Manufacturing Bricks with Fly Ash and Advanced Coal Combustion By-products

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Front Cover: (a) and (b) Full-size bricks, sawn in half, after firing. (c) Full-size bricks before firing.
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Abstract

This study investigated the use of bottom ash or flue gas desulfurization (FGD) sulfite and sulfate coal combustion by-products (FGD-sulfite and FGD-sulfate CCBs) instead of, or in combination with, fly ash in the production of high-quality building bricks. Various combinations of fly ash, bottom ash, FGD-sulfite, and FGD-sulfate were used as partial substitutes for the shale component of bricks. Commercial-size fired bricks made with these substituted materials had good physical appearance without scum, lime pops, cracks, black hearts, or red hearts. The majority of the test bricks met the ASTM classification for severe-weathering grade; the remainder were acceptable for moderate- or negligible-weathering grade. Bricks containing FGD-sulfite were whiter and had lower compression strength and greater water absorption capacity than regular fired bricks without CCBs. The fired bricks containing blends of fly ash and bottom ash were comparable in color to regular fired bricks without CCBs. In particular, the addition of bottom ash to the brick composition increased brick redness, improved compressive strength, and decreased water absorption capacity.

All of the fired bricks containing CCBs produced in these tests can be considered to be environmentally safe construction products. The fly ash and bottom ash from our specific project source can be recommended for use in making fired bricks. To fully evaluate the environmental impact of using higher-sulfur content FGD CCBs as an ingredient in fired bricks, further studies are warranted to determine the fate of the sulfur during brick firing.

Introduction

More than 122 million tons of coal combustion by-products (CCBs) are produced nationwide each year by coal-burning utilities that generate electricity. About 60% of these CCBs are disposed of as waste (American Coal Ash Association 2006). In addition to fly ash and bottom ash CCBs, the annual production of flue gas desulfurization (FGD) CCBs is expected to continue to increase as more utilities add FGD systems to their existing plants or build new plants with FGD systems in order to meet more stringent nitrogen oxide and sulfur dioxide standards. A portion of the high-quality FGD sulfite CCBs (FGD-sulfite) is similar to mined gypsum and is used by the wallboard industry (American Coal Ash Association 2006). However, additional amounts of high-quality FGD CCBs and most of the low-quality FGD CCBs (FGD-sulfite) are discarded in landfills. As more utility plants adopt FGD technologies, the production of both high-quality and low-quality FGD solid CCBs will increase sharply, requiring more landfill space and increased disposal costs. Consequently, value-added applications are needed to expand the utilization of these CCBs.

A previous study developed high-quality, marketable fired bricks containing high volumes of Class F fly ash generated from burning Illinois Basin coals (Chou et al. 2005, 2006a, 2006b). The brick-making process used fly ash as a raw material substituting for part of the shale component. Clay and shale are the two primary ingredients used to make conventional fired bricks. Bricks containing fly ash at up to 40 vol% have been successfully produced in commercial-scale production test runs. The fired bricks met or exceeded ASTM standard specifications (ASTM 2005). This present study investigated the possible use of CCBs other than fly ash, or in combination with fly ash, for the production of high-quality building bricks.

Experimental Procedures

Sample Acquisition

Seven CCB samples were acquired from four different sources that burn Illinois Basin coals—two in Illinois (Utilities A and C) and two in Indiana (Utilities B and D). The sample number, source, and a brief description of these CCB samples are listed in Table 1.

The FGD-sulfite material from Utility A had been discharged together with the fly ash into a storage pond prior to permanent disposal at off-site locations. Therefore, the ponded sample (RAW-1) received from Utility A was a mixture of the FGD-sulfite material and fly ash. The FGD-sulfite collected from Utility B had been stabilized (conditioned) by the addition of about 30% fly ash and 3% lime prior to its disposal. Samples of FGD-sulfite were acquired from Utility B before (RAW-3) and after (RAW-2) conditioning. The FGD-sulfate (FGD-formed gypsum) from Utility C was collected and identified as RAW-4. The dry fly ash sample from Utility C, collected from an electrostatic precipitator, was identified as RAW-5. The fly ash and bottom ash of Utility D had been discharged into a common holding pond. Because bottom ash contains large, dense particles that settle near the discharge point and finer fly ash particles settle farther away from the discharge point, the bottom ash sample (RAW-7) was collected near the discharge point, and the fly ash sample (RAW-6) was collected from the opposite end of the pond, farthest from the discharge point.

The CCB samples were acquired in buckets (40 pounds per bucket) and processed for analyses. An FGD-sulfate (FGD-formed gypsum) sample from the University of Illinois’ Abbott Power Plant in Champaign was used as the reference standard sample in the X-ray diffraction (XRD) analysis of the FGD-sulfite material (FGD-formed gypsum) from Utility C. The purity of the Abbott Power Plant sample was >98% (Chou et al. 1998). All raw materials except RAW-3 and RAW-5 were evaluated for their use in brick making.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Utility</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW-1</td>
<td>A</td>
<td>FGD-sulfite ponded with fly ash</td>
</tr>
<tr>
<td>RAW-2</td>
<td>B</td>
<td>FGD-sulfite, conditioned</td>
</tr>
<tr>
<td>RAW-3</td>
<td>B</td>
<td>FGD-sulfite, unconditioned</td>
</tr>
<tr>
<td>RAW-4</td>
<td>C</td>
<td>FGD-sulfite material (gypsum)</td>
</tr>
<tr>
<td>RAW-5</td>
<td>C</td>
<td>Dry fly ash</td>
</tr>
<tr>
<td>RAW-6</td>
<td>D</td>
<td>Ponded fly ash</td>
</tr>
<tr>
<td>RAW-7</td>
<td>D</td>
<td>Ponded bottom ash</td>
</tr>
</tbody>
</table>

1FGD, flue gas desulfurization.
Characterization of Materials and Products

The chemical analyses of raw materials included analyses of major, minor, and trace elements (including sulfur and mercury); carbon was measured as loss on ignition (LOI). In addition, samples of full-size test bricks before and after firing were pulverized and analyzed for chemical composition. Samples of the final fired bricks with optimized formulations for potential commercial production were pulverized and subjected to a simulated acid rainwater extraction, followed by element analysis of the extracts, to determine the environmental impact of the production process.

Chemical analyses were conducted at the Illinois State Geological Survey (ISGS) analytical laboratory, a University of Illinois at Urbana-Champaign laboratory, the Illinois Waste Management Research Center (now the Illinois Sustainable Technology Center) laboratory, and the ALS Chemex commercial laboratory. At least one of these laboratories was equipped with the following instruments: an inductively coupled plasma spectrometer, an atomic emission spectrometer for analyzing 30 elements, an X-ray fluorescence spectrometer for analysis of major elements as metal oxides, an X-ray diffractometer for mineralogical characterization of the samples, a scanning electronic microscope for particle image analysis, and a cold-vapor atomic absorption spectrometer for mercury analysis.

Fired bricks from the bench-scale and commercial firing runs were first analyzed for color, shrinkage, physical appearance, and marketability based on the participating brick plant’s specifications. Following visual inspections, engineering properties of these bricks were tested. Water absorption and compressive strength were tested according to the ASTM C67 standard method (ASTM 2007). Data were evaluated according to ASTM C62 specifications (Table 2) (ASTM 2005). ASTM standard methods were used to ensure appropriate comparisons between bricks made with and without CCBs.

### Table 2 ASTM C62 standard specifications for building bricks (ASTM 2005).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Minimum compressive strength (psi)</th>
<th>Maximum 5-h boiling water absorption (wt%)</th>
<th>Maximum 24-h cold water absorption (≤8 wt%)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>5-brick average 3,000 5-brick individual 2,500</td>
<td>5-brick average 17 5-brick individual 20</td>
<td>5-brick average 0.78 5-brick individual 0.80</td>
</tr>
<tr>
<td>NW</td>
<td>5-brick average 2,500 5-brick individual 2,200</td>
<td>5-brick average 22 5-brick individual 25</td>
<td>5-brick average 0.88 5-brick individual 0.90</td>
</tr>
</tbody>
</table>

¹If the cold water absorption does not exceed 8 wt%, then the boiling water absorption and saturation coefficient specifications are waived.
²The saturation coefficient is the ratio of absorption by 24-hour submersion in cold water to the absorption after 5-hour submersion in boiling water.
³Classification: SW, severe weathering; MW, moderate weathering; NW, negligible weathering.

### Production of Full-Size Green Bricks and Fired Bricks

#### Batch 1 Runs

Small batches of full-size (4 x 2.5 x 8.25 inches) green building bricks were produced by a proprietary mold-press method. For each formulation, three identical green bricks were made. One was fired at the ISGS, and the other two bricks were fired as part of commercial firings at Brick Plant I (BP-I) and Brick Plant II (BP-II).

The feed formulations for the Batch 1 runs are indicated in Table 3. A reference standard formulation containing only clay and shale and no CCB (brick formulation 1) was included in the test runs for comparison. All other bricks contained 10 wt% of clay and various amounts of CCBs substituted for part of the shale (Table 3). Brick formulation 2 contained 25 wt% of RAW-1 (FGD-sulfite material of Utility A) and 15 wt% of RAW-7 (bottom ash) balanced with the shale. All other bricks contained RAW-1 at 20, 30, and 40 wt%, respectively, balanced with the shale.

#### Batch 2 Runs

In the Batch 2 runs, brick formulations containing fly ash (RAW-6), bottom ash (RAW-7), conditioned FGD-sulfite (RAW-2), and FGD-sulfate (gypsum) (RAW-4) were tested for fired brick making (Table 4). One reference standard brick formulation was included for comparison. Mold-pressed full-size green building bricks were made at the ISGS and fired as part of a commercial firing run by BP-I. BP-I formulated its fired bricks based on volume ratios. The weight percent equivalents were calculated, and both measures are indicated in Table 4. The reference standard brick formulation (Brick 7) contained a 1:6 mixture of BP-I clay and BP-I shale (14.29:85.71 vol%).

As mentioned earlier, the fly ash and the bottom ash from Utility D were discharged into a common holding

### Table 3 Feed formulations (wt%) for Batch 1 runs at Brick Plants I and II.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Clay</th>
<th>Shale</th>
<th>Bottom ash (RAW-7)</th>
<th>FGD-sulfite (RAW-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>50</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>70</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>60</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>50</td>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>

¹Flue gas desulfization (FGD) sulfite coal combustion by-product.
²Reference standard.
pond, and the fly ash and bottom ash were sampled separately from different locations in the pond. To understand how the amount of bottom ash affected the quality of the fired bricks, we evaluated formulations with various mixes of fly ash and bottom ash (brick formulations 1 through 4).

The engineering properties of the fired bricks were determined using ASTM (2007) standard test methods for absorption and compressive strength and were evaluated according to ASTM C62 classification (ASTM 2005).

Environmental Assessment

The possible environmental impacts of using fired bricks containing CCBs generated from burning Illinois Basin coal were assessed by means of extraction experiments conducted on pulverized fired brick samples (−60 mesh) according to U.S. EPA Method 1320 (U.S. Environmental Protection Agency 1986). Pulverized samples of three selected fired bricks (Bricks 4, 6, and 10) from Batch 2 runs were agitated in simulated acid rainwater for 24 hours. The concentrations of 20 elements were determined, including arsenic, boron, cadmium, chromium, mercury, nickel, and lead, in the extracts from these samples. The element composition of the extracts generated from simulated acid rainwater extraction was analyzed using the inductively coupled plasma spectrometer, an atomic emission spectrometer, and/or an atomic absorption spectrometer. A cold-vapor atomic absorption spectrometer was used for mercury determination.

Economic Assessment

An economic assessment was conducted for production of bricks containing CCBs, particularly fly ash and bottom ash. Factors considered included current plant costs and the transportation costs associated with shipping ash. Because both fly ash and bottom ash are ponded or landfilled as waste, the major cost to the brick company for obtaining the ash is transportation. The possibility of obtaining shipping and production cost incentives also must be evaluated on a case-by-case basis. However, no new major equipment is needed to retrofit existing brick plant machinery to use CCBs. Each brick company that partnered in this study has an existing source of CCBs and could readily market CCB-containing brick products to meet or exceed conventional brick specifications.

Results and Discussion

Raw Materials and Characterization

Chemical Analyses

The samples were analyzed for their major, minor, and trace element composition. Table 5 lists the major metal oxide composition and carbon content, measured as LOI for the CCB samples and BP-I clay and shale samples. Table 5 also shows the sulfur and mercury contents of the CCB samples. The concentrations of 15 other elements in the samples are shown in Table 6. The dry ash sample, RAW-5, was not analyzed, other than XRD, because it was not tested as a brick ingredient in this project.

As indicated in Table 5, the samples containing FGD-sulfite or FGD-sulfate (RAW-1, RAW-2, RAW-3, and RAW-4) had calcium oxide (CaO) values ranging from 26.29% to 38.87%. The ponded fly ash sample (RAW-6) and bottom ash sample (RAW-7) had CaO values of 1.19% and 7.22%, respectively. The CaO values of the clay and shale samples were <0.8%. The samples containing FGD-sulfite or FGD-sulfate materials (RAW-1, RAW-2, RAW-3, and RAW-4) had lower silicon oxide (SiO₂), aluminum oxide (Al₂O₃), and iron oxide (Fe₂O₃) values than the remaining samples. The SiO₂ contents were ≤6.15%, the Al₂O₃ contents were ≤6.15%, and the Fe₂O₃ contents were ≤6%. Evidently, conditioning (RAW-2) added quantities of SiO₂, Al₂O₃, and Fe₂O₃ to the FGD-sulfite sample (RAW-3), which is reflected by the metal oxide values.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Unit</th>
<th>BP-I clay (RAW-1)</th>
<th>BP-I shale (RAW-2)</th>
<th>Fly ash (RAW-6)</th>
<th>Bottom ash (RAW-7)</th>
<th>FGD-sulfite (RAW-2)</th>
<th>FGD-sulfate (RAW-4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>vol%</td>
<td>14.29</td>
<td>42.86</td>
<td>14.29</td>
<td>28.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.70</td>
<td>46.31</td>
<td>12.50</td>
<td>24.49</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>vol%</td>
<td>14.29</td>
<td>42.86</td>
<td>28.57</td>
<td>14.29</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.47</td>
<td>47.02</td>
<td>28.57</td>
<td>12.62</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3</td>
<td>vol%</td>
<td>14.29</td>
<td>57.13</td>
<td>14.29</td>
<td>14.29</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>15.59</td>
<td>58.85</td>
<td>12.55</td>
<td>13.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>vol%</td>
<td>14.29</td>
<td>28.57</td>
<td>28.57</td>
<td>28.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.32</td>
<td>31.71</td>
<td>25.59</td>
<td>26.38</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>vol%</td>
<td>14.29</td>
<td>57.14</td>
<td>-</td>
<td>14.29</td>
<td>14.29</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.89</td>
<td>63.87</td>
<td>-</td>
<td>13.21</td>
<td>6.03</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>vol%</td>
<td>14.29</td>
<td>42.85</td>
<td>28.58</td>
<td>-</td>
<td>14.29</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.29</td>
<td>50.93</td>
<td>26.74</td>
<td>-</td>
<td>6.04</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>vol%</td>
<td>14.29</td>
<td>85.71</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>14.96</td>
<td>50.93</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>vol%</td>
<td>14.29</td>
<td>71.42</td>
<td>-</td>
<td>-</td>
<td>14.29</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.55</td>
<td>77.56</td>
<td>-</td>
<td>-</td>
<td>5.89</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>vol%</td>
<td>14.29</td>
<td>57.14</td>
<td>-</td>
<td>-</td>
<td>28.57</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>18.24</td>
<td>68.93</td>
<td>-</td>
<td>-</td>
<td>12.83</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>vol%</td>
<td>14.29</td>
<td>71.42</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.29</td>
</tr>
<tr>
<td></td>
<td>wt%</td>
<td>16.01</td>
<td>70.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13.90</td>
</tr>
</tbody>
</table>

1Flue gas desulfurization (FGD) sulfite and sulfate coal combustion by-product samples.
2Reference standard brick formulation without coal combustion by-products.
for sample RAW-2. The ponded fly ash sample (RAW-6) and the ponded bottom ash sample (RAW-7), like the clay and shale samples, had SiO₂, Al₂O₃, and Fe₂O₃ as their major metal oxides.

For the samples containing FGD by-products (RAW-1, RAW-2, RAW-3, and RAW-4), calcium contents ranged from 15.50 to 26.10% (Table 6), and sulfur contents ranged from 14.10 to 21.30% (Table 5), reflecting the calcium sulfate or calcium sulfite present in the FGD materials. Mercury contents of these four samples ranged from 0.18 to 0.44 mg/kg (Table 5). The fly ash and bottom ash samples (RAW-6 and RAW-7) and the clay and shale samples all had calcium contents of ≤5.17%, sulfur contents of ≤0.57%, and mercury contents of ≤0.06 mg/kg. For the 15 other elements determined, no specific similarities or differences could be found between the CCB samples and the clay or shale samples.

X-ray Diffraction Analysis
The major mineralogical composition of the raw materials was determined by XRD analyses. The fly ash, clay, and shale samples were analyzed at the ISGS XRD laboratory. Typical X-ray diffractograms from a dry fly ash (powder fly ash) sample and a ponded fly ash sample are shown in Figure 1; they appear to be similar. The diffractograms for the shale, clay, and mixed shale and clay samples are shown in Figure 2.

Because fly ash samples were subjected during coal combustion to heat high enough to cause some melting of the minerals present, the diffractograms of the fly ashes (Figure 1) show a mixture of crystalline and amorphous materials. The crystalline components include quartz that escaped melting and minerals such as mullite, hematite, and magnetite that formed at high temperature during coal combustion.

### Table 5  Metal oxide composition, loss on ignition (LOI) value, and sulfur and mercury contents of the coal combustion by-product samples (given as wt% except as indicated).1,2

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>TiO₂</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>LOI</th>
<th>S</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW-1</td>
<td>17.21</td>
<td>6.15</td>
<td>5.68</td>
<td>0.30</td>
<td>0.02</td>
<td>0.58</td>
<td>26.29</td>
<td>0.57</td>
<td>0.71</td>
<td>0.09</td>
<td>15.00</td>
<td>14.20</td>
<td>0.18</td>
</tr>
<tr>
<td>RAW-2</td>
<td>13.93</td>
<td>6.15</td>
<td>6.00</td>
<td>0.27</td>
<td>0.01</td>
<td>1.30</td>
<td>30.03</td>
<td>0.71</td>
<td>0.77</td>
<td>0.07</td>
<td>8.17</td>
<td>14.10</td>
<td>0.36</td>
</tr>
<tr>
<td>RAW-3</td>
<td>2.89</td>
<td>0.54</td>
<td>0.45</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>1.99</td>
<td>38.87</td>
<td>0.10</td>
<td>0.02</td>
<td>0.04</td>
<td>4.25</td>
<td>20.80</td>
<td>0.44</td>
</tr>
<tr>
<td>RAW-4</td>
<td>0.85</td>
<td>0.16</td>
<td>0.15</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.15</td>
<td>34.79</td>
<td>0.06</td>
<td>0.02</td>
<td>0.06</td>
<td>17.35</td>
<td>21.30</td>
<td>0.21</td>
</tr>
<tr>
<td>RAW-5</td>
<td>53.57</td>
<td>23.86</td>
<td>12.88</td>
<td>1.24</td>
<td>0.03</td>
<td>1.15</td>
<td>1.19</td>
<td>0.71</td>
<td>2.70</td>
<td>0.16</td>
<td>1.86</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>RAW-6</td>
<td>46.49</td>
<td>21.23</td>
<td>17.25</td>
<td>1.12</td>
<td>0.11</td>
<td>0.95</td>
<td>7.22</td>
<td>1.03</td>
<td>1.75</td>
<td>0.06</td>
<td>1.10</td>
<td>0.57</td>
<td>0.05</td>
</tr>
</tbody>
</table>

1The sulfur dioxide value is 2 × S (sulfur content), wt%.
2SiO₂, silicon oxide; Al₂O₃, aluminum oxide; Fe₂O₃, iron oxide; TiO₂, titanium dioxide; MnO, manganese oxide; MgO, magnesium oxide; CaO, calcium oxide; Na₂O, sodium oxide; K₂O, potassium oxide; P₂O₅, phosphorus pentoxide; LOI, loss on ignition; S, sulfur; Hg, mercury.

### Table 6  Concentrations of elements in the coal combustion by-product samples (mg/kg except as indicated).1

<table>
<thead>
<tr>
<th>Sample</th>
<th>As</th>
<th>B</th>
<th>Ba</th>
<th>Ca (wt%)</th>
<th>Cd</th>
<th>Cr</th>
<th>Li</th>
<th>Ni</th>
<th>Pb (wt%)</th>
<th>Na (wt%)</th>
<th>Mg (wt%)</th>
<th>Mn</th>
<th>Sr</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW-1</td>
<td>9.0</td>
<td>1,360</td>
<td>110</td>
<td>17.60</td>
<td>1.48</td>
<td>74</td>
<td>15.8</td>
<td>39</td>
<td>15.8</td>
<td>0.65</td>
<td>0.41</td>
<td>0.33</td>
<td>171</td>
<td>179</td>
</tr>
<tr>
<td>RAW-2</td>
<td>46.0</td>
<td>510</td>
<td>60</td>
<td>20.30</td>
<td>0.93</td>
<td>64</td>
<td>36.2</td>
<td>71</td>
<td>55.1</td>
<td>0.69</td>
<td>0.57</td>
<td>0.82</td>
<td>151</td>
<td>324</td>
</tr>
<tr>
<td>RAW-3</td>
<td>&lt;5.0</td>
<td>280</td>
<td>30</td>
<td>26.10</td>
<td>0.44</td>
<td>9</td>
<td>4.5</td>
<td>&lt;1</td>
<td>4.7</td>
<td>0.10</td>
<td>0.03</td>
<td>1.31</td>
<td>143</td>
<td>332</td>
</tr>
<tr>
<td>RAW-4</td>
<td>&lt;5.0</td>
<td>20</td>
<td>&lt;10</td>
<td>15.50</td>
<td>0.02</td>
<td>37</td>
<td>0.6</td>
<td>&lt;1</td>
<td>1.9</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>0.07</td>
<td>17</td>
<td>78</td>
</tr>
<tr>
<td>RAW-5</td>
<td>89.7</td>
<td>450</td>
<td>550</td>
<td>0.82</td>
<td>3.74</td>
<td>239</td>
<td>154.5</td>
<td>260</td>
<td>168.5</td>
<td>2.11</td>
<td>0.48</td>
<td>0.59</td>
<td>244</td>
<td>345</td>
</tr>
<tr>
<td>RAW-6</td>
<td>21.9</td>
<td>ND</td>
<td>480</td>
<td>5.17</td>
<td>0.50</td>
<td>211</td>
<td>169.5</td>
<td>233</td>
<td>69.5</td>
<td>1.47</td>
<td>0.83</td>
<td>0.50</td>
<td>886</td>
<td>353</td>
</tr>
<tr>
<td>BP-I clay</td>
<td>15.1</td>
<td>114</td>
<td>440</td>
<td>0.45</td>
<td>0.05</td>
<td>94</td>
<td>214.0</td>
<td>65</td>
<td>28.2</td>
<td>1.78</td>
<td>0.34</td>
<td>0.74</td>
<td>629</td>
<td>282</td>
</tr>
<tr>
<td>BP-I shale</td>
<td>10.2</td>
<td>ND</td>
<td>480</td>
<td>0.48</td>
<td>0.22</td>
<td>68</td>
<td>88.0</td>
<td>54</td>
<td>23.2</td>
<td>2.22</td>
<td>0.67</td>
<td>1.01</td>
<td>683</td>
<td>159</td>
</tr>
<tr>
<td>BP-I clay and shale</td>
<td>4.4</td>
<td>ND</td>
<td>440</td>
<td>0.33</td>
<td>0.11</td>
<td>61</td>
<td>87.8</td>
<td>50</td>
<td>21.9</td>
<td>2.35</td>
<td>0.63</td>
<td>0.98</td>
<td>578</td>
<td>159</td>
</tr>
</tbody>
</table>

1As, arsenic; B, boron; Ba, barium; Ca, calcium; Cd, cadmium; Cr, chromium; Li, lithium; Ni, nickel; Pb, lead; K, potassium; Na, sodium; Mg, magnesium; Mn, manganese; Sr, strontium; Zn, zinc.
2ND, Not determined.
The diffractograms of the shale sample, the clay sample, and the mixed shale and clay sample (Figure 2) show peaks for chlorite, illite, kaolinite, quartz, K-feldspar, plagioclase feldspar, and all other clay minerals. The shale and clay samples contained refractory minerals that do not melt at brick-firing temperatures and generally larger particles (kaolinite and quartz) that help to maintain the brick's body shape during firing. The shale and clay samples also contained enough minerals with lower melting points (i.e., feldspars, chlorite, and iron-rich illite) to melt and form a steel-hard body with low water absorption.

Based on these XRD analyses, the resulting semi-quantitative mineral composition data, including the clay index (CI) of the clay, the shale-clay mix, and the ponded fly ash samples, are listed in Table 7. The CI is the sum of clay mineral percents [illite + kaolinite + chlorite] divided by 100. The CI provides a relative measure of the extrudability of feed materials; a higher value represents greater extrudability. The feed materials should have adequate extrudability (a CI value of about 0.4 would meet BP-I's requirement) in order to form strong and firm green bricks for firing. Based on a survey of more than half of the participating brick manufacturing plants in the United States, the primary method of forming green bricks is extrusion (93.2%) (Brick Industry Association 2006).

The mineral composition data (Table 7) indicate that the BP-I clay had the greatest CI (0.61), and the BP-I clay-shale mixture had a CI of 0.41. Fly ash, which functions as filler for the brick body, does not improve extrudability.

Samples of bottom ash, FGD-sulfite, and FGD-sulfate (gypsum) were analyzed by XRD at the XRD facility at the University of Illinois. The X-ray diffractograms of samples collected from different time periods were compared to examine sampling consistency in mineral composition over time. The X-ray diffractograms of both the conditioned FGD-sulfite samples (RAW-3) collected from the same sources a year apart showed very similar peak distribution patterns. This result suggested that there was no notable mineralogical change in the FGD-sulfite material over the sampling time and that the utility plant could supply consistent raw feed materials over time.

![Figure 1](image1.png)

**Figure 1** X-ray diffractograms of dry fly ash and ponded fly ash samples. The mineral peak indications are mullite (M), quartz (Q), hematite (H), anatase (A), and magnetite (Mg). The broad “hump” in the background between about 13 and 30 degrees 2θ is due to abundant noncrystalline glass in the samples. CPS, counts per second.

![Figure 2](image2.png)

**Figure 2** X-ray diffractograms of random bulk pack of Brick Plant 1 shale, clay, and clay and shale brick mix. The mineral peak indications are chlorite (C), illite (I), kaolinite (K), (020) peak (common to all clay minerals), quartz (Q), K-feldspar (Kf), and plagioclase feldspar (Pf). CPS, counts per second.
**Table 7** Mineral composition (wt %) and clay index for the samples of fly ash, clay, and clay plus shale.1

<table>
<thead>
<tr>
<th>Sample</th>
<th>I</th>
<th>K</th>
<th>C</th>
<th>Kf</th>
<th>Pf</th>
<th>Cl</th>
<th>Q</th>
<th>M</th>
<th>Cc</th>
<th>Mg</th>
<th>H</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponded fly ash</td>
<td>0</td>
<td>15</td>
<td>24</td>
<td>1.9</td>
<td>2.9</td>
<td>2.3</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP-I clay</td>
<td>38</td>
<td>15</td>
<td>7.6</td>
<td>0.4</td>
<td>2.7</td>
<td>0.61</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP-I shale-clay mix</td>
<td>26</td>
<td>7.5</td>
<td>7.3</td>
<td>0.7</td>
<td>8.1</td>
<td>0.41</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 I, illite; K, kaolinite; C, chlorite; Q, quartz; Kf, k-feldspar; Pf, plagioclase feldspar; Cl, clay index; M, mullite; Cc, calcite; Mg, magnetite; and H, hematite.

**Product Evaluation**

**Batch 1 Runs**

Three full-size green building bricks were made for each formulation (Table 3). One set of five green bricks was fired at the ISGS, and the other two sets were fired as parts of commercial firings at BP-I and BP-II. Figure 3a shows one set of the bricks before firing; Figure 3b shows the bricks fired at BP-I sawn in half for examination; Figure 3c shows the bricks fired at BP-II sawn in half for examination.

The physical appearance of the fired bricks suggested that firings at BP-I and BP-II were successfully completed. The fired bricks were without scum, lime pops, cracks, black hearts, or red hearts. The bricks exhibited slight color differences, which varied depending on composition. Bricks were lighter in color as the weight percentage of RAW-1 in the formulation increased.

The total weight loss and shrinkage of the bricks after drying and firing are shown in Tables 8 and 9. The bricks made with RAW-1 (Bricks 2, 3, 4, and 5) lost more weight (22.8 to 32.1% at BP-I and 20.1 to 22.5% at BP-II) during drying and firing than did the reference standard commercial formulation Brick 1 (15.8%). However, during drying and firing, bricks made with RAW-1 in the formulation (Bricks 2, 3, 4, and 5) shrank less (2.4% for the bricks fired by BP-I and 1.6 to 3.9% for the bricks fired by BP-II) than the reference standard Brick 1 (7.1% for the bricks fired by BP-I and 6.3% for the bricks fired by BP-II). These differences could be due to differences in firing method and tempera-

**Table 8** Total weight loss and shrinkage for Batch 1 bricks fired at Brick Plant I.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Total weight loss (%)</th>
<th>Total shrinkage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.8</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>24.9</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>22.8</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>25.4</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>32.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

1 Reference standard. Brick formulations are given in Table 3.

**Table 9** Total weight loss and shrinkage for Batch 1 bricks fired at Brick Plant II.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Total weight loss (%)</th>
<th>Total shrinkage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.8</td>
<td>6.3</td>
</tr>
<tr>
<td>2</td>
<td>22.5</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>20.5</td>
<td>3.1</td>
</tr>
<tr>
<td>5</td>
<td>22.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

1 Reference standard. Brick formulations are given in Table 3.
turer program. BP-I is equipped with a stationary kiln, and BP-II is equipped with a tunnel kiln.

The engineering properties of the Batch 1 fired bricks were determined. The fired bricks were sawn in half to test absorption and compressive strength tests according to ASTM method C67. Results are shown in Table 10 for the bricks fired at BP-I and in Table 11 for those fired at BP-II.

A distinct trend was observed for the cold water and boiling water absorption and compressive strength of the bricks fired at BP-I or BP-II (Tables 10 and 11). Bricks 2, 3, 4, and 5, which contained FGD-sulfite (RAW-1), absorbed more cold water (11.76% at BP-II to 23.58% at BP-I) than the reference standard brick (4.93% at BP-I to 6.91% at BP-II). The bricks containing FGD-sulfite also were softer (lower compressive strength) than the reference brick. Compressive strengths of Bricks 2, 3, 4, and 5 ranged from 1,481 at BP-I to 3,415 psi at BP-II; the compressive strengths of the reference standard brick was 7,680 psi at BP-I and 7,353 psi at BP-II. The saturation coefficients of the bricks containing RAW-1 fired at BP-I ranged from 0.84 to 0.86, and those of the bricks fired at BP-II ranged from 0.77 to 0.85.

A general trend was observed for the compressive strength of the fired bricks containing RAW-1. As the concentration of RAW-1 in the bricks increased, the compressive strength decreased. However, Brick 2, containing 15% bottom ash and 25% RAW-1, showed about 1.1 to 2 times greater compressive strength than the bricks without bottom ash (Bricks 3, 4, and 5). The bricks containing FGD material, which were whiter and weaker, would be acceptable for use as specialty bricks in areas with warmer climates. The results of this study suggest that the engineering properties of bricks containing FGD materials can be improved through the addition of bottom ash.

According to ASTM C62 specifications, Bricks 3, 4, and 5 (with 20, 30, and 40 wt% FGD-sulfite, respectively) fired at BP-I (Table 10) belong to the negligible-weathering grade, and Brick 2 (with 15% bottom ash) belongs to the moderate-weathering grade. For the bricks fired by BP-II (Table 11), Brick 5 belongs to the negligible-weathering grade, Bricks 3 and 4 belong to the moderate-weathering grade, and Brick 2 (with 15% bottom ash) belongs to the severe-weathering grade.

Results from our previous study (Chou et al. 2006a) showed that the engineering properties of the bricks made by mold pressing were significantly improved when commercial production used extrusion to form the green bricks. For example, the molded bricks from the study’s bench-scale production had compressive strengths that ranged from 5,800 to 8,000 psi, whereas extruded bricks with the same feed formulation from the commercial-scale testing showed a compressive strength of 16,905 psi. If a similar ratio is applied, the engineering properties of Batch 1 bricks formed by extrusion might be acceptable for use under moderate or severe weathering when produced by commercial methods.

**Batch 2 Runs**

The formulations for the Batch 2 runs are shown in Table 4. Firing of the test bricks was successfully completed at BP-I during a normal commercial firing. The fired bricks were cut in half to examine color and other characteristics inside and outside the brick body and to prepare for the engineering property tests. Photographs of these sawn bricks are shown in Figure 4.

Brick Plant I found that the color and appearance of all their commercially fired Batch 2 bricks were acceptable. The bricks showed no cracks, lime pops, scum, black hearts, or red hearts. The bricks containing fly ash blended with bottom ash (Bricks 1, 2, 3, and 4) were similar in their red color to Brick 7, the reference standard brick made without CCBs.

In the Batch 1 runs, Bricks 2, 3, 4, and 5 containing FGD-sulfite from Utility

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**Table 10** Engineering properties of Batch 1 bricks fired at Brick Plant I.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Cold water absorption (wt%)</th>
<th>Boiling water absorption (wt%)</th>
<th>Saturation coefficient</th>
<th>Compressive strength (psi)</th>
<th>ASTM C62 classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.93</td>
<td>6.88</td>
<td>0.72</td>
<td>7,680</td>
<td>SW</td>
</tr>
<tr>
<td>2</td>
<td>17.57</td>
<td>20.92</td>
<td>0.84</td>
<td>2,811</td>
<td>MW</td>
</tr>
<tr>
<td>3</td>
<td>16.40</td>
<td>19.30</td>
<td>0.85</td>
<td>2,143</td>
<td>NW</td>
</tr>
<tr>
<td>4</td>
<td>20.18</td>
<td>23.60</td>
<td>0.86</td>
<td>1,965</td>
<td>NW</td>
</tr>
<tr>
<td>5</td>
<td>23.58</td>
<td>27.97</td>
<td>0.84</td>
<td>1,481</td>
<td>NW</td>
</tr>
</tbody>
</table>

1Brick formulations are given in Table 3.
2See Table 2 for complete information; SW, severe weathering; MW, moderate weathering; NW, negligible weathering.
3Reference standard.

**Table 11** Engineering properties of Batch 1 bricks fired at Brick Plant II.

<table>
<thead>
<tr>
<th>Brick formulation</th>
<th>Cold water absorption (wt%)</th>
<th>Boiling water absorption (wt%)</th>
<th>Saturation coefficient</th>
<th>Compressive strength (psi)</th>
<th>ASTM C62 classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.91</td>
<td>8.98</td>
<td>0.77</td>
<td>7,353</td>
<td>SW</td>
</tr>
<tr>
<td>2</td>
<td>12.72</td>
<td>16.33</td>
<td>0.78</td>
<td>3,415</td>
<td>SW</td>
</tr>
<tr>
<td>3</td>
<td>13.87</td>
<td>16.36</td>
<td>0.85</td>
<td>3,160</td>
<td>MW</td>
</tr>
<tr>
<td>4</td>
<td>11.76</td>
<td>15.05</td>
<td>0.78</td>
<td>2,374</td>
<td>MW</td>
</tr>
<tr>
<td>5</td>
<td>14.51</td>
<td>18.77</td>
<td>0.77</td>
<td>1,978</td>
<td>NW</td>
</tr>
</tbody>
</table>

1Reference standard. Brick formulations are given in Table 3.
2See Table 2 for complete information; SW, severe weathering; MW, moderate weathering; NW, negligible weathering.
3Reference standard.
A (RAW-1) were much lighter in color than the bricks without FGD materials. However, in the Batch 2 runs, Bricks 5, 6, 8, 9, and 10 containing FGD-sulfite from Utility B or C had a red color similar to the reference standard brick (Brick 7). The amount of $\text{Fe}_2\text{O}_3$ in the feed material is generally the major factor determining the redness of the fired products. The redder color of the Batch 2 bricks could be due to the relatively small amount of added FGD CCBs ($\leq 28.6$ vol%; $\leq 12.8$ wt%) compared with the 20 to 40 wt% added to the Batch 1 bricks. Therefore, the amounts of $\text{Fe}_2\text{O}_3$ in the feed for the Batch 2 bricks were less diluted by the FGD material.

The engineering properties of the Batch 2 fired bricks were measured. The data for water absorption, compressive strength, and ASTM C62 classification are shown in Table 12.

According to the ASTM C62 specifications (Table 2), the cold water absorption for the reference standard (Brick 7) and brick formulations 1 to 3 containing fly ash and bottom ash met the specified standard of less than 8 wt%; formulation 4, at 8.48 wt%, slightly exceeded the maximum allowed absorption (Table 12). This result indicated that addition of the FGD CCBs increased water absorption by the brick. The cold water absorption for bricks containing FGD CCBs ranged from 11.55 to 13.00 wt%. All of the bricks had a maximum saturation coefficient of $\leq 0.78$ and a compressive strength of greater than 3,000 psi, meeting the ASTM specification for building bricks of severe-weathering grade (ASTM 2005).

**Environmental Assessment**

To study the possible environmental impacts of using fired bricks containing CCBs, pulverized fired-brick samples made with optimized formulations for potential commercial production were subjected to a simulated acid rainwater extraction. Fired brick samples with feed formulations 4, 6, and 10 (Table 4) were chosen for these tests. Brick sample extracts were analyzed according to the U.S. EPA Method 1320 (U.S. Environmental Protection Agency 1986). Table 13 presents the concentrations of 20 elements in the extracts and the regulatory thresholds for these elements for acid extractions from comparable solid wastes. The concentrations of the elements of concern (having available U.S. EPA limits) in the extracts of these brick samples are well below the regulatory thresholds, which indicates that the fired bricks containing CCBs can be considered environmentally safe construction products.

Additionally, a set of the intermediate (green bricks) and final (fired) bricks were pulverized and analyzed for their chemical composition. As expected, all of the brick samples showed a major loss of carbon (measured as loss on ignition [LOI value]), sulfur, and mercury in the fired products (data not shown). A direct method for determining the amounts of sulfur and mercury that were released into the air during brick firing was beyond the scope of this investigation. The chemical composition tests on the raw materials, however, indicated that the bricks containing FGD materials had sulfur contents of 14.10 to 21.30% and mercury contents of 0.18 mg/kg to 0.44 mg/kg; the fly ash, bottom ash, clay, and shale samples all had sulfur contents of $\leq 0.57$% and mercury contents of $\leq 0.06$ mg/kg (Table 5).

Based on the test results, the fired bricks with FGD materials had good...
physical appearance and engineering properties. The U.S. EPA Method 1320 standards showed that these fired bricks could be considered environmentally safe construction products. However, further investigation is needed to determine whether the high sulfur concentration introduced to the bricks by the addition of FGD material poses an issue of secondary emission during brick firing.

**Economic Assessment**

This study assessed the economic feasibility of producing fired bricks with fly ash and bottom ash blended with clay and shale at BP-I. Because the existing machinery at BP-I could be used for production, there were no associated capital costs. The cost of obtaining the raw materials and the production costs were the two major economic factors affected by the raw material substitution.

Fly ash and bottom ash CCBs are readily available throughout the year. Power plants pay substantial amounts to dispose of their ash in landfills and holding ponds; consequently, the plants are eager to sell these by-products at little or no cost. In some cases, they are willing to financially assist a company that wants to use the ash. The main cost of the CCBs is transportation from the power plant to the brick plant.

To help quantify costs, as part of our study, a trucking company was contacted to estimate the cost of shipping ash from a specific utility plant to BP-I. Because the distance between the two locations was less than 5 miles, the trucking company estimated its charge at an hourly rate of $65 rather than charging per mile. The truck could carry 25 tons of ash, and a maximum time of 2 hours was thought to be needed for loading, transportation, and unloading the ash. With these constraints, the overall shipping cost was estimated at $5.20/ton ($65 × 2)/25. However, if the utility plant were to incur half of the shipping cost, the transportation cost estimate would be $2.60/ton for the brick company. Using fly ash and bottom ash as substitute raw materials in bricks can reduce the annual consumption of clay and shale, thereby reducing the annual mining costs for BP-I. BP-I owns and operates mines to produce its clay and shale raw materials. According to its estimate, the cost of mining is $127,000 annually (excluding depreciation costs). The shared cost of transporting fly ash and bottom ash from the util-

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**Table 12** Engineering properties of Batch 2 bricks fired at Brick Plant I.

<table>
<thead>
<tr>
<th>Brick formulation¹</th>
<th>Cold water absorption (wt%)</th>
<th>Boiling water absorption (wt%)</th>
<th>Saturation coefficient</th>
<th>Compressive strength (psi)</th>
<th>ASTM C62 classification²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.97</td>
<td>11.44</td>
<td>0.70</td>
<td>4,931</td>
<td>SW</td>
</tr>
<tr>
<td>2</td>
<td>6.29</td>
<td>9.76</td>
<td>0.64</td>
<td>4,048</td>
<td>SW</td>
</tr>
<tr>
<td>3</td>
<td>6.43</td>
<td>9.80</td>
<td>0.66</td>
<td>5,384</td>
<td>SW</td>
</tr>
<tr>
<td>4</td>
<td>8.48</td>
<td>12.23</td>
<td>0.69</td>
<td>3,934</td>
<td>SW</td>
</tr>
<tr>
<td>5</td>
<td>12.50</td>
<td>15.94</td>
<td>0.78</td>
<td>3,137</td>
<td>SW</td>
</tr>
<tr>
<td>6</td>
<td>13.00</td>
<td>17.67</td>
<td>0.74</td>
<td>3,538</td>
<td>SW</td>
</tr>
<tr>
<td>7³</td>
<td>3.47</td>
<td>5.76</td>
<td>0.60</td>
<td>5,854</td>
<td>SW</td>
</tr>
<tr>
<td>8</td>
<td>11.81</td>
<td>15.13</td>
<td>0.78</td>
<td>3,204</td>
<td>SW</td>
</tr>
<tr>
<td>9</td>
<td>11.55</td>
<td>15.07</td>
<td>0.77</td>
<td>3,962</td>
<td>SW</td>
</tr>
<tr>
<td>10</td>
<td>12.41</td>
<td>17.39</td>
<td>0.71</td>
<td>3,541</td>
<td>SW</td>
</tr>
</tbody>
</table>

¹Brick formulations are given in Table 3.
²See Table 2 for complete information; SW, severe weathering; MW, moderate weathering; NW, negligible weathering.
³Reference standard.

**Table 13** Concentrations (mg/L) of elements in the extracts generated from simulated acid rainwater extractions.¹ ²

<table>
<thead>
<tr>
<th>Sample</th>
<th>Al³</th>
<th>As</th>
<th>B</th>
<th>Ba</th>
<th>Ca</th>
<th>Cd</th>
<th>Co</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank 1</td>
<td>&lt;0.02</td>
<td>&lt;0.001</td>
<td>&lt;0.02</td>
<td>0.004</td>
<td>&lt;0.1</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Blank 2</td>
<td>&lt;0.02</td>
<td>&lt;0.001</td>
<td>&lt;0.02</td>
<td>0.003</td>
<td>&lt;0.1</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Brick 4</td>
<td>0.09</td>
<td>0.007</td>
<td>0.57</td>
<td>0.069</td>
<td>57.0</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>1.21</td>
</tr>
<tr>
<td>Brick 6</td>
<td>0.08</td>
<td>0.008</td>
<td>0.72</td>
<td>0.069</td>
<td>57.0</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.036</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Brick 10</td>
<td>0.16</td>
<td>0.004</td>
<td>0.31</td>
<td>0.072</td>
<td>117.5</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>1.08</td>
</tr>
<tr>
<td>EPA limit</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>5.00</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>K</th>
<th>Li</th>
<th>Mg</th>
<th>Na</th>
<th>Ni</th>
<th>Pb</th>
<th>S</th>
<th>Se</th>
<th>Zn</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank 1</td>
<td>&lt;0.1</td>
<td>&lt;0.001</td>
<td>&lt;0.02</td>
<td>0.18</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>32</td>
<td>&lt;0.001</td>
<td>&lt;0.004</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>Blank 2</td>
<td>&lt;0.1</td>
<td>&lt;0.001</td>
<td>&lt;0.02</td>
<td>0.21</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>29</td>
<td>&lt;0.001</td>
<td>&lt;0.004</td>
<td>&lt;0.000001</td>
</tr>
<tr>
<td>Brick 4</td>
<td>1.40</td>
<td>0.087</td>
<td>3.85</td>
<td>7.00</td>
<td>0.007</td>
<td>&lt;0.001</td>
<td>48</td>
<td>&lt;0.001</td>
<td>&lt;0.004</td>
<td>&lt;0.000001</td>
</tr>
<tr>
<td>Brick 6</td>
<td>1.45</td>
<td>0.043</td>
<td>4.00</td>
<td>7.75</td>
<td>0.005</td>
<td>&lt;0.001</td>
<td>46</td>
<td>&lt;0.001</td>
<td>&lt;0.004</td>
<td>&lt;0.000001</td>
</tr>
<tr>
<td>Brick 10</td>
<td>2.05</td>
<td>0.051</td>
<td>2.35</td>
<td>7.10</td>
<td>0.004</td>
<td>&lt;0.001</td>
<td>86</td>
<td>&lt;0.001</td>
<td>&lt;0.004</td>
<td>&lt;0.000001</td>
</tr>
<tr>
<td>EPA limit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.00</td>
<td>5.00</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

¹Solid to acidic water ratio, 1:20.
²Extracts from fired Bricks 4, 6, and 10 are identified in Table 4; Blanks 1 and 2 are values for the simulated acid rainwater before used for extraction.
³Al, aluminum; As, arsenic; B, boron; Ba, barium; Ca, calcium; Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper; Fe, iron; K, potassium; Li, lithium; Mg, magnesium; Na, sodium; Ni, nickel; Pb, lead; S, sulfur; Se, selenium; Zn, zinc; Hg, mercury.
ity plant to BP-I is $2.60/ton. If BP-I
uses a substitution formula of 20% fly
ash, 20% bottom ash, and 60% clay
and shale, the cost of transporting the
ash would be $26,520/year (12,000,000
bricks/year × 4.25 lb/brick × 1/2000
ton/lb × 2.60 $/ton × 0.4 part ash).
The savings in mining costs would be
$50,800/year ($127,000 × 0.4 part ash).
The net cost savings would be $24,280/
year ($50,800 – $26,520), assuming no
cost for ash.

During raw material processing, mined
clay and shale must be crushed and
extensively ground. Fly ash, a mate-
rnal with a fine particle size, does not
require such procedures, which can
reduce raw material costs in propor-
tion to the amount of fly ash used.

Conversely, bottom ash contains
coarser particles and requires prepara-
tion similar to that of clay and shale.
The cost of grinding raw materials at
BP-I is $75,000 annually (excluding
depreciation costs). By using 20% fly
ash, BP-I could be expected to save
$15,000/year ($75,000 × 0.2). The
total cost savings for BP-I by using a
feed formulation of 20% fly ash, 20% bottom ash, and 60% clay and shale for
its brick production would be $39,280/
year.

Conclusions
Various combinations of fly ash,
bottom ash, and FGD-sulfite and FGD-
sulfate CCBs were used as a partial
replacement for the shale that is gen-
erally mixed with clay to make fired
bricks. Fired bricks made with these
raw materials contained no scum,
lime pops, cracks, black hearts, or red
hearts. Engineering properties of the
majority of these fired bricks met the
ASTM classification for a severe-weather-
ing grade brick, although some were
suited only for moderate-weathering
or negligible-weathering grade. Fired
bricks made with fly ash and bottom
ash blends were comparable in color
to fired bricks without CCBs. Bricks
containing substantial quantities of
FGD-sulfite were lighter in color, lower
in compressive strength, and greater
in water absorption capacity than the
reference standard fired bricks made
without CCBs. The addition of bottom
ash to the brick composition increased
brick redness, improved its compres-
sive strength, and decreased its water
absorption capacity.

Simulated acid rainwater extraction
tests showed that all of the fired bricks
containing CCBs produced in our tests,
including those containing fly ash and
bottom ash, can be considered environ-
mentally safe construction products. The fly ash and bottom ash from our specific project source can be
recommended for use in making fired
bricks. However, to fully evaluate the
environmental impact of using higher
sulfur content FGD CCBs as an ingredi-
ent in fired bricks, further studies are
warranted to determine the fate of the
sulfur during brick firing.

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