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Research Article

Effects of Tailings Gradation on Rheological Properties of Filling Slurry

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The key technology in filling mining is the gravity transportation of high-density slurries, and the filling system design is a significant part of this technology. The filling effect depends on the fluidity of the filling slurry. To investigate the influence of the gradation of tailings on the rheological properties of the filling slurry, this study uses particle size analysis to prepare three types of tailings: powder-, relatively fine-, and fine-grained tailings, which are then mixed in different proportions. The rheological properties of the resulting filling slurries are tested; the viscosity coefficients and yield stresses of the slurries are obtained using the analysis software provided with the MCR102 advanced rheometer that is used to measure the rheological properties of the slurries. The experimental results demonstrate that there is no absolute relationship between the rheological properties of the slurry and the size of the tailings particles, but the rheological properties are related to the gradation of tailings. Lubricating effect is weakened with an insufficient content of powder-grained particles in the tailings. On the contrary, when the content of powder-grained particles in the tailings is too high, the viscous substances in the slurry increase. Both of these conditions can increase the friction loss of the slurry.

1. Introduction

The mining process leaves behind a large number of goafs, which are a potential safety hazard in mine production [1]. The filling of tailings is treated as a safe disposal method in the Linglong gold mine. However, a serious slurry blockage phenomenon can occur during the filling process [2–4]. Many factors contribute to blockage of the pipe. During filling with aggregates, bulky debris often inadvertently enters the filling pipeline, and the presence of too many angular stones in the filling material or insufficient mixing may cause a pipe blockage accident. However, the root cause is poor fluidity of the slurry in the tube [5, 6]. The yield stress and viscosity of the slurry are important indicators for evaluating the fluidity of the slurry. The greater the yield stress and viscosity, the more difficult it is to overcome the frictional loss between the slurry particles and the worse the flow performance of the slurry [7, 8]. The rheological properties of the filled slurry mainly depend on the mass concentration, cement-sand ratio, hydration reaction temperature, hydration reaction time, and physicochemical properties of the constituent slurry materials [9]. The shear rate of the slurry decreases with increasing concentration under the same strength conditions [10]; the yield stress of the slurry increases as the ratio of lime to sand increases [11–13]; the higher the temperature, the greater the yield stress of the slurry and the worse the fluidity [14–16]; the longer the reaction time, the more the hydration products and the worse the fluidity of the slurry [17].

In addition, many studies had investigated the fluidity of fillers. The properties of cemented paste backfill (CPB) had been considered by many researchers, and a multiphysics model on CPB strength was proposed and had been successfully validated against a series of experimental data [18, 19]. The effect of the properties of the CPB mixture on the uniaxial compressive strength (UCS) of the filling body had been investigated, and the results show that the early strength of the filling body was related to many factors, such as the filling time, slurry concentration, and different cementing materials [20–22]. Liu et al. studied the improvement mechanism of special additives for the fluidity of a tailings filler slurry by measuring the exudation rate and compressive strength of the slurry, and it was shown that the structure became denser and increased the compressive strength of the filling material at an early age after adding the special additive [23]. Wang et al. determined the effect of fine fly ash particles on a filling slurry, and it was shown that the slump, divergence, setting time, and compressive strength of the paste firstly increased and then decreased with increasing fine gangue rate [24]. The practice of using ultrafine tailings cementing filling technology in a gold mine had also been researched and a good filling effect was obtained [25]. The relationship between the fineness content and the fluidity in the slurry tailings particles was analyzed. The experimental results show that the slurry strength increased with the increase of the specific gravity of the fine particles in the tailings [26, 27].

Many studies had investigated the effects of mass concentration and the lime-sand ratio, but relatively few have studied the effect of particle sizes of tailings on the rheological properties of the slurry [28, 29]. The gradation of tailings is described by the particle size distribution of the material, which refers to the percentage of different-sized particles in a granular material. The particle size distribution of the tailings controls the full filling process. The finer particles in the tailings have a smooth surface and play a role in ball lubrication at the contact of the tailings particles, which can effectively reduce the frictional loss between the angular tailings particles [30]. If the particle size distribution of the tailings in the filling slurry is not suitable, the slurry will segregate in the pipeline, which can cause a series of serious consequences, such as pipe wears and blockages. Different particle size distributions of tailings can also cause changes in the rheological properties of the filling slurry.

2. Methodology and Equipment

2.1. Experimental Equipment. An MCR102 advanced rheometer, a sandstone sieve, a vibrating machine, and an LS-POP (8) laser particle size analyzer manufactured were used in this experiment.

2.1.1. MCR102 Advanced Rheometer. The experiment in this study was carried out using the MCR102 advanced rheometer (Anton Paar, Austria). The rheometer consists of an air compressor, an air filter, a constant-temperature water bath, and its own system analysis software.

2.1.2. LS-POP (8) Laser Particle Size Analyzer Manufactured. To ensure reliable experimental results, a particle size analysis was performed on all tailings formulated for the experiments. The tailings were analyzed using an LS-POP (8) laser particle size analyzer manufactured by OMEC.

2.1.3. Sandstone Sieve and Vibrating Machine. A sandstone sieve and vibrating machine were used to prepare tailings with different grain sizes. The standard test sieve used in the experiment was manufactured by Shangyu Test Instrument Factory. The sandstone sieves embedded had pore diameters of 40 μm, 160 μm, and 315 μm. The standard vibrating screen machine used in the experiment was produced by Shangyu Feida Test Equipment Manufacturing Co., Ltd.

2.2. Experimental Material. The main materials used in this experiment are water, cement, and tailings.

2.2.1. Water and Cement. Water used for the experiment was tap water. Ordinary Portland cement (PO42.5) was used as the cementing material at the filling site. In order to ensure the test is compatible with the site, ordinary Portland cement (OPC) was also used as the cementing material for these experiments. The main chemical constituents of OPC are shown in Table 1.

2.2.2. Tailings. In these experiments, the effect of the particle size ratio of the tailings on the rheological properties of a high-concentration full tailings filling slurry was investigated using Linglong gold tailings as the raw material. The main chemical composition of the tailings is shown in Tables 1 and 2.

2.3. Experimental Content. The particle size characteristics were analyzed, and the results are shown in Figure 1.

Figure 1 shows that the cumulative content of the Linglong gold deposit particles reached 33%, 66%, and 99%, corresponding to particle sizes of approximately 40 μm, 160 μm, and 315 μm. Therefore, it is assumed that the ratio of powder-grained particles : relatively fine-grained particles : fine-grained particles in Linglong gold mine tailings is approximately 1 : 1 : 1. With the existing experimental apparatus, particles with a diameter less than 40 μm are classified as powder-grained particles, particles with a diameter of 40–160 μm are defined as relatively fine-grained particles, and particles with a diameter of 160–315 μm are designated fine-grained particles [31].

A sandstone sieve and vibrating machine were used to prepare tailings with different grain sizes. Before sieving, a sufficient amount of Linglong tailings sand was dried in a drying oven for 24 h at a temperature of 105°C. The dried tailings were then placed in a sandstone sieve with a pore size of 315 μm. After the tailings were sieved, the powder-, relatively fine-, and fine-grained tailings obtained from different batches of sieves were mixed uniformly, and self-sealing bags were loaded for use in the tests.

The main purpose of these experiments is to determine the influence of the gradation of tailings on the rheological properties of the filling slurry. In the experiments, the proportion of one of the three types of particles (powder-, relatively fine-, and fine-grained) was constant. The proportions of the other two types of particles were varied, and the resulting friction loss was calculated. To increase the

Table 1: Main chemical constituents of the tailings.

Element unit	SiO_2 (wt.%)	Al_2O_3 (wt.%)	K_2O (wt.%)	Na_2O (wt.%)	CaO (wt.%)	Fe_3O_4 (wt.%)	MgO (wt.%)	S (wt.%)
Tailings	66.90	18.06	4.70	2.85	2.27	1.52	0.88	0.25
OPC	21.86	15.49	0.34	0.35	63.59	2.66	2.19	2.42

Table 2: Part of the physical parameters of the tailings.

Element unit	Density ($kg \cdot m^{-3}$)	Porosity (%)	Permeability coefficient ($cm \cdot s^{-1}$)
Tailings	2320	46.5	6.23×10^{-3}

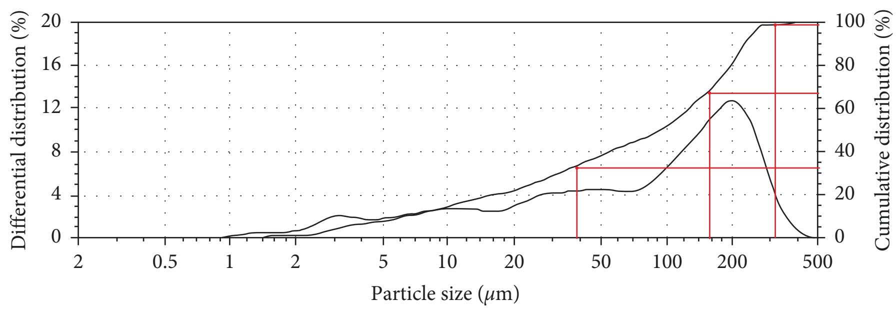


Figure 1: Particle size distribution of Linglong gold mine tailings.

degree of test discrimination, the ratio of powder-grained particles in the tailings was increased by 10%, while the proportion of relatively fine- and fine-grained particles in the tailings was increased by 20% during the experiments, as shown in Table 3.

Table 3 summarizes the experimental scheme with varying particle size ratios of tailings. Slurry No. 1 has a ratio of ingredients of 1 : 1 : 8, which means that the powder-grained particles account for 10%, relatively fine-grained particles account for 10%, and fine-grained particles account for 80% of the tailings. A set of full tailings (1 : 1 : 1) was added as a control group for these experiments.

2.4. Data Collection. The design temperature of these experiments was 20°C, the mass concentration of all slurry controls was 68%, and the cement-to-sand ratio was 1 : 8. A design time gradient was used to measure the rheological parameters of the slurry. The weighed tailings and OPC were mixed in a container until a uniform color was obtained. Then, the weighed water was added to the container, and mixed uniform paste was obtained. They were then stirred with a mixer for 5 min. The time at which the cement, tailings, and water were combined was taken as the start of the experiment. From this time, the time gradient was monitored at times of 5, 30, 60, 90, 120, 150, and 180 min. Before the experiments, the rheometer was turned on, and the air compressor was operated to output a constant pressure of 5 bar. The constant temperature water bath was then turned on, and the temperature of the water bath was allowed to stabilize. Then, the rheometer and computer used for the experiments were switched on and connected. The samples were then removed from the self-sealing bags and weighed according to the desired composition ratio. The water, cement, and tailings were poured into the experimental cylinder individually, stirred with a glass rod for 1 min to ensure the slurry in the cylinder was fully and evenly mixed, and then the blade was placed into the barrel to begin measurement. The time at which the water, cement, and tailings were mixed is defined as the start of the timed measurements. The first dataset is measured at 5 min, followed by a second dataset at 30 min, and so on. After the sixth dataset is measured at 180 min, the shear rate and shear stress maps are generated, the file is saved, the slurry in the cylinder is processed, and the test ends.

3. Results and Discussion

The rheological properties of the slurry are indicated through the viscosity coefficient, yield stress, and friction loss. Using the above experimental design, a total of 15,120 raw data points were obtained, and the experimental results were analyzed.

3.1. Preliminary Treatment of Experimental Results. All the data points were processed with the Origin software to obtain a shear rate-shear stress curve for each slurry, as shown in Figure 2.

Figure 2 shows the rheological characteristic curves of 18 different experimental proportions at different times. As can be seen from Figure 2, the slope of each curve is very high in the first half and then in the second half of the curve, and the slope gradually becomes smaller but always positive.

A large slope means that the shear rate is slightly increased and the shear stress is greatly increased. This is because the gel material generated inside the cement hydration reaction encloses the tailings particles in the slurry to form a floc structure having a certain strength [32, 33]. As the shear rate of the rotor increases, more and more web

Table 3: Experimental design for investigating the fluidity of a filling slurry by varying the gradation of high-concentration tailings.

Number	Ratio of ingredients	Powder-grained particles (g)	Relatively fine-grained particles (g)	Fine-grained particles (g)	Cement (g)	Water (g)	Total weight (g)
1	1 : 1 : 8	13.6	13.6	108.8	17	72	225
2	1 : 3 : 6	13.6	40.8	81.6			
3	2 : 1 : 7	27.2	13.6	95.2			
4	2 : 3 : 5	27.2	40.8	68			
5	2 : 5 : 3	27.2	68	40.8			
6	2 : 7 : 1	27.2	95.2	13.6			
7	3 : 1 : 6	40.8	13.6	81.6			
8	3 : 3 : 4	40.8	40.8	54.4			
9	3 : 5 : 2	40.8	68	27.2			
10	4 : 1 : 5	54.4	13.6	68			
11	4 : 3 : 3	54.4	40.8	40.8			
12	4 : 5 : 1	54.4	68	13.6			
13	5 : 1 : 4	68	13.6	54.4			
14	5 : 3 : 2	68	40.8	27.2			
15	6 : 1 : 3	81.6	13.6	40.8			
16	6 : 3 : 1	81.6	40.8	13.6			
17	7 : 1 : 2	95.2	13.6	27.2			
18	Full tailings		136				

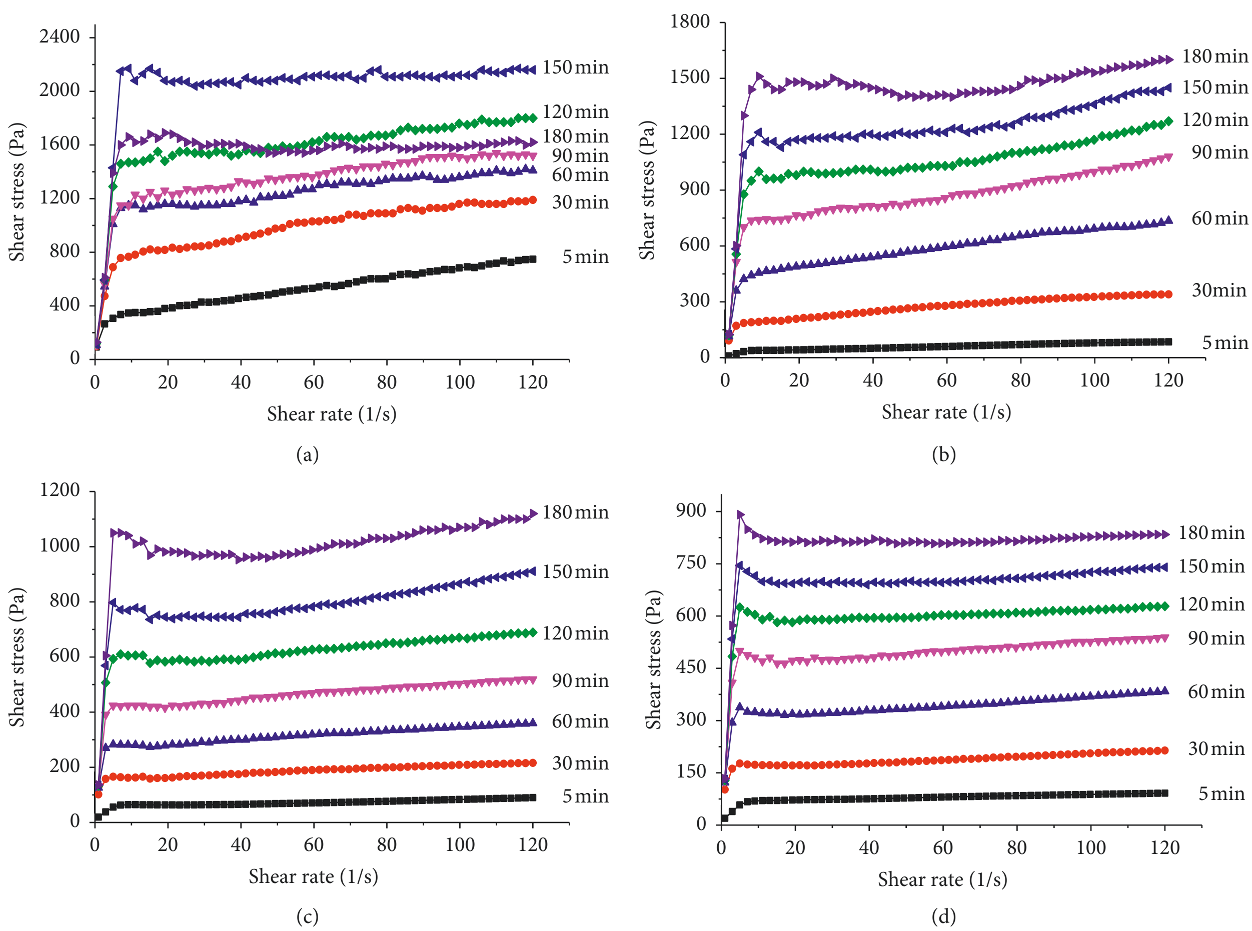
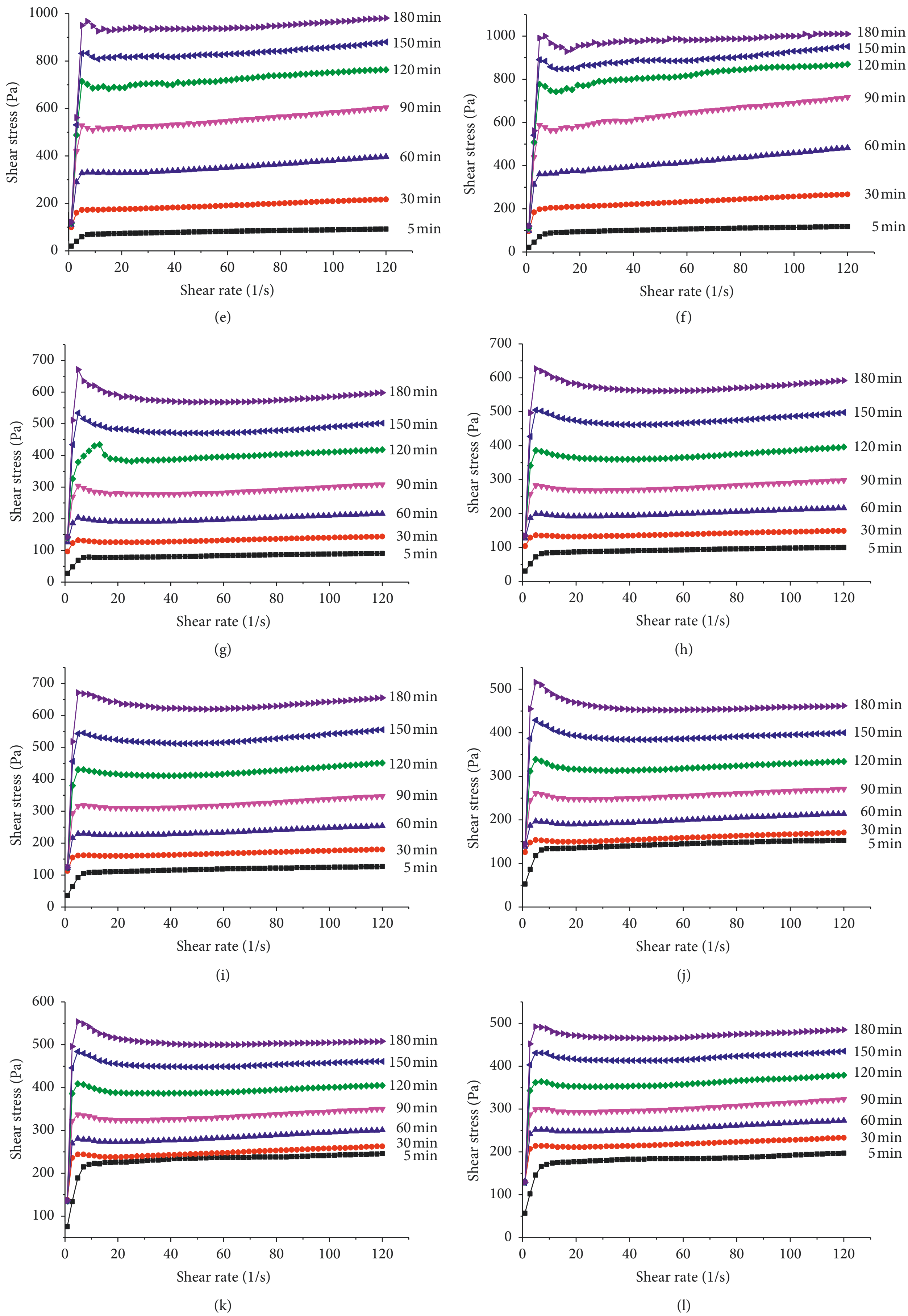


Figure 2: Continued.



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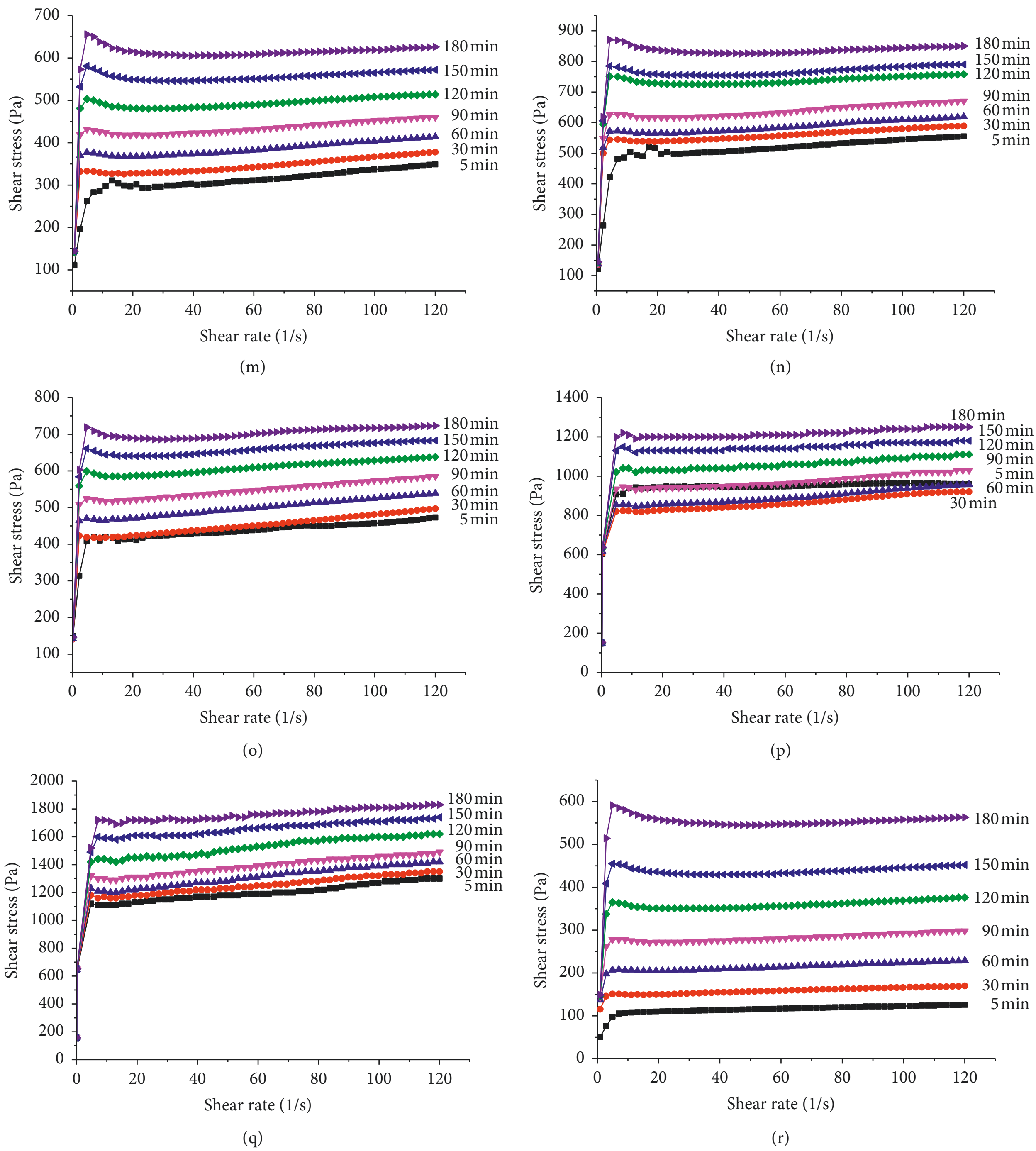

Figure 2: Rheological characteristics of tailings with different gradations at varying times. (a) No. 1 (1 : 1 : 8). (b) No. 2 (1 : 3 : 6). (c) No. 3 (2 : 1 : 7). (d) No. 4 (2 : 3 : 5). (e) No. 5 (2 : 5 : 3). (f) No. 6 (2 : 7 : 1). (g) No. 7 (3 : 1 : 6). (h) No. 8 (3 : 3 : 4). (i) No. 9 (3 : 5 : 2). (j) No. 10 (4 : 1 : 5). (k) No. 11 (4 : 3 : 3). (l) No. 12 (4 : 5 : 1). (m) No. 13 (5 : 1 : 4). (n) No. 14 (5 : 3 : 2). (o) No. 15 (6 : 1 : 3). (p) No. 16 (6 : 1 : 3). (q) No. 17 (7 : 1 : 2). (r) No. 18 (full tailings).

structures are broken and the shear stress begins to decrease. The interaction between the particles causes the flocculation structure to be overlapped and repaired with the continuation of the hydration reaction and the constant agitation of the slurry by the rotor. The measurement curve becomes gentle and stabilizes at a certain value, when the rate of failure and repair of the web structure reaches a dynamic equilibrium.

In the middle and end sections of the curves, 126 of the rheological properties can be regarded as a straight line; these would have an intercept on the ordinate axis if extended. This rheological model conforms to the Bingham plastic model [34–37]. The slope of the line is the viscosity coefficient of the slurry, while the intercept represents the yield stress of the slurry.

3.2. Influence of Gradation of Tailings on Slurry Viscosity Coefficient. The viscosity coefficient is calculated from the experimental results (Figure 3).

An increase along the abscissa in Figure 3 indicates that the content of powder-grained particles in the slurry tailings remains unchanged or increases. It can be seen that, for almost all of the slurries, the viscosity coefficient changes over time by initially increasing and then decreasing; the exceptions are a few groups of experimental errors. This occurs because there is still material in the slurry reaction that is yet to be stabilized. The viscosity coefficients of slurry No. 1, No. 2, and No. 3 have a larger variance, and these slurries exhibit an unstable performance making them unsuitable for filling. Compared to the other slurries, the viscosity coefficients of slurry No. 10, No. 11, No. 12, and No. 18 have a smaller variance. The performance of these slurries is relatively stable, and they are suitable for filling. The remaining slurries have large viscosity coefficients. Their fluidity is poor, which is not conducive to transport. Observing all the slurries shows that the viscosity coefficient of the slurry initially decreases and then increases with increasing proportion of powder-grained particles. With continuing increase in the content of powder-grained particles in the tailings, the viscosity coefficient of the slurry and its variance also increased. Even with the same proportion of powder-grained particles, there are still differences in the viscosity coefficients of the slurries owing to the varying proportions of fine-grained and powder-grained particles, such as for slurry No. 10, No. 11, and No. 12.

A proportion of powder-grained particles that is too great or too small will affect the rheological properties of the slurry, making it not conducive to filling. The addition of appropriate powder particles acts as a ball lubrication between the coarse particles, effectively reducing the viscosity of the slurry [38]. The influence mechanism of the grade-matching slurry fluidity requires a more in-depth analysis of the microscopic aspects of the slurry [39, 40]. Relevant research will be continued in the next scientific research work. When the content of powder-grained Linglong tailings is maintained at approximately 40% and the ratio of relatively fine-grained tailings to fine-grained tailings is reasonable, the viscosity coefficient and variance of the slurry are minimized.

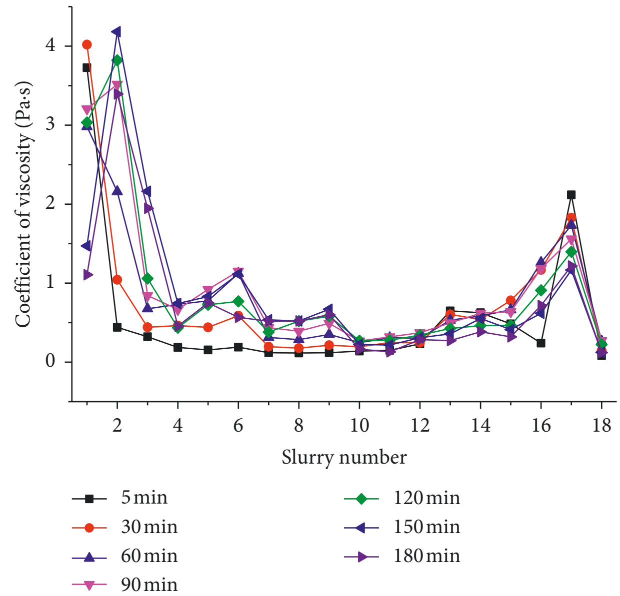

Figure 3: Relationship between slurry viscosity and slurry content.

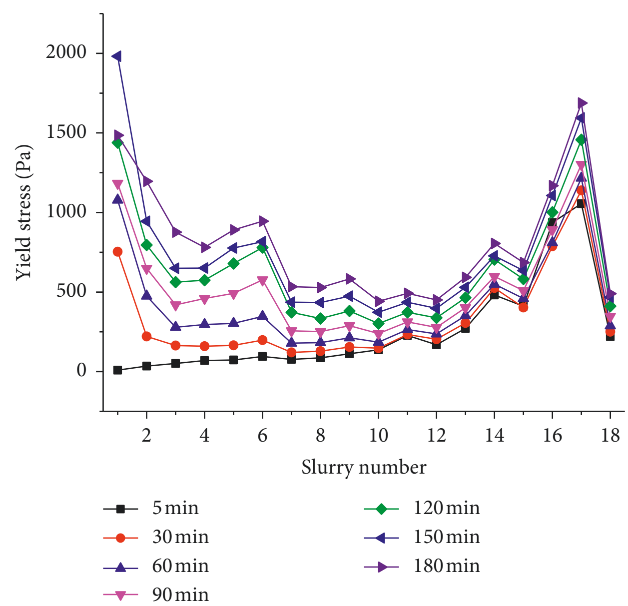

Figure 4: Relationship between yield stress and slurry number.

3.3. Influence of Gradation of Tailings on Slurry Yield Stress. The yield stress is calculated from the experimental results (Figure 4).

An increase along the abscissa in Figure 4 indicates that the content of powder-grained particles in the slurry tailings remains unchanged or increases. It can be seen that the yield stress for almost all slurries increases with time, indicating that the fluidity of the slurry deteriorates; the exceptions are a few groups of experimental errors. The initial yield stresses of slurry No. 1 and No. 2 are relatively small and increase significantly after 30 min. This indicates that the powder-grained particles in the tailings account for a small proportion and the slurry has more fluidity in the initial stage but less fluidity in the middle and final stages. The yield stresses of slurry No. 10, No. 12, and No. 18 are initially low, and their final growth is small. The rheological properties of these slurries are better.

Analysis of all slurries shows that a powder-grained particle content which is too high or too low will affect the rheological properties of the slurry. If the proportion of powder-grained particles is too low, the slurry will disintegrate easily. If the proportion of powder-grained particles is too high, viscous substances in the slurry will increase. In both cases, the yield stress of the slurry will increase and the slurry fluidity will reduce. Research on the mechanism of the influence of the level-matching slurry fluidity will continue in the next research work. When the proportion of powder-grained Linglong gold mine tailings is 40% and the ratio of relatively fine-grained tailings to fine-grained tailings is reasonable, the yield stress of the slurry is minimized.

3.4. Effect of Gradation of Tailings on Slurry Friction Loss.

The ultimate goal of measuring the rheological parameters of a slurry is to calculate its friction loss coefficient to indicate its performance in a pipeline.

The pipe friction loss under different flow rates based on the Bingham flow model is calculated using the following formula [41–44]:

$$i = \frac{16\tau_0}{3D} + \frac{32\eta v}{D^2}, \tag{1}$$

where i is the friction loss (Pa/m), τ_0 is the yield stress of the slurry (Pa), η is the viscosity coefficient of the slurry (Pa·s), v is the flow rate of the slurry in the pipeline (m/s), and D is the inner diameter of the pipe conveying the slurry (m).

According to an actual situation on-site, the flow velocity is 1 m/s and the inner diameter of the pipe D is 0.1 m. Thus, the equation for calculating friction loss can be simplified as follows:

$$i = 53.33\tau_0 + 3200\eta. \tag{2}$$

From the experimental results, the relationship between the gradation of tailings and the slurry friction loss coefficient can be obtained.

Figure 5 shows the relationship between the slurry friction loss and slurry content, and an increase along the abscissa indicates that the content of powder-grained tailings in the slurry remains unchanged or increases. The No. 1 and No. 2 slurries exhibit a small friction loss initially, but the friction loss increases sharply after 30 min. This indicates that the slurry exhibits poor fluidity after a short time. These slurries are thus not conducive to filling. The initial friction loss of slurry No. 10, No. 12, and No. 18 is small, and the friction loss in the later period is also small. This indicates that the fluidity of the slurry is stable for a period of time.

With the large ordinate interval in Figure 5, the relationship between the ratios of tailings content and the lowest values of friction losses cannot be clearly observed. Thus, the data for slurry No. 10, No. 12, and No. 18 are extracted and shown in Figure 6 for better observation.

It can be seen from Figure 6 that, at any point in time, the best flow performance is achieved by slurry No. 10. This is followed by slurry No. 12, and slurry No. 18 exhibits the poorest fluidity. Furthermore, the flow performance of slurry No. 10 after one hour is better than that of slurry No. 18 immediately after preparation. It can be concluded that, for all slurries, the proportion of powder-grained particles affects the friction loss. The addition of the powder particles increases the bulk density of the particles in the slurry. The water required to fill the voids between the particles is reduced, and excess moisture forms a water film on the surface of the particles, which reduces the sliding resistance between the particles [45, 46]. A proportion of powder-grained particles that is too high or too low will cause the material fluidity to deteriorate, as shown by Figures 5 and 6.

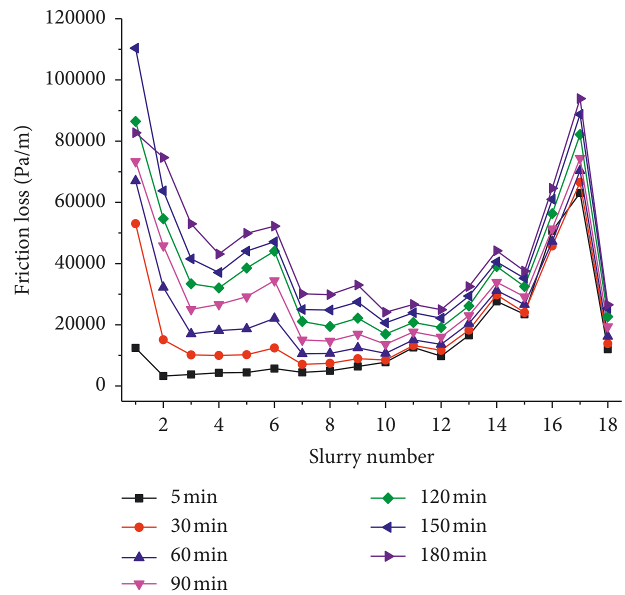

Figure 5: Relationship between friction loss and slurry content.

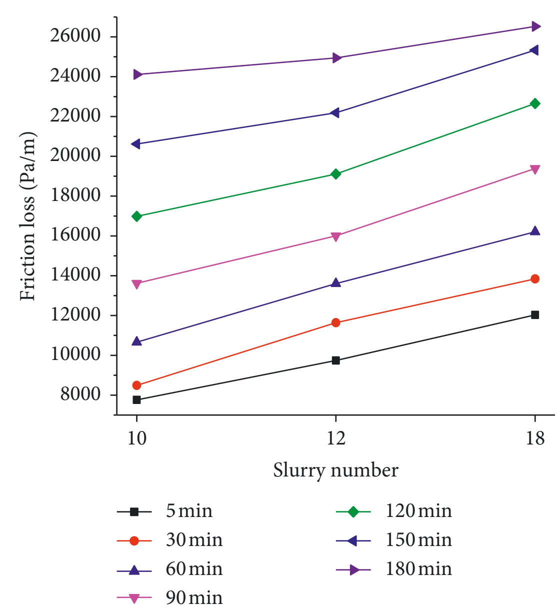

Figure 6: Friction loss in select slurries.

In order to test its uniaxial compressive strength (UCS), a standard sample (70.7 mm × 70.7 mm × 70.7 mm) was prepared using slurry No. 10, No. 11, No. 12, and No. 18. The UCS of their samples was tested with TYE-300D (Wuxi Jianyi Instrument Machinery Co., Ltd., Wuxi, China). The UCS test results are shown in Figure 7.

The UCS test results show that the sample made of slurry No. 10 has higher UCS and the UCS of the sample made of No. 12 and No. 18 slurries is poor. The 7-day UCS of the sample made of slurry No. 18 was 0.48 MPa, while that of No. 10 was 20% higher than it. And slurry No. 10 has the lowest resistance loss and is most suitable for filling; its tailings ratio is 40% powder-grained sand, 10% relatively fine-grained

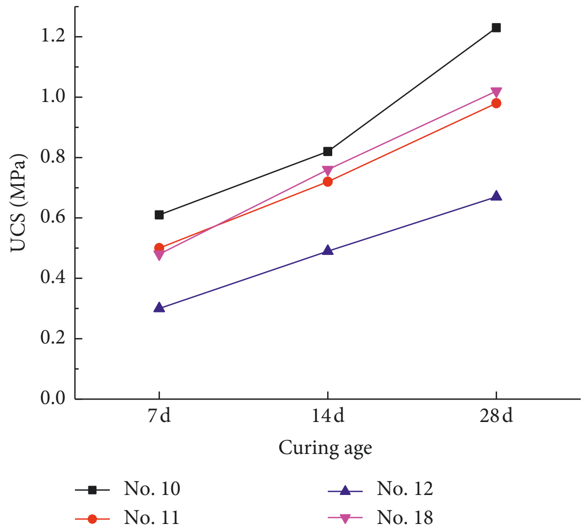

Figure 7: UCS of slurry samples.

sand, and 50% fine-grained sand from the Linglong gold mine.

4. Conclusions

In this study, a particle size analysis of tailings from the Linglong gold mine was carried out, and the tailings were sieved and classified as powder-, relatively fine-, and fine-grained according to certain standards. These three types of tailings were mixed to create filling slurries with various ratios, and the rheology of the resulting slurries was measured using a rheometer. Ultimately, the influence of the gradation of the Linglong tailings on the fluidity of the filling slurry was analyzed.

This study has yielded the following conclusions: (1) The particle size distribution of tailings from the Linglong gold mine was obtained. Particle sizes of 40 μm and 160 μm were used to demarcate the transition from powder, relatively fine, and fine grains. The entirety of the tailings was sieved into three classes: powder-, relatively fine-, and fine-grained sand. (2) With increasing content of powder-grained particles in the tailings, the viscosity coefficient and yield stress decrease continuously until the proportion of powder-grained particles in the tailings is approximately 40% of the total content; with further increase in the content of powder-grained tailings, the viscosity coefficient and yield stress of the slurry begin to increase. This indicates that a powder-grained tailings content that is too high or too low will increase the viscosity coefficient and yield stress of the slurry. (3) There is no absolute relationship between the friction loss of the slurry and the particle size of the tailings, but there is strong correlation between the friction loss of the slurry and the composition of the tailings. A too-high or too-low content of powder-grained particles in the tailings will cause friction loss in the slurry. If the coefficient is too large, it is not conducive to the transport of slurry in a pipeline. When the content of powder-grained particles in the tailings is too low, the lubricating effect of the slurry will decrease. When the content of the powder-grained particles in the tailings is too high, the slurry becomes more viscous. Both these cases will increase the friction loss of the slurry. (4) Regardless of the point in time, the types of slurry tailings with the best flow performance are, in turn, slurry No. 10, No. 12, and No. 18. Of all the slurries, slurry No. 10 (40%, 10%, and 50% content of powder-, relatively fine-, and fine-grained tailings) was observed to exhibit the best rheological properties.

This study summarizes the influence of the gradation of tailings on the rheology of a filling slurry and determines the optimal ratio of tailings. The results show that the characteristics of slurry No. 10 are optimal. However, grading the full tailings is a huge challenge by adopting slurry No. 10 instead of a full tailings one due to lack of grading equipment and increased costs and processes. It is necessary to conduct comparative research on the field industrial test in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] W. D. Song, J. X. Fu, J. H. Du, and C. L. Zhang, "Analysis of stability of goaf group in metal mines based on precision detection," *Rock and Soil Mechanics*, vol. 33, no. 12, pp. 3781–3787, 2012.

[2] M. F. Cai, W. D. Liu, and Y. Li, "In-situ stress measurement at deep position of Linglong gold mine and distribution law of in-situ stress field in mine area," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 2, pp. 227–233, 2010.

[3] X. X. Zhang and D. P. Qiao, "Simulation and experiment of pipeline transportation of high density filling slurry with coarse aggregates," *Chinese Journal of Nonferrous Metals*, vol. 25, no. 1, pp. 258–267, 2015.

[4] J. Liu, Y. Zhang, Z. L. Hou, and R. F. Zhu, "Analysis of the causes of filling pipe burst and its prevention measures in metal mines," *Gold*, vol. 39, no. S1, pp. 80–83, 2018.

[5] N. Jiang, J. H. Zhao, X. Z. Sun, L. Y. Bai, and C. X. Wang, "Use of fly-ash slurry in backfill grouting in coal mines," *Heliyon*, vol. 3, no. 11, article e00470, 2017.

[6] R. J. Farris, "Prediction of the viscosity of multimodal suspensions from unimodal viscosity data," *Transactions of the Society of Rheology*, vol. 12, no. 2, pp. 281–301, 1968.

[7] A. Kesimal, E. Yilmaz, B. Ercikdi, I. Alp, and H. Deveci, "Effect of properties of tailings and binder on the short-and long-term strength and stability of cemented paste backfill," *Materials Letters*, vol. 59, no. 28, pp. 3703–3709, 2005.

[8] X. X. Zhang and D. P. Qiao, "The rheological properties and yield stress model of high-density slurry added with coarse

sands," *Applied Mechanics and Materials*, vol. 580–583, pp. 231–237, 2014.

[9] A. P. Shapiro and R. F. Probstein, "Random packings of spheres and fluidity limits of monodisperse and bidisperse suspensions," *Physical Review Letters*, vol. 68, no. 9, pp. 1422–1425, 1992.

[10] R. F. Storms, B. V. Ramarao, and R. H. Weiland, "Low shear rate viscosity of bimodally dispersed suspensions," *Powder Technology*, vol. 63, no. 3, pp. 247–259, 1990.

[11] C. Qi, A. Fourie, Q. Chen, and Q. Zhang, "A strength prediction model using artificial intelligence for recycling waste tailings as cemented paste backfill," *Journal of Cleaner Production*, vol. 183, pp. 566–578, 2018.

[12] T. H. M. Le, P. Dae-Wook, and S. Jung-Woo, "Evaluation of ponded ash as a sustainable backfill material," *Journal of Materials in Civil Engineering*, vol. 30, no. 8, article 04018158, 2018.

[13] D. Simon and M. Grabinsky, "Apparent yield stress measurement in cemented paste backfill," *International Journal of Mining, Reclamation and Environment*, vol. 27, no. 4, pp. 231–256, 2013.

[14] I. Elkhadiri, M. Palacios, and F. Puertas, "Effect of curing temperature on cement hydration," *Ceramics-Silikáty*, vol. 53, no. 2, pp. 65–75, 2009.

[15] N. Schwarz, M. Dubois, and N. Neithalath, "Electrical conductivity based characterization of plain and coarse glass powder modified cement pastes," *Cement and Concrete Composites*, vol. 29, no. 9, pp. 656–666, 2007.

[16] F. D. Tamás, E. Farkas, M. Vörös, and D. M. Roy, "Low-frequency electrical conductivity of cement, clinker and clinker mineral pastes," *Cement and Concrete Research*, vol. 17, no. 2, pp. 340–348, 1987.

[17] S. Popovics, *Concrete Materials. Properties, Specifications and Testing*, Elsevier, Amsterdam, Netherlands, 2nd edition, 1992.

[18] L. Cui and M. Fall, "Multiphysics modeling and simulation of strength development and distribution in cemented tailings backfill structures," *International Journal of Concrete Structures and Materials*, vol. 12, no. 1, pp. 353–374, 2018.

[19] L. Liu, Z. Fang, C. Qi, B. Zhang, L. Guo, and K.-I. Song, "Experimental investigation on the relationship between pore characteristics and unconfined compressive strength of cemented paste backfill," *Construction and Building Materials*, vol. 179, pp. 254–264, 2018.

[20] S. Cao, W. Song, and E. Yilmaz, "Influence of structural factors on uniaxial compressive strength of cemented tailings backfill," *Construction and Building Materials*, vol. 174, pp. 190–201, 2018.

[21] W. Li and M. Fall, "Strength and self-desiccation of slag-cemented paste backfill at early ages: link to initial sulphate concentration," *Cement and Concrete Composites*, vol. 89, pp. 160–168, 2018.

[22] W. B. Xu, P. W. Cao, and M. M. Tian, "Strength development and microstructure evolution of cemented tailings backfill containing different binder types and contents," *Minerals*, vol. 8, no. 4, p. 167, 2018.

[23] J. H. Liu, R. D. Wu, A. X. Wu, and S. Y. Wang, "Bleeding characteristics and improving mechanism of self-flowing tailings filling slurry with low concentration," *Minerals*, vol. 7, no. 8, p. 131, 2017.

[24] Z. Wang, Z. Wang, and W. Zhao, "Microscopic pore and filling performance of coal gangue cementitious paste," *Journal of Wuhan University of Technology-Materials Science Edition*, vol. 33, no. 2, pp. 427–430, 2018.

[25] D. Q. Deng, L. Liu, Z. L. Yao, K. I. Song, and D. Z. Lao, "A practice of ultra-fine tailings disposal as filling material in a gold mine," *Journal of Environmental Management*, vol. 196, pp. 100–109, 2017.

[26] X. Ke, H. Hou, M. Zhou, Y. Wang, and X. Zhou, "Effect of particle gradation on properties of fresh and hardened cemented paste backfill," *Construction and Building Materials*, vol. 96, pp. 378–382, 2015.

[27] C. Chang and R. L. Powell, "Effect of particle size distributions on the rheology of concentrated bimodal suspensions," *Journal of Rheology*, vol. 38, no. 1, pp. 85–98, 1994.

[28] C. Servais, R. Jones, and I. Roberts, "The influence of particle size distribution on the processing of food," *Journal of Food Engineering*, vol. 51, no. 3, pp. 201–208, 2002.

[29] P. Gondret and L. Petit, "Dynamic viscosity of macroscopic suspensions of bimodal sized solid spheres," *Journal of Rheology*, vol. 41, no. 6, pp. 1261–1274, 1997.

[30] R. Siddique, "Properties of concrete incorporating high volumes of class F fly ash and san fibers," *Cement and Concrete Research*, vol. 34, no. 1, pp. 37–42, 2004.

[31] YS/T 5225-2016, *Specification for Soil Test*, Vol. 11, China Planning Press, Beijing, China, 2016.

[32] Z. Li, T.-A. Ohkubo, and Y. Tanigawa, "Theoretical analysis of time-dependence and thixotropy of fluidity for high fluidity concrete," *Journal of Materials in Civil Engineering*, vol. 16, no. 3, pp. 247–256, 2004.

[33] Z. Li, T. A. Ohkubo, and Y. Tanigawa, "Yield model of high fluidity concrete in fresh state," *Journal of Materials in Civil Engineering*, vol. 16, no. 3, pp. 195–201, 2004.

[34] J. A. Tichy, "Hydrodynamic lubrication theory for the Bingham plastic flow model," *Journal of Rheology*, vol. 35, no. 4, pp. 477–496, 1991.

[35] Y. Li and B. Yu, "Study of the starting pressure gradient in branching network," *Science China Technological Sciences*, vol. 53, no. 9, pp. 2397–2403, 2010.

[36] G. M. Oliveira, C. O. R. Negrão, and A. T. Franco, "Pressure transmission in Bingham fluids compressed within a closed pipe," *Journal of Non-Newtonian Fluid Mechanics*, vol. 169–170, pp. 121–125, 2012.

[37] T.-S. Vu, G. Ovarlez, and X. Chateau, "Macroscopic behavior of bidisperse suspensions of noncolloidal particles in yield stress fluids," *Journal of Rheology*, vol. 54, no. 4, pp. 815–833, 2010.

[38] C. K. Park, M. H. Noh, and T. H. Park, "Rheological properties of cementitious materials containing mineral admixtures," *Cement and Concrete Research*, vol. 35, no. 5, pp. 842–849, 2005.

[39] Y. K. Liu, Q. L. Zhang, Q. S. Chen, C. C. Qi, Z. Su, and Z. D. Huang, "Utilisation of water-washing pre-treated phosphogypsum for cemented paste backfill," *Minerals*, vol. 9, no. 3, p. 175, 2019.

[40] Y. Feng, J. Kero, Q. X. Yang et al., "Mechanical activation of granulated copper slag and its influence on hydration heat and compressive strength of blended cement," *Materials*, vol. 12, no. 5, p. 772, 2019.

[41] X. Wang, J. Li, Z. Xiao, and W. Xiao, "Rheological properties of tailing paste slurry," *Journal of Central South University of Technology*, vol. 11, no. 1, pp. 75–79, 2004.

[42] L. Staron, P.-Y. Lagrée, P. Ray, and S. Popinet, "Scaling laws for the slumping of a Bingham plastic fluid," *Journal of Rheology*, vol. 57, no. 4, pp. 1265–1280, 2013.

[43] R. Liu and Q. S. Liu, "Non-modal stability in Hagen-Poiseuille flow of a Bingham fluid," *Physics of Fluids*, vol. 26, no. 1, article 014102, 2014.

[44] H. Fahs, G. Ovarlez, and X. Chateau, "Pair-particle trajectories in a shear flow of a Bingham fluid," *Journal of Non-Newtonian Fluid Mechanics*, vol. 261, pp. 171–187, 2018.
[45] S. H. Lee, H. J. Kim, E. Sakai, and M. Daimon, "Effect of particle size distribution of fly ash-cement system on the fluidity of cement pastes," *Cement and Concrete Research*, vol. 33, no. 5, pp. 763–768, 2003.
[46] A. K. H. Kwan and J. J. Chen, "Adding fly ash microsphere to improve packing density, flowability and strength of cement paste," *Powder Technology*, vol. 234, pp. 19–25, 2013.