Quality Evaluation of Cemented Backfill Mass Based on Segregation Degree Analysis: a Case Study of a Real Mine

Xiaopeng Peng[1,2], Lijie Guo[1,2]*, Guangsheng Liu[1,2], Xiaoming Wei[1,2], and Lei Zhang[1,2]

[1]Beijing General Research Institute of Mining and Metallurgy, Beijing 100160, China

[2]National Centre for International Research on Green Metal Mining, Beijing 102628, China

*Correspondence: guolijie@bgrimm.com

Abstract

The quality of cemented backfill mass is of great importance for utilizing mining with backfill method, thus the quality evaluation of backfill mass has long been the research focus for researchers and engineers of mining. Generally, the evaluation can be analyzed based on the strength value fluctuation of the samples drilled from *in situ* backfill, which can demonstrate the peak strength value or the position of weak quality areas, while the essential causes leading to the changes and distribution cannot be acquired. Therefore, in this study the quality evaluation method based on segregation degree analysis, which mainly utilizes the measurement results of cemented contents and porous properties of samples, has been described. Based on this method, the strength distributions and segregation indexes of cemented backfill samples of a real mine have been analyzed, and the following results have been determined:

1. The cement content increases gradually along the drilling hole, while the porosity has a fluctuating trend, which are all different from the strength distribution.
2. The strength of the sample is not just determined by cement content but also is coupled and affected by porous properties.
3. By analyzing the segregation properties of drilled samples, some optimization suggestions about the particle size distribution of backfill materials can be gained.

Key words: mining with backfill, cemented backfill, segregation, porous properties, paste backfill

Introduction

Mining with backfill has been widely used (Grice, 1998) as it can effectively dispose of solid wastes from mines, achieve the goals of backfilling mined-out stopes, increase ore recovery rates, and ensure safe production in the underground mining area (Belem and Benzaazoua, 2004, Yang et al., 2018). In the application of this method, the mechanical strength of the backfill mass (usually regarded as backfill strength) is of great importance as it must meet the specific requirements depending on its function in different mining methods (Belem and Benzaazoua, 2008, Sheshpari, 2015). Therefore, the backfill mass quality evaluation is usually be analyzed based on the values and distribution of the uniaxial compressive strength (UCS) of backfill samples drilled from *in situ* backfill mass; namely if the peak value is small or the fluctuation of drilled samples' strength is large the quality will be regarded as poor (Thompson, 2012, Peng, 2021).It is generally believed that the strength of backfill mass is primarily determined by the properties of the backfill materials (tailings, cementitious materials, and water) and the material ratio in the slurry (Henderson et al., 2005, Belem and Benzaazoua, 2008, Huang, 2014). Indeed, for specific mines that utilize backfill mining method, the strength of the backfill is mainly determined by the material ratio, which is typically expressed as the binder content (the proportion of cementitious materials in all solid materials) and the filling concentration of slurry (mass concentration, also known as filling concentration). With a constant filling concentration, a higher binder content results in a greater backfill strength. Similarly, with a fixed binder content, a higher slurry filling concentration leads to a greater backfill strength.

However, it needs to be considered that for tailings backfill slurry, when it has not reached the paste state (in China there are still some mines using cemented tailings backfill slurries), after being transported into the underground mining stope, the backfill materials will inevitably undergo sedimentation, settling and segregation (Belem et al., 2000, Benzaazoua et al., 2008, Liu, 2020, Peng, 2021), leading to the water bleeding from backfill materials and thereby increasing the actual concentration of the backfill mass. Moreover, during the backfill slurry flowing, the particle size distribution (PSD) of backfill materials will also be affected, namely that coarse particles will be more likely to gather near the discharge point while fine particles will gather further away from the discharge point (Deschamps et al., 2011, Peng, 2021, Yin, 2022). Consequently, due to bleeding the actual water-to-binder ratio between different backfill bodies will be significantly reduced. And because of the segregation of material particles, the distribution of cement will be more inhomogeneous. Thus, the segregation of tailings backfill slurries also has a considerable effect on backfill strength.

Therefore, evaluating the quality of *in situ* backfill solely based on the fluctuations and extreme values of the drilled samples' strength only highlights the superficial aspect. If the segregation characteristics of the *in situ* backfill mass can be empirically characterized, then the quality evaluation can be more quantitative. In this field, Fall et al. (2005) and Ke et al. (2016) investigated the impact of fine tailings segregation on the uniaxial compressive strength (UCS) of cemented backfill, and concluded that this segregation would affect the hydration cementation framework and the pore structure of the backfill; as a result, the area with more fine particles will have low structure strength. Yilmaz et al. (2009, 2014) described that the segregation of pore structures and porosities of cemented backfills can affect the structural responses during the UCS tests of samples and after that influence the strength.

In terms of the quantitative testing research on the specific segregation characteristics of cemented backfills, Peng et al (2021) conducted a detailed study of the heterogeneity of aggregates, cementitious materials, and pore structures of cemented backfill mass, and worked out a strength impact factor based on the degree of segregation to evaluate the quality of *in situ* backfill mass. This paper will draw on this evaluation method, and through the segregation characteristic tests of drilled backfill samples from a real mine the quality evaluation of the mine backfill mass will be analyzed. Additionally, the optimization suggestions for tailings' PSD of the backfill materials from the perspective of reducing segregation will be proposed.

Methodology

***In situ* core sampling method**

To evaluate the backfill mass quality of a real copper mine which utilizes the sublevel stoping with delayed backfill mining method, the core drilling is conducted on the stope backfill mass. Normally, a barrier wall (also called barricade) is designed to prevent the outflow of the filling slurry from the stope to tunnels. To ensure the stability of the backfill mass and the subsequent barricade, the bottom of the stope will be backfilled with high-cement-content slurry until it reaches a certain height above the barricade (Yilmaz and Guresci, 2017, Grabinsky et al., 2021, Guo et al., 2022) after which a low-cement-content fill is used to cut down the backfill budget. This section of high-cement-content filling is so called a ‘plug’ and as explained above is crucial for stope backfilling. Therefore, the sampling location is designed at the bottom of the stope near the barricade to obtain the core specimen of the plug area along the length of the stope by drilling (Figure 1).

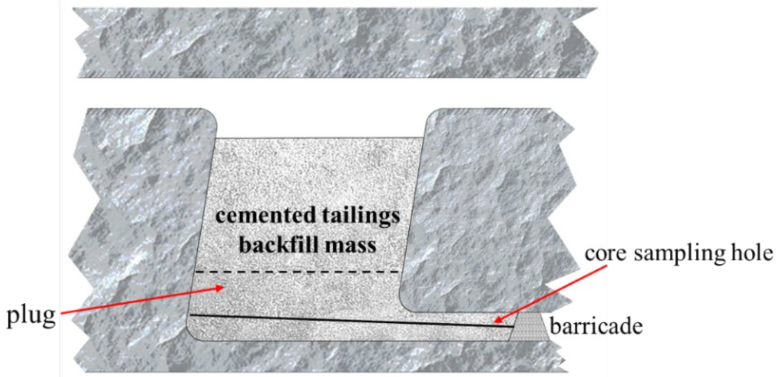

Figure 1. Schematic diagram of backfill mass core sampling design.

For the copper mine, the plug is made of cemented tailings backfill with a designed cement content of 20% and a filling concentration of 70%.

UCS test of drilled samples

By launching drilling sampling, an approximately 30 m *in situ* backfill mass samples were obtained. The drilled out *in situ* backfill core samples should be sealed by plastic to avoid exposure to air. Reprocess the obtained core samples and cut them into standard cylinder test specimen for UCS with a size of φ5×10 cm (diameter × height). During reprocessing, it should be ensured that at least two or more samples can be obtained within each 1 m drilling depth. After this, the UCS of each sample was measured using an HM-5030 uniaxial loader. The load cell of this apparatus has a measurement range of 0–50 kN and an accuracy of ± 0.01 kN, thus meeting the UCS testing accuracy requirements. The test specimens are shown as Figure 2.

Figure 2. The drilled CTB specimens test process, including: (a) the drilled core backfill mass, (b) UCS testing specimens, and (c) the testing apparatus.

Cement content test of drilled samples

To study the cement content variation of the backfill mass along flowing direction in stope, a set of samples are selected every 3 m (10 test specimens in total) from the obtained backfill cores for testing the cement content and characteristics of pore structures. The cement content of each sample was monitored via titration with EDTA-2Na, which is a standard cement content test method for cement-based materials (Peng et al., 2021, Chen et al., 2018). It is a chemical method that uses 10 wt% NH_4Cl solution to react with $Ca(OH)_2$, the main hydration product of cement, thus generating $CaCl_2$. By subsequently adding EDTA-2Na standard solution, the amount of Ca^{2+} produced from the dissolution of $CaCl_2$ can be titrated and measured, thereby indirectly reflecting the sample cement content. Chen et al. (2019) experimentally proved the applicability of this method on the cement content measurement of CTB.

Pore structures test of drilled samples

The porosities and pore structures of the obtained samples were tested using the MK-Autopore IV 9510 model automatic mercury intrusion porosimeter (MIP). This instrument presses liquid mercury into the sample under constant temperature and pressure conditions until a certain pressure is reached. By recording the cumulative curve of the pressure applied on the sample and the amount of mercury intruded, and utilizing the principle that the pore size through which liquid mercury can pass is proportional to the external pressure, the porosity and pore size distribution characteristics of the sample are obtained. Ke et al. (2016) and Sari et al. (2023) have utilized this method to analyze the pore structures of cemented paste backfill, proving the applicability for the backfill mass sample test. The measurement range of the mercury porosimeter is from φ0.003 to φ1000 μm, and the accuracy of the mercury intrusion and extrusion sensors is 0.1 μL, which can fulfill the needs of analyzing the pore structures of CTB samples.

Tailings PSD test

The PSD of mine tailings has a decisive impact on the segregation characteristics of the *in situ* backfill mass. Thereby, samples of backfill tailings from the copper mine were collected, and after air-drying and oven-drying, tests were conducted to determine their PSD. For the tailings portion with a particle size > 74 μm, the sieving method is used for testing, while for the tailings portion with a particle size < 74 μm, the Mastersizer 2000 laser particle size analyzer is employed. It has an entire measurement range of 0.02–2000 μm, which can match the requirements of the PSD test of tailings.

Results and Discussion

Strength distribution of drilling samples

Here, we summarize the strength values of the test specimens obtained from the *in situ* backfill mass. Base on the original positions corresponding to each specimen, the strength distribution diagram of the backfill mass in plug area along slurry flowing direction can be derived (Figure 3).

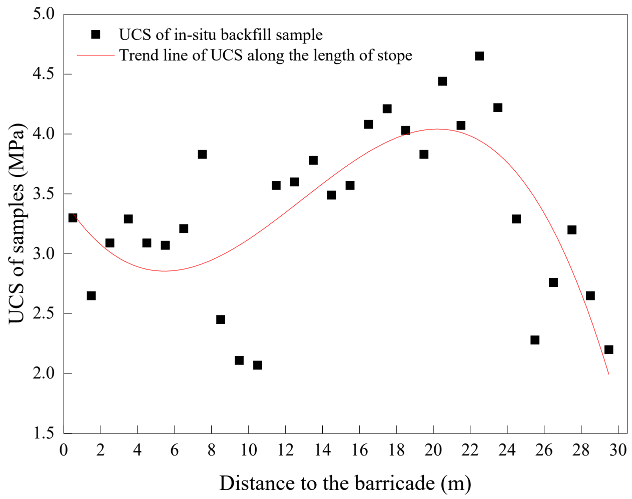

Figure 3. The strength distribution of the drilled out *in situ* samples

From Figure 3 it can be seen that the UCS distribution of the specimens shows an 'S'-shaped trend along the length of the stope, beginning with a decrease. The minimum value appears at about 10 m from the barricade (approx 25% of the length), which is 2.07 MPa. The maximum strength value occurs at about 22.5 m from the barricade (approximately 75% of the length), which is 4.65 MPa. Nether of the extreme values are found at start or end point of the stope.

Based on the test data, the difference between the extreme strength values of the specimens reaches 2.58 MPa, with a standard deviation of approximately 0.71 MPa. This is relatively quite different compared to the average value of 3.34 MPa. The preliminary judgment is that the quality of the backfill mass of plug is not good.

Cement content distribution of selected samples

Results of the cement content testing of selected samples were collected, compared with results from the strength distribution, and plotted (Figure 4). Except for minor fluctuations near the barricade, the cement content generally shows an increasing trend along the length of the stope. It is also observable that in over half of the length, the cement contents of *in situ* backfill mass are less than the design value (20%), and the difference between extreme values > 10%, which indicates a high degree of segregation in the cement content distribution. Comparing the distribution of cement content and strength, it can be seen that within 5–20 m from the barricade, the strength of the backfill sample gradually increases along with the increase of cement content. However, beyond this range, even though the cement content continues to grow, the strength sharply decreases. This is mainly due to the bleeding of water from the backfill slurry which will flow along the stope and eventually accumulate at the far end, resulting in a significant increase of water-to-cement ratio in the area and correspondingly reducing the strength of the backfill mass. Additionally, as cement particles are generally finer than tailings, the cement content distribution will reflect the distribution of tailings particles, ie, fine particles are more likely to accumulate at the far end of the stope while coarse particles tend to gather near the barricade.

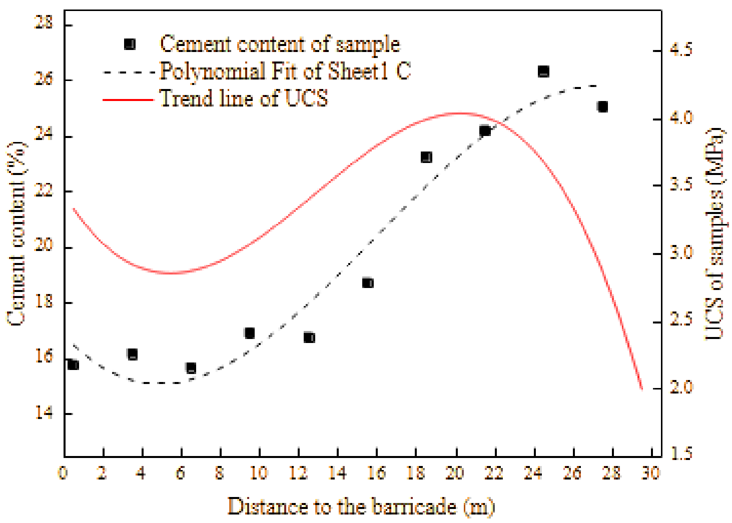

Figure 4. The cement content distribution of the selected samples.

Pore structure properties of selected samples

Porosities of the backfill mass specimens were analyzed first. The tests results are compiled to create a trend line showing the porosity changing along the length of the stope and then compared with the strength distribution trend line (Figure 5). As indicated in the figure, the porosity values exhibit certain fluctuations, generally showing a trend of first decreasing and then increasing, with > 6% of difference between extreme values. This suggests a reasonably high degree of segregation in porosity.

When comparing the relation of porosity and strength, two regions can be distinguished. The first is the area beyond 8 m, where the two variables generally show a negative correlation, indicating that as porosity decreases, the strength gradually increases, and *vice versa*. This is consistent with common understanding. However, in the range of 0–8 m, despite a gradual decrease in porosity, the strength does not correspondingly increase but shows certain fluctuations. Moreover, the minimum porosity value appears in the range of 14–18 m from the barricade, which differs from the range where the extreme strength value occurs. This is mainly influenced by the cement content. In the initial area, despite lower porosity, the cement content is also low, resulting in fewer hydration reaction products to fill the pores and causing fluctuations in strength. In the area with the lowest porosity, the cement content has not reached its maximum value yet, therefore the strength is also not at its maximum.

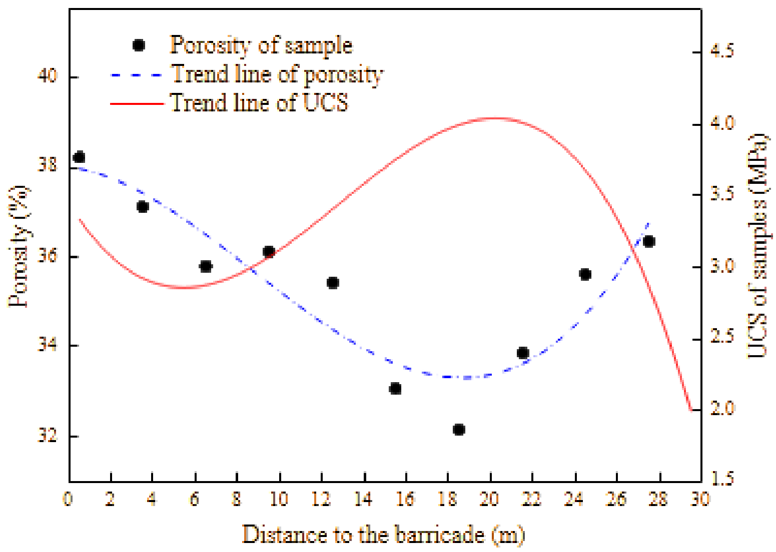

Figure 5. The porosity distribution of the selected samples

To analyze further the pore structures of backfill mass, pore diameters of samples at the distance of 3, 15, and 24 m have been measured by MIP test respectively (Figure 6).

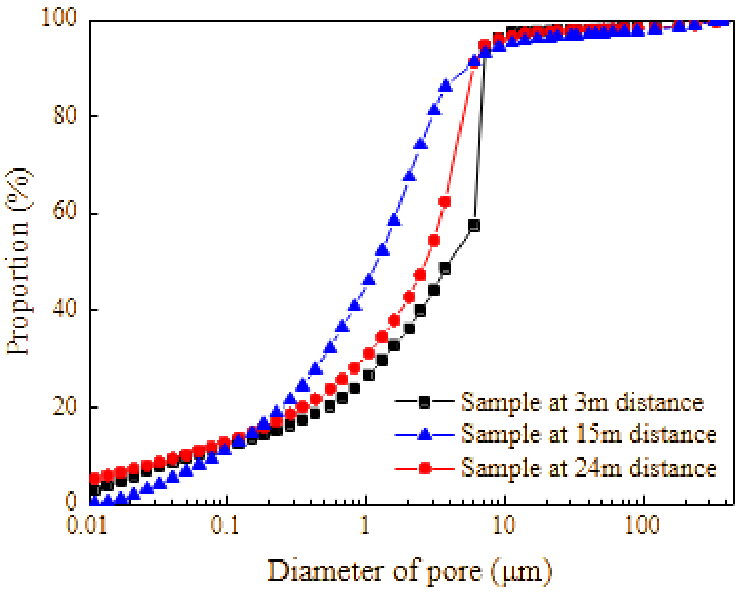

Figure 6. Comparison of the pore diameter of three samples.

From Figure 6, at the 3 m position the sample porosity is dominated by large pores, with the pore size mainly concentrated in the 1–10 μm range. This is mainly because near the barricade, coarse tailings particles are gathered and lack fine tailings to fill their gaps, resulting in larger pore sizes. While the porosity at the 24 m position is smaller than that of the 3 m sample, due to the lack of coarse particles at the far end the particle size compatibility is also poor, correspondingly leading to more and higher porosities. In contrast, at the 15 m position both coarse and fine particles are accumulated, and fine particles can better fill the gaps between the coarse particles; this results in a lower porosity for the backfill mass at this location, which has pores mainly concentrated in the 0.1–1 μm range. This is also one of the reasons for the higher UCS of sample at this position

Quality evaluation and optimization suggestions

Based on the test results analysis of *in situ* coring specimens, it is evident that the strength distribution of the backfill mass in the plug area is relatively uneven, with significant differences between extreme values and a large standard deviation (compared to the lowest strength). Combined with the results of segregation characteristic tests, both the cement content and pore properties in this area show a high degree of segregation. Consequently, it is judged that the quality of the backfill mass is not good.

As mentioned above, the segregation characteristics can reflect some issues related to PSD of tailings, recipe of backfill, etc. From the cement content results, what is noteworthy is that even though the cement content increases further away from the barricade, the strength of the backfill mass decreases along the distance. According to the previous analysis, this is primarily due to the excess bleeding water accumulating at the far end, dramatically increasing the water-cement ratio. Therefore, the first optimization suggestion to control this phenomenon is to increase the filling concentration and reduce bleeding water volume to enhance quality of the filling material.

From both the results of cement content and pore structure tests, segregation characteristics indicate that there is a prominent separation between coarse and fine particles of the filling aggregates, resulting in the cement content staying below the design value (20%) within a range of approximately 18 m and porosity rates at both near and far ends being relatively high. It is necessary to optimize the PSD of the aggregates. According to the PSD test results (Figure 7), nearly 30% of the tailings are fine particles < 10 μm and approx 25% are coarse particles > 74 μm.

The coefficient of uniformity of the tailings, which is used to characterize the difference in the proportion of coarse and fine particles, is around 15.22, indicating the inhomogeneity of tailings is high. Therefore, if the concentration is fixed, from the perspective of PSD, it is possible to increase the content of fine particles appropriately to prevent water bleeding from the slurry while reducing cement loss.

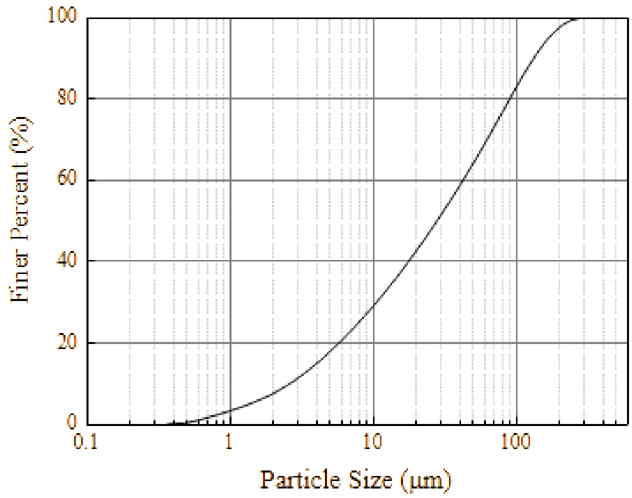

Figure 7. The PSD of the tailings obtained from the copper mine

Conclusions

1. The segregation characteristics of backfill specimens were tested and studied by sampling of *in situ* backfill mass from a real copper mine. The cement content generally increases gradually along the backfill slurry flowing direction, while the porosity of the backfill mass shows a fluctuating trend of initially decreasing and then increasing. Moreover, the pore size is larger at both ends of the backfill mass and smaller in the middle area. These segregation properties are primarily influenced by the PSD of the tailings.

2. The cement content and pore structure properties have a coupled impact on the strength of the backfill mass. When the cement content is sufficient, and the porosity

and pore size are relatively small, the hydration products can better fill the backfill pores, resulting in higher strength. Additionally, for lower-concentration filling slurries, at the distant end of the stope, there may be an accumulation of bleeding water, leading to an excessive water-cement ratio, which in turn reduces the strength of the backfill mass.

3. Based on the strength distribution and segregation characteristics of *in situ* specimens, the filling quality in the copper plug area is judged to be not good. Combining the analysis of segregation characteristics, this is related to the relatively insufficient filling concentration and the inhomogeneity of the tailings PSD. It can be considered to reduce the segregation by increasing the filling concentration and appropriately increasing the proportion of fine aggregates. This will help to reduce slurry bleeding and the loss of cement, thus improving the backfill quality.

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