SELECTIVE DESLIMINGS OF FINE IRON ORES BASED ON AGGREGATION BETWEEN MAGNETITE AND HEMATITE

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ABSTRACT

Hematite fines were found to form aggregates with magnetite particles in the same slurry, without the help of any flocculants. Because of this aggregation, fine iron ores containing hematite and magnetite can be successfully concentrated by multi-stage deslimings, provided that the ore is finely ground and silicate gangues properly dispersed. The effectiveness of this technique has been tested on a commercial scale (100 ton/h). The increased magnetic attraction between magnetite and hematite due to the terrestrial magnetization of magnetite and its size effect are revealed as responsible for the aggregation, considering the fact that the hematite-magnetite system is already in relatively weak dispersion because of their low zeta potentials.

INTRODUCTION

A large part of the iron resources in the world occurs as low-grade finely disseminated hematite ores with magnetite often in association. This is particularly true in the case of ores in China and the United States. To make use of such resources, some simple and efficient concentration methods are indispensable because of the large quantities and low price of iron ores. Desliming and selective flocculation by use of natural and synthetic polymers has been studied extensively for separating hematite fines from gangues [1,2], but selective flocculation of real ores is achieved with difficulty because the bridging mechanism responsible for polymer flocculation makes the process very sensitive to changes in the chemical conditions in the solution as well as on the surface of the mineral particles. This is especially true if the ore is a complex one or contains soluble species. As a result, few cases of selective flocculation have been reported on a commercial scale.

An innovative method for recovering fine iron ores is reported in this paper. It was found that selective desliming of fine hematite ores is easily achieved if certain amount of magnetite (either associated in the same ore or extraneously added) is present in the feed, and the silicate gangue is properly dispersed (by pH adjustment and use of such common dispersants as sodium silicate and sodium hexametaphosphate). In this process, the sedimentation of iron ore particles is enhanced by the formation of aggregates among hematite and magnetite particles even without any flocculants. For
commercial tests (100 ton/h), an iron concentrate assaying >65%Fe was produced at 85% recovery from a feed containing 40%Fe by fine grinding and multi-stage deslimings with caustic soda and sodium silicate added to the ball mills and the conditioning tanks to disperse the silicate gangues. Results obtained using this technique are presented here and the mechanism of aggregation between hematite and magnetite is discussed.

MATERIALS AND METHODS

Pure hematite, magnetite and augite (silicate gangue) were hand-picked at Baiyun E-bo Mine in Inner Mongolia, China. These minerals were further enriched by gravity means to yield 95% pure samples. Ore sample (A) of 42% Fe with magnetite and hematite in an approximate ratio of 1:1 was taken from Baotou Concentrator in China. Because of the complex mineralogical composition (114 minerals were commonly found in the deposit) and fine dissemination, various conventional concentration methods and their combinations attempted during the last two decades could produce only a concentrate assaying 55-58% Fe at a recovery of 60-70%. Most of the hematite was lost in the tailings as fine particles.

Another ore sample (B) of 31.5% Fe was prepared from ore sample A by removing magnetite using low intensity magnetic separation at $H = 800$ Oe. X-ray diffraction analysis showed hematite, augite, quartz, fluorite and carbonates as the main minerals. This sample was ground in a steel ball mill to 98% passing 400 mesh in tap water (hardness 140 ppm) and then dewatered and dried at 40 °C for future use.

Selective desliming of pure minerals and ore sample B were carried out in a 40 ml settling tube using 3-gram batches. The pulp was agitated in a 100 ml conditioning tank under 20% pulp density for 15 minutes (impeller diameter 15 mm, speed 1500 rpm) and then diluted to 11% pulp density for desliming. The experiments were conducted in distilled water. For selective desliming tests of ore sample A, 90 gram samples were ground with sodium silicate and sodium hydroxide in a steel ball mill at 50% pulp density. The slurry was then transferred to a 500-ml glass beaker and diluted to 11% for desliming by settling-and-syphoning method. All the experiments with this sample were conducted in tap water (hardness 140 ppm).

RESULTS AND DISCUSSION

Selective Desliming

The results of desliming tests with pure mineral mixtures are shown in Figure 1. The addition of fine magnetite markedly increases the recovery of hematite in the settled products. For each test, the silicate gangue mineral, i.e. augite, was fixed at 1 gram. The total amount of magnetite and hematite, with their ratio at different levels, was maintained at 2 grams. Magnetite was almost exclusively found in the settled products. The aggregates of magnetite and hematite under microscope were found to be in the 100 - 200 micrometer size range.

Desliming results with ore sample B in the presence of added fine magnetite and ferrite powder as aggregation media are shown in Figure 2. It is seen that both
magnetite and the ferrite powder can increase the recovery of hematite. The -1.5 µm ferrite powder, manufactured for making permanent magnets, was of the magnetic domain size and thus was a collection of magnetic particles. The effectiveness of ferrite powder for desliming purposes suggested that magnetic force was important in the aggregation process.

FIG. 1. Effect of fine magnetite addition on desliming of pure mineral mixtures. Augite -20+10 µm; hematite -20+10 µm; NaOH 200 mg/l, Na$_2$SiO$_3$ 500 mg/l, pH11.5.

FIG. 2. Effect of fine magnetite and ferrite powder addition on desliming of ore sample. - - - - , -1.5 µm ferrite powder as aggregation medium; - - - - , -7 µm magnetite as aggregation medium; NaOH 200 mg/l, Na$_2$SiO$_3$ 500 mg/l, pH11.5.
The fineness of magnetite was found to be an important parameter for improving recovery in desliming experiments. It is seen from Figure 3 that finer the magnetite, higher is the iron recovery, while the grades remain the same.

Figure 4 shows that agitation intensity was not a critical factor in this case. This rules out shear flocculation or hydrophobic flocculation[3,4], which require strong agitation to provide particles with energy to overcome the potential barriers, as a possible mechanism for aggregation between magnetite and hematite.

The effect of sodium hydroxide and sodium silicate on desliming of ore sample A is shown in Figure 5. It is seen that sodium silicate alone (not NaOH) is effective for achieving selective desliming at high dosage by simultaneously increasing the recovery and grade. In practice, however, sodium hydroxide is used together with sodium silicate so that the pH can be easily adjusted to above 9 and excessive addition of sodium silicate is avoided. Experiments with pure augite showed that the role of sodium silicate and pH adjustment is to eliminate the nonselective coagulation effects of such cations as Fe$^{3+}$, Ca$^{2+}$, and Mg$^{2+}$. Other dispersants such as sodium hexametaphosphate or humates were also found to be effective for selective desliming.

Results obtained for the five stage desliming of ore sample A in tap water (hardness 140 ppm) are given in Table 1. Locked-circuit tests (slime II, III, IV and V returned to their preceding desliming stages), yielded a concentrate of 65.52% Fe at 86.87% iron recovery. Reagent consumption was observed to be at 3.3 kg/t NaOH and 5.6 kg/t sodium silicate for locked-circuit tests.

![FIG. 3. Effect of magnetite fineness on desliming of ore sample B. Magnetite addition = 20% of the total feed; NaOH 200 mg/L, Na$_2$SiO$_3$ 500 mg/L, pH 11.5.](image-url)
AG, 4. Effect of pulp agitation on desliming of ore sample B. Agitation time = 15 min; magnetite (-7 μm) = 20% of the total feed.

FIG. 4. Effect of pulp agitation on desliming of ore sample B. Agitation time = 15 min; magnetite (-7 μm) = 20% of the total feed.

FIG. 5. Effect of NaOH or Na₂SO₃ addition on desliming of ore sample A. Tap water hardness 140 ppm.
### TABLE I. Results for five-stage desliming of ore sample A.

<table>
<thead>
<tr>
<th>Product</th>
<th>Yield % Wt</th>
<th>Grade %Fe</th>
<th>Recovery %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slime I</td>
<td>25.05</td>
<td>10.20</td>
<td>6.07</td>
</tr>
<tr>
<td>Slime II</td>
<td>10.61</td>
<td>14.10</td>
<td>3.56</td>
</tr>
<tr>
<td>Slime III</td>
<td>5.50</td>
<td>19.60</td>
<td>2.56</td>
</tr>
<tr>
<td>Slime IV</td>
<td>3.34</td>
<td>26.50</td>
<td>2.10</td>
</tr>
<tr>
<td>Slime V</td>
<td>2.45</td>
<td>46.95</td>
<td>2.73</td>
</tr>
<tr>
<td>Concentrate</td>
<td>53.05</td>
<td>65.80</td>
<td>82.97</td>
</tr>
<tr>
<td>Feed</td>
<td>100.00</td>
<td>42.07</td>
<td>100.00</td>
</tr>
</tbody>
</table>

#### Mechanism of Aggregation Between Magnetite and Hematite

It is known that flotation and surface characteristics of magnetite are essentially the same as those of hematite[5-7]. The aggregation between magnetite and hematite therefore cannot be explained solely on the basis of their surface properties. However, considering the fact that aggregation is normally obtained if the zeta potential is less than 14 mV [8], the zeta potential values of magnetite and hematite (≈ -30 mV as shown in Figure 6) make them in weak dispersion [9] and aggregation may therefore be possible by providing some extra-force. Magnetic attraction between magnetite and hematite is considered to be the reason here as suggested by the effectiveness of ferrite powder as aggregation medium (Figure 2).

![Zeta potentials of pure minerals as a function of pH, 10^{-3} M KNO₃.](image)

**FIG. 6.** Zeta potentials of pure minerals as a function of pH, 10⁻³ M KNO₃.
To understand the magnetic attraction between magnetite and hematite particles, a model spherical magnetite particle with uniform terrestrial magnetization, $M$, was selected and the coordinates were set as shown in Figure 7, with $M$ in $z$ axis direction. The particle is hypothetically sliced into laminae perpendicular to the $z$ axis. Each of the laminae can be equalized by equivalent surface current theorem[10] into a circle carrying electric current $dI$:

$$dI = M \sin \theta \, dS \tag{1}$$

An electric current circle of this type gives magnetic induction, $dB$, on $z$ axis at point $P$ as[11]:

$$dB = \frac{\mu}{4\pi} \frac{r^2 \, dl}{(r^2 + (1-z)^2)^{3/2}} \tag{2}$$

Integrating the contributions of each laminae yields $H$ at point $P$:

$$H = \frac{B}{\mu} = \frac{M}{2\mu} \left( 5 \frac{R}{l} \right)^3 + 3 \left( \frac{R}{l} \right) \right) / 6 \tag{3}$$

and

$$\text{grad}H = \frac{dH}{dl} = -M \left( 5 \frac{R}{l} \right)^4 + \left( \frac{R}{l} \right)^2 \right) / 2R \tag{4}$$

$$H_{\text{grad}H} = -M^2 \left( 25 \left( \frac{R}{l} \right)^7 + 20 \left( \frac{R}{l} \right)^5 + 3 \left( \frac{R}{l} \right)^3 \right) / 12R \tag{5}$$

Where
- $M$ - Terrestrial magnetization of magnetite
- $R$ - Radius of spherical magnetite particle
- Distance from the center of the magnetite sphere to point $P$ on $z$ axis ($l > R$)

**FIG. 7. Model magnetite particle for magnetic calculation.**
The calculated results of eq.(4) and (5) are shown in Figures 8 and 9, respectively. It is seen that both $|\text{grad} H|$ and $|\text{Hgrad} H|$ near the surface of a magnetite particle increases significantly when the particle size is less than a certain value. This phenomenon is similar to the "High Gradient Effect" of steel wool or other magnetic matrices in high gradient magnetic separators and is in agreement with the experimental results that finer magnetite can attain better desliming results (Fig. 3). Terrestrial magnetization for calculation is taken as low as 1040 A/m (0.2 emu/g), but the $|\text{grad} H|$ at the surface of a 10 $\mu$m magnetite particle can be as high as $6.24 \times 10^9$ A/m (7.8 Tesla/cm). This is of the same order as the value of up to 10 Tesla/cm that can be reached in high gradient magnetic separators [12]. Also taking into account the relatively weak electrical repulsion between magnetite and hematite because of their low zeta potentials, we may conclude that the increased magnetic attraction in the fine particles size region is sufficient to bring the particles into aggregation. Further support to this consideration is that aggregation of hematite fines (1.2 $\mu$m) can be obtained by weak geomagnetic fields [13].

![FIG. 8. Calculated $|\text{grad} H|$ by eq.(4). $M=1040$ A/m.](image1)

![FIG. 9. Calculated $|\text{Hgrad} H|$ by eq.(5). $M=1040$ A/m.](image2)

Because of the magnetic nature of the attraction between the magnetite and the hematite, the desliming process is quite insensitive to the chemical properties of the slurry. Selective separation is therefore possible even with complex ore systems and in the presence of hard water (140 ppm). We have tested iron ores containing magnetite and hematite from various sources and selective desliming results were always achieved. This is attributed to the fact that the magnetic properties are intrinsic to these minerals and therefore the aggregation is to a large extent independent of the origin of the minerals. Also because of the magnetic nature of aggregation, applied magnetic fields were found in our experiments as beneficial to the desliming process by enhancing the settling rate of the aggregates. But no applied field was used for all the tests reported in this paper.
CONCLUSIONS

A selective desliming process for recovering fine iron ores without using any
floculant has been developed. The main feature of the process includes use of fine
magnetite to aggregate hematite particles. Aggregation is revealed to be related to the
terrestrial magnetization of magnetite. Magnetic attraction on hematite is higher in the
fine particle size region due to the "High Gradient Effect". This aggregation is
analogous to the capturing process of hematite fines to wire wool or ball bearing
matrices in high gradient magnetic separators. This technique is especially suitable for
fine iron ores containing magnetite and hematite, but it can also be used for hematite-
only ores by adding extraneous magnetite that can be recycled.

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