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Permeability and Related Properties of Coal Refuse

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Perpetual treatment of acid water from coal waste dumps or from embankments constructed with coal refuse may be uneconomical. The only practical and economical method available for controlling this pollution problem appears to be the isolation of acid-generating ingredients such as pyrite from the other reagents, oxygen and water. Accordingly, controlling the permeability and air content of mine waste has become one of the most important measures in achieving this purpose. This paper focuses on the permeability of coal refuse. Data from both foreign and domestic sources were used to determine the relationship between the permeability found in the laboratory and the various index properties and to assess the effect of the reduction in void ratio caused by compaction, or other means, on the permeability of coal refuse. Traditional relationships between permeability and void ratio of soils were examined for coal refuse. Better regression models between permeability and other properties for both coarse and fine refuse were developed by using stepwise regression analysis. Some established relationships for soils were found to be unsuitable for coal refuse. Good models were developed for both coarse and fine refuse, despite the fact that the data obtained for the analyses were widely scattered in range.

Increased coal production, since the energy crisis, has generated more coal refuse, which in turn creates many environmental problems and sometimes tragic events (2, 3). Large-scale utilization of coal waste material in engineering construction and properly planned economical transformation of disposal areas into reclaimed land are believed to be the most effective measures to ameliorate the coal waste disposal problem.

In addition to the conventional engineering aspects of earthwork design, the following special considerations in using coal mine waste as a construction material should be observed: degradation, combustion, and pollution. Degradation and combustion problems have been discussed by Elnaggar, Chen, and Bullen (4, 5). The pollution problem is greatly affected by permeability. Consequently this paper focuses on the permeability of coal refuse by (a) determining the relationship between the permeability found in the laboratory and various index properties and (b) by assessing the effect of the reduction in void ratio, caused by compaction or other means, on the permeability of coarse and fine coal refuse.

NOTATION

The following notation is used in this paper:

- C.I. = confidence interval,
- R^2 = coefficient of determination of sample,
- $\bar{R}^2$ = coefficient of determination corrected for degree of freedom,
- s = standard deviation of sample,
- S_{yx} = standard error of estimate,
- t = t-statistic assuming null hypothesis is true,
- K = number of regressors,
- k = permeability,
- e = void ratio,
- F = fine fraction,
- D_{50} = average size, and
- D_{10} = effective size.

SOURCES OF DATA

A total of 57 sets of laboratory permeability results with void ratios and gradation curves were obtained from four different sources for coarse refuse (6, 7, 8, 9). Thirty-eight sets of laboratory permeability results with void ratios and gradation curves for fine refuse were also obtained from two different sources (9, 10).

ANALYSIS AND DISCUSSION

As a first step toward determining the effect of void ratio on permeability, the straight-line relationships between k and e^2 and between log k and e (11, 12, 13) were examined for both coarse and fine refuse. For coarse refuse, the linear relationship was found to have an $R^2 = 0.023$ for k versus e^2 and an $R^2 = 0.068$ for log k versus e, indicating that these two models lack explanatory power. Other statistics of these analyses further support this conclusion. As for fine refuse, a similar analysis for both models showed even poorer results. The equations obtained from regression analyses suggest two intuitively incorrect models; i.e., k decreases as e increases. Consequently, those models suggested in the literature for soils do not apply to coal refuse, particularly fine refuse.

Considering prior knowledge from soil mechanics regarding the influence of void ratio and grain size on permeability (11, 12, 13, 14), the variables used in establishing regression models for k versus void ratio and various grain sizes for mill tailings (15), and study conducted on tailing sands (16), we decided that the void ratio, average size, fine fraction, and their various products would be used as independent variables in regression analyses for coarse refuse. Subsequently, simple regression analyses were performed by using $\ln(k)$ as the dependent variable and $\ln(eD_{50})$, $\ln(e/F)$, $\ln(F)$, $\ln(e)$, $\ln(D_{50})$, and $\ln(e^2D_{50})$ as independent variables.

The results of those simple regression analyses revealed that the model with $\ln(e^2D_{50})$ as an independent variable was the best model among those six tested, as indicated by the highest t and R^2 and the lowest S_{yx}. Further analyses using step-wise multiple regression were performed. The models that showed the independent variables to be collinear were discarded, and these analyses revealed a "best" regression model with two independent variables, ln(e) and $\ln(D_{50})$. This best model confirms that the previous model having one independent variable of $\ln(e^2D_{50})$ is a very good one. A third model of these two independent variables, e and D_{50}, when expressed in nonlinear form, is

Figure 1. Calculated versus measured permeability for coarse refuse.

$\ln(k) = 6.180 + 3.257 \ln(e) + 1.594 \ln(D_{50})$
(or $k = 483e^{3.257} D_{50}^{1.594}$)
$R^2 = 0.449$ $\bar{R}^2 = 0.429$
t = 4.200 for coef. of ln(e) (95% C.I. = ± 1.551)
t = 5.855 for coef. of $\ln(D_{50})$ (95% C.I. = ± 0.545)
n = 57

$$Syx = \sqrt{\frac{\Sigma(Y_i - \hat{Y}_i)^2}{n-K-1}} = 2.481\ (s = 3.254)$$

(K = 2)

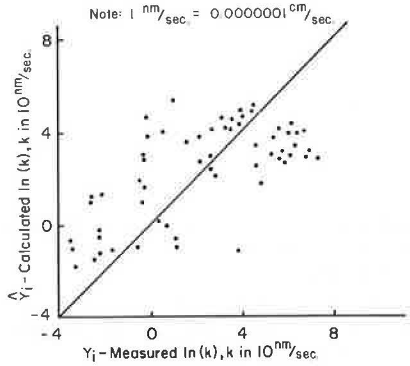
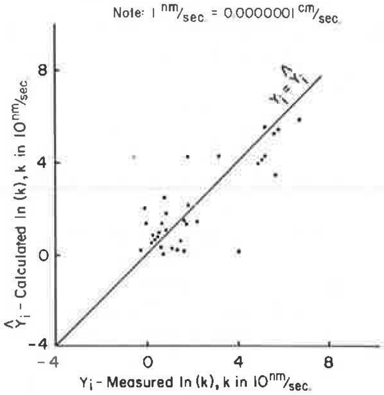


Figure 2. Calculated versus measured permeability for fine refuse.

$\ln(k) = 7.617 + 3.486 \ln(e) + 1.235 \ln(D_{50})$
(or $k = 2033e^{3.486} D_{50}^{1.235}$)
$R^2 = 0.695$ $\bar{R}^2 = 0.678$
t = 3.266 for coef. of ln(e) (95% C.I. = ± 2.169)
t = 8.860 for coef. of $\ln(D_{50})$ (95% C.I. = ± 0.283)
n = 38

$$Syx = \sqrt{\frac{\Sigma(Y_i - \hat{Y}_i)^2}{n-K-1}} = 1.248\ (s = 2.167)$$

(K = 2)



$$k = 483\ e^{3.257} D_{50}^{1.594} \tag{1}$$

This third model is shown in Figure 1, which also shows the comparison between calculated and measured ln(k). For coarse refuse, the model given by Equation 1 is the best model obtained in this study. Although the R^2 is 0.449 and the $\bar{R}^2$ is 0.429, it is a good model considering the wide variability and scatter in the permeability results (range = 0.31 to 16 000 Nm/s, average = 1837 Nm/s, and standard deviation = 3275.1 Nm/s) obtained from four different sources in two different countries.

Regression analyses were also performed for 38 sets of fine refuse data. A procedure similar to that used for coarse refuse was followed to select variables and models in performing the regression analyses. In addition to the parameters, e, D_{50}, and F, D_{10} (the effective size or the size at which 10 percent is finer) was also used (D_{10} was not used in analyzing the coarse refuse because of insufficient data).

A total of eight independent variables, $\ln(eD_{50})$, $\ln(e/F)$, ln(F), $\ln(eD_{10})$, $\ln(D_{10})$, ln(e), $\ln(D_{50})$, and $\ln(e^2D_{50})$, were regressed on ln(k) individually. Among those eight bivariate regression models, the results indicate that the best model is the one with $\ln(eD_{10})$ as the independent variable. It has the highest t and R^2 and the lowest S_{yx}. The regression equation is

$$\ln(k) = 8.709 + 1.033\ln(eD_{10}) \tag{2}$$

or

$$k = 6057(eD_{10})^{1.033} \tag{3}$$

To find a better regression model, multiple regression analyses using the step-wise method were performed. When the models whose independent variables are collinear are discarded, the model with two independent variables of ln(e) and $\ln(eD_{50})$ is considered to be the best for fine refuse. The regression equation of the best model for fine refuse, therefore, is

$$\ln(k) = 7.617 + 3.486\ln(e) + 1.235\ln(D_{50}) \tag{4}$$

This model is shown in Figure 2, which also displays the comparison between the calculated and measured ln(k). This model is considered to be a good one, given that the permeability results (range = 3 to 8860 Nm/s, average = 634.06 Nm/s, and standard deviation = 1601.52 Nm/s) obtained and used in the analysis are quite scattered.

The model for predicting the permeability of mill tailings as developed by Bates and Wayment (15) was not pursued in this study because of apparent structural problems and the resulting multicollinearities that developed when the refuse data were analyzed. Besides, Bates and Wayment's model deals only with the mill tailings, which are cohesionless, free of clays and micas, and have a well-defined grain size distribution.

The results of the following analyses, for both coarse and fine refuse, strongly indicate that of all those index properties selected and used in the regression analyses the void ratio appears to be the most important. This is clearly shown in Figure 1 for coarse refuse and in Figure 2 for fine refuse.

The results of multiple regression analyses also indicate that the coefficients of determination are generally higher for fine refuse than for coarse refuse. This might be attributed to the fact that the data for coarse refuse were obtained from four different sources including the data from England, whereas the data for fine refuse were obtained only from two different sources, both of which represent Appalachian coal refuse. Because of this, the stochastic errors were smaller for the fine refuse than for the coarse refuse and thereby increased the coefficient of determination in the regression analysis.

Certain assumptions were made for the analyses in which inferences were made for the parent populations from which samples were drawn. These assumptions are mainly the independence and normality of data. Because of the methods and procedures used in developing and obtaining data, and the fact that each sample was obtained from an infinite population, the probabilistic sampling procedure was assured. Accordingly, the most important assumption, the independence of the random variables, is considered to be valid. The normality assumption is met because of the sample size, the use of t-distribution, and the transformation of variables. Visual inspection of the data distributions confirmed the normality assumptions.

CONCLUSIONS

The following conclusions can be drawn as a result of this study.

1. The laboratory permeability results obtained at almost full saturation and corrected to the constant temperature of 20°C show considerable scatter as can be seen from the following data:

Refuse	No.	Range (Nm)	Avg (Nm)	s (Nm)
Coarse	57	0.31 to 16 000	1837.0	3275.1
Fine	38	3 to 8860	634.1	1601.5

2. The approximate linear relationships between log k versus e and between k versus e^2, which are traditionally believed to be true for all soil types, cannot be reasonably established for coal refuse.

3. The best equations that can be used to describe the empirical relationships between the permeability and both void ratio and grain size are the multiple regression equations with both e and D_{50} as independent variables in accordance with the results of this study. This conclusion is true for both coarse and fine refuse.

4. Among all factors affecting permeability, void ratio is the most important. This suggests that the reduction in void ratio, particularly by compaction, can substantially reduce the permeability of the material in accordance with the statistical relations developed in this study.

5. Within the ranges of various material properties given below, the equations developed in this study can be used to describe and assess the permeability from various index properties.

Property	Coarse Refuse	Fine Refuse
Permeability, Nm	0.31 to 16 000	3 to 8860
Void ratio	0.202 to 1.14	0.495 to 1.256
Average size, mm	0.14 to 7.0	0.0022 to 0.4
Effective size, mm	—	0.000 23 to 0.088
Fine fraction	0.03 to 0.46	0.10 to 0.97

All refuse data used in this study came from Appalachian bituminous coal refuse, except coarse refuse data from the South Yorkshire Main Colliery of the Yorkshire bituminous coal refuse in England. This should also be considered as a limitation on the conclusions of this study.

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**Mr. Elnaggar was on the faculty of the University of Pittsburgh when this research was done.*

Soil Stresses and Displacements in a Concrete Pipe Trench Installation

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The field performance of a full-scale reinforced concrete pipe in a trench installation is described. Total normal stresses were measured by specially designed stress cells placed in the soil and at the soil-pipe interface. Relative displacements between the pipe wall and various discrete points in the soil immediately adjacent to the pipe were determined by means of settlement plates with stems extending through sleeves into the pipe. Stresses and relative displacements, as well as horizontal and vertical diameter changes, were monitored periodically as the height of cover above the pipe increased. In general, the experimental measurements are mutually consistent and compatible with previous experience and judgment; however, there are some differences between the experimental data and the results calculated from a plane strain, finite element model with appropriate soil parameters.

Described here is the field performance of a full-scale reinforced concrete pipe buried in a trench installation. Instrumentation was provided to measure the normal stresses at the soil-pipe interface and in the adjacent soil, the displacements in the soil above and below the pipe, and deformations of the pipe. Experimental measurements are shown to be mutually compatible and in qualitative agreement with intuitive expectations based on engineering judgment. Typical results at discrete points in the soil-pipe system are compared with values calculated by use of a plane strain, finite element model and soil parameters determined, insofar as possible, from uniaxial strain tests and triaxial compression tests on the actual disturbed and undisturbed soils from the field installation.

FIELD EXPERIMENT

The test site, which is shown in Figure 1, is located in East Liberty, Ohio, about 64 km (40 miles) northwest of Columbus, on the grounds of the Transportation Research Center of Ohio. A 1.5-m (60-in) inside diameter, 2300 D, B-wall concrete pipe (manufactured by the wet cast method) was installed in a trench with a cover of 7.6 m (25 ft). The required strength of the pipe was determined by means of the Marston-Spangler theory, and the pipe was installed in accordance with the specifications of the Ohio Department of Transportation. The pipe size selected is the result of a compromise between the smallest pipe that allowed reasonable access of personnel and instruments and the largest pipe that could be used with the available cover height, which was dictated by topography and economics. As shown in Figure 2, the installation consists of five 2.4-m (8-ft) lengths of instrumented pipe (the middle one of which is most heavily instrumented), several buffer sections at either end, and a vertical access shaft.

Prior to the manufacture of these pipe sections, an instrumented pipe was tested to ultimate load in a three-edge bearing test to ascertain (a) that the inclusion of internal instrumentation (with the associated holes and inserts) in the pipe cross section would not measurably reduce the strength of the section, (b) that the techniques for applying the instrumentation within the walls of the pipe were adequate to protect the instrumentation during casting, and (c) that measured results (when interpreted within the context of a theoretical model of the pipe only) realistically represent the actual values. Since the results of this test were favorable, the pipe sections for the field installation were manufactured in a similar manner.

The installation of the test pipe was undertaken in June 1971 and was completed within a period of 9 d. As indicated in the boring log shown in Figure 3, two distinct soils were encountered during excavation. To a depth of approximately 3.7 m (12 ft) there was a coarse to very fine sand with stone fragments and some silt, and from 3.7 m (12 ft) to about 9.1 m (30 ft) there was a dark gray clayey silt; at a point about 9.1 to 10.7 m (30 to 35 ft) below the surface a very granular layer and considerable water were encountered. The soil increased in silt content with depth from 10.7 to 12.8 m (35 to 42 ft), at which point the boring was terminated. The pipe was bedded at a level about 9.4 m (31 ft) below the surface. As a consequence of the unstable nature of the top 4.5 to 6.0 m (15 to 20 ft), the trench was excavated with somewhat unsymmetrical, sloped sides with an approximate 1:1 ratio on one side and about 0.7:1 on the other as shown in Figure 2b; the width of the trench varied from about 3.0 to 3.7 m (10 to 12 ft); the greater width was near the vertical access shaft. Some photographs of the test installation are shown in Figure 4.

Although the laying of the pipe was done basically in accordance with practices recommended by the state of Ohio, a few points are worthy of note. First, the 15 cm (6 in) of compacted granular material at the bottom of the trench was not shaped to fit the contour of the pipe; hence, the pipe had essentially line support along the