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DETERMINATION AND APPLICATION OF PRESSURE LOSS IN LONG DISTANCE PIPELINE TRANSPORTATION OF PASTE SLURRY BASED ON PIPE LOOP EXPERIMENT

Industrial size pipe loop tests were conducted to determine the effect of paste mass concentration, cement content, conveying pipe diameter and conveying volumetric flow rate, on the pipeline pressure loss of paste slurry. The tests were conducted to determine the pressure losses in the backfill system at a Copper Mines major ore body. Results show that the pressure loss of paste slurry increases with the increase in mass concentration, and when the mass concentration exceeds 70%, the pressure loss will increase sharply and would be an exponential function of paste mass concentration; as the cement content increases, the pressure loss would decrease at first and then increase with the maximum pressure loss at 11% cement content; the pressure loss increases with the increase in conveying the volumetric flow rate accordingly, while the growth rate of pressure loss will increase after the volumetric flow rate exceeds 50 m^3/h; the pressure loss of paste slurry decreases sharply with the increase in pipe diameter, i.e., the larger pipe diameter, the smaller pressure loss; lastly, the paste conveying parameters were determined as mass concentration of lower than 70% (pressure loss: 2.55 MPa/km), cement content of 5% to 11%, inside diameter of conveying pipe of 150 mm and the maximum allowable pipeline pressure of 6 MPa.

Keywords: paste slurry; pipeline transportation; pressure loss; pipe loop test; industrial application

1. Introduction

The western ore body has complex geological conditions, with siltized ore rock in the presence of water and less than 50% of ore recovery ratio [1-3]. Therefore, an upward drift stoping with backfill was adopted for mining the western ore body to improve the ore recovery ratio to over 80%. In view of the successful application of paste filling in the western ore body, paste

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filling would be used for mining the major ore body. However, the paste filling is located at the western ore body, as shown in Fig. 1, with an approximately 2.5 km straight line distance to the slope ramp entrance of the major ore body and a 5.6 km straight line distance to the underground stopes of the major ore body. Therefore, the method used to convey the paste slurry from the filling station to the underground stope of the major ore body is crucial for the successful delivery of the paste fill to the major ore body. For this reason, determining the pipeline pressure loss and effect of paste slurry before designing of conveying pipeline is necessary.

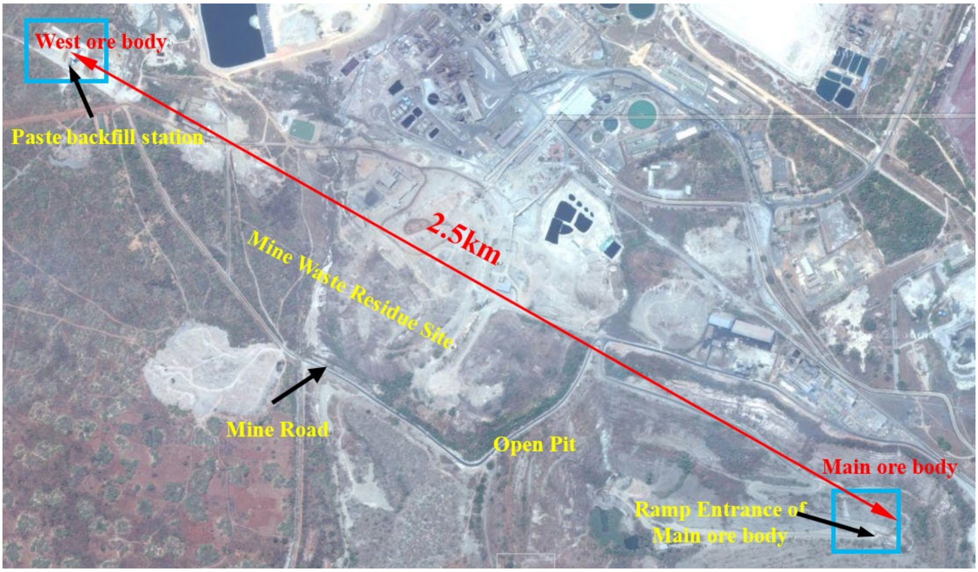

Fig. 1. Plan view of mining area of a Copper Mine

When compared with the low-concentration and hydraulic backfill, the paste backfill has obvious non-Newtonian fluid characteristics, wherein research on its rheology is particularly important and significant to the slurry preparation and delivery and other processes [4-7]. The key to research on paste rheological behaviors lies in experimental test tools and methods, which comprised a direct and indirect method at present [8]. The direct method adopts the rotational viscometer for measurement [9-10] and is simple, but the slip effect may occur between the rotating element and test sample, especially when the coarse aggregate is present and the measurement error is often large [11-14]. The indirect method estimates the rheological parameters from the test data on several diameters, while the results obtained are close to actual values, but it has several disadvantages, such as the large labor intensity, high cost, and so on [15-16]. Some researchers adopted inclined pipe and L-pipe and other test methods [17-18] to measure the slurry flow in unit time and calculated its rheological parameters, while the accuracy of conclusions obtained from the method is between what was obtained from the rheometer test and the pipe loop test. The delivery through the long-distance paste slurry pipeline has a higher requirement for paste pressure loss [19-20] to guarantee the reflection of actual situation of pressure loss. Therefore, the rule for impact of mass concentration, cement content, conveying pipe diameter and conveying volumetric flow rate on delivery pressure loss of paste slurry was obtained through round-pipe test in this paper to determine the conveying parameters of paste slurry for major ore body of a copper mine and implement the scheme design and engineering application of the conveying pipeline.

2. Experiment

2.1. Experimental principle

Paste slurry is characterised by high mass concentration with no segregation or water release and its rheological properties are different to that of solid-liquid phase flow and Newtonian fluids, so the paste slurry is generally regarded as non-Newtonian fluid [6,11-13]. Others[19-21] regard paste slurry as a homogeneous fluid and the slurry presents the plug flow in pipeline, and the paste flow behavior can be described by Hershel-Bulkey model in general. Paste has a certain initial shear deformation resistance capacity, i.e., yield stress. The stress analysis of paste slurry delivered in pipeline, is shown in Fig. 2, where *D* is pipeline inside diameter, *R* is pipeline radius, τ is shear stress and v is slurry volumetric flow rate.

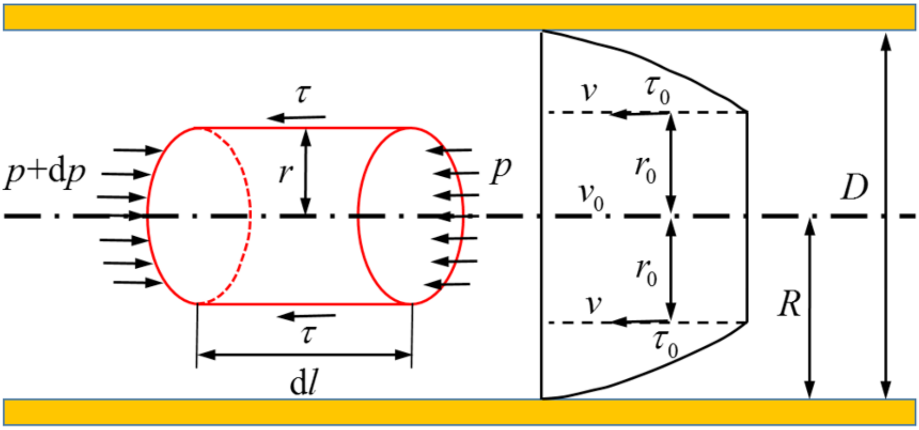

Fig. 2. Force analysis of paste slurry in a pipeline

Suppose differential pressure d*p*, length d*l* and radius *r* are the infinitesimal elements of cylindrical slurry to establish the stress equation of paste slurry in accordance with pipe flow hydrostatic equilibrium theory:

$$(p + \mathrm{d}p)\pi r^2 = p\pi r^2 + \tau \cdot 2\pi r \cdot \mathrm{d}l \tag{1}$$

Then:

$$\tau = \frac{r}{2} \cdot \frac{\mathrm{d}p}{\mathrm{d}l} \tag{2}$$

When the paste slurry is delivered in pipeline, $r = R = D/2$ and the delivery resistance of slurry pipeline is equal to the wall shear stress τ_w when the slurry flows:

$$\tau = \frac{D}{4} \cdot \frac{\mathrm{d}p}{\mathrm{d}l} \tag{3}$$

$\mathrm{d}p/\mathrm{d}l$ is the slurry resistance in unit pipeline length during pipeline delivery, i.e., pressure loss of pipeline delivery. Therefore, the resistance change rule of slurry in pipeline delivery process can be obtained through research on the impact factor and rule of $\mathrm{d}p/\mathrm{d}l$.

2.2. Experimental materials

The test material is whole-tailings paste, which is composed of whole-tailings, cement and water through mixing. The whole-tailings is 2.67 t/m^3 in density, 1.39 t/m^3 in volume weight, and 47.87% in porosity. As shown in Fig. 3, the contents of tailings whose size under –74 μm and 37 μm are 70.8% and 46.9%, respectively, while the tailings size is excessively small. The P.O 32.5 cement produced by Lafarge in Ndola and tap water for production are adopted for the test.

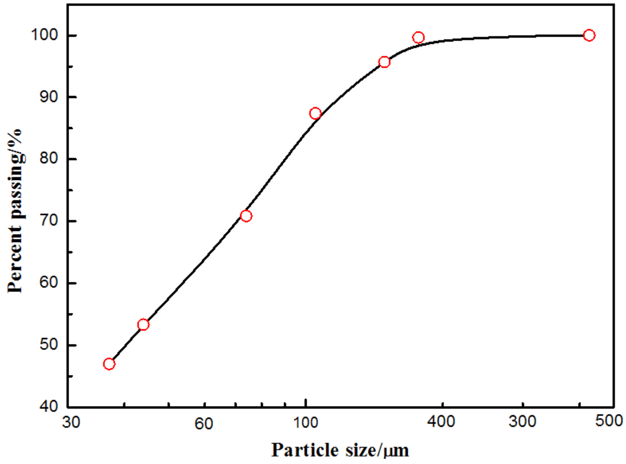

Fig. 3. Grain size distribution of unclassified tailings

2.3. Experimental device

2.3.1. Composition of pipe loop system

The pipe test loop comprises a tailings thickening system, paste preparation and pumping system, a pipeline and circulating pipeline and data acquisition system, and so on, among which the thickening and preparation and pumping system adopts the existing facilities of the filling station and circulating pipeline, which is arranged in accordance with test requirements, as shown in Fig. 4.

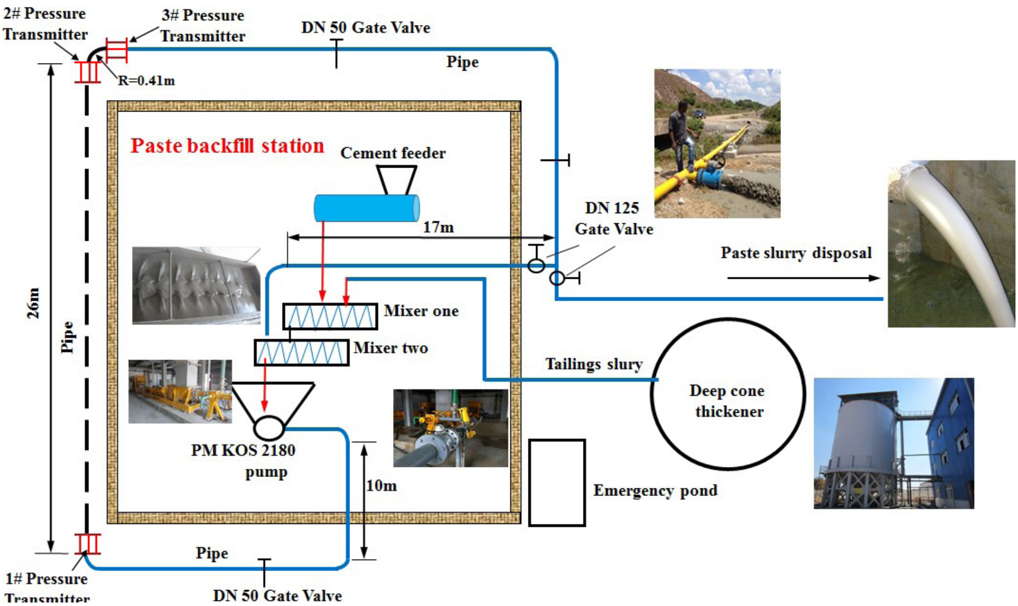

Fig. 4. Diagrammatic sketch of paste slurry transportation pipe loop test platform

As shown in Fig. 4, the tailings slurry, after being thickened by the deep-cone thickener, is delivered into a stirred tank for two-stage agitation with cement and pumped by ram pump into round-pipe and flows circularly in the pipeline before returning to the stirred tank. The pipe loop test system comprises three types of pipelines, whose inside diameters are Φ108 mm, Φ124 mm, and Φ150 mm. The pipeline, which is about 80 m in length (Fig. 5), connects to the filling ram pump and surrounds the wind preparation station for a circle before returning to the two-stage stirred tank. In the test, two pressure transmitters spacing 26 m are provided and are connected to the DCS (distributed control system) in the central control room through a communication cable. The distributed control system is applied for controlling cement addition and paste stirring, filling and pumping in the test. The Φ11 m deep-cone thickener is adopted for tailings thickening, for which the maximum under flow mass concentration is 71% to 72%. The nuclear concentration meter and flow meter are mounted on the discharge pipe at the bottom of thickener and pump outlet pipeline, for real-time monitoring of the concentration and flow of underflow and the paste in the deep-cone thickener.

2.3.2. Paste slurry preparation

Two-stage horizontal stirring (Fig. 6) is adopted for the paste, with the volume of 4.6 m^3 and rated preparation capacity of 75 m^3/h for a single stirred tank. The cement addition and measurement is controlled by a TS series powder scale, which has the maximum feeding flow rate of 33 t/h and a feeding error of lower than 5 kg/h. The KOS 2180 HP pump manufactured by Putzmeister was adopted for filling, with the working pressure of 6.9 MPa and rated flow of 60 m^3/h.

Fig. 5. Pipe for pipe loop experiment

Fig. 6. Paste slurry in mixer (wt.70.4%)

2.3.3. Detecting instruments

As shown in Fig. 7, the OPTIFLUX 4300C flow meter manufactured by KROHNE was adopted for system flow monitoring and was placed at the outlet of the positive displacement piston pump. The paste concentration was detected by the Thermo nuclear densimeter, which was placed at the outlet of ram pump. The pressure monitoring was conducted by a diaphragm-type smart pressure transmitter, which has a measuring range of 0 to 14 MPa, as shown in Fig. 8. The monitoring data above is transmitted through a communication cable to the DCS room for uniform collection purposes.

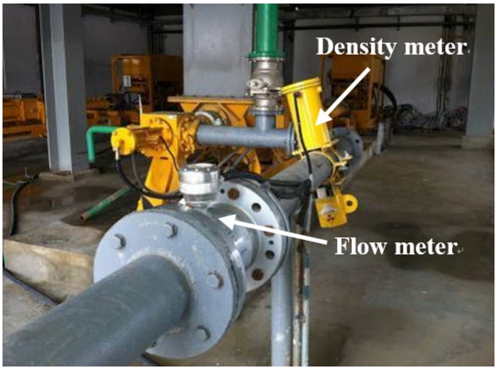

Fig. 7. Density meter and flow meter

Fig. 8. Smart Pressure Transmitter

2.3.4. Data acquisition and processing

The data acquisition instrument is used for data acquisition during the test, which includes slurry concentration, flow, pressure, and so on. Fig. 9 shows the pressure data within a certain period of time during the test (sampling frequency: once per second) and the piston pump has reciprocating motion characteristics and the paste pressure in pipeline is discontinuous, in which the pressure data is fluctuating. Therefore, selecting an appropriate data processing method for the analysis of test results is crucial. In the research, the test data is subject to statistical description by use of SPSS and in accordance with statistics principles and deductive statistical analysis principles, the analysis and extraction of descriptive index is capable of reflecting pressure data adequately. Results show that the pressure data basically satisfies the normal distribution and the median may be selected for the statistic of central tendency of data. PT0102 and PT0104 in Fig. 9 are the numbers of 1# pressure transmitter and 2# pressure transmitter during data collection.

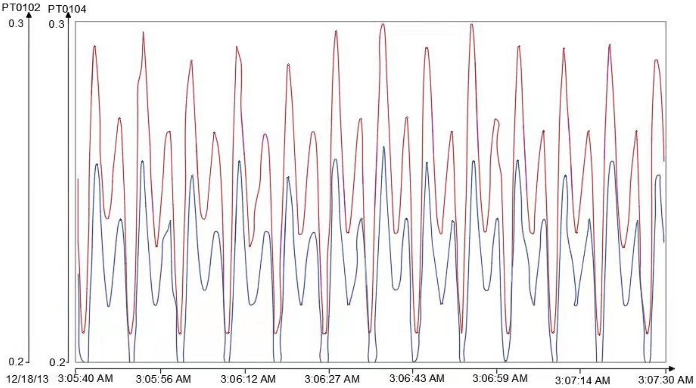

Fig. 9. Pressure monitoring data

2.4. Experimental scheme and experimental procedures

2.4.1. Experimental scheme

During the test, the effect of paste concentration, cement content and pipe diameter and other factors on pipeline pressure loss was taken into account. See Table 1 for the specific test scheme, which involves in nine groups of tests. Each group of experiments were conducted when the diameter of the pipe was Φ108 mm, Φ124 mm, and Φ150 mm.

TABLE 1

Experimental scheme

Test number	Mass concentration /%	Density /(t/m^3)	Volume concentration /%	Cement content /%	Volumetric flow rate /(m^3/h)	Test content
1	71.8	1.862	48.81	11	12~60	The influence of concentration on pressure loss
2	70.8	1.801	47.59			
3	69.6	1.781	46.16			
4	68.8	1.756	45.23			
5	67.8	1.743	44.09			
6	70.80	1.781	47.59	0	12~60	The influence of cement content on pressure loss
7	71.01	1.804	47.85	6		
8	71.26	1.810	48.15	8		
9	71.65	1.821	48.63	11		

2.4.2. Experimental procedures

Concentration regulation: During the test, the resistance test is conducted for high concentration slurry. After the test is completed, the high concentration slurry is diluted by water for the concentration regulation before the next group of tests. The specific test procedures are shown as follows:

(1) Observe the nuclear densimeter at the bottom of deep-cone thickener. When the underflow concentration reaches the design value, open the relevant valves on the discharge pipeline to discharge it into the stirred tank and start the powder scale at the same time to feed cement in accordance with the mix design.
(2) Start the one-stage and two-stage mixers to mix the ore pulp and cement in the stirred tank uniformly. If the paste in the stirred tank reaches a certain amount (approximately 75% of the stirred tank's volume), stop feeding the tailings and cement.
(3) Start the piston pump to pump the paste in the round-pipe circularly and collect the monitoring data of various pressure transmitters through the DCS system in the process.
(4) The group of tests is completed after operation for 15 min. Then, dilute the paste with water from the clean water pipeline at the top of the stirred tank, while the water addition shall be calculated in advance and under strict control during the test, to prevent ex low slurry concentration.
(5) After the aforementioned slurry is mixed uniformly in the stirred tank, start the piston pump to conduct the pumping pressure test in accordance with previous steps, and the slurry concentration may be subject to real-time monitoring by the density meter at the pump outlet or determined through manual sampling.
(6) Dilute it with water and conduct the next group of tests after the group of test is completed.

Flow and volumetric flow rate regulation: The system conveying volumetric flow rate can be controlled by regulating the pump speed. The pump speed and flow basically have a linear relationship and the corresponding flow and volumetric flow rate under various pump speed conditions are shown in Table 2.

TABLE 2

Relationships between flow/flow velocity of paste slurry and pump speed

Pump speed	20%	40%	60%	80%	100%
Volumetric flow rate /(m^3/h)	12.00	24.00	36.00	48.00	60.00
Flow velocity /(m/s)	0.276	0.552	0.828	1.105	1.38

3. Results and discussion

3.1. The influence of concentration on pressure loss

Fig. 10 shows the pipe loop test results of the paste concentration's impact on pressure loss. According to Fig. 10, the pressure loss increases with the increase in paste mass concentration and flow and is in the range of 1500 to 4000 Pa/m under test conditions. Meanwhile, the concentration has a significant impact on pressure loss: if the concentration is as low as 67% to 70%, the pressure loss changes slightly, but when the mass concentration exceeds 70%, the pressure loss increases sharply.

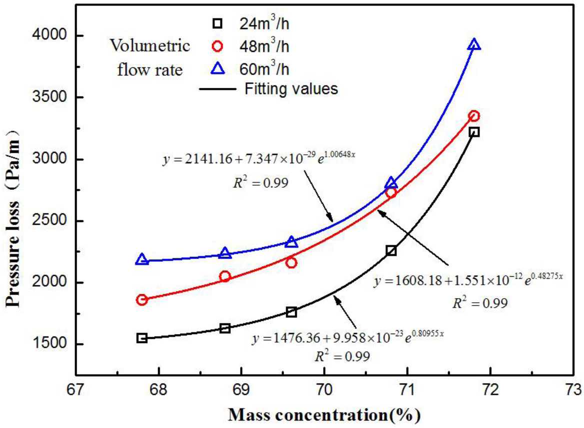

Fig. 10. Relationships between slurry mass concentration and pressure loss

3.2. The influence of cement content on pressure loss

Fig. 11 shows the relationship on the effect of cement content on pressure loss for a range of volumetric flow rates when the paste mass concentration is 70% and the pressure loss ranges from 3000 Pa/m to 4000 Pa/m. Fig. 11 shows that at the same paste mass concentration, with the increase in cement content, the pressure loss first decreases then increases. When the cement content is 8%, the pressure loss reaches the lowest value and gradually increases when the cement content exceeds 8%. This is because the addition of cement fine particles changes the gradation of

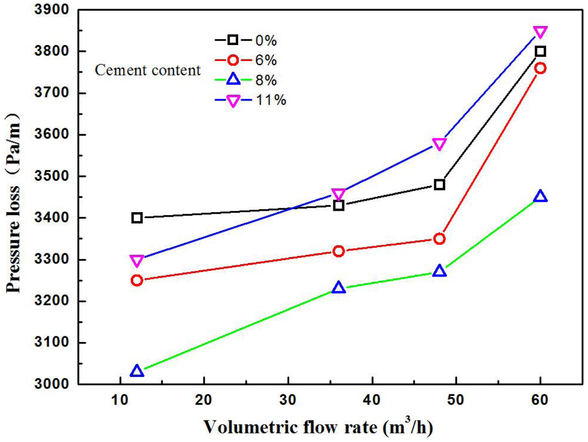

Fig. 11. Relationships between slurry flow and pressure loss

paste materials in a certain range, and changes the rheological properties and slip characteristics of paste to a certain extent [22]. With the same cement content, paste pressure loss increases with the increase in conveying volumetric flow rate. When the pipe diameter is Φ124 mm, when the paste conveying flow exceeds 50 m^3/h, the pressure loss value increases greatly.

3.3. Influence of pipe diameter on pressure loss

For the purpose of studying the rule for pressure loss of paste slurry in pipelines of various diameters, the pipe loop test deals with three pipeline diameters: 108 mm, 124 mm, and 150 mm. Fig. 12 is the pressure loss curve of the same slurry in various pipe diameters and shows that the pressure loss in pipeline conveying of slurry decreases sharply with the increase of pipe diameter, i.e., the larger pipe diameter, the lower pressure loss. Therefore, the pressure loss in pipeline conveying may be reduced through the increase in pipeline diameter in the conveying process, to archive the longer conveying distance.

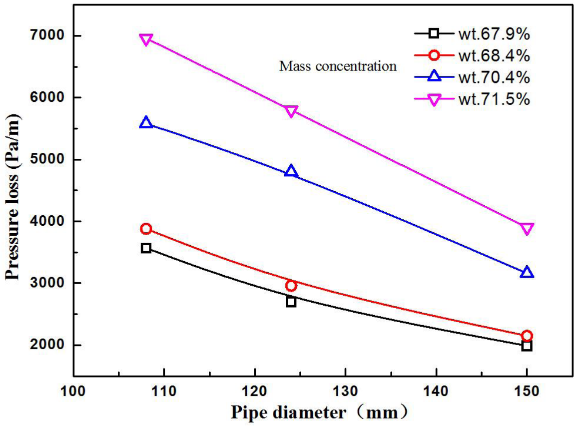

Fig. 12. Relationships between pipe diameter and pressure loss

4. Project design and engineering application

4.1. Determination of pressure loss

The pipe loop test results show that the mass concentration has the greatest effect on paste delivery pressure loss, followed by conveying pipe diameter, and the cement content has the least effect on it. Therefore, the pipeline of the large inside diameter shall be adopted as far as possible when the concentration is not changed, to ensure the smooth long-distance delivery of paste slurry for the major ore body of a copper mine. For this reason, the conveying pipeline of the 150 mm inside diameter is chosen preliminarily and based on which the paste conveying pipeline and appropriate conveying concentration are determined. Table 3 shows the pressure loss of paste slurry at various concentrations.

TABLE 3

Pressure loss of paste slurry at different mass concentration (inside diameter:150 mm)

Mass concentration /%	67	68	69	70	71	72	73
Resistance loss /(MPa/km)	2.05	2.18	2.25	2.55	3.04	4.32	8.09

4.2. Scheme for paste conveying line

The paste conveying pipeline comprised the surface horizontal section, inclined section in open pit, and the underground pipeline, with the total conveying distance of 5600 m, i.e., surface conveying distance of 2985 m and underground conveying distance of 2615 m. The surface conveying line is shown in Fig. 13.

Fig. 13. Surface conveying line of paste slurry for major ore body

The paste conveying pipeline is shown in Fig. 14: paste filling station→1928 m in distance and 20 m in altitude difference; open pit entrance → slope ramp entrance, 1057 m in distance and 114 m in altitude difference; belt road entrance→200 ml group A drill hole, 456 m in distance and 84 m in altitude difference; 200 ml group A drill hole→300 ml group B drill hole, 182 m in distance and 100 m in altitude difference; 300 ml group B drill hole→400 ml group C drill hole, 571 m in distance and 100 m in altitude difference; 400 ml C group drill hole→500 ml segmented roadway, 261 m in distance and 100 m in altitude difference; 500 ml segmented roadway→600 ml segmented roadway (passing through 1470 pipes and cable shafts), 160 m in distance and 100 m in altitude difference; 600 ml segmented roadway→683 ml segmented roadway (passing through 1470 pipes and cable shafts), 111 m in distance and 83 m in altitude difference; 683 ml segmented roadway→704 ml segmented roadway (passing through 1440 pipes and cable shafts), 46 m in distance, and 21 m in altitude difference; 704 ml segmented roadway→770 ml segmented roadway (passing through 1440 pipes and cable shafts), 78 m in distance and 66 m in altitude difference; 770 ml segmented roadway→800 ml segmented roadway (passing through 1440 pipes and cable shafts), with the horizontal distance of 720 m to #49 stope of line 2060 and of 285 m to #12 stope of line 1260 and 30 m in altitude difference; 800 ml segmented roadway→829 ml segmented roadway (passing through 1440 pipes and cable shafts),with the horizontal distance of 730 m to #49 stope of line 2060 and of 292 m to #12 stope of line 1260 and 29 m in altitude difference.

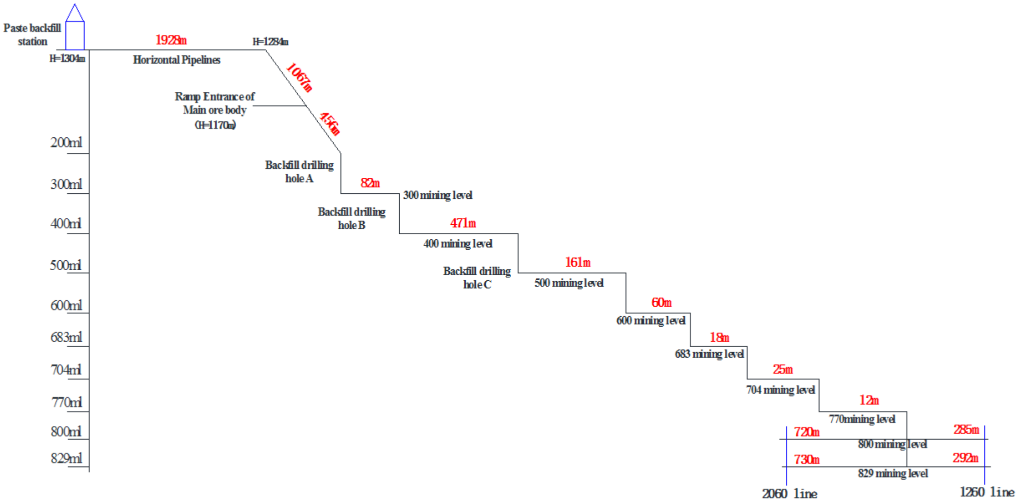

Fig. 14. Schematic diagram of paste conveying pipeline

4.3. Pressure distribution calculation

The paste delivery pump for the major ore body adopted the existing KOS 2180 HP ram pump, which has a maximum working pressure of 6.9 MPa. Therefore, the appropriate slurry conveying concentration shall be determined through pressure distribution calculation to prevent pipeline blockages and other accidents resulting from when the conveying pressure exceeds the maximum working pressure of the pump.

4.3.1. Calculation principle

(1) The slurry has a certain potential energy in the vertical pipe, which is called a natural pressure head, as it ensures the slurry transportation with gravity within a certain range and can be calculated in accordance with the formula below:

$$P_N = \rho g H / 1000 \tag{4}$$

where P_N the is natural pressure head, MPa; ρ is slurry density, 1.8 t/m^3 based on the previous test; g is acceleration of gravity, 9.8 m/s^{-2}; and H is slurry height, m;

(2) The local resistance loss and other factors shall be taken into account during the calculation
(3) The pipeline's inside diameter is 150 mm and the paste pressure loss at various mass concentrations is selected in accordance with Table 3 in the calculation process.

4.3.2. Calculation result

Based on the conveying line in Fig. 14 simplified, the pressure distribution on conveying pipeline, when the paste mass concentration is 70% and 71%. The pipeline pressure loss is 2.55 MPa/km when the mass concentration is 70%, so the minimum delivery pressure should be offered by the pump is 4.45 MPa after calculation, to deliver the slurry to the stope on line 2060 at the level of 829 ml. If the mass concentration is 71% and the pipeline pressure loss is 3.04 MPa/km, the minimum delivery pressure that should be offered by the pump is 8.44 MPa after calculation, to deliver the slurry to the stope on line 2060 at the level of 829 ml. The maximum delivery pressure of the existing KOS 2180 HP ram pump is 6.9 MPa and it cannot ensure to deliver the paste to the underground stope smoothly after the paste mass concentration exceeds 70% to 71%, in which the paste conveying concentration shall not exceed 70%, but it must be greater than 67%.

4.4. Engineering application

According to experimental research and theoretical calculations, the parameters of the paste conveying scheme for the major ore body of the copper mine are determined as that the paste mass concentration is lower than 70% (pressure loss: 2.55 MPa/km), the cement content is 5% to 11%, the conveying pipe diameter is 150 mm, the maximum allowable pipeline pressure is 6 MPa, and the total conveying distance is 5600 m, i.e., the surface conveying distance of 2985 m and underground conveying distance of 2615 m. According to Fig. 15, the paste conveying through surface horizontal pipeline has the greatest difficulty and potential risk in pipe blockage in the paste conveying process, in which a quick coupling is used to connect the surface pipeline lengths to facilitate the rapid handling of pipe blockages. Three emergency discharge points are provided on the surface to facilitate the rapid discharge of slurry, as shown in Fig. 15(a). The paste slurry


(a) Emergency discharge point (b) Paste discharge (c) After stope paste condensation

Fig. 15. Photos of paste conveying site

has good mobility after being delivered into the shaft (Fig. 15(b)) and achieves a good goaf filling, while the paste, after consolidation and setting (Fig. 15(c)), improves the working environment for underground mining and ore recovery ratio.

5. Conclusion

(1) The mass concentration has a significant effect on pressure loss: if the concentration is as low as 67% to 70%, the pressure loss changes slightly, but when the mass concentration exceeds 70%, the pressure loss will increase sharply and will be an exponential function of paste mass concentration.

(2) At the same paste mass concentration, with the increase in cement content, the pressure loss first decreases then increases. When the cement content is 8%, the pressure loss reaches the lowest value, and gradually increases when the cement content exceeds 8%. With the same cement content, the paste pressure loss increases with the increase in the conveying volumetric flow rate. When the pipe diameter is Φ124 mm, when the paste conveying flow exceeds 50 m^3/h, the pressure loss value increases significantly.

(3) The pressure loss of paste slurry decreases linearly with the increase in pipe diameter, i.e., the larger pipe diameter, the smaller the pressure loss would be.

(4) According to the round-pipe test and theoretical calculations, the parameters of the paste conveying scheme for a major ore body of a copper mine are determined as that the paste mass concentration is greater than 67%, but lower than 70% (pressure loss: 2.55 MPa/km), in which the cement content is 5% to 11%, while the conveying pipe diameter is 150 mm and the maximum allowable pipeline pressure is 6 MPa.

Acknowledgments

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