GEOTECHNICAL PROPERTIES OF A FINE-GRAINED SPENT SHALE WASTE

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ABSTRACT

Waste disposal schemes, envisioning the use of spent shale in embankments, require a thorough knowledge of their geotechnical engineering properties for safe, efficient, and environmentally sound disposal. In this context, the objective of this laboratory investigation was to determine the physical properties, compaction, consolidation, shear strength, and permeability parameters of a spent shale.

Physical properties consisted of grain size distribution, Atterberg limits after nine months of soaking in water, and specific gravity determinations. Six-inch-diameter (15 cm) compaction tests and 12-inch-diameter (30.5 cm) consolidation tests were used to determine compaction and consolidation characteristics and particle break down for three compactive efforts. Unconfined compression and consolidated-undrained triaxial compression tests on 6-inch-diameter (15 cm) specimens, compacted to three densities, were performed to evaluate compressive strength gains over 28 days, and total and effective strength parameters for undrained conditions. Companion 3- by 3-inch (7-1/2 cm) consolidated-drained direct shear tests on specimens compacted to one density were used to obtain strength parameters for drained conditions. Permeability values for the spent shale were also determined on the consolidated-undrained triaxial test specimens.

Results of these tests showed that the spent shale is a silty sand (SM) and that, with proper compaction, it possesses a good shear strength, has a low permeability with minimal compaction, and exhibits some self-cementing tendencies.

INTRODUCTION

A major problem area in considering a commercial oil shale operation is disposal of the spent shale in a structurally and environmentally safe manner. Since the shale occupies about 20 percent greater volume after retorting, some material will have to be deposited in surface impoundments, regardless of whether the main scheme is underground or surface disposal. With tightening environmental restrictions, results of various related research projects are needed to provide industry with strength, permeability, and other engineering parameters required to design sound disposal facilities.

One of the first major studies in this area was: Disposal of retorted oil shale - Paraho oil shale project (Woodward Clyde 1976). The Waterways Experiment Station (WES), under funding and technical direction of the Bureau of Mines (interagency agreement No. H0262064), is conducting a major laboratory testing program to obtain the physical and engineering properties necessary for the design of a large scale disposal system.

This report presents engineering property test results on a fine-grained, indirectly heated, retorted oil shale. Maximum particle size was about 1/2 in. (12.7 mm) with approximately 35 percent of the material passing a No. 200 U. S. Standard sieve. Results of compaction, consolidation, unconfined compression at various curing times, triaxial shear, direct shear, and permeability tests are summarized.

LIST OF SYMBOLS

LL	Liquid limit - Atterberg Limits test
PL	Plastic limit - Atterberg Limits test
PI	Plasticity index - Atterberg Limits test
G	Specific gravity
w	Water content
γ_d	Dry unity weight (dry density)
$\emptyset$	Total stress parameter angle of apparent internal friction
$\emptyset'$	Effective stress parameter angle of apparent internal friction
c	Total stress parameter cohesion intercept
c'	Effective stress parameter cohesion intercept
e	Void ratio
p	Pressure
σ_n	Normal stress
τ	Shear stress
k	Coefficient of permeability

TEST RESULTS AND DISCUSSION

Material Processing and Classification

Material processing consisted of determining a representative gradation for the material, processing, and reconstituting the material to this gradation. Representative samples were obtained from two of ten 55-gal. (198 l) drums containing the material and their respective gradations determined, as shown in figure 1. Since no significant differences existed in these two random samples, the remaining material was combined, with representative gradation also shown in figure 1. These sieve analyses indicate that 9 percent is plus No. 4 sieve size (gravel) and about 35 percent is minus No. 200 sieve size (fines).

Also presented in figure 1 are the results of Atterberg limits analyses performed on the minus No. 40 sieve-size fraction, in accordance with Corps of Engineers procedures (EM 1970). Unless otherwise indicated, all laboratory testing was in accordance with

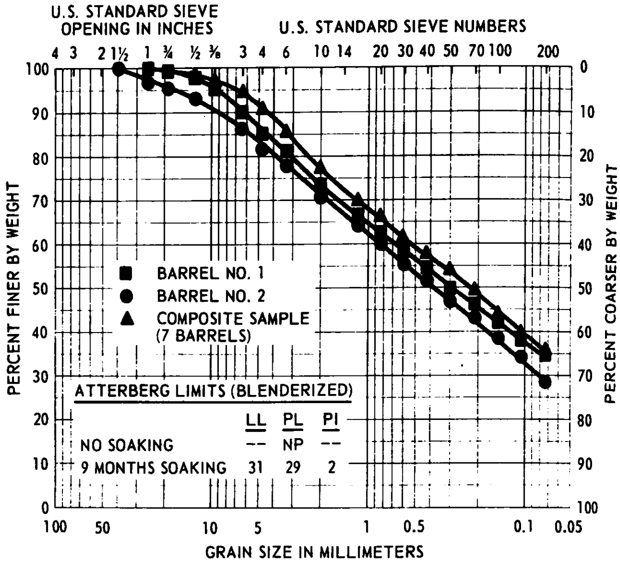

Figure 1. Gradation analysis of retorted oil shale waste.

equipment and procedures described in this reference. The fines are essentially nonplastic, even after 9 months soaking. Hence, this material would be classified as a silty sand (SM), according to the Unified Soil Classification System (Tech Memo 1960).

Specific gravity of the minus No. 4 sieve fraction was 2.61, while the apparent specific gravity of the plus No. 4 sieve size fraction was 2.55, resulting in a specific gravity of 2.60 for the combined material.

Heley and Terrell (1971) and Dames and Moore (1971) found similar results on spent shale materials from the Rocky Flats and the Parachute Creek facilities. The material which they described contained 1.5 to 7.3 percent, plus No. 4 sieve fraction (gravel), and 58.2 to 74.3 percent, minus No. 200 sieve fraction (fines). Both references quote Atterberg limits values of 30-percent moisture content for the liquid limit and 6 percent for the plasticity index, which would classify this material as silt "ML." An apparent specific gravity of 2.53 was reported.

Compaction Characteristics

Compaction curves were generated for three compactive efforts; i.e., 60 percent of standard effort

[7,425 ft-lb/ft^3 (3.693×10^5 joules/m^3)],

standard effort

[12,375 ft-lb/ft^3 (5.989×10^5 joules/m^3)],

and modified effort

[56,250 ft-lb/ft^3 (27.221×10^5 joules/m^3)].

Maximum dry densities, at optimum moisture content for each effort, were 96.2 pcf (1,541 kg/m^3) at 21.2 percent for 60 percent of standard effort, 98.4 pcf (1,576 kg/m^3) at 19.3 percent for standard effort, and 103.1 pcf (1,652 kg/m^3) at 17.8 percent for modified effort. Results of these 6-inch-diameter (15 cm) compaction tests are presented in figure 2.

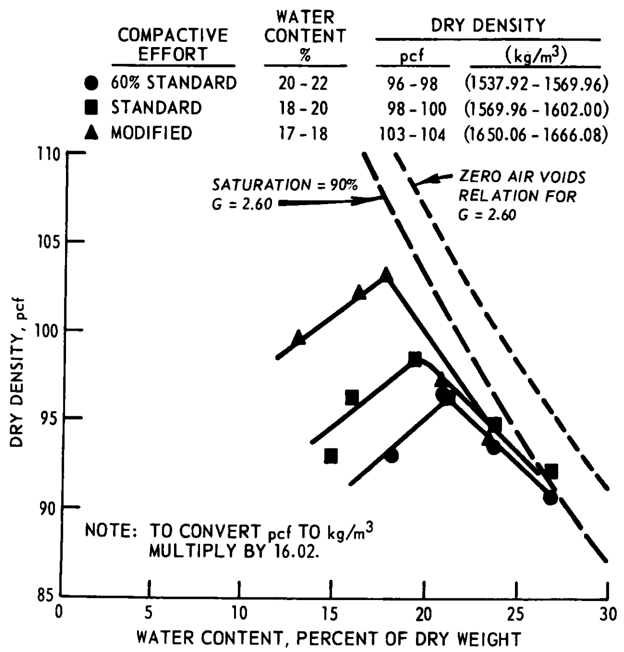

Figure 2. Compaction characteristics for 60 percent of standard, standard, and modified compactive efforts.

Based upon the results of these compaction tests, all appropriate test specimens were prepared to the water contents and dry densities corresponding to each of the three compactive efforts shown in figure 2. For comparison, compaction tests on materials from the Rocky Flats and the Parachute Creek facilities, as reported in Heley and Terrell (1971) and Dames and Moore (1971), indicated that, for standard compactive effort, the dry densities at optimum water content varied from 88 pcf (1,409 kg/m^3) at 22 percent water content, to 100 pcf (1,602 kg/m^3) at 16 percent water content. For modified compactive effort, densities ranged from 101 to 109 pcf (1,618 to 1,746 kg/m^3) while the moisture contents varied from 19 to 15 percent, respectively.

Unconfined Compression Characteristics

To investigate the self-cementing characteristics reported (Snethen and others 1978; Trans. Data 1977a; Nevins and others 1977) for wastes from other retorting processes, 6-inch-diameter (15 cm) unconfined compression test specimens were compacted, using three compactive efforts, and allowed to cure at ambient temperatures for periods of 0 to 28 days. Strengths increased from 20 to 54 psi (1.4 to 3.8 kg/cm^2), 41 to 61 psi (2.9 to 4.3 kg/cm^2) or from 73 to 104 psi (5.1 to 7.3 kg/cm^2) for specimens compacted to densities equivalent to 60 percent of standard, standard, and modified compactive efforts, respectively.

Procedures for these tests varied slightly from those outlined by Woodward (1976) and were as follows:

1. After adding water to the material to be compacted, a 1-hour mellowing time was used before compaction. (A 1-hour mellowing time is an accepted practice, used in lime stabilization of soils.)

2. Specimens were compacted in 6-inch-diameter (15 cm) waxed cardboard containers. Following compaction, these

containers were sealed with paraffin wax, weighed, and placed in buckets, each containing a small container of water. These buckets were sealed and placed in an environmental room where a constant temperature of 72°F was maintained during the specified curing time.

3. Following the required curing time, each specimen was reweighed to verify that no weight change had occurred, e.g., the moisture content of the specimen had not changed. All other testing procedures are as outlined in EM-1110-2-1906.

The changes in unconfined compressive strength as a function of curing time are presented in figure 3. These results indicate that self-cementing is a characteristic of this retorted oil shale which agrees with results by others (Snethen and others 1978; Trans. Data 1977a; Nevins and others 1977).

These results show that self-cementing is dependent upon density and time. Although higher densities produced greater strengths,

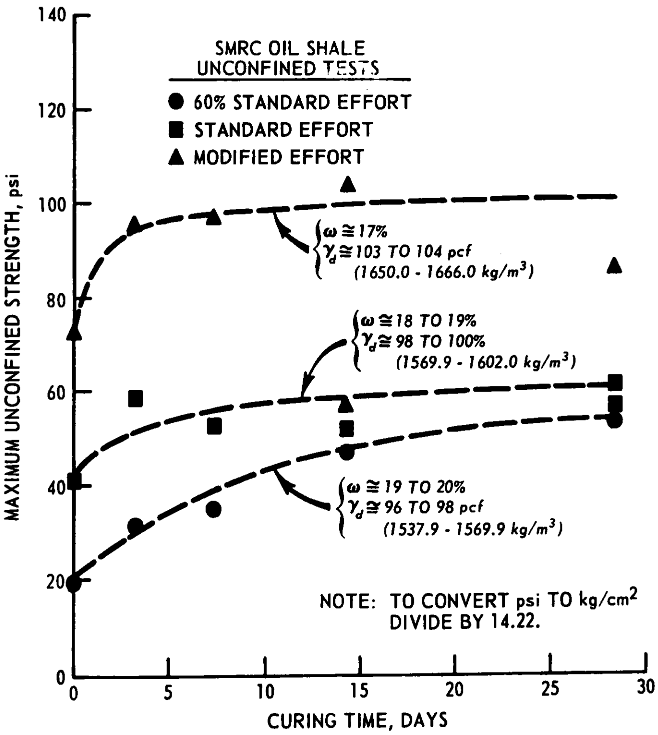

Figure 3. Effect of curing time on unconfined compressive strength of 6-inch-diameter (15 cm) specimens.

in terms of percent, the greatest strength gains occurred at the lowest densities. The major portion of the strength increase occurs within 3 days after compaction.

Triaxial Compression Strength Characteristics

Strength parameters for each compactive effort were determined by performing consolidated-undrained triaxial compression tests with pore pressure measurements on 6-inch-diameter (15 cm) specimens. Test procedures corresponded with those in Eng. Man. 1110 (1970), with the exception that specimens were allowed to cure in the environmental room for three days following compaction, before testing. The self-cementing property added additional strength to the specimens so that they were less friable and easier to handle. Stress path data and Mohr's circles are presented in figures 4, 5, and 6 for 60 percent of standard, standard, and modified compactive efforts, respectively. The total and effective stress parameters are summarized in the following tabulation:

	Total Stress		Effective Stress	
Compactive Effort	Ø, degrees	c, kilograms per square centimeter	Ø', degrees	c', kilograms per square centimeter
60 percent Standard	19	0.8	37	0
Standard	18	0.6	35	0
Modified	25	1.4	43	0

Strength parameters, discussed in the preceding paragraphs, appear to be reasonable when compared to those of a dense sand, i.e., Ø' ∿ 40 degrees. Consolidated-undrained triaxial tests values, reported by Dames and Moore (1971), for specimens with dry densities of 85 to 90 lb/ft^3 (1362 to 1442 kg/m^3) were: cohesion intercept was 0 and apparent angle of internal friction was 20 degrees. This agrees reasonably well with the total stress data obtained in this investigation.

Consolidation Characteristics

Twelve-inch-diameter (30.5 cm) consolidation tests for each of the three compactive efforts were conducted to

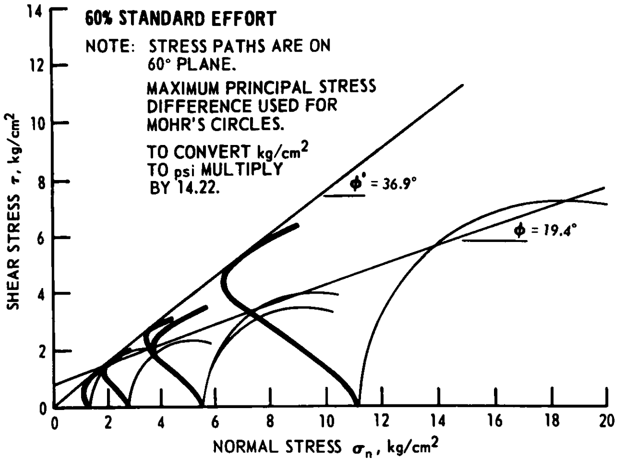

Figure 4. Effective stress paths and failure envelopes for 6-inch-diameter (15 cm) consolidated-undrained triaxial specimens compacted to 60 percent of standard effort.

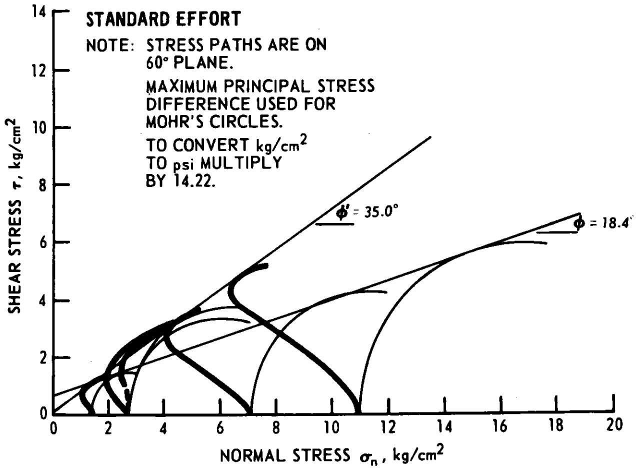

Figure 5. Effective stress paths and failure envelopes for 6-inch-diameter (15 cm) consolidated-undrained triaxial specimens compacted to standard effort.

maximum vertical stresses of 800 psi (56.3 kg/cm^2) (Trans. Data 1977b). The corresponding vertical strains were 8.4, 6.7, and 4.7 percent for 60 percent of standard, standard, and modified efforts, respectively. Results of these three consolidation tests are presented in figure 7 as plots of void ratios, e, versus log of consolidation pressure, p.

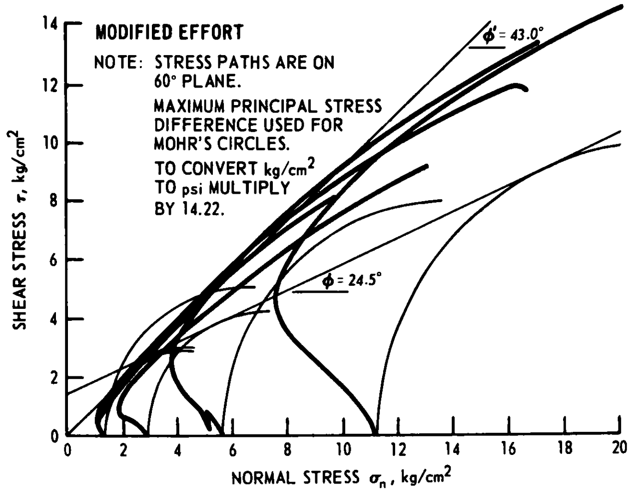

Figure 6. Effective stress paths and failure envelopes for 6-inch-diameter (15 cm) consolidated-undrained triaxial specimens compacted to modified effort.

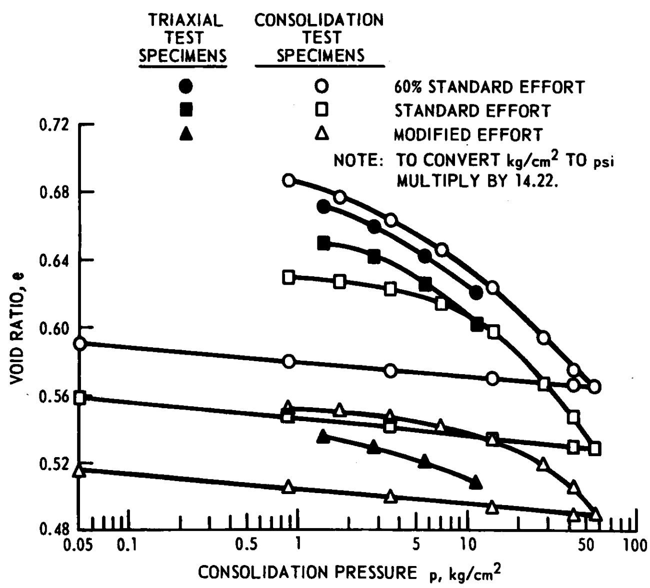

Figure 7. Consolidation characteristics of 12-inch-diameter (30.5 cm) consolidation and 6-inch-diameter (15 cm) triaxial specimens compacted to 60 percent of standard, standard, and modified compactive efforts.

Also presented in figure 7 are the consolidation data obtained during isotropic consolidation of the triaxial specimens at confining pressures of 20, 40, 80, and 160 psi (1.4, 2.8, 5.6, and 11.2 kg/cm^2). While the consolidation stresses in an odometer are quite different than triaxial isotropic consolidation, an examination of all the consolidation data, from both types of tests, indicates that the compression index for the virgin loading curve from the consolidation tests increases from 0.1 to 0.2 cm^2/kg for 60 percent of standard compactive effort to modified effort, respectively. The coefficient of compressibility for the 1 to 10 kg/cm^2 pressure ranges, for both types of tests, increased slightly with higher pressures, but generally decreased from 10^{-5} to 10^{-6} cm^2/kg for the 60 percent of standard and the modified compactive effort densities, respectively. Likewise, the coefficient of consolidation was about 10^{-1} cm^2/sec for all compactive efforts, but decreased slightly with increasing consolidation pressures.

By comparison, results of consolidation tests (Dames and Moore 1971a), loaded to a maximum vertical stress of 700 psi (49.2 kg/cm^2), had vertical strains which varied from 16 to 25 percent. Although WES test data indicated substantially less vertical strains on 12-inch-diameter (30.5 cm) test specimens tested to a comparable stress level, reexamination of initial void ratios indicated that WES tests had values of 0.69, 0.63, and 0.55 at 60 percent of standard, standard, and modified compactive effort densities, respectively, whereas Dames and Moore's data had initial void ratios which varied from 0.87 to 1.29. Although direct comparisons are difficult, the WES results indicate appropriate trends of decreasing vertical strain with smaller initial void ratios.

Particle Breakage

Post-test grain size determinations were made on compaction and consolidation specimens to study particle breakage. Gradation curves obtained from compaction specimens indicated that a sort of particle agglomeration occurred, possibly due to the self-cementing characteristic of the material. Postconsolidation gradation relations presented in figure 8 were obtained for specimens tested at densities for 60 percent of standard compactive effort and standard effort. The percentage of minus No. 200 fraction increased from 32 percent for the initial gradation to 61 and 76 percent for standard compactive and effort for 60 percent of standard effort, respectively. At this time it is not known why the less dense specimens incurred more particle breakage.

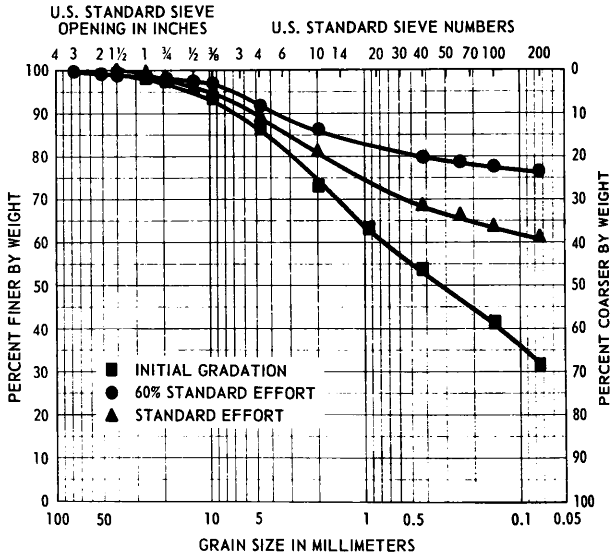

Figure 8. Effects of particle breakage during consolidation testing to 800 psi (56.3 kg/cm^2) vertical stress.

Permeability Characteristics

In addition to the consolidation data and shear strength parameters obtained from these consolidated-undrained triaxial test specimens, the coefficient of permeability was obtained for each test specimen after consolidation at various confining pressures had occurred. Generally, the coefficient of permeability decreased from 10^{-6} cm/sec, for specimens compacted at 60 percent of standard and standard compactive effort densities, to 10^{-7} cm/sec for specimens compacted at modified compactive effort densities. These permeability test results are presented in figure 9, comparing the coefficient of permeability as a function of void ratio. Similar permeability values were obtained based upon calculations using the consolidation data presented previously.

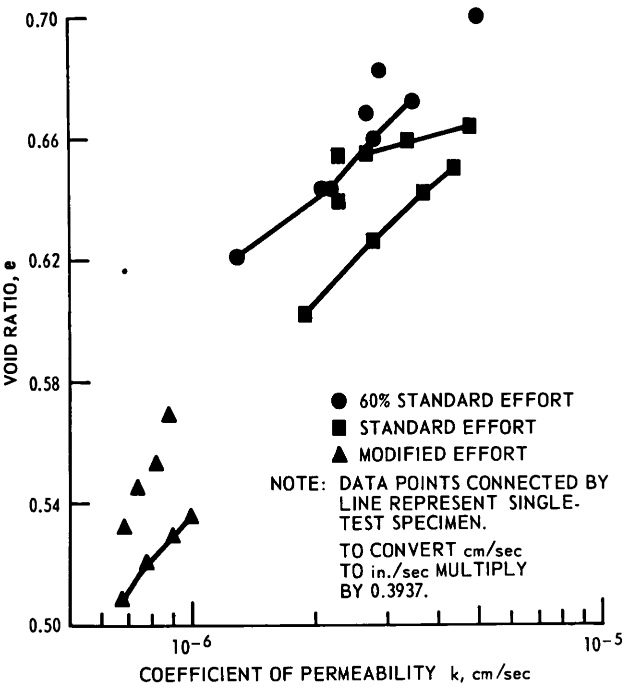

Figure 9. Permeability characteristics for different compactive efforts and void ratios.

Direct Shear Tests

Consolidated-drained direct shear tests were conducted on 3- by 3-inch (7.6 cm) specimens, compacted with standard compactive effort. A total of four tests were conducted, two with specimens inundated, and two without inundation. The strength parameters obtained from these tests indicated that for inundated conditions, the cohesion intercept was zero and the angle of apparent internal friction was 34 degrees; for specimens not inundated, apparent cohesion was 1.0 kg/cm^2 and apparent internal friction was 36 degrees. Results of these four tests are plotted as shear stress versus normal stress in figure 10. Due to particle size limitations (No. 4 sieve max) of the 3- by 3-inch (7.6 cm) direct shear box, the gradation and density [93 pcf (1489 kg/m^3)] were different than other tests [1-inch-diameter (2.5 cm) max particle size and 98-100 pcf (1570-1602 kg/m^3) standard effort density] conducted in this investigation. Nevertheless, these strength values are comparable with those obtained from triaxial compression tests.

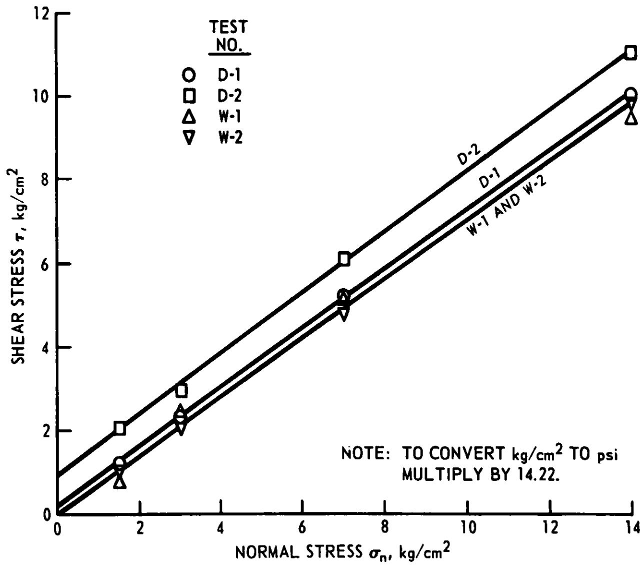

Figure 10. Failure envelopes for direct shear tests.

CONCLUSIONS

The spent shale was classified as a silty sand (SM) with 35 percent nonplastic fines and approximately 9 percent gravel. Compaction tests at 60 percent of standard effort, standard effort and modified effort gave maximum densities of 96, 98, and 103 lb/ft^3 (1541, 1576, and 1652 kg/m^3) respectively, with corresponding optimum water contents of 21.2, 19.3 and 17.8 percent. Consolidation tests to a maximum vertical stress of 800 psi (56.3 kg/cm^2) revealed settlements ranging from 8 to 5 percent with increasing compactive effort. Corresponding examinations of particle breakdown under this stress revealed an increase in the minus No. 200 sieve fraction from 32 to 61 percent for standard effort, and to 76 percent for 60 percent of standard compactive effort. A self-cementing property of the spent shale was obvious from the results of unconfined compression tests. From these tests, the 28-day strengths increased from 1.4 to 3.8 kg/cm^2, 2.9 to 4.3 kg/cm^2, and 5.1 to 7.3 kg/cm^2 for 60 percent of standard, standard, and modified compactive efforts, respectively. Results of consolidated-undrained triaxial tests with pore pressure measurements showed these total stress strength parameters: apparent cohesion values of 0.8, 0.6, and 1.4 kg/cm^2 and apparent angles of internal friction of 19, 18, and 25 degrees for each of the respective increasing compactive efforts, while effective strength parameters were zero for cohesion and apparent angles of internal friction of 37, 35, and 43 degrees for the three increasing compactive efforts. Consolidated-drained, direct shear tests, on specimens compacted to a standard effort density, gave effective strength parameters of: zero for cohesion and an internal friction of 34 degrees for inundated specimens, while specimens not inundated had slightly higher strengths of 1 kg/cm^2 for cohesion and 36 degrees for internal friction. Permeability values of 10^{-6} and 10^{-7} cm/sec were determined from the consolidated-undrained triaxial tests for increasing compactive efforts.

In conclusion, there were no unusual engineering characteristics for this material. It behaved as a moderately dense to dense sand, depending upon the applied compactive effort, and had a fairly high strength. Its self-cementing property also helped to enhance strengths. In addition to its high strength, this material has a low permeability, even under minimal compactive effort, which is an asset that would help to reduce contamination caused by ground water flow.

ACKNOWLEDGMENTS

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