Study on Transport Characteristics of Coarse Aggregate Paste

YIN Shenghua,1,2 YAN Zepeng,1,2 CHEN Dapeng,1,2 CHEN Junwei,1,2 ZHANG Ming,1,2 and YANG Chun3

1School of Civil and Resources Engineering, University of Science and Technology Beijing, Beijing 100083, China

2Key Laboratory of High-Efficient Mining and Safety of Metal Mines, Ministry of Education, University of Science and Technology Beijing, Beijing 100083, China

3School of Resources and Safety Engineering, Central South University, Changsha, 410083, China

Abstract

The main purpose of this study is to investigate the rheological characteristics and resistance evolution behavior of tailings-waste rock paste backfill. An AMETEK Brookfield R/S+ rheometer was used to test and study the rheological parameters of the paste, and a formula for calculating the transport resistance considering volume concentration, bulk density, and water-cement ratio was established. Secondly, the developed formula was put into COMSOL Multiphysics® to build a numerical model, and the filling loop test data was used to compare and verify the error of the numerical model was less than 8%, proving the numerical model's robustness. Finally, the effects of different tailings-waste rock ratios, inlet velocities, and concentrations on conveying resistance were analyzed, and the optimal filling parameters were obtained: tailings-waste rock ratios 5:5 and initial velocity 2.2 $m \cdot s^{-1}$. The properties of aggregate used in this study are different from those currently used in the concrete field; the optimal ratio obtained by computational fluid dynamics (CFD) simulation is applicable to the field in general. The research results of this paper have positive significance for developing coarse aggregate paste transportation technology, reducing pipeline transportation resistance, and extending transportation distance.

Key words: coarse aggregate, tailing-waste rock ratio, rheological characteristics, resistance model, numerical simulation

Introduction

Cemented paste aggregate fill (CPAF) is a common feature of mine development in China (Yang, 2017; Yin, 2020). The paste is usually prepared at the backfill plant and then transported to the underground mining area through the pipeline system (Wu, 2015; Liu, 2018). To ensure the productivity of the mine and the stability of pipeline transportation, the paste is expected to meet certain flowability requirements, and the common evaluation indices of flowability are the rheological property parameters (Zhang, 2018). Boylu et al. (2004) investigated the effect of particle size distribution on the rheology of coal-water slurries. Petit et al. (2006) evaluated the effect of time and temperature on the yield stress value of two different types of slurry with the coupled effect of time. Previous studies were carried out on fine-grained pastes and the results obtained do not apply to CPAF. The transport resistance characteristics are also an important basis for evaluating the feasibility of pipeline transportation of pastes (Wu, 2016). The traditional studies on the resistance of paste pipeline transportation are generally categorized into two ways. For example, Ye (Ye, 2017) and others have established a small-scale conveying simulation system to study the conveying resistance of paste under different conditions; based on this, a pressure loss equation was established. Although this method provides ideas for the study of pipeline conveying, the results differ from the actual conveying situation due to the variability of field conditions. Another method is to calculate the corresponding pressure loss value by substituting relevant parameters through the empirical formula of pressure loss, such as the Jinchuan formula and the Anshan Mining Institute formula (Liu, 2015). However, the above formulas apply to the filling and transportation under specific conditions, which is not widespread and less applied in the actual production.

Due to the large number of external influences on physical experiments and the poor operability of experiments, CFD simulation has become an effective method to study the pressure loss characteristics of pastes (Wu, 2015). For example, Yang (2021) and others applied Fluent software to model the isoparametric filling pipeline according to the actual filling pipeline of the mine and investigated the law of different influencing factors on the pressure loss. Zhang (2015) and others established a two-dimensional pipeline model for long distances and found that the self-flow transportation of slurry needs to satisfy the value of pressure generated by gravity greater than the value of pressure loss. Wu et al. (2012) used simulation to analyze the force on bends in the conveying process of a mine filling pipeline, which provided theoretical support for the smooth operation of the filling system. Using FLOW-3D computational fluid dynamics, Wang et al. (2018) synthesized a variety of influencing factors and found that the optimal conveying multiplier for a paste filling station in the west was 3.0. However, there is not yet an effective model for the flow of the total tailings-waste gypsum body.

The main objective of this paper is to investigate the rheological properties and resistance evolution behavior of CPAF. The variation characteristics of the rheological parameters of the coarse aggregate paste were investigated, and a numerical model of the conveying resistance considering the volume concentration, bulk density, and water-cement ratio was constructed. Using COMSOL Multiphysics® software, the influence of tailing ratios, inlet velocity, and concentrations on the flow resistance was analyzed. The research results of this paper have positive significance for the development of coarse aggregate paste flowing technology, reducing pipe flow resistance and extending flow distance.

Materials

The materials used in this experiment are all taken from the second mining area of Jinchuan Company, and the physical and chemical properties of all tailings and waste rock are as follows:

1. Total tailings are taken from the dressing plant, and the specific gravity (relative density) determined after airing and drying is 2.785, and the loose packing density and packing density are 1.21 $g\cdot cm^{-3}$ and 1.527 $g\cdot cm^{-3}$, respectively. The particle size composition of the whole tailings was tested with the LMS-30 laser particle size analyzer, and the particle size distribution was shown in

Figure 1(a). It can be seen that tailings with particle size less than 80 μm account for 91.31%. The main chemical composition of tailing were analyzed by X-ray fluorescence (XRF) spectroscopy, and the results are shown in Table 1.

2. Waste rock is taken from the bin of the filling station. Its specific gravity (relative density) is 2.876. The loose packing density and dense packing density are 1.675 $g \cdot cm^{-3}$ and 1.968 $g \cdot cm^{-3}$, respectively. The particle size distribution of waste rock was tested by the screening method, and the particle size curve is shown in Figure 1(b). It can be seen that waste rock of 0–12 mm accounted for 87%, and waste rock of < 15 mm accounted for 99.9%. The coarse particle content of waste rock aggregate was relatively large, which would have adverse effects on pipeline transportation.
3. Packing compactness is an important index to characterize the mixing performance of coarse aggregate, which mainly reflects the interstitial effect of fine aggregate. The compactness is calculated as shown in Equation 1. The compactness of different total tailings:waste rock ratios obtained through experiments is shown in Table 2. In this paper, three different ratios (tailings:waste ratios of 4:6, 5:5, and 6:4) were selected for the experiment.

$$\phi = \frac{\rho}{\gamma} \qquad \text{Equation 1}$$

where ϕ is the compactness, ρ is volume weight, γ is the density.

Table 1. Chemical composition of filling material.

Materials	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	SO_3	K_2O	TiO_2	MnO	other
Total tailings	42.20	3.73	32.71	4.04	12.14	3.37	0.39	0.33	0	0.85
Waste rock	47.71	16.39	15.22	7.81	7.17	2.58	1.95	0.54	0.12	0.39

Table 2. Stacking compactness of mixed aggregate.

Tailings:waste rock ratio	Density of mixed aggregate ($g \cdot cm^{-3}$)	Compactness (Φ)
0:1	2.826	0.476
1:9	2.815	0.489
2:8	2.801	0.508
3:7	2.788	0.521
4:6	2.774	0.542
5:5	2.761	0.593
6:4	2.752	0.614
7:3	2.743	0.589
8:2	2.732	0.571
9:1	2.724	0.552
1:0	2.715	0.537

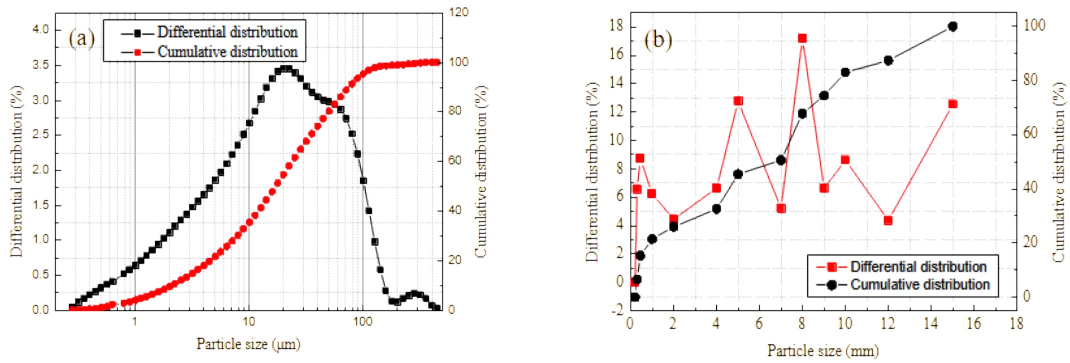

Figure 1. Particle size analysis results: (a) total tailings, (b) waste rock.

Rheological characterization of CPAF

Rheology Test

The rheological properties of the CPAF were determined using a AMETEK Brookfield R/S+ model rheometer. The rheological properties of the waste gypsum body were tested using the controlled shear rate method (Table 3), and the rheological test shear process is shown in Figure 2. The rheological characteristic curve of the overall tailing sand-waste gypsum body was also obtained (Figure 3).

Table 3. Summary of the rheological test.

Scheme	Mass content/%	Volume concentration/ %	Cement-tailings ratio	Water-cement ratio	Tailing-waste rock ratio	Bulk density
1-3	67	55.20%	1:4	1.41	4:6/5:5/6:4	0.542/0.593/0.614
4-6	69	52.39%	1:4	1.57	4:6/5:5/6:4	0.542/0.593/0.614
7-9	71	49.72%	1:4	1.75	4:6/5:5/6:4	0.542/0.593/0.614
10-12	73	47.19%	1:4	1.94	4:6/5:5/6:4	0.542/0.593/0.614
13-15	75	44.77%	1:4	2.14	4:6/5:5/6:4	0.542/0.593/0.614
16-18	77	42.47%	1:4	2.35	4:6/5:5/6:4	0.542/0.593/0.614

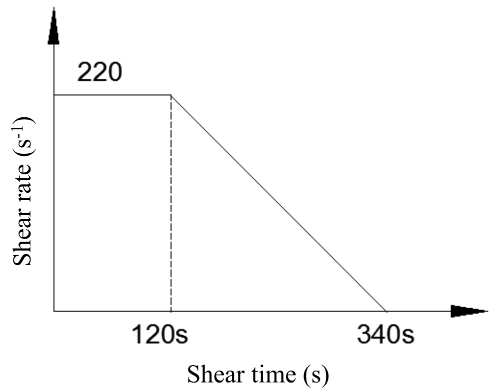

Figure 2. Schematic diagram of the rheological shearing process.

Figure 3 shows the rheological characteristics of the CPAF for different mass content conditions. It can be seen that the "second stage" of the rheological curve is linearly increasing, and its behaviour is consistent with the characteristics of Bingham's plasticity (Xue, 2020). Therefore, Bingham's formula (Equation 2) was used to fit the rheological results to obtain the values of the rheological parameters of the paste under different working conditions. The fitting results are shown in Table 4, where: τ_0 is the yield stress of the paste, η is the plastic viscosity of the paste.

$$\tau = \tau_0 + \eta(\frac{du}{dy}) \quad \text{Equation 2}$$

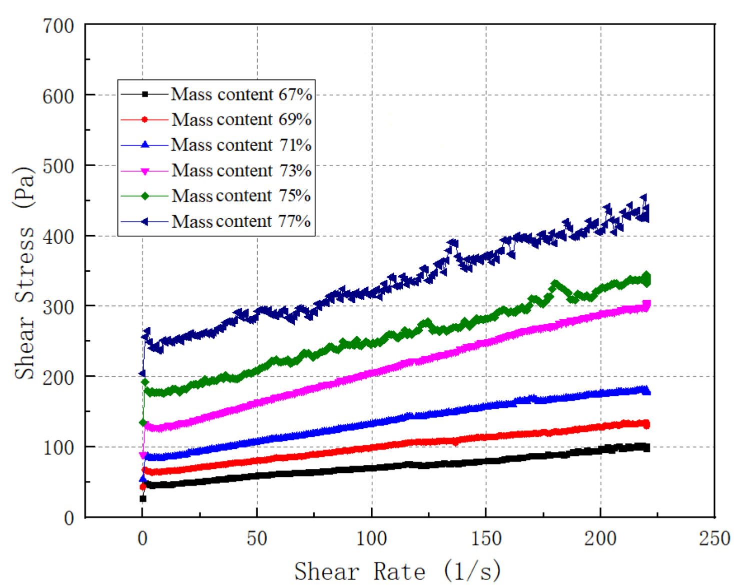

Figure 3. Typical flow curves or rheograms for tailings-waste ratio of 6:4

Table 4. Fitting results of rheological parameters.

Tailing-waste rock ratio	Mass content/%	Yield stress (Pa)	Plastic viscosity ($Pa\cdot s^{-1}$)	R^2
4:6	77%	184.32	0.74	0.9971
	75%	85.85	0.65	0.9977
	73%	61.38	0.43	0.9924
	71%	43.53	0.27	0.9889
	69%	26.97	0.18	0.9844
	67%	18.00	0.14	0.9631
5:5	77%	206.57	0.83	0.9743
	75%	138.07	0.75	0.9993
	73%	91.13	0.65	0.9992
	71%	69.50	0.41	0.9927
	69%	53.83	0.27	0.9876
	67%	39.41	0.17	0.9798
6:4	77%	236.98	0.90	0.9612
	75%	172.71	0.87	0.9849
	73%	118.84	0.75	0.9996
	71%	81.17	0.51	0.9986
	69%	63.02	0.35	0.9941
	67%	46.60	0.23	0.9861

Result analysis

The effect of mass content and tailings-waste rock ratio on the rheological parameters were plotted according to the data in Table 4 (Figures 4–5). Figure 4 shows that with the increase of mass content in paste, the yield stress of filling material is constantly increasing. The increase range grew larger and larger, while the plastic viscosity also increased, but the increase ranged gradually decreased.

According to the analysis, when the mass content increased, the formation process of the 'flocculated mesh' structure (Wu, 2014) between tailings particles will be promoted, and the flocculated mesh structure will have a large resistance effect on the rotation of the rotor. Therefore, the yield stress of the slurry will increase with the increase of mass content. The coarse aggregate paste has more pores and has a certain amount of water retention; the "wrapped" water releases when subjected to shear action, reducing plastic viscosity rate increases. Figure 5 shows that the yield stress and plastic viscosity of the CPAF increased with the proportion of tailings. This is mainly because the particle size of the tailings was smaller than that of the waste rock, and could be filled to form a relatively stable skeleton structure between the waste rock particles. With increasing tailings content, the structure became more stable, promoting the increase of yield stress and plastic viscosity.

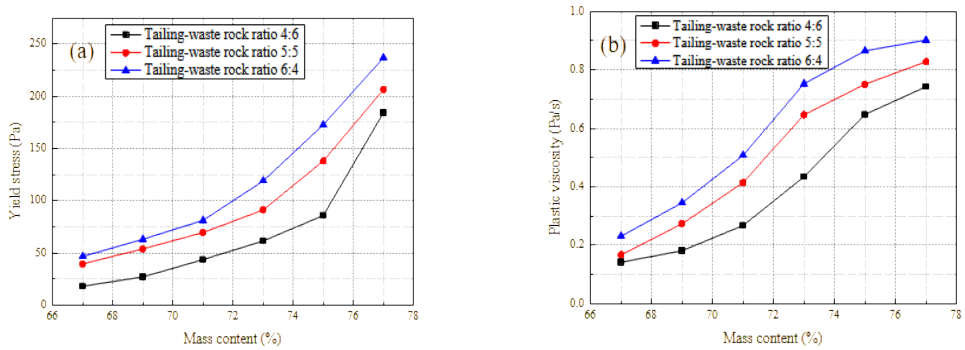

Figure 4. Effect of mass content on rheological properties.

Resistance model

Rheological parameter equation

Yield stress is closely related to water content in paste, cement content, and aggregate gradation (Zhang, 2015). The results showed that there was a qualitative relationship between yield stress aggregate volume concentration and water-cement ratio. The yield stress of the CPAF was fitted with yield stress-volume concentration and yield:stress-water-cement ratio, and the fitting results are shown in Table 5. It can be seen that the paste yield stress and volume concentration, yield stress and water-cement ratio are negative power exponential relations.

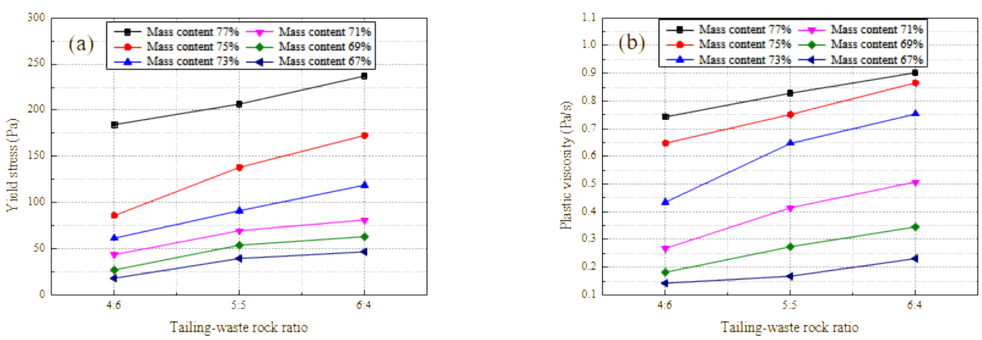

Figure 5. Effect of tailings-waste rock ratio on rheological properties

Table 5. Yield stress fitting result.

Tailings-waste rock ratio	Fitting equation of yield stress and slurry volume concentration	R^2	Fitting equation of yield stress and slurry water-cement ratio	R^2
4:6	$\tau_0 = 0.0029 * exp(20.49 * C_v)$	0.97	$\tau_0 = 1384.01 * (w/c)^{-5.10}$	0.97
5:5	$\tau_0 = 0.113 * exp(13.91 * C_v)$	0.99	$\tau_0 = 820.24 * (w/c)^{-3.46}$	0.99
6:4	$\tau_0 = 0.196 * exp(13.18 * C_v)$	0.99	$\tau_0 = 894.21 * (w/c)^{-3.28}$	0.99

It can be seen from the data in Tables 2–3 that the increase of volume concentration (increase of mass concentration) and the decrease of water-cement ratio (increase of mass concentration) will both lead to the increase of yield stress, so the influence of water-cement ratio and aggregate volume on yield stress is synchronous. At the same time, there is a close relationship between yield stress and the ratio of paste. To simplify the equation and clearly express the relationship between influencing factors and yield stress, the following yield stress prediction model is proposed:

$$\tau = a * \Phi * \exp\left(C_{\mathrm{V}}\right) * \left(\frac{W}{C}\right)^{b} \quad \text{Equation 3}$$

where W/C is the water-cement ratio, Φ is the aggregate compactness, C_v is the volume concentration; *a* is a constant, and *b* is an experimental constant. Because the water-cement ratio and volume concentration in the expression are dimensionless quantities, the yield stress τ is only related to the magnitude of the experimental constant *a*, so the units of *a* is set as Pa.

The specific gravity of mass in the flocculated network structure and the fine-grained grades content in the paste are the fundamental causes of viscosity change, which provides ideas for the construction of the viscosity calculation model. Through the analysis of the influencing factors of plastic viscosity, it was found that the main factors affecting plastic viscosity were paste concentration and compactness; the

viscosity characteristics were affected by the gradation characteristics, but the parameters of fine-grained content could not directly describe the plastic viscosity increase characteristics.

The plastic viscosity increased basically in the form of a power function with the concentration of the paste; concurrently under a certain volumetric concentration, the reduction of the stacking compactness implies an increase in the effective concentration of the paste, which further contributes to the increase of viscosity. To express the relationship between different factors and plastic viscosity, and at the same time to realize the concise prediction of plastic viscosity, a prediction model for the plastic viscosity is proposed:

$$\eta = a * C_V^b * \left(\frac{C_V}{\varphi}\right)^{c} \quad \text{Equation 4}$$

where C_v is the volume concentration, a, b, and c are experimental constants. In origin, Equations 3 and 4 were used to fit experimental data to obtain the determined values of unknown constants in the formula

under different tailings-waste rock ratios, as shown in Table 6. The results show that R^2 are all > 0.95, indicating that the rheological parameter model has good adaptability.

Table 6. Parameter fitting result

Tailing-waste rock ratio	Yield stress		R^2	Plastic viscosity			R^2
	a	b		a_1	b_1	c	
4:6	1232.80	-4.85	0.97	1.98	0.64	5.58	0.97
5:5	799.77	-3.21	0.99	3.84	2.39	2.72	0.99
6:4	924.96	-3.03	0.99	1.28	0.77	3.76	0.99

Flow resistance calculation equation

The flow resistance of the CPAF is usually calculated by the typical Bingham fluid resistance equation (Hou 2021), as shown in Equation 5. When the pipe diameter and flow rate are known, the pipe resistance is mainly restricted by the yield stress and the plastic viscosity. By bringing the yield stress and plastic viscosity formulas obtained above into Equation 5, the flow resistance (i) calculation formula considering the materials' property is obtained, as shown in Equation 6; this equation captures the influence of aggregate ratio on flowing resistance from multiple perspectives (volume concentration, compactness, and water-cement ratio), which is conducive to the further development of CPAF flowing theory.

$$i = \frac{32v\mu}{D^2} + \frac{16\tau_0}{3D} \quad \text{Equation 5}$$

$$i = \frac{32va_1 * C_V^{b_1} * \left(\frac{C_V}{\varphi}\right)^c}{D^2} + \frac{16a * \Phi * \exp\left(C_V\right) * \left(\frac{W}{C}\right)^b}{3D} \quad \text{Equation 6}$$

where i is the paste pressure loss, D is the pipe diameter, and v is the flow velocity.

Numerical model

COMSOL Multiphysics® is a finite element software applied to simulation, which is different from the complicated operation of traditional finite element simulation software. When a multi-physical field coupling analysis is conducted, only the required differential equation must be selected, making the modeling software very convenient and fast.

Basic control equations

The flow equation embedded in COMSOL Multiphysics® to describe the fluid is the Navier-Stokes (N-S) equation (Cheng, 2019); its basic expression (Equation 7) is:

$$\begin{cases} \rho\dfrac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=\nabla\cdot\left[-pl+\mu(\nabla u+(\nabla u)^{T})-\dfrac{2}{3}\mu(\nabla\cdot u)l\right]+F \\ \dfrac{\partial\rho}{\partial t}+\nabla(u\cdot\rho)=0 \end{cases} \quad \text{Equation 7}$$

By modifying the volume force (F) in the formula, Equation 5 is introduced into the N-S equation to discretize the weak solution form of the equation, and a numerical model considering volume concentration, bulk density, and water-cement ratio is established.

Geometric model construction and parameterization

The simulation experiment is based on the construction of the geometric model of the filling pipeline system (currently filling pipe diameter used is 150 mm) from the surface filling hole to -1350 m level in Jinchuan No. 2 Mine. According to the Reynolds number similarity theory, it is simplified into an 'L-shaped' model with a length of 10 m and a height of 2.5 m. The model sets the entry as velocity entry and adds gravity in the vertical direction. Due to the addition of gravity as volume force, setting the boundary condition of the pipe outlet as 0 or laminar flow outflow will lead to non-convergence of simulation calculation, so it is necessary to set the outlet as an open boundary without viscous stress and add the constraint that the pressure integral is 0.

COMSOL Multiphysics® software has a strong ability to edit the mesh division; users can adjust the mesh shape, size, and so on according to their own needs. The free triangular mesh was selected to divide the geometry. Considering the boundary layer effect of the paste, the boundary layer of the model was set to 6 and the boundary stretch coefficient to 1.2, to make the mesh near the wall more dense, and the final number of units was 708690. The mesh details are shown in Figure 6.

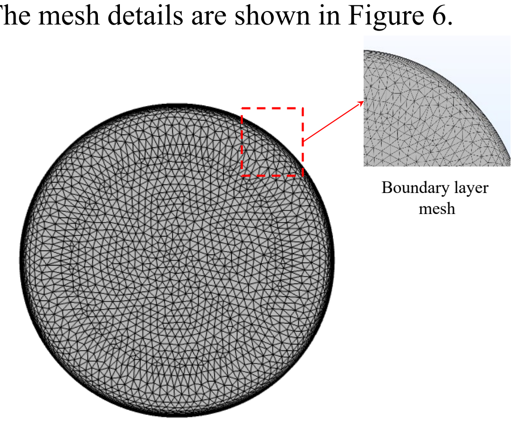

Figure 6. Mesh diagram of the pipeline section

Numerical simulation scheme

There are three influencing factors considered in this numerical simulation: tailings to waste rock mass ratio of 4:6, 5:5, and 6:4, mass content of 73, 75, and 77%, and initial flow velocity of the model of 2.0, 2.2,$^{-}$ and 2.4 m/s^{-}, respectively. The evolution of pressure drop under different tailings to waste ratios, concentrations, and initial flow velocities are obtained from COMSOLSoftware post-processing for analysis of pressure drop evolution under different tailings to waste rock ratio, concentration, and initial flow velocity conditions. The flow pattern of the filling material was determined by Reynolds number (Re), where Re < 2300 belongs to laminar flow and Re > 4000 belongs to turbulent flow. The formula (Equation 8) for Re is as follows:

$$R_e = \frac{\rho U d}{\mu} \qquad \text{Equation 8}$$

where ρ is the fluid density, U is the characteristic velocity, μ is the dynamic viscosity, and d is the diameter of the pipe. According to the aforementioned setup conditions, the Re of the tailings-waste gypsum is less than 2300, which is considered to be in a laminar flow state in the pipeline flow process. The formula can also express the Re for non-Newtonian fluids.

Resistance evolution characteristics

Simulation verification

To evaluate the reliability and applicability of the numerical model established in this paper, the flow loop test was carried out with the filling material obtained from Jinchuan No. 2 Mine, and the paste resistance loss was measured by installing a pressure transmitter on the filling pipe. Flow loop parameters included: pipe diameter 133 mm; mass content approx 73–77%; tailings to waste ratio 4:6; flow rate of 100 m^3/h (corresponding flow velocity is approx 2.0 m/s), and the length of the pressure monitoring pipeline at 17.13 m. The geometric model verified by the simulation was built strictly according to the parameters of the flow loop. The measured data and numerical simulation data of the loop are shown in Figure 7.

As can be seen from Figure 7, the relative error between the measured data and the numerical simulation data of the flow loop under different mass content is less than 8%, and the good adaptability of the model indicates that the numerical model constructed above is reliable for calculating the resistance of the CPAF pipeline transport.

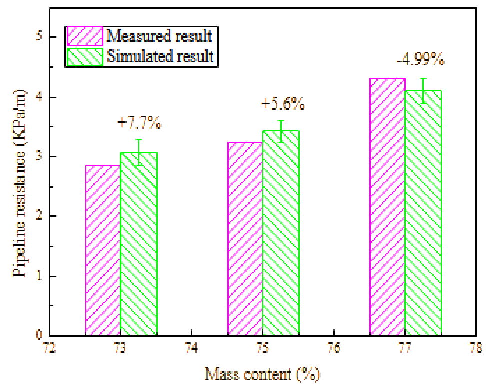

Figure 7. Model validation

Characterization of resistance evolution

Effect of tailings-waste rock ratio

The difference in aggregate particle size composition has an important influence on transportation behavior. To reduce the production cost of the mine and carry out the cooperative utilization of multi-solid waste during the filling process, the pipeline transportation resistance loss under different tailing-waste rock ratios was simulated (Figure 8).

Figure 8 shows that with the increase of the tailings:waste rock ratio, the friction loss is first reduced and then increased, the pressure loss under different conditions in the 5:5 when the pressure loss reaches the minimum value, indicating that these conditions are favorable for practical applications. This phenomenon can be attributed to the effect of the particle grading of the paste material; when the tailings waste rock ratio is 4:6, the content of coarse particles (waste rock) in the paste is higher, and the stability of the paste under this condition is poor, leading to an increase in the pressure loss. However, with the tailings:waste rock ratio of 6:4, there are more fine particles in the material and the paste has the highest degree of densification, indicating that the aggregate structure is denser. At this ratio, the viscosity of the slurry is stronger which makes the friction between the particles and the pipe wall increase, leading to a larger pressure loss. It can be seen for the tailings:waste rock ratio of 5:5 that the paste material has a more stable structure while at the same time having the lowest flowing resistance, which is more conducive to pipeline transportation. Determining the correct ratio is a key condition affecting the transportation of coarse aggregate paste, which is relatively easy to control in the process of material preparation. Based on our results, it is recommended that the optimal ratio is 5:5.

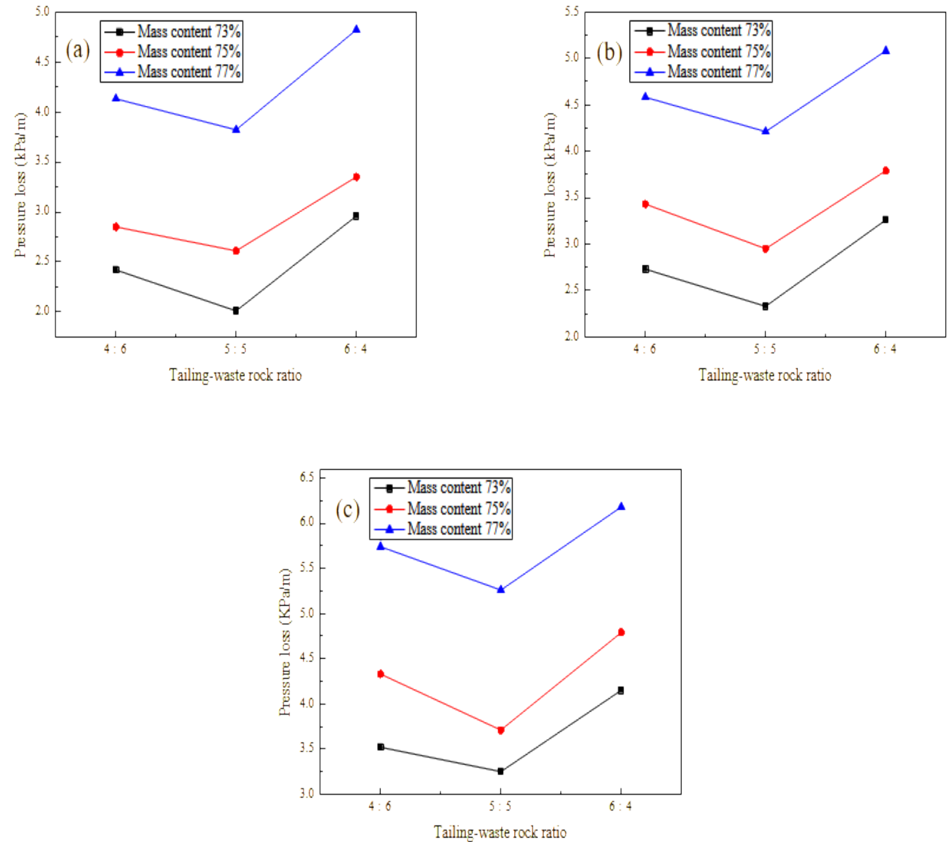

Figure 8. Effect of tailings-waste rock ratio on friction loss or pressure drop at: a) 2.0 m/s; b) 2.2 m/s, and (c) 2.4 m/s.

Effect of mass content

Mass content is an important factor affecting the performance of slurry pipeline transportation. High mass content will lead to pipe blocking and pipe failure, which will cause the filling material not to be transported smoothly to the underground stopes. Figure 9 shows the change of paste transport pressure loss under different mass content conditions.

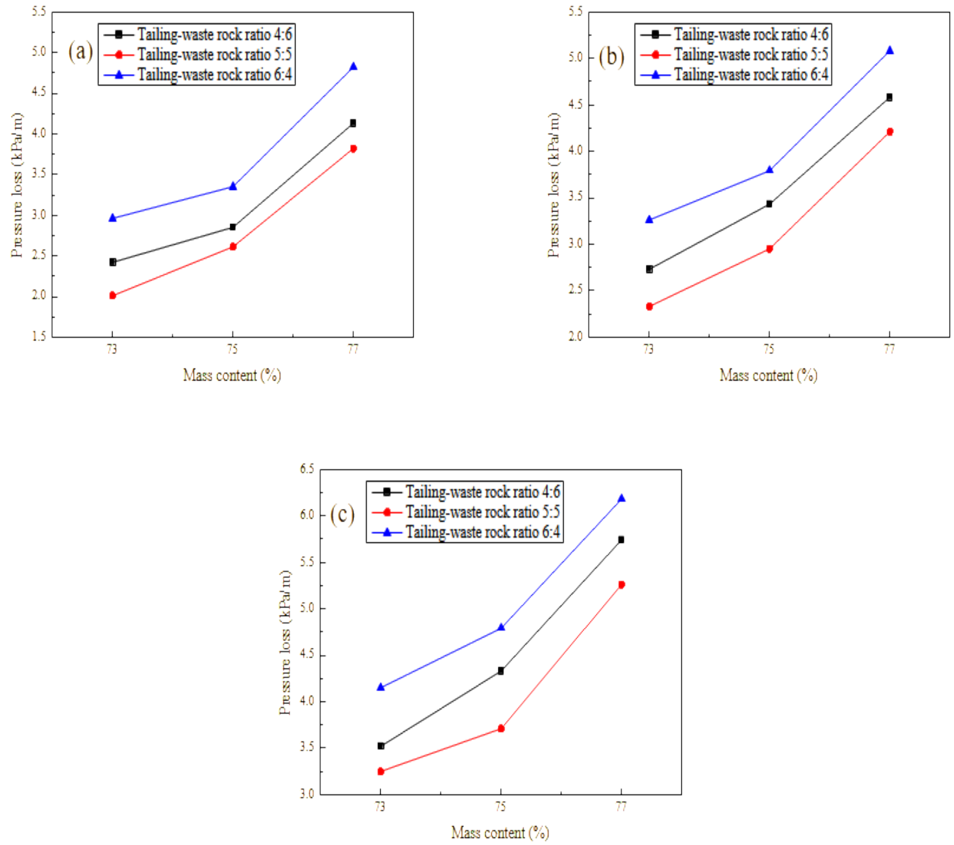

Figure 9. Effect of Mass content on drag loss at: a) 2.0 m/s, b) 2.2 m/s, and c) 2.4 m/s.

As expected, the pressure loss increased with the increase of mass content and the increase rate increased gradually. The main reason for this behavior is that the increase in mass content leads to a decrease in water content in the paste. As the coarse aggregate paste flows through the pipe, the water acts as a lubricant. Therefore, the decrease in water content (the increase of mass content) makes it difficult for the coarse aggregate paste to flow, thus increasing the pressure loss of the paste transport. In the actual filling process of mine, appropriate mass content should be selected to achieve good flowing performance. In addition, the pressure loss should also meet the actual filling situation of the mine (processing capacity of the paste mixer, the flowing capacity of the pump, etc.); while ensuring the paste fluidity and flowing ability, the concentration of the paste should be maximized to ensure that the filling mining capacity and mass waste consumption capacity of the mine can be maximized.

Effect of initial velocity

The different initial flow rates of slurry will affect the stability of paste transportation, and then affect the pressure loss of pipeline. The influence of initial velocity on paste is mainly reflected in promoting particle collision and friction. To determine the optimal transport velocity of the CPAF, a simulation method was used to simulate the pressure loss under the conditions of 2.0–2.4 m/s, and the simulation results are shown in Figure 10.

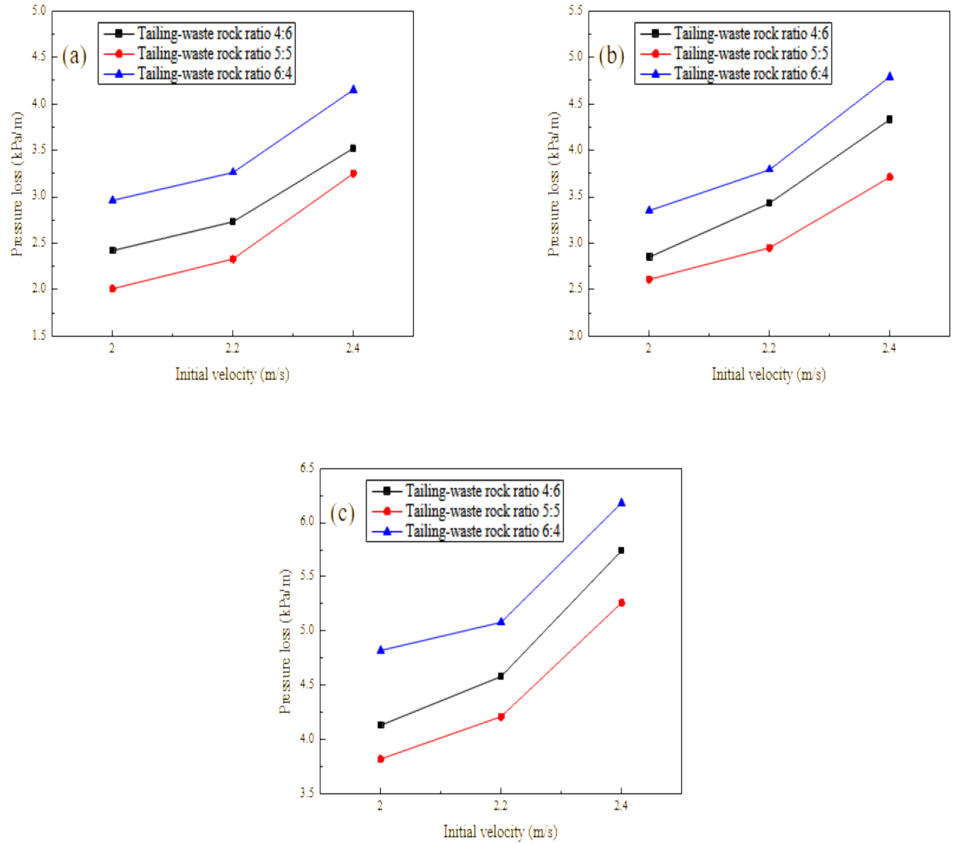

Figure 10. Effect of initial velocity on friction loss on: a) mass content 73%, b) mass content 75%, and c) mass content 77%

As can be seen from Figure 10, as initial flow velocity increases, friction loss also increases, with rates trending sharply positive as initial flow velocities are set higher. Taking the pressure loss under the condition of 77% mass content and 5:5 waste ratio as an example, when the initial velocity increases from 2.0 m/s to 2.2 m/s, the pressure loss increases by 0.39 kPa/m, with a increase rate of 10.2%. When the pressure loss increases from 2.2 m/s to 2.4 m/s, the pressure loss increases by 1.05 kPa/m, with a increase rate of 24.94%. The initial velocity of 2.2 m/s is the inflection point of the pressure loss. The analysis shows that some amount of energy from turbulence will be generated during the transport process of the particles inside the coarse aggregate paste, reflected in turbulence intensity (Xue, 2020). The formula of turbulence force subjected to material particles is as follows:

$$F_p = \frac{1}{6}\pi d_f^{\,3}\left(P_f - P_w\right)\frac{u_0^{\,2}}{y} \qquad \text{Equation 9}$$

Where F_p is the force on particles in turbulent water, d_f is the particle size of the tailings, P_f and P_w are the density of tailings sand particles and water, u_0 is the average flowing velocity in the pipe.

As can be seen in Equation 9, when the initial velocity increases, the turbulence force borne by the tailings particles in the pipe changes, thus increasing the collision probability and friction effect of the particles, which reduces the energy utilization rate and increases the corresponding pressure loss during the pipeline transportation of materials. At the same time, due to the stratification effect of fluid (Gan, 2021), the shear action between different flow layers increases with the increase of initial flow velocity, which leads to the phenomenon that the growth rate of pressure loss increases with the increase of flow velocity. Proper initial velocity is an important factor in ensuring mine production efficiency, but an excessive flow rate will lead to an excessive increase in pressure loss. Therefore, combined with the numerical simulation results, it is suggested that the optimal initial velocity of the CPAF should be controlled at 2.2 m/s.

Conclusion

- The plastic viscosity and yield stress both tend to increase with the increase of the mass content of coarse aggregate paste and the ratio of tailings:waste rock.
- The flowing resistance equation considering paste material compactness, volume concentration, and water-cement ratio was established, and the corresponding numerical model was constructed based on COMSOL Multiphysics® simulation software. The numerical simulation results are compared with the measured results of the flow loop, and the relative errors are within 8%, which provides strong evidence that the model is reliable in calculating the flowing resistance of CPAF.
- The influence law of tailings:waste rock ratio, mass content, and initial flow rate on the friction loss is obtained using numerical simulation. Due to the friction effect between the particles, the friction loss increases and then decreases with the increase of the tailings-waste rock ratio; the increase of mass content leads to the decrease of water content, which makes it difficult for the paste to flow, thus leading to the rapid increase of the pressure loss. With the increase of the initial flow rate, the particle movement becomes unstable, friction intensifies, and the pressure loss increases.
- The optimal parameters for pipeline transportation of the paste were obtained by simulation: tailing:waste rock ratio of 5:5 and an initial velocity of 2.2 m/s.

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