ABSTRACT

Iron ore pellets use bentonite clay as binder at dosages from 0.5 to 1.0% (10 to 20 pounds per ton) of moist iron ore concentrate. Bentonite is typically shipped hundreds of miles from Wyoming to the Lake Superior iron ore district. It is therefore best to know how effective a bentonite will be before it is shipped and used to bind concentrate into pellets. Current tests of bentonite effectiveness include: plate water absorption, methylene blue uptake, free swell, exchangeable cations, and glycolated layer expansion. However, these tests have many disadvantages: First, they only measure the ability of a bentonite to expand, disperse, or absorb, not how well it will bond. Second, most of the tests require up to 20 hours to perform. Bentonite only has a few minutes to interact within the concentrate before it is indurated (sintered). These long-term tests may not reflect the true behavior of bentonite. Third, the tests are tedious and often results are inconsistent between different iron ore concentrates, labs, and technicians. Fourth, some of the testing equipment is difficult to procure. Fifth, procedures are often difficult to standardize. In this paper, the Binder Effectiveness Strength (BESt) test to evaluate binders for iron ore pellets is presented that: measures the ability of bentonite to bond, requires only about two hours to complete, is simple and reproducible, and utilizes readily available equipment that has been standardized for decades.

INTRODUCTION

Bentonite clay is used to bond iron ore concentrates into pellets. The clay is a significant cost item, with individual plants spending US$3-5 million for bentonite annually. These bentonites are evaluated by the amount of water that they can absorb, measured by the plate water absorption (PWA) test. The PWA value is the weight percent of distilled water a bentonite absorbed over 18 hours (ASTM E946-92 1996). However, in the pellet plants, the bentonite does not have 18 hours to absorb water. The bentonite binder only has a few minutes to absorb moisture from the concentrate before the pellets are formed, dried, and fired. The PWA test has been discontinued as an ASTM standard, but is still used in the iron ore industry because there is no alternative. However, a better test is needed because, it was shown in laboratory tests that PWA did not correlate with pellet strength (Kawatra and Ripke, 2002).

Water Chemistry

Iron ore concentrators produce a 60% solids iron ore concentrate that is then dewatered by vacuum filtration to 10% moisture. In previous work, the authors have shown that water chemistry is very important to pelletizing and strongly affected pellet strengths. It was also discovered that calcium was concentrated 500 times more in the moisture remaining in the filtered concentrate than the water filtered from it. Calcium is known to decrease the effectiveness of bentonite. Since the PWA test uses distilled water only, it does not account for cations present in the iron ore concentrate moisture, even though these cations will be present in large quantities in the plant. These cations have been shown to significantly reduce the amount of water a bentonite can absorb. More importantly, these cations reduced the effectiveness of bentonite to bond iron ore pellets, decreasing dry pellet compressive strength by 46% (Ripke and Kawatra, 2002).

Binder Effectiveness Strength (BEST) Test

The BEST test was designed to measure the relative amount of strength that a bentonite would contribute to the dry compressive strength of an iron ore pellet without actually having to make iron ore pellets. Until now, there was no test that could accurately predict the amount of strength that a bentonite would provide to a dry iron ore pellet. Not even a laboratory procedure for making iron ore pellets could be agreed upon. This is primarily because iron ore concentrates vary significantly from mine to mine and when pellets are made in a laboratory, their strengths varied widely from different operators and labs. Currently, only the amount of water that a bentonite can absorb, measured by the PWA test, is used to characterize and select bentonites for iron ore pelletizing. However, previous work by the authors has shown that PWA is not a good predictor of the strength a bentonite will provide to a dry iron ore pellet.

Iron ore concentrates differ in their particle size and morphology, moisture chemistry, and composition. This was one of the major stumbling blocks in attempting to make a standard pelletization procedure, as no single ore could be specified as a standard substrate. Therefore, for this test, standardized silica sand and glass shot were selected for the substrate to be bonded by the bentonite matrix.
EXPERIMENTAL

In order to develop a useful bentonite quality test, pelletization data was needed for several bentonites with different characteristics. Five different bentonites were selected from an iron ore company for evaluation. First, iron ore pellets were made with each bentonite used as binder. The dry compressive strengths that each bentonite gave to the pellets were determined.

Then, an alternative test needed to be designed that would correlate with the strength that a bentonite would provide to the iron ore pellets. The foundry industry also uses the bentonite/ water system to bond sand into foundry molds. The American Foundry Society has standard equipment and tests that measure the strength that a bentonite will give to a foundry mold. Therefore, these tests had an excellent chance to be adapted to measuring the effectiveness of bentonite in iron ore pelletization. Therefore, the standard American Foundry Society (AFS) testwork was adapted to measure the strength that each bentonite gave to standard test specimens. During these experiments, mixing procedures, material types and dosages were optimized into the Binder Effectiveness Strength (BESt) test to evaluate binders for iron ore pelletization, as presented in this paper.

Materials

The magnetite concentrate for these experiments was obtained from an iron ore concentrator located in the Lake Superior district of the U.S. The concentrate had 10% moisture, a particle size of 80% passing 25 microns (500 mesh), a Blaine specific surface area of 2200 cm²/gram, and contained 4.9% silicate gangue.

The foundry sand was obtained from Badger Mining Co. characterized by a grain fineness number (GFN) of 55.

The glass shot had a spherical morphology. The particle size was 80% passing 121 microns with a narrow size distribution of 95% of the material between 62 and 176 microns. It had a BET specific surface area of 268 cm²/gram.

Bentonite clay binder samples were obtained from the Cleveland-Cliffs industrial research laboratory. The bentonites were Na-montmorillonite clays that were mined from the Western United States. Particle size distributions of the bentonites are shown in Table I.

Equipment

A 4.3 liter (4.5 quart) household style kitchen mixer, operating at 60, 140, and 220 rpm, was used to mix the materials together. The mixer had a reverse orbital motion of 2.25 times the rpm speed of the mixing impeller.

Standard American Foundry Society (AFS) testing equipment was used to prepare compressive strength specimens for comparison to iron ore pellets made in the lab.

Table I: The 10%, 50%, and 80% wet passing sizes of the five bentonites studied. Dry screen analysis gives the weight percent passing 75 microns (200 mesh) and 45 microns (325 mesh).

<table>
<thead>
<tr>
<th>ID#</th>
<th>Bentonite PWA, %</th>
<th>Size distributions in distilled water suspension by microtrac, microns</th>
<th>Dry screened weight% passing 75 microns</th>
<th>45 microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>871</td>
<td>1.7 4.4 8.3</td>
<td>83.6</td>
<td>60.5</td>
</tr>
<tr>
<td>2</td>
<td>751</td>
<td>1.5 4.0 9.7</td>
<td>88.7</td>
<td>67.1</td>
</tr>
<tr>
<td>3</td>
<td>733</td>
<td>1.6 4.5 15.0</td>
<td>87.3</td>
<td>70.8</td>
</tr>
<tr>
<td>4</td>
<td>717</td>
<td>1.7 4.7 12.9</td>
<td>91.0</td>
<td>73.3</td>
</tr>
<tr>
<td>5</td>
<td>556</td>
<td>1.8 5.3 14.1</td>
<td>83.7</td>
<td>61.0</td>
</tr>
</tbody>
</table>

Procedures

Iron Ore Pelletization

The procedure used for forming pellets was developed by industry to closely reproduce the conditions that exist in the full-scale plant. This procedure was described in the earlier publications (Ripke and Kawatra, 2000; Kawatra and Ripke, 2001) and for reasons of brevity will not be repeated here. The dry compressive strengths of the pellets were measured (ASTM E382, 1998). The pellets were completely dried at 105°C (221°F) for at least 1 hour; single pellets were then compressed using an Instron compression test machine. The peak load required to fracture the pellet was recorded. This procedure was performed on 20 pellets, and the results were averaged. This test measured the ability of dried pellets to survive handling during the firing process. The dry pellet strengths should be at least 22 newtons (5 pounds force) per pellet and is the most critical measurement of bentonite binder performance.

For each value reported, the mean and standard deviation were determined for 20 pellets. The error bars shown on the graphs represent the 95% confidence intervals (P95) calculated using the t-distribution, as described in standard statistics texts (Dixon and Massey, 1983).

Binder Effectiveness Strength (BESt) Test

Since there was no standard iron ore concentrate, a standard substrate was needed for the test. The substrate itself should not influence the strength of test specimens. It should have the following qualities:

1. reactivity - an unreactive material can allow variations of solution chemistry without reaction problems.
2. particle size - the substrate should have a tight size distribution, to minimize effects of differential packing.
3. uniform shape - to minimize the effects of mechanical locking and packing differences.

It is important to have a simple and reliable test that can be used to predict the performance of a bentonite in iron ore pelletization.

Water chemistry strongly affects the effectiveness of bentonite. Therefore the BESt test uses water with a chemistry that is representative of that remaining in the iron ore concentrate that the bentonite will be used to bond.

The procedure for the BESt test was developed from the work presented here and is described in the Results & Discussion section. This test was adapted from tests developed by the American Foundry Society (AFS). The AFS has developed standards for testing the quality of foundry sands used for metal casting molds. Foundry molds are composed of sand, water, and binder, very similar to the iron ore, water, and binder system found in iron ore pelletization. In fact, bentonite is a common binder for each system. The BESt test was...
Development of the Binder Effectiveness Strength (BEST) Test

The bentonite to water ratio for the binder was maintained according to that used to bond iron ore concentrate into pellets in the industrial plants; at an iron ore concentrate moisture of 10%, bentonite is added at 0.66%. Therefore the weight ratio of water to bentonite was 15:1.

Initial experimental work was used to determine the appropriate bentonite dosage. Specimens were made at dosages of 6.0% and 1.5% bentonite. A linear extrapolation was used to determine that a bentonite dosage of 2.5% for the AFS strength specimens corresponded to the typical compressive strength obtained in an iron ore pellet, at 1/4 inch diameter cross-sectional area. Therefore the following tests all use binder dosages of 2.50% bentonite and 37.9% water.

Initial experimental work was also used to determine the type of water to be used. Specimens made with "high-salt" water having the same concentration of cations as the moisture remaining in the iron ore concentrate correlated much better with pellet strength than specimens made with distilled water. This also agreed with the previous work noted earlier. The cationic concentrations of the moisture remaining in the concentrate is compared to the plant filtrate water and tap water in Table III.

Procedure for analyzing the dissolved cations

The iron ore concentrate used in this paper had a pH of 10.5. At this high pH, the magnetite surface had a negative charge and cations were adsorbed on the magnetite particle surface. When distilled water at a pH of 5.5 was used, the magnetite surface charge became positive and the cations were removed.

Water was extracted for analysis from the as received iron ore concentrate by first mixing fifty grams of the magnetite concentrate containing 10.2% moisture with 100 grams of distilled water. This suspension was filtered to recover the water. The resulting water sample contained the cations originally present in the moisture contained in the concentrate, diluted by a factor of 20.6 by the added distilled water. The water was sent for analysis by a certified laboratory, and the 20.6 dilution factor was used to back-calculate the original concentrations of cations in the filter cake moisture.

The "high-salt" water was prepared with the same concentrations of cations as the magnetite concentrate moisture and both had a pH of 10.5

Mixing procedures were optimized to get the most uniform mix without significant drying or loss of materials. Not enough mixing would give non-homogenous specimens with a wide range in the data. Too much mixing dried the material, making it too dry before specimens could be formed, weakening the specimens. Mixing too fast would blow the bentonite out of the mixer. The materials were mixed according to the following procedure:

1. Mix 37.9 grams of water high-salt plant water with 1000 grams of substrate (sand or glass shot) at 60 rpm for 30 seconds.
2. Stop the mixer and add 25.00 grams of bentonite. Mix at 140 rpm for 2 minutes.
3. Mix at 220 rpm for 30 seconds.

Then, the mixed material was formed into 5 cm x 5 cm (2 inch by 2 inch) cylindrical test specimens according the AFS procedures for testing foundry sand mold strengths.

The first set of tests were conducted with silica sand as the substrate, high-salt water, and bentonite. The high-salt water was used because distilled water is not representative of the moisture remaining in the iron ore concentrate and would only be of academic interest. This BEST test was developed in order to be useful to industry; The results are shown in Figure1. The correlation between the specimen strength and the pellet strength from this first set of tests was not very good. Using silica sand as a substrate did not provide a test that could accurately predict the effectiveness of a bentonite for iron ore pellets. It was hypothesized that the poor correlation was from: 1) mechanical locking between the silica grains from their irregular shape and/or 2) differential packing due to the broad particle size distribution of the sand. Since using a smooth substrate with a narrower size distribution would eliminate these effects, glass shot was selected for the remaining experimental work.

The final set of tests were conducted by making AFS specimens with glass shot as the substrate, the high-salt water, and bentonite. The effectiveness of the bentonite was determined by measuring the dry compressive strength of the AFS test specimens. These strengths were then compared to the strength of the pellets made with the same bentonites. The results shown in Figure 2 show a very good correlation between iron ore concentrate pellet strength and the AFS specimen strength when glass shot was used. Therefore, this test can be used to accurately predict the effectiveness that a particular bentonite will impart to the strength of iron ore pellets.

The Binder Effectiveness Strength (BEST) Test

1. Analyze the chemistry of the water remaining in the iron ore concentrate that the bentonite will be used to bond. The procedure for analyzing the dissolved cations was described earlier.
2. Prepare water with the same pH and cation concentrations as the water remaining in the iron ore concentrate. Use this “high-salt water” for preparing strength-test samples for the BEST test.
3. Mix 37.9 grams of the high-salt plant water with 1000 grams of glass shot substrate at 60 rpm for 30 seconds.

Table II: Strengths of iron ore pellets made with the different bentonites at 0.66% bentonite dosage

<table>
<thead>
<tr>
<th>ID#</th>
<th>Bentonite PWA, %</th>
<th>Pellet Strength +/- P95 lbf</th>
<th>P95 newtons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>871</td>
<td>8.4 +/- 0.5</td>
<td>37.4 +/- 2.2</td>
</tr>
<tr>
<td>2</td>
<td>751</td>
<td>6.1 +/- 0.3</td>
<td>27.1 +/- 1.3</td>
</tr>
<tr>
<td>3</td>
<td>733</td>
<td>7.9 +/- 0.4</td>
<td>35.1 +/- 1.8</td>
</tr>
<tr>
<td>4</td>
<td>717</td>
<td>9.7 +/- 0.5</td>
<td>43.1 +/- 2.2</td>
</tr>
<tr>
<td>5</td>
<td>556</td>
<td>5.0 +/- 0.2</td>
<td>22.2 +/- 0.9</td>
</tr>
</tbody>
</table>

Table III: Ionic concentrations of water samples. Values are reported as mg/L (ppm).

<table>
<thead>
<tr>
<th>Ion</th>
<th>Mag. conc. moisture (undiluted)</th>
<th>Plant filtrate water</th>
<th>Tap water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>5088</td>
<td>9</td>
<td>40</td>
</tr>
<tr>
<td>Magnesium</td>
<td>5995</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Potassium</td>
<td>1680</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Sodium</td>
<td>725</td>
<td>151</td>
<td>17</td>
</tr>
<tr>
<td>Sulfate</td>
<td>803</td>
<td>54</td>
<td>21</td>
</tr>
</tbody>
</table>
4. Stop the mixer and add 25.00 grams of bentonite. Mix at 140 rpm for 2 minutes.
5. Increase mixer speed to 220 rpm and mix for another 30 seconds.
6. Form the mixed material by ramming 3 times into a 5 cm x 5 cm (2 inch by 2 inch) cylindrical test specimen holder according the AFS procedures for testing foundry sand mold strengths. Typically between 150 and 170 grams of the glass shot, bentonite, and water mixture was needed to form specimens of the proper height. Six individual strength test specimens can be made.
7. Remove the specimens from the ramming machine and specimen holder while slightly twisting to reduce surface imperfections. Carefully set the specimens on a flat pan and place in an oven at 105°C oven until completely dried.
8. Crush the specimens in the AFS compression testing machine and record their strength.

CONCLUSIONS

• The Binder Effectiveness Strength (BEST) test for iron ore pellets accurately correlated with the compressive strength of dry iron ore pellets. The test measured the ability of bentonite to bond, required only about two hours to complete, was simple and reproducible, and utilized readily available equipment that has been standardized for decades.
• This test can be conducted at or near the bentonite mine and used to select bentonites for iron ore pelletizing before they are shipped.
• When silica sand was used as the substrate, the strengths did not correspond well to the pellet strengths. However, specimens made with glass shot corresponded well.

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REFERENCES


Figure 2. Comparison between the strength of iron ore concentrate pellets and glass shot AFS specimens made with the high-salt water to simulate the chemistry of the water remaining in the iron ore concentrate. Each data point corresponds to a particular bentonite sample. The correlation is good; this test was an accurate predictor of the strength that a particular bentonite gave an iron ore pellet. The linear equation represents the least-squares fit and is represented by the dashed line through the data. The $R^2$ value is the coefficient of determination. The AFS specimen error bars represent the 90% confidence interval. The pellet strength error bars represent the 95% confidence interval.