Effect of Water Film Thickness (WFT) on the Fluidity, Rheology, Cohesiveness and Segregation Resistance of Multi-Mineral Cement Paste

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Abstract. The main purpose of this paper is to investigate the effect of water film thickness (WFT) on grouting performance. To this end, the relationship between WFT and rheological parameters, flow parameters, segregation resistance and cohesiveness was established by mathematical statistical methods and regression analysis. The results show that the WFT is the most significant factor in determining the fluidity and rheology of the cement paste. In engineering, WFT can be used to characterize the fluidity and rheology of the grout. WFT is not the only factor that determines the cohesiveness of cement paste, but there is a good dynamic correlation between WFT and cohesiveness. The correlation between WFT and bleeding rate increases with time, which is caused by the physical sedimentation process of the particles.

1. Introduction

Grouting is to infuse some solidified materials, such as cement, lime or other chemical materials, into the ground and soil within a certain range under the foundation, so as to fill cracks and pores in the ground and soil, prevent the foundation from leakage, and improve the integrity, strength and stiffness of the ground and soil. Fluidity, rheology, cohesiveness, segregation resistance and mechanical properties are important indicators of paste, which can ensure the construction quality of grouting. However, it is more troublesome and difficult to measure multiple parameters at the same time in grouting construction. Whether it is possible to find a simple parameter to characterize these grouting properties and establish a good correlation is a challenging and meaningful subject.

The WFT considers simultaneously the filling effect and surface effect of the cementitious material. The formation mechanism of WFT is shown in figure 1. The free water released by the fine particles of the mineral admixture filling the voids wraps the surface of the particles to form a water film, which acts as a lubricant to reduce friction and collision of the particles. In recent years, the WFT has been shown to have a good correlation with the fluidity of the paste [1-3]. However, there is less research on the relationship between the WFT and the micro-rheology at a deeper level, and no research has established the relationship between WFT and segregation resistance.
The water exists in the form of flocculated water and chemically bound water. There is no excess water to fill the void, and the cement paste cannot flow.

The water gradually fills the void, and the cement paste cannot flow.

The water just fills the void, the water film thickness is zero, and the paste cannot flow at this time.

Adding a finer mineral admixture will increase the packing density of the cement paste. WFT is determined by the net effect of packing density and specific surface area.

Therefore, the mathematical statistics and regression analysis methods were used to explore the relationship between WFT and grouting properties in different cementitious systems. The grouting properties to be tested in this paper include rheological parameters, flow parameters, bleeding rate, cohesiveness.

2. Materials and Methods

2.1. Materials

The cement was selected according to the Chinese standard GB175-2007, the strength grade is 42.5. The utilization of ZP and BP conforms to the ASTM C 618 standard.

The average particle size, specific surface area and SEM images of BP, ZP and OPC are shown in figure 2.

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.

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 [4]. 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.

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

Figure 1. Formation mechanism of WFT.

Figure 2. SEM morphology of (a) OPC, (b) ZP, and (c) BP.
Cohesiveness is indicated by the sieve separation index (SSI), which is measured by miniature version of the sieve separation test (0.6 mm sieve) [5]. The lower the SSI coefficient is, the better the cohesiveness of the cement paste.

The segregation resistance is characterized by the bleeding rate. The bleeding rate is tested using a bleeding cone.

The compressive strength was tested according to the Chinese standard GB50204-2002.

The calculation of WFT requires the packing density and void rate of the cementitious material, and the wet filling density method proposed by Kwan was used for calculation in this study [6]. This test method is to mix the cementitious material with water, measure the apparent density of the paste to determine the solid concentration, and obtain the highest solid concentration as the packing density of cementitious material at different w/c ratios.

The calculation equation of WFT is as follows:

\[
\mu_s = \mu_w - \mu_t \times \frac{(1 - \mu_{pd})}{\mu_{pd}},
\]

\[
A = A_0 \times R_0 + A_1 \times R_z + A_2 \times R_B,
\]

\[
WFT = \frac{\mu_s}{A},
\]

where \(\mu_w\) is the volume of the mixing water; \(\mu_t\) is the volume of the solid particles; \(\mu_{pd}\) is the packing density of the particles; \(A_0, A_1, A_2\) are the specific surface areas of OPC, ZP, and BP, respectively; and \(R_0, R_z, R_B\) are the volumetric ratios of the OPC, ZP, and BP to the total solid volume, respectively.

2.3. Statistical Approach

Spearman correlation coefficient (Scc) and gray correlation coefficient (Gcc) represent the static correlation and dynamic correlation of two statistical variables, respectively. The Spearman correlation coefficient is a random process based on probability theory to evaluate variables, while the gray correlation coefficient is evaluated from the relative change degree of two statistical variables such as the size, direction, speed and other indicators [7].

3. Result and Discussion

3.1. The Relationship between Flow Spread, Flow Rate and WFT

The results of figure 3 indicate that in the binary blending cement paste system containing ZP or BP, the relationship between flow parameters and WFT is very excellent, \(R^2\) exceeds 0.95, and Scc, Gcc also get extremely high values. This results show that WFT is the significant factor to control the fluidity of cement paste. In the study of grouting materials, the WFT can characterize the fluidity of the cement paste. It is well understood that the larger thickness of the WFT makes the friction and collision effects between the particles smaller and the greater the lubrication effect, so the fluidity of the paste becomes better.
3.2. The Relationship among Yield Stress, Apparent Viscosity and WFT

Similar to the fluidity results, figure 4 shows that the relationship between rheological parameters and WFT is also very good. The static correlation coefficient SCC and the regression coefficient R² are very high, indicating that WFT is also a key parameter that determines the rheology of cement paste. However, the dynamic correlation coefficient GCC is low, and the dynamic relative change between the rheological parameters and WFT is inconsistent, indicating that there is a WFT threshold. ZP and BP have different ability to change the rheology of cement paste before and after this WFT threshold. At higher WFT, ZP and BP lose the ability to change the yield stress and apparent viscosity of the paste. Only in the lower WFT, the effects of ZP and BP can play a changing role. The rheology of cement paste is mainly affected by the combined effect of Brownian force, colloidal attractive force, and gravity. The colloidal attractive force and Brownian force are both affected by the distance between particles. Because WFT indirectly represents the distance between particles, ZP and BP have no significant ability to change the colloidal attractive force and Brownian force at a long distance, so ZP and BP have lost the ability to change the rheology of cement paste.
3.3. The Relationship between Cohesiveness and WFT

It can be seen from figure 5 that the correlation between WFT and cohesiveness is not good, and WFT is not the only factor that determines the cohesiveness of cement paste. From the degree of dispersion of the curve, it can be seen that the amount of mineral admixture is also the main factor affecting the cohesiveness. This has been proven by relevant literature, and it will not be elaborated here [8, 9].

![Figure 5. Cohesiveness versus WFT.](image)

3.4. The Relationship between Bleeding Rate and WFT

The relation between WFT and 1-h, 3-h bleeding rates for the OPC-BP and OPC-ZP systems is shown in figure 6. The Scc, Gcc and $R^2$ between WFT and bleeding rate is lowly at 1 h and is preferably at 3 h. This result indicated that the relationship between bleeding rate and WFT increases with time, whether it is OPC-BP or OPC-ZP system. The model in figure 7 explains why the correlation between WFT and bleeding rate increases over time.

![Figure 6. 1h and 3h bleeding rate versus WFT.](image)
The particles were in the original concentration zone, and all particles had the same WFT. Particle precipitation and bleeding occurred for a variety of reasons related to the material composition, resulting in a bleeding zone and a sediment zone. However, since the bleeding zone, sedimentation zone, and original concentration zone were homogeneous, there was no direct connection between them, and thus, a variable concentration zone existed as a transition zone. The original concentration zone disappeared completely, and the sizes of the other three zones increased. The particles in the variable concentration zone were influenced by three competing forces, e.g., colloidal attraction, Brownian, and gravitational forces, and they were finally stabilized in the sediment zone. All the particles settled. For particles that settled in the sediment zone, their WFTs were reduced, and the excess water between the particles gradually entered the bleeding zone. As a result, the correlation coefficients between the WFT and bleeding rate increased with time.

Figure 7. Mechanism of WFT and bleeding rate change with time.

4. Three-Parameter Models of WFT
In figure 8, three-parameter models of WFT and rheological parameters, flow parameters, bleeding rate and cohesiveness were established respectively. The results show that WFT and flow parameter system have excellent correlation, which is similar to the conclusion of the above two-dimensional relationship, that is, WFT plays a decisive role in the fluidity of cement paste. In addition, the correlation between WFT and the rheological parameters system is significantly higher than the yield stress or apparent viscosity, which shows that the formation of WFT is due to the combined effect of yield stress and apparent viscosity. After the formation of WFT, it will in turn affect the yield stress or the apparent viscosity. From the results of WFT and cohesiveness, the bleeding rate system, it can be seen that WFT is more likely to affect the bleeding rate than the cohesiveness, and the cohesiveness is more affected by the coagulation properties of the particles themselves. The bleeding rate is related to the penetration network formed in the cement paste, which is related to the particles spacing. The WFT indirectly represents the particle spacing, so WFT is more likely to affect the bleeding rate.

Figure 8. Models of WFT and flow parameter system, rheological parameter system and cohesiveness, bleeding rate system.

5. Comparison of Gray Correlation Coefficient between Various Properties and WFT
In the case of considering both OPC-BP and OPC-ZP systems, the comparison results of the gray correlation coefficients between various properties and WFT are shown in figure 9. The Gcc of rheological parameters and WFT are the lowest of all parameters, indicating the degree of change between rheological parameters and WFT is not consistent before and after, this is similar to the above
result. While WFT and other parameters have high correlation coefficients, indicating that changes in WFT will result in significant effects on flow parameters, cohesiveness, and bleeding rate, and the degree of this relative change is highly consistent and has good dynamic correlation.

Figure 9. Comparison of GCC between WFT and various parameters.

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

1. The correlation between WFT and the flow parameters of cement paste is excellent, which is the most important factor in determining the fluidity of the paste. The WFT can be used to characterize the fluidity of grouting materials.

2. The correlation between rheological parameters and WFT is good, and it has high $R^2$ and Scc values. WFT is also the most important factor to determine the rheology of cement paste. But the Gcc values of WFT and rheological parameters are low, which indicates that their relative changes are low, so the dynamic correlation is weak.

3. WFT is not the only factor that determines the cohesiveness of cement paste. Mineral admixture content is also one of the important factors.

4. The relationship between bleeding rate and WFT increases with time due to the mechanism of particle settling.

5. The $R^2$ of the three-parameter model between WFT and rheological parameters is significantly improved compared to the two-parameter model. The formation of WFT is affected by both the apparent viscosity and the yield stress, and the formed WFT in turn affects the rheological parameters.

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