EFFECT OF COAL DUST ON RAILROAD BALLAST STRENGTH AND STABILITY

By

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Hai Huang
OUTLINE

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  - Fouling Mechanism / Need for Laboratory Study

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  - Specific Gravity
  - Optimum Moisture Content (OMC)
  - Triaxial Tests
  - Direct Shear Tests

- **Clean and Coal Dust Fouled Ballast Behavior**
  - Large Direct Shear Box Tests

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INTRODUCTION

✓ **Coal** is the leading source of energy generation in the U.S. In 2003, 90% of the total coal production, (1.07 billion tons) was driven by the electric power sector (Bankowski et al., 2006).

✓ **Coal transportation** in the U.S. strongly relies on rail transport. Approximately 72% of coal deliveries to U.S. power plants are made by rail transport (EIA, 2006).
INTRODUCTION (CONT’D)

✓ Unexpected operating flaws on existing rail lines reduce the coal production

For example: From 2000 to 2005, BNSF/UP Joint Line transported only 325-million tons of the 348-million total forecast value due to operating problems

✓ In 2005, coal dust accumulation in track ballasts caused 2 derailments as a result of
  • Moisture accumulation
  • Decreased stability of the tracks

It threatened to delay the supply of coal to power plants
ORIN LINE – GILLETTE, WY
SOUTH POWDER RIVER BASIN

BNSF Railway Company
Powder River Operating Division
System Maintenance and Planning January 1, 2005
BALLAST FOULING IN ORIN LINE 7/24/07

MP 91

MP 96
BALLAST FOULING IN ORIN LINE

7/24/07
BALLAST FOULING IN MP 37 ORIN LINE
7/24/07
INTRODUCTION – PROBLEM STATEMENT

- As ballast ages, fine grained materials progressively fill the void spaces resulting in fouled ballast.
- **Coal Dust Fouled Ballast** has been identified as a contributing factor to recent derailments on the BNSF/UP joint line out of the Powder River Basin, WY.

![Graph showing percent passing by weight vs. sieve opening size](image-url)
INTRODUCTION – PROBLEM STATEMENT

- Current methods of track inspection including visual assessment, pumping and ponding at ballast toe, etc., lack the necessary techniques to accurately quantify ballast fouling condition except for

  **Ground Penetrating Radar**

- Strength properties of coal dust fouled ballast to be investigated in **Laboratory Experiments**
INTRODUCTION – FOULING MECHANISM

- Critical Phases of Fouling

Clean - Partially to Fully Fouled - Heavily Fouled
Coal Dust (primarily carbon and hydrogen) has never been identified as a significant ballast fouling material to cause the source of multiple derailments and widespread track failure.

- **Typical foulants identified in Railroad Texts (Selig and Waters, 1994)**
  - 76% ballast breakdown
  - 13% underlying granular layer
  - 7% surface materials (such as coal dust)
  - 3% subgrade materials
  - 1% tie breakdown
Gradation

- **Grain Size Distribution** established by a set of sieves

  | Size of the opening in the sieve | Below 1/4 in. | 1-1/2 in. | 1 in. | 3/4 in. | 1/2 in. | 3/8 in. | 1/4 in. |
  |--------------------------------||--------------|----------|-------|--------|--------|--------|-------|
  |                                |              | No. 4    | 4.76 mm | No. 10 | 2.00   | No. 20 | 0.84  | No. 40 | 0.42   |
  |                                |              | No. 200  | 0.075 mm |        |        |        |       |        |        |

- Sieve analysis performed acc. to weight of sample retained on each sieve and converted to percent passing each sieve.

- **Gradation Curve** - Graphical plot of sieve analysis
Grain Size Analysis

The coal dust sample was collected from Orin line milepost 62.4 and was sampled on March 10, 2007.
MECHANICAL PROPERTIES OF COAL DUST

- **Grain Size Analysis (ASTM C 136, ASTM C 117)**

![Graph showing grain size analysis](image)

- 24% fines content (passing No. 200 sieve or 0.075 mm) by weight
  - $D_{\text{max}} = 0.187$ in.
  - $D_{50} = 0.030$ in.

COAL DUST LOOKS LIKE A SAND, BUT WE WILL SEE LATER ACTS LIKE A VERY FINE CLAY
ATTERBERG LIMITS

Plastic Limit (PL)
Water content where 1/8" soil thread begins to crumble by rolling

Liquid Limit (LL)
Water content where soil halves close 1/2” at 25 drops of Casagrande’s cup

Plasticity Index (PI)

\[ \text{PI} = \text{LL} - \text{PL} \]

Very important soil property
A beach sand is non-plastic
MECHANICAL PROPERTIES OF COAL DUST

- **Atterberg Limits**
  - Plastic Limit (PL) = 50%
  - Liquid Limit (LL) = 91%
  - Plasticity Index (PI) = 41%

Weak Soil Examples (Terzaghi et al., 1996)

- **Panama organic silt**
  - PL: 17%
  - LL: 55%
  - PI: 38%

- **Venezuela Clay**
  - PL: 25%
  - LL: 40%
  - PI: 15%

- **Dupont Clay**
  - PL: 26%
  - LL: 53%
  - PI: 27%

CH soil, 55% clay, 42% silt
The ratio of the density of solid constituents to the density of water (generally at 68°F) is called the specific gravity of solid constituents.

- Specific gravity of the coal dust: 1.28
- Specific gravity of clay particles: 2.5 – 2.9
- Specific gravity of sand particles: 2.65
COMPACTION TEST

Compaction is the process of increasing soil density and strength by adjusting its water content.

How much solid material can you pack in a unit volume?

![Graph showing the relationship between moisture content (MC) and dry density. The graph peaks at the optimum moisture content (MC), above which the dry density decreases.]
MECHANICAL PROPERTIES OF COAL DUST

- **Standard Proctor Compaction (ASTM D698)**

  ![Graph showing dry density vs. water content]

  - **Optimum water content (OMC):** 35% **High!**
  - **Maximum dry density (MDD):** 54.2 pcf **Low!**
Standard Proctor Compaction Test (ASTM D 698)

✓ Standard Proctor compaction test results for some known weak soils:

**Lean silty clay:**
- OMC: 17%
- MDD: 108 pcf

**Loessial silt:**
- OMC: 18%
- MDD: 105 pcf

**Heavy clay:**
- OMC: 21%
- MDD: 102 pcf

**Dupont clay:**
- OMC: 24%
- MDD: 98 pcf

**Coal Dust:**
- OMC: 35%
- MDD: 54.2 pcf

CH soil, 55% clay, 42% silt
MECHANICAL PROPERTIES OF COAL DUST

- Triaxial (Unconsolidated-Undrained) Tests

- Servo-pneumatic test frame used as UTM
- 2 in. in diameter by 4 in. high specimens
Triaxial Test Results

The internal friction angle ($\phi$) of the coal dust is approximately 1.8°, almost equal to zero for such undrained conditions.

\[ \tau_{\text{max}} = \text{cohesion (c)} + \sigma_n \tan \phi \]

Unconfined Compressive Strength, $Qu = 3$ psi  Very Low!
SHEAR STRENGTH TEST RESULTS – COAL DUST

Qu = 3.5 psi
OMC = 35%

C.P. = 2 psi
C.P. = 4 psi
C.P. = 6 psi
Unconfined

SHEAR STRENGTH TEST RESULTS – COAL DUST

Qu = 3.5 psi
OMC = 35%
Approximately \textbf{10 times lower} than weak DuPont Clay at optimum moisture content.
MECHANICAL PROPERTIES OF COAL DUST

- Direct Shear (Shear Box) Tests

Coal dust samples at different water contents sheared horizontally in a 3.94 in. x 3.94 in. (100mm x 100mm) shear box under different normal loads; relation between the normal stress and shear stress established.
MECHANICAL PROPERTIES OF COAL DUST

- **Direct Shear Test Results**

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Internal Friction Angle, Φ (Degrees)</th>
<th>tan Φ</th>
<th>Cohesion Intercept, C (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>34.1</td>
<td>0.68</td>
<td>1.11</td>
</tr>
<tr>
<td>35</td>
<td>33.53</td>
<td>0.66</td>
<td>1.23</td>
</tr>
<tr>
<td>37</td>
<td>31.83</td>
<td>0.62</td>
<td>1.13</td>
</tr>
<tr>
<td>39</td>
<td>27.22</td>
<td>0.51</td>
<td>1.07</td>
</tr>
<tr>
<td>41</td>
<td>21.91</td>
<td>0.4</td>
<td>1.01</td>
</tr>
<tr>
<td>43</td>
<td>19.23</td>
<td>0.35</td>
<td>0.81</td>
</tr>
</tbody>
</table>

- **Drained Conditions** - grain to grain contact friction
  - 47% decrease in shear strength
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- Direct shear tests were conducted at the University of Illinois on both clean and coal dust fouled ballast samples of granite aggregate.

- Comparison of test results can provide better understanding of fouling mechanisms.
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- Clean Granite Ballast Sample (AREMA No. 24) from Gillette, WY and commonly used in Powder River Basin

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>in.</td>
<td>mm</td>
</tr>
<tr>
<td>2.5</td>
<td>63.5</td>
</tr>
<tr>
<td>2</td>
<td>50.8</td>
</tr>
<tr>
<td>1.5</td>
<td>38.1</td>
</tr>
<tr>
<td>1</td>
<td>25.4</td>
</tr>
</tbody>
</table>

- Specific gravity: 2.62
- Unit weight: 93 pcf
- Compacted Air Voids: 43%
- $D_{\text{max}} = 2.5 \text{ in.}$
- $D_{\text{min}} = 1 \text{ in.}$
- $D_{50} = 1.77 \text{ in.}$
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- Large Direct Shear Equipment

12 in. x 12 in. square box
6-in. deep lower box
3-in. deep upper box
up to 30-kip loading
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- **Direct shear box test procedure**
  - Obtain 54 lbs. (24.5 kg) of ballast aggregate
  - Compact ballast sample into lower box using two lifts

- Use vibratory compactor on top of a flat plexiglas compaction platform and compact until no noticeable movement of particles is observed
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- Direct shear box test procedure (continued)
  - Obtain prescribed weight of coal dust and water
  - Spread coal dust over compacted ballast and shake down the coal dust using vibratory compactor. Place upper ring on and align ring with the lower box.
CLean and Coal Dust Fouled Ballast Behavior

- Direct shear box test procedure (continued)
  - Place box and ring assembly into shearing apparatus

- Three normal pressures (25, 35, and 45 psi) were used;
  Shearing rate: 0.48 in./min; Maximum strain recorded: 15%
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- **Direct Shear Tests Results**

- Coal dust fouling fines content: 0%, 5%, 15%, and 25% by weight of ballast

- Coal dust moisture state: **Dry and wet (35% OMC)**

- **25% coal dust by weight** completely filled the voids in the clean ballast structure – **“fully fouled” stage**

*Any coal dust fouling beyond this percentage should be considered as heavily fouled ballast as aggregate to aggregate contact is lost*
CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

- **Direct Shear Test Results**

![Graph showing shear stress vs. normal stress for different conditions.](image)

- Fully fouled with wet coal dust

*R² ranges from 0.97 to 0.99*
## Clean and Coal Dust Fouled Ballast Behavior

### Direct Shear Test Results

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fouling % *</th>
<th>Cohesion, c (psi)</th>
<th>φ (rad.)</th>
<th>φ (deg.)</th>
<th>Max Shear Stress, $\tau_{\text{max}} = c + \sigma_N \tan(\phi)$</th>
<th>Regression Coef, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>0</td>
<td>15.24</td>
<td>1.022</td>
<td>45.6</td>
<td>$\tau_{\text{max}} = 15.24 + \sigma_N \tan(43.9^\circ)$</td>
<td>0.99</td>
</tr>
<tr>
<td>Dry</td>
<td>5</td>
<td>13.96</td>
<td>0.991</td>
<td>43.9</td>
<td>$\tau_{\text{max}} = 13.96 + \sigma_N \tan(43.9^\circ)$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>13.46</td>
<td>0.773</td>
<td>36.2</td>
<td>$\tau_{\text{max}} = 13.46 + \sigma_N \tan(36.2^\circ)$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>10.90</td>
<td>0.688</td>
<td>36.6</td>
<td>$\tau_{\text{max}} = 10.90 + \sigma_N \tan(36.6^\circ)$</td>
<td>0.97</td>
</tr>
<tr>
<td>Wet (OMC)</td>
<td>5</td>
<td>8.89</td>
<td>0.963</td>
<td>44.7</td>
<td>$\tau_{\text{max}} = 8.89 + \sigma_N \tan(44.7^\circ)$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>11.12</td>
<td>0.731</td>
<td>37.7</td>
<td>$\tau_{\text{max}} = 11.12 + \sigma_N \tan(37.7^\circ)$</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>5.10</td>
<td>0.744</td>
<td>34.5</td>
<td>$\tau_{\text{max}} = 5.102 + \sigma_N \tan(34.5^\circ)$</td>
<td>0.97</td>
</tr>
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</table>

* percentage by ballast weight

**Similar to the friction angle of coal dust itself**

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SUMMARY AND CONCLUSIONS

- Mechanical properties of representative coal dust samples obtained from the Powder River Basin (PRB) joint line in Wyoming were determined for the first time through laboratory testing at the Univ. of Illinois.

- Coal Dust Liquid Limit = 91% – VERY HIGH!
- Coal Dust Optimum Moisture Content (OMC) = 35% – much higher than typical weak soils!
- Coal Dust can absorb and hold a lot of water when compared to clays and silts
- Triaxial Shear Strength of Coal Dust at OMC = 3 psi – VERY LOW!
- Coal Dust friction angle at OMC = 33.5° indicated a large REDUCTION with increasing moisture content
SUMMARY AND CONCLUSIONS

- Large-sized direct shear (shear box) laboratory tests conducted at the Univ. of Illinois on granite ballast samples also obtained from the Powder River Basin (PRB) joint line in Wyoming to investigate the strength and deformation characteristics of both clean (new) and fouled ballast at various stages.

- The highest shear strength values were obtained from the clean ballast at all applied normal stress levels.

- When ballast samples were fouled, the shear strength always decreased. Wet (35% OMC) coal dust fouling resulted in the lower ballast shear strengths than dry coal dust fouling.

- For the fully fouled case with 25% wet coal dust by weight of ballast, internal friction angle and cohesion obtained were equivalent to those properties of the wet coal dust itself.

- Even more drastic strength reductions can be realized when dry coal dust is subjected to inundation and 100% saturation.
Effect of First Time Saturation (6 in. accumulation)

Dry Coal Dust that has never been saturated can:
- have higher strength properties
- hold excessive moisture when it rains or snows

When dry coal dust is wetted, this results in a drastic loss of strength.

![Diagram showing the relationship between moisture content and unconfined compressive strength]

Unconfined Compressive Strength, $Q_u$

Moisture Content

Unsoaked Specimen

Soaked Specimen

OMC
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