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Research Article

Study on the Relationship between the Fluidity of Paste in Stope and the Rheological Properties of Paste

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Paste should be kept in homogeneous state without segregation or weak segregation during pipeline transportation, which can reduce the occurrence of pipe blockage accidents in engineering application. Only when the paste is homogeneous can the paste have good stope fluidity, and the stope fluidity is also restricted by the geometric size of the stope and other factors. Therefore, it is very important to study the homogeneity of paste and analyze the influence of paste rheological characteristics on stope fluidity. In this paper, it is pointed out that the vertical settling velocity of solid phase materials in paste in the liquid-phase dense medium is the main factor affecting the homogeneity of paste. Increasing the plastic viscosity and yield stress of the liquid-phase dense medium is beneficial to increase the drag force of aggregate and then reduce the settling speed of aggregate in the liquid-phase dense medium. On this basis, the homogeneity of paste can be judged. In the simplified paste flow field, using Cauchy stress equation and flow boundary conditions, the relationship between paste stope flow performance and paste rheological properties was analyzed, and the relationship model between the slope angle of paste flow formation and paste rheological properties was established. Compared with the experimental results, the error of the model results is small, and the slope angle of paste flow can be well predicted.

1. Introduction

For the study of flow capacity of filling slurry in stope: Shi et al. [1] have carried out a similar simulation test of filling slurry flow and mechanical strength test of in situ filling in stope. The results show that the final slope of filling slurry flow tends to be normal distribution when cutting at a single point. During the flowing process, the filling slurry produced segregation and delamination, which mainly showed that the particle size of filling material increased first and then decreased along the flowing direction of slurry. The research results of Lu et al. [2] show that the trajectory curve of filling slurry along the flow direction tends to be normal distribution, and the strength of filling body along the flow direction of filling slurry shows an inverted S-shaped distribution of decreasing-increasing-decreasing. The results of theoretical analysis by Tang and Xiao [3] show that after the filling slurry enters the stope, it flows to the periphery, and the shape of the pile surface obeys the normal distribution law. The size of the mean square deviation reflects the smoothness or steepness of the surface formed after the slurry flows, and its value mainly depends on the filling material and mixture ratio. Hui et al. [4] tested the fluidity of paste under different concentrations and ratios by loop experiment and finally determined the best paste filling concentration, the best lime sand, and the corresponding resistance along the way. Xue et al. [5] carried out the slurry slump test aiming at the influence of different pumping agent content on filling slurry in a mine. The results show that pumping agent has a nonlinear gradient effect on slump, and with the increasing amount of pumping agent, the influence ability of pumping agent with the same dose on slump gradually weakens; the yield stress and plastic viscosity decrease with the increase of pumping agent content. When the pumping agent content exceeds 3%, the yield stress decreases obviously. For plastic viscosity, when the pumping agent content exceeds 2%, the decrease begins to slow down obviously. Tao et al. [6], aiming at the problems of poor rheological stability, delamination in slurry and pipe blockage caused by coarse aggregate settlement in long-distance filling slurry of pumped large double line in coal mine filling mining, measured the fluidity value and fluidity loss with time of four groups of filling slurry by using the fluidity loss experiment method. On the basis of diffusion theory, Li [7] deduced the vertical distribution formula of coarse aggregate filling slurry concentration, considering the factors of solid particle size, particle shape and density, slurry density, and yield stress. Xue et al. [8] aimed at naphthalene series water-reducing agent and BF high-efficiency water-reducing agent, studied the role of water-reducing agent in filling slurry flow process by analyzing the influence of adding ways and types of water reducing agent on slurry rheological properties. The test results show that the fluidity of slurry prepared by adding water-reducing agent by the postmixing method is relatively good, and the fluidity of graded tailings slurry after adding water-reducing agent is significantly improved. Under the same conditions, the yield stress and apparent viscosity of slurry decrease. Niu and Peng [9] carried out experimental research on the fluidity and studied the workability of slurry with different concentrations and lime-sand ratio aggregates by using slump bucket and L-tube, and finally obtained the rheological parameters of this kind of tailings. Gao et al. [10] studied the influence of polycarboxylate and naphthalene superplasticizer on the fluidity of phosphorus tailings filling slurry by expansion method, fluidity method, and L-tube method. The results show that polycarboxylate superplasticizer is superior to naphthalene superplasticizer. At the same time, polycarboxylate superplasticizer has a strong dispersing effect on phosphorus tailings filling slurry, which can change the flocculation structure of cement and improve the fluidity of filling slurry. Xie et al. [11] gave a new definition of ultrafine particles in filling slurry and analyzed the influence of ultrafine particles on rheological properties of slurry.

As mentioned above, many scholars have analyzed the influencing factors of filling slurry fluidity by means of experiments and theoretical research, and established some qualitative analysis models. However, most of the analysis is based on the pipeline transportation capacity of slurry, and there is no in-depth discussion on the free flow and leveling of slurry in the open area. It cannot directly solve the problem of slurry flowing ability in stope. In this paper, the relationship between rheological properties of filling slurry and stope fluidity is studied by constructing a direct physical and mechanical model of filling slurry rheological properties and stope fluidity.

2. Theoretical Study

2.1. Influence of Rheological Properties of Heavy Medium on Slurry Homogeneity. Filling slurry can be regarded as a suspension system formed by the aggregate and liquid-phase heavy medium, so the rheological properties of the liquid-phase heavy medium and the basic physical and mechanical parameters of aggregate will affect the movement of aggregate in slurry, thus affecting the homogeneity of slurry.

The slurry meeting the condition of critical flow state concentration is paste, and the paste should have enough antisegregation ability. Insufficient antisegregation ability often leads to the separation of aggregate in the process of slurry flow, and the coarse aggregate settles and accumulates in the process of pipeline transportation, forming embolism and causing pipeline blockage; or the uneven accumulation in stope makes the filling layer form a weak surface, which is extremely unfavorable to the control of backfill strength. Therefore, it is very important to analyze the stress of aggregate in slurry, so as to establish the quantitative characterization of the critical flow concentration condition in the slurry and judge whether the slurry belongs to the paste.

It is assumed that there is no relative movement between aggregate and liquid heavy medium in horizontal direction. In the vertical direction, the aggregate is balanced by its own gravity, buoyancy, and viscous resistance in the liquid-phase heavy medium (as shown in Figure 1):

$$F_v = g\Delta\rho V. \tag{1}$$

In the above formula, F_v represents viscous resistance, $\Delta\rho$ represents density difference between liquid heavy medium and aggregate, and V represents volume of aggregate.

It is noted that the viscous resistance in the liquid-phase heavy medium is

$$F_v = C_D \rho_S \frac{v^2}{2} \pi r^2. \tag{2}$$

C_D represents drag coefficient, v represents vertical velocity of coarse aggregate, and ρ_S is apparent density of the liquid-phase heavy medium.

Therefore, the relative movement speed v of aggregate relative to the liquid-phase heavy medium is equal to

$$v = \frac{8g\Delta\rho r}{3C_D\rho_S}. \tag{3}$$

When Reynolds number is low, the drag coefficient of C_D can be expressed as

$$C_D = f\left(R_e\right). \tag{4}$$

Equation (4) can be expressed by Reynolds number; that is, the relative movement speed of aggregate in the vertical direction in the liquid-phase medium can be expressed by Reynolds number of slurry flow.

However, the Reynolds number exists only for Newtonian fluid. As the filling slurry is a Bingham fluid in non-Newtonian fluid, compared with Newtonian fluid, it has a yield stress τ_0; that is, the shear stress needs to overcome τ_0 before the fluid can flow. Therefore, the Reynolds number formula of Newtonian fluid is not applicable and needs to be replaced by the generalized Reynolds number of Bingham fluid [12].

The generalized Reynolds number R_e of slurry as Bingham fluid is

$$R_e = \frac{2\rho_P r v}{\eta + \tau_0 r/3v}, \tag{5}$$

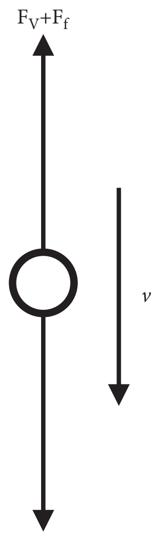

Figure 1: Stress analysis of aggregate.

where η represents the viscosity of slurry, τ_0 represents the yield stress of slurry, ρ_P represents the apparent density of slurry, and r represents the pipe radius of slurry in the process of pipe flow.

Equation (5) gives the speed expression of relative movement of coarse aggregate in the liquid-phase heavy medium. From (2), it can be seen that the relative movement speed of aggregate in the liquid-phase heavy medium is the result of plastic viscosity and yield stress of the liquid-phase medium, which is different from Newtonian fluid only affected by viscosity. In fact, when the plastic viscosity and yield stress are small, the speed of aggregate relative to slurry will increase; that is, the settlement will accelerate, causing the segregation of slurry in the flow process; when the plastic viscosity increases and the yield stress remains unchanged, if the vertical velocity of the aggregate relative to the liquid dense medium decreases, the slurry can still remain homogeneous in the flow process and yield stress will also cause the decrease of relative movement speed of aggregate. Therefore, the homogeneity of slurry depends not only on the plastic viscosity of liquid heavy medium, but also on the yield stress.

A large number of documents [13–17] show that the slump spread test can well characterize the segregation state of slurry movement.

In fact, the aggregate and the surface-covered liquid-phase heavy medium can be considered as a unit (as shown in Figure 2). When the aggregate particles move, the surface-covered liquid-phase medium and aggregate move evenly together. If the relative movement distance exceeds the thickness of the unit, it means that the slurry is separated during the movement. Generally, the test time of slump spread is $T_i \approx 5s$.

From this, the judgment formula of slurry segregation is obtained:

$$\int_0^{T_i} v d_t \leq \left(\frac{1}{\lambda} - 1\right) \cdot r. \quad (6)$$

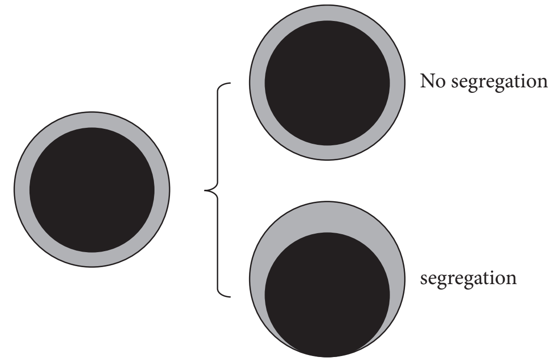

Figure 2: Schematic diagram of slurry segregation.

Equation (6) is the discriminant of slurry homogeneity without segregation, where λ refers to the ratio of aggregate particle size in slurry to the particle size of globules composed of the liquid medium. It is noted that there is a distribution range of aggregate particle size, so r in the above formula refers to the average radius of aggregate particle in mathematical sense.

It can be seen from the above formula that the homogeneity of slurry is affected by the yield stress and viscosity of the liquid medium, and it is also related to the gradation of aggregate (λ is the comprehensive reflection of gradation and content). If the slurry does not meet the above inequality, it means that segregation will occur in the process of natural flow and pipeline transportation, or if it does not meet the critical flow state concentration condition, it is not a paste.

2.2. Influence of Rheological Properties of Paste on Stope Fluidity. An important index of paste filling performance is its flow performance in the stope. The paste with good fluidity has the characteristics of long-distance self-leveling, and the slope angle formed by paste from the feeding point to the farthest end of stope is small. For the case of requiring top connection, under the condition of ensuring the roof rate of stope, it can effectively reduce the number of roof connection and ensure the quality of filling body; when the filling body is used as the working platform for equipment operation, the thickness uniformity of the working platform can be ensured, and the damage of the filling body caused by insufficient thickness can be reduced.

The flow of paste in stope is shown in Figure 3: the paste is affected by conveying pressure, gravity, and yield stress. When the sum of conveying pressure and gravity is greater than yield stress, the paste starts to flow. With the flow of paste, the stacking height of paste decreases, and the pressure generated by its own gravity decreases. When the pressure is less than the yield stress, the paste stops flowing; then, a slope of accumulation is formed. For the paste which produces the stacking slope at the stop, its flow form can be simplified as the free flow of a certain volume of fluid in a horizontal infinite space.

The shear stress required by the paste flow is provided by the pressure in the paste, and the shear stress of paste obtained from Cauchy stress equation is

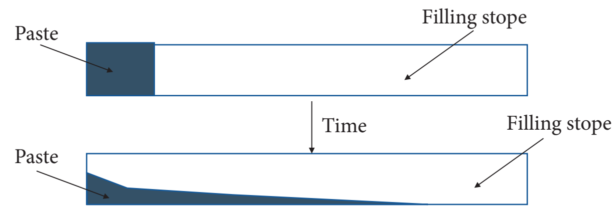

Figure 3: Schematic diagram of paste flowing in stope.

$$\tau = \frac{\Delta p y}{2L}, \tag{7}$$

in which Δp is the resistance loss of paste flow.

From the relationship between the rheological model of paste and shear stress,

$$\begin{aligned} -\tau &= -\frac{\Delta p y}{2L} \\ &= \tau_0 + \eta \frac{du}{dy}. \end{aligned} \tag{8}$$

The integral of the above formula is

$$u = \frac{1}{\eta} \times \left[-\frac{\Delta p y^2}{4L} - \tau_0 y - c \right]. \tag{9}$$

It is noted that there is a part with shear stress less than τ_0 at the top of the paste (as shown in Figure 4), which means that the paste in this part will not move, so the speed $u = 0$ at this time; then, bring it into the above formula:

$$\begin{aligned} u = \frac{1}{\eta} \times \Bigg[\frac{\Delta p}{2L} \Bigg(H \times \left(H - \frac{\tau_0}{\rho g} \right) - H y \\ + \frac{1}{2} \left(y^2 - \left(H - \frac{\tau_0}{\rho g} \right)^2 \right) \Bigg) - \tau_0 \left(\frac{H}{2} - \frac{\tau_0}{\rho g} \right) \Bigg]. \end{aligned} \tag{10}$$

Let the average speed be v, and the expression of the average speed is

$$v = \frac{1}{H - \tau_0/\rho g} \int_0^{H - \tau_0/\rho g} u_x \mathrm{d}y. \tag{11}$$

The relationship between the average velocity of paste on AB plane and the resistance loss Δp can be obtained. It is noted that the paste has velocity distribution along Y direction, and the velocity decreases with the increase of Y, but the velocity of paste is consistent in horizontal X direction, which means that in order to maintain the velocity, the resistance loss is increasing along X positive direction:

$$\Delta p = \frac{6 v \eta L}{(H - \tau_0/\rho g)^2} + \frac{3 \tau_0 L}{(H - \tau_0/\rho g)}. \tag{12}$$

It can be seen from the above formula that Δp is related to the average velocity, the height H of paste flowing, and the flowing distance L. It is noted that when the paste stops flowing, $V = 0$, and the pressure $\rho g h_2 = \Delta p$ provided by the paste at this time; therefore, it is obtained:

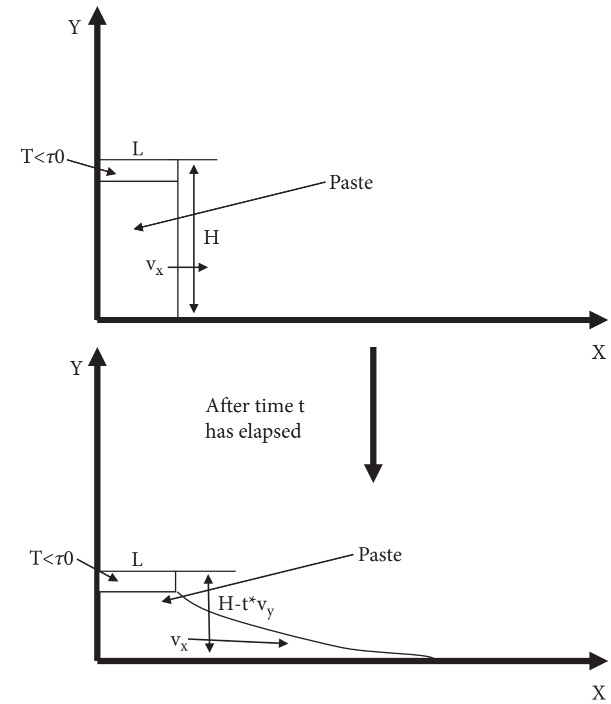

Figure 4: Simplified flow diagram of paste stope.

$$\rho g h_2 = \frac{3 \tau_0 L}{(H - \tau_0/\rho g)}. \tag{13}$$

Then, the flow angle of paste is obtained:

$$\tan\alpha = \frac{3\tau_0}{(H - \tau_0/\rho g)\rho g}. \tag{14}$$

The above formula illustrates the relationship between the leveling angle of a certain volume of paste and its physical properties and can be used to judge the flowing distance and angle of a certain volume of paste. In fact, when the rheological properties of paste are determined, the angle of paste flow is only related to the height.

As shown in Figure 5, the higher the paste height means that the paste has greater potential energy and can provide greater pressure. Under the condition of constant paste resistance loss, the greater the paste pressure, the farther the paste can flow, and the smaller its flow angle.

Under the same flow height, the flow distance of different pastes is related to their yield stress (as shown in Figure 6); that is, the yield stress is inversely proportional to the flow distance, and the greater the yield stress, the smaller the flow distance, whereas the smaller the yield stress, the farther the flow distance. This is the same trend as the relationship between paste expansion and yield stress in slump test. In fact, the farther the flowing distance is, the smaller the angle formed by the paste after stopping flowing, and the smaller the stacking angle is, the more favorable it is for the top connection of paste and the leveling of working face, and the safety of mining activities and the operation of large-scale equipment.

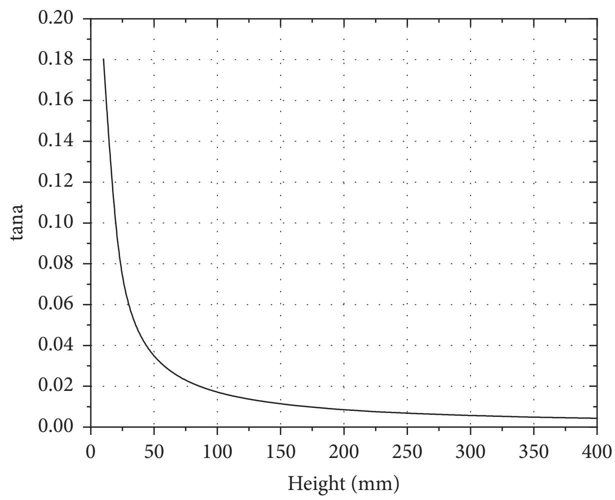

Figure 5: Relationship between leveling angle and height of paste.

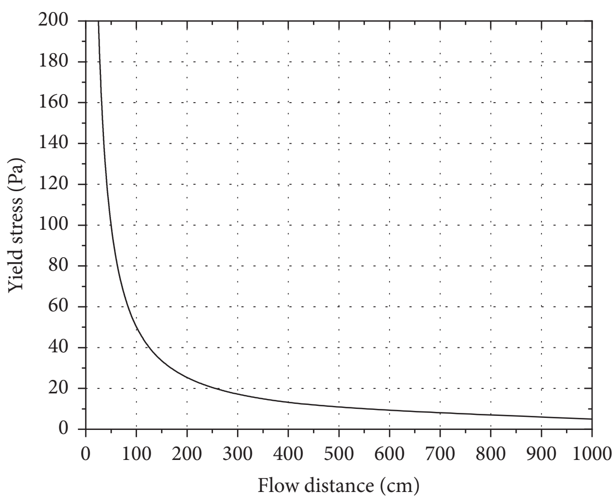

Figure 6: Relationship between flow distance and yield stress.

3. Experimental Study

3.1. Test Material. The fine aggregate used in the test is desert sand and river sand, and the coarse aggregate is waste rock. The basic physical parameters and gradation are shown in Table 1.

It can be seen from Table 1 that the apparent density gap of the three kinds of filling aggregate is not large. The difference of packing compactness between waste rock and desert sand is small, and that of river sand is the largest, which means that river sand has smaller packing volume and the highest packing compactness in natural loose state.

Table 2 shows the mineral composition analysis, and it can be seen that the main components of the tailings are calcite and mica. The chemical properties of the tailings are relatively stable, and there is no chemical reaction with water.

As fine aggregate, the biggest difference between river sand and desert sand is the difference of gradation between them. The negative cumulative distribution of gradation of three aggregates is shown in Figure 7.

The following can be seen from Figure 7:

Table 1: Basic physical parameters of filling aggregate.

Category	Apparent density (kg/m³)	Moisture content (%)	Packing compactness (%)
Waste rock	2625	1.255	59.6
River sand	2610	0.757	62.2
Desert sand	2570	0.219	59.1

Table 2: Analysis results of mineral composition.

Mineral name	Mineral content of waste rock (%)	Mineral content of river sand (%)	Mineral content of desert sand (%)
Calcite	40–50	50–55	25–30
Mica	25–35	20–30	25–30
Fluorite	5–10	1–5	5–10
Dolomite	5–10	1–5	5–10
Amphibole	1–5	1–5	5–10

(1) The grading range of wind sand is below 1.18 mm. Generally speaking, 99% of the wind sand is within 0.6 mm; the median particle size and average particle size of negative cumulative distribution of wind and sand are 0.23 mm and 0.3 mm, respectively.

(2) The grading range of river sand is below 9.5 mm. Generally speaking, 90% of river sand particles are below 4.75 mm; the median particle size of negative cumulative distribution of river sand is 0.89 mm; average particle size is 1.82 mm.

(3) The grading range of waste rock is below 10 mm, and generally speaking, 90% of waste rock particles are below 9.5 mm; the median particle size of negative cumulative distribution of waste rock is 3.56 mm; average particle size is 4.81 mm.

3.2. Homogeneity Test of Slurry. Homogeneity of slurry is a necessary condition to evaluate whether it belongs to paste or not. Homogeneous slurry can flow smoothly and reduce segregation in the flow process. According to the theoretical research, whether the slurry segregates or not depends on the formula (6), which essentially depends on the ratio of the central particle size to the spherical particle size of aggregate, the yield stress of the liquid-phase heavy medium, the plastic viscosity, and the average particle size of coarse aggregate.

The test scheme of slurry homogeneity is based on the paste with the ratio of waste rock to tailings of 7 : 3. The rheological properties of the liquid-phase heavy medium in slurry are adjusted by adjusting the mass concentration or cement content. The test scheme is shown in Table 3.

The following can be seen from equation (6): the necessary condition to judge whether the slurry is segregated or not is the rheological properties of the liquid medium in coarse aggregate slurry, including plastic viscosity and yield stress. Therefore, it is necessary to use rheometer to test the rheological properties of the liquid medium. It can be seen from the

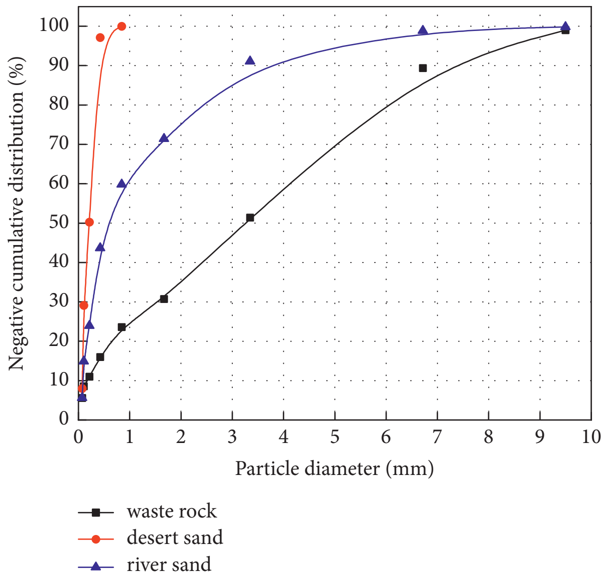

Figure 7: Gradation of Jinchuan filling aggregate.

Table 3: Homogeneity test of slurry.

Type of aggregate	Ratio of coarse aggregate to fine aggregate (mass ratio)	Cement content (kg/m^3)	Mass concentration (%)
Waste rock-desert sand	7 : 3	310	80–84
Waste rock-desert sand	7 : 3	280	80–84
Waste rock-desert sand	7 : 3	260	80–84

test scheme in Table 2 that the coarse aggregate is waste stone and the fine aggregate is desert sand. Therefore, it is necessary to test the rheological properties of desert sand slurry with different concentrations. Test scheme is shown in Table 4.

3.2.1. Results of Slurry Homogeneity Test. According to the test scheme in Table 4, the rheological properties of the liquid medium are tested, and the test results are shown in Table 5.

The following can be seen from Table 4: with the same cement content, the plastic viscosity of the liquid medium will increase with the increase of mass concentration, and the yield stress follows the same rule. At the same concentration, with the decrease of cement content, the plastic viscosity of the liquid-phase medium decreases, which is caused by the decrease of fine particle content in the liquid-phase medium.

According to the test scheme in Table 3, the homogeneity of slurry was tested, and the segregation results were obtained by observing the segregation conditions of slurry, and compared with the predicted results of formula (6) (in the formula, the flow rate is 2.41 m/s and the pipe diameter is 0.138 m according to the actual parameters of Jinchuan No. 2 Mining Area).

Table 4: Rheological test of the liquid medium.

Type of aggregate	Ratio of coarse aggregate to fine aggregate (mass ratio)	Cement content (kg/m^3) (%)	Rheological property
Desert sand	310	75–79	τ_0, η
Desert sand	280	75–79	τ_0, η
Desert sand	260	75–79	τ_0, η

As shown in Table 6, there is almost no difference between the predicted results and the actual results, and the slurry begins to show no segregation at 82%, reaching the critical flow state concentration, indicating that the homogeneity is better at this concentration. However, it is noted that the predicted results are different from the actual results when the cement content is 280 kg/m and the mass concentration is 82%, and the measured results are no segregation, but the predicted results show segregation, which is caused by the difference between the yield stress and viscosity test results. In fact, prediction formula (6) should be stricter, and the judgment of segregation will be more conservative.

3.3. Fluidity Test of Paste Stope. In order to verify the theoretical research results, a similar simulation test was carried out on the fluidity of paste stope, and the test scheme is shown in Table 7.

In the test, a filling stope model with a length of 4 m, a width of 0.7 m, and a height of 0.6 m was constructed with wooden boards (Figure 8). Paste with the above ratio was injected from one end of the device to keep the device closed. When the filling paste stopped flowing, the height of the filling body was measured and the maximum slope angle of the filling body was calculated. In addition, it is compared with the slope angle calculated by formula (13).

3.3.1. Results of Stope Fluidity Test. According to the stope fluidity test scheme, the stope fluidity test was carried out for pastes with different proportions and concentrations, and the process is as Figure 9.

The following can be seen form Figure 9: during the experiment, a rectangular groove with a length of 4 meters, a width of 0.7 m meters, and a height of 0.6 meters was built with wooden boards. Inject the prepared paste from one end of the rectangular groove. Because the top of the rectangular groove is not closed, the flow process of paste can be clearly seen. There was no segregation of paste during the experiment. After the paste is solidified and molded, measure the maximum slope angle of the paste and compare it with the predicted result.

According to the results of the stope fluidity test, Table 8 is drawn.

According to the contents shown in Table 8 and Figure 10 under the condition of the same material and gradation, the maximum slope angle increases with the increase of mass concentration, because the plastic viscosity and yield stress of paste increase with the increase of mass concentration, which leads to the increase of shear stress to be overcome in the flow process, which leads to the increase of maximum slope angle.

Table 5: Rheological test results of the liquid medium.

Type of aggregate	Cement content (kg/m³)	Mass concentration (%)	Plastic viscosity (Pa∗s)	Yield stress (Pa)
Desert sand	310	75	0.19	1.734
Desert sand	310	76	0.23	2.007
Desert sand	310	77	0.28	2.331
Desert sand	310	78	0.35	2.715
Desert sand	310	79	0.44	3.174
Desert sand	280	75	0.18	1.811
Desert sand	280	76	0.21	2.094
Desert sand	280	77	0.26	2.427
Desert sand	280	78	0.32	2.821
Desert sand	280	79	0.40	3.289
Desert sand	260	75	0.17	1.882
Desert sand	260	76	0.20	2.173
Desert sand	260	77	0.24	2.516
Desert sand	260	78	0.30	2.920
Desert sand	260	79	0.38	3.400

Table 6: Homogeneity judgment of slurry.

Mass concentration (%)	Cement content (kg/m³)	Measured results	Calculation result
80	310	Segregated	Segregated
81	310	Segregated	Segregated
82	310	Nonsegregation	Nonsegregation
83	310	Nonsegregation	Nonsegregation
84	310	Nonsegregation	Nonsegregation
80	280	Segregated	Segregated
81	280	Segregated	Segregated
82	280	Nonsegregation	Segregated
83	280	Nonsegregation	Nonsegregation
84	280	Nonsegregation	Nonsegregation
80	260	Segregated	Segregated
81	260	Segregated	Segregated
82	260	Nonsegregation	Nonsegregation
83	260	Nonsegregation	Nonsegregation
84	260	Nonsegregation	Nonsegregation

Table 7: The scheme of the paste stope fluidity test.

Type of aggregate	Ratio of coarse aggregate to fine aggregate (mass ratio)	Cement content (kg/m³)	Mass concentration (%)	Test content (°)
Waste rock-desert sand	7 : 3	310	82	Slope angle
Waste rock-desert sand	7 : 3	310	83	Slope angle
Waste rock-desert sand	7 : 3	310	84	Slope angle
Waste rock-desert sand	7 : 3	280	82	Slope angle
Waste rock-desert sand	7 : 3	280	83	Slope angle
Waste rock-desert sand	7 : 3	280	84	Slope angle
Waste rock-desert sand	7 : 3	260	82	Slope angle
Waste rock-desert sand	7 : 3	260	83	Slope angle

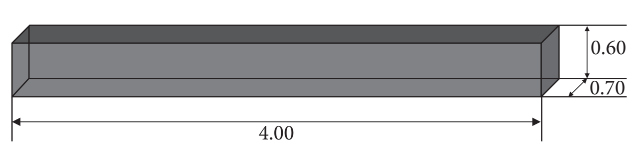

Figure 8: Paste fluidity test device.

(a) (b)

Figure 9: Paste fluidity test.

Table 8: Results of the paste fluidity test.

Type of aggregate	Ratio of coarse aggregate to fine aggregate (mass ratio)	Cement content (kg/m^3)	Mass concentration (%)	Slope angle (°)	Predicted slope angle (°)	Error (%)
Waste rock-desert sand	7 : 3	310	82	1.14	1.27	11.40
Waste rock-desert sand	7 : 3	310	83	1.19	1.25	5.04
Waste rock-desert sand	7 : 3	310	84	1.25	1.29	3.20
Waste rock-desert sand	7 : 3	280	82	1.09	1.21	11.01
Waste rock-desert sand	7 : 3	280	83	1.12	1.23	9.82
Waste rock-desert sand	7 : 3	280	84	1.17	1.26	7.69
Waste rock-desert sand	7 : 3	260	82	1.05	1.12	6.67
Waste rock-desert sand	7 : 3	260	83	1.09	1.16	6.42
Waste rock-desert sand	7 : 3	260	84	1.15	1.20	4.35

The predicted slope angle has the same change trend as the actual measured maximum slope angle, but the predicted value is too large because the predicted slope angle does not take into account the influence of paste kinetic energy on the final flow situation in the process of paste flow. However, the predicted slope angle is effective as a basis for measuring paste flow in stope, which is equivalent to adding a safety factor to paste flow state. If the predicted degree angle of paste cannot meet the flow requirements in stope, its actual flow state will naturally not meet the demand of stope.

Generally speaking, the predicted value is close to the actual value, and the error is between 3% and 11%. Under the same filling material, the higher the concentration, the smaller the error. This is because the higher the concentration, the better the average property of the slurry, which means that the slurry is more stable, and the possibility of its yield stress changing in the flow process is reduced, thus reducing the error. The lower the slurry concentration, the greater the possibility of shear thinning, which leads to the increase of error.

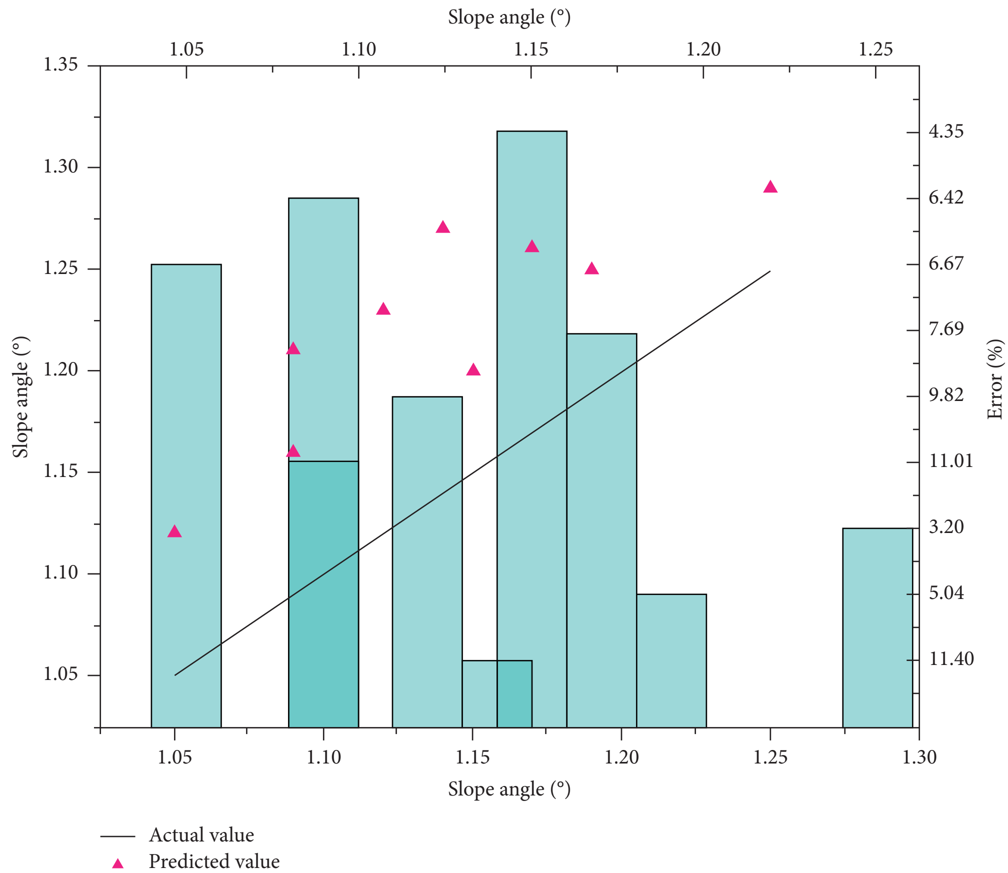

Figure 10: Test result.

4. Conclusion

In this paper, the force analysis of solid materials in the dense medium of paste liquid is carried out, and the judgment model of paste homogeneity is established. The model is verified by experiments. Based on Cauchy stress equation, the prediction model of paste profile angle is established by simplifying the flow behavior of paste in the mining field. The prediction model is verified by a similar simulation test. The results show that there is little difference between the prediction model and the actual results, and the prediction error is less than 11%. The prediction model has a greater safety factor. The above two models provide a theoretical basis for the design and optimization of paste and stope structure.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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