

Strength and fluidity of cemented paste backfill at Qijiaoqing Iron Mine, Northwest China

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Abstract

Open stope mining with sequent backfilling was the major method adopted at Qijiaoqing Iron Mine, and mix proportions of backfill materials were performed to produce the industrially required cemented paste backfill (CPB). The materials mainly comprise unclassified extra-fine tailings, waste rocks and Portland cements, and the experiments of the mix proportions followed the $L_{16} (4^5)$ orthogonal design. The results showed that contents of -20 and -37 μm extra-fine grains within tailings accounted for 54 and 69wt%, respectively. The range analysis of orthogonal experiments shows that mass concentration, tailing-waste ratio and waste-cement ratio are the most to least sensitive factors to the slurry slump, 3-day and 7-day strengths. For 28-day strength, the sensitive variables are sequentially mass concentration, waste-cement ratio and tailing-waste ratio. Additionally, the optimal mix proportion for cement paste backfill is obtained with a mass concentration of 78wt%, a tailing-waste ratio of 0.7 and a waste-cement ratio of 25. The slump and 28-day strength of the optimal CPB are 25.2 cm and 1.29 MPa, respectively.

1 Introduction

During the past few decades, cemented paste backfilling has been increasingly attractive for metal mines worldwide (Koohestani et al., 2016) as it is economical, safe and environmental friendly. It not only utilizes enormous waste rocks and tailings but also effectively fills the underground voids. Compared with backfill that uses traditional materials, the cemented paste backfill (CPB) features little separation, segregation and dehydration (Aldhafeeri and Fall, 2016) and is mainly used to prevent the collapse of roofs and pillars and to support a solid work platform in mined stopes. Therefore, its strength needs to be precisely designed to balance the safety effects and economic input. CPB is usually transported to underground voids using piston pumps, and due to its high concentration and great resistance, its fluidity is strictly required. Hence, strength and fluidity are key preconditions for the implementation of cemented paste backfilling.

Qijiaoqing Iron Mine is located in Gobi desert in northwest China at an altitude of 2300 m and with an iron reserve of over 110 million tons. Ores are extracted using sublevel open stoping with subsequent backfilling. The combined effects of pillar and backfilling materials control the ground pressure, and therefore the strength of CPB only needs to support itself with over 0.5 MPa required. In this work, attention has been paid to optimize the mix proportions of backfilling raw materials to produce the CPB with satisfactory fluidity and strength. Firstly, a batch of orthogonal experiments on the mix proportions of CPB are carried out using unclassified raw ultra-fine tailings, waste rocks and cements. Secondly, range analysis is conducted to investigate the sensitivities of independent variables to dependent variables. In this case, the independent variables include slurry mass concentration, tailing-waste ratio and waste-cement ratio, and the dependent variables include paste slump and strength. Furthermore, the optimal mix proportion of CPB with targeted properties is proposed according to the regression analysis. The work shows a feasible way to produce the industrial standard CPB for Qijiaoqing Iron Mine.

2 Methods and materials

2.1 Materials

The unclassified tailings were directly sampled from the discharge pipes of the processing plant. The laser particle analyzer showed that the gradations below 20, 37 and 74 μm were 54, 69 and 87%, respectively. The chemical analysis revealed that the tailings contained 50.63% SiO_2 , 25.54% Fe_2O_3 , 9.39% CaO , 5.39% MgO , 2.72% Al_2O_3 and 1.92% SO_3 ; despite a relatively wide range of distribution of the tailings grain size, a smooth and continuous distribution was also observed (Figure 1).

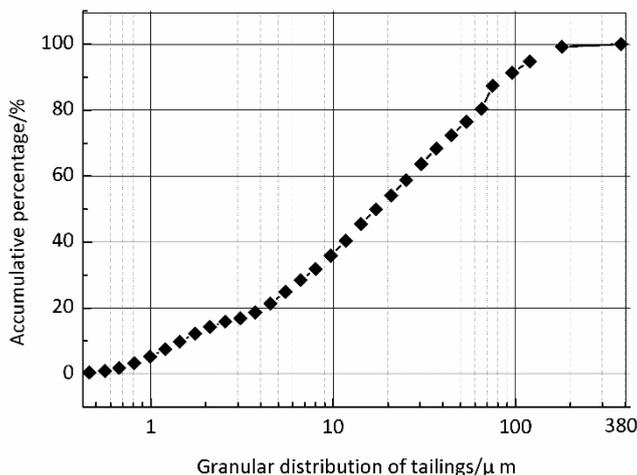


Figure 1 The granular distribution of the tailings at Qijiaoqing Iron Mine

Waste rocks mined out from underground stopes were milled to -5 mm before being delivered to the processing plant. The X-ray fluorescence test showed that the composition of rocks were similar to that of tailings. The 32.5R Portland cement chosen as the binder to produce the CPB was supplied from a local cement plant and has a specific surface area of $380\text{ m}^2/\text{kg}$ and specific gravity of $3050\text{ kg}/\text{m}^3$.

2.2 Experimental scheme

Following the orthogonal approach (Suttaphakdee et al., 2016), a total of 16 mix proportions of CPB were designed according to the $L_{16}(4^5)$ orthogonal array (Table 1). Slurry mass concentration, tailing-waste (waste means tailings and rocks) ratio and waste-cement ratio were designed as the independent variables, whereas slurry slump, uniaxial compressive strength (UCS) on day 3 (R3), 7 (R7) and 28 (R28) were taken as dependent variables. Slurry mass concentrations were in the range of 77~80wt%, the tailing-waste ratio of 0.7~0.9, and the waste-cement ratio of 15~30.

Table 1 Orthogonal design of CPB mix proportions

Mixture	Density (wt%)	tailing-waste ratio	waste-cement ratio	Mixture	Density (wt%)	tailing-waste ratio	waste-cement ratio
1	77	0.9	30	9	79	0.9	20
2	77	0.85	25	10	79	0.85	15
3	77	0.8	20	11	79	0.8	30
4	77	0.7	15	12	79	0.7	25
5	78	0.9	25	13	80	0.9	15
6	78	0.85	30	14	80	0.85	20
7	78	0.8	15	15	80	0.8	25
8	78	0.7	20	16	80	0.7	30

All mixtures were prepared according to the designed mix proportions of tailings, rocks, cement and water. After testing the slumps, each mixture was divided into nine duplications, each placed into a cylinder steel mould, 80 mm in diameter and 200 mm in height, and cured for 24 hours at ambient temperatures. All mixtures were then moved to the curing room at 30°C and with a relative humidity of 95%. At 3-day, 7-day and 28-day intervals, three samples for each concreted mixture were cut for UCS tests into standard test specimen 80 mm in diameter and 160 mm in height.

The slurry slump testing followed the national standard for test method of performance on ordinary fresh concrete (GB/T 50080-2002) (Ministry of Construction, 2003a). The UCS tests were carried out according to the national standard for test method of mechanical properties on ordinary concrete (GB/T 50081-2002) (Ministry of Construction, 2003b).

2.3 Analysis methods

Range analysis was introduced to understand the impacts of the key factors on the slumps and strengths of CPT. It provides a reliable way to select the best runs for each factor and the best mix proportions at initial parameters. The range R refers to the maximum difference value in each experimental run for each influential factor, given as follows:

$$R_j = \max K_r - \min K_r \tag{1}$$

where j is the sequence number of key factors, $j=1, 2, \dots, N$; r is the sequence number of the experimental run for each factor, $r=1, 2, \dots, M$; K_r is the average value of all runs of r for factor j .

The data processing system (DPS) software was introduced for the regression analysis of independent variables and dependent variables. A satisfying fitting effect of the experimental results usually requires the regression parameters to meet certain limits. For instance, the correlation coefficient R of the regression equation has to be higher than 0.9 and significant level p lower than 0.05.

3 Results and discussion

3.1 Range analysis of slump and strength

The range analysis of slurry slumps (Table 2) shows a wide diversity of ranges for the three independent variables. Unsurprisingly, mass concentration (referred to as a in Table 2), whose range R is 15.4, is the most sensitive factor to influence the slurry slump. The second and the third sensitive factors are respectively tailing-waste ratio (referred to as b , $R=8.0$) and waste-cement ratio (referred to as c , $R=3.6$). Therefore, the best run for the above three influential factors is 77wt% mass concentration, tailing-waste ratio of 0.7 and waste-cement ratio of 25.

Table 2 Range analysis of slurry slump and CPB strength

Range Analysis	Slump(cm)	R3(MPa)	R7(MPa)	R28(MPa)
range A	15.4	0.12	0.35	3.83
range B	8.0	0.09	0.22	0.19
range C	3.6	0.04	0.19	0.76
significance	A>B>C	A>B>C	A>B>C	A>C>B
best run	A1,B4,C2	A4,B1,C4	A4,B1,C4	A4,B3,C4
best mixture	A1B4C2	A4B1C4	A4B1C4	A4B3C4

Following the same analytical approach, the results of the range analysis indicate that mass concentrations dominant the sensitivity to R3, R7 and R28. However, although tailing-waste ratio is the second sensitive factor to R3 and R7, it turns out to be the third one to R28. From Table 2, the best optimum mix proportion for R3 and R7 can be derived as A4B1C4 (80wt%, tailing-waste ratio of 0.9 and waste-cement ratio of 15),

while the optimal combination is A4B3C4 (80wt%, tailing-waste ratio of 0.8 and waste-cement ratio of 15) for R28.

Furthermore, the regression analysis quantitatively demonstrates the relationships between independent and dependent variables. The slurry slump y_1 , the 3-day uniaxial compressive strength (R3) y_2 , R7 y_3 and R28 y_4 can be predicted using the following equations (Equations 2 to 5). All regression equations show high correlation coefficients, indicating satisfying fitting effects of experimental results.

$$y_1 = 5810.2 - 162.4x_1 + 1601.8x_2 + 12.5x_3 + 1.14x_1^2 + 19.7x_2^2 - 0.03x_3^2 - 21.7x_1x_2 - 0.2x_1x_3 + 0.8x_2x_3 \quad (2)$$

$$y_2 = 5206 - 1.23x_1 - 13.8x_2 + 0.028x_3 + 0.007x_1^2 + 0.19x_1x_2 - 0.04x_2x_3 \quad (3)$$

$$y_3 = 477.7 - 12.6x_1 + 9.4x_2 + 0.85x_3 + 0.008x_1^2 - 4.91x_2^2 - 0.01x_1x_3 - 0.05x_2x_3 \quad (4)$$

$$y_4 = 3215.3 - 83.9x_1 + 30.9x_2 + 1.8x_3 + 0.55x_1^2 - 21.1x_2^2 - 0.02x_1x_3 + 0.04x_2x_3 \quad (5)$$

where x_1 is the mass concentration of CPB; x_2 is the tailing-waste ratio; x_3 is the waste-cement ratio; when the correlation coefficient $R=0.99$, the significant level $p=0.0001<0.05$ in Equation 2; when the correlation coefficient $R=0.91$, the significant level $p=0.0044<0.05$ in Equation 3; when the correlation coefficient $R=0.98$, the significant level $p=0.0006<0.05$ in Equation 4; when the correlation coefficient $R=0.98$, the significant level $p=0.0001<0.05$ in Equation 5.

3.2 Optimization of mix proportions

An ideal mix proportion of CPB must simultaneously meet the slump and strength standards. To obtain a fluent fluidity during pumping, the slurry slump is always restricted within 23~26 cm. The use of open stope mining with sequent backfilling and the relatively long transfer period from the lower stage to the upper stage (usually several months) makes the 3-day and 7-day strengths less favorable choices. Hence, 28-day strength is designed to be a primary factor, and it only has to be higher than 0.5 MPa.

As the range analysis indicated, mass concentration is the most significant independent variable in all cases. When the tailing-waste ratio is 0.7 and the waste-cement ratio is 25, slump slurry decreases as the mass concentration increases, while R28 shows a rising trend during the same period (Figure 2). Considering the favorable slump ranges, 78wt% mass concentration is an optimal value.

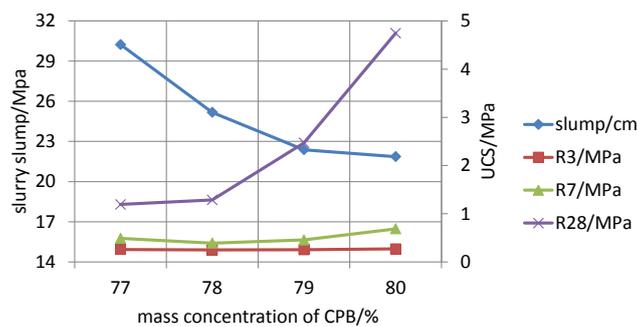


Figure 2 The variations of slurry slump and CPB strengths as mass concentration increases

When the mass concentration is 78wt% and the tailing-waste ratio is 0.7, all slurry slumps meet the industrial standards within the experimental ranges of waste-cement ratios (Figure 3). However, with the increase of waste-cement ratio, R28 linearly decreases to only 1.09 MPa at the waste-cement ratio of 30. To reduce the consumption of expensive cements, the waste-cement ratio of 25 becomes a balanced alternative between the slurry slump and R28.

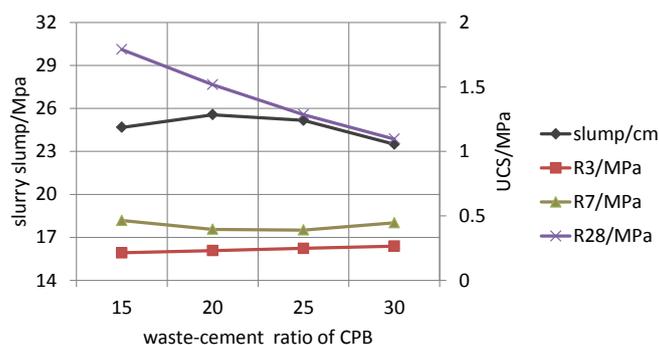


Figure 3 The variations of slurry slump and CPB strengths as waste-cement ratio increases

When mass concentration is 78wt% and the waste-cement ratio is 25, an increase in the tailing-waste ratio results in a dramatic decrease in the slump slurry (Figure 4). Under this trend, CPB becomes hardly pumpable when the tailing-waste ratio is greater than 0.7. Additionally, R28 shows a slight rise when the tailing-waste ratio is below 0.8 but sees a rapid decrease afterwards. Therefore, the optimal tailing-waste ratio is 0.7.

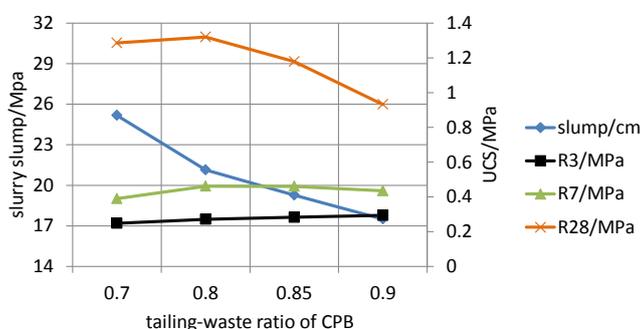


Figure 4 The variations of slurry slump and CPB strengths as tailing-waste ratio increases

Hence, the optimal mix proportion of CPB is 78wt% mass concentration, tailing-waste ratio of 0.7 and waste-cement ratio of 25. With this precondition, the slurry slump is predicted to be 25.2 cm, and 28-day uniaxial compressive strength achieves 1.29 MPa, with which the open stope mining with sequent backfilling can be employed safely and relatively economically.

4 Conclusions

Tailings at Qijiaojing Iron Mine have a relatively wide range as well as a smooth and continuous distribution, and are classified as ultra-fine tailings with 54wt% -20 μm grains. For open stope mining with sequent backfilling method, the CPB that meet the industrial standards can be produced with ultra-fine tailings, -5 mm waste rocks and Portland 32.5R cement.

The range analysis of orthogonal experiments shows that the mass concentration, tailing-waste ratio and waste-cement ratio are the most to the least sensitive factors to slurry slump, 3-day and 7-day strength. For the 28-day strength, the sensitive variables are sequentially mass concentration, waste-cement ratio and tailing-waste ratio.

The optimal mix proportion for cement paste backfill with extra-fine unclassified tailings is obtained with a mass concentration of 78wt%, a tailing-waste ratio of 0.7 and a waste-cement ratio of 25. The slump and 28-day strength of CPB are 25.2 cm and 1.29 MPa, respectively.

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