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Research Article

Experimental Study on Water Reduction Modification and Efficient Utilization of Coal-Based Solid Waste Slurry

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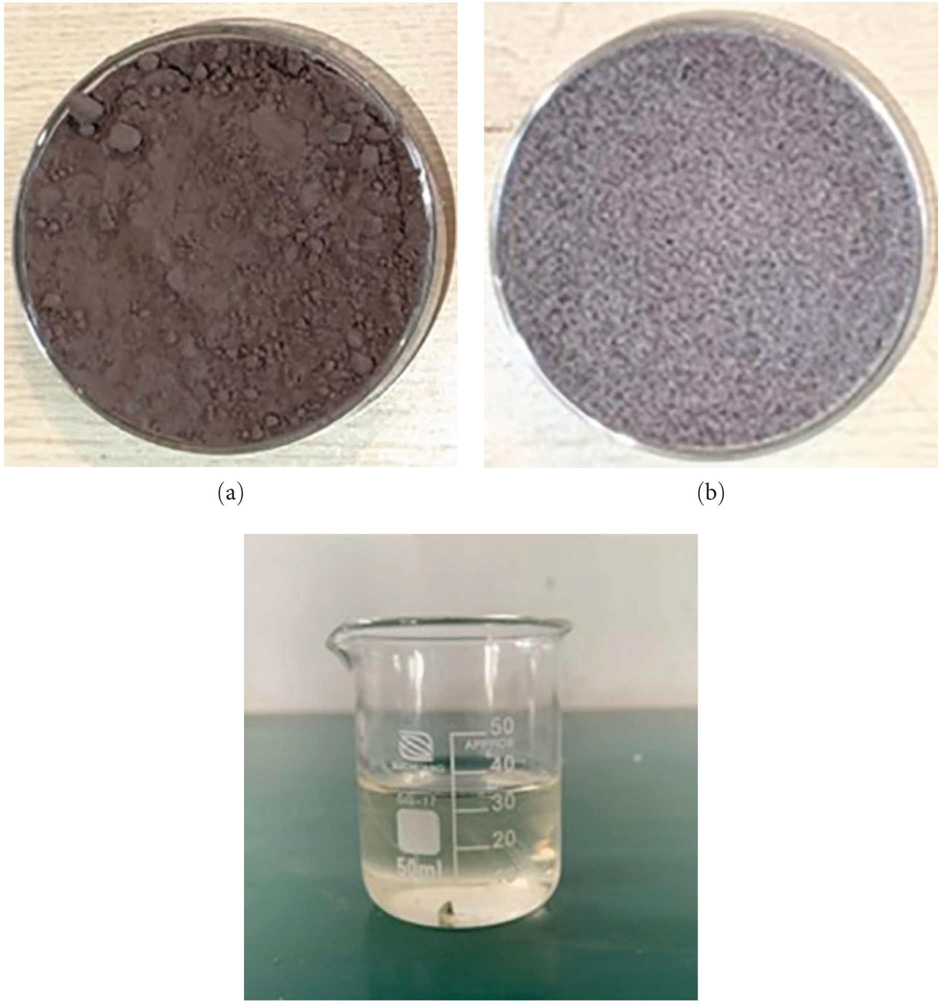
Unreasonable treatment of coal-based solid waste and coal mining damage are important factors that cause negative environmental effects. Overburden isolated grouting, a green mining method, can realize solid waste emission reduction and coal mine impairment mining. Fluidity and economy are important indices to measure the performance of slurry. Although fly ash slurry with a high water–cement ratio has good fluidity, it is wasteful in terms of water resources, the filling efficiency is low, and tectonic complexity affects its safe production; similarly, gangue powder slurry has good fluidity but comes with a high cost and complex implementation. Here, the relationship between fluidity and water–cement ratio in fly ash and gangue powder slurries was studied experimentally; the effects of particle size and dosage of gangue powder and polycarboxylic acid water reducer on the water consumption of fly ash slurry preparation were analyzed. Our results show that the fluidities of fly ash and gangue powder slurries increased with increasing water–cement ratios under laboratory conditions; the fluidity of gangue powder slurry was much higher than that of fly ash slurry under the same water–cement ratio and particle size conditions. When 50% gangue powder with particle sizes of 40–45, 50–55, 60–70, and 70–80 mesh was added to make composite slurries, the water reduction rate of fly ash slurry was 20%, 31%, 34%, and 36%, respectively. Adding a 1% polycarboxylic acid water reducer on top of the effect of the gangue powder gave comprehensive water reduction rates of 29%, 44%, 49%, and 53%, respectively. The critical particle size of gangue powder in the fly ash slurry to achieve stable suspension was 0.27–0.33 mm; when this was exceeded, the precipitation speed accelerated, and the water reduction rate reduced. A flocculation structure exists in fly ash and composite slurries, and the water reducer can breakdown this flocculation structure, increase the proportion of free water, and improve the fluidity of the resultant slurry. This high-efficiency utilization method of coal-based solid waste modified by water reduction can improve the utilization efficiency of coal-based solid waste and improve the effect and safety of grout-filling technology.

1. Introduction

Coal-based solid waste refers to solid waste, such as coal gangue and fly ash, with low carbon content produced during the process of coal mining, washing, and combustion [1, 2]. If the treatment and utilization methods of this solid waste are unreasonable, it will cause land occupation, environmental pollution, river siltation, and other problems [3, 4]. Meanwhile, longwall mining can also cause large-scale movement and fracturing of roof strata [5–7], which may lead to a series of safety and environmental problems, including cracks in overlying strata, that gradually transfer to the surface inducing surface collapse [8–10].

When fly ash and coal gangue are backfilled into spaces left by mining activity to form a load-bearing structure, solid waste treatment, and coal impairment mining can be realized simultaneously [11–13]. Overburden-isolated grouting technology makes full use of the law of strata movement; it uses ground drilling to carry out high-pressure grouting on mining cracks in overlying strata [14, 15] to form a compact load-bearing structure in goaf, effectively protecting ground buildings [16–18]. In practical engineering, either a fly ash slurry or gangue powder slurry with a high water–cement ratio (ratio of slurry preparation water to filling material mass) is usually used as the crack-filling material; this brings



(a) (b)

(c)

Figure 1: (a) Fly ash, (b) gangue powder, and (c) water reducer used in the experiment.

problems of water resource wastage, low filling efficiency, and a complex structure affecting safe production [19–21]. Therefore, it is necessary to modify the grouting slurry to improve the safety and applicability of grout-filling technology and realize the efficient utilization of coal-based solid waste.

The fluidity of coal gangue slurry is usually better than that of fly ash slurry, but its preparation is more complicated and costly [22, 23]. The raw materials of fly ash slurry are easily available and cheap, but its fluidity is relatively poor. Meanwhile, it is thought that the high water demand of slurry results from the difference in surface charges of granular materials; particles attract each other to form flocculation structures, which bind a large amount of free water [24–26], increasing the water demand of slurry [27–29]. Water-reducing agent is a kind of admixture applied in concrete engineering, which can reduce the allocation water of concrete under the condition of maintaining the slump of concrete [30–32]. The present research results show that the water-reducing agent can improve the flow of the slurry and reduce the water demand by breaking the flocculation structure in the slurry and releasing bound-free water [33–35]. At present, research in this field mainly focuses on the influence of water reducers on the properties of a single type of slurry [19], but there is little research on the properties of gangue powder–fly ash composite slurries and the influence of water reducers on these. In this study, we carried out a water-reducing modification experiment of fly ash slurry, investigating the effects of gangue powder particle size, dosage, and a water reducer on slurry preparation water use; this provides certain experimental support for improving the isolation grout-filling technology of overlying strata and improving the utilization efficiency of coal-based solid waste.

2. Test Materials and Methods

2.1. Test Materials. The bulk density of fly ash used in the experiment was 0.5 g/cm^3, with a true density of 2.2 g/cm^3 and particle size of 100–110 mesh. The gangue powder comprised undisturbed gangue obtained through crushing, ball milling, and sieving with a porous screen; the bulk density of gangue powder with particle size of 100–110 mesh are 1.4 and

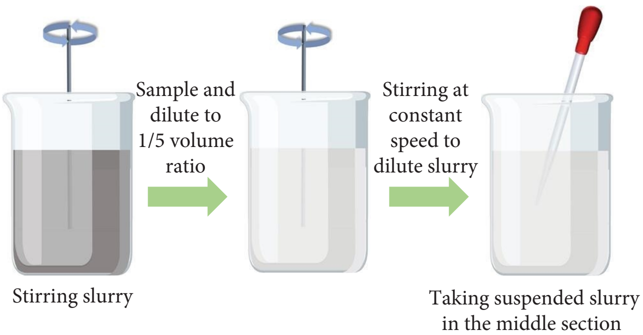


Figure 2: Sample preparation process diagram.

3.1 g/cm^3, respectively. The research group's previous study found [19] that compared with other types of superplasticizers, polycarboxylic acid superplasticizer has the most significant effect on fly ash and gangue powder slurry, so this experiment directly selected polycarboxylic acid high-performance superplasticizer (HLX type). These materials are shown in Figure 1.

2.2. Testing Program

2.2.1. Slurry Fluidity Test. The effect of adding gangue powder and water reducer on the fluidity of fly ash slurry was studied, and the optimal additions of gangue powder and water reducer were determined. The testing process was carried out in accordance with the *Standard Test Method for Homogeneity of Concrete Admixtures* (GB/T 8077-2000).

2.2.2. Slurry Microstructure Observation. The microstructure of the slurry samples was observed under an optical microscope, and the mechanistic action of the water-reducing agent was analyzed. To enable observation, slurry with a water–cement ratio of 1 : 1 was first placed in a beaker and fully stirred. To avoid the concentration being too high to distinguish the particle state, five times the volume of distilled water was added to the beaker to dilute the slurry; finally, the middle portion of the suspension was extracted via a pipette to make the sample for observation (Figure 2).

3. Results and Discussion

3.1. Relationship between Water–Cement Ratio and Fluidity of Slurry. Fluidity is an important index to measure the pumpability of slurry; generally, a higher water–cement ratio equates to better fluidity. Meanwhile, the types of filling materials, slurry preparation methods, and other factors will also affect the fluidity. Therefore, it is first necessary to clarify the relationship between the water–cement ratio and fluidity of coal-based solid waste under laboratory conditions.

The fluidity of gangue powder and fly ash slurries having identical particle sizes (100–100 mesh) was tested, and the results are shown in Figure 3. In coal-based solid waste slurry, the water–cement ratio has a direct impact on fluidity, conforming to the general law that fluidity increases with increasing water–cement ratio. For fly ash slurry, there was an evident quadratic function relationship between water–cement ratio and fluidity under laboratory conditions

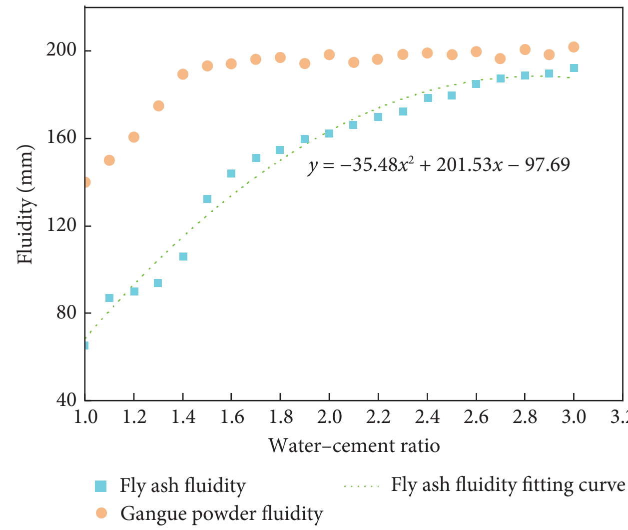


Figure 3: Fluidity of fly ash and gangue powder slurries under changing water–cement ratios.

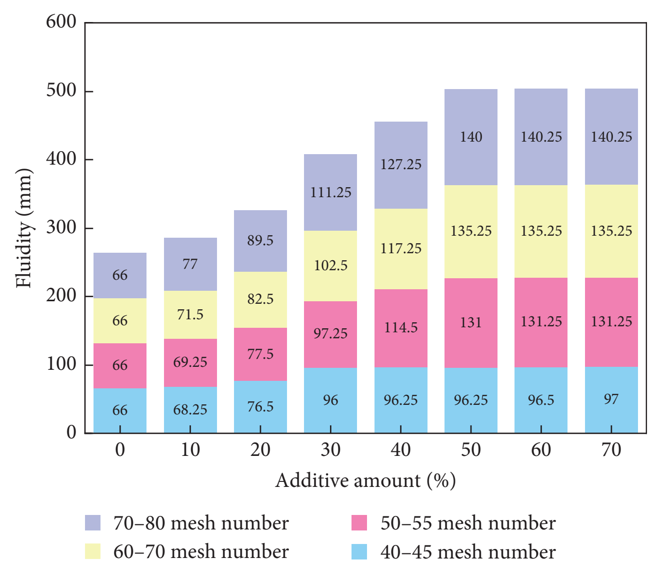


Figure 4: Influence of different particle sizes and doses of gangue powder on slurry fluidity.

(for water–cement ratios in the range of 1–3). Meanwhile, the water–cement ratio versus fluidity relationship for gangue powder slurry was evidently different from that for fly ash slurry; under the same water–cement ratio and particle size conditions, the fluidity of gangue powder slurry was notably higher than that of fly ash.

3.2. Influence of Gangue Powder on the Fluidity of Fly Ash Slurry. According to the particle size distribution in the actual grouting project, the gangue powder was screened into 40–45, 50–55, 60–70, and 70–80 mesh, then added to the fly ash according to the total mass of the filling material in the following doses: 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 70%.

As shown in Figure 4, our results demonstrate that gangue powder can markedly improve the fluidity of fly ash slurry;

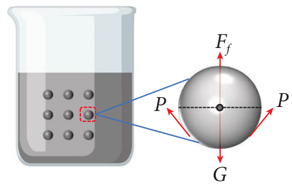


Figure 5: Diagram of the forces acting on gangue powder particles in fly ash slurry.

the fluidity increased with increasing dosage over a certain range, and the particle size of the gangue powder also affected the fluidity of the resultant slurry.

When the dosage of gangue powder with particle sizes of 50–55, 60–70, and 70–80 mesh reached 50%, the fluidity of the slurry increased by 98%, 105%, and 112%, respectively. Because the addition of gangue powder can improve the fluidity of slurry, if the fluidity of the composite slurry reaches that of pure fly ash slurry, the water used for slurry preparation can be reduced. The reduction rate of water consumption for slurry preparation is termed the "water reduction rate"; that is, the ratio of the difference between the unit water consumption of pure fly ash slurry and composite slurry and the unit water consumption of pure fly ash slurry under the same fluidity can be expressed using Equation (1):

$$W_R = \frac{W_p - W_m}{W_p} \times 100\%, \qquad (1)$$

where W_R is the water reduction rate, W_p is the unit water consumption of pure fly ash slurry, and W_m is the unit water consumption of composite slurry. Combined with the water–cement ratio versus fluidity function relationship of fly ash slurry obtained in Section 3.1, it can be seen that when the dosage of gangue powder with particle sizes of 50–55 mesh was 50%, the fluidity of the composite slurry is 131 mm, and the water–cement ratio of fly ash slurry can be obtained from the function of water–cement ratio of fly ash slurry. In the pure fly ash slurry, the fluidity of 131 mm corresponds to the water–cement ratio of 1.45, and then the water reduction rate is 31%. When the addition of 60–70 and 70–80 mesh gangue powder reaches 50%, the water reduction rate was 34% and 36%, respectively. When the dosage of gangue powder with a 40–45 mesh particle size reached 50%, the fluidity of the slurry increased by 45.8%, and its water reduction rate was 20%; i.e., the improvement in fluidity was far lower than for gangue powders of other particle sizes.

To address the issue that gangue powders with different particle sizes had different effects on improving the fluidity of fly ash slurry, the forces of gangue powder in composite slurry were analyzed. The maximum particle size of gangue powder that can be suspended in slurry without settling was calculated, and the effect of the suspended state of gangue powder on the water reduction rate was analyzed. According to the particle state and flow environment, the problem was simplified as follows: the gangue powder particles were regarded as regular spheres, and the movement of gangue powder particles in the static slurry was assumed to be free settlement.

Gangue powder particles are affected by gravity (G), buoyancy (F_f), and medium resistance (P) in fly ash slurry, as shown in Figure 5. When gangue powder particles remain suspended in fly ash slurry, G, F_f, and P must reach a balanced state.

The equilibrium state of gangue powder particles is affected by the particle size; the maximum particle size of solid particles in a static slurry can be obtained using Equation (2) [36]:

$$D_{\max} = \frac{6\tau_B}{k\left(\gamma_g - \gamma_f\right)}, \qquad (2)$$

where $D_{\max}$ is the maximum particle size of particles in suspension; τ_B is the ultimate shear stress of a Bingham fluid, this being 10 Pa for the fly ash slurry used in this experiment; K is the spherical diameter coefficient, which is 0.3 herein; γ_g is the particle density of gangue powder, which is 3,000 kg/m^3 herein; and γ_f is the density of fly ash slurry, which is 2,250–2,400 kg/m^3 herein.

After calculation, the particle size range of coal gangue powder particles in suspension in fly ash slurry was found to be 0.27–0.33 mm, corresponding to 45–50 mesh. Therefore, gangue powder with a particle size of 40–45 mesh has a poor water-reducing effect on fly ash slurry owing to the difficulty in forming a stable suspended slurry because of the fast settling speed of such particles in the slurry.

3.3. Effect of a Water Reducer on the Fluidity of Composite Slurry. During preparation, fly ash slurry requires abundant water to reach the fluidity required for pumping, but after the slurry reaches the grouting layer and is subjected to external pressure, most of the water in the slurry will be expelled. A similar problem exists in concrete engineering owing to the high water demand of cement slurry. This phenomenon has been explained by the surface charges of filling materials being different; hence, particles will attract each other to form a flocculation structure, which will trap approximately 10%–30% of the free water and reduce the fluidity of the slurry.

A water reducer can breakdown the flocculation structure of a slurry through electrostatic repulsion or steric effects, release bound free water, and improve the fluidity of the slurry. Building on the results outlined in Section 3.2, we added a polycarboxylic acid water reducer to various types of slurry and analyzed the influence of the water reducer on the fluidity and water reduction rate of the resultant composite slurries. For this experiment, gangue powder with particle sizes of 40–45, 50–55, 60–70, and 70–80 mesh was used; the dosage of gangue powder was 50% of the total mass of the composite, and the dosage of water reducer was 0%, 0.5%, 1%, or 1.5% of the total mass of the dry material of the composite.

The experimental results are shown in Figures 6 and 7, where it can be seen that the water reducer improved the

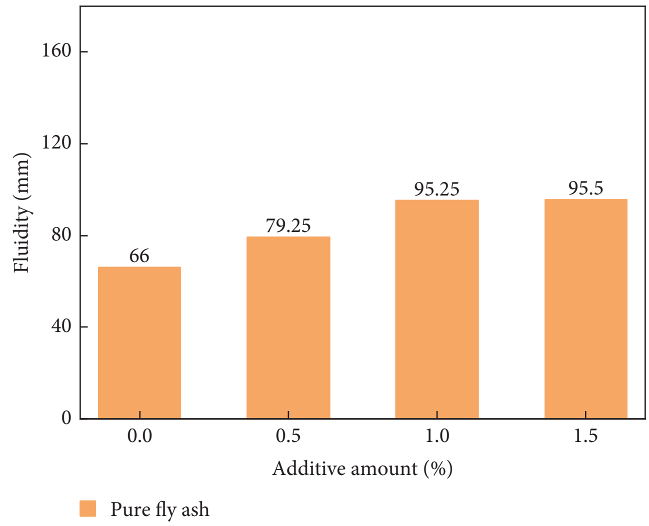


Figure 6: Effect of polycarboxylic acid superplasticizer on the fluidity of fly ash slurry.

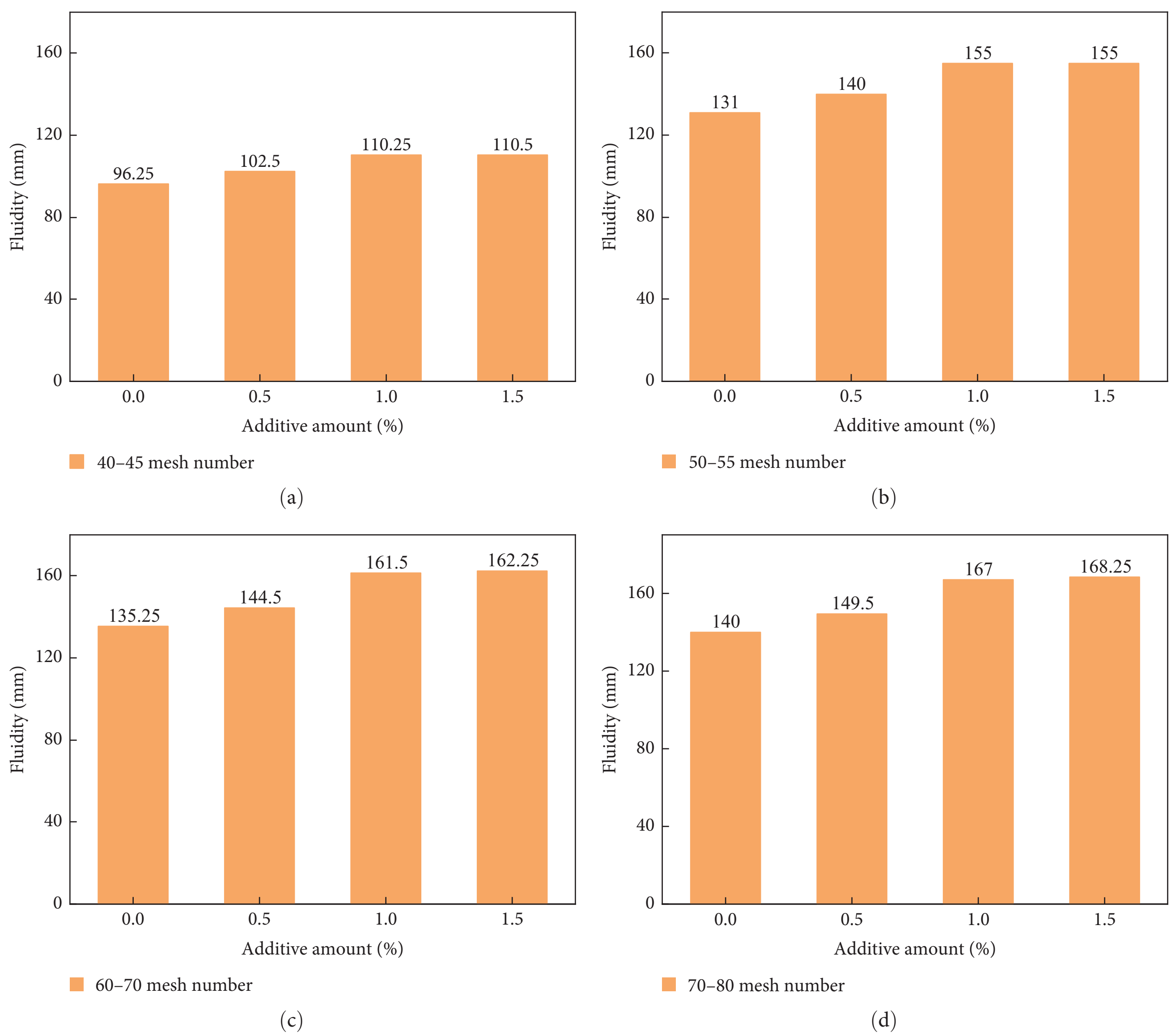


Figure 7: (a–d) Effect of polycarboxylic acid superplasticizer on the fluidity of mixed grout.

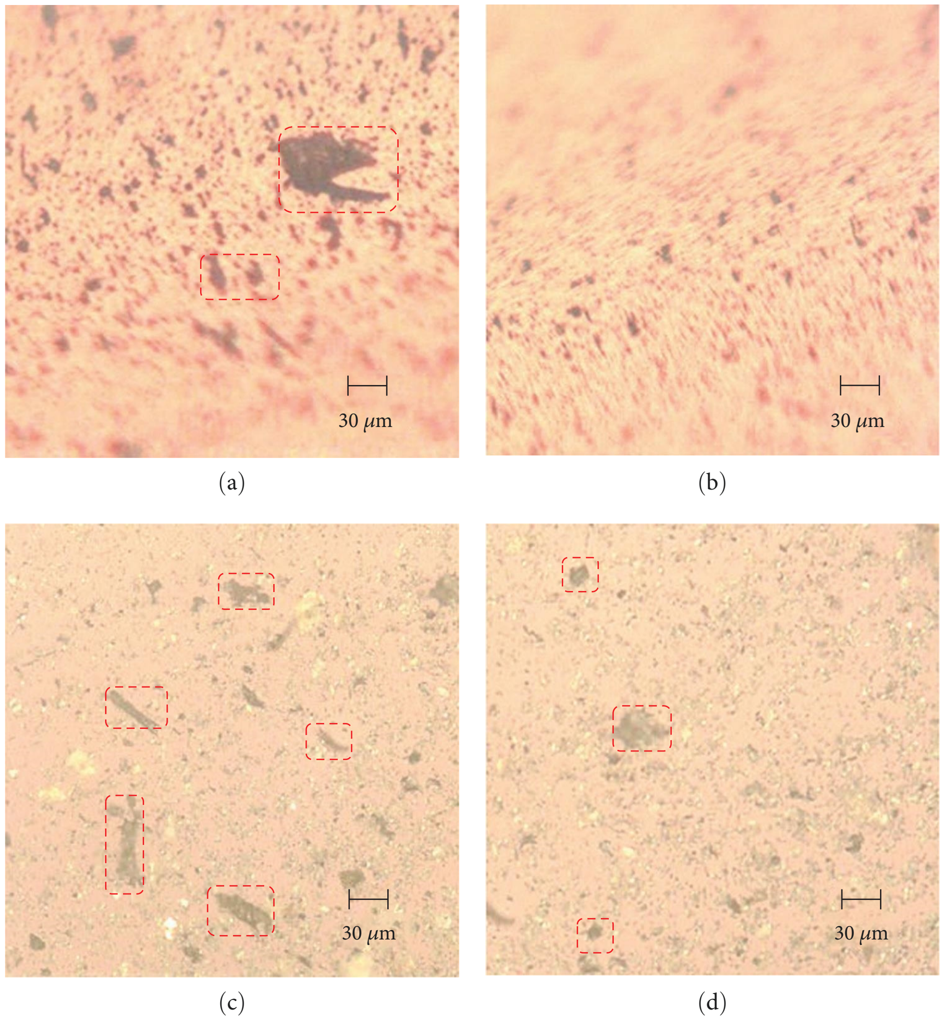


FIGURE 8: Microscopic images of flocculation structures within fly ash and mixed slurries: (a) fly ash slurry; (b) fly ash slurry with water-reducing agent; (c) mixed slurry; (d) mixed slurry with water-reducing agent.

fluidity of both pure fly ash slurry and composite slurry, but the effects in the two slurry types were different. Figure 6 shows that the water reducer evidently improved the fluidity of fly ash slurry, and over a certain range (0%–1.0%), the fluidity increased as the amount of water reducer increased. When the amount of water reducer added was 1.0%, the fluidity of the slurry increased by approximately 45%, corresponding to a water reduction rate of 26%.

Figure 7 shows the effect of water reducing agent on the fluidity of mixed grout of gangue powder and fly ash with different particle sizes. Figure 7(a)–7(d) correspond to the changes in the fluidity of grout after adding water reducing agent to 40–45, 50–55, 60–70, 70–80 mesh composite grout, respectively. Upon the incorporation at a dosage of 1%, the fluidity enhancement was noted to be approximately 15%, 19%, 20%, and 20%, respectively. Correspondingly, the water reduction rate was observed to be 29%, 44%, 49%, and 53%. By comprehensively comparing the effects of a water reducer in fly ash slurry and composite slurry, it can be seen that the water reducer had a relatively poor water-reducing effect in fly ash slurry and large-particle-size gangue powder composite slurry but a better water-reducing effect in small-particle-size composite slurry.

To determine the reasons for the different water-reducing effects of the water reducer in composite slurry and pure fly ash slurry and study the mechanism of the water reducer, the pure fly ash and composite slurries were observed under an optical microscope, where the changes in slurry composition and structure before and after adding the water reducer were analyzed.

The microstructures of the slurries are shown in Figure 8, in which black masses represent flocculated material. It can be seen that the grout particles are indeed subjected to the action of van der Waals force and interlayer charge force, resulting in agglomeration formation in both the fly ash slurry (Figure 8(a)) and composite slurry (Figure 8(c)); compared with the composite slurry, the flocculated material in the fly ash slurry had a higher density and larger volume, indicating that the flocculation degree of the fly ash slurry was higher than that of the composite slurry.

Figures 8(c) and 8(d) show that the sizes of flocculation structures in both types of slurry were markedly reduced after adding the water reducer; this indicates in fly ash slurry and composite slurry, water reducing agent may also break the flocculation structure through electrostatic repulsion or steric hindrance effect. Water reducers can improve slurry fluidity, and the amount by which the flocculation structure was broken down was greater in the fly ash slurry compared with the composite slurry; i.e., the water-reducing effect of the water reducer in the fly ash slurry was more pronounced than that in the composite slurry.

4. Conclusions

(1) The relationship between fluidity and water–cement ratio of fly ash and gangue powder slurries under laboratory conditions was obtained. The fluidity of fly ash and gangue slurries increased with increasing water–cement ratio, and there was an evident quadratic function relationship between water–cement ratio and fluidity in fly ash slurry. The fluidity of gangue slurry was evidently higher than that of fly ash slurry under the same water–cement ratio and particle size conditions.

(2) The influence of particle size and dosage of gangue powder on the fluidity of fly ash slurry was determined, and the maximum particle size of gangue powder exhibiting a good water-reducing effect was obtained. When 50% gangue powder with particle sizes of 40–45, 50–55, 60–70, and 70–80 mesh was added to the fly ash slurry to make composite slurries, the water reduction rates were 20%, 31%, 34%, and 36%, respectively. Of these, gangue powder with a particle size of 40–45 mesh exceeded the critical particle size that can be suspended in the slurry, leading to a faster sinking speed and poorer water reduction rate.

(3) The mechanistic action of the water reducer was revealed, and the relationship between the dosage of polycarboxylic acid water reducer and the water-reducing effect on fly ash slurry and composite fly ash–gangue powder slurries was obtained. Owing to the differences in surface charge of various particles, fly ash will form abundant flocculation structures in the slurry, which will bind free water. The water reducer can breakdown the flocculation structure and release the flocculated water, thus improving the fluidity of the slurry. With the addition of the water reducer over a dosage range of 0%–1%, the fluidity of all slurries gradually increased. When the dosage was 1%, the comprehensive water reduction rate of the water reducer combined with small-particle-size gangue powder in fly ash slurry was approximately 50%.

Data Availability

The authors will supply the relevant data in response to reasonable requests.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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