The Effect of Calcined Colemanite Addition on the Mechanical Strength of Magnetite Pellets Produced with Organic Binders

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Iron ore pellets must have sufficient mechanical strengths against degradation in all stages of pellet production. Low strength is also a problem for product pellets since they abrade during transportation to the reduction furnaces. The use of a binder is necessary to provide sufficient strength to the pellets and for better operation and handling of pellets. Bentonite is the standard binder in the industry; however, it is considered an impurity due to its acid oxide contents. Organic binders have been tested for many years as alternative binder to bentonite. They have been found to give sufficient wet pellet properties. However, they failed to provide sufficient strength to the preheated and fired pellets due to lack of slag bonding. It has been assumed that one possible effective method to improve the preheated and fired pellet strengths is addition of a slag-bonding constituent. In this study, calcined colemanite was added to the pellet feed to overcome the lower strength problem encountered with organic binder use. The strength of pellets produced with organic binders and calcined colemanite alone and in combination was comparatively studied against the strength of pellets made with standard bentonite binder in magnetite concentrate pelletizing. The results showed that addition of calcined colemanite into the pellet mixture improved the preheated and fired pellet strengths of pellets produced with organic binders.

Keywords: bentonite, binder, boron compounds, colemanite, iron ore, organic binder, pelletizing

INTRODUCTION

Bentonite is the standard binder for iron ore pelletizing. It is relatively inexpensive, controls the moisture of wet pellets in balling, and provides sufficient mechanical strength to the wet pellets (wet drop number and wet compressive strength). Furthermore, it provides a good dry and sintered/fired compressive strength to the pellets. However, it is considered as an impurity due to its acid oxide contents (SiO₂ and Al₂O₃). These acid oxides are known for their adverse effects on the iron making economy. For instance, the addition of 1% bentonite decreases the iron content...
by about 7 kg/ton of iron ore (Kater and Steeghs 1984). In addition, an increase in the silica content of the pellet charge to blast furnace leads to an increase in the unit cost of steel production (Chizhikova et al. 2003). In the case of direct reduced pellets, every percent of acid gangue addition is associated with an increased energy consumption of 30 kWh/ton (Heerema et al. 1989). Therefore, investigation of alternative to bentonite binders that do not contaminate the pellet composition is an important topic in the industry. The dilution of Fe content of pellets cannot be prevented by using a SiO₂ free alternative inorganic binder. However, the problems arising from additional SiO₂ with bentonite binder can be overcome by using a SiO₂ free alternative binder.

Organic binders have been proposed as an alternative to the standard bentonite binder and tested by many researchers (de Souza, de Mendonca, and Kater 1984; Kater and Steeghs 1984; Goetzman, Bleifuss, and Engesser 1988; Sivrikaya and Arol 2008). Organic binders hold many advantages over bentonite. Pellets made with organic binders have lower gangue concentrations and are generally more porous in their structure. Higher porosity allows reducing gases to permeate the pellet more quickly during reduction. By having lower gangue concentrations in the pellet, substantial improvements in energy and flux consumptions can be realized in iron making processes. Cost savings in energy/flux for each 1% reduction in silica can reach $2.50 USD per ton of hot metal making (Schmitt 2005). However, organic binders have a very important disadvantage: organic binders lower the mechanical strength (particularly preheated and sometimes fired strength) of pellets since they burn out without any residue at a temperature over 250°C. Therefore, the use of organic binders in industry is limited. Ripke and Kawatra (2000) gave a statistic about the pellet plants in USA. Eight of the nine plants utilized bentonite clay as a binder, while the ninth plant used an organic binder.

Sufficient mechanical strength of pellets is significant to problem-free pellet plant operation. Low strength pellets breakdown and generate dust. Pellet breakdown studies by Copeland and Kawatra (2005) revealed that as much as 43% by weight of the fine particles were 10 µm in diameter and smaller (material regulated by the U.S. Environmental Protection Agency).

Malyševa et al. (1996) studied the effect of boron on the quality of iron ore pellets. They used chemically pure boron oxide (B₂O₃) for fluxed pellets. They reported that boron has beneficial effect at all stages of metal production and the quality of pellets was increased (Malyševa et al. 1996). This benefit was believed to be due to the low melting point of boron compounds. Schmitt (2005) also studied the addition of some boron containing compounds (colemanite, sodium tetraborate pentahydrate, sodium tetraborate decahydrate, and synthetic calcium borate) to the organic binder Peridur to improve physical quality of pellets. It was reported that boron compounds increase the physical strength, tumble indices, reducibility, and reduce the sulfur content of iron ore pellets.

Preliminary studies conducted by Sivrikaya (2011) showed that the addition of 0.50–1.00% boron minerals such as colemanite or tincal into pellet feed caused pellet spalling after thermal treatment. The spalling of pellets can be explained by the decrepitation of boron minerals since they contain considerable amount of chemically-bonded water in their structure. Decrepitation, shrinkage, and expansion of boron minerals, namely colemanite, ulexite, and borax, under heat treatment were presented by some researchers in literature (Çelik, Uzunoğlu, and Arslan 1994, Çelik...
et al. 1998; Arslan, Arslan, and Çelik 1999). Coşar et al. (2010) studied the effect of boron minerals on pelletizing of iron ore concentrate. They added colemanite, ulexite, and borax to the magnetite concentrate in the range of 0.05–0.20% together with 0.70% bentonite. They concluded that the addition of these boron minerals decreased the fired pellet compressive strength. Therefore, the use of boron compounds in iron ore pellet feed requires a precalcination process.

The purpose of this work is to demonstrate the impacts of calcined colemanite addition on the mechanical strength of pellets. Colemanite is a Ca-boron mineral and has a chemical composition $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5(\text{H}_2\text{O})$. Previous results by Sivrikaya and Arol (2009) showed that compressive strength of fired hematite pellets at $1300^\circ\text{C}$, and made with 0.50–1.00% colemanite addition, were significantly higher than the industrially required limit. Therefore, in this study we tested the lower firing temperatures, 1100 and $1200^\circ\text{C}$, to get industrially sufficient fired pellet strength, which is 250 kg/pellet.

MATERIALS AND METHODS

Magnetite

The iron oxide mineral used in the pelletizing experiment was a magnetite concentrate sample from a mine in the Lake Superior district (Michigan, USA). Particle size distribution analysis showed that the magnetite concentrate had a particle size of $P_{100}: 62.23 \mu\text{m}$ and $P_{80}: 27.60 \mu\text{m}$. Specific surface area measurement carried out by a Blaine number apparatus and was found $2212 \pm 38 \text{cm}^2/\text{g}$. Specific gravity of magnetite concentrate was found to be 4.64 by pycnometer method. Elemental analysis of magnetite concentrate sample was determined by XRF method and results are shown in Table 1.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Magnetite</th>
<th>Analyte</th>
<th>Bentonite 1</th>
<th>Bentonite 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fe</td>
<td>65.52</td>
<td>SiO$_2$</td>
<td>58.36</td>
<td>67.76</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>4.87</td>
<td>Al$_2$O$_3$</td>
<td>21.14</td>
<td>16.86</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>0.09</td>
<td>FeO</td>
<td>3.96</td>
<td>4.17</td>
</tr>
<tr>
<td>CaO</td>
<td>0.44</td>
<td>CaO</td>
<td>1.43</td>
<td>2.19</td>
</tr>
<tr>
<td>MgO</td>
<td>0.37</td>
<td>MgO</td>
<td>2.98</td>
<td>3.62</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>&lt;0.01</td>
<td>Na$_2$O</td>
<td>3.82</td>
<td>1.38</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.02</td>
<td>K$_2$O</td>
<td>0.58</td>
<td>0.73</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
<td>LOI</td>
<td>6.75</td>
<td>2.93</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.05</td>
<td>TiO$_2$</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
material that the plant was using as the binder for their conventional pellets. This bentonite was provided in dry powder form, and it had a plate water absorption (PWA) value of 1000 ± 50. Mineralogical analyses of the first bentonite sample revealed that it composed of bentonite, sodium/calcium aluminum silicate, and potassium aluminum silicate hydroxide. The second sodium-bentonite was obtained from a bentonite clay mine in Reşadiye, Turkey. The chemical compositions of bentonite samples are shown in Table 1. The first bentonite sample had a particle size distribution of $P_{100}$: 124.50 μm and $P_{80}$: 13.11 μm. The second bentonite sample had a particle size distribution of $P_{100}$: 88.00 μm and $P_{80}$: 16.13 μm.

**Organic Based Binders**

One organic material, technical grade CMC (carboxymethyl cellulose) and two different manufactured organic-based materials; DPEP06-0007 polymer and superfloc A150LMW flocculant, were used as agglomeration aids. The CMC is a derivative of cellulose and is commercially available. DPEP06-0007 polymer is an anionic copolymer blend supplied by Ciba® Specialty Chemicals Holding Inc. Superfloc A150LMW is anionic polyacrylamide flocculant supplied by Cytec® Industries Inc. They are intentionally synthesized for agglomeration and flocculation purpose.

**Colemanite**

A colemanite concentrate from Eti Mine Bigadiç Concentration Plant (Balikesir, Turkey) was used as binder alone or as additive to organic binders. The colemanite has a chemical formula $\text{Ca}_2\text{B}_6\text{O}_{11.5}\text{H}_2\text{O}$ and a melting point of 986°C (Tektas 2003). Chemical compositions of colemanite are shown in Table 2. The original colemanite sample was washed, dried, crushed, and calcined at 550°C to remove chemically bonded water. Calcined colemanite with a specific gravity of 1.95 was dry ground in a laboratory mill to a particle size of $P_{100}$: 176.00 μm and $P_{80}$: 54.67 μm.

**Sampling**

The magnetite concentrate was received on July 28, 2010 in six containers weighing approximately 200 kg in total (weight of original sample with filter cake moisture). The original sample was blended and then divided into 77 representative samples of 2500 g each by cone and quartering and riffling sampling methods (ASTM E 877-03) and sealed in individual plastic bags. Figure 1 shows the

<table>
<thead>
<tr>
<th>Table 2 Chemical composition of colemanite sample obtained from Bigadiç Concentration Plant, Balikesir, Turkey</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analyte (%)</strong></td>
</tr>
<tr>
<td>$\text{B}_2\text{O}_3$</td>
</tr>
<tr>
<td>$\text{CaO}$</td>
</tr>
<tr>
<td>$\text{SiO}_2$</td>
</tr>
<tr>
<td>$\text{SO}_3$</td>
</tr>
</tbody>
</table>
representative sample preparation procedure. The as-received magnetite concentrate had 7.51% original moisture content.

**Equipment**

A particle size analyzer, Microtrac SRA, was used to determine the particle size distribution of materials. Elemental analyses of magnetite and bentonite samples were determined with Spectro IQ X-ray fluorescence (XRF) spectrometer. A Blaine number apparatus was utilized to determine the specific surface area of magnetite concentrate. A laboratory scale kneader mixer (Figure 2a) was used to mix the binder and magnetite concentrate. A laboratory scale balling drum with a 40.6 cm overall diameter and 25.4 cm mouth diameter was used to produce the pellets. The depth of the drum was 17.8 cm and rotation speed was 25 rpm (Figure 2b). A laboratory scale drying oven and a box furnace were used for drying and thermal treatment of pellets. Determination of pellet strength was done by using a compression test machine (Figure 2c) with two different load cells (50 and 500 + 10% lbf). The pellets were crushed on this mechanical press at a constant cross head speed of 40 mm/min.

**Pelletizing Experiments**

The moist magnetite concentrate and a predetermined amount of dry binder were mixed in the mixer for 5 min. The binder dosages were calculated as percent by weight of the moist magnetite concentrate. Mixed material was screened through 8 mesh (2.38 mm) screen before pelletizing. A small amount of material was put into
the drum to form the pellet seeds. The seeds were moistened by a water spray during fresh mix addition to enlarge the seeds into pellets. Pellets were periodically removed from the drum and a nest of screens was used to control pellet size. The operation was continued until all fresh mix converted to the finished pellet size from 11.2 mm (7/16 in.) to 12.7 mm (1/2 in.) in diameter. Wet drop number and wet compressive strength were determined on these wet pellets accord to the methods explained in Table 3. The remaining pellets were dried in a laboratory oven to determine the moisture content and to get dry pellets to use in subsequent tests. Dry compressive strength was determined on these dry pellets according to the methods explained in Table 3. Remaining dry pellets were thermally treated at different temperatures. Dry pellets were put, as one layer in plate crucible, into a box furnace at room temperature. After that, the furnace was set to the desired temperature. The heating chamber dimension of box furnace with molybdenum desilicide (MoSi₂) heating elements was 20 × 35 × 20 cm (W × D × H). The heating rate of box furnace is about 10°C/min. The pellets were heated for 30 min at one of the temperatures 800, 1000, 1100, 1200, 1300°C, then they were cooled to room temperature in the box furnace and the strength of pellets were determined according to related ASTM standard (ASTM E 382-07).

RESULT AND DISCUSSION

All individual pelletizing experiments were carried out at least three times to ensure experiment reproducibility. In each pellet batch, 20 randomly selected pellets

Table 3 Descriptions of the tests used for evaluating pellet quality. The values reported for each procedure are the average and standard deviation of testing 20 pellets. During crushing, the pellets are individually crushed between flat parallel platens (Ripke and Kawatra 2000)

<table>
<thead>
<tr>
<th>Test</th>
<th>Procedure</th>
<th>Use of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet drop number</td>
<td>Individual freshly-made undried pellets were dropped repeatedly from a height of 45 cm (18 in.) onto a steel plate. The number of drops required for fracture was recorded.</td>
<td>Measures the ability of the wet pellets to remain intact during handling.</td>
</tr>
<tr>
<td>Wet compressive strength</td>
<td>Individual undried pellets were compressed using a compression test machine with a crosshead speed of 40 mm/min. The peak load required to fracture the wet pellet was recorded.</td>
<td>Measures the ability of the wet pellets to retain their shape during handling.</td>
</tr>
<tr>
<td>Dry compressive strength</td>
<td>Individual pellets dried at 105°C for at least 1 h, were compressed using a compression test machine. The peak load required to fracture the dry pellet was recorded.</td>
<td>Measures the ability of dried pellets to survive handling during the firing process. Should be at least 22 N (5 lbf) per pellet. This is the most critical measurement of binder strength.</td>
</tr>
<tr>
<td>Preheated or fired compressive strength</td>
<td>Individual pellets preheated or fired at 800, 1000, 1100, 1200, and 1300°C for 30 min were compressed using a compression test machine. The peak load required to fracture the dry pellet was recorded.</td>
<td>Measures the ability of preheated or fired pellets to survive during the firing process and handling. Fired pellet should have at least 250 kgf (560 lbf) per pellet.</td>
</tr>
</tbody>
</table>
were tested to determine pellet quality, indicated by the mean value and calculated the 95% confidence interval (P95). Results of the pelletizing experiment tests (moisture contents and drop numbers of wet pellets, dry and thermally treated pellet compressive strengths) are given in Table 4.

*Wet pellet moisture content (WPMC)* values are shown in Table 4 and graphically represented in Figure 3. They varied from 8.38 to 10.22%. The smallest WPMC was found to be 8.38% for the pellets produced without binder. The WPMCs of pellets made with bentonite are 8.53% and 8.44%. The WPMC produced with only calcined colemanite is 8.52 - about the same as bentonites. However, the WPMCs are greater for the pellets containing organic binders (codes 5–10). The value increased up to 10.22% for the pellets produced with CMC plus calcined colemanite addition. The reason of the relatively high WPMCs obtained with organic binders is the water absorption capacity of the organic-based binders, since organic-based materials are used industrially to increase the “water holding capacity of materials” for several applications.

*Wet pellet drop numbers (WPDN)* of the pellets can be seen in Table 4 and graphically drawn in Figure 3. According to experience, the industrially required minimum value should be at least 4 from a height of 45 cm (18 in.) (Meyer 1980). The WPDNs obtained by using reference bentonite binders were found to be 4.27 and 4.40, which are slightly over the limit so they are sufficient. However, WPDN values for pellets made with no binder and with only calcined colemanite addition were determined to be 3.17 and 3.21, which are a little lower than the required value. Therefore, they can be considered insufficient and the production of pellets without binder or only with calcined colemanite seems impossible in terms of sufficient WPDN. The WPDNs produced with organic binders were found to be much greater (>10.00). As the required drop number limit is four, drop number tests were stopped at 10 for pellets with high drop numbers. It was concluded that these organic binders and tested dosage have made the pellets plastic with such a fine particle size of magnetite concentrate. Hence, lower addition rates of these organic binders should be tested for this type of finely ground magnetite concentrates. It is well known fact that when the material fineness increases, the mechanical strength and plasticity of wet pellets increase due to the increasing surface area of the material. Plasticity is related with saturation of wet pellets. The effect of saturation degree of wet pellets was studied by Forsmo et al. (2006).

*Wet pellet compressive strengths (WPCS)* are given in Table 4 and graphically shown in Figure 4. The WPCS usually lies between 1.0 and 2.0 kg (2.2 and 4.4 lbf) (Meyer 1980). Therefore, industrially acceptable minimum compressive strength value for wet pellets should be greater than 1 kg/pellet or 2.2 lbf. All WPCSs were found to be greater than the required value.

*Dry pellet compressive strengths (DPCS)* are given in Table 4 and graphically shown in Figure 4 as well. The DPCS should be, at minimum, 2.2 kg/pellet or 5.0 lbf. The DPCSs vary from 2.97 lbf to 14.04 lbf. The lowest value, determined as insufficient, was for the pellets made with no binder (code 1). The second lowest and insufficient value was 4.18 lbf for pellets bonded with calcined colemanite (code 4). These results together with the insufficient WPDN of these pellets show that the production of pellets with sufficient wet and dry quality is impossible without a binder or only with calcined colemanite addition. However, the DPCSs of pellets
Table 4 Results of the pelletizing experiments. The mean values are given with the 95% confidence interval (P95)

<table>
<thead>
<tr>
<th>Binder codes</th>
<th>Binder name and dosages</th>
<th>Moisture content (%)</th>
<th>Wet drop number from 45 cm</th>
<th>Wet Compressive strengths/C3</th>
<th>Dry @ 105°C/C3</th>
<th>Heated @ 800°C/C3</th>
<th>Heated @ 1000°C/C3</th>
<th>Heated @ 1100°C/C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Binder</td>
<td>8.38</td>
<td>3.17±0.23</td>
<td>4.23±0.31</td>
<td>2.97±0.16</td>
<td>66.32±3.40</td>
<td>106.43±6.47</td>
<td>170.74±12.70</td>
</tr>
<tr>
<td>2</td>
<td>Bentonite-1 0.66%</td>
<td>8.53</td>
<td>4.27±0.33</td>
<td>5.21±0.25</td>
<td>12.16±0.72</td>
<td>89.54±4.41</td>
<td>160.81±10.50</td>
<td>241.74±14.19</td>
</tr>
<tr>
<td>3</td>
<td>Bentonite-2 0.66%</td>
<td>8.44</td>
<td>4.40±0.32</td>
<td>5.56±0.28</td>
<td>14.04±0.83</td>
<td>121.36±8.05</td>
<td>217.75±12.01</td>
<td>306.31±23.06</td>
</tr>
<tr>
<td>4</td>
<td>Calcined colemanite 0.66%</td>
<td>8.52</td>
<td>3.21±0.22</td>
<td>4.22±0.32</td>
<td>4.18±0.32</td>
<td>52.55±3.63</td>
<td>273.13±22.44</td>
<td>&gt;550.00</td>
</tr>
<tr>
<td>5</td>
<td>Technical CMC 0.10%</td>
<td>10.06</td>
<td>&gt;10.00</td>
<td>4.13±0.24</td>
<td>13.09±1.09</td>
<td>40.75±2.40</td>
<td>65.88±4.27</td>
<td>108.92±7.37</td>
</tr>
<tr>
<td>6</td>
<td>DPEP06-0007 polymer 0.10%</td>
<td>8.78</td>
<td>&gt;10.00</td>
<td>5.06±0.34</td>
<td>7.45±0.55</td>
<td>69.00±3.93</td>
<td>104.62±6.87</td>
<td>176.90±14.40</td>
</tr>
<tr>
<td>7</td>
<td>Superfloc A150-LMW 0.10%</td>
<td>9.43</td>
<td>&gt;10.00</td>
<td>4.85±0.33</td>
<td>9.94±0.69</td>
<td>66.66±5.58</td>
<td>95.91±5.21</td>
<td>152.34±9.59</td>
</tr>
<tr>
<td>8</td>
<td>Technical CMC 0.10% +Calcined colemanite 0.66%</td>
<td>10.22</td>
<td>&gt;10.00</td>
<td>4.17±0.19</td>
<td>6.37±0.49</td>
<td>37.25±2.22</td>
<td>209.33±16.18</td>
<td>&gt;550.00</td>
</tr>
<tr>
<td>9</td>
<td>DPEP06-0007 Polymer 0.10% +Calcined colemanite 0.66%</td>
<td>9.44</td>
<td>&gt;10.00</td>
<td>4.99±0.26</td>
<td>5.58±0.34</td>
<td>48.5±2.58</td>
<td>276.11±20.13</td>
<td>&gt;550.00</td>
</tr>
<tr>
<td>10</td>
<td>Superfloc A150-LMW 0.10% +Calcined colemanite 0.66%</td>
<td>10.14</td>
<td>&gt;10.00</td>
<td>3.84±0.24</td>
<td>4.39±0.25</td>
<td>45.17±2.17</td>
<td>264.17±18.19</td>
<td>&gt;550.00</td>
</tr>
</tbody>
</table>

*Compressive strengths of pellets fired at 1200°C and 1300°C were found greater than 550 lbf, which is the maximum limit of the present compression test machine.
bonded with bentonite were found to be 12.16 lbf and 14.04 lbf (code 2 and 3). On the other hand, the DPCSs of pellets by organic binders were found to be lower than those obtained by bentonite pellet but they are still greater than the minimum required limit. The DPCSs of pellets produced with combination binders (codes 8, 9, and 10) were found to be sufficient as well. However, the calcined colemanite addition decreased the DPCSs of these pellets when compared to values obtained using organic binders alone (codes 5, 6, and 7). The decrease is most probably due to the presence of calcined colemanite powder between magnetite grains in dry pellets.

**Figure 3** Wet pellet moisture content (WPMC) and wet pellet drop numbers (WPDN) obtained with different binders. The mean values are given with the 95% confidence interval (P95). Dashed line shows 4, which is the required minimum limit for WPDN.

**Figure 4** Wet pellet compressive strengths (WPCS) and dry pellet compressive strengths (DPCS) obtained with different binders. The mean values are given with the 95% confidence interval (P95). Dashed lines show 2.2 lbf and 5 lbf, which are the required minimum limit for WPCS and DPCS, respectively.
Thermally treated pellet compressive strength can be divided in two parts: preheated and fired pellet strengths, since firing is accomplished by two stages: preheating and firing of pellets. Preheated pellet strength is particularly important for the thermal treatment of pellets with the travelling grate and rotary kiln induration system. The pellets must have a sufficient strength while cascading from the travelling grate to the rotary kiln. If the strength is insufficient, pellet chip and dust will form and both pellet quality and operation efficiency will be affected adversely. To show the effect of the different binders on the thermally treated pellet strength, dry pellets were heated at different temperatures, i.e., 800, 1000, 1100, 1200, and 1300°C.

The results are tabulated in Table 4 and graphically shown in Figure 5. The compressive strengths of pellets increase with the increasing temperatures. However, compressive strengths of pellets made without binder (code 1) and with organic binders (codes 5, 6, and 7) were found to be lower than the reference pellets with bentonite binders (codes 2 and 3). The reason of this is the burning out of organic binders virtually without any residue at such temperatures. The residual contents and burning behaviors of these tested binders under TGA experiments are reported elsewhere (Sivrikaya 2011). The pellets preheated at 800°C with calcined colemanite (code 4) or combination of calcined colemanite and an organic binder (codes 8, 9, and 10) were found to be lower than those obtained with bentonite bonded pellets (codes 2 and 3) or even than pellets made without binder (code 1). Decrease is most probably due to the presence of calcined colemanite, since the compressive strengths of pellets produced without binder and heated at 800°C are greater than those containing calcined colemanite. At 800°C colemanite did not start to melt since it has a melting point of 986°C and could not effectively bind the magnetite ore grains. The presence of un-melted calcined colemanite at this temperature affects the self-slag formation of magnetite grain adversely. Another evidence to prove this is the almost equal compressive strengths of pellets produced with organic-based binders and

![Figure 5](image-url)  
**Figure 5** Thermally treated pellets compressive strengths (800°C, 1000°C, and 1100°C) produced with different binders. The mean values are given with the 95% confidence interval (P95). Dashed line shows 550 lbf, which is the industrially desired minimum strength limit for fired product pellets.
without binders. Since the organic-based materials burned out with fewer residues at 800°C, they could not contribute to the pellet strengthening.

However, when the temperature increased to 1000°C, the compressive strengths of pellets made with only calcined colemanite (code 4) or combination of calcined colemanite and an organic binder (codes 8, 9, and 10) were found greater than the reference values obtained with bentonites (codes 2 and 3). Since this temperature (1000°C) is near the melting point (986°C) of colemanite, it started to melt and bond the magnetite grains together. The melted colemanite provides bonding at the contact points of magnetite grains. The bonding mechanism and the microstructures of thermally treated pellets produced with addition of calcined colemanite were investigated and published by Sivrikaya (2011).

When the temperature is increased to 1100°C, the effect of colemanite addition on the pellet strength increase is more pronounced. The strengths of pellets with calcined colemanite addition (codes 4, 8, 9, and 10) are significantly greater than the bentonite bonded reference pellets (codes 2 and 3). These values were determined to be greater than the limit of the present compression test machine (550 lbf). These strengths are without doubt considered to be sufficient, since the minimum industrially required strength for product pellets is 550 lbf (250 kg/pellet) (Ball et al. 1973). Firing temperature of iron oxide pellets is generally 1250–1350°C depending on the genesis of iron oxides. The industrially sufficient compressive strength was obtained for the pellets hardened at only 1100°C with the addition of 0.66% calcined colemanite. This result showed that the negative effect of organic binder on the compressive strength of heated pellets is compensated by addition of calcined colemanite in pellet mixture. Furthermore, the lower firing temperature would be enough to get industrially sufficient strength. This means an energy saving in firing unit of pelletizing plants is possible with calcined colemanite bonded pellet production.

The compressive strength of pellets fired at 1200 and 1300°C could not be determined with the present compression test equipment, since their strengths are much greater than the equipment maximum limit.

**CONCLUSION**

In the study, the addition of calcined colemanite into pellet mixture was found to improve the lower pellet mechanical strength encountered with use of organic binder in iron ore pelletizing. Since, organic binders are being eliminated during thermal processes and colemanite does not contain much silica and alumina oxides, they do not interfere with iron making. Organic binders (0.10%) and calcined colemanite (0.66%) alone and in combination were comparatively tested against bentonite binder (0.66%) in magnetite concentrate pelletizing. The performances of the tested binders on wet, dry and thermally-treated pellet strengths have been compared with the bentonite performance.

The strength tests results showed that pellets produced with:

- organic binders alone have sufficient wet and dry pellet qualities, but insufficient preheated and fired pellet strengths;
- calcined colemanite alone have insufficient wet and dry pellet qualities; however, they have improved preheated and fired pellet strengths;
combined binders (an organic binder and calcined colemanite) have both sufficient wet and dry pellet qualities and improved preheated and fired pellet strengths.

Significant improvements in mechanical strength have been observed, particularly for pellets made with calcined colemanite addition and sintered at 1100°C for 30 min. The increase in strength was believed to be due to the low melting point of boron compound (colemanite). The strength of these pellets was found to be greater than 550 lbf, which is industrially sufficient for the product pellets. This result can lower the firing temperature of a pelletizing plant and might lead to energy saving.

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