes a very important factor influencing the field performance of these concretes [1,2]. Normally, the rheological performance of fresh concrete mainly depends on the cement paste matrix when similar amounts of coarse and fine aggregates are used. On the other hand, the performance of aggregates could be very unstable in one small test sample compared to another one. Therefore, in many cases, the studies of rheological performance were carried out on cement pastes instead of concrete mixtures [3,4]. Fresh paste can be normally regarded as a mixture of solid, water and air. The particle characteristics of solid ingredients have great effects on the rheological property of cement paste [5].

The packing density of solid particles is one of the important parameters to describe particle properties. To explain the relationship between packing density of particles and performance of fresh paste, there is a viewpoint that the mixing water firstly fills into the packing voids among particles, secondly covers the surface of particles and finally the excess water contributes to the fluidity.

* Corresponding author at: School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China.
E-mail address: gaoxj@hit.edu.cn (X. Gao).

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While the amount of mixing water is just enough for filling up the packing voids among particles, the fresh paste reaches the maximum density [6,7]. The packing density of particles depends on both the particle size distribution and particle shape. It is believed that the wider range of particle size distribution leads to the higher packing density, and spherical particles have a higher packing density than irregular particles [8]. Although most of particle packing models presented in previous studies are based on spherical particle which is far different from real cementitious materials, several models have been used to relate the particle size distribution and rheological performance of cement system [9,10]. Except for the packing density, the surface area of particles also has great effects on the rheological properties of fresh paste, mortar and concrete. This can be attributed to the variable thickness of water film coating on solid particles. The formation of water film around particle surface increases the space between particles, reduces the van der waals forces among particles, works as lubricant and reduces the friction between particles [11,12]. Therefore the water film thickness has great influences on the flowability, cohesiveness and stability of cement paste [13].

Mineral admixture has been regarded as a necessary ingredient in modern concretes and there are many researches focusing on the rheological performance of cement and concrete containing mineral admixture. Kwan found that the addition of up to 40% fly ash microsphere significantly increased the packing density and consequently the flowability of cement paste [14]. It was also reported that both yield stress and viscosity value of cement-fly ash paste increased with the particle number density in paste and fly ash mainly acted as a diluent which is coarser than cement [15]. The influence of limestone on cement paste fluidity is attributed by different authors to dispersing ability, lower reactivity or packing density and the overall effect depends on the mixing water content [16–18]. Studies revealed that the rheological parameters including yield stress and plastic viscosity can increase or decrease with a granulated blast furnace slag (GGBS) additive, being dependent on the relation between the specific surface area of cement and GGBS [19,20]. Park et al. [21] observed the decrease tendency of plastic viscosity with the addition of GGBS to replace cement. Other experimental results showed that yield stress and plastic viscosity of SCC mixtures increased with the more addition of GGBS [22,23]. It can be concluded that different effects of every mineral admixture on rheological performance are the consequence of many interfering factors. Among them the particle features should be further studied [24], and there are limited studies on the relationship among particle characteristic, water film thickness and rheological performance of fresh pastes containing different mineral admixtures.

In this work, the particle characteristic including particle size distribution and morphology observation were carried out on cement, fly ash (Class F), ground granulated blast-furnace slag and limestone powder. The packing density and rheological performance was performed for different mineral admixture added sample by the wet packing method and mini-slump flowability test respectively. Based on experimental data and particle packing models, the relationship among particle characteristic, packing density, water film thickness and flowability of fresh paste were analyzed.

2. Materials and methods

2.1. Raw materials

The cement used in this study was Ordinary Portland cement with strength grade of 42.5 in accordance with Chinese Standard GB175-2007 [25]. This cement has a Blaine specific surface area of 327.4 m^2/kg. Fly ash (Class F), ground granulated blast-furnace slag (GGBS) and limestone powder (LS) were used as three mineral admixtures with Blaine specific surface area of 672.6 m^2/kg, 424.4 m^2/kg and 436.7 m^2/kg respectively. The chemical composition for every cementitious material is summarized in Table 1. A polycarboxylate-based superplasticizer (SP) with a solid content of 40% and a specific density of 1.07 was used to prepare cement paste with good homogeneity. Except for the plain cement sample, nine binary systems containing different dosages of mineral admixtures were prepared as shown in Table 2.

Table 1
Chemical composition of cement and mineral admixtures (%).

Oxide	Cement	Fly ash	GGBS	LS
SiO_2	19.5	42.47	33.52	4.79
Al_2O_3	4.7	26.01	14.42	1.33
Fe_2O_3	2.80	8.44	0.29	0.51
CaO	64.2	14.01	42.8	52.14
MgO	2.50	3.15	5.91	0.59
SO_3	2.6	1.57	0.8	1.08
Density (g/cm^3)	2.97	2.35	2.81	2.70

Table 2
Ingredients of different cementitious system (%).

Sample	Cement	Fly ash	GGBS	LS
pC1	100	0	0	0
pF1	90	10	0	0
pF2	80	20	0	0
pF3	70	30	0	0
pG1	90	0	10	0
pG2	80	0	20	0
pG3	70	0	30	0
pL1	90	0	0	10
pL2	80	0	0	20
pL3	70	0	0	30

2.2. Testing methods

The particle size distribution for every single material and binary cementitious system was measured automatically by a laser particle size analyzer. Isopropyl alcohol was used as a liquid carrier to disperse cementitious particles before this measurement. Particle shape and morphology for every cementitious material were observed by a JEOL SX-4 scanning electron microscope (SEM) with the accelerating voltage of 25 kV.

The packing density of solid particles was determined according to the wet packing method developed by other researchers [26]. For every cementitious system, around 20 fresh pastes with different w/b ratio by volume ranging from insufficient to more than sufficient to fill the voids between the solid particles were prepared. For every sample, the same dosage of SP (3% by weight of solid content) was added and the added SP was also included in the total water volume. Based on the mixing ratios and every cementitious ingredient density, the solid concentration ϕ (defined as the ratio of the solid volume to the bulk volume of mixture) can be calculated. With the increasing w/b ratio from a relatively low value of about 0.35 to 0.55 in this experiment, the solid concentration first increased to a maximum value and then decreased. The maximum solid concentration ϕ_{max} was obtained as the packing density of the solid particles. With the packing density and specific surface area of each cementitious system, the excess water content and average water film thickness can be determined for pastes with different w/b ratios by volume.

Based on the tested packing density value, 10–12 of cement pastes with different solid volume fractions were prepared. To make sure the good dispersion of particles in paste, the SP was added by 0.8% of cementitious materials by weight for every paste. The fresh cement paste was performed the mini slump cone test immediately after preparation. The mini-slump cone has a base diameter of 60 mm, a top diameter of 36 mm and a height of 60 mm. To perform this test, the paste was filled into the slump cone until the slump cone was full and the top paste surface in the slump cone was trowelled flat and smooth. The slump cone was lifted vertically upwards to allow the paste to slump downwards and flow outwards. The final slump flow and the time required for the paste to spread to a diameter of 150 mm, 200 mm and 250 mm (T150, T200 and T250) were recorded for every sample. These parameters can be used to evaluate the rheological performance of fresh paste. It has been widely believed that the slump flow is decided by the yield stress while the flow rate is related to the viscosity.

3. Result and discussion

3.1. Particle shape and particle size distribution

The particle shape was observed for every cementitious material by SEM with magnification of $\times 300$. From the images