Coal Ash Reuse Options:
A Strategy for Moving Forward

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Electricity Generation by Fuel

Source: EIA Annual Energy Outlook, 2010
Non-Hydro Renewable Generation

Source: EIA, Annual Energy Outlook 2012

Source: Energy Velocity

Add Campaign
Funded by Chesapeake Energy
(natural gas producer)
Source: Gooden Group Public Relations
Projecting Ash Production

Source: ACAA, National Mining Assoc.
Coal Consumption, Mst

Ash Production, Mst


Coal Consumption
Ash Production**
Fly Ash and Bottom Ash

Production and Utilization, Million tons

- % Utilized
- Tons Produced
- Tons Utilized

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Fuel Delivered to US Utilities

Electric Utility Receipts, K tons

- Lignite
- Bituminous
- Subbituminous

Ash Content, %

- Lignite
- Bituminous
- Subbituminous
Portland and Masonry Cement Consumption

Source: PCA
Wallboard Demand

Housing Starts, SAAR

Wallboard Demand, BSF

Source: American Homebuilders Assoc.
Assumptions

• Unconfined CCB uses will be curtailed and eventually eliminated by regulation

• Renewable energy growth will be realized by co-firing biomass primarily in FBC units
## Summary Projections

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2012</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal Utilization</strong></td>
<td>M tons</td>
<td>1,035.2</td>
<td>1,122.3</td>
</tr>
<tr>
<td><strong>Production</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC Ash</td>
<td>M tons</td>
<td>85.5</td>
<td>91.9</td>
</tr>
<tr>
<td>FGD Products</td>
<td>M tons</td>
<td>43.0</td>
<td>48.2</td>
</tr>
<tr>
<td>FBC Ash</td>
<td>M tons</td>
<td>10.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Total CCBs</td>
<td>M tons</td>
<td>138.8</td>
<td>154.4</td>
</tr>
<tr>
<td><strong>Utilization</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC Ash</td>
<td>M tons</td>
<td>33.3</td>
<td>28.0</td>
</tr>
<tr>
<td>FGD Products</td>
<td>M tons</td>
<td>10.7</td>
<td>11.2</td>
</tr>
<tr>
<td>FBC Ash</td>
<td>M tons</td>
<td>8.7</td>
<td>5.0</td>
</tr>
<tr>
<td>Total CCBs</td>
<td>M tons</td>
<td>52.7</td>
<td>44.2</td>
</tr>
<tr>
<td><strong>Utilization Rate</strong></td>
<td>%</td>
<td>38.0%</td>
<td>28.6%</td>
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Current CCP Research Efforts

• Beneficiated Ash
  – To improve concrete performance

• New cements based on CCPs
  – CSAB Cements
  – Clinkerless Cements
  – Plaster Cements
# Beneficiate Ash to Reduce Water Demand

<table>
<thead>
<tr>
<th>Product</th>
<th>Water %</th>
<th>D$_{50}$</th>
<th>Fineness (cm$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underflow Product</td>
<td>95</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>Ghent Lab Product (20%)</td>
<td>93</td>
<td>6.0</td>
<td>8850</td>
</tr>
<tr>
<td>Ghent Lab Product (20%)</td>
<td>93</td>
<td>3.0</td>
<td>13400</td>
</tr>
<tr>
<td>Ghent Field Product (20%)</td>
<td>93</td>
<td>5.5</td>
<td>9680</td>
</tr>
<tr>
<td>Ghent Field Product (20%)</td>
<td>95</td>
<td>4.5</td>
<td>10700</td>
</tr>
<tr>
<td>Ghent Econosizer Product (20%)</td>
<td>93</td>
<td>20.3</td>
<td>4570</td>
</tr>
<tr>
<td>Ghent Flotation Product (20%)</td>
<td>93</td>
<td>20.3</td>
<td>4430</td>
</tr>
<tr>
<td>Mill Creek Product (20%)</td>
<td>97</td>
<td>4.4</td>
<td>11110</td>
</tr>
<tr>
<td>Coleman Product (20%)</td>
<td>96</td>
<td>7.3</td>
<td>7370</td>
</tr>
<tr>
<td>Trimble (20%)</td>
<td>98</td>
<td>25.8</td>
<td>3270</td>
</tr>
<tr>
<td>Rockport (20%)</td>
<td>95</td>
<td>13.1</td>
<td>6770</td>
</tr>
<tr>
<td>Mill Creek (20%)</td>
<td>97</td>
<td>17.8</td>
<td>4580</td>
</tr>
<tr>
<td>Micron3 (20%)</td>
<td>91</td>
<td>3.0</td>
<td>14600</td>
</tr>
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</table>
## Product Evaluations in Mortar

<table>
<thead>
<tr>
<th>Processed Fly Ash Product</th>
<th>Flowsheet 1</th>
<th>Flowsheet 2</th>
<th>Flowsheet 3</th>
<th>Flowsheet 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>FP</td>
<td>UFA</td>
<td>FUFA</td>
<td></td>
</tr>
<tr>
<td>d50 microns</td>
<td>14.3</td>
<td>19.2</td>
<td>3.2 - 6.0</td>
<td>4.8 - 5.5</td>
</tr>
<tr>
<td>Water Reduction %</td>
<td>96</td>
<td>97 - 98</td>
<td>93 - 95</td>
<td>93 - 95</td>
</tr>
<tr>
<td>S.A.I. @20% Substitution</td>
<td>% of Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Day</td>
<td>85</td>
<td>80 - 85</td>
<td>102 - 110</td>
<td>102 - 107</td>
</tr>
<tr>
<td>28 Day</td>
<td>100</td>
<td>93 - 100</td>
<td>129 - 135</td>
<td>122 - 129</td>
</tr>
<tr>
<td>56 Day</td>
<td>130</td>
<td>103</td>
<td>132 - 140</td>
<td>126 - 133</td>
</tr>
<tr>
<td>Mortar Air</td>
<td>ul of AEA To Constant 6% air</td>
<td>620</td>
<td>500</td>
<td>700 - 1600</td>
</tr>
</tbody>
</table>

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Chloride Permeability with Processed Fly Ash

<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>RCP (coulombs)</th>
<th>ASTM Chloride Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2418</td>
<td>Moderate</td>
</tr>
<tr>
<td>F Ash 20%</td>
<td>1200</td>
<td>Low</td>
</tr>
<tr>
<td>Ghent CP 20%</td>
<td>426</td>
<td>Very Low</td>
</tr>
<tr>
<td>Ghent CP 40%</td>
<td>150</td>
<td>Very Low</td>
</tr>
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CSAB Cements

- Not a new idea…Quillin, Mehta and others

- Purpose: To develop a calcium sulfoaluminate-belite cement (CSAB) with CFBC ash as a key ingredient
  - High strength, low-energy, and low CO₂ emitting

- Calcium sulfoaluminate ($C₄A₃S'$)
  - Increases early strength
  - Hydration of this phase forms ettringite
    - ($C₆A₃S₃H₃₂$)
    - Contributes to early strength

- Belite ($C₂S$)
  - Hydrates slowly
  - Low compressive strengths compared to Alite ($C₃S$)
Formulation of CSAB Cement

• Commercially produced CSAB cement acquired from China
  – Shenzhen Chenggong Trade Co. CSA
  – Major cementitious phases and oxide compositions
    • X-ray Diffraction (XRD) and X-ray Fluorescence (XRF)
    • Klein’s compound and belite need to be optimized

• Initial formulations
  – Bogue equations modified for CSAB cement
    • These normative equations could not be used
    • Minor amounts of other phases formed (i.e. gehlenite; C$_2$AS)

• Formulations adjusted to meet several objectives:
  – **Minimize limestone** and thus the free lime formed (CaO)
  – **Maximize the byproduct** used (CFBC and PCC ash)
  – Produce a cement that approaches the performance of commercial CSAB cement
    • CSAB#1
    • CSAB#2
    • CSAB#4
## Laboratory Cement Formulations

<table>
<thead>
<tr>
<th>Component</th>
<th>CSAB#1</th>
<th>CSAB#2</th>
<th>CSAB#4 HS</th>
<th>CSAB#4 MS</th>
<th>CSAB#4 LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>39.1</td>
<td>46.0</td>
<td>29.6</td>
<td>24.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Bauxite</td>
<td>15.0</td>
<td>15.2</td>
<td>30.2</td>
<td>25.0</td>
<td>13.9</td>
</tr>
<tr>
<td>FBC Spent Bed(^1)</td>
<td>13.0</td>
<td>13.1</td>
<td>19.6</td>
<td>16.3</td>
<td>9.0</td>
</tr>
<tr>
<td>Class C Fly Ash</td>
<td>6.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>-</td>
<td>12.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gypsum(^2)</td>
<td>13.3</td>
<td>12.8</td>
<td>20.6</td>
<td>17.1</td>
<td>31.7</td>
</tr>
<tr>
<td>Ultra Fine Ash(^3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17.1</td>
<td>31.7</td>
</tr>
<tr>
<td><strong>Total CCBs</strong></td>
<td>33.1</td>
<td>38.8</td>
<td>40.2</td>
<td>50.5</td>
<td>72.4</td>
</tr>
</tbody>
</table>

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1. Byproduct of fluidized bed combustion (FBC) of coal
2. Gypsum and Ultra Fine Ash are milled with the clinker; percentage is calculated on a mass basis of the cement product
3. Ultra Fine Ash is a processed material from ponded, Class F fly ash

**Procedure:**

1. Raw materials are milled to 16 microns
2. Fired in a furnace at 1250°C for 1 hr to produce clinker
3. Clinker is milled with FGD gypsum to produce cement
Laboratory Cement made from FBC Ash

Compressive Strength

PSI

Time (days)
XRD Analysis of Cement Clinkers

K = Klein’s Compound  An = Anhydrite  B = Belite
Future CSAB Work

• Large scale production of CSAB#4 for testing in concrete with new rotary kiln

• Sources of aluminum other than bauxite are being investigated (i.e. aluminum refinery byproduct)
Clinkerless Cement

- Mainly produced from Class C fly ash and/or Clean Coal Technology byproducts.
- Cementitious reactions are mainly ettringite- and pozzolan-based.
- Main problems:
  - Slow strength gain
    - Calcium Sulfate Hemihydrate
  - Potential for destructive expansion
    - Excessive Ca(OH)₂
    - High pH
    - Colloidal ettringite crystals

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### Clinkerless Cement Formulation

1. Spent bed material is prehydrated with 10% water then dried
2. Material milled with fly ash to a median size of ~15 microns
3. Some formulations milled with FGD gypsum hemihydrate ("plaster") for rapid strength gain
   - Moistened with 7.5% water; pressed at 4,000 lbs (1815 kg)
   - Steam autoclave and heated 130°C and 3 bars for 4 hours

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Formulation (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBC Spent Bed</td>
<td>70</td>
</tr>
<tr>
<td>Ultrafine Fly Ash</td>
<td>30</td>
</tr>
<tr>
<td>Ordinary Fly Ash</td>
<td>0</td>
</tr>
<tr>
<td>Hemihydrate</td>
<td>0</td>
</tr>
</tbody>
</table>
Plaster Cements

- All are based on calcium sulfate
- Many varieties
  - Alpha hemihydrate: produced by heating gypsum in autoclave
- Rapid hardening, but poor durability
- Cementitious reactions produce gypsum:
  Plaster: $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O} + 1.5\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
ASTM C 109 Compressive Strength Data for FBC:Fly Ash:Plaster Mortars
ASTM C 157 Expansion of FBC:UFA Mortars

Expansion (%) vs. Time (days)

- FBC:UFA 70:30
- FBC:UFA 40:60
- 70:30 HH Dry
- 40:60 HH Dry
ASTM C192/C 39 Compressive Strength of FBC:UFA 40:60 HH Concrete
ASTM C 666 Freeze Thaw Resistance

Dynamic Modulus (% of initial)

Cycles

- Control (OPC) #1
- Control (OPC) #2
- FBC:UFA 40:60HH#1
- FBC:UFA 40:60HH #2