Study on the Grouting Properties of Multi-Mineral Cement Paste

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Abstract. In this study, the effect of zeolite powder (ZP) and basalt powder (BP) on the grout properties of cement slurry was explored. The grout properties include fluidity, rheology, cohesiveness, segregation resistance and mechanical properties. In addition, the three-parameters mathematical models were established to better understanding the relationship above properties. The experimental results show that the incorporation of ZP or BP can effectively reduce the bleeding rate and improve the cohesiveness of cement paste, and this improvement become more significant with the increase of the ZP, BP content and the w/c ratio. Under the appropriate dosage, the cement paste can also have good compressive strength and rheological properties. The results of the three-parameter model indicated that rheological parameters, flow parameters, and cohesiveness-bleeding rate systems all can become the main factors affecting the 28day compressive strength. Flow parameters systems and rheological parameter systems were not the main factors that determine the cohesiveness of cement slurry. On the contrary, cohesiveness can significantly affect the rheological properties of cement paste.

1. Introduction

Grouting is a method of hydraulically flowing a slurry with fluidity and gelation into the cracks of a stratum or a building through drilling (or pre-buried pipes) to improve its physical and mechanical properties through replacement, filling and extrusion [1-2]. Grouting has been widely used in various field applications (tunnels, dams, foundations, slopes, etc.) to improve the reliability and service life of engineering structures. Therefore, the grouting material is required to have good filling properties, flow properties, rheological properties, cohesiveness, segregation resistance, early strength and high strength properties [3]. However, conventional cement-based grouting materials have the problems of poor rheology, insufficient strength and poor cohesiveness or segregation resistance. Now the most common practice in engineering is to use green grouting materials [4]. The addition of some industrial waste ash or volcanic ash as grouting materials can not only improve grouting performance, but also reduce engineering cost and protect the environment.

Zeolite powder (ZP) and basalt powder (BP) have pozzolanic effect and have been widely used in engineering as a substitute for cement [5-6], but there is little research on whether BP and ZP can be used as grouting materials, especially BP as an emerging mineral admixture, there is almost no literature to explore its rheological properties. Therefore, it is necessary and meaningful to study grouting materials containing ZP and BP.
This paper evaluated the water film thickness, rheological properties, segregation resistance, cohesiveness and mechanical properties of unary, binary and ternary cement paste systems containing cement, ZP and BP, and provided application guidance for the proportion of grouting materials. In addition, three-parameter mathematical models were used to better understand the relationship between the grouting properties.

2. Materials and Methods

2.1. Materials

Three types of cementitious materials, namely, ordinary Portland cement (OPC), zeolite powder (ZP) and basalt powder (BP) were used in the experiments. The utilization of OPC conforms to the Chinese standard GB175-2007, and the strength grade is 42.5. The utilization of ZP and BP conforms to the ASTM C 618 standard. The SEM morphologies of OPC, ZP, and BP were shown in figure 1.

![SEM morphology of OPC, ZP, and BP.](image)

2.2. Experimental Methods

In the experimental program, cement paste samples mixes with varying waste ash content and w/c ratio (0.50, 0.55, 0.60, 0.65 and 0.70) were prepared with NJ-160 type paste mixer, and the ratio of cement paste is shown in table 1.

| Material | Volume fraction (%) |
|----------|---------------------|
| Mix number | 100% | 5% | 10% | 20% | 5% | 10% | 20% | 5% ZP+5% | 10% |
| OPC       | 50 | 95 | 90 | 80 | 95 | 90 | 80 | 90 | 80 |
| ZP        | 5 | 10 | 20 | - | - | - | - | 5 | 10 |
| BP        | - | - | - | 5 | 10 | 20 | 5 | 10 | 10 |

2.2.1. Flow Spread and Flow Rate. The fluidity of cement paste is characterized by flow spread and flow rate. The micro-slump cone test proposed by Hajime Okamura can be used to test the flow spread [7]. The flow rate was tested by the marsh cone (a cone with dimensions of 94 mm × 30 mm × 7 mm) according to JC/T 1083-2008.

2.2.2. Yield Stress and Apparent Viscosity. The NXS-11A coaxial rotary viscometer was used to test yield stress and apparent viscosity, and the improved Bingham model was applied.

2.2.3. Cohesiveness. Cohesiveness is indicated by the sieve separation index (SSI), which is measured by miniature version of the sieve separation test (0.6 mm sieve). The SSI coefficient and cohesiveness are inversely related, the lower the SSI coefficient, the higher the cohesiveness [8].
2.2.4. Segregation Resistance. The segregation resistance is characterized by the bleeding rate. The bleeding rate is tested using a bleeding cone.

2.2.5. Compressive Strength. The compressive strength is tested with a universal testing machine, and the test method follows the Chinese standard GB50204-2002.

3. Result and Discussion

3.1. Grouting Properties

It is more obvious from figure 2 (f, i, j) that both ZP and BP can effectively increase the cohesiveness and reduce the bleeding rate of cement paste, and this improvement effect is further strengthened with the increase of ZP, BP content and the increase of w/c ratio. This result showed that the grout containing ZP and BP can ensure that the grout itself is not easy to bleed and separate, and it is more likely to adhere to the boundary when it penetrates into the pores of rock or soil. ZP and BP have better improvement effect under high content, which can not only improve cohesiveness and anti-segregation performance, but also save cost and protect environment. ZP and BP have better improvement effect at high water-cement ratio, which can ensure that when the high water-cement ratio grouting is needed, the slurry itself will not be separated and isolated, and the construction quality will be ensured.

As shown in figure 2 (g, h), the changes of mechanical properties of cement paste by ZP and BP are opposite. The increase of ZP at high content can effectively increase the compressive strength, while the low content reduces the compressive strength. The performance of BP is just the opposite. ZP and BP have basically the same tendency to change the compressive strength under different w/c ratios.

![Figure 2](image-url)  
**Figure 2.** The grouting properties of unary, binary, ternary cement systems containing cement, ZP, BP under different w/c ratio.
The change of water film thickness (WFT) is basically the same as the change of fluidity according to figure 2 (a, b, e). Except for a few data points, the general rule is roughly as follows: ZP adversely affects the fluidity of the cement paste. With the increase of the ZP content, the flow spread and flow rate decrease. The addition of BP presents different phenomenon, a small amount of BP adversely affects the flow parameters of cement paste, while a high amount of BP can promote the fluidity of cement paste. The flow spread and flow rate of cement paste become the worst when the BP content is 10%, and become the best when the BP content is 20%. The result of the change in fluidity is caused by the combined effect of the filling effect, surface effect and morphological effect of the mineral admixture.

The changes of yield stress and apparent viscosity of cement paste containing ZP and BP are opposite to the changes in flow parameters, as shown in figure 2. However, the rheological parameters are not only affected by the mineral admixture, but also by the w/c ratio. Under different w/c ratios, ZP and BP have different effects on the rheological parameters of cement paste. With the increase of w/c ratio, the changes of rheological parameters under different mineral admixture systems gradually become smaller, which shows that ZP and BP gradually lose their function under high w/c ratio.

The ternary blending of ZP and BP can effectively enhance the compressive strength and cohesiveness of cement paste, and reduce the bleeding rate. However, the high blending (10%) of ZP and BP has great damage to the fluidity, which is not conducive to the construction of grouting.

3.2. Optimal Mixture Proportion

Through the above discussion, it is very difficult to select a grout with excellent fluidity, rheology, cohesiveness, segregation resistance, and mechanical strength. Only the optimal mixture proportion can be selected as the grouting material. The optimal ratio that satisfies all properties can be observed from figure 3. The X, Y and Z axis is used to represent the flow expansion, flow velocity, and cohesiveness respectively. The size of the sphere is used to characterize the 28 day compressive strength.

The results show that ternary blending can improve the cohesiveness of paste more than binary blending, but the high blending (10%) of ZP and BP effect adversely on the fluidity of paste. On the contrary, the 5% ternary blending has limited harmful effect on the fluidity of cement paste. The 5% ternary blending also had the highest 28-day compressive strength and the second-best cohesiveness. In summary, 5%ZP+5%BP was the optimal ratio that can satisfy all grouting properties.

![Figure 3. Comprehensive evaluation of flow spread-flow rate-cohesiveness-28day compressive strength systems.](image)

3.3. Models Establishment

This section established mathematics models to quantify the relationship between rheological parameters, flow parameters, compressive strength, bleeding rate, cohesiveness, and in order to gain a deep understanding of the grouting properties. Rheological parameters system, flow parameters system, cohesiveness and bleeding rate system were used as a single system to explore the relationship with other properties.
3.3.1. Flow Spread-Flow Rate Systems. With the flow spread as the x-axis and the flow rate as the y-axis, with the 28-day compressive strength, 0.6 mm SSI, and the bleeding rate as the z-axis respectively, the unary, binary, ternary cement systems containing cement, ZP, and BP were plotted in figure 4(a, b, c), and the best fitting surface equations were marked in red word. The results indicated that the flow parameters have good relationship with 28 day compressive, the fitting equation is 

\[ z = 30.9 - 0.004x - 0.42y \]

and \( R^2 = 0.893 \). On the contrary, the relationship between the flow parameters and cohesiveness is very poor, \( R^2 \) is only 0.572, which shows that flow parameters are not the main factor affecting cohesiveness. The relationship between flow parameters and bleeding rate is favorable, \( R^2 \) is 0.772. This is easy to understand, the better the fluidity of the grouting material, the higher the possibility of bleeding.

![Figure 4](image)

(a) 28 day compressive strength  
(b) Cohesiveness  
(c) Bleeding rate

Figure 4. Models of flow parameters system and other parameters.

3.3.2. Yield Stress-Apparent Viscosity Systems. With the yield stress as the x-axis and the apparent viscosity as the y-axis, figure 5(a, b, c) were plotted in the same way as above. Similar to the fluidity results, rheological parameters have a good correlation with compressive strength and bleeding rate, and have a poor relationship with cohesiveness. Among them, the rheological parameter is improved in the correlation of the bleeding rate compared with the flow parameter. Because the yield stress represents the stability of the network structure formed in the cement paste, and the stable network structure can prevent the particles from sinking. The plastic viscosity represents the ability of the flocculation structure inside the paste to prevent the paste from flowing. A large internal flocculation structure can also prevent the effective sinking of particles.

![Figure 5](image)

(a) 28 day compressive strength  
(b) Cohesiveness  
(c) Bleeding rate

Figure 5. Models of rheological parameters system and other parameters.

3.3.3. Cohesiveness-Bleeding Rate Systems. With the cohesiveness as the x-axis and the bleeding rate as the y-axis, with the 28-day compressive strength, yield stress, and the apparent viscosity as the z-axis respectively, figure 6 (a, b, c) were plotted in the same way as above. The relationship between cohesiveness-bleeding rate systems and bleeding rate is also favorable, \( R^2 \) is 0.772. The results indicated that all three systems can become the main factors affecting the compressive strength. However, different from the above results, the relationship between cohesiveness-bleeding rate
systems and rheological parameters is good, $R^2$ is 0.886 and 0.884, respectively. Because cohesiveness indicates the binding properties of the particles, it has an important influence on the flocculation structure and the formation of the colloidal network between the particles, but on the contrary, the formation of the colloidal network and flocculation does not affect the bonding properties of the particles.

(a) 28 day compressive strength  
(b) Yield stress  
(c) Apparent viscosity  

Figure 6. Models of cohesiveness, bleeding rate system and other parameters.

4. Conclusion
Through the above discussion, the following conclusions can be drawn:

1) Both ZP and BP can effectively increase the cohesiveness and reduce the bleeding rate of cement paste, and this improvement effect increases with the increase of w/c ratio and mineral admixture content.

2) 5%ZP+5%BP has the highest 28-day compressive strength properties, and its cohesiveness is second only to 10%ZP+10%BP. At the same time, 5%ZP+5%BP also has excellent segregation resistance, and the damage to the fluidity of the grouting material is very limited. It is the optimal ratio for the utilization of grouting material.

3) Flow parameters, rheological parameters and cohesiveness-bleeding rate systems all can become the main factors affecting the 28 day compressive strength.

4) Neither the flow parameter system nor the rheological parameter system is the main factor that determines the cohesiveness. On the contrary, the cohesiveness can affect the flow parameters and rheological parameters significantly.

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