Physical, mechanical, and hydraulic properties of coal refuse for slurry impoundment design

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ABSTRACT: Coal mining processes result in two general types of by-products: coarse coal refuse (CCR), a mixture of soil and rock commonly used to construct an impoundment coal refuse dam or embankment, and fine coal refuse (FCR) slurry, a mixture of soil, rock dust, coal fines and water that is pumped into such an impoundment. The physical, mechanical, and hydraulic conductivity properties of CCR and FCR are critical in designing coal refuse disposal dams and impoundments for both static and seismic stability. This paper provides a summary of laboratory and in-situ strength, and hydraulic conductivity test results performed on CCR and FCR in association with the design and construction of several coal refuse dams and impoundments in England and Western Pennsylvania in the United States. Predominant mean values and statistical variabilities are reported for each material property. These parameters are subsequently employed in a simple statistical model to evaluate the reliability of the design of coal refuse impoundments.

1 INTRODUCTION

Coarse coal refuse (CCR) is commonly used to construct dams to retain a slurry of fine coal refuse (FCR) and water. A site investigation, and in-situ and laboratory testing programs are customarily performed to determine the necessary material properties for static and seismic design of the dam. Physical properties include, but are not limited to, specific gravity, water content, unit weight, and grain size distribution, in addition to the plastic and liquid limits for FCR. The primary mechanical and hydraulic properties include, but are not limited to, the shear strength and permeability or hydraulic conductivity of the refuse, respectively.

The CCR properties are often characterized through in-situ permeability testing and laboratory geotechnical testing (index, strength, and permeability tests) of reconstituted samples, which sometimes includes resonant column testing, as necessary, to address seepage through the dam, design internal drains, assess the dynamic response of the dam, and evaluate static and seismic slope stability. In-situ testing, such as, seismic piezocone testing, is widely used to characterize FCR behavior with respect to equivalent soil type, static and dynamic properties (including shear strength and shear wave velocity) and permeability. These data for FCR are especially important for upstream dam construction, as the FCR is a major consideration in the prediction of seepage conditions, designing internal drains, assessing the dynamic response of the dam and FCR foundation, assessing liquefaction susceptibility, and evaluating static and seismic upstream slope stability.

In the construction of upstream CCR embankments, the FCR constitutes much of the embankment foundation, and is partly replaced by, mixed with, and compressed by the CCR fill. This results in the formation of a suitable foundation to support the upstream embankment. The alteration of the FCR foundation during the upstream construction process results in a more stable configuration than is often suggested by upstream slope stability analyses that assign FCR properties to the entire foundation (i.e., the entire zone below the FCR surface at the onset of upstream construction).

2 DATABASE

A database was developed from geotechnical investigations of existing coal refuse disposal sites in Western Pennsylvania of the USA and England, and consists of test data from project files prepared by the authors over several years, and test data collected by Chen (1976). In-situ samples were collected from the sites using disturbed methods, such as bucket samples from test pits and FCR deltas, and split spoon samples from boreholes, and using undisturbed sampling methods using Shelby tubes and Denison tube samplers. These samples were tested in laboratory to identify the physical and mechanical properties of coal refuse materials. In-situ testing was performed, including seismic piezocone tests and falling head field permeability tests in CCR. Also, pore pressure dissipation tests were performed during the cone penetration tests to study the rate of consolidation of the FCR.

3 INDEX AND CLASSIFICATION PROPERTIES

One of the first steps in geotechnical investigation program for a coal refuse disposal facility is to identify the index properties of the coal refuse and foundation materials, including unit weight and specific gravity, grain size distribution, and the plasticity of fine materials. For soft soils, the unit weight is typically measured from undisturbed Shelby-tube samples. In the case of hydraulically deposited FCR, it is very difficult to obtain undisturbed samples from the slurry impoundment. Since recently pumped fines cannot support a vehicle or an equipment surcharge, a work platform of CCR is typically constructed over the settled FCR to gain access for in-situ sampling and testing. During construction of the work platform, the underlying FCR or fines are partly displaced, intermixed with the CCR, and compressed to form a relatively stable surface for a drill rig or a cone truck to drive on. The process of constructing the work platform and the attendant alteration of the FCR foundation is analogous to the initial phase of upstream embankment construction. Therefore, the sampled FCR is altered and improved by the surcharge effect of the work platform. In the case of extensive upstream construction, FCR might extend beneath the crest of the CCR dam and also require investigation. In the latter case, the FCR has consolidated under its own weight and the overburden of the CCR embankment.

A summary of the FCR total unit weight (γ_t), dry unit weight (γ_d) and specific gravity (G_s) data is shown in Table 1, including the average (AVG), standard deviation (STDEV) and coefficient of variation (COV) of each property. Typically, coefficients of variations below 10% are thought to be low, between 10% and 30% moderate, and above 30% high (Harr, 1987). Table 1 indicates low variability of the FCR γ_t and moderate variability of the FCR γ_d and G_s.

The total unit weight of CCR in-place typically is measured using nuclear density gauge as a quality control measure for CCR compaction during construction of the impoundment embankment (dam). Samples of CCR are collected from the density test location and sent to a laboratory for a moisture content determination and to estimate the CCR γ_d. Table 2 summarizes the AVG, STDEV and COV of the CCR γ_t, γ_d and G_s. The coefficients of variations summarized in Table 2 indicate low variability of CCR γ_t and γ_d and moderate variability of CCR G_s and water content (w).

Tables 1 and 2 indicate that the G_s values of FCR and CCR are relatively low, averaging 1.5 and 2.0, respectively, because of the carbon content. However, for most natural soils, the G_s is on the order of 2.5 to 2.7. Figure 1 shows the increase in G_s as the carbon content decreases in the FCR and CCR samples.

The consistency of FCR samples is determined based on measured Atterberg limits. Table 3 summarizes the water content (w), liquid limit (LL), plastic limit (PL) and plasticity index (PI) results, which indicate, on the average, a clayey soil of low plasticity. However, some FCR samples were non-plastic and classified as silty soil.

Grain size distributions of coal refuse samples were obtained using sieve analysis. For FCR samples, Figure 2 shows these sieve analysis results, and Table 4 summarizes the percent passing sieve #200 (0.075 mm) and selected particle sizes in mm: D_{10}, D_{30}, D_{50} and D_{60} corresponding to percent passing of 10%, 30%, 50% and 60%, respectively. Figure 2 indicates a wide range of variability for the FCR grain size distribution due to its placement method, as explained herein. FCR is the product of extracting, crushing, and cleaning the raw coal. The FCR slurry is typically pumped upstream of the main dam. The coarser material settles out more quickly nearer the discharge location (customarily near the upstream of the dam), forming a fines delta or beach. The finer material migrates throughout the impoundment, as it takes longer to settle out. Therefore, samples collected from or closer to the delta are predominantly sand and silt size material, whereas samples collected away from the delta are predominantly silt and clay size material.

Table 1. Summary of FCR unit weight and specific gravity.

Property	Average	Standard deviation	Coefficient of variation
γ_T	13.0 (kN/m^3)	1.24	0.096
γ_D	9.0 (kN/m^3)	1.46	0.162
G_s	1.52	0.25	0.165

Table 2. Summary of in-place CCR unit weight, specific gravity and water content.

Property	Average	Standard deviation	Coefficient of variation
γ_T	18.5 (kN/m^3)	0.89	0.048
γ_D	19.7 (kN/m^3)	0.93	0.047
G_s	2.02	0.31	0.154
w	6.4 %	1.60	0.252

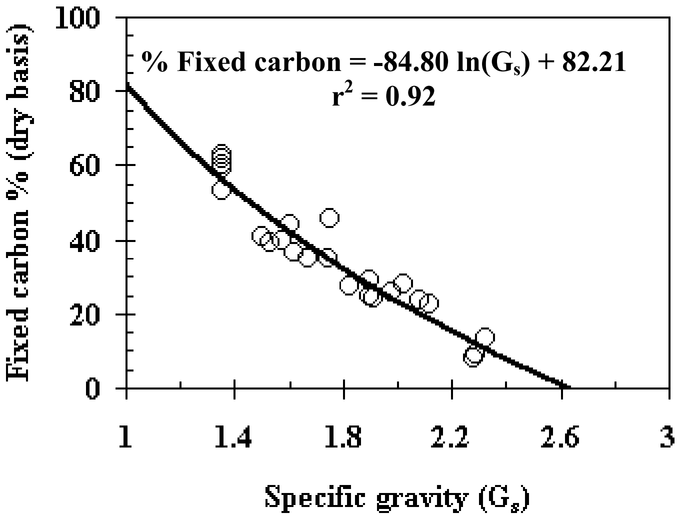

Figure 1. Effect of carbon content on specific gravity of coal refuse material.

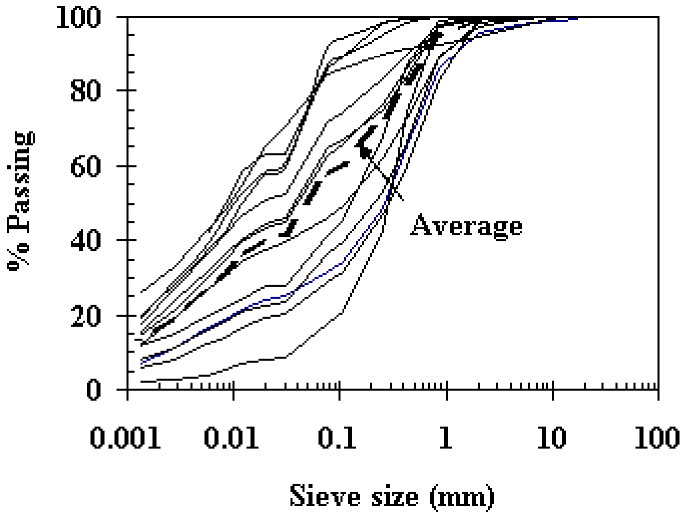

Figure 2. Grain size distribution of FCR.

Table 4 indicates a high variability in the percent passing sieve #200, which varied between 18% and 92%, with an average of 58%. A relatively higher variability, with a COV above 1, was encountered for the selected particle sizes D_{10}, D_{30}, D_{50} and D_{60}. Based on the sieve analysis results and measured Atterberg limits, the FCR classification ranged between silty clayey sand and clayey silty sand to sandy clayey silt and sandy silty clay. The coarser materials were generally found closer to the delta, or at locations where the slurry was pumped into the impoundment.

Similarly, sieve analysis was performed for CCR samples collected from fresh stock piles or from embankments of compacted CCR. Figure 3 shows the grain size distribution of the collected samples. Table 5 summarizes the percent of fines passing

Table 3. Summary of FCR Atterberg limits and water content.

property	Average %	Standard deviation	Coefficient of variation
LL	31.2	5.2	0.17
PL	20.1	3.4	0.17
PI	11.2	3.1	0.28
w	33.0	11.5	0.35

Table 4. Summary of FCR sieve analysis.

Particle size or % passing	Average	Standard deviation	Coefficient of variation
D_{10}	0.010 (mm)	0.015	1.50
D_{30}	0.037 (mm)	0.055	1.49
D_{50}	0.127 (mm)	0.128	1.01
D_{60}	0.196 (mm)	0.209	1.07
Passing sieve 200 (0.075 mm)	57.7 (%)	25.0	0.43

sieve # 200, with an average of 20% and a COV of 0.55. Also, Table 5 indicates a high variability of selected particle sizes including D_{30}, D_{50} and D_{60}, with COVs ranging between 0.44 and 0.71. Based on the results of the sieve analysis, the CCR was classified as silty clayey sand with gravel to clayey silty sand with gravel.

In compacting the CCR, and as a result of equipment traffic and weathering, the CCR experiences some degradation. Thus, the resulting percentage of fines in “aged” CCR can be perceptibly greater than in fresh or recently placed CCR. Sieve analyses were performed for fresh CCR samples and were repeated after samples were compacted to study the effect of compaction on the fines content (i.e., the percent passing #200 sieve). Figure 4 depicts that the average increase of fines was approximately 4% due to compaction alone.

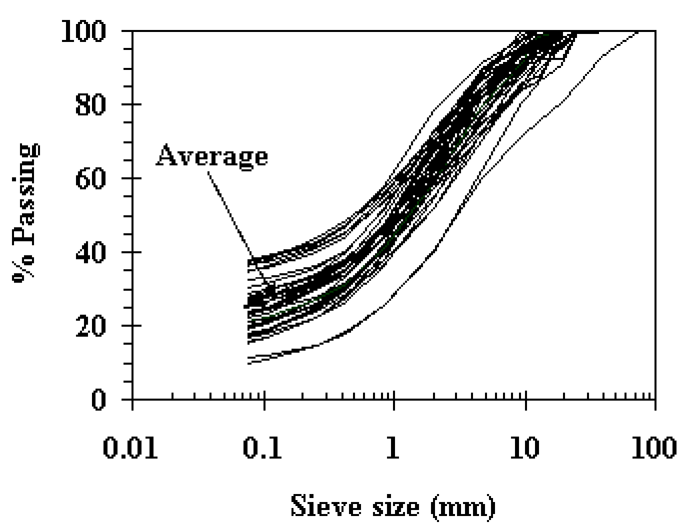

Figure 3. Grain size distribution of CCR.

Table 5. Summary of CCR sieve analysis.

Particle size or % passing	Average	Standard deviation	Coefficient of variation
D_{10}*		See note below	
D_{30}	0.35 mm	0.25	0.71
D_{50}	1.23 mm	0.62	0.50
D_{60}	2.02 mm	0.89	0.44
Passing sieve 200 (0.075 mm)	19.76 %	10.79	0.55

* D_{10} was less than 0.075 mm for all samples except one.

4 HYDRAULIC CONDUCTIVITY

The permeability of FCR was estimated using piezocone dissipation tests at sites in western Pennsylvania. Figure 5 shows the degree of excess pore water pressure decay ($\delta u/\delta u_i$) with time. The δu is the difference between the measured pore pressure after an elapsed time and the hydrostatic water pressure (u_o); whereas, δu_i is the pore pressure generated in excess of u_o. The horizontal coefficient of consolidation of the FCR was estimated as follows (Teh and Houlsby, 1991):

$$c_h = \frac{T_{50} a^2 \sqrt{I_r}}{t_{50}} \tag{1}$$

in which T_{50} is the modified time factor at 50% degree of consolidation, a is the cone radius, I_r is the undrained rigidity index, and t_{50} is the measured time to reach 50% degree of consolidation. For the analyses presented herein, T_{50} = 0.245 for a cone shoulder filter element (Teh and Houlsby, 1991), and a = 1.78 cm for a 10-cm^2 cone. Keaveny and Mitchell (1986) reported that I_r varies as a function of PI and OCR. On this basis, I_r was estimated equal to 240.

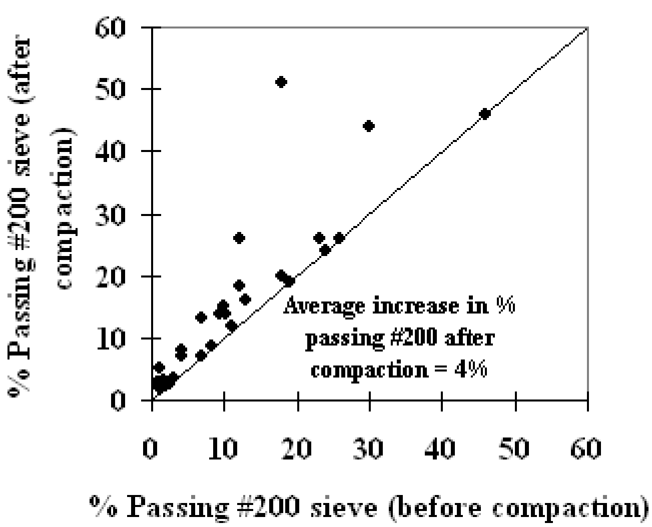

Figure 4. Effect of compaction on CCR fines content.

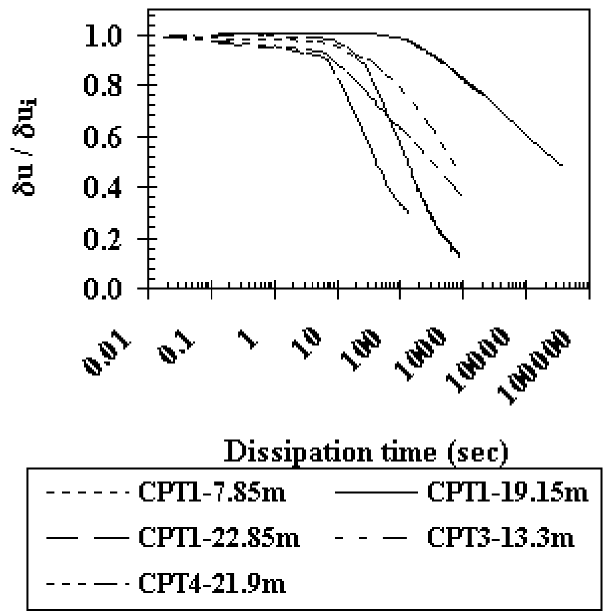

Figure 5. Piezocone dissipation tests at sites in western PA.

Table 6. Summary of estimated FCR horizontal permeability based on piezocone dissipation tests at sites in western PA.

Piezocone	Depth (m)	t_{50} (seconds)	c_h (cm^2/s)	k_h (cm/s)
PCPT1	7.9	800	15E-3	1.21E-5
PCPT1	19.2	30,000	0.4E-3	0.03E-5
PCPT1	22.9	40	301E-3	24.30E-5
PCPT3	13.3	128	94E-3	7.59E-5
PCPT4	21.9	300	40E-3	3.24E-5

Note: Pool level was approximately 3 meters below ground surface. Cone radius (a), T_{50}, and I_r were equal to 1.78 cm, 0.245, and 240, respectively.

Table 6 summarizes the resulting estimated c_h values, which average 0.09 cm^2/sec with a COV of 1.37. The average c_h of FCR is relatively high compared to that of natural soils because the FCR is deposited in nearly horizontal layers, and consists of a mixture of sand, silt and clay as discussed previously. The FCR horizontal permeability (k_h) was estimated as follows (Kulhawy and Mayne, 1990):

$$k_h = \frac{\gamma_w \ c_h}{D} \tag{2}$$

$$D = 8.25(q_T - \sigma_{vo}) \tag{3}$$

where, γ_w is the water unit weight, q_T is the corrected cone tip resistance, and σ_{vo} is the total vertical stress. Table 6 summarizes estimated k_h values, which average 7.3E-5 cm/s with a COV of 1.37. The range of estimated k_h indicates that the FCR behaves similar to very fine sands, silts and mixtures of sand, silt and clay (Holtz and Kovacs, 1981).

Falling head and rising head slug tests were performed at piezometer locations to estimate the permeability of the CCR material at coal refuse disposal facilities in western Pennsylvania. An electronic pressure transducer was utilized to measure water level changes during the duration of the tests. Prior to the tests, the pressure transducer was submerged in the water of the piezometer to allow the transducer to stabilize to ambient pressure and temperature. Upon the completion of each test, the water level in the piezometer was measured using a water level probe to confirm the pressure transducer readings. The CCR horizontal permeability (k_h) averaged 3E-5 cm/s with a STDEV and a COV equal to 2.7E-5 and 0.9, respectively.

5 SHEAR STRENGTH PARAMETERS

The shear strength of FCR was estimated using laboratory and in-situ tests. Drained shear strength parameters were determined using consolidated isotropic undrained compression (CIUC) triaxial tests with pore pressure measurements and consolidated isotropic drained compression (CIDC) triaxial tests. Shelby tube FCR samples were collected from underneath the upstream stages of the dam or working platforms built over the FCR in the impoundment. The test results are summarized in Table 7, including: drained angle of internal friction (ϕ'), drained cohesive strength (c'), and ϕ' by forcing the regressed shear envelope to go through the origin (c' = 0). The average ϕ' is equal to 33 degrees and the average ϕ' (c' = 0) is equal to 35 degrees. Table 7 indicates that the variability of ϕ' is low to moderate, but that of c' is relatively high. The above shear strength parameters are peak values, which were found to decrease by increasing the fines contents (passing #200), as shown on Figure 6. The residual shear strength values at large strains are typically used in the design and vary based on the percentage of fines.

The undrained shear strength of FCR was determined using cone data as follows (Lunne et al., 1997):

$$c_u = \frac{q_t - \sigma_{vo}}{N_K} \qquad (4)$$

in which, q_t is the corrected cone tip resistance and N_k is the cone bearing factor, which was taken equal to 15. Figure 7 shows the average c_u from seven cone tests performed in western Pennsylvania and indicates that c_u decreases with depth. The average c_u value is equal to 88 kPa with a COV of 0.42.

The field vane shear test (FVST) is most applicable in soft to medium clays; and therefore, must be used prudently in FCR, recognizing that FCR is often comprised of variable mixtures of sand, silt, and clay. Remolded strengths from the FVST, with consideration of other data, can be helpful in determining representative properties for use in deformation analyses, when such analyses are warranted.

Table 7. Summary of FCR shear strength parameters based on CIUC and CIDC triaxial test results.

Parameter	Average	Standard deviation	Coefficient of variation
ϕ'	33 (degrees)	4	0.12
c'	11 (kPa)	14	1.30
ϕ' (c' = 0)	35 (degrees)	4	0.11

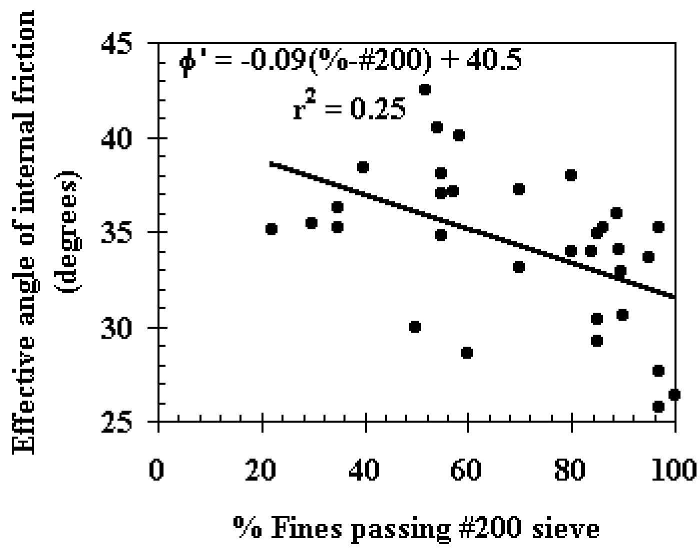

Figure 7. Effective angle of internal friction of FCR decreases with increasing % fines.

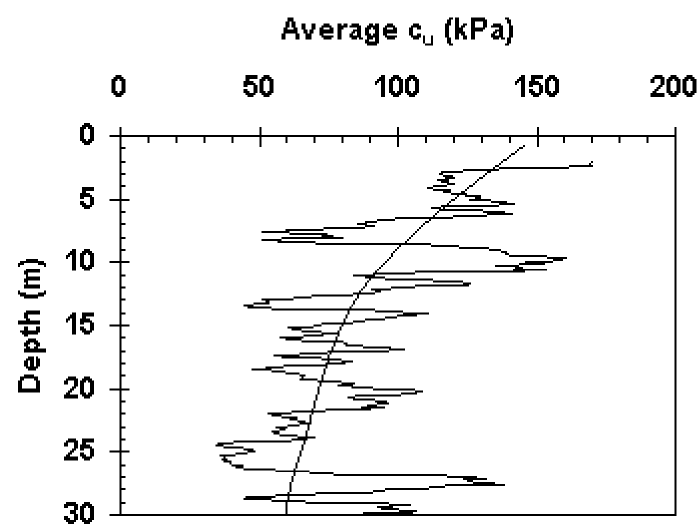

Figure 7. Average undrained shear strength of FCR with depth based on cone data at sites in western PA.

The shear strength parameters of CCR were estimated using CIUC and CIDC triaxial test data and standard penetration test (SPT) results, and are summarized in Table 8. The laboratory tests were performed using remolded CCR samples. The ϕ' values were estimated from SPT data according to Peck, et al. (1974). The average c' and ϕ' values, based on laboratory tests, are equal to 13 kPa and 34 degrees, respectively. The average ϕ' value ($c' = 0$), based on laboratory tests and the SPT number of blows for 305 mm penetration (N), is approximately equal to 37 degrees. The shear strength parameters of CCR have low to moderate variability as indicated by the COV values in Table 8.

The estimated ϕ' of CCR was greater when the measured SPT N was adjusted to $(N_1)_{60}$, which is the blow count normalized to an overburden pressure of approximately 100 kPa and a hammer energy ratio or hammer efficiency of 60%, as shown on Figure 8. The $(N_1)_{60}$ was determined according to Youd, et al. (2001):

$$(N_1)_{60} = N_m (P_a / \sigma_{vo}')^{0.5} C_E C_B C_R C_S \qquad (6)$$

where, N_m is the measured standard penetration resistance, P_a is atmospheric pressure and approximately equal to 100 kPa, σ_{vo}' is the vertical effective stress, C_E is the correction for hammer energy ratio, C_B is the correction for borehole diameter, C_R is the correction for rod length and C_S is the correction for samples with or without liners. Also, ϕ' of coal refuse (FCR and CCR) was lower at higher effective confining stresses in the CIUC and CIDC triaxial tests, as shown on Figure 9.

6 DATA RELIABILITY

The variability of each coal refuse parameter was expressed using the COV. The engineer may simply evaluate the reliability of the design using the AVG and COV of the coal refuse properties significantly affect the design. For example, performing a downstream slope stability analysis of the dam is primarily a function of the CCR shear strength parameters. Table 8 indicates that the AVG, STDEV, and COV of ϕ' (based on laboratory test results and ignoring c') are equal to 37 degrees, 2.6 and 0.072, respectively. Assuming that ϕ' follows a standardized normal distribution and the most probable range of ϕ' is between ± 2 STDEV, the probability (pr) that ϕ' is less than (min-ϕ' = 33.4 degrees) is determined as follows:

$$pr(\phi' < \min - \phi') = 1 - pr\left(Z = \left|\frac{33.4-37.0}{2.6}\right|\right) = 8\% \qquad (11)$$

where, Z is the standardized normal distribution value. As another example, assume that the upstream slope stability analysis of the dam is mostly affected by the FCR c_u. The AVG and COV of c_u (estimated using cone data) are 88 kPa and 0.42, respectively. Assume that the potential critical slip surface is only affected by c_u values in the upper 10 meters of the impoundment FCR, with a minimum value of 51 kPa as shown on Figure 7. The probability (pr) that c_u is less than min-c_u is determined as follows:

$$pr(c_u < \min - c_u) = 1 - pr\left(Z = \left|\frac{51-88}{37}\right|\right) = 16\% \qquad (12)$$

Table 8. Summary of CCR shear strength parameters based on CIUC and CIDC triaxial test and SPT test results.

Parameter	Average	Standard deviation	Coefficient of variation
ϕ'	34 (degrees)	3	0.09
c'	13 (kPa)	12	0.92
ϕ' ($c' = 0$)	37 (degrees)	3	0.08
ϕ' (SPT)	37 (degrees)	4	0.11

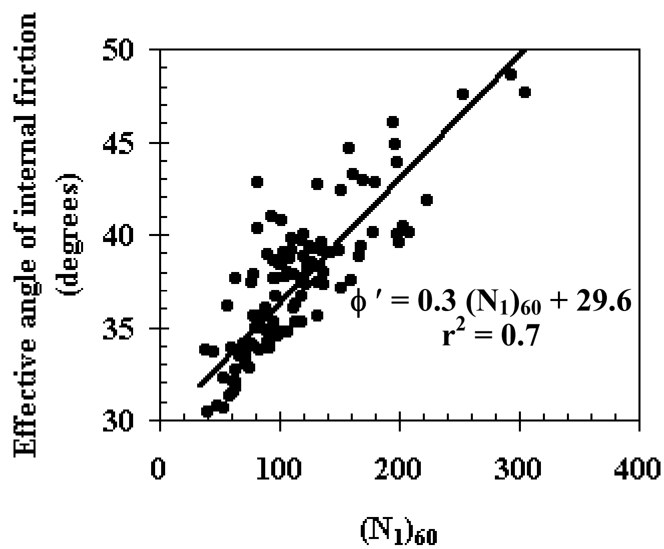

Figure 8. Correlation between angle of internal friction of CCR and normalized SPT data.

In the above example, the AVG and COV of the c_u population were assumed similar to those of the c_u values in the upper 10 meters.

7 CONCLUSIONS

This paper summarizes the state-of-practice in the geotechnical design of slurry impounding, coal refuse disposal dams. The proper characterization of the FCR and CCR properties is essential to arrive at an acceptable and reasonable design for a coal refuse slurry impoundment facility. A database of FCR and CCR properties was formulated from different sites in the United Sates and UK. The database included index, hydraulic, and strength properties of FCR and CCR which were measured using laboratory and in-

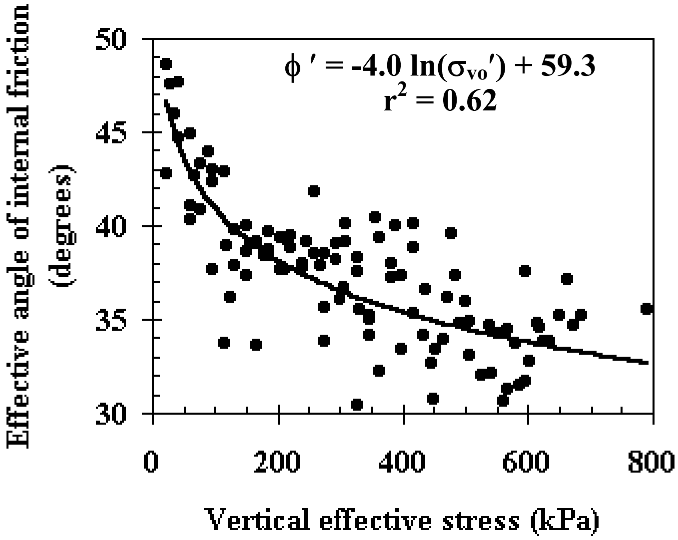

Figure 9. The angle of internal friction of coal refuse material decreases by increasing the confining effective stress.

situ tests. The variability of each material property was evaluated as a function of the data coefficient of variation (COV). A simple first order statistical method was used to determine the reliability of using the average (AVG) material properties for different geotechnical design aspects (e.g., upstream and downstream slope stability of a CCR dam).

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