Paste-like Pumping Backfilling Technique with High Stowing Gradient and Long Distance

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ABSTRACT: In order to achieve the maximum recovery of the shallow residual ore resources in Xikuangshan Mine Flash Star Antimony Ltd. in Hunan province of China, on the premise of safe mining, a new paste-like pumping backfilling technique characterized by long-distance pipeline transportation and a high stowing gradient (the ratio of the whole length to the vertical height of the filling pipeline) was studied through the proportion test, pumpability experiment, system process design and reliability analysis of the backfilling system. It is revealed that the optimum proportions (cement: fly-ash: tailings) applied in the stope and mined-out gobs are 1:2:8 and 1:4:15, respectively with mass fractions both being 74%-76% and the rheological property both being paste-like. Furthermore, the backfill pump HBT80/21-220S has been proved to meet the requirements of the backfill industry. The cost of the backfill system is 23.46 yuan per ton, and the remnant ore recovery rate is 60%. In the end, the output value increased by 2.322 billion yuan. The remarkable economic benefits indicate that the application of horizontal sand silos is feasible. As this backfilling technique sets a precedent in China, it can not only enrich the backfilling theories but also provide some constructive guidance for environmental protection and mining in mines with similar conditions.

Keywords: paste-like; pumping backfill; pumpability experiment; backfill system

1 INTRODUCTION
With a long history of mining, a large amount of ore resources has been left behind and excessive mined-out gobs appeared in shallow parts of the mine. The slurry backfilling technology has been frequently utilized in many mines to protect the environment, ensure the surface safety and advance the resource utilization [1-2]. Taking the advantage of larger elevation difference, self-flowing pipeline transportation back filling technique with small stowing gradient has been commonly applied in many metal mines. Nevertheless, few researches in China have been conducted on paste-like pumping backfilling system concerning long-distance pipeline transportation with high stowing gradient [3-4].

Xikuangshan Mine, Flash Star Antimony Ltd., Hunan province, China, with the history of more than a century, has left enormous valuable antimony resources during hundreds of years’ exploitation. For example, the 1,297,160-ton residual ore in the South Deposit, mainly scatters from the first middle section to the fifteen middle section. The shallow residual resources distributing on both sides of the third middle section and above it weigh about 300,000t. The shallow filling system in the South Deposit of Xikuangshan Mine has to apply pressurizing pumping pipeline transportation because the maximum horizontal pipe is 1117 meters in length and the maximum stowing gradient is 112.7, which fails to meet the requirements of pipeline gravity transportation technology. Besides, the mass fraction of backfilling slurry is required to be more than 70%, and the backfilling capability is set as 50m³/h due to the limited filling quantity in the shallow mine. Therefore, in this study, a long-distance paste-like pumping backfilling technique with high stowing gradient, characterized by feasibility and rationality, is developed. Not only does this technology promise obvious economic and environmental benefits, but also it starts a precedent of a long-distance pipe-
line transportation of paste-like pumping backfilling system with high stowing gradient, deserving a deep research [5].

2 STUDY ON THE BACKFILLING MATERIAL

2.1 Requirements of the backfill

The main requirements of the aggregate used in the long-distance pipeline transportation of paste-like pumping backfilling system are as follows:

1. The backfill should possess good flow-ability to lower the technical requirements of the backfilling pump and enhance the reliability of the pumping backfilling system.

2. The resources of the backfill are easily accessible and cheap.

3. The process of the backfill materials must be simple, economical and reasonable for the popularization of the application.

2.2 Properties of the backfill

Based on the above performance requirements of the backfill, the classified tailings of Xikuangshan Mine are selected as backfilling aggregates, taking the domestic backfilling techniques into consideration. And the bagged cement, as well as the common Portland cement, is regarded as the cementing materials by adding a certain amount of fly-ash as the activation material.

Physical and mechanical properties and chemical compositions of the backfill materials not only affect backfilling craft parameters but also contaminate underground working environment if there are some harmful ingredients. Therefore, it is of vital importance to determine the main physical and mechanical properties and chemical composition of the backfill and its content accurately. Through field sampling, the determination of loose dry density, specific gravity, angle of rest, size grading, permeability coefficient and chemical compositions can be obtained. The results are shown in Table 1-3, which suggest that:

1. The classified tailings are regarded as ideal aggregates for its good dehydration, whose void rate is 0.61-0.69 and mediate size is 0.19mm, respectively, and a quick initial setting time for its high permeability coefficient (208.1mm/h) is far larger than the requirement 100 mm/h. Besides, the classified tailings have a good granular distribution and the asymmetry index is 7.5 which is more than 5 and can increase the initial strength of the backfill body.

2. Fly-ash possesses potential binding capability due to its large content of SiO2 (56.9%) and Al2O3 (20.3%). Fly-ash, according to experience, should be grinded to 3000 cm$^2$/g in order to take full advantage of its cementation activity. Furthermore, the fly-ash can restrain the isolation and delamination of the backfill body during the transportation for its chemical activity [6-7] and specific weight (only 2.43), which is beneficial for fluent pipeline transportation of backfilling materials.

3. The content of SiO2 and Al2O3 account for 70.7% and 3.74%, respectively, which means large strength of the backfill. Further, both the contents of the useful and harmful compositions occupy low proportions, and therefore, the backfill materials can be selected as backfilling aggregates.

2.3 Proportion test

The main purpose of the proportion test is to make some cemented samples of different proportions to measure the uniaxial compressive strengths using the Instron 250KN rigid hydraulic pressure servo machine after a period of maintenance. Through the technical and economic analysis of the results, the optimized proportion of the backfill is proposed. Afterwards, the corresponding rheological properties of suggested proportion are measured to provide theoretical basis for the cemented backfilling industry. Experiments and results of the laboratory test are shown in Table 4-6, and the following conclusions can be drawn:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm$^3$)</th>
<th>Bulk density (t/m$^3$)</th>
<th>Void ratio</th>
<th>Mediate size (mm)</th>
<th>Asymmetry index</th>
<th>Angle of rest in water (°)</th>
<th>Angle of rest out water (°)</th>
<th>Permeability coefficient (cm·s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classified tailings</td>
<td>2.67</td>
<td>1.54</td>
<td>0.61-0.69</td>
<td>0.19</td>
<td>7.5</td>
<td>33.6</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>2.41</td>
<td>0.97</td>
<td>0.09-1.51</td>
<td>0.03</td>
<td>2.29</td>
<td>19</td>
<td>19</td>
<td>1.02x10$^{-4}$</td>
</tr>
</tbody>
</table>

Note: The permeability coefficient is measured under normal temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Size/mm</th>
<th>5~2</th>
<th>0.5-2</th>
<th>0.25-0.075</th>
<th>0.075-0.005</th>
<th>0.05-0.005</th>
<th>&lt;0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classified tailings</td>
<td>0.2</td>
<td>2.2</td>
<td>27.7</td>
<td>37.2</td>
<td>9.7</td>
<td>9.0</td>
<td>72.0</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0.5</td>
<td>2.1</td>
<td>2.7</td>
<td>11.7</td>
<td>9.0</td>
<td>72.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO$_2$</th>
<th>Ca</th>
<th>Al$_2$O$_3$</th>
<th>K</th>
<th>Mg</th>
<th>Pb</th>
<th>Fe</th>
<th>Na$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classified tailings</td>
<td>70.07</td>
<td>2.07</td>
<td>3.74</td>
<td>5.93</td>
<td>0.65</td>
<td>1.8</td>
<td>0.55</td>
<td>0</td>
</tr>
<tr>
<td>Fly-ash</td>
<td>56.9</td>
<td>9.7</td>
<td>20.3</td>
<td>1.2</td>
<td>0.074</td>
<td>0.85</td>
<td>1.97</td>
<td>1.1</td>
</tr>
</tbody>
</table>
The strength of the backfilling body increases with the increase of the mass fraction. However, that declines with the increase of the classified tailings mass ratio of solid materials. For example, the compressive strengths of the backfilling body after 28 days with the mass ratio (cement: fly-ash: classified tailings) of 1:2:6 are 1.63 MPa, 1.88 MPa and 1.94 MPa when their mass fraction are 70%, 76% and 78% respectively. And those on the 28th day with the mass fraction of 70% and mass ratios of 1:2:6, 1:2:8 and 1:2:10 are 1.63 MPa, 1.41 MPa and 1.09 MPa respectively.

The backfilling bodies with the proportion (cement: fly-ash: classified tailings) of 1:2:6 or 1:2:8, whose mass fraction is 70%-78%, all meet the requirements of overhand horizontal layering cut-and-backfilling or drift cut-and-backfilling as its uniaxial compressive strength on the 28th day is around 1.5 MPa. Similarly, the backfilling body with the proportion of 1:4:15, whose mass fraction is 70%-78% satisfies the requirements of the general backfill mining methods for the uniaxial compressive strength after 28 days is around 0.6 MPa.

Table 4. Results of laboratory tests of cemented classified tailings.

<table>
<thead>
<tr>
<th>No.</th>
<th>Cement: fly-ash: classified tailings</th>
<th>Mass fraction of solid material (%)</th>
<th>7d uniaxial compressive strength</th>
<th>28d uniaxial compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Strength (MPa)</td>
<td>Yield strength (MPa)</td>
</tr>
<tr>
<td>1</td>
<td>1:2:6</td>
<td>70</td>
<td>0.63</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>1:2:6</td>
<td>76</td>
<td>0.65</td>
<td>0.64</td>
</tr>
<tr>
<td>3</td>
<td>1:2:6</td>
<td>78</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>4</td>
<td>1:2:8</td>
<td>70</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>5</td>
<td>1:2:8</td>
<td>76</td>
<td>0.51</td>
<td>0.49</td>
</tr>
<tr>
<td>6</td>
<td>1:2:8</td>
<td>78</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>7</td>
<td>1:2:10</td>
<td>70</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>8</td>
<td>1:2:10</td>
<td>76</td>
<td>0.34</td>
<td>0.37</td>
</tr>
<tr>
<td>9</td>
<td>1:2:10</td>
<td>78</td>
<td>0.42</td>
<td>0.44</td>
</tr>
<tr>
<td>10</td>
<td>1:4:15</td>
<td>70</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>11</td>
<td>1:4:15</td>
<td>76</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>12</td>
<td>1:4:15</td>
<td>78</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>13</td>
<td>1:4:18</td>
<td>70</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>14</td>
<td>1:4:18</td>
<td>76</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>15</td>
<td>1:4:18</td>
<td>78</td>
<td>0.25</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 5. The weight and bleeding rate of the backfilling slurry.

<table>
<thead>
<tr>
<th>No.</th>
<th>Cement : fly ash : classified tailings</th>
<th>Mass fraction (%)</th>
<th>Weight (t/m³)</th>
<th>Bleeding rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1:2:8</td>
<td>70</td>
<td>1.84</td>
<td>4.69</td>
</tr>
<tr>
<td>5</td>
<td>1:2:8</td>
<td>76</td>
<td>1.8</td>
<td>3.27</td>
</tr>
<tr>
<td>6</td>
<td>1:2:8</td>
<td>78</td>
<td>1.83</td>
<td>2.37</td>
</tr>
<tr>
<td>7</td>
<td>1:4:15</td>
<td>70</td>
<td>1.81</td>
<td>3.53</td>
</tr>
<tr>
<td>8</td>
<td>1:4:15</td>
<td>76</td>
<td>1.77</td>
<td>3.31</td>
</tr>
<tr>
<td>9</td>
<td>1:4:15</td>
<td>78</td>
<td>1.78</td>
<td>2.87</td>
</tr>
</tbody>
</table>

Table 6. The values of the slump and slump spread of the backfilling slurry.

<table>
<thead>
<tr>
<th>Cement : fly ash : classified tailings</th>
<th>Mass fraction (%)</th>
<th>Degree of slump (cm)</th>
<th>Slump proliferation (cm)</th>
<th>Slump proliferation/degree of slump</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual measurement</td>
<td>Average</td>
<td>Actual measurement</td>
<td>Average</td>
</tr>
<tr>
<td>1:2:8</td>
<td>22.5</td>
<td>22.6</td>
<td>22.56</td>
<td>65.4</td>
</tr>
<tr>
<td>1:4:15</td>
<td>20.7</td>
<td>20.7</td>
<td>20.33</td>
<td>66.6</td>
</tr>
</tbody>
</table>

(1) The strength of the backfilling body increases with the increase of the mass fraction. However, that declines with the increase of the classified tailings mass ratio of solid materials. For example, the compressive strengths of the backfilling body after 28 days with the mass ratio (cement: fly-ash: classified tailings) of 1:2:6 are 1.63 MPa, 1.88 MPa and 1.94 MPa when their mass fraction are 70%, 76% and 78% respectively. And those on the 28th day with the mass fraction of 70% and mass ratios of 1:2:6, 1:2:8 and 1:2:10 are 1.63 MPa, 1.41MPa and 1.09MPa respectively.

(2) The backfilling bodies with the proportion (cement: fly-ash: classified tailings) of 1:2:6 or 1:2:8, whose mass fraction is 70%-78%, all meet the requirements of overhand horizontal layering cut-and-backfilling or drift cut-and-backfilling as its uniaxial compressive strength on the 28th day is around 1.5 MPa. Similarly, the backfilling body with the proportion of 1:4:15, whose mass fraction is 70%-78% satisfies the requirements of the general backfill mining methods for the uniaxial compressive strength after 28 days is around 0.6 MPa.

(3) The backfilling slurry with the proportion of 1:2:8 or 1:4:15 has a good rheological property with the slump degree more than 160 mm and its bleeding rate is around 3%, which conduces to the pipeline transportation. Compared with the general backfill material with the bleeding rate varying from 4% to 9%, the solidifying water performance of the backfill body has improved evidently. For this reason, the backfilling slurry is referred as the paste-like backfilling slurry [8-9].

(4) Taking some economic and technological factors of the fluent pipeline transportation into consideration, the suggested optimized proportion (cement: fly ash: classified tailings) applied in the stope is 1:2:8 with the mass fraction being 74%-76% and the uniaxial compressive strength being about 1.5 MPa within 28 days. Besides, the suggested best ratio applied in the goaf treatment is 1:4:15. And the corresponding mass fraction and uniaxial compressive strength within 28 days are 74%-76% and 0.6 MPa respectively, which satisfies the requirements of general backfill mining methods.

Table 4. Results of laboratory tests of cemented classified tailings.
3 BACKFILLING PUMP

The selection of filling pump is based on the requirements of its minimum pressure and filling capacity.

3.1 Calculation of pipeline resistance

3.1.1 The frictional resistance of horizontal pipeline

The computation theory of hydraulic gradient mainly includes diffusion theories, gravity theory and some theories relating to both of them [10-11]. The empirical formulas proposed by Jinchuan Non-ferrous Metal Group, which specializes in nickel and copper and is located in the northwest of China, and the Hydro Academy of Science in Shanxi province of China, respectively, are applied by comparison with many other hydraulic computation formulas used by numerous scholars and references of backfilling applications at home and abroad.

The equation proposed by Jinchuan Non-ferrous Metal Group is

\[
i = i_0 \left\{ 1 + 108C_v^{-3.96} \left[ \frac{gD_i (r_m - 1)}{v^2 \sqrt{C_x}} \right]^{-1.12} \right\}
\]

(1)

where \( i \) means the hydraulic gradient of per unit length of slurry in horizontal pipe; \( i_0 \) denotes the hydraulic gradient of per unit length of fresh water; \( C_v \) is bulk concentration of the slurry; \( D_i \) is particle size; \( r_m \) is density of backfill material; \( v \) and \( C_x \) are flow rate of slurry and settlement resistance coefficient, respectively. Furthermore, \( C_x \) is approximated as

\[
C_x = \frac{1308(\gamma_f - 1)d_{sp}}{\omega^2}
\]

(2)

where \( r_s \) is density of backfilling slurry; \( d_{sp} \) is average particle size; \( \omega \) is the average settlement speed of particle. And \( w \) is estimated by

\[
\omega = k \sum \omega_i a_i
\]

(3)

where \( \omega_i \) is settlement rate of the particle with the particle-size fraction \( i \); \( a_i \) is yield rate of the particle with the size fraction \( i \); \( k \) is the shape coefficient of the particle.

The parameter \( A \) is given by

\[
A = \sqrt[3]{0.0001 / (\gamma_f - 1)} = 0.05
\]

(4)

Besides, \( d_i \) is the size of particle with the particle-size fraction \( i \) when \( d_i \) is less than 0.3A, and \( \omega_i \) is given by

\[
\omega_i = 5450d_i^2 (\gamma_f - 1)
\]

(5)

Since \( d_i \) is less than \( A \) but greater than 0.3A, \( \omega_i \) can be obtained by the following equation:

\[
\omega_i = 123.04d_i^{1.1}(\gamma_f - 1)^{0.7}
\]

(6)

When \( d_i \) is less than 0.3A but greater than \( A \), \( \omega_i \) can be computed as

\[
\omega_i = 102.71d_i (\gamma_f - 1)^{0.7}
\]

(7)

If \( d_i \) is greater than 4.5A, \( \omega_i \) is calculated as

\[
\omega_i = 51.1\sqrt{d_i (\gamma_f - 1)}
\]

(8)

The average settlement speed of classified tailings is 2.090cm/s through calculation, which is showed in Table 7. Finally, the hydraulic gradient of classified tailings is \( i = 0.8869 \) by substituting values mentioned above into Formula (1).

The formula put forward by Hydro Academy of Science is as follow:

\[
i = 1.96 \left( \frac{\gamma_m - \gamma_w}{\gamma_w} \right)^{1/6} \frac{v^2}{2gD_i} \frac{Y_f}{100}
\]

(9)

where \( \gamma_w \) denotes density of water. Correspondently, the hydraulic gradient of backfill slurry is obtained as 0.6033.

Therefore, the maximum of the two values obtained by Equation (1) and (2), i.e., the hydraulic gradient in this work being 0.8869 should be regarded as hydraulic gradient of backfill slurry.

3.1.2 Local resistance of pipeline

The local resistance of pipeline includes the installation resistance, resistance of pipe elbows and the resistance resulting from sudden change of pipe line size. The estimated local resistance of all pipelines is 8% of linear resistance [11-12], namely

<table>
<thead>
<tr>
<th>Table 7. The results of classified tailings on the settlement speed.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size/cm</td>
</tr>
<tr>
<td>( a_i ) (%)</td>
</tr>
<tr>
<td>Density (t/m³)</td>
</tr>
<tr>
<td>( A )</td>
</tr>
<tr>
<td>Formulas</td>
</tr>
<tr>
<td>( \omega_i )</td>
</tr>
<tr>
<td>( \omega_i a_i )</td>
</tr>
<tr>
<td>Average settlement rate (cm/s)</td>
</tr>
</tbody>
</table>
\[ i = 8\% i \]  \hspace{1cm} (10)

where \( i \) is hydraulic gradient; \( i_1 \) denotes local resistance of all pipelines.

### 3.1.3 The total resistance of the pipeline

The total resistance of the pipeline can be expressed as

\[ H_t = H_h + H_l + H_a \]  \hspace{1cm} (11)

where \( H_t \) is the total resistance, \( H_h \) denotes the resistance of horizontal pipes, \( H_l \) means the local resistance and \( H_a \) refers to the resistance resulting from height delivery of slurry. Combining Formula (10) and (11), the equation can be concluded as follows:

\[ H_t = 1.08 H_h + H_a \]  \hspace{1cm} (12)

The resistance \( H_a \) is estimated based on stowing gradient, for the simplification of calculation in this design. The hydraulic gradient of the vertical height is 62 meters (from the possible backfilling station to the third middle section) which is equal to 1.5 times of horizontal transportation, namely 93 meters in length. As the maximum transmission is 1687.5 meters long, the total resistance of pipeline can be expressed as

\[ H_t = 1687.5 \times 1.08 i - 93i \]  \hspace{1cm} (13)

excluding the hydraulic gradient produced by the vertical height of the pipeline, the obtained total resistance can be 1729.5i. Furthermore, the hydraulic gradient of the backfilling slurry meets the following equation:

\[ i = 0.3787 \times m(H_2O) \]  \hspace{1cm} (14)

Accordingly, the hydraulic gradient is 3712 Pa/m.

Finally, the maximum resistance in the most difficult period is 6.41 MPa. Accordingly, the resistance of horizontal pipes is 6.76MPa, namely \( H_h + H_l = 6.76 \) MPa. Therefore, the minimum pressure of the pump is 8.41 MPa as the activating pressure of the pump is 2 MPa.

### 3.2 Option of backfilling pumps

According to requirements of minimum pressure of filling pumps and filling capability, the piston-filling pump HBT80/21-220S, produced in Feiyi Corporation Ltd. in Hunan province of China, is selected as the backfilling pump. Some major technical indicators of the pump are shown in Table 8.

#### 3.3 Pumpability test

The pumpability of the backfill is the key to the success of the pump backfilling system. The pumpability of the backfill with high concentration refers to flowability, plasticity, stability of the backfill materials during the pipeline transportation. Theoretical analysis alone is inadequate to perform the pumpability analysis as it will cause great errors. Therefore, conducting circular pipe test is necessary to ensure the stability and reliability of the backfilling system.

According to the engineering experiences of pump backfilling systems and crafts at home [12] and abroad [13-14] and the design backfilling system in the shallow South Deposition in Xikuangshan Mine, seamless steel pipes with the 100mm in inner diameter and 7mm in thickness and one type of piston backfilling pumps HBT80/21-220S, were utilized in this circular pipe test on the delivery of classified tailings. Some other equipment, such as one type of velocity determination instrument, two pressure sensors and numerous bends with radius curvature being 600 mm and the right-angle 90 degrees, were included as well. Pipes were connected by fast joins and the exit of the backfilling pump was joined with reducer pipes (7 mm in thickness and 400 mm in length). Based on the characteristics of backfilling systems in mines, the pipeline was laid horizontally with the total length being around 120m, including the length of the horizontal pipeline, reducer pipes and bends. The layout of the test is as shown in Figure1.

![Figure 1. Layout of circular pipe test.](image)

Table 8. The main technical parameters of HBT80/21-220S.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum delivery capacity (average voltage/high voltage)</td>
<td>m³/h</td>
<td>85/50</td>
</tr>
<tr>
<td>Outlet pressure (average voltage/high voltage)</td>
<td>MPa</td>
<td>13/21</td>
</tr>
<tr>
<td>Length of horizontal pump transportation (average voltage/high voltage)</td>
<td>m</td>
<td>1050/1700</td>
</tr>
<tr>
<td>The height of vertical pump transportation (average voltage/high voltage)</td>
<td>m</td>
<td>230/350</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>mm</td>
<td>φ 100</td>
</tr>
<tr>
<td>Acceptable range of slump degree</td>
<td>cm</td>
<td>18~25</td>
</tr>
<tr>
<td>Maximum aggregate size</td>
<td>mm</td>
<td>Gavel for 50, rubble for 40</td>
</tr>
</tbody>
</table>
ment. To ensure the uniformity and qualification of the backfilling slurry, the mixing time was required to last 5 to 6 minutes.

Filling pump is working with reciprocating motion of the piston, so the velocity of the slurry in the pipe fluctuates, and the measured velocity values have no practical significance. Therefore, the piston of the pump HGBS80.21.220 should move 13 times per minute to control the throughput which should reach 50m$^3$/h as designed.

The backfill with the proportion (cement: fly-ash: classified tailings) of 1:4:15 is transported by the pipeline more easily than the backfilling material with the proportion of 1:2:8. And the lower the concentration of the slurry is, the easier the transportation will be. Finally, the backfill slurry with the proportion and concentration being 1:2:8 and 76%, respectively, was tested in this pumpability test. Furthermore, the values of inlet and outlet pipe pressure were measured when the pump starts, restarts after 20 minutes’ shut-down and restarts after one hour’s shutdown at a throughput of 50 m$^3$/h. Accordingly, the results are shown in Figure 2, Figure 3, Figure 4, where p1, p2 are the values of test points 1 and 2 respectively; and dp1 = p1 - p2; and $p^*$ denotes the average value of p. Note: the unit of values is bar and one bar means 0.1 MPa.

From the figures, we can conclude the following results:

(1) According to Figure 2, when the pump starts, the pressure loss of the pipeline with a length of 100 meters is around 0.4 MPa at the flow rate of 50m$^3$/h. The pressure loss is presumed to be around 6.73 MPa when the length is 1687 meters, which is in line with the resistance of horizontal pipes (6.76 MPa) calculated above. Therefore, the calculation of the pipe resistance above is justified.

(2) Given the pressure loss of the pipeline which is 100 meters long is around 0.4 MPa, the pressure loss, therefore, is estimated to be 8MPa when the pipeline length is 2000 meters, which suggests that the industry pump meets the requirements of the backfilling system as the pump can provide the pressure of 13 MPa at low voltages.

(3) The pressure loss (around 0.7 MPa) increases significantly if the pump is restarted after 20 minutes’ shutdown, indicating that the backfilling slurry has a certain degree of settlement within 20 minutes. However, the pressure loss can still be provided by the industrial backfilling pump, suggesting that the industry backfilling pump satisfies the requirements of the stable operation of the system.

(4) When the pump restarts after 60 minutes’ shutdown, pressure loss exceeds 1.0 MPa. Accordingly, the pressure loss of the pipeline which is 2000 meters long is reckoned to be more than 20 MPa, which fails to ensure the stable operation of the system. In this case, it is recommended to discharge the backfilling slurry in the pipeline with high pressure water before the pump is restarted.

4 BACKFILLING SYSTEM

The backfilling system is divided into backfill material preparation, storage units, backfill material mixing units, and conveying units [15].

Generally, the sand silo, which is divided into the saturated sand silo and the dry sand silo, is used for the storage of tailings. In recent years, the jets of saturated vertical sand silos, brought in from the outside, always clog up, and is difficult to replace. Worse still, the concentration of the slurry fluctuates and declines...
once the operation is not appropriate. Consequently, the dry sand silo is widely used in China. The dry silo can be also divided into two types: vertical and horizontal sand silos. As for the vertical sand silo, the sand is exiled through the high pressure water injection. As a result, the flow rate and concentration are not easy to control, which should be avoided. While, the horizontal sand silo uses rakes to deliver sand, combining with mechanical mixing systems. Both the flow rate and concentration are easy to control. Undoubtedly, the horizontal sand silo is supposed to be applied in the Xikuangshan Mine [16].

According to requirements of the paste-like backfilling programme, the unclassified tailings should be processed by desliming before transported to the backfilling station from the preparation plant. The classified tailings are conveyed to the horizontal sand silo through pipes first, then feed the storeroom after draining, and finally reach the mixing tank through vibrated feeder fixed at the bottom of storehouse. The cement and fly-ash are transported by tank cars and unloaded into the vertical sand silos and fly-ash storerooms respectively, and then the mixing tanks through gate valves at the bottoms of the storerooms, star feeders, electronic steelyards and spiral conveyers. The backfill water is produced by the sedimentation of the classified tailings, transported by the pump and delivered to the mixing tanker. Besides, the water in the high-seated field pond located at the original backfill station is considered as an alternate emergency water resource. The above backfill materials are stirred in the mixing tanker completely so as to form the paste-like slurry with some qualified mass fraction. Afterwards, it is delivered to the stope through the pipeline by the high pressure pump. The backfill craft process is shown as Figure 5 [17-18].

5 APPLICATION EVALUATION

The results of the application in Xikuangshan Mine are shown as follows:

1) The backfill volume is 50m$^3$/h and 400m$^3$ per shift, which meets the average backfilling capacity of the backfilling system. The total investment of the backfilling system is up to $1,566,930, among which the filling slurry with mass fraction being 76%, costs 9.02 dollars/m$^3$ or 3.4 dollars/t. The traditional paste backfill system is 7 times the cost of this proposed backfilling technique.

2) After the adoption of the filling method in Xikuangshan Mine, the 60% of remnant ore has been recovered, and 77,400 tons of antimony is expected to be recovered and the payback period is supposed to be around three months. Further land occupation of classified tailings decreases obviously and the tailing dam management becomes easier.

3) The backfilling technique with a simple craft process has a low accident rate including pipe blocking, abrasion and exploding. Besides, with the application of horizontal sand silos, the concentration of the backfilling slurry is easy to control and the backfilling quality can be guaranteed. According to Figure 6, the roof-contacted filling has good effects, because the subsidence of the roof is only 1.32 mm. We can readily tell that the slurry is densely distributed around the stope boundary with the average compress strength being 1.5 MPa, which boosts the safety of mining.

4) This backfilling technology, which is applied in Xikuangshan Mine, concerning long-distance pipeline transportation of paste-like pumping backfilling system with a high stowing gradient is fully feasible and rational.

Figure 5. Backfill craft process.
6 CONCLUSIONS

(1) The new paste-like pumping backfilling technique based on the horizontal sand silo, characterized by long-distance pipeline transportation and high stowing gradient, can only achieve the maximum recovery of residual ore resources in shallow mines on the premise of safe mining, but also provide a profitable and feasible backfill craft for shallow mining.

(2) The best ratios (cement: fly ash: classified tailings), suggested in the stope and mined-out area, are 1:2.8 and 1:4.15 respectively with the mass fraction both being 74%-76%. And the backfill slurry is referred as the paste-like slurry, which can enhance the capability of pipeline transportation and initial strength of the backfill body for its low bleeding rate, high concentration and good slump proliferation.

(3) The HBT80/21-220S filling pump, with the minimum pressure being 13 MPa, is capable of meeting the requirements of the whole backfilling system. Also it should be noted that the maximum time required for system activation after emergency shutdown is less than 30 minutes as the pipeline resistance increases considerably as a result of the backfilling slurry settlement in the pipeline.

(4) The fly-ash is able to improve the rheological properties of backfill materials because its chemical activation and density (only 2.41 g/cm³) are less than those of the classified tailings (2.67 g/cm³), which is worth further study on the exact correlation between the rheological properties of backfill materials and the mass fraction of fly-ash so as to improve the performance of the backfilling slurry during long-distance pipeline transportation.

(5) The techniques presented in this paper have enriched the paste-like pump filling researches and provided technical guidance for analogical mines in China and abroad.

REFERENCES