Studies on the relationship between plate water absorption and unfired iron ore pellet strength

S.K. Kawatra and S.J. Ripke
Professor and Ph.D. student with the Department of Chemical Engineering, Michigan Technological University, Houghton, Michigan

Abstract
Bentonites vary in their ability to absorb water. The plate water absorbance (PWA) test measures the amount of water that a bentonite can absorb. Plant operators disagree on whether or not the PWA value is a good predictor of how a bentonite will perform as a binder. In this study, experiments were conducted to determine the relationship between the bentonite PWA value and the dry compressive strength of iron ore pellets. Pellet strength correlated poorly with the standard PWA test results, where bentonites are allowed to absorb distilled water for 18 hours. Correlations improved, but remained marginal, when PWA was measured in water having high concentrations of cations, representative of the water that remains in the iron ore during pelletization.

Key words: Iron ore processing, Taconite pellets, Bentonite clay, Plate water absorbance test

Introduction
There are several iron ore pelletization plants located in the Lake Superior District of the United States. These plants use rotary pelletizing drums to agglomerate fine moist iron ore concentrates. Bentonite clay is typically added as a binder, and pellets are completely formed within about two minutes. Bentonites are ranked according to their ability to absorb distilled water, as measured by the plate water absorption (PWA) test. For the PWA test, bentonite is allowed to absorb distilled water for 18 hours. Opinions vary from plant to plant regarding the usefulness of PWA on pelletization. The following important questions remain unanswered: Should PWA be measured at a few minutes instead of at 18 hours? Should the industry continue to measure PWA with distilled water or should it switch to the type of water remaining in the concentrate?

Recent work by the authors has shown that the water remaining in the concentrate has a very high concentration of cations that reduced the effectiveness of the bentonite (Ripke and Kawatra, 2002). High concentrations of these cations have been shown to strongly affect the strength of unfired pellets (Rice and Stone, 1972). The purpose of this study was to determine if PWA could be correlated with pellet strength. PWA was measured with both distilled water and high-salt water, similar to the water remaining in the iron ore during pelletization. PWA values were measured after only a few minutes and again after the standard 18 hours.

Background
The current iron ore concentrate pelletization practice was developed in the 1950s when bentonite clay became established as the most acceptable binder. Over the past 50 years, iron ore pelletization has generally expanded, while the high-quality western-type bentonite reserves (located within the United States) have been depleted, allowing lower-quality bentonites to be marketed. Bentonite is used primarily for improving an iron ore concentrate pellet's dry compressive strength, so that the pellets can survive handling, drying and firing. The minimum industrially acceptable dry pellet compressive strength is typically 22 N (5 lbf). A typical dosage of bentonite is 0.66% or 6.6 kg/t (15 lb/long ton) of moist iron ore concentrate filter cake (typically 10% moisture). Adding more bentonite is a disadvantage because pellets containing more bentonite cost more to produce and have higher silica contents. This gives the industry incentive to use bentonites that can produce adequate strength at lower dosages. The amount of water a bentonite absorbs is related to the types of exchangeable cations it contains.

A bentonites bonding quality is widely believed to be related to its ability to absorb water, as measured by PWA (plate water absorbance). Bentonite is composed of discrete platelets that are separated by an exchangeable cation layer. Water molecules can hydrate the cations and the surfaces of the platelets allowing the bentonite to absorb water and expand. Sodium-bentonites have sodium exchangeable cat-
ions and calcium bentonites have calcium exchangeable cations. These two bentonites behave quite differently. Sodium bentonites are more highly absorbent than calcium bentonites. This is because the divalent calcium ions hold the clay platelets more strongly together, allowing less water to be absorbed between the platelets, compared to the monovalent sodium cations. When calcium exchanges with sodium between bentonite clay platelets, the platelets are bonded more strongly together. This restricts the bentonite from expanding and dispersing into a gel and, thus, improves the pellet’s plasticity, thereby, increasing the wet knock value of the pellet. Different bentonites can absorb water at different rates. For example, Fig. 1 shows that, while calcium bentonites initially absorb water at a faster rate, sodium bentonites absorb much more water overall. Sodium-rich bentonites are important binders for iron ore pelletization, while calcium-rich bentonites are assumed to be much less effective and are not often used in this application. Bentonites with a ratio of 2:3 calcium to sodium tend to provide the best pellet strengths. Some calcium content is necessary to provide bonding strength between the bentonite and the iron ore. A pure sodium bentonite can expand and disperse more easily but would not have the bonding strength provided from the calcium ions (Iwasaki, 1999).

**Bentonite binding mechanisms.** Bentonite is a mixture of layered hydrated alumino-silicate clay that is primarily composed of the smectite class mineral montmorillonite. The ideal chemical formula for montmorillonite is (Na,Ca)0.33(Al1.67Mg0.33)Si4O10(OH)2.nH2O. Isomorphic substitution of Al³⁺ by Mg²⁺ alters the crystal-charge balance, giving the lattice a net negative charge. This results in adsorption of cations (commonly Na⁺ and Ca²⁺) to balance the charge. The hydration of these exchangeable interlayer cations causes the bentonites to expand on wetting (Reisch, 2000).

Bentonite increases the dry strength of iron ore pellets in two ways. First, it acts as colloidal material that decreases interparticle distances, thus increasing the van der Waal’s forces. Second, it forms a solid bridge of hardened gel that strengthens particle contact points. Explanations of bentonite bonding are available in the literature (Smiernow et al., 1980; Wilson, 1980; Elzea and Murray 1994). The mechanisms of bentonite bonding have been further explained in previous works by the authors (Ripke and Kawatra, 2000a, 2000b). An additional novel bentonite bonding mechanism was identified (Ripke and Kawatra 2003c) and is summarized as follows: When bentonite clay is moistened, it begins expanding and the bonds between the individual platelets becomes relaxed, allowing the platelets to slip across each other and spread like a deck of cards pushed across a table. A specific mixing type efficiently distributed the clay particles into fibers and sheets over the surface of the material being bonded. Utilization of this mechanism allowed dry pellet compressive strengths to be doubled or allowed compressive strengths to be maintained while reducing bentonite dosage by half.

In either case, the bonding mechanism relies on the ability of bentonite platelets to expand, then either disperse or slip. This expansion is directly related to the amount and type of interlayer cations present between the clay platelets. Bentonites with sodium exchangeable cations tend to expand much more than bentonites with calcium exchangeable cations. This is a concern because PWA may be related to the ability of a bentonite to expand, which in turn may be related to its bonding ability.

**Bentonite evaluation.** The plate water absorbance (PWA) value, determined by a laboratory test, is a measure of the absorbency of bentonite. The test determines how much water is absorbed by 2.00 g of bentonite over 18 hours. The result is expressed as a percentage of bentonite weight.

After extensive visits to all pelletizing plants in the United States, it was determined that there is disagreement about how bentonite PWA is related to pellet strength. Some plant operators believe that bentonites with higher PWA values produce prefired pellets with higher dry compressive strength, while other operators do not believe PWA is important at all. Over the years, operators forced to use lower PWA bentonites have either observed a drop in binding effectiveness or no relationship between bentonite PWA and pellet strength.

Regardless, most iron ore pellet producers impose specification requirements for the bentonites they receive from their suppliers.

Pellet producers usually prefer bentonites with a PWA in the range of 700 to 900. Suppliers can meet these specifications by blending low- and high-quality bentonites at the mine (Reisch, 2000). All of the tests presented in this paper used samples of bentonite that were sold to the pellet plants, not specimens collected from the mine just for this project.

Besides PWA, additional tests for bentonite characteristics include chemical analysis, exchangeable cations, methylene blue uptake, colloid percentage, grit, X-ray diffraction and Marsh funnel. A survey conducted through the Iron Ore Cooperative Research Committee found that none of these specifications, singly or collectively, guaranteed that a bentonite would perform well in a plant. Thus, a particular bentonite can meet quality specifications and still perform poorly (Bleifuss 1999, Engesser 2000b), or it may perform well but be rejected based on these selection criteria.

In this paper, dry iron ore pellet compressive strength was used to measure the effectiveness of a variety of different bentonites now used as iron ore concentrate pellet binders. The relationship between the PWA of each bentonite binder and binder performance (measured by dry pellet strength) was evaluated.
Experimental Equipment. A laboratory-scale balling drum was used to form pellets. A kneader-mixer was used to mix the concentrate with the binder. Pellets were dried in a forced-air drying oven at 105°C (221°F). A compression test machine was used at a constant cross-head speed of 40 mm/min (1.57 in./min) to crush the pellets and determine their ultimate compressive strength. Particle size analyses were performed with laser diffraction.

Materials. The magnetic concentrate used in these experiments was the unfluxed filter cake used for pelletization feed. The sample was obtained from an iron ore concentrator located in the Lake Superior district of the United States. The concentrate contained 10% moisture, had a particle size of 80% passing 25 μm (500 mesh) and contained 4.9% silicate gangue.

Bentonite clay binder samples were obtained from the Cleveland-Cliffs industrial research laboratory and was categorized according to their reported PWA value. These bentonites were representative samples that were sold to iron ore plants and used in their industrial pelletizing operations. The bentonites were Na-montmorillonite-based clays that were mined from the Western United States. Particle size distributions of the bentonites are shown in Table 1. The dry screen analysis gave a coarser distribution than the wet laser diffraction analysis because the bentonite particles remained agglomerated when dry.

Table 1 — The 10%, 50% and 80% wet passing sizes of the eight bentonites studied. Dry screen analysis showing the percent passing 75 μm (200 mesh) and 45 μm (325 mesh).

<table>
<thead>
<tr>
<th>Bentonite ID#</th>
<th>PWA, %</th>
<th>10%</th>
<th>50%</th>
<th>80%</th>
<th>75 μm</th>
<th>45 μm</th>
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<tr>
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Plate water absorption (PWA) test. A 2.0-g sample of bentonite was evenly distributed with a vibratory spatula over a 51-mm (2.0-in.) diam. concentric circle located on a round filter paper. This was then placed on an alumina ceramic plate partially immersed in an enclosed distilled water bath at a depth of 6.4 mm (0.25 in.) below the top of the plate. The distilled water was delivered to the plate to the bentonite sample through capillary action. The bentonite sample was allowed to absorb water for 18 hours. The water absorbed by the filter paper was determined separately and subtracted. The PWA was then calculated as the percent of water absorbed by the bentonite alone (ASTM E946, 1996).

Bentonite typically absorbs from five to ten times its weight in distilled water over the 18-hour test. Therefore, typical PWA values range from 500% to 1,000%. The absorption rate was measured by periodically weighing the individual samples. Additional tests were conducted using high-salt water at the concentrations shown in Table 2. The high-salt water was representative of the moisture remaining in the iron ore concentrate.

Pelletization procedure. Industry developed the basic procedure used for forming pellets to closely reproduce the conditions in a full-scale plant. Bentonite was added to the magnetic concentrate in a kneader-mixer and mixed at 350 rpm with a 150-rpm orbital motion for up to 5 minutes. Binder dosages are reported as percent by weight of magnetic concentrate. The mixed material was delumped through a 2.4-mm (8-mesh) screen before pelletizing. A small amount of material was then added to the pelletizing drum, rotating at 25 rpm, to create pellet "seeds." The seeds were moistened with water mist to retain its moisture content while adding additional material to enlarge them into pellets. The pellets were removed from the drum periodically to screen for pellet diameter. This procedure was continued until 1 to 2 kg (2 to 5 lb) of finished pellets, screened between 12.7 and 11.2 mm (0.5 and 0.4375 in.) in diameter were produced for testing. The time required for pelletization was approximately 20 minutes. The finished pellets were then immediately dried at 105°C (221°F) for 20 to 24 hours to ensure that they were completely dried. The dry compressive (crush) strengths of the pellets were tested (ASTM E382-97, 1998). Pellets were completely dried at 105°C (221°F) for at least one hour. Single pellets were then crushed 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. The dry crush strength measures the ability of dried pellets to survive handling during the firing process. Pellet strengths should be at least 22 N (5 lbf) per pellet. The pellet dry crush strength is most critical measurement of bentonite binder performance.

For each value reported, the mean and standard deviations 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).

Results and discussion

How does particle size affect PWA? Table 1 shows the particle size distributions of seven bentonites with different plate water absorbance (PWA) values. The size distributions were measured with laser diffraction of each bentonite in a distilled water slurry. The bentonites with the finer particle size distributions tended to have higher PWA values. This was expected for two reasons. First, finer size bentonites have a higher specific surface area and can absorb more water. Therefore, the finer the bentonite, the higher its PWA value.
Bentonite water absorption rates. The plate water absorbance (PWA) value is used as the primary parameter to select bentonites for iron ore concentrate pelletization. The PWA value measures the weight percent of distilled water absorbed by the bentonite after it has been allowed to absorb the water for 18 hours (ASTM E946-92 1996). However, in the pellet plants, the bentonite does not have 18 hours to absorb water. Pelletizing bentonites only have a few minutes to absorb moisture from the concentrate before the pellets are formed, dried and fired. Therefore, PWA may not correlate with pellet strength.

The standard 18-hour measurement is relevant as long as these bentonites absorb water at a consistent rate. However, Fig. 2 shows that the rate of water absorption is quite variable. Bentonites that initially absorbed water at a relatively high rate actually had a much lower 18-hour PWA value than bentonites that initially absorbed water more slowly. Because it was not known whether the 18-hour value or the absorption rate was the most important parameter, both were measured. In addition, PWA tests were conducted with high-salt water (HSW), having the same concentration of cations as that of the moisture remaining in the concentrate. The PWA values dropped significantly when the high salt water was used and reached nearly constant values in only a few minutes.

How did PWA affect pellet strength? Figure 3 shows that the dry compressive strength of the iron ore concentrate pellets varied when bentonites having different PWA values were used as a binder. The coefficient of determination (R² value) was used to determine how well PWA could predict pellet strength. The R² value was only 0.20. Figure 3 shows that the dry compressive strength of the iron ore concentrate pellets varied with bentonites having different PWA values. The variation was not linear; the correlation cannot be used to predict how a bentonite with a particular PWA value will perform as a binder for the dry iron ore concentrate pellets.

Pellet strengths were plotted against values of water absorption measured at four different times. Figure 4 shows that earlier measurement of distilled water absorption did not improve the correlation with pellet strength.

Figure 5 shows a relationship between the same dry compressive strengths, but compares them to PWA of the bentonites measured using the high-salt water. When HSW was used, the coefficient of determination improved to 0.47, although this is still a marginal relationship.
Conclusions

- Bentonites did not absorb water at the same rates. Some bentonites that initially absorbed water at a relatively high rate actually had much lower 18-hour PWA values than bentonites with initially lower absorption rates.

- The standard PWA test, where bentonites absorb distilled water for 18 hours, did not correlate well with pellet strength.

- Measurement of distilled water PWA at shorter times, to take into account differences in absorption kinetics, did not improve the correlation between PWA and pellet strength.

- When high-salt water (duplicating the water remaining in the iron ore during pelletization) was used, correlations between PWA and pellet strength improved but were still only marginal.

- The inconsistent correlation between PWA and pellet strength is due to at least two factors. First, there are kinetic differences between bentonite water absorption rates. Second, bentonites are strongly affected by the chemistry of the water remaining in the concentrate, while the PWA test is run using distilled water.

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Figure 4 — The strength of iron ore pellets made with a wide range of bentonites. The bentonite water absorption value was determined with distilled water at four different times. A bentonite that has a PWA value of 800% to 1,000% (by weight) only has a water absorption value of 100% to 200% (by weight) while bonding (within 10 minutes). Each data point has a number to its left that corresponds to the particular bentonite used for the test, as identified in Table 1. The minimum industrially acceptable specification for dry pellet compressive strength is 22 N (5 lbf).

Figure 5 — The strength of iron ore pellets made with a wide range of bentonites. The bentonite PWA value was determined with high-salt water after 18 hours. The correlation coefficient for a linear fit for these data was 0.47. The minimum industrially acceptable specification for dry pellet compressive strength is 22 N (5 lbf).
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