Research Report
UKTRP-82-20

ENGINEERING PROPERTIES OF KENTUCKY OIL SHALES

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October 1982

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Abstract

Excavation, handling, and the environmentally safe disposal of spent oil shale and overburden materials require a knowledge of their geotechnical engineering properties. To determine these properties, a laboratory investigation of the physical and geotechnical engineering properties was made. The physical tests consisted of mechanical analyses, Atterberg Limits, and specific gravity determinations. Geotechnical properties were determined by moisture-density analyses, triaxial compression, permeability tests, slake-durability, one-dimensional compression tests, and Los Angeles abrasion. A one-dimensional compression test was devised to address the problem of placement, loading, and saturation of the spent shales and overburden materials. The compacted, unprocessed oil shales were more susceptible to inundation and compression than compacted specimens of retorted shales and chars. Comparisons of the geotechnical properties of the unprocessed oil shales and processed shales are made.

INTRODUCTION

The current energy shortage and a diminishing supply of petroleum have prompted efforts to search for alternate sources of energy. Serious attention has recently focused on the commercial development of oil shales because of a large abundance of these materials and their proximity to markets. Processsing of raw oil shale by heating to recover petroleum products involves the use of surface retorts and/or in situ retorting. Regardless of the technique used, sizeable volumes of retorted, or spent shales will be produced and require disposal. Generally, the oil shales are overlain by materials which do not contain oil and must be removed to recover the oil shales. The excavation, handling and environmentally and structurally safe disposal of the spent oil shales and overburden materials will require a knowledge of their geotechnical properties. This paper is a condensed version of a report (1) submitted in November 1981. For additional details, especially the application of these findings to slope design and settlement, the reader is referred to the report.

OBJECTIVES

The primary objective of this study was to characterize the various geotechnical properties of overburden materials, raw oil shales and processed, or spent shales. This information is needed in the commercial development of oil shale for developing environmental regulations, and providing for a means of safely disposing of the overburden and spent shales.

DESCRIPTION OF MATERIALS

Materials received for laboratory testing consisted of two basic categories: overburden materials and oil shales. The second category of materials consisted of the raw, or unprocessed oil shales, the retorted oil shales, the charred oil shales and the combusted oil shales. Brief descriptions of the materials submitted for testing are as follows:

OVERBURDEN MATERIALS

Overburden materials consisted of three shales and a siltstone. Two overburden shales were collected from the Borden and the Bedford formations of Lewis County, Kentucky. The siltstone sample was obtained from the Farmers Member of the Borden Formation in Lewis County, Kentucky. The third overburden shale was obtained from the New Providence Member in Bullitt County, Kentucky. The shale samples obtained from the Borden and Bedford formations consisted of flat light yellow, subangular particles. The siltstone was light olive gray in color, hard, and fine-grained. The New Providence Shale was gray to light yellow in color, very friable, platy and angular.

UNPROCESSED OIL SHALES

Seven oil shale samples submitted for testing were collected from the Sunbury, New Albany, Chattanooga, and the Ohio shale formations. The stratigraphy and composition of these shales are similar. In Ohio, and in Kentucky from Lewis County southwest to the vicinity of Irvine, a wedge of Bedford Shale and Berea Sandstone occurs between the underlying (Ohio) and overlying (Sunbury) black shales. The Ohio Shale has been subdivided into upper (Cleveland) and lower (Huron) members. Beyond the pinchout of the wedge of Bedford sediment the entire black shale interval (equivalent to the Ohio and Sunbury) is referred to as the New Albany Shale. This nomenclature is carried westward through Kentucky and into Indiana and Illinois. To the south, the black shale interval thins considerably and is referred to as the Chattanooga Shale. This nomenclature is used throughout southern Kentucky and Tennessee. Samples of the New Albany Shale were collected from Nelson, Powell, Lincoln, and Bullitt counties, Kentucky. The Sunbury and Ohio samples were obtained from Lewis County, Kentucky. Samples of the Chattanooga Shale were obtained from Russell County, Kentucky. Particle-shapes of the raw oil shales and the overburden shales were similar. However, the raw oil shales were harder and contained less fines than the overburden shales. The raw oil shales ranged in color from dark yellow to gray and were darker than the overburden shales.

RETORTED SHALES

Six retorted samples were tested. Materials collected for the retorting process were obtained from the Sunbury, New Albany, Cleveland, and Chattanooga shale formations. The New Albany samples were collected from Nelson, Bullitt, and Powell counties, Kentucky. Samples of the Cleveland and Sunbury shales were obtained from Lewis County, Kentucky. The Chattanooga shale samples were obtained from Lincoln County, Kentucky. The double auger steam retorting process was used. Maximum particle-sizes of the retorted shales were smaller and individual particles were less angular than the raw oil shales or the overburden shales. The retorted shales contained little or no fines and were gray to black in color.

CHARRED SHALES

The next group of shales tested were the charred shales produced by the HYTORT process. Materials obtained for the charring process were obtained from the Sunbury, Cleveland, and New Albany Shale formations. Samples of the Sunbury and Cleveland shales were collected from Lewis County, Kentucky. The New Albany samples were obtained from Bullitt County, Kentucky. This group consisted of three shales which appeared to be identical. These materials were composed of much smaller particle sizes and contained fewer fines than the retorted shales. The charred shales were black in color and had an appearance similar to coal.

COMBUSTED SHALES

The last group of shales submitted for testing was the combusted shales and consisted of six materials. These materials were obtained from the Sunbury, Cleveland, New Albany, and Chattanooga shale formations, retorted, and then subsequently combusted. Samples of the Sunbury and Cleveland shales were obtained from Lewis County, Kentucky. Samples of the New Albany shale were obtained from Bullitt, Lincoln, and Powell counties, Kentucky while samples of the Chattanooga shale were collected from Russell County, Kentucky. These were processed in a gasifier with a 5% - 10% excess of oxygen. The combusted group of shales was hard and contained red, black and light gray, sub-angular particles.

TEST SPECIFICATIONS AND RESULTS

The testing program was divided into three categories: 1) material preparation, 2) classification, or physical property tests, and 3) engineering tests. Physical property tests consisted of particle size analyses, liquid and plastic limits, and specific gravity determinations. Engineering tests consisted of moisture content-density determinations, consolidation, permeability, triaxial compression, Los Angeles abrasion, a specially devised, one-dimensional compression test, and slake-durability. Test methods and results are described below.

MATERIAL PREPARATION

Particle sizes of the materials as received for laboratory testing ranged from cobbles, 3 inches in diameter, to fine-grained material passing the No. 200 sieve. The largest particle size that could be accommodated by the 4-inch diameter mold of the triaxial, permeability, and compaction tests was 3/4-inch. For this reason, after removing sufficient material for classification testing, the particle sizes of samples which had particles greater than 3/4-inch were reduced by the scheme outlined in Drnevich, et. al. (2). This procedure maintains the same percentages of gravel in the sample, as contained in the original sample and as received for testing.

PHYSICAL PROPERTY TESTS AND CLASSIFICATIONS

Liquid and plastic limit tests were performed on the shales and overburdens according to ASTM D 423-66 and ASTM D 424-59. The specific gravities of the soil solids were determined according to ASTM D 854-58. Particle-size analysis was determined according to ASTM D 422-63. Particle-size distribution curves for the overburden shales and the raw oil shales are given in Figure 1. The retorted shales and the charred shales are shown in Figure 2. The materials were classified according to both the AASHTO and Unified Soil Classification systems. Specific gravities, liquid limits, plasticity indices, and classifications are summarized in Table 1.

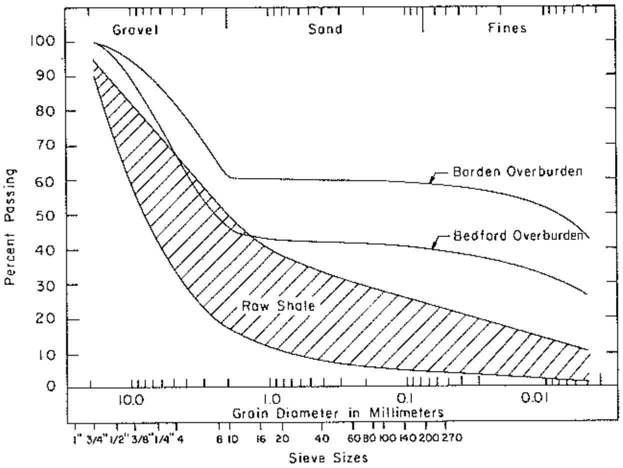

Figure 1. Particle Size Distribution Curves for Overburden Materials and Raw Shale.

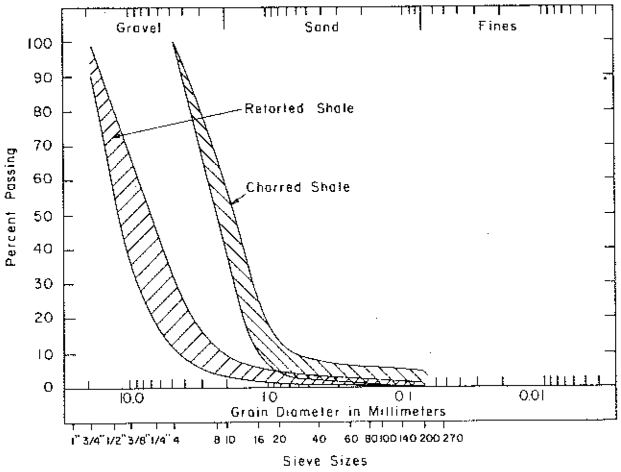

Figure 2. Particle Size Distribution Curves for Retorted Shales and Charred Shales.

ENGINEERING TESTS

Moisture - Density Relationships

Standard compaction tests were performed on the Borden and Bedford overburden shales using two different gradations. One moisture-density curve was developed for the portion of the overburden shales passing the No. 10 sieve. This compaction test was performed on this portion of the sample, instead of the portion passing the No. 4 sieve according to ASTM D 698-70 method A, because particle sizes of the materials as received for testing could not be accommodated in a 2.5-inch consolidometer ring and values of maximum dry density and optimum moisture content were needed for compacting the consolidation specimens. The second set of standard compaction tests were performed on the overburden shales to obtain values of maximum dry density and optimum moisture content which were needed for preparing triaxial specimens. These tests were performed using material that passed the No. 3/4-inch sieve. Because of the limited amount of material available, and because the overburden shales were so friable that each compaction sample could only be used once,

Table 1. Results of Physical Properties tests and Engineering Classifications.

MATERIAL	LIQUID LIMIT	PLASTICITY INDEX	SPECIFIC GRAVITY	CLASSIFICATION AASHTO	UNIFIED	C_u*	C_c**
OVERBURDEN							
Borden (Lewis)	43	17	2.75	A-7-6(8)	CL	-	-
Bedford (Lewis)	37	16	2.68	A-6(6)	SC	-	-
RAW SHALES							
New Albany (Powell)		NP	2.39	A-1- b	GM	15	3.0
New Albany (Bullitt)		NP	2.41	A-1- b	GM	12	2.7
Sunbury (Lewis)	28	3	2.47	A-1- b	GM	680	3.7
Ohio (Lewis)	35	9	2.37	A-1- b	GM	50	2.3
Raw Blend			2.43				
RETORTED SHALES							
Cleveland (Lewis)		NP		A-1- a	GP	3.9	1.2
Chattanooga (Lincoln)		NP		A-1-a	GP	3.3	1.1
New Albany (Nelson)		NP		A-1- a	GP	3.1	1.5
New Albany (Bullitt)		NP		A-1- a	GW	4.0	1.4
New Albany (Powell)		NP		A-1-a	GP	3.2	1.3
Sunbury (Lewis)		NP		A-1-a	GW	4.3	1.2
Retorted Blend			2.54				
CHARRED SHALES							
New Albany (Bullitt)		NP		A-1- b	GP	3.3	1.2
Sunbury (Lewis)		NP		A-1-a	GP	3.0	0.9
Cleveland (Lewis)		NP		A-1-a	GP	2.8	0.6
Charred Blend			2.51				
COMBUSTED SHALES							
Sunbury (Lewis)		NP	2.36	A-1-a	SW	8.4	1.2
Cleveland (Lewis)							
New Albany (Bullitt)							
New Albany (Lincoln)							
New Albany (Powell)							
Chattanooga (Russell)							

*C_u is the coefficient of uniformity
**C_c is the coefficient of concavity

a 4-inch diameter mold was used.

Results of the compaction tests performed on the overburden shales are shown in Figures 3 and 4. Values of maximum dry densities of the overburden shales were less for specimens prepared with material passing the No. 10 sieve than values obtained for specimens prepared using material passing the 3/4-inch sieve. The Borden shale, the overburden which appeared to have the lowest shear strength at standard compaction, was selected for more extensive testing in the triaxial testing phase of the program.

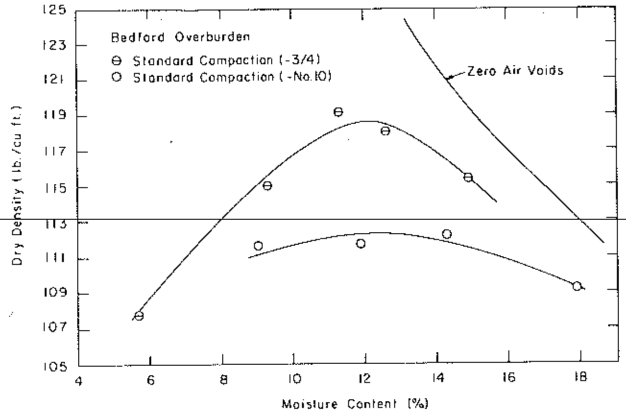

Figure 3. Moisture-Density Curves for Bedford Overburden Shale.

Two other compaction tests were performed on the Borden shale (Figure 4) using compactive energies which were lower and higher than the compactive energy of the standard compaction test. The high-energy compaction test was similar to ASTM 1557-78 method D (Modified Compaction) which uses a 10-pound hammer and an 18-inch drop, except a 4-inch mold was used instead of a 6-inch mold. The low-compactive energy was 20 percent of the compactive energy used in the standard method. This energy was obtained by using 1.84 pound aluminum hammer, 12 inch drop, and a reduced number of blows in a compaction procedure developed for use on mine spoils (2). Specifications of the different types of compaction tests are shown in Table 2.

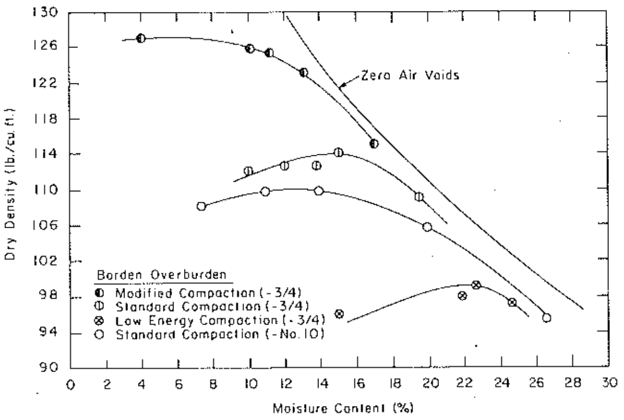

Figure 4. Moisture-Density Curves for Borden Overburden Shale.

Table 2. Compaction Specifications for Compaction and Triaxial Molds

Compaction Technique	Compactive Effort (ft. lb/ft^3)	AASHTO/ASTM Standard Mold (4.0" diameter x 4.584" high)	Triaxial Mold (4.0" diameter x 8.0" high)
Modified	56250		
10 lb hammer 1.5 ft drop		5 lifts 25 blows/lift	8 lifts 27 blows/lift
Standard	12730		
5.5 lb hammer 1.0 ft drop		3 lifts 25 blows/lift	5 lifts 25 blows/lift
Low Energy	2500		
1.84 lb hammer 1.0 ft drop		3 lifts 15 blows lift	5 lifts 16 blows/lift

Since a limited amount of material from each location and geological formation was available for testing and since the oil shales within each major shale group had essentially the same classification, portions of the oil shales within each major shale group were combined to form a blended shale sample. With the exception of the overburden materials, all engineering tests were performed on a blended sample of each major shale group -- the raw oil shale group, retorted group of shales and the charred group of shales.

The results of the compaction tests on the raw, retorted, and charred oil shale blends are shown in Figure 5. As shown in this figure the retorting process greatly influences the maximum dry density of the samples when compared to the raw shales. The retorting process significantly decreases the maximum dry density of the oil shales while only slightly lowering the optimum moisture content. The process of charring the shales, on the other hand, causes the optimum moisture content to rise considerably while the maximum dry density is also greatly decreased. Maximum dry densities and optimum moisture contents obtained from the various compaction tests for the overburden materials, the raw oil shale blends, retorted blends and charred blended shales are compared in Table 3.

Consolidation Tests on the Two Overburden Shales

Consolidation tests were performed on the portion of the overburden shales -- Borden and Bedford -- passing the No. 10 sieve. This part of the overburden materials was used because any particles larger than the No. 10 could not be accommodated by the testing apparatus, and a specimen composed of only material passing a smaller sieve would not give an accurate representation of the behavior of the material as found in the field.

ASTM standard D 2435-70 was used as the test procedure. The specimens were 1 inch in height by 2 1/2 inches in diameter and were compacted at optimum moisture to the standard maximum compaction density.

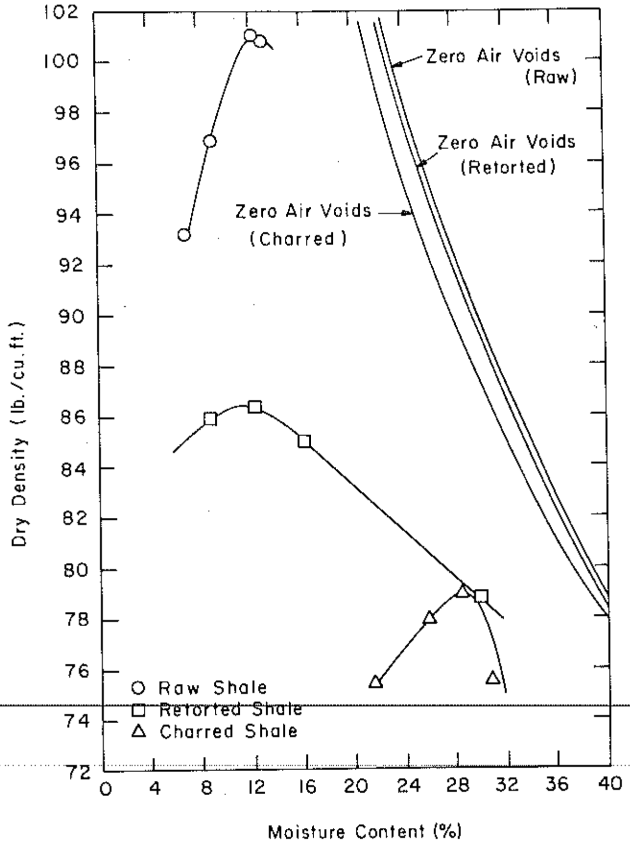

Figure 5. Moisture-Density Curves for the Raw Oil Shale Blended Samples, Retorted Blended Samples, and Charred Blended Samples.

Table 3. Comparison of Maximum Dry Densities and Optimum Moisture Contents Obtained from Compaction Tests Performed on Overburden Shales and Oil Shales.

Material	Size	Compactive Effort	Optimum Moisture Content (%)	Maximum Dry Density (lb/cu ft)
BORDEN	-10	standard	13.2	110.1
	-3/4	low	23.2	99.8
		standard	15.8	113.8
		modified	4.2	127.2
BEDFORD	-10	standard	12.1	112.2
	-3/4	standard	12.3	118.7
RAW BLEND	-3/4	standard	12.6	100.3
RETORTED BLEND	-3/4	standard	11.3	86.4
CHARRED BLEND	-3/4	standard	29.1	79.1

Void ratio-log of effective stress curves are shown in Figure 6 for the two overburden shales. The log-of-time and the square-root-of-time fitting methods were used to obtain the time corresponding to ninety per cent consolidation and to obtain the coefficient of consolidation, c_v. The average value of c_v obtained from the two fitting methods is also plotted as a function of the log of effective stress in Figure 6 for the two overburden shales.

Permeability

Permeability tests were performed on the overburden shales and on the oil shales, the raw oil shale blends, the retorted oil shale blends, and the charred oil shale blends. A constant head test used by the Army Corp of Engineers and outlined in their laboratory soils testing manual (3) was used. The procedure utilized a cylindrical specimen confined in a rubber membrane and subjected to an external hydrostatic pressure during the test. This was accomplished by placing the specimen in a triaxial cell where confining and back pressures were applied.

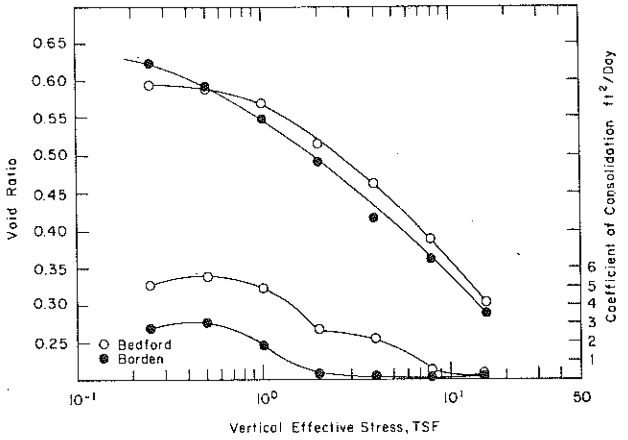

Figure 6. Void Ratio and Coefficient of Consolidation as a Function of Effective Log-of-Stress Obtained from The Consolidation Test on the Borden and Bedford Overburden Shales.

This method of performing the permeability test was selected because of the following reasons: (1) The specimen can be easily formed in the same manner as the triaxial specimens, using the same molds and membranes; (2) the leakage along the sides, which occurs especially in permeameters, is prevented by the cell pressure acting against the wall of the membrane; (3) the specimen can be consolidated to a certain confining stress representing field conditions; (4) back pressure can be applied to the pore water to dissolve air entrapped in the compacted specimens; (5) and the saturation of the specimen can be checked in the same manner as in the triaxial tests.

Results of the permeability tests are given in Table 4. Low permeabilities obtained for the overburden materials were due to the presence of large percentages of fines, i.e. soil particles smaller than the No. 200 sieve. It has long been established that the percentages of fines of a soil have a large effect on its permeability. The results reported herein should be used with caution since these values are ones that represent the soil compacted at the standard compaction density and tested in a saturated condition. The materials also contained particle sizes smaller than 3/4 of an inch. The permeability of the material at any other particle size distribution may be different.

Table 4. Summary of Permeability Results.

Material	As Compacted		As Tested		Permeability
	Dry Density (lb/cu ft)	M. C. (%)	Dry Density (lb/cu ft)	M.C. (%)	k (cm/sec)
BORDEN	113.0	15.2	124.8	16.6	2.9×10^{-8}
BEDFORD	118.6	10.8	120.5	16.3	4.6×10^{-8}
RAW BLEND	-	-	-	-	1.5×10^{-4}
RETORTED BLEND	82.9	15.6	85.4	28.4	1.0×10^{-4}
CHARRED BLEND	77.9	25.9	76.5	39.9	2.3×10^{-3}

Field values of permeability may be different than values given in Table 4 because of the degree of compaction and the percent of saturation. It has been shown that the higher the density of a soil, the lower the permeability; also, the permeability of saturated soil is greater than non-saturated soil. In addition to density and saturation, the water content at which the soil is compacted can also influence the value of the permeability of a soil. The water content of the soil influences its microstructure when compacted.

As the water content at the time of compaction increases, orientation of the particles become more parallel due to the compaction. This results in a reduced permeability for the soil.

Triaxial Compression Tests

Stability of a compacted shale embankment can be evaluated using either total stress parameters or effective stress parameters. Generally, effective stress parameters, ϕ', and c' -- the effective internal angle of friction and effective cohesion -- have more validity than total stress parameters, ϕ and c. Effective stress parameters can be obtained from drained triaxial tests or from undrained triaxial tests if pore pressure measurements are made. With the exception of two consolidated-drained triaxial tests, consolidated-undrained, triaxial compression tests with pore pressure measurements were used to obtain the effective stress parameters for the overburden shales and the oil shale blends. These tests were performed at a constant rate of axial deformation which was sufficiently small so that pore pressure equalization criteria were satisfied (4). The specimens were compressed at a constant rate of axial deformation of 0.001 inch per minute. The two consolidated-drained triaxial compression tests were performed on the retorted and charred blended samples using the same axial rate of deformation as used in the consolidated-undrained triaxial tests.

The triaxial specimens were compacted to maximum dry density at optimum moisture content determined from the compaction phase of the testing program for the portion of the material passing the 3/4-inch sieve. The specimens measured 4 inches in diameter and 8 inches in height. These dimensions limited the largest particle size to 3/4-inch. Filter paper strips were mounted along the length of each specimen to permit faster equilization of pore water pressure. To prevent air from entering the specimen through the rubber membrane when the cell pressure was applied, water was used in the chamber as the confining medium.

In performing consolidated-undrained triaxial tests with pore pressure measurements, it is essential that the specimens be saturated to avoid pore pressure lag during the shearing stage. To facilitate saturation and force air bubbles into solution, a back pressure technique similar to one described by Lowe and Johnson (5) was used. After saturation, the specimen was consolidated to the desired effective stress. For the overburden shales (clayey shales), the time for ninety percent of consolidation to occur was determined from the square-root-of-time fitting method and used to determine when the axial loading of the test could be initiated. When the consolidation pressure was applied to the oil shale specimens, consolidation occurred so rapidly that the volume changes were difficult to obtain as a function of time. To have reasonable assurances that the specimens were saturated, all were allowed to consolidate for a minimum of 24 hours under the desired back pressure and cell pressure.

Although several definitions of failure may be used to define the Mohr-Coulomb failure envelope, two criteria are commonly used in soils. These criteria are the maximum principal stress difference, or $(\sigma'_1 - \sigma'_3)_{max}$, and the maximum principal stress ratio, or $(\sigma'_1/\sigma'_3)_{max}$. The latter definition is also known as maximum obliquity. In a drained triaxial test, the two criteria yield the same results, since the minor effective principal stress, σ'_3, is constant and the peak values of $(\sigma'_1 - \sigma'_3)$ and (σ'_1/σ'_3) occur simultaneously during the shearing stage of the test. However, σ'_3 cannot be held constant during the undrained shearing stage when the specimen is fully saturated. For saturated and highly overconsolidated materials, σ'_3 changes during undrained shearing and the peak value of (σ'_1/σ'_3) may occur before the peak value of $(\sigma'_1 - \sigma'_3)$ is obtained. The choice of which failure criterion to use for compacted materials has been discussed by Drnevich, et al (2).

For triaxial test results reported herein, the maximum obliquity failure criterion was used to develope failure envelopes and shear strength estimates of the overburden and oil shales. Triaxial test results are summarized in Table 5. Values of ϕ' obtained for the Borden overburden shale remolded to three different compactive efforts ranged from 26.6 degrees to 30.2 degrees. Essentially the same values of ϕ' --26.6 degrees -- were obtained for the Borden shale specimens compacted at standard and low compactive energies. No cohesion was obtained for the Borden shale at any of the compactive energies. Specimens compacted at a high compactive energy had a ϕ'-value that was 3.6 degrees higher than ϕ'-values of specimens compacted at standard and low compactive energies.

Values of ϕ' and c' obtained for the Bedford overburden shale compacted at standard compaction were 26.3 degrees and 216 pounds per square foot. These values were similar to values obtained for the Borden specimens compacted at low and standard compactive energies.

Table 5. Summary of Triaxial Test Data.

Test No.	Material	Compaction	Effective Confining Pressure (psi)	'B' Pore Pressure Coeff.	ϕ' (Degree)	c' (psf)
51	Borden (Lewis)	standard	10	0.88	26.7	0.0
52			30	0.88		
511			45	0.90		
55	Borden (Lewis)	modified	70	0.90	30.2	0.0
56			50	0.95		
57			20	0.98		
58	Borden (Lewis)	low	70	0.97	26.6	0.0
59			50	0.98		
510			20	0.94		
51	Bedford (Lewis)	standard	60	1.00	26.3	216
52			30	1.00		
53			10	0.99		
51	Raw Blend	standard	20	1.00	42.2	317
52			56	0.93		
53			70	0.57		
51	Retorted Blend	standard	70	0.87	*	*
52			50	0.65		
53			20	0.83		
51	Charred Blend	standard	50	0.48	*	*
52			20	0.86		
55			30	1.05		

*A curved failure envelope was obtained for the retorted and charred shale blends. See Table 6.

Blended specimens of the raw oil shales remolded at standard compaction had a ϕ- value of 42.2 degrees and a c'- value 317 pounds per square foot.

Shear strengths of retorted and charred blended specimens remolded at standard compaction were very similar as illustrated in Figure 7. The two linear stress paths were obtained from the drained triaxial tests while the remaining stress paths were obtained from the undrained tests. A curved K_f-line was obtained for these series of tests and ϕ'- values ranged from 45 degrees to 22 degrees. (See next to last column in Table 6.)

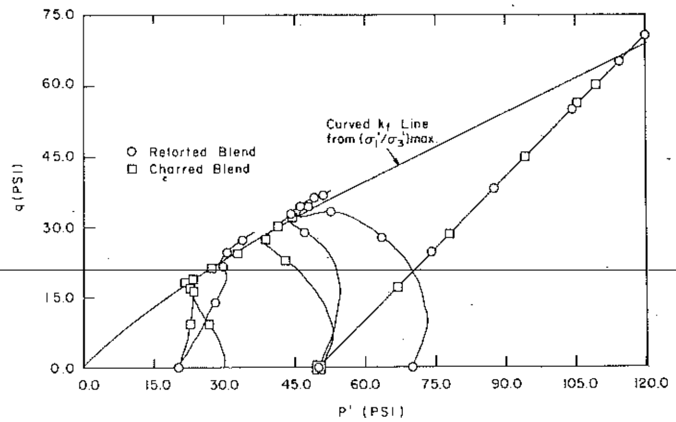

Figure 7. Triaxial p'-q Stress Paths Obtained from Retorted and Charred Blended Specimens Remolded at Standard Compaction.

Abrasion

The abrasion test on the Farmers Siltstone was performed in accordance with ASTM C 131-76, grading B. This test commonly called the Los Angeles Abrasion Test was only performed on the siltstone because the other shales appeared to be of much less hardness. Preparation of the material for testing consisted of breaking siltstone into roughly 3-inch pieces and then reducing it to particle sizes smaller than 3/4-inch using a mechanical crusher. The siltstone was then washed and dried to remove any dust adhering to the sides of the particles. The siltstone was sieved and combined to the required grading.

Table 6. Recommended Design Values of ϕ' for Various Pressures of Embankments Constructed of Charred and Retorted Materials.

p (psi)	q (psi)	$\sin\phi'$	σ_n (psi)	ϕ'_{curve} (Degrees)	$\phi'_{recommended}$ (Degrees)
10	9.2	0.71	3.5	45.2	36.0
20	16.2	0.68	9.0	42.8	36.0
30	22.8	0.65	15.2	40.5	35.0
40	29.2	0.62	21.9	38.3	34.0
50	35.2	0.59	29.2	36.2	33.0
60	41.0	0.56	37.1	34.0	32.0
70	46.4	0.53	45.4	32.0	31.0
80	51.6	0.50	54.2	30.0	30.0
90	56.4	0.47	63.5	28.0	29.0
100	61.0	0.44	73.2	26.1	28.0
110	65.2	0.41	83.3	24.2	27.0
120	69.2	0.38	93.7	22.3	26.0

The siltstone was then placed in the L. A. Abrasion machine with eleven steel balls. The number and weight of steel balls used depends on the gradiation of the material being tested. The machine was rotated at 33 revolutions per minute for 500 revolutions and then the material was removed. The siltstone was sieved again using the same sieve sizes as used before and subtracting the amount retained on each sieve from the original weight retained on each sieve to calculate the amount of wear. This amount divided by the original weight of the material gives the percentage of wear. The percentage of wear for the Farmers Siltstone was calculated to be 80.

One-Dimensional Compression Tests

One-dimensional compression tests were performed on blends of the unprocessed and processed oil shales. These tests were performed instead of consolidation tests because the oil shales had high permeabilities and excess pore water pressures would dissipate too quickly to give meaningful results. The test consisted of two different phases. The first phase of testing was designed to determine how the material in a dry state performed under one-dimensional loading. The purpose of the second phase was to evaluate creep characteristics of the oil shales when inundated with water.

The procedure for the first phase consisted of compacting the shales to ninety percent of maximum dry density in a 6-inch diameter mold to a height of 2.625 inches. These dimensions were used to minimize the effects of frictional forces acting on the sides of the mold during loading. To simulate field placement, the specimens were compacted in a dry state to ninety percent of maximum dry density. The specimens were loaded and deformations were recorded in a manner similar to the consolidation tests. Loads of 1, 2, 4, 8, and 16 tons per square foot were used. For each load, when the sample deformed less than .0025 inch in two minutes, the next load was applied. After loading to 16 tons per square foot, the samples were rebounded and the dial readings were recorded.

The strain for each load was calculated by dividing the deformation occurring under each load by the original height of the specimen. The stress-strain curves for the three oil shale blends and the Farmers Siltstone are given in Figure 8. A crushed limestone, considered a good construction material, was also tested for comparative purposes.

Creep characteristics of the oil shales were studied by reloading the previously loaded specimen to 4 tons per square foot. The specimen was allowed to compress for approximately fifteen minutes or until all deformation had stopped. The mold and specimen were inundated in water while the stress level remained constant at 4 tons per square foot. The time required to submerge the specimen was less than five seconds. Upon inundation, a timer was immediately started and deformations and elapsed times were recorded. Strains were calculated by dividing deformations associated with time after inundation by the original specimen height before loading. The strains after inundation were plotted as a function of the log of time as shown in Figure 9. After sufficient time had elapsed to show the creep characteristics of the material, (approximately 1,000 minuties) the sample was removed and dried. The samples were observed to be wet throughout when removed. A sieve analysis was performed before and after the test on each material to determine if any appreciable amount of crushing had occurred. Based on particle size curves of the materials obtained before and after testing, no noticeable crushing of the particles was observed. Any slight differences that occurred was attributed to normal variances associated with sampling. Two of the materials tested, siltstone and retorted blend, had low creep on the same order as limestone. The charred blend exhibited slightly greater creep. The raw oil shales exhibited significant creep upon inundation.

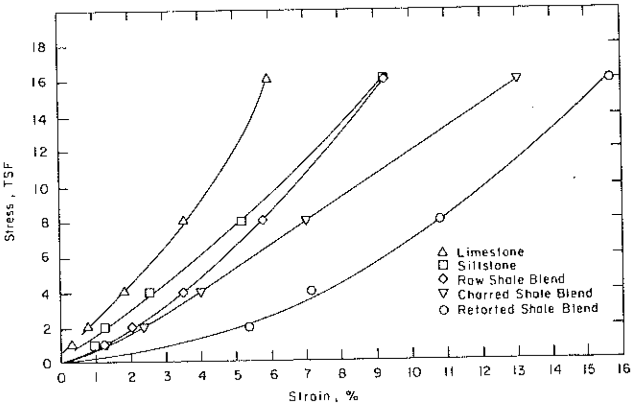

Figure 8. Stress-Strain Curves Obtained from One-Dimensional Compression Tests.

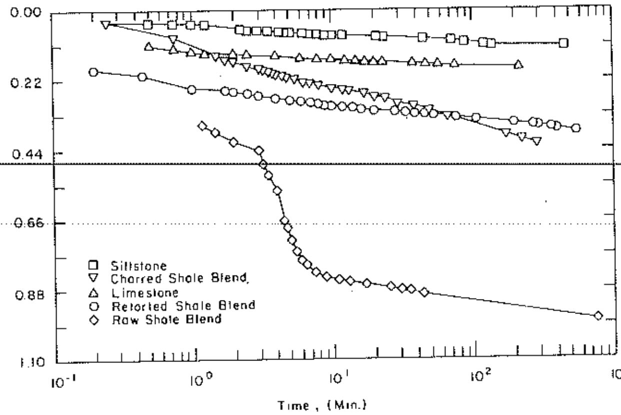

Figure 9. Strain-Time Curves for Inundated One-Dimensional Compression Specimens.

Slake-Durability

To evaluate the weathering resistance of the shales, slake-durability tests were performed. The procedure used was a method originally proposed by Franklin and Chandra (6) and modified by Gamble (7). In this method, approximately ten representative pieces of oven-dried shale are selected to be as nearly equidimensional as practical. Each piece weighs approximately 40-60 grams. The material is placed in a rotating test drum which is partially submerged in water. The drum is rotated at 20 revolutions per minute for 10 minutes. The drum is comprised of a 2.00 millimeter standard wire mesh which allows abraded and slaked material to fall into a trough. After the first cycle has been completed, the material retained on the wire mesh of the drum is removed and oven-dried. A first-cycle slake-durability index is computed as the ratio of the oven-dried material remaining in the drum to the total oven-dried material originally placed in the drum. The remaining oven-dried material is placed in the drum and a second, 10 minute cycle is performed. Material retained in the drum is removed and oven-dried. A second and final slake-index is obtained as the ratio of the oven-dried wieght of material retained after the second cycle to the total oven-dried weight originally placed in the drum. Normally the slake-durability index (expressed as a percentage) is reported.

Slake-durability indices obtained from tests performed on the raw oil shales and retorted oil shales are summarized in Table 7. Results obtained for both cycles are shown. Slake-durability tests were not performed on the charred oil shales because the particle sizes of this material were too small. Slake-durability indices of the Borden and Bedford overburden shales were 43.2 and 42.5 percent, respectively. Those shales can be characterized as having very low slake-durability properties. The raw oil shales (New Albany, Ohio, and Sunbury) had slake-durability values in excess of 95 percent. Hence, these shales have very high slake-durability properties. Slake-durabilities of the retorted shales (New Albany, Sunbury, and Cleveland) were also very high, greater than 94 percent. Apparently, slake-durability of the oil shales is not lowered after processing or retorting.

Table 7. Values of Slake-Durability Obtained for the Overburden Shales, the raw Oil Shales, and Retorted Oil Shales.

MATERIAL	CYCLE 1			CYCLE 2		
	Initial dry wt (gms)	Final dry wt (gms)	SDI* (%)	Initial dry wt (gms)	Final dry wt (gms)	SDI* (%)
			OVERBURDEN			
Borden (Lewis)	507.74	357.41	70.44	357.41	219.15	43.2
Bedford (Lewis)	508.00	372.11	73.25	372.11	215.97	42.5
			RAW SHALES			
New Albany (Bullitt)	197.34	196.27	99.45	196.27	195.51	99.1
New Albany (Powell)	364.40	362.32	99.42	362.32	361.01	99.1
Ohio (Lewis)	172.18	169.47	98.43	169.47	168.82	99.4
Sunbury (Lewis)	197.90	193.69	97.87	193.69	189.81	95.9
			RETORTED SHALES			
Sunbury (Lewis)	70.93	70.50	99.39	70.50	70.28	99.1
New Albany (Powell)	169.42	168.20	99.28	168.20	167.45	98.8
Cleveland (Lewis)	97.68	97.09	99.40	97.09	96.72	99.0
Chattanooga (Lincoln)	204.03)	202.91	99.45	202.91	202.11	99.1
New Albany (Nelson)	122.10	121.08	99.16	121.08	120.71	98.9
New Albany (Bullitt)	220.41	212.15	96.25	212.15	209.01	94.8

*Slake Durability Index

ANALYSIS AND DISCUSSION OF RESULTS

PHYSICAL PROPERTIES

Physical properties test data obtained for the oil shales and overburden materials can be used to give a general indication of their desirability for use as an engineering material. Properties such as compressibility, permeability, and shear strength are related to the physical characteristics of the material, such as its particle-size distribution. For this reason, classifications of the materials were made to place a material within a group of materials which have similar engineering properties. The classifications of the overburden materials and oil shales can be used with the engineering use chart devised by Wagner (cf8) to give general physical properties of the shales and their desirability for use as a homogeneous embankment material. This system of rating the desirability of a material for various purposes uses a scale ranging between 1 and 10, where 1 represents the best material and 10 the worst for engineering purposes. Using this system, the Bedford shale is rated as a 3 for use as a homogeneous embankment material, while the Borden shale is rated as a 5. The raw shales have negligible compressibility and a value of 2 as a rating for use as an embankment material. The retorted shale has a rating of 2. The charred and combusted shales has a rating of 3 as an embankment material.

Based on the engineering classifications and the ratings as an embankment construction material, it is obvious that a disposal embankment constructed of the retorted, charred, or combusted materials, should be strong but very pervious. If a disposal embankment is constructed of the overburden material, then it would be weaker, have a medium shear strength, and be impervious. This assumes that the actual materials are identical to the ones tested herein.

MOISTURE-DENSITY RELATIONSHIPS

The results of the compaction tests are shown in Figures 3 thru 5 and summarized in Table 3. If the specific gravities of several materials are the same, in general, the more granular a soil is the lower the optimum moisture content and the higher the maximum dry density. The Bedford shale which as classified as a sandy clay has a maximum dry density higher than, and an optimum moisture content lower than the Borden shale which was classified as a clay of low plasticity.

The standard optimum moisture content of the raw oil shale which was classified as a silty gravel was less than the standard optimum moisture contents obtained for the clay overburden shales. However, the standard maximum dry densities obtained for the overburden shales. Such a result is caused by such factors as different specific gravities, particle-size distributions, and particle shapes.

The retorted shales, which are either poorly- or well-graded gravels, also have a lower standard optimum moisture content and maximum dry density than values obtained for the overburden shales. The charred shales have a greater standard optimum moisture content than any of the materials tested while the maximum dry density was the lowest.

Compactive energy has a significant effect on the compaction results obtained for a given soil. Greater energy supplied in the compacting process causes the optimum moisture content to decrease while the maximum dry density increases. This can be seen in Figure 4 for compaction tests performed with three different levels of energy.

PERMEABILITY

Soils can be classified by their coefficients of permeability, k. One set of classifications have been recommended by Terzaghi and Peck (9). Using this method of classifying soils the overburden shales, which are clays, should have permeabilities less than 10^{-7} cm/sec. This is consistent with the values of permeabilities obtained and reported in Table 4. The overburden shales classify as practically impermeable. It is important to note that in performing the permeability tests on the overburden shales, a well graded shale with a large percentage of the sample passing the No. 200 sieve was used. This is representative of a shale which has been weathered or broken down by abrasive action. If the permeability tests were performed on the overburden shales at a different particle size distribution, then the results would not, necessarily, be the same.

The relative permeability classification for the raw oil shale blend is "low", and this corresponds to coefficients of permeabilities between 10^{-3} and 10^{-5} cm/sec. The classification for the retorted is also low. This classification is often used to describe sand or in this case silty gravels. The permeability of the charred shales is 2.3×10^{-3} cm/sec which would be classified as a "medium" relative permeability. Such a permeability is associated with a soil composed of sand and gravel.

TRIAXIAL TESTS

Overburden materials - The triaxial tests on both the Borden and the Bedford overburdens compacted to 100 percent of standard compaction, yielded similar shear strength parameters (ϕ' approximately 26.5 degrees and c' equal to zero). Two additional series of triaxial tests on the Borden overburden shales at high energy compaction and low energy compaction gave sufficient data to assess the effects of density, as well as confining stress, on shear strength. A normalizing parameter, C_R, was used for density. This parameter was used by Drnevich, et al (2) in a study of Eastern Kentucky mine spoil materials. It is the ratio of the dry density of the test specimen after compaction and consolidation to standard compaction dry densities. Therefore, C_R, or density ratio, includes the effects of volume change associated with the testing process.

The Borden and Bedford data were then combined and analyzed together. Multiple, linear regression analyses were used to establish equations for the abscissae and ordinates of the stress points corresponding to failure. The independent parameters were confining stress, σ'_3, and density ratio, C_R.

Using equations from the above analysis shear strength parameters were determined for standard compaction conditions. The angle of shearing resistance, ϕ', was 26.5 degrees and the cohesion was approximately 100 pounds per square foot. The angle of shearing resistance compares well with values for various mine spoils as shown by the data point labeled "overburdens" in Figure 10.

Values of ϕ' and c' were determined for density ratios, C_R, of 0.95 and 1.05 and were normalized by dividing by their respective values from tests at standard compaction. These compared well with curves from Drnevich, et al (2) on mine spoils. It is obvious that the cohesion is significantly affected by the density ratio whereas the angle of shearing resistance is not affected.

Based on this analysis, a ϕ'-value of 26.5 degrees is recommended for the overburden shales independent of the compaction density. The value of cohesion, on the otherhand, is quite dependent on the amount of compaction. A cohesion of 100 pounds per square foot is recommended for compaction dry densities equal to standard compaction dry densities and a cohesion of zero is recommended for compaction dry densities less than or equal to 90 percent of standard compaction dry densities. For dry densities between 90 percent and 100 percent, linear interpolation may be used to establish the cohesion.

Raw Oil Shales - These materials classified as coarse-grained materials and high shearing strength was to be expected. Results of the triaxial tests gave an angle of shearing resistance, ϕ', of 42.2 degrees and a cohesion of 316 pounds per square foot. These are similar to values reported by Allen (10) for dense graded aggregate. This angle of shearing resistance plots slightly higher than data from Drnevich, et al (2) as shown in Figure 10. For this reason, and because of weathering and variability of the material in the field, it is recommended that the angle of shearing resistance for design, ϕ'_{design}, be limited to 40 degrees.

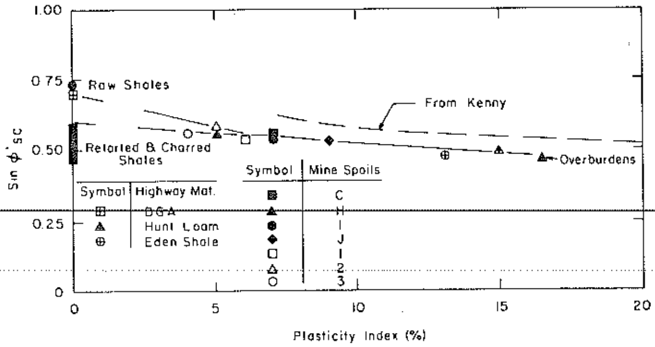

Figure 10. Variation of Angle of Shearing Resistance with Plasticity Index for Materials Compacted to Maximum Dry Density at Optimum Moisture Content by Standard Compaction (After Drnevich et al (1)).

Retorted and Charred Shales - These two materials are handled together because very little difference between the two was noted in the test results. Great difficulty was encountered in performing these tests. Multiple check tests had to be performed and an alternate type of triaxial test was performed. The problems stemmed from the nature of the material. First of all, there were little or no fines and the particles were relatively incompressible which gave a fairly stiff specimen even though the dry densities were quite low. Next, a chemical reaction was observed when water was added to the material. The reaction provided a gas (probably hydrogen sulfide) which also hampered the saturation process. The specimen was considered to be saturated when negligible additional water entered the pore space for an incremental increase in back pressure.

In order to circumvent the back pressuring and saturation problem, two additional triaxial tests were performed on specimens compacted at standard optimum moisture contents and maximum dry densities. These specimens were not saturated but simply tested in the drained condition. Since these materials are very free draining and because proposed regulations (11) require protection of these materials from ground water, it is recommended that drained triaxial tests be used in the future to establish shear strength parameters in terms of effective stress.

Effective stress paths for all triaxial test performed on the charred and retorted blends are shown in Figure 7. Rather than fit a straight line through the data (this would under estimate the shear strength for low fills), a second order least squares curve was fitted through the data. The curved K_f-line gave a cohesion of 280 pounds per square foot and an angle of shearing resistance which ranged from slightly over 45 degrees at low confining pressures to about 22 degrees at very large confining pressures.

For the design of embankments containing these materials, a cohesion of 200 pounds per square foot is recommended when the material is placed at dry densities equal to those of standard compaction. This value should be reduced to zero at dry densities corresponding to 90 percent of those for standard compaction. For intermediate values of dry density a linear interpolation may be used. It is also recommended that values of angles of shearing resistance be dependent on the confining stress within the embankment and that the values of ϕ' for design range from 36 degrees for low stresses to 26 degrees for very high stresses. Specific values of ϕ'_{design} for various pressures are given in the last column of Table 6.

CONCLUSIONS AND RECOMMENDATIONS

The materials tested in this program represent overburdens from several formations, several types of raw oil shales, and spent shales with three different process histories which were termed retorted, charred, and combusted. Conventional index tests used in geotechnical engineering can be performed on all of these materials. The results can be used to classify these materials according to schemes used in soil mechanics. The measured engineering properties of these materials from physical (as opposed to index) tests are in good agreement with the expected properties based on the classifications and geotechnical engineering experience. Hence, the classification systems can be applied to these materials as an aid in determining their physical characteristics and approximate engineering behavior. It is recommended that index tests be used to classify materials from new sites or different processes as a means of establishing estimates of their engineering characteristics.

The overburden materials tested were shown to have low permeability and shear strength and to have medium compressibility. They also have low durability and as a result will break down with weathering from rock-like materials to soil-like materials. In actual mining operations, the overburdens may appear rock-like upon excavation. If placed in fills without processing, they will exhibit medium to high shear strength and high permeability for some time but will eventually breakdown into soil-like materials. Associated with this will be reduced shear strength and permeability, both of which can contribute to slope instability problems. It is recommended that overburden samples at each site be obtained during the actual mining process by use of the equipment actually doing the mass excavation. This material will most likely have a significantly different appearance from the material tested in this program because the means of obtaining the samples are different. The nature of the samples obtained will dictate what processing and what placement procedures will be needed in order that the constructed fills of this material be impermeable and stable over the long term. Most likely, different placement procedures will be needed for mountain top fills than for head-of-the-hollow fills.

The raw oil shales tested have significantly different engineering characteristics from the overburdens. These materials are more durable, less compressible, more permeable, and have much higher shear strengths. It is expected that they would be more difficult to mine but easier to handle. Stockpiles of these shales should not degrade appreciably. Fractions not used in processing could be deposed in fills that could be easily constructed by ordinary techniques. In the long-term, such fills, if properly designed and constructed, should not suffer from excessive settlement or slope failures. However, the geotechnical engineering properties of the materials actually obtained at a given site may vary from those reported herein due to local variations in the natural deposits, particle size distribution, and type of mining processing (transport, crushing, sieving, etc.). Consequently, it is recommended that geotechnical tests be performed on these materials at each site for a given process.

Three spent shales were studied and they were termed: retorted shale, charred shale, and combusted shale. Extensive tests were performed on the first two, but the combusted shale was received too late in the program for any testing but index testing. Visually, the three spent shales appeared significantly different. However, all were quite durable, and they had low compressibilities, high permeabilities, and substantially high shear strengths. The retorted and charred shales had significantly lower dry densities than the raw shales. The optimum moisture contents of these two materials differed significantly (factor of 2.5) which shows that the process used has a major influence on the resultant product. Both possessed an unpleasant odor and appeared to react with the water used in specimen preparation. The reaction produced a gas which hampered the saturation process that was needed for both the permeability tests and the triaxial tests. Nonetheless, good test data were obtained.

Both the retorted and the charred shales exhibited nearly the same shear strength characteristics when the two materials were compacted to standard, maximum dry densities and optimum moisture contents. The failure envelope for these tests was curved downward, giving high angles of shearing resistance at low confinement and low angles at high confining stresses. Some small cohesion was obtained. Friction angles ranging from 36 degrees to 26 degrees, depending on confining stress, were recommended and a cohesion of 200 pounds per square foot was recommended. More shear strength testing is highly recommended on these materials. The tests should be of the drained type since excess pore pressures will rarely be generated in these materials after disposal in fills. The additional testing should include the effects of the degree of compaction since it is quite likely that densities in disposal fills could differ significantly from standard compaction values. Additional study is also needed on the effects of the chemical reaction on shear strength, compressibility, and permeability. Over the long-term, the physical behavior of the spent shale fill could be substantially altered by ongoing reactions.

ACKNOWLEDGMENTS

This work was a part of a project sponsored by the Kentucky Department for Natural Resources and Environmental Protection. It was done in cooperation with the Institute for Mining and Minerals Research, (IMMR) the Department of Civil Engineering, and the Transportation Research Program, all of the University of Kentucky. The authors wish to acknowledge the assistance of the IMMR staff, especially Dr. Thomas L. Robl.

LIST OF REFERENCES

1. Drnevich, V. P., Hopkins, T. C., Allen, D. L. and Hale, S. S., "Engineering Properties of Kentucky Oil Shales," University of Kentucky, Department of Civil Engineering, Soil Mechanics Series No. 29, November, 1981.

2. Drnevich, V. P., and Ebelhar, R. J., Evaluation of a Technique for Estimating Shearing Strength of Mine Spoil Material; Final Report of a Cooperative Project Between the U. S. Department of Agriculture, Forest Service and the University of Kentucky, Institute for Mining and Mineral Research, Study No. 4300-FS-NE-1605-121 August 1976.

3. Army Corps of Engineers; Laboratory Soils Testing Manual, EM-1110-21906; U. S. Government Printing Office, Washington, D. C., 278 P.; 1970.

4. Bishop, A. W.; and Henkel, D. J.; The Measurement of Properties in the Triaxial Test; 2nd, ed.; Edward Arnold LTD., 239 P.; 1962.

5. Lowe, J.; and Johnson, T. C.; Use of Back Pressure to Increase Degree of Saturation of Triaxial Test Specimens, ASCE Research Conference on Shear Strength of Cohesive Soils, American Society of Civil Engineers, New York, pp. 819-836.

6. Franklin, J. A.; and Chandra, R.; The Slake-Durability Test; International Journal of Rock Mechanics and Mining Science, Vol 9, Perganon Press, Great Britain, pp. 325-341; 1972.

7. Gamble, J. C.; Durability-Plasticity Classification of Shales and Other Argillaceous Rocks, Ph.D. Thesis, University of Illinois at Urbana-Champaign; 1971.

8. Lambe, T. W.; Whitman, R. V.; Soil Mechanics, John Wiley and New, 55 p., 1969.

9. Terzaghi, K; and Peck, R. B.; Soil Mechanics in Engineering Practice, 2nd. ed., John Wiley and Sons, New York, 729 p., 1967.

10. Allen, D. L.; Determination of Rutting in Asphaltic Concrete Pavements: Field Instrumentation and Laboratory Characterizations, Kentucky Department of Transportation, Division of Research, August, 1978.

11. Proposed Regulations for Oil Shale Operations; Commonwealth of Kentucky, Department for Natural Resources and Environmental Protection, Informational Copy, June 1981.