Engineering Properties of Combined Coarse and Fine Coal Wastes

By Bill M. Stewart and L. A. Atkins
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ENGINEERING PROPERTIES OF COMBINED COARSE AND FINE COAL WASTES

by

Bill M. Stewart \(^1\) and L. A. Atkins \(^2\)

ABSTRACT

The Bureau of Mines conducted laboratory tests to determine the effects on the physical properties of coarse coal waste of adding large amounts of fine coal waste. Maximum laboratory dry density, optimum moisture content, shear strength, and permeability tests were conducted on samples that contained 18 to 60 pct minus No. 4 (U.S. Standard sieve size) coal waste. For the nonslaky materials, maximum laboratory densities were highest and permeabilities lowest when the samples contained between 30 and 40 pct minus No. 4. Shear strength increased rapidly when the proportion of minus No. 4 was increased from 20 to 40 pct, but then increased only slightly or leveled off when the minus No. 4 was increased to 60 pct. Optimum moisture content and permeability were the physical properties most affected by the addition of fines. Optimum moisture content increased as much as 3 pct, and permeabilities decreased up to three orders of magnitude. Slaky coal waste material had physical property reactions to the addition of fines substantially different from those of nonslaky material.

INTRODUCTION

Space limitations, high costs of impoundment construction, and adverse environmental impacts associated with impoundments have caused many coal companies to consider dewatering the fine coal refuse from the thickener underflow. Fine coal refuse is generally classified as minus 28 Tyler mesh (0.699 mm) and is commonly collected from the preparation plant process water in a stream that includes sizes ranging from 8 Tyler mesh (2.46 mm) to 0.0005 mm. In a typical preparation plant, the fine-refuse stream contains only about 5 pct\(^3\) solids and therefore requires thickening prior to dewatering or other treatment. Feeds to the thickener are treated with flocculants; the solids settle to the bottom (underflow); and the clarified water is skimmed off at the top (overflow). The underflow typically contains about 30 pct solids and the overflow less than 1 pct solids.

Underflow material can be further dewatered by mechanical, thermal, or chemical processes, or by a combination of these processes. Generally, economics and the type of material to be dewatered dictate the methods to be used. Dewatering allows the operator to dispose of the fine fraction (minus 28 mesh) in a semi-dry state along with the coarse fraction (generally classified as minus 3 inch to plus 28 mesh) produced in the preparation process. With this method, only one

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\(^3\)In this report, "weight-percent" will be designated simply as "percent."
disposal transportation system is needed, and the surface area required for disposal is reduced, compared with that used for impoundment. Disposing of coarse wastes and dewatered fines together should produce a more stable mass because the water used to transport the fines would be eliminated. This is a definite advantage; many past failures of coal waste embankments were directly related to high phreatic surfaces.

However, there are some factors in the "dry fill" method that may affect stability. One of these factors, the basis of this research, is the change in physical properties of total coal waste when large amounts of dewatered fines are added. To investigate these changes, the Bureau of Mines Spokane Research Center, under the Bureau's Minerals Health and Safety Technology program, conducted several physical property tests on mixes of coarse and fine coal waste. The only variable imposed was the percentage of minus No. 4 (U.S. Standard sieve size) material in the test samples.

SAMPLE COLLECTION AND TEST PROCEDURES

Test samples were collected from four coal mines in four States (Colorado, Ohio, Pennsylvania, and West Virginia). For the purpose of this report, the Colorado mine will be designated mine A, and the three eastern mines will be designated mines B, C, and D. Mines A and B are using filters to dewater the fines; mine C is using chemical methods for dewatering; and mine D is using a series of filter presses. All of the mines use either truck or conveyor transport of the coarse and fine refuse to the refuse pile. Prior to transport of the fines to the refuse pile, mine C pumps the thickener underflow to a series of curing ponds where it is chemically treated and dewatered.

Approximately 2 tons of waste were collected from each mine waste dump. Because it was not the intent of this research project to compare field physical properties of the material with laboratory physical properties, in-place tests were not performed during sampling. The material was placed in sealed drums and shipped via truck to the Spokane Research Center.

The laboratory tests were performed using the following procedures:

1. Grain-size distribution for the plus No. 200 (U.S. Standard sieve size) fraction was evaluated according to American Society for Testing and Materials (ASTM) standards. The grain-size distribution of the minus No. 200 fraction was determined using a particle-size analyzer, which operates on the principle of Stokes' law, using X-ray absorption.

2. The specific gravity of the plus No. 4 material and of the minus No. 4 material was determined according to ASTM standards.

3. Maximum and minimum densities and optimum moisture contents of the mixed coarse and fine material were determined according to ASTM standards.

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4. Triaxial shear tests of the samples were conducted according to ASTM designation D2850-70 under drained conditions.7

5. Permeability of the samples was determined according to the U.S. Bureau of Reclamation Earth Manual designation E-14.8

MATERIAL

As Received

The as-received material is described in table 1. The laboratory test program was designed to determine the effects on the maximum density, moisture content, and permeability of coal waste materials when varied amounts of fines were added. Such would be the case when dewatered fines are combined with coarse waste in a common dump.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Soil classification</th>
<th>Minus No. 4, pct</th>
<th>Minus No. 200, pct</th>
<th>Effective size (D10), mm</th>
<th>Uniformity coefficient (D60/D10)</th>
<th>Specific gravity</th>
<th>Description of material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A</td>
<td>GM-SM</td>
<td>54</td>
<td>18</td>
<td>0.03</td>
<td>203.0</td>
<td>1.83</td>
<td>Poorly graded gravel-sand-silt mixture.</td>
</tr>
<tr>
<td>Mine B</td>
<td>GP-GM</td>
<td>38</td>
<td>7</td>
<td>0.23</td>
<td>44.8</td>
<td>1.80</td>
<td>Poorly graded gravel, gravel-sand mix with small amount of silt.</td>
</tr>
<tr>
<td>Mine C</td>
<td>GP-GC</td>
<td>25</td>
<td>7</td>
<td>0.32</td>
<td>33.8</td>
<td>1.92</td>
<td>Poorly graded gravel, gravel-sand mixture with clay binder.</td>
</tr>
<tr>
<td>Mine D</td>
<td>GW-GM</td>
<td>38</td>
<td>8</td>
<td>0.17</td>
<td>58.8</td>
<td>2.12</td>
<td>Well-graded gravel, gravel-sand-silt mixture.</td>
</tr>
</tbody>
</table>


8U.S. Bureau of Reclamation (Department of the Interior). Permeability and Settlement of Soil Containing Gravel.
To establish a baseline on grain-size distribution, the as-received material, after thorough drying, was separated on a shaker into U.S. Standard sieve sizes of plus 1-1/2 inches (plus 38 mm), 1 inch (25.4 mm), 3/4 inch (19.5 mm), 3/8 inch (9.6 mm), No. 4 (4.9 mm), and minus No. 4. The minus No. 4 material was separated into sieve sizes of No. 10 (2.0 mm), No. 16 (1.2 mm), No. 30 (0.59 mm), No. 50 (0.31 mm), No. 100 (0.16 mm), No. 200 (0.08 mm), and minus No. 200. The minus No. 200 material was separated on a Particle-size analyzer into clay and silt sizes. Figures 1 and 2 show the grain-size curves of the as-received material for the four samples collected.

Varying the Grain-Size Distribution

Once the baseline (as-received) grain-size distributions were established for each mine, minus No. 4 material was added or subtracted. The minus No. 4 size was selected as the variable because there was an abundance of this size material from each of the mines; it is the smallest fraction obtainable on the large particle shaker; and, most importantly, it includes all the finer coal refuse sizes (2.46 mm to 0.0005 mm) commonly collected in preparation plant process water. From 18 to 60 pct minus No. 4 was mixed with the coarser (plus No. 4) material. In this report, 18 to 25 pct minus No. 4 will be called a low level; 32 to
40 pct, a medium level, and 54 to 60 pct, a high level. Table 2 shows the percentage of minus No. 4 and minus No. 200 material used in each sample. After addition of the correct amount of each size material and water to approximate the as-received water contents, the samples were handmixed for the maximum density, moisture contents, shear strength, and permeability tests.

**TABLE 2.** Minus No. 4 material, including minus No. 200 fines, used in tests, percent

<table>
<thead>
<tr>
<th>Sample</th>
<th>Minus No. 4</th>
<th>Minus No. 200</th>
<th>Sample</th>
<th>Minus No. 4</th>
<th>Minus No. 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A:</td>
<td></td>
<td></td>
<td>Mine C:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>3</td>
<td>71</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>10</td>
<td>8</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>18</td>
<td>9</td>
<td>60</td>
<td>26</td>
</tr>
<tr>
<td>Mine B:</td>
<td></td>
<td></td>
<td>Mine D:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>5</td>
<td>10</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>51</td>
<td>38</td>
<td>7</td>
<td>111</td>
<td>38</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>58</td>
<td>11</td>
<td>12</td>
<td>58</td>
<td>12</td>
</tr>
</tbody>
</table>

1As-received samples.

**TEST RESULTS**

**Effects on Maximum Laboratory Densities**

Maximum laboratory dry densities (MLD) of the coal waste samples were determined by impact (standard compactive effort) and vibration methods. Maximum particle size was three-fourths of an inch for the impact method and 3 inches for the vibration method. Results of the MLD test can be seen in table 3. One point of interest is the densities of material from mine C. This material had high slaking properties; because of the cohesive attraction of the clay particles, all three samples showed higher densities using the impact method than were observed using the vibration method. The effects of fines additions on the physical properties of the slaky mine C material will be addressed throughout this report.

**TABLE 3.** Maximum densities for various mixes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Standard effort maximum dry density, lb/ft$^3$</th>
<th>Vibration maximum wet density, lb/ft$^3$</th>
<th>Sample</th>
<th>Standard effort maximum dry density, lb/ft$^3$</th>
<th>Vibration maximum wet density, lb/ft$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A:</td>
<td></td>
<td></td>
<td>Mine C:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>88.7</td>
<td>89.1</td>
<td>71</td>
<td>99.7</td>
<td>91.2</td>
</tr>
<tr>
<td>2</td>
<td>96.6</td>
<td>98.7</td>
<td>8</td>
<td>98.9</td>
<td>90.6</td>
</tr>
<tr>
<td>31</td>
<td>93.1</td>
<td>89.0</td>
<td>9</td>
<td>98.3</td>
<td>86.1</td>
</tr>
<tr>
<td>Mine B:</td>
<td></td>
<td></td>
<td>Mine D:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ND</td>
<td>92.4</td>
<td>10</td>
<td>108.9</td>
<td>106.1</td>
</tr>
<tr>
<td>51</td>
<td>95.7</td>
<td>95.4</td>
<td>111</td>
<td>115.2</td>
<td>118.2</td>
</tr>
<tr>
<td>6</td>
<td>93.0</td>
<td>93.9</td>
<td>12</td>
<td>114.0</td>
<td>109.7</td>
</tr>
</tbody>
</table>

ND Not determined.

1As-received samples.

Works cited in footnote 6.
Figure 3 shows the effects on MLD when different amounts of minus No. 4 material were added to the samples. Material from mines A, B, and D containing 30 to 40 pct minus No. 4 showed the highest MLD. With lower or higher percentages, the MLD declined. Mine C material showed a gradual decline in MLD as the percent minus No. 4 increased, with the highest MLD at only 25 pct minus No. 4. However, though 25 pct minus No. 4 was present in the as-received sample, it is highly possible that the actual amount at the time of the density test had increased to the optimum 30- to 40-pct range. This increase would be attributed to the slaking nature of the material, which is induced by the wet, dry, wet preparation preceding the density tests, and the compaction effort during the tests.

Effects on Optimum Moisture Content

Optimum moisture contents are affected by the amount of fines added to coarse coal waste. Figure 4 shows the optimum moisture content at MLD (standard compactive effort) versus the percentage of minus No. 4 in each sample. As a general rule, the optimum moisture content increases as the percentage of minus No. 4 increases. However, as can be seen in figure 4, the increases in optimum moisture content are variable and depend on the type of coal waste being tested. For instance, material from mines B and C showed a very slight rise in optimum moisture content as the percent minus No. 4 was increased from low to medium, but then a much larger rise when the percent minus No. 4 increased from medium to high. Material from mines A and D acted just the opposite and actually showed no change in optimum moisture content when the percentage of minus No. 4 was increased from medium to high.

Moisture-Density Relation

The best results from the addition of large amounts of fines to coarse coal waste would be an increase in density and a decrease in optimum moisture content. The actual effects on MLD and moisture content when the percent minus No. 4 was increased were quite variable. The effects depended on the gradation of the coal waste coming from the preparation plant and on the mineral content and grain size of the original material.
The highest MLD's were obtained in samples containing 30 to 40 pct minus No. 4 (fig. 3). In three of the four samples, increasing to a high level of minus No. 4 had little effect on the MLD (a decrease of less than 2 lb/ft$^3$). At the same time, however, in two of these samples, the optimum moisture content increased nearly 3 pct (fig. 4). In water-scarce areas, this would be an important consideration in water management. Of the four samples tested, mine D material best satisfied the moisture-density criteria, with an MLD range of 108 to 115 lb/ft$^3$ and optimum moisture content under 8 pct.

Effects on Initial Void Ratio and Soil Strength

To determine the effects on soil strength when fines were added to coarse coal waste, consolidated-drained triaxial compression tests were performed. The samples were 9 inches in diameter by 22.5 inches long and were compacted in the test chamber (fig. 5) at 95 pct MLD. The samples were compacted with a hand-held, flat-bottomed tamping bar. Seven layers, each approximately 3.2 inches thick, were tamped. The top of each layer was scarified prior to adding the next layer. The major principal intergranular
stress ($\sigma_1$) was applied at a rate of 0.025 in/min. Pore pressure was monitored at the top of the samples, and the samples were allowed to drain at the bottom. Most of the samples showed some pore pressure during initial loading. However, at the beginning of each test (after consolidation) and throughout each test, no pore pressure developed at the top of the samples. Because of this, neutral stresses due to pore pressure were considered negligible. Therefore, the effective lateral pressure ($\sigma_3$) is the applied lateral pressure, and the deviator stress ($\sigma_1-\sigma_3$) is the effective normal stress.
As a general rule, the lower the initial void ratio (IVR) of the material at placement, the higher the shear strength. Figure 6 shows that the IVR in materials from mines A, B, and D decreased significantly with an increase from low to medium levels of minus No. 4. However, the IVR then increased in A and D materials with an increase to the high level of minus No. 4. This indicates, for these materials, that an "optimum" IVR is found in the 30- to 40-pct range of minus No. 4.

A more detailed analysis of void ratios is seen in table 4. With the increase from low to medium percentages of fines, material from mines A, B, and D showed an increase in volume of solids and decrease in volume of voids. This indicates that the fines filled the original voids and created less void space. However, in A and D material, increasing to a higher percentage of fines caused the opposite to occur. The fines replaced and pushed the plus No. 4 particles away from each other and thereby created higher void ratios.

### Table 4. Changes in volume, specific gravity, and weight as percent minus No. 4 changes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Minus No. 4, pct</th>
<th>Initial void ratio</th>
<th>Volume, ft³</th>
<th>Specific gravity</th>
<th>Weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solids</td>
<td>Voids</td>
<td>Water</td>
</tr>
<tr>
<td>Mine A:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1...</td>
<td>18</td>
<td>0.410</td>
<td>0.59</td>
<td>0.242</td>
<td>0.068</td>
</tr>
<tr>
<td>2...</td>
<td>32</td>
<td>0.245</td>
<td>0.67</td>
<td>0.164</td>
<td>0.113</td>
</tr>
<tr>
<td>31...</td>
<td>54</td>
<td>0.292</td>
<td>0.64</td>
<td>0.187</td>
<td>0.105</td>
</tr>
<tr>
<td>Mine B:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4...</td>
<td>25</td>
<td>0.301</td>
<td>0.64</td>
<td>0.192</td>
<td>0.070</td>
</tr>
<tr>
<td>51...</td>
<td>38</td>
<td>0.240</td>
<td>0.67</td>
<td>0.161</td>
<td>0.081</td>
</tr>
<tr>
<td>6...</td>
<td>58</td>
<td>0.239</td>
<td>0.67</td>
<td>0.160</td>
<td>0.112</td>
</tr>
<tr>
<td>Mine C:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71...</td>
<td>25</td>
<td>0.266</td>
<td>0.66</td>
<td>0.174</td>
<td>0.137</td>
</tr>
<tr>
<td>8...</td>
<td>40</td>
<td>0.301</td>
<td>0.64</td>
<td>0.193</td>
<td>0.143</td>
</tr>
<tr>
<td>9...</td>
<td>60</td>
<td>0.337</td>
<td>0.62</td>
<td>0.209</td>
<td>0.161</td>
</tr>
<tr>
<td>Mine D:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10...</td>
<td>18</td>
<td>0.267</td>
<td>0.66</td>
<td>0.176</td>
<td>0.084</td>
</tr>
<tr>
<td>111...</td>
<td>38</td>
<td>0.178</td>
<td>0.70</td>
<td>0.125</td>
<td>0.123</td>
</tr>
<tr>
<td>12...</td>
<td>58</td>
<td>0.234</td>
<td>0.67</td>
<td>0.156</td>
<td>0.117</td>
</tr>
</tbody>
</table>

1As-received samples.
Mine C material showed a continuous decrease in volume of solids and increase in volume of voids from low to high percentage of minus No. 4. The volume of water is much higher in mine C material than in the others, which may be typical of a highly slakable material.

Figure 7 shows the effects on the angle of internal friction when minus No. 4 was added to coarser coal waste. To obtain the friction angles, three triaxial shear tests were run on each mix. As reflected by the decrease in IVR (fig. 6), the friction angle of material from mines A, B, and D increased as the percent minus No. 4 increased from low to medium. Increasing the minus No. 4 to 60 pct did not have a great effect on the strength, even though the void ratios tended to increase. The friction angles of mines A and D material stayed about the same at the high level of minus No. 4 as at the medium level. Mine B material showed a steady increase of the friction angle; the strength of this material was increasing even at 58 pct minus No. 4. This indicates that the shape of the particles was such that they fit very well together, similar to the pieces of a puzzle, with a lot of contact between particles and very little void space.

Mine C material had a much lower friction angle than the other materials. Based on two triaxial test sets, the friction angle decreased from 28.2° to 25.7° when the percent minus No. 4 was increased from 25 to 60. The addition of fines and the material's slaking nature resulted in high void volumes at placement and, therefore, lower strengths. Much more water was entrapped in the voids of mine C material than in the others, first, because there were more voids, and second, because of the attraction of the water to the clay particles.

Effects on Permeability

Constant head permeability tests were conducted for each mix according to the U.S. Bureau of Reclamation Earth Manual designation E-14.¹⁰ The samples were placed in the permeability test chamber (fig. 8) at 95 pct MLD. A flat-head tamping bar was used to compact the samples. The samples were compacted in three layers, each 3 inches thick. The top of each layer was scarified prior to adding the next layer. The samples were 18-1/2 inches in diameter and 9 inches thick. The samples were tested at 100 pct saturation, and the temperature of the water was the same for all tests. For each mix, permeability readings were taken several times a day for several days until the permeability rate became nearly constant.

The effects on permeability are shown in figure 9. The permeability curves for mines A, B, and D correspond, as expected, with the IVR curves (fig. 6). The permeabilities decreased rapidly when the level of minus No. 4 in the mixes was changed from medium to

¹⁰Work cited in footnote 8.
FIGURE 8. - Constant head permeability test apparatus.
The permeability of mine C material did not correspond with its IVR. In the 40- to 60-pct minus No. 4 range, it had higher IVR's but much lower permeabilities than the other materials. Even though the initial void volume of mine C material continually increased as minus No. 4 was added, one overriding factor contributed to its low permeability. When the material was saturated before the test, it slaked to clays, filling the initial voids with solids, creating smaller pores, and inhibiting waterflow.

**Additional Tests**

Three additional tests were performed to determine (1) the shear strengths of samples with 100 pct minus No. 4 and 100 pct plus No. 4, (2) the time-dependent effects on shear strength after water is added to the sample, and (3) the effects on shear strength and permeability if the sample is in alternating layers of coarse and fine, rather than a mixture of coarse and fine. Because each of these tests was performed on waste from only one site, the results cannot be construed as representative of all sites.

**Comparison of Coarse and Finer Samples**

The first additional test shows the importance of adding well-graded fines to coarse waste for stability purposes. Direct shear tests were conducted on two samples of mine D material, one consisting of 100 pct minus No. 4 and the other as 100 pct plus No. 4 coal waste. The gradation curves for each sample are shown in figure 10. Table 5 shows the results of the tests.
TABLE 5. - Differences in physical properties of coal waste samples containing 100 pct minus No. 4 and 100 pct plus No. 4

<table>
<thead>
<tr>
<th>Minus No. 4, pct</th>
<th>Maximum laboratory density, lb/ft³</th>
<th>Angle of internal friction, deg</th>
<th>Cohesion, lb/in²</th>
<th>Initial void ratio</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>88.1</td>
<td>29.2</td>
<td>2.8</td>
<td>0.555</td>
<td>2.08</td>
</tr>
<tr>
<td>100</td>
<td>107.8</td>
<td>39.3</td>
<td>15.9</td>
<td>0.332</td>
<td>2.18</td>
</tr>
</tbody>
</table>

The MLD and the angle of internal friction are much lower in the sample with 100 pct plus No. 4. Two factors contribute to this. First, the coarse material has a limited range of grain sizes (uniformly graded), and, second, because of the absence of fines, the coarse material has a much higher IVR. The large void spaces between the coarse particles reduce the sample's resistance to shear. Because of the large difference in the results, it can be concluded that, for mine D material, fines are essential for strength. For this material, much greater amounts of minus No. 4 than the 38 pct in the as-received sample could be added without detrimental effects to the strength.

Time Factor in Testing

The second additional test was to determine if the shear strength was affected by a delay in time between addition of moisture to a sample and shear strength testing of the sample. The time between adding moisture to the mixed coarse and fine samples and shear testing had varied considerably throughout the course of the earlier research. Two identical samples were prepared with mine D material containing 18 pct minus No. 4 and 6.1 pct moisture. Identical direct shear tests were performed, 24 hours after mixing with water for one sample, and 7 days after mixing with water for the other. The angle of friction was 29.4° for the 24-hour sample and 28.8° for the 7-day sample; cohesion was 5.4 lb/in² for the 24-hour sample and 5.7 lb/in² for the 7-day sample. These results indicate that, for mine D material, and probably for all nonslaking soils, time between adding water to the sample and testing is not a factor in the shear strength.

Alternating Coarse and Fine Layers

The third additional test was conducted to determine the effects on shear strength and permeability if the samples are placed in the testing apparatus.
in alternating coarse and fine layers, rather than mixing the coarse material and fines together. The as-received samples from mine B, containing 38 pct minus No. 4, were used as the coarse material, and 100 pct minus No. 4 material, which included 24 pct minus No. 200, from the same mine was used for the fines. For the triaxial shear tests, seven alternating layers 3 inches thick (four coarse and three fine) were placed in the test apparatus, and for the permeability test, three alternating layers (two coarse and one fine) were placed. The water content, saturation, and dry density at placement were 7.7 pct, 50.4 pct, and 87.0 lb/ft³, respectively. The IVR was 0.271. The angle of internal friction for the layered sample was 35.1°, which is only a slight reduction from the friction angle of 37.6° for the mixed mine B samples containing medium levels of minus No. 4.

Layering of the sample produced 3.2-lb/in² cohesion. This is interesting because no cohesion was produced in the mixed samples, even with a high level of minus No. 4. The permeability of the layered sample was $2.25 \times 10^{-5}$ cm/sec or about five times lower than the permeability of the sample containing 58 pct minus No. 4. The lower permeability indicates that the layers of fines act as barriers to the flow of water and could result in perched water zones above the fine layers.

CONCLUSIONS

The waste samples used in this research were collected from coal mines in four States (Colorado, Ohio, Pennsylvania, and West Virginia). The results are based on limited data and therefore cannot be construed as representative of all sites. Each sample tested had a different classification according to the Unified Soil Classification System and, therefore, different physical properties. The actual numbers derived from these tests are probably not as important as the trends (increases and decreases) in the physical properties when fine waste is mixed with coarse.

The following conclusions were reached:

1. Physical properties of coal waste change as the minus No. 4 size is increased from 20 to 60 pct. In the non-slaky samples tested, the MLD and soil strength are at an optimum high, and the IVR at an optimum low, when the coal waste contains 30 to 40 pct minus No. 4. Somewhere in this range, the fines fill the voids of the coarse particles but do not replace or spread out the coarse particles.

2. The MLD and soil strength of nonslaky material improve substantially when the minus No. 4 size is increased from 20 to 40 pct. With an increase from 40 to 60 pct, the changes in density and strength are much less.

3. Optimum moisture content and permeability are the physical properties most affected. A 2- to 3-pct increase in optimum moisture content was found in all the samples as minus No. 4 was increased from 20 to 60 pct. In two of the materials, the optimum moisture content stayed about the same in samples with low and medium levels of minus No. 4 but increased 2 to 3 pct with an increase to a high level of minus No. 4. In the other two samples, the opposite occurred. The permeabilities of the nonslaky materials decreased one to three orders of magnitude when the percent minus No. 4 was increased from low to medium. The permeabilities of all the samples were at or near the lowest points when the samples contained 30 to 40 pct minus No. 4.
4. Highly slakable materials reacted differently to the addition of fines than did nonslaky materials. The MLD and the angle of internal friction (in the highly slakable sample tested) decreased as the minus No. 4 was increased from 20 to 60 pct. However, over the same range, the IVR increased. Overall, optimum moisture contents were much higher and permeabilities much lower for the highly-slakable material.

5. For mine material D, there was no effect on material strength as a result of extended periods of time elapsing between adding moisture to the sample and testing the sample.

6. The MLD, angle of internal friction, and cohesion were much higher in a sample containing 100 pct minus No. 4 than in a sample from the same mine that contained 100 pct plus No. 4. A well-graded mine D sample containing about 40 pct minus No. 4 produced the best physical properties for stability purposes.

7. Layering the coarse and fine waste decreased the angle of internal friction only slightly; however, the permeability of the layered sample was five times less than that of a similar sample in which 58 pct minus No. 4 and 42 pct plus No. 4 were mixed. The layers of fines seemed to act as barriers to the flow of water and could result in perched water tables under field conditions.

8. Mine operators contemplating disposal of large amounts of dewatered fines with coarse refuse should conduct physical property tests to determine proper disposal and mixing procedures, mixing proportions, water requirements for optimum moisture content, and drainage and stability requirements. The tests should be conducted as close to planned field conditions as possible.