Laboratory Characterization of Coal Dust Fouled Ballast Behavior

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ABSTRACT

Fouling refers to the condition of railroad ballast when voids in this unbound aggregate layer are filled with finer materials. As a fouling agent, coal dust coming from coal trains and accumulating in the ballast has become a major concern for railroads. This paper aims to provide a better understanding of adverse impacts of coal dust on railroad ballast drainage and load carrying functions. First, mechanical properties of coal dust were investigated at the University of Illinois through laboratory tests such as grain size distribution, Atterberg limits, specific gravity, moisture-density compaction relationships, and shear strength properties. Then, ballast aggregates were added coal dust at different percentages by weight and moisture contents to represent coal dust fouling in the field. When fouled samples were tested in large direct shear (shear box) equipment, it was found that 25% coal dust by weight of aggregates were enough to fill up all the voids in ballast corresponding to a void ratio of 43%. When the coal dust percentage in ballast samples increased, the ballast shear strength steadily decreased. In the case of ballast fully fouled with wet coal dust at 35% moisture content, the friction angles obtained from the direct shear equipment were close to the friction angle of coal dust itself. This implies that individual aggregate particles within ballast layer would be completely separated by coal dust to most likely cause the worst track instability problems in the field.

Key Words: Railroad track, ballast, fouling, coal dust, shear strength, laboratory testing
INTRODUCTION

Railroad ballast is uniformly-graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the heavy loading applied by trains. As ballast ages, it is progressively fouled with fine-grained materials filling the void spaces. Methods specifically used to assess track ballast condition only deal with checking visually for evidence of fouling, pumping and water accumulation (ponding) at ditches and shoulders. Additionally, ballast sampling and testing for fouling through laboratory sieve analyses generally provide some insight into the compositions of the larger aggregate particles and the amount of fines. Nonetheless, for a better evaluation of the serviceability and proper functioning of the existing ballast layer, ballast strength and deformation behavior needs to be characterized for different percentages of fine-grained materials, such as plastic soil fines, mineral filler, and more recently coal dust coming from coal trains, which can fill the voids and cause ballast fouling.

For hundreds of years, coal has been a major energy source in the United States. Indeed, there has been a historical link between the economic progress of the U.S. and the use of coal for numerous basic needs of the country, ranging from energy for domestic purposes to industrial applications and electricity generation. As the demand for coal transportation increases with the growing energy need, the coal transportation in the U.S. strongly relies on rail transport. Since rail transport, particularly a unit train, provides the most efficient means of transporting bulk commodities such as coal (Morrison, 1985), the role of rail lines in coal transport has always been predominant.

Today, Powder River Basin (PRB) coal is the largest source of incremental low-sulfur coal supplies in the U.S. (Gaalaas, 2006). From 2000 to 2005, the 5.6 percent increase in
nationwide coal production chiefly stemmed from the concurrent expansion in PRB coal production, and the Burlington Northern Santa Fe/Union Pacific (BNSF/UP) joint line provided for over 60 percent of the total increase in PRB coal production (42 million tons of 69 million tons) from 2000 to 2005. However, while the National Coal Transportation Association forecast of the corresponding total coal shipments was 348 million tons, the joint line was able to achieve 325 million tons of the total forecast value because of major operating problems on the joint line (Gaalaas, 2006). In 2005, two derailments occurred in the BNSF/UP joint coal line in PRB which threatened to interrupt the supply of coal to power plants. Both of the derailments were suspected to be attributed by coal dust fouling, where coal dust spilled over the ballasts and accumulated moisture, allegedly resulting in the loss of strength of the track. In both places where derailments happened, ballast was heavily fouled by coal dust.

This paper presents findings from a comprehensive laboratory-testing program recently initiated at the University of Illinois to study effects of coal dust fouling on railroad ballast strength. Using large direct shear (shear box) tests, strength and deformation characteristics of granite type ballast material were investigated for both clean and coal dust fouled aggregates at various stages of fouling under both dry and wet conditions. The shear strength properties, i.e., cohesion intercept and friction angle, and the stress-strain response are linked to field ballast fouling levels to better assess the impact of coal dust fouling on track instability and ultimately loss of track support leading to derailments.

**BALLAST FOULING**

Selig and Waters (1994) proposed two indices to describe ballast fouling: (1) *fouling index* is the sum of the percent by weight of ballast sample passing the No. 4 (4.75 mm) sieve plus the
percent passing the No. 200 sieve and (2) *percentage of fouling* is the ratio of the dry weight of material passing 3/8 in. (9.5 mm) sieve to the dry weight of total sample. Figure 1 shows grain size distributions obtained for both clean and fouled materials. The fouled ballast material was collected from a location of derailed (track had buckled out) section of the BNSF railroad line near milepost 43 in Utica, Nebraska in spring of 2006. As indicated, these clean and fouled samples have 1.5% and 14.0% passing the No. 200 sieve (0.075mm), respectively. Although the fines content (% passing the No. 200 sieve) of the fouled sample is not very high, the *fouling index* values computed for the clean and fouled samples were 6.9 and 45.7, respectively. In this case, a *fouling index* of 45.7 corresponds to a *percentage fouling* of nearly 38% (see Figure 1).

In a clean ballast sample, almost all aggregates are supposed to establish contact with each other at the aggregate surface to carry the load (see Figure 2a). As shown in Figure 2b, dirty or partially fouled ballast will have the voids in between contacting aggregates filled with fine particles, however, still maintaining aggregate to aggregate contact. Whereas, in a fouled ballast, due to the excessive amount of fine particles, aggregate to aggregate contacts are mostly eliminated and the aggregate particle movements are then only constrained by the fine particles filling the matrix or voids between the particles (see Figure 2c). In regards to excessive fouling conditions, for example, as in the case of 2005 PRB joint line derailments with wet coal dust completely filling all voids in ballast and pumping on the surface of railroad track, the low strength of the fouling agent will govern for carrying the wheel load. Hence, train derailments may take place due to unstable support under the crossties.
MECHANICAL PROPERTIES OF COAL DUST

Coal dust sample tested in this study was collected from the PRB Orin line milepost 62.4 and was sampled on March 10, 2007. Figures 3 and 4 depict the received coal dust sample in its loose state and close-up view, respectively. To investigate first the mechanical behavior of coal dust itself, several laboratory tests were conducted at the Advanced Transportation Research Laboratory (ATREL) of the University of Illinois at Urbana-Champaign (UIUC). The following sections briefly describe the conducted laboratory tests and present the coal dust test results.

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

To begin with, dry and wet sieve analyses of the coal dust were performed in compliance with ASTM C 136 and ASTM C 117 test procedures. As Figure 5 indicates from the more accurate wet sieve analyses, the fines content of the coal dust sample was found to be 24%, which means 76% of the coal dust particles were primarily sand sized, coarser than 0.00295 in. (0.075 mm) or retained on No. 200 sieve. The top size (D_{max}) of the coal dust sample is 0.187 in. (4.75 mm), and the particle size corresponding to 50 percent finer by weight (D_{50}) is 0.03 in. (0.76 mm).

Atterberg Limits

The Atterberg limits tests performed indicated that the coal dust sample had a plastic limit (PL) of 50%, a considerably high liquid limit (LL) of 91% thus resulting in a plasticity index (PI) of 41%. This means, at 50% water content, the coal dust starts to exhibit plastic behavior whereas at 91% water content or higher, it behaves like a viscous liquid. Note that the LL of the coal dust is significantly higher than some known weak soils, such as Panama Organic Silt (55%), Georgia Kaolinite (48%), Venezuela Clay (40%), mica powder (75%) from Terzaghi et al. (1996).
Similarly, the PI of the coal dust also exceeds typical values for weak soils, such as Panama Organic Silt (17%), Georgia Kaolinite (16%), Venezuela Clay (25%) and mica powder (20%) (after Terzaghi et al., 1996). Therefore, the high LL and PI of the coal dust sample clearly highlighted its much higher moisture holding capability compared to many silty and clayey subgrade soils.

**Specific Gravity**

The specific gravity of the coal dust sample was found to be 1.28, which simply meant the density of the coal dust solids was a rather low 79.9 pcf (1.28 g/cm$^3$) when compared to solid densities of typical soils and aggregates. These results were in accordance with the findings of Fitch (2005), who gave a specific gravity range for coal dust from 1.3 to 1.5. On the other hand, the specific gravities of clay particles typically vary from 2.5 to 2.9 with a statistical average of 2.7 whereas the average specific gravity of sand grains is about 2.65 (Terzaghi et al., 1996). Thus, compared to most soils, the coal dust is a significantly lighter material as far as the low specific gravity of its solid constituents is considered.

**Standard Proctor Compaction Test (AASHTO T99/ASTM D 698)**

To establish a relationship between the water content and dry density of coal dust, standard Proctor compaction test was performed at different water contents (AASHTO T99/ASTM D698). Figure 6 shows the laboratory obtained compaction curve of the coal dust samples studied. It indicates that the optimum moisture content for the coal dust is 35%, at which the maximum dry density of 54.2 pcf (0.87 g/cm$^3$) is achieved with the given compactive effort.

Compared to most fine-grained soils such as clays and silts, the 35% optimum moisture content (OMC) is a very high value corresponding to a quite low maximum dry density of 54.2
pcf (0.87 g/cm³). As far as the results of the standard Proctor compaction test are considered, the coal dust displays not only higher moisture holding capability but also significantly lower dry density compared to most fine-grained soils.

**Triaxial (Unconsolidated-Undrained) Test**

In this test, cylindrical coal dust specimens were sheared at their OMC (35%) and maximum dry density (54.2 pcf) determined by the previously conducted standard Proctor compaction test. A servo-pneumatic test frame was used as a UTM setup to conduct triaxial tests on small 2 in. (50.8 mm) in diameter by 4 in. (101.6 mm) high specimens. Shear strength tests were conducted under unconfined and confined conditions with the monotonic loading until failure. Figure 7 shows photos of the triaxial cell and the cylindrical coal dust specimen tested. A vertical actuator applies the axial monotonic load and the confining pressures are applied through the inside the chamber.

Since the drainage valves of the triaxial cell were closed from the beginning, the samples were not allowed to consolidate under the effect of confining pressure after they reached 100% saturation and the shearing stage was achieved under undrained conditions. Since the increase in stress was carried by the pore water (Holtz and Kovacs, 1981), the internal friction angle of the coal dust is found almost equal to zero for the undrained conditions. Figure 8 shows the Mohr circles for the unconsolidated-undrained tests and the resultant Mohr-Columb failure envelope of the coal dust. As the failure envelope levels up, it is concluded that the internal friction angle (Φ) of the coal dust is approximately 1.8 degrees, i.e., almost equal to zero, which is very typical of cohesive clayey soils tested under such undrained conditions.
Figure 9 shows applied deviator stresses graphed with vertical specimen displacements at different confining pressures. Once again, there was no effect of varying confining pressure on the shear strength of the coal dust, which was obtained as the maximum deviator stress at failure of only 3.5 psi (24.1 kPa). This is almost the same as twice the amount of cohesion intercept indicated on the y-axis in Figure 8, which is often called the unconfined compressive strength (Qu) for cohesive (Φ=0) soils.

**Direct Shear Test**

In this test, coal dust samples at different water contents were sheared horizontally in a 3.94 in. by 3.94 in. (100mm by 100mm) shear box under different normal loads so that the relationships between the normal stress and shear stress were established. A direct shear test equipment Humboldt ShearScan 10 direct/residual apparatus utilizing the pneumatic loading concept was used to apply the vertical load to the sample. In doing so, this self-contained model eliminates the need for loading weights used in dead weight-type systems. The ShearScan 10 is complete with a 2,000-lb. (10-kN) capacity load cell, 1-in. (25.4-mm) stroke horizontal deformation transducer, 0.4-in. (10.2-mm) vertical deformation transducer and a built-in 4-channel analog data acquisition system. Figure 10 shows a picture of the ShearScan 10 direct/residual shear test device used to shear the specimen under a series of applied normal stresses.

Table 1 summarizes the results obtained from the direct shear tests and illustrates the change in the internal friction angle of the coal dust with respect to moisture content. The internal friction angles and cohesion intercepts of the coal dust samples are tabulated with regard to the moisture contents of the test samples. Considering the significant decrease in the friction
angle and as a result approximately 47% decrease in shear strength contributed by $\tan \Phi$, cohesion intercept stayed almost constant.

**CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR**

To investigate whether the fouling condition indicated in Figure 2c takes place, i.e., fouling agent’s strength dominates over the ballast layer strength properties when heavily fouled, direct shear tests were conducted at the University of Illinois on both clean and coal dust fouled ballast samples. The ballast material tested was a granite aggregate obtained from Gillette, WY and commonly used in the PRB joint line railroad track structures as the ballast layer.

Figure 11 shows the grain size distribution of the granite sample tested in compliance with ASTM C 117 test procedure. Table 2 lists the gradation sieve sizes and the percent passing each sieve properties for the clean granite aggregate. The grain size distribution conforms to the typical AREMA No. 24 ballast gradation having a maximum size ($D_{\text{max}}$) of 2.5 in. (63.5 mm), a minimum size ($D_{\text{min}}$) of 1 in. (25.4 mm), and an average particle size corresponding to 50 percent passing by weight ($D_{50}$) of approximately 1.77 in. (45 mm). Also listed in Table 2 are the specific gravity, unit weight and corresponding compacted air voids of the clean granite aggregates. ASTM C29 test procedure was used for finding porosity or air voids with known values of the specific gravity and volume and weight of ballast compacted.

Direct shear strength tests were performed on the reconstituted clean and coal dust fouled granite aggregate samples. Figure 12 shows the large shear box equipment used for testing at the University of Illinois. The test device is a square box with side dimensions of 12 in. (305 mm) and a specimen height of 8 in. (203 mm). It has a total 4-in. (102 mm) travel of the bottom 6-in. (152 mm) high component, which is large enough for ballast testing purposes to record peak shear stresses. The vertical (normal direction) and horizontal load cells are capable of applying
and recording up to 30-kip and 20-kip load magnitudes, respectively. The device controls and the data collection are managed through an automated data acquisition system controlled by the operator through a build-in display and the test data are saved on to a personal computer.

**Direct Shear Test Procedure**

1. Obtain 54 lbs. (24.5 kg) of ballast aggregate

2. Compact ballast sample into lower box (14 in. x 12 in. x 6 in. or 356 mm x 305 mm x 152 mm) using two 3 in. (76 mm) lifts. Use vibratory compactor on top of a flat Plexiglas compaction platform and compact until no noticeable movement of particles is observed (see Figure 13).

3. Obtain prescribed weight of fouling material (e.g., coal dust) and water to mix with compacted ballast.

4. Spread fouling material over compacted ballast evenly in two lifts (half of material each lift). Shakedown material using vibratory compactor after each lift. If test is conducted with wet fouling material (for example, at the optimum moisture content or OMC), pour proportional amount of water over ballast after shakedown of each lift (see Figure 14). Place upper ring (3 in. or 76 mm high) on top of lower box. Align ring with sides and back edge of box (opposite of block) and fill with single lift of ballast and compact (see Figure 15).

5. Place box and ring assembly into shearing apparatus. Clamp lower box in place. Place load bearing plate on ballast and inside upper ring. Place air-bladder on bearing-plate. Close normal force load cell over air-bladder. Open air supply and set pressure using an in-line pressure regulator (see Figure 16).
6. Adjust shear force load cell directly against the upper ring.

7. Prepare LabVIEW Data Logger software to record normal and shear force while the test is running.

8. Input shear rate of 0.48 in./min. (12.2 mm/min.) which is approximately 4% strain per minute and run test until shear force output becomes constant or 15% strain has occurred.

**Direct Shear Test Results**

The ballast samples were sheared horizontally in the shear box under target normal pressures of 25, 35, 45 psi (172, 241 and 310 kPa), typical ballast layer confining pressures, so that the relationships between the normal stress and shear stress could be established. The maximum shear stress at failure under each applied normal pressure was recorded from each test. This maximum shear stress typically occurred when approximately 10% shear strain was reached during testing. The shear strength \( \tau_{max} = C + \sigma_n \tan \Phi \) (where \( C \) is the cohesion intercept, \( \sigma_n \) is the applied normal stress, and \( \Phi \) is the internal friction angle) expression was then developed for each ballast sample tested at a corresponding fouling fines content and moisture state.

Figure 17 shows the maximum shear stresses predicted under the applied normal stresses during shear box testing. As the applied normal stresses increased, the maximum shear stresses at failure or simply shear strength \( \tau_{max} \) also increased primarily influenced by the ballast fouling percentage and the moisture condition of the coal dust, i.e., dry or wet at OMC = 35%. As expected, the highest shear strength values were obtained from the clean ballast at all applied normal stress levels. When ballast samples were fouled, the shear strengths typically decreased. For all the samples tested, wet coal dust fouling resulted in lower shear strengths when compared to those obtained from dry coal dust fouling. The lowest shear strength values were recorded for
the fouling level of 25% by weight of ballast when wet coal dust filled all the voids at 35% moisture content.

Table 3 shows cohesion intercepts (C) and internal friction angles (from slopes of Mohr-Coulomb envelopes in Figure 17) obtained for the clean and fouled ballast samples. The highest friction angle $\Phi$ of 45.6 was achieved for the clean granite. For the case of 25% wet coal dust fouling by weight of ballast, the friction angle computed is as low as 34.5 degrees, which is very close to 33.5 degrees at OMC for the coal dust itself. Similarly, a low cohesion intercept of 5.1 psi (35 kPa) value is close to the very low unconfined compressive strength of 3.5 psi (24 kPa) for the coal dust itself. Therefore, the shearing action in the direct shear apparatus was mainly resisted by the wet coal dust governing the behavior. Again, one should note that 35% OMC condition does not represent fully saturated coal dust state. After soaking or 100% saturation, soil suction would be destroyed thus resulting in fairly lower strengths and unstable ballast conditions.

**SUMMARY AND CONCLUSIONS**

Mechanical properties of representative coal dust samples obtained from the Powder River Basin (PRB) joint line in Wyoming were determined through laboratory testing at the University of Illinois. From the grain size analysis of the coal dust, material finer than 0.00295 in. (0.075 mm) or No. 200 sieve size was found to be 24%. The specific gravity of the coal dust sample was 1.28. While the fines content of the coal dust was lower than that of most silty and clayey soils, the optimum moisture content (OMC) of the coal dust determined from the standard Proctor compaction test was remarkably higher than that of some of the weak cohesive soils, which highlights its ability to hold much greater amounts of moisture. Likewise, the high liquid limit,
LL, and plasticity index, PI, of coal dust, i.e., 91% and 41%, respectively, also underscore its high moisture sensitivity. When subjected to precipitation, coal dust can therefore hold excessive amounts of moisture to prevent free draining of the ballast, i.e., can keep ballast wet and saturated, and act as a lubricant between the ballast stones, enabling much greater movement within the ballast layer.

As for the strength characteristics of the coal dust, the unconfined compressive strength of the coal dust tested was a remarkably low $Qu = 3.5$ psi (24.1 kPa) at the OMC of 35%. The results of direct shear tests indicated a large reduction in the internal friction angle of the coal dust with increasing moisture content. For instance, the internal friction angle of the coal dust was found as 33.5 degrees at 35% OMC whereas the internal friction angle corresponding to 43% moisture was only 19.2 degrees. Therefore, exposure of coal dust to moisture drastically reduces the friction component of the shear strength and can cause significant reduction in bearing capacity and load carrying ability.

Large-sized direct shear (shear box) laboratory tests were next conducted at the University of Illinois on granite ballast samples also obtained from the Powder River Basin (PRB) joint line in Wyoming to measure strength and deformation characteristics of both clean (new) and fouled ballast aggregates with coal dust at various stages of fouling. The grain size distribution of the aggregate conformed to the typical AREMA No. 24 ballast gradation with a maximum size ($D_{\text{max}}$) of 2.5 in. (63.5 mm) and a minimum size ($D_{\text{min}}$) of 1 in. The coal dust, also obtained from the PRB joint line, was used as the fouling agent and mixed with clean aggregates for achieving fouling levels of 5%, 15%, and 25% by weight of ballast under dry and wet (at 35% OMC) conditions.
From the direct shear tests, the highest shear strength values were obtained from the clean ballast at all applied normal stress levels which were representative of the stress states experienced in the ballast layer under train loading. When ballast samples were fouled, the shear strengths always decreased. Wet (35% OMC) coal dust fouling resulted in lower ballast shear strengths when compared to those obtained from dry coal dust fouling. For the case of 25% wet coal dust fouling by weight of ballast, internal friction angle and cohesion obtained were equivalent to those properties of the coal dust itself at 35% OMC. Therefore, the wet coal dust was governing the ballast behavior as the worst fouling agent for its impact on track substructure and roadbed when compared to even the highly plastic type clayey soil fines. Note that even more drastic strength reductions can be realized when dry coal dust, never been saturated or soaked in the field and therefore having a high suction potential, is subjected to inundation and 100% saturation.

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Table 1. Internal friction angles and cohesion intercepts of coal dust measured by direct shear tests at different moisture contents

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Internal Friction Angle, $\Phi$ (Degrees)</th>
<th>$\tan \Phi$</th>
<th>Cohesion Intercept, $C$ (psi)</th>
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<tr>
<td>33.00</td>
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<td>33.53</td>
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<td>41.00</td>
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<td>43.00</td>
<td>19.23</td>
<td>0.35</td>
<td>0.81</td>
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Table 2. Properties of the clean granite aggregate

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<tr>
<td>2.5</td>
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Table 3. Summary of ballast internal friction angles and cohesion intercepts

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

* percentage by ballast weight
Figure 1. Sample grain size distributions of clean and fouled ballast samples (25.4 mm=1 in.)
Figure 2. Critical ballast fouling stages illustrating loss of aggregate to aggregate contact

(a) clean ballast  (b) dirty ballast with fine particles filling voids  (c) fouled ballast with aggregate to aggregate contact lost
Figure 3. Sample of coal dust in its loose state

Figure 4. Close-up view of the coal dust sample studied
Figure 5. Grain size distribution of the coal dust sample

Figure 6. Standard Proctor moisture-dry density curve for the coal dust sample
Figure 7. Photographs showing the triaxial test setup and the failed coal dust specimen

Figure 8. Triaxial shear test results and the Mohr-Coulomb failure envelope for coal dust
Figure 9. Shear strength of coal dust from undrained triaxial tests
Figure 10. Photograph showing the ShearScan 10 Direct Shear Test equipment

Figure 11. Grain size distribution of the clean granite aggregate sample (25.4 mm=1 in.)
Figure 12. The shear box shear strength test equipment at the University of Illinois
Figure 13. Stages of ballast compaction

Figure 14. Mixing fouling material as outlined in steps 3 and 4

Figure 15. Loading upper ring
Figure 16. Setting-up the direct shear box apparatus
Figure 17. Direct shear box ballast strength test results