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Close Packing Theory of Binary System of Fly Ash-Cement with Different Fineness

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Abstract: The high packing density of particle mixtures is an important factor in achieving ultra-high performance in cement-based composites. In this study, the effect of fly ash with different fineness on the dense packing performance of cement-based composite cementitious material mixing systems are investigated. The results found out that when the particle size of fly ash is significantly smaller than that of cement particles (such as D50=1.0 μm, 3.0 μm), it can effectively fill the voids between cement particles and reduce the void ratio; when the particle size is similar to that of cement (such as D50=12.0 μm), there is no filling effect, and even the packing effect may be deteriorated. At the same time, the smaller the particle size, the better the filling effect. In specific, at the optimal dosage, fly ash with D50=1.0 μm can achieve a lower porosity than fly ash with D50=3.0 μm, and the overall effect of reducing porosity is more significant.

Keywords: Fly ash, cement, compacted solid void ratio.

1. Introduction

The high packing density of particle mixtures has become a key factor in achieving ultra-high performance in cement-based composites, such as the development of reactive powder concrete (RPC) [1-3]. Previous research has mainly focused on the filling effect of single mineral admixtures in particle mixtures. When dual mineral admixtures are used, the workability and mechanical properties of concrete mixtures are often the main research objects [5-7]. Further research is needed to explore the physical dense packing performance of cement composite binder particle mixture systems with different fineness of mineral admixtures when used individually, as well as the dense packing performance and effect of multi-component and multi-particle size mineral admixtures when used together.

Research [8] indicated that ternary composite cementitious materials blended with slag, fly ash, metakaolin, limestone powder, silica fume, and rice husk ash not only make the preparation of high-performance concrete more economical, but also exert a synergistic effect among them, improving the properties of fresh and hardened concrete.

In this work, the impact of single addition of fly ash with different fineness on the dense packing performance of cement-based composite cementitious material mixing systems are investigated. Additionally, a model is also employed to verify the test results of the bulk density of compacted bodies of cement composite cementitious materials with single mineral admixture. The experiment also investigates the mutual influence and relationship between the fluidity, mechanical strength, pore structure of hardened paste, and bulk density of binary cement-based composite cementitious materials consisting of cement and fly ash with different fineness.

2. Materials and Experiment

The types and properties of the raw materials used in the experiment are as follows:

Cement: P·O 42.5 cement produced by a cement plant in Hubei; P·II 52.5 cement produced by a cement plant in Hubei, whose physical performance indicators meet the requirements specified in "General Portland Cement" (GB175-2007). The cement performance indicators are shown in Table 1 and Table 2.

Fly ash: Fly ash with a D50 of 3.0 μm produced in Yangluo, Hubei (D50-3.0 μm fly ash) and fly ash with a D50 of 12.0 μm produced in Macheng, Hubei (D50-12.0 μm fly ash), as well as microspheres with a D50 of 1.0 μm produced by a manufacturer in Tianjin (D50-1.0 μm fly ash). Specific performance indicators are shown in Table 2 and Table 3.

Table 1. Properties of cement

Type	Water/g	Flexural strength /MPa		Compressive strength/MPa	
		3d	28d	3d	28d
P·II 52.5	134	6.3	9.4	33.6	60.5
P·O 42.5	136	4.8	8.2	27.5	48.7

Table 2. Physical properties of cement and fly ash

Materials	Density/g·cm^{-3}	specific surface area /m^2·kg^{-1}	R_{28}/MPa	28d Compressive strength ratio /%
P·II 52.5	3.2	350	60.5	100.0
P·O 42.5	3.2	330	48.7	100.0
$D_{50\text{-}1.0\mu m}$ Fly ash	2.73	950	50.3	81.8
$D_{50\text{-}3.0\mu m}$ Fly ash	2.41	780	47.2	76.7
$D_{50\text{-}12.0\mu m}$ Fly ash	2.20	330	42.0	68.3

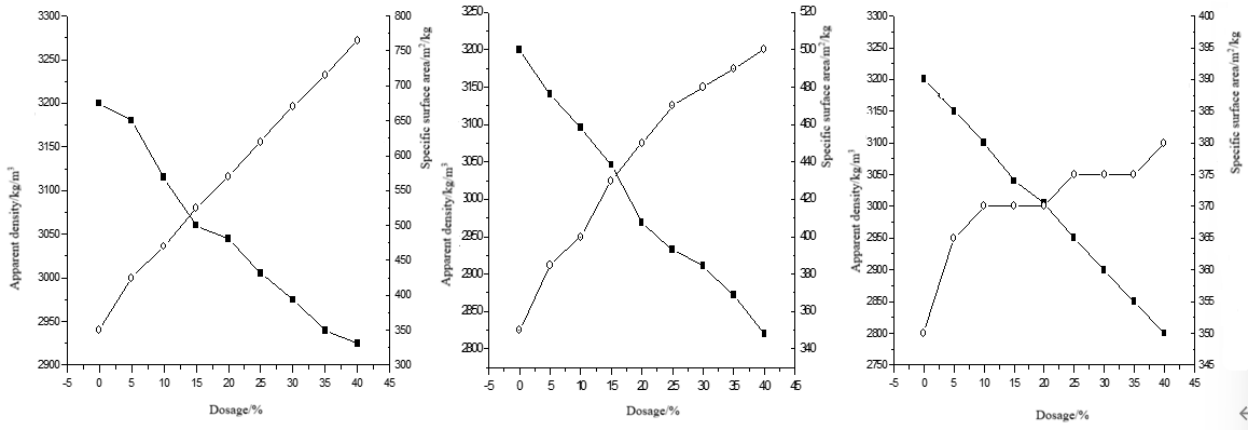
Table 3. Particle size distribution of fly ash

No	D_{50}/μm	D_{10}/μm	D_{25}/μm	D_{75}/μm	D_{90}/μm
$D_{50\text{-}1.0\mu m}$ Fly ash	1.00	0.61	0.78	1.42	1.99
$D_{50\text{-}3.0\mu m}$ Fly ash	3.0	0.95	1.72	5.1	9.7
$D_{50\text{-}12.0\mu m}$ Fly ash	12.0	2.53	5.19	27.15	48.52

3. Results and Discussion

3.1. Density and Specific Surface Area of Compound Powder

The influence of fly ash fineness on the apparent density and specific surface area of composite cement powder is illustrated in Figure 1. The density of composite cement powder gradually decreases with the increase in fly ash content, while the specific surface area of composite cement gradually increases with the increase in fly ash content. Additionally, as the fineness of fly ash increases, the specific surface area of composite cement powder significantly increases.



(a) D50-1.0μm fly ash (b) D50-3.0μm fly ash (c) D50-12.0μm fly ash

Figure 1. Effect of fly ash fineness on apparent density and specific surface area of composite cement powder

3.2. Compacted Solid Void Ratio of Compound Powder

The composite cement dry powder compact was prepared using the mechanical pressure method, and the porosity of the compact was tested to reflect the initial particle packing. A customized cylindrical mold with an inner cavity diameter of 76mm and a height of 70mm was used. 200.00g of powder was precisely weighed and filled into the mold. The mold was pressed on a press at a speed of 0.5kN/s until reaching 200kN, and the pressure was maintained for 2 minutes. Then, the press cover was removed, the mold was placed upside down on the press, and the test block was extruded. The weight of the compacted test block was measured, and the height of the compact was also measured.

The void ratio of powder compacted body is calculated according to formula (2-1):

$$v = \left(\pi \times R^2 \times \mathrm{h} - \frac{\mathrm{m}}{\rho} \right) \Big/ \pi \times R^2 \times h \qquad (1)$$

Where υ is the void ratio of the powder compact body, m is the mass of the weighed powder, ρ is the apparent density of the powder, R and h are the radius and height of the compact body, respectively. The influence of fly ash fineness on the porosity of compacted composite cement powder is illustrated in Figure 2.

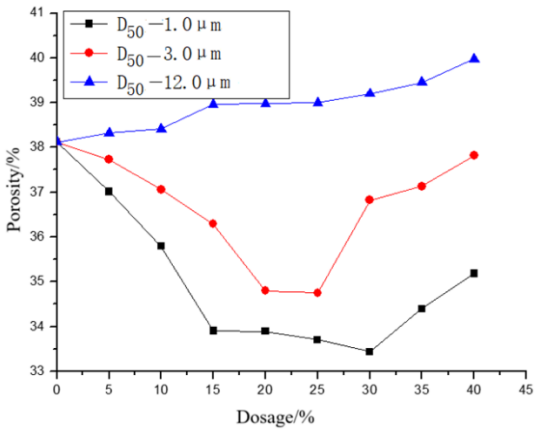


Figure 2. Effect of fly ash fineness on the porosity of compacted composite cement powder

When the content of fly ash with a D50 of 1.0 μm ranges from 0 to 40%, it reduces the porosity of cement powder to varying degrees. When the content ranges from 0 to 15%, the porosity of the compacted composite powder decreases significantly as the content increases. When the content ranges from 15 to 30%, the porosity of the compacted composite powder fluctuates slightly around 34.0%. Specifically, when the content of fly ash with a D50 of 1.0 μm is 30%, the porosity of the compacted composite powder is the smallest, at 33.4%. As the content of fly ash with a D50 of 1.0 μm continues to increase, the porosity of the compacted composite powder gradually increases again.

When the content of fly ash with a D50 of 3.0 μm ranges from 0 to 40%, it also reduces the porosity of the composite cement powder to varying degrees. However, the reduction

rate for each content is smaller than that of fly ash with a D50 of 1.0 μm. When the content ranges from 0 to 25%, the porosity of the compacted composite powder decreases significantly as the content increases. Specifically, when the content of fly ash with a D50 of 3.0 μm is 25%, the porosity of the compacted composite powder reaches its minimum, which is 34.8%. When the content of fly ash with a D50 of 3.0 μm ranges from 25 to 40%, further increasing its content leads to a gradual increase in the porosity of the compacted composite powder.

When the D50 is 12.0μm and the fly ash content ranges from 0 to 40%, the porosity of the composite powder gradually increases with the increase of its content. The compact packing pattern of the composite cement compacted body with D50 of 12.0μm fly ash is significantly different from that of D50 of 1.0μm fly ash and D50 of 3.0μm fly ash, which is related to the particle size of the fly ash. When the particle size of the fly ash is similar to that of the cement, the fly ash particles cannot fill the voids between cement particles, thus failing to reduce the porosity of the composite cement powder.

Due to the smaller particle sizes of fly ash with a D50 of 1.0μm and fly ash with a D50 of 3.0μm, within a certain range of mixing proportions, they can effectively fill the voids between cement particles, reduce the void ratio, and transform large voids into smaller ones, fully exerting their packing and compaction effect. This improves the packing density of the solid particle system and reduces the void ratio. However, when the mixing proportion of fly ash with a D50 of 3.0μm exceeds a certain level, the void ratio of the compacted body gradually increases. This is because the particles of fly ash with a D50 of 3.0μm have been fully filled into the large particle voids, and the solid particle system has reached its most compacted state. Further increasing the mixing proportion of fly ash with a D50 of 3.0μm can, due to effects such as wall adhesion, affect the packing between large particles, leading to a decrease in the overall packing density of the solid particle system and an increase in the void ratio.

4. Summary

Particle size is the core factor affecting the filling effect: only when the particle size of fly ash is significantly smaller than that of cement particles (such as D50=1.0μm, 3.0μm), can it effectively fill the voids between cement particles and reduce the void ratio; when the particle size is similar to that of cement (such as D50=12.0μm), there is no filling effect, and even the packing effect may be deteriorated.

There exists an "optimal mixing ratio": the filling effect of fine-grained fly ash has a "critical mixing ratio" (30% for D50=1.0μm and 25% for D50=3.0μm), at which the system achieves the most compact packing and the lowest void ratio; beyond this mixing ratio, wall-adhering effects and the like will disrupt the packing structure, leading to an increase in void ratio.

The smaller the particle size, the better the filling effect: at the optimal dosage, fly ash with D50=1.0μm can achieve a lower porosity than fly ash with D50=3.0μm, and the overall effect of reducing porosity is more significant.

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