Application of Jig Separation for Pre-Concentration of Low-Grade Scheelite Ore
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Jig separation, one of the oldest methods of gravity separation, is commonly used to reduce the costs of subsequent processes by pre-concentrating the valuable minerals from the product following coarse particle crushing. In this study, jig separation was used to pre-concentrate scheelite prior to grinding for the next process. Experiments were carried out using 0.21 to 5 mm samples, in order to determine and evaluate optimal conditions by varying factors, including the thickness of the bed, the water flow rate and the number of scavenging. The results of the experiments show that when pre-concentration of low-grade scheelite ore (0.75% WO\(_3\)) using jig separation is conducted, a concentrate with a mass percentage of about 22.0%, a WO\(_3\) grade of about 3.1% and WO\(_3\) recovery of about 90.0% can be obtained. It is therefore expected that when this concentrate is supplied to the next separation process, the grade, economic feasibility, and separation efficiency will be improved compared with separations that do not involve a pre-concentration.

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Keywords: pre-concentration, jig separation, low-grade scheelite, brittleness

1. Introduction

The effective separation of valuable minerals from gangue minerals often involves a crushing process, but in the case of low-grade ore, the economic value of mineral processing operation decreases due to excessive crushing costs. A possible solution would be to pre-concentrate the valuable minerals following coarse particle crushing.

The sample used in this study is low-grade scheelite (0.75%WO\(_3\)) that is easily ground to fine particles during the crushing process due to its brittleness. Finer particles tend to be lost in the separation process used for improving grade, which makes the early recovery of scheelite crushed by coarse particles more necessary than other minerals.

Generally, gravity separation methods, such as jig separation, Knelson concentration, multi-gravity separation, spiral concentration and the use of a shaking table, are applied for the pre-concentration of high specific gravity minerals like scheelite (5.9–6.1 S.G.). Of these, jig separation is one of the oldest types of gravity separation equipment in its class for treating relatively coarser particles. It also has the advantage of being low cost, easy to operate, and capable of handling large quantities of material; for these reasons, it has been used for the beneficiation of ore minerals as well as the washing of coal. However, most of the literature on jig separation only concerns coal washing and iron ore separation. In addition, most of the literature related to the separation of scheelite was in the area of flotation for improving the grade after crushing by fine particles. No significant literature on jig separation of scheelite was found.

In this study, jig separation was conducted for the pre-concentration of low-grade scheelite crushed by coarse particles. The jig separation was performed using a laboratory scale plunger jig and optimal conditions parameters were identified and examined under various conditions.

2. Materials & Methods

The sample used in this study was scheelite ore collected from the Dongbo mine in Uljin, Gyeongbuk, Korea.

The result of chemical analysis of XRF (x-ray fluorescence) and ICP (inductively coupled plasma) spectrometry on the ore are given in Table 1. It is comparatively low-grade scheelite ore with a grade of 0.75% WO\(_3\). Most of the gangue minerals are silicate minerals that contain SiO\(_2\) and Al\(_2\)O\(_3\), as high as 74.43% and 8.29%. In addition, it was confirmed that Fe\(_2\)O\(_3\) and CaO were 8.15% and 3.14%. Figure 1 shows the XRD analysis result of the ore with the following minerals being observed: quartz, albite, biotite, magnetite, chlorite, as well as scheelite and calcite that contain calcium.

Particle size analysis is useful in understanding the char-

<table>
<thead>
<tr>
<th>Component</th>
<th>WO(_3)</th>
<th>SiO(_2)</th>
<th>Al(_2)O(_3)</th>
<th>Fe(_2)O(_3)</th>
<th>CaO</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents (%)</td>
<td>0.75</td>
<td>74.43</td>
<td>8.29</td>
<td>8.15</td>
<td>3.14</td>
<td>0.97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>K(_2)O</th>
<th>Na(_2)O</th>
<th>TiO(_2)</th>
<th>MnO</th>
<th>P(_2)O(_5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents (%)</td>
<td>0.77</td>
<td>1.78</td>
<td>0.23</td>
<td>0.04</td>
<td>0.44</td>
</tr>
</tbody>
</table>

\(\text{Fig. 1 XRD analysis of the ore.}\)
characteristics of scheelite distribution in various size frac-

tions. Table 2 shows the results of the particle size analy-
sis of this sample. The ore was crushed to less than 5 mm
using a jaw crusher and cone crusher for particle size analy-
sis. Results showed that the crushed sample is a compar-
atively coarser as over 28 mesh (590 μm) particles making up
about 75% of total mass. It was confirmed that WO3 is
mostly distributed in +65 mesh products of about 85% in
mass. Based on these preliminary results, however, there is a
possibility that liberation could not be achieved due to the
coarse nature of the particles.

The jig separation was performed using a laboratory scale
plunger jig, as shown in Fig. 2. Experiments were exclu-
sively carried out with 0.21 to 5 mm samples, crushed to
−5 mm and screened through a 65 mesh sieve. A representa-
tive sample of 500 g was used for each experiment. During
the experiment, water is supplied to the plunger chamber
and plunger movement allows water to flow into the jig
chamber and overflow out during pulsation of the bed (layer
of balls). When the prepared samples are fed into the jig,
particles with a higher specific gravity settle down through a
porous bed, while lower specific gravity particles overflow
out of the chamber with the water flow. The heavy product
collected in the hutch of the jig is classified as concentrate
(U/F, under flow) and the light product that overflows out
of the chamber is called tailing (O/F, over flow). Both heavy
and light products were analyzed using ICP. For this jig sep-

<table>
<thead>
<tr>
<th>Size range (mesh)</th>
<th>Mass (%)</th>
<th>WO3 grade (%)</th>
<th>Cumulative mass (%)</th>
<th>WO3 distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+8</td>
<td>32.1</td>
<td>0.54</td>
<td>32.1</td>
<td>23.1</td>
</tr>
<tr>
<td>−8/+16</td>
<td>27.2</td>
<td>0.67</td>
<td>59.3</td>
<td>24.3</td>
</tr>
<tr>
<td>−16/+28</td>
<td>15.5</td>
<td>0.87</td>
<td>74.8</td>
<td>18.0</td>
</tr>
<tr>
<td>−28/+35</td>
<td>3.7</td>
<td>0.92</td>
<td>78.5</td>
<td>4.5</td>
</tr>
<tr>
<td>−35/+48</td>
<td>6.3</td>
<td>1.11</td>
<td>84.8</td>
<td>9.3</td>
</tr>
<tr>
<td>−48/+65</td>
<td>4.4</td>
<td>0.98</td>
<td>89.2</td>
<td>5.7</td>
</tr>
<tr>
<td>−65/+100</td>
<td>3.7</td>
<td>0.88</td>
<td>92.9</td>
<td>4.3</td>
</tr>
<tr>
<td>−100</td>
<td>7.1</td>
<td>1.15</td>
<td>100.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>0.75</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

The effects of bed thickness were studied using three dif-
ferent thicknesses, ranging from the minimum to maximum
thicknesses possible: a thin bed (0 cm), an intermediate bed
(3 cm), and a thick bed (6 cm). Figure 3 shows the experi-
mental results of separation using different bed thicknesses.
The results confirm that the separation efficiency varies ac-
cording to the thickness of bed. Specifically, the results
show that an increase in bed thickness results in a decrease
in the mass percentage of the concentrate. However, WO3
grade and recovery are found to be higher at a bed thickness

3. Results & Discussion

The main purpose of jig separation is to maximize
scheelite recovery, while minimizing the mass of concen-
trate. Therefore, the separation efficiency was estimated by
calculating the amount of recovered concentrate and recov-
er of WO3.

The formula used to calculate recovery is as follows:

\[ R = \frac{C \times c}{F \times f} \times 100 \]

Here, C and c are the mass percentage and WO3 grade of
the concentrate, and F and f are the mass percentage and
WO3 grade of feed.

3.1 Thickness of bed

The thickness of the bed formed in the jig chamber affects
the separation efficiency. A thick bed in the jig allows less
concentrate to pass through because of more friction during
the suction stage. On the other hand, thin bed will allow
easy passage for the concentrate, because of reduction of
friction action during suction stage. A thin bed also makes
the stratification process rapid. This may be due to excessive
movement of the bed, which would mean that there is a
higher possibility that the particles will overflow. The bed
thickness was therefore investigated to determine its effects
in jig separation.

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thicknesses possible: a thin bed (0 cm), an intermediate bed
(3 cm), and a thick bed (6 cm). Figure 3 shows the experi-
mental results of separation using different bed thicknesses.
The results confirm that the separation efficiency varies ac-
cording to the thickness of bed. Specifically, the results
show that an increase in bed thickness results in a decrease
in the mass percentage of the concentrate. However, WO3
grade and recovery are found to be higher at a bed thickness
of 3 cm. The separation efficiency using a bed thickness of 0 cm is lower than that seen using a bed thickness of 3 cm because WO₃ grade and recovery are both low and the mass percentage of the concentrate is high. In the case of the bed thickness of 6 cm, the mass percentage of the concentrate is lowest at 14.9%, but WO₃ recovery is about 45% lower than that seen using a bed thickness of 3 cm. This means that the separation efficiency of the 6 cm bed is lower than that of the 3 cm bed. In the present study, it was confirmed that the most effective bed thickness is 3 cm, which is in the middle of the chamber.

### 3.2 Water flow rate

In jig separation, the water flow rate is related to the water pressure delivered to the chamber, which therefore affects the motion of particles in relation to the porosity of the bed filled with balls.₁₅–₁₇ As the water flow rate increases, the porosity of the bed increases. Although there is an increased possibility that the particles settle down, there is also a possibility that the particles overflow with the water. A low water flow rate can also affect the motion of the particles. As control of the water flow rate is an important factor in jig separation efficiency, its effects were thoroughly examined.

In this series of tests, the bed thickness was fixed at 3 cm and the water flow rate was varied, using levels of 500 ml/min, 750 ml/min and 1,000 ml/min. Figure 4 shows that the results varied with different water flow rates. As the water flow rate increases, the mass percentage of concentrate decreases, but the grade of WO₃ increases; the concentrate mass percentage and WO₃ grade are 33.7% and 2.04% at the lowest water flow rate of 500 ml/min, but 15.5% and 3.24% at the highest 1,000 ml/min. Compared with 500 ml/min, the recovery of WO₃ at 750 ml/min is not different, but the mass percentage of the concentrate is 12% lower. Therefore, the separation efficiency using a rate of 500 ml/min is lower than that using 750 ml/min. In addition, the concentrate mass percentage using a flow rate of 1,000 ml/min is lowest at 15.5%, but the recovery of WO₃ is 24.7% lower than when using 750 ml/min. This is considered to be due to the change in water pressure and porosity. Therefore, it confirms that using a suitable water flow rate is an important factor, for improving the separation efficiency in jig separation. In this study, the effective water flow rate is 750 ml/min taking into account the mass percentage and WO₃ recovery of concentrate.

### 3.3 Number of scavenging

The purpose of jig separation is to increase the concentration of valuable minerals while minimizing the loss of valuable minerals to the tailing. For this reason, a scavenging process is required to re-treat the tailing generated by the rougher process. And so, the effects of number of scavenging on separation efficiency was examined.

In this section, the bed thickness and the water flow rate were fixed at 3 cm and 750 ml/min, and the effects of number of scavenging were observed. The jig process has two products, concentrate and tailing. Heavy product collected in the hutch of a jig are concentrate, marked U/F₁, and the light product overflowed out of the chamber is a tailing, which are marked as O/F₁. As the tailing (O/F₁) may still contain valuable minerals, it was processed again using the same conditions in the jig separator as used for the rougher, a process called scavenging, this time marking the products as U/F₂ and O/F₂. A secondary scavenging was performed on O/F₂ with the final concentrate, U/F₃, and final tailing, O/F₃, being the end products. Figure 5 shows that a large amount of WO₃ was distributed in the U/F₁ product. In the rougher process 90.3% of WO₃ was recovered, and 2.5% and 1.5% of WO₃ was recovered in the subsequent scavenging processes. It was also found that 5.8% of WO₃ was discarded to the final tailing (O/F₃). Based on these results, if the U/F₂ and U/F₃ products are mixed in with the U/F₁ product, the recovery of WO₃ can be increased by about 4%. However, the mass percentage of final concentrate also rose by 15.7%, with only a slight increase in the recovery of WO₃. It is therefore not recommended that that the U/F products recovered during the scavenging process be added to the final concentrate.

### 3.4 Analysis and evaluation of jig separation products

Various combinations of bed thickness, water flow rate, and number of scavenging were studied in jig separation, and the optimal conditions identified. The optimal conditions for jig separation in these experiments occurs when the thickness of the bed is 3 cm, the water flow rate is 750 ml/min, and without scavenging. Using these conditions, the
mass percentage, grade and recovery of WO$_3$ of the concentrate were 21.7%, 3.12% and 90.3% and those of the tailing were 78.3%, 0.09% and 9.7%, respectively.

In order to examine the particle size distribution and WO$_3$ distribution of concentrate and tailing, each product was classified in size ranges of +8 mesh, −8/+16 mesh, −16/+35 mesh, and −65 mesh (−210 μm). WO$_3$ grade and distribution analysis results are shown in Fig. 6. In the case of the concentrate, 80 mass% or more of WO$_3$ were distributed in under 1,000 μm size fractions, while in the case of the tailing, 80 mass% or more is distributed over 1,000 μm size. This means that particles with a high degree of liberation are moved to the concentrate, and the particles of large gangue mineral with a low degree of liberation are moved to the tailing. The figure shows that WO$_3$ grades tend to increase as the particle size increases in the concentrate, while the tailing shows opposite trends. Finally, the distribution of WO$_3$ is consistent regardless of particle size in the concentrate, but in the tailing, about 80% is found in particles larger than 1,000 μm. This is also inferred to be related to the liberation. In other words, it could be inferred that fluctuations in the contents of scheelite and gangue minerals, in accordance with the degree of liberation, may have an effect on the movement of particles.

In order to prove this hypothesis in detail, the sink and float test was performed on each product, concentrate and tailing. Tetrabromoethane (2.89 S.G.) and diiodomethane (3.32 S.G.) were used for the sink and float test. First, a certain amount of tetrabromoethane was put into a beaker and the feed added for the sink and float test. Using the sink product from this step, the sink and float test was repeated using diiodomethane. The products of −2.89 S.G, +2.89/−3.32 S.G, and +3.32 S.G. were recovered by the sink and float test and characteristics of these samples were examined.

Figure 7 shows the result of the sink and float test. In the case of the concentrate, most WO$_3$ (approximately 95%) is distributed in the +3.32 S.G. product. This, as previously described, demonstrates that the particles with some degree of liberation have moved toward the concentrate. In the case of the tailing, most WO$_3$ (approximately 68%) is distributed in the −2.89 S.G. product. This might also be related to the ratio of scheelite and gangue minerals in unliberated particles, or the fact that scheelite exists as fine particles that do not greatly affect the specific gravity of particles.

Figure 8 shows images of the products recovered by the sink and float test under UV (ultraviolet) light illumination. Blue-colored mineral particles are fluorescent particles of scheelite. As can be seen from the photographs, in the case of the concentrate, the scheelites are predominantly accumulated in the +3.32 S.G. product, and are distributed throughout all of the size fractions from fine particles to coarse particles. Some unliberated scheelites are also observed in the −2.89 S.G. and +2.89/−3.32 S.G. product. In the case of the tailing, a small amount of unliberated fine scheelites exists in gangue mineral, and a small amount of unliberated coarse scheelites is observed in the +3.32 S.G. product. These photographic images qualitatively demonstrate the results of jig separation according to particle size of products obtained.
separation and the sink and float test.

4. Conclusion

Scheelite, due to its brittleness, is ground easily into fine particles during the crushing process. Finer scheelite particles tend to be lost in the separation process for improving grade. In this study, jig separation was conducted for pre-concentration of scheelite crushed by coarse particles and the following conclusions were made.

(1) The sample is comparatively low-grade scheelite ore with 0.75% WO$_3$, and most of the gangue minerals are silicate minerals that contain SiO$_2$ and Al$_2$O$_3$, as high as 74.43% and 8.29%. Experiments were carried out using 0.21 to 5 mm samples, crushed to ~5 mm and screened with a 65 mesh sieve. As a result of the particle size analysis, the sample crushed to less than 5 mm is a comparatively coarser as over 28 mesh (590 μm) particles making up about 75% of total mass. The majority of WO$_3$ (approximately 85%) is distributed in +65 mesh products.

(2) The jig separation was performed using a laboratory scale plunger jig, and optimal conditions were determined and examined by varying the thickness of the bed, the water flow rate and the number of scavenging. Optimal conditions for jig separation occurred using a bed thickness of 3 cm, a water flow rate of 750 ml/min, and without scavenging. Using these conditions, the mass percentage, grade and WO$_3$ recovery of the concentrate were 21.7%, 3.12% and 90.3%, and those of the tailing were 78.3%, 0.09% and 9.7%, respectively.

(3) To examine the WO$_3$ distribution in the recovered concentrate and tailing, the characteristics in different particle sizes, the result of the sink and float test, and photographs of each product under UV light illumination were used. These experiments demonstrated that particle movement during jig separation is related to liberation. In other words, it should be considered that fluctuations in contents of scheelite and gangue minerals, in accordance with the degree of liberation, may have an effect on the movement of particles.

(4) In conclusion, when low-grade scheelite ore (0.75% WO$_3$) crushed by coarser particles is pre-concentrated using jig separation, a concentrate at a mass percentage of about 22%, a WO$_3$ grade of about 3.1% and WO$_3$ recovery of about 90% can be obtained. Therefore, if this concentrate were to be supplied to the next separation process, improvements in grade, economic feasibility, and separation efficiency can be expected compared with a sample that has not been pre-concentrated.

Acknowledgments

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