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T. E. Gates

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SUMMARY

A literature review of available geotechnical properties for PARAHO retorted shale was conducted. Also reported are laboratory measurements made at PNL on key hydraulic properties of the PARAHO retorted shale. A determination and working knowledge of the geotechnical properties of the retorted oil shale are useful in considering the proposed options for efficient disposal of the spent shale in a structurally and environmentally safe manner.

The PARAHO retorted shale is classifed as a GP or GM soil depending on the amount of gravel present and the plasticity of the fines. Soils under these classifications indicate good compaction characteristics, good to excellent strength values, slight to medium compressibility, and overall a good foundation material.

The PARAHO material can be compacted in the laboratory to dry densities of 12.1 KN/m^3 (77.0 pcf)[a] to 17.0 KN/m^3 (108.4 pcf) depending on compaction effort. Optimum water content for these densities range from 14.4 to 23.7 percent (dry weight), however, PARAHO can achieve high densities without requiring water for compaction. Vibration compaction is the best method of field compaction, with densities ranging from 98 to 110 percent of standard depending on the number of passes, lift thickness, and moisture content. Particle breakage up to 28 percent occurs with PARAHO shale, depending on compactive effort.

The addition of small quantities of water causes bulking of the PARAHO materials and corresponding low densities. This, however, is common for materials of these gradations and this "bulking" effect does not occur for the better graded scalped and replaced materials.

Water retention characteristics indicate that optimum moisture contents ("field capacity") range from 13 to 14% (dry weight). Water contents in excess

(a) Numerical values also may be expressed as mass per unit volume, where N = 0.102 Kg; i.e., 9.8 KN/m^3 = 1 Mg/m^3.

of these values are likely to drain with time. In semi-arid climates it seems possible that a significant amount (up to 0.1 MT of water/MT of shale) of waste water could be deposited in the spent shale piles with little or no seepage. [Note: MT (metric ton)].

PARAHO shale can be considered as semipervious to pervious with permeability values of 10^{-3} to 10^{-4} cm/s, depending on compaction effort. Lower permeability values have been reported (Holtz 1976, Snethen et al. 1978) with values ranging from 10^{-6} to 10^{-7} cm/s due to the greater amount of fines present. Large, but inconsistent, changes in permeability are observed with changes in compaction (void ratio). Additional study needs are indicated in this area.

PARAHO shale exhibits self-cementing characteristics. Under normal conditions cementing reactions are slow, with strength gains still indicated after 28 days. With its 3 to 8-fold strength gain and a design loading value of 572 KN/m^2 (83 psi), based on a safety factor of 3, PARAHO materials can be considered for construction of waste disposal dams and embankments. Inconsistent quality of the material would require careful considerations of its properties and variability for engineering design use, however.

The shear strength of PARAHO is comparable to similarly graded gravel with effective angles of internal friction, ϕ', of 33 to 34 degrees. Depending on compactive effort and gradation of the material, effective cohesion values of 0.09 MN/m^2 to 0.19 MN/m^2 (128.05 psi to 277.45 psi) can be expected. Increased compaction effort does not noticeably improve PARAHO's shear strength parameters and generally exhibit positive pore pressures when sheared.

Drop height tests have been performed to determine densities achieved when processed oil shale is dropped from various conveyor heights. Major increase in density occurs within the initial 1.5 m (5 ft) of drop, from 10.3 KN/m^3 to 12.5 KN/m^3 (66.0 pcf to 80.0 pcf). Only a small amount of additional densification can be achieved by increasing the drop height to 5.0 m (16.5 ft).

CONTENTS

FIGURES

TABLES

NOTATIONS

A = coefficient related to ultimate compressive strength

B = breakage factor

C = cohesion

CS = compressive strength

D = coefficient related to initial compressive strength

D_r = relative density

e = void ratio

G = specific gravity

k = coefficient of permeability

K = coefficient related to rate of cementation

LL = liquid limit

n = porosity

PI = plasticity index

PL = plastic limit

$\overline{R}$ = consolidated-undrained triaxial compression tests

S = consolidated-drained triaxial compression tests

T = curing time

$u-u_0$ = induced pore pressure

$\frac{\Delta V}{V}$ = volumetric strain

w = water content

γ_d = unit weight of soil if water is entirely replaced by air

ϵ = strain

σ_1 = major principal stress

σ_3 = minor principal stress

ϕ = angle of internal friction; angle of shearing resistance

1.0 INTRODUCTION

Oil shale is a sedimentary rock containing kerogen. When heated the kerogen decomposes to yield oil. The principle concentration of oil shale in the United States is the Green River Formation, located in the three states of Colorado, Wyoming, and Utah. Of the total 64,750 km^2 (25,000 mi^2) of oil shale in the Green River Formation, approximately 44,030 km^2 (17,000 mi^2) are estimated to contain oil shale suitable for commercial development.

One of the major problems inherent to commercial oil shale production is the efficient and safe disposal of 80 to 85 percent of the total raw weight after retorting. To date several options have been proposed for the disposal of retorted oil shales, some of these being:

1. backfilling the mine with spent shale as the raw shale is removed;
2. filling deep narrow canyons of the oil shale mine area with the spent shale; and
3. using the spent shale for productive uses, such as material for road bases, waste disposal dams, and embankments.

The options require a determination and working knowledge of the geotechnical properties of the retorted oil shale for efficient disposal in a structurally and environmentally safe manner.

The processing method will determine the majority of the key geotechnical parameters. Currently, there are several retorting processes in various stages of development. These include the Chevron, Lurgi, Occidental, PARAHO, TOSCO, and others. Occidental is largely an in situ process with some above ground retorting, where the other processes listed completely utilize above ground retorting methods. The various processes can utilize fine or coarse materials, low or high temperatures, and direct or indirect heat mode producing different types of retorted shale.

The report is primarily a review of available geotechnical properties for PARAHO retorted shale reported in the literature, but also includes laboratory measurements made at PNL. The PARAHO internal combustion process is one of the simplest processes, utilizing gravity feed through a vertical retort operating at about 649°C (1200°F) in the direct heat mode. The raw shale is crushed to about 6 cm (2 1/2 in.) maximum size, with the minus 9 mm (3/8 in.) fines removed and presently discarded.

The following section presents the materials used for testing by the various institutes. This is an important consideration since ASTM specifications limits the maximum size of the large fraction used in many tests, which could effect the resulting data.

Section 3.0 presents the physical properties of PARAHO material. Of interest to geotechnical engineers for classification and comparison purposes are gradation, specific gravity, and Atterberg limits.

Engineering properties needed for design considerations include compaction, consolidation, strength, permeability, and soundness which are discussed in Section 4.0. Section 5.0 presents properties not specifically covered under Sections 3.0 or 4.0.

2.0 MATERIALS USED FOR TESTING

The PARAHO materials used in the testing needs to be considered in the comparison of results. Description of the sampling materials used for testing by the various institutes are provided below.

2.1 WATERWAY EXPERIMENT STATION (WES)

The PARAHO material was processed by passing the material through a Trommel rotating drum screen into various sieve sizes. The stored fractions were reconstituted for test specimens using the gradation determined by hand sieving. This gradation (Figure 3.2) was selected as representing the gradation of PARAHO material as it leaves the retort.

The reconstituted fractions consisted of two groups: 1) full-scale material, and 2) scalped and replaced. In the full-scale group fractions 8 cm (3 in.) and below were reconstituted based on the gradation determined by hand sieving. Specifications limit the maximum particle diameter to one fourth to one sixth of the corresponding mold diameter, hence, the larger particles must be scalped and replaced with an equal weight of finer material. This constituted the Group 2 material.

2.2 WOODWARD-CLYDE CONSULTANTS (WCC)

The PARAHO material passed the 8 cm (3 in.) screen with 96 to 98 percent passing the 4 cm (1 1/2 in.) screen. The plus 4 cm (1 1/2 in.) material was not used in the laboratory tests. Due to the small amount of this material to the total, it was felt that insignificant change on the properties would result.

2.3 COLORADO STATE UNIVERSITY (CSU)

The experimental approach was designed to simulate the operating conditions from a modeled sense. The initial raw oil shale was crushed to minus 4 cm (1 1/2 in.) to represent the 8 cm (3 in.) commercial shale size. All tests were conducted using this "modeled" material after retorting.

2.4 PACIFIC NORTHWEST LABORATORY (PNL)

The PARAHO material was processed, using a Ro-Tap mechanical shaker, by passing the material through various sieve sizes. To assure uniformity between test specimens the fractions were reconstituted using the average percentage retained, during processing, for each respective sieve size. Full size material was used during reconstitution of the fractions.

3.0 PHYSICAL PROPERTIES

Gradation, specific gravity, and Atterberg limits are physical properties of interest to geotechnical engineers. From these physical properties, comparisons may be made with other soils exhibiting similar characteristics and expected behavior predicted. Not considered to be a physical property, but of equal importance, is the classification of the material.

3.1 GRADATION

Since the gradation of retorted shale is dependent on mining operation, type of crusher, and amount of crushing the material undergoes prior to retorting, gradation is highly variable. The gradation of retorted shale is, however, helpful in classifying the material and indicating its suitability for engineering purposes. The influence of the retorting process on gradation is evident in Figure 3.1.

Figure 3.2 presents the results of the gradation analysis performed by WES (Townsend and Peterson 1979) on PARAHO material, plus those determined by WCC (Holtz 1976). Comparison between the hand-sieved and Gibson shaker-sieved gradation results (WES) show that the PARAHO material is friable and experiences some breakdown by the shaker, producing approximately 10 percent more fines.

Comparison of the gradations determined by WES with those of WCC show fairly close agreement in one case and a finer gradation obtained by WCC for another (Townsend and Peterson 1979). The agreement shown in Figure 3.2 is representative of the gradation of PARAHO retored shale considering the variability of oil shale and gradations entering the retort.

3.2 SPECIFIC GRAVITY

The specific gravity may be expressed in three forms (Snethen et al. 1978, Townsend and Peterson 1979):

1. the specific gravity of solids, which is applied to soils finer than a No. 4 sieve;
2. the apparent specific gravity; and
3. the bulk or mass specific gravity.

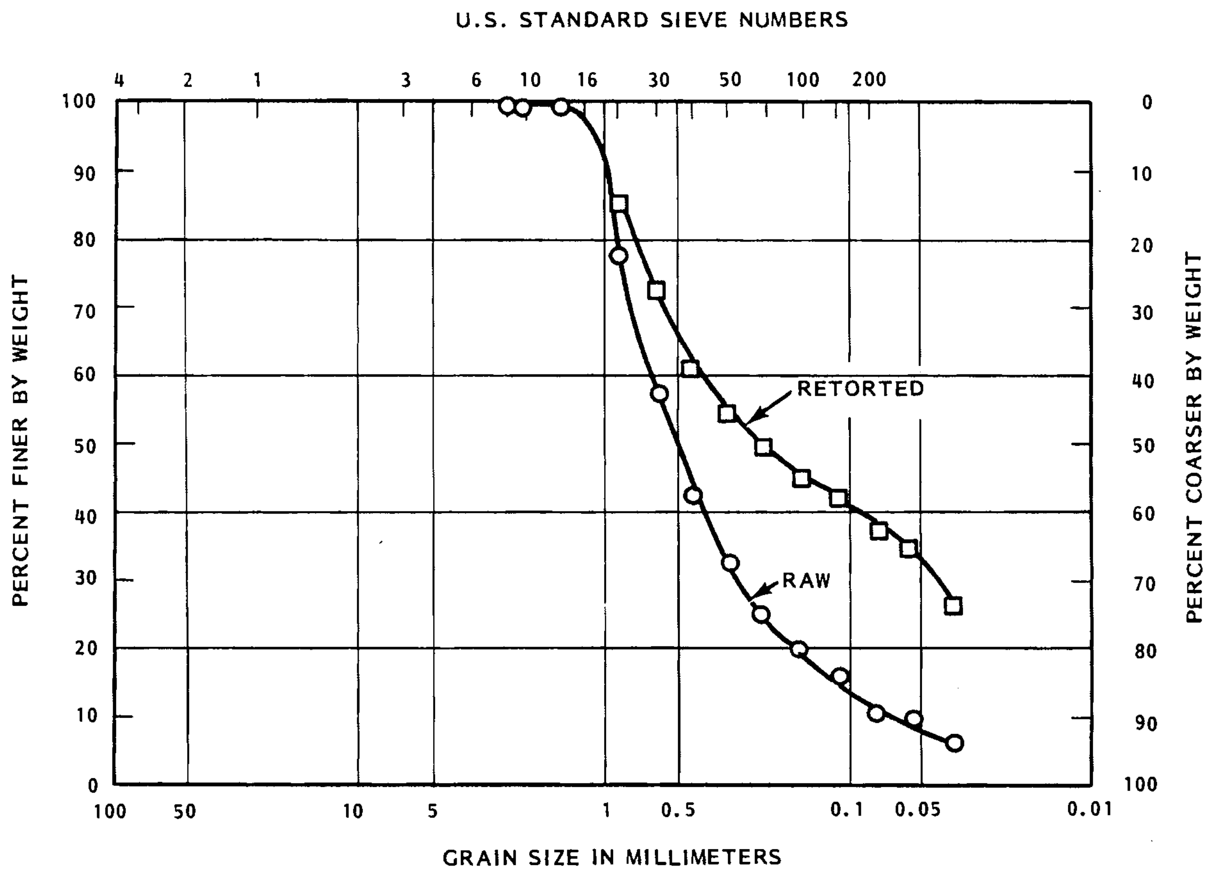


FIGURE 3.1. Comparison of Raw and Retorted Oil Shale Gradation. Based on all material less than 2 mm (Townsend and Peterson 1979)

The apparent and mass specific gravities are both applied to soils coarser than the No. 4 sieve. The apparent specific gravity is routinely used when dealing with coarse aggregates.

Snethen et al. (1978) reported that the majority of apparent specific gravities for PARAHO material varied from 2.52 to 2.59. The apparent specific gravity of the PARAHO material used by WES and WCC was determined to be 2.42 and 2.54, respectively.

Mass specific gravity (relative bulk density) for PARAHO material range between 1.80 and 1.85, and specific gravity of solids around 2.67.

In comparison with sandstone, limestone, basalt, and granite rockfill materials with values ranging from 2.65 to 2.87 for apparent specific gravity and 2.29 to 2.84 for mass specific gravity, the specific gravity values of PARAHO material are quite low.

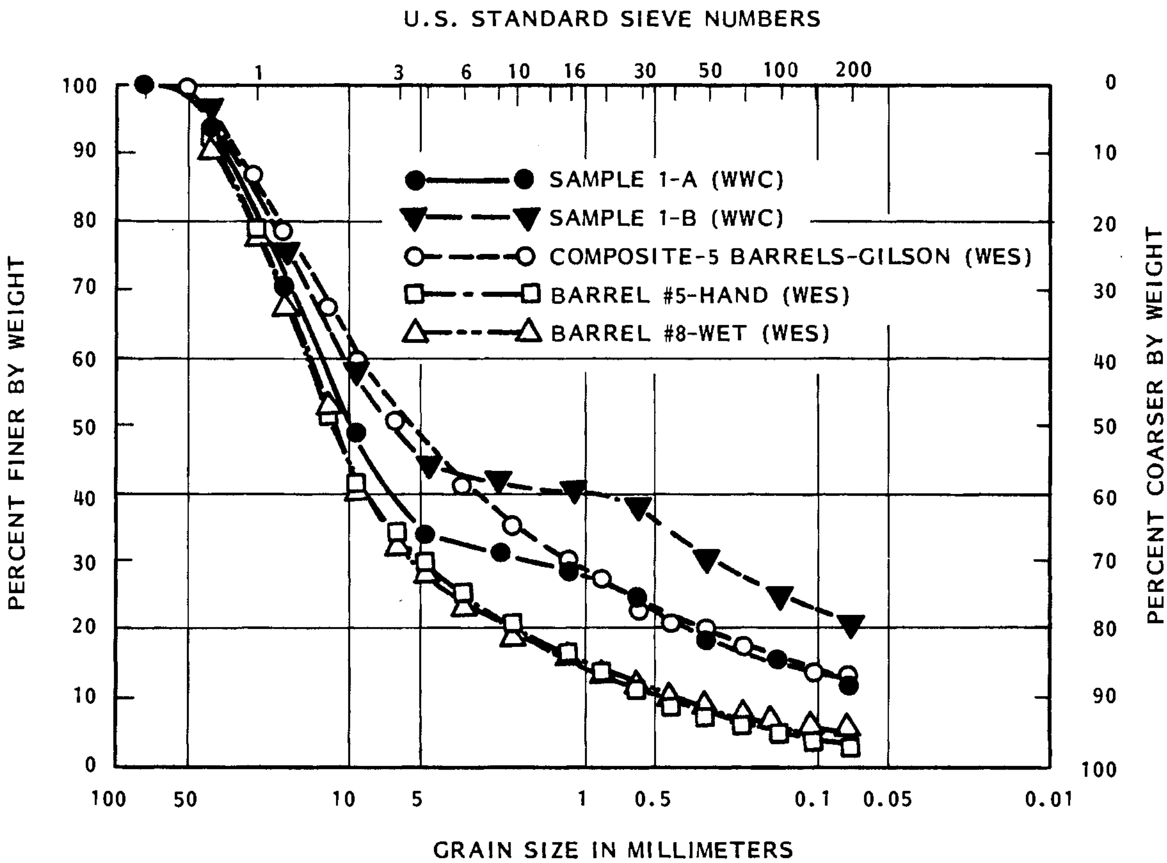


FIGURE 3.2. Comparison of Gradation Analyses for PARAHO Retorted Oil Shale (Townsend and Peterson 1979)

3.3 ATTERBERG LIMITS

The Atterberg limit tests determine, for fine-grained soils, the water contents at the boundaries between liquid, plastic, semisolid, and solid states. The plasticity index (PI), the difference between liquid and plastic limits, and liquid limit can be used to characterize mechanical properties of soil particles. The lower the plasticity index at a given liquid limit, the more likely it is that organic material is present and the greater the permeability and compressibility.

Summarized below are results of Atterberg limit tests conducted on PARAHO material by WES. WCC (Holtz 1976) listed PI values of 3 percent for PARAHO, which agree well with the results in Table 3.1.

TABLE 3.1. Summary of Atterberg Limits for PARAHO Shale (Townsend and Peterson 1979)

Fraction Number	LL[a]	PL[a]	PI[a]	Remarks
-40	29	29	NP[b]	Blenderized
-40	32	28	4	Blenderized, 9 mo. soak
-40	37	32	5	Blenderized, 18 mo. soak

(a) LL, PL, and PI = liquid limit, plastic limit, and plasticity index, respectively.
(b) NP = nonplastic

The increase in PI values from nonplastic to 5 percent after 18 months of inundation indicates that some breakdown and softening can occur with weathering of the shale.

3.4 SOIL CLASSIFICATION

The retorted PARAHO shales, as sampled, would be classified as a GP or GM soil under the Unified Classification System depending on the amount of gravel present and the plasticity of the fines. Soils in the GP group are poorly graded gravels and sands containing less than 5% of nonplastic fines.

In general, soils in the GM group include gravels or sands which contain more than 12% of fines having little or no plasticity. Gradation is not important, with both well graded and poorly graded materials included. Some soils and gravels in this group may have a binder composed of natural cementing agents, thus the dry strength is provided by a small amount of soil binder or by cementation of calcareous material or iron oxide. The fine fraction of noncemented materials may be composed of silts or rock-flour types having little or no plasticity, and the mixture will exhibit no dry strength.

It may be concluded that, in general, soils under these classifications indicate good compaction characteristics, good to excellent strength values, slight to medium compressibility, and overall a good foundation material.

4.0 ENGINEERING PROPERTIES

The major engineering properties pertinent to geotechnical engineers for the determination of an efficient disposal method for retorted oil shale in a structurally and environmentally safe manner are compaction, consolidation, strength, permeability, and soundness.

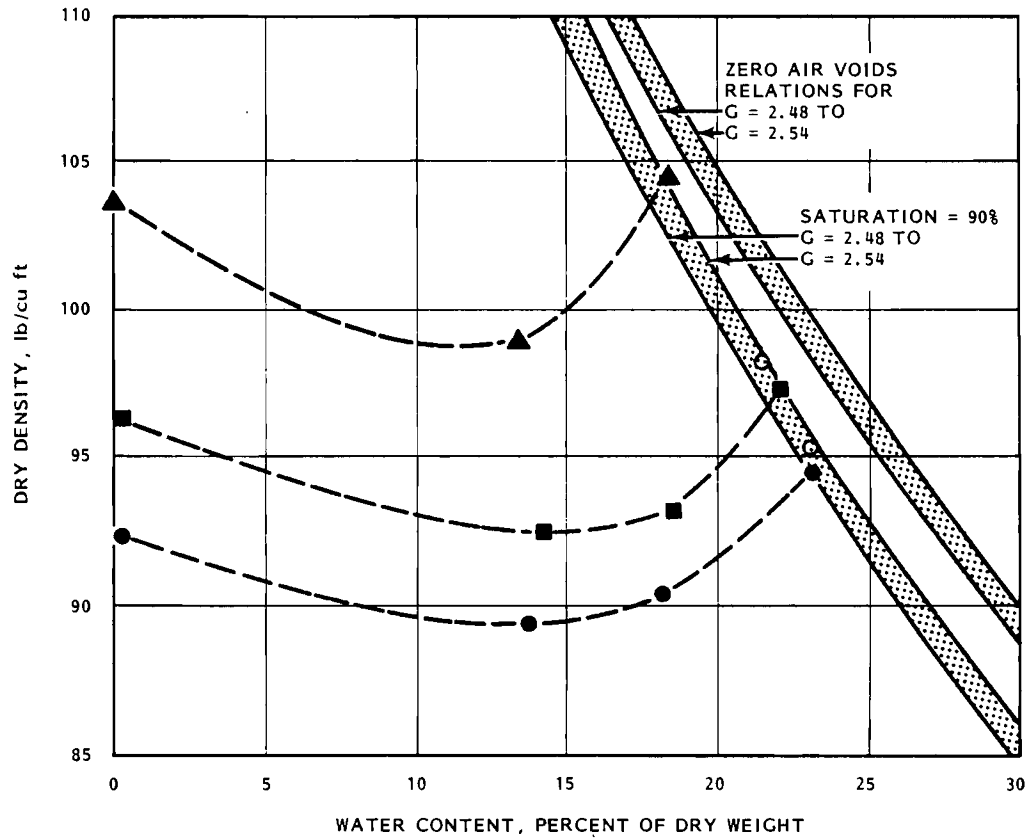
4.1 COMPACTION

Numerous laboratory compaction tests have been performed to evaluate the compaction characteristics of PARAHO material due to the importance of compaction in disposing of spent shale. Snethen et al. (1978) summarized the variability in compaction characteristics for this material in the following tabulation.

Compaction Energy KN/m^2 (psf)	ASTM Standard	Optimum Water Content w, %	Maximum Dry Density $\gamma_{d_{max}}$, KN/m^3 (pcf)
297 (6,200)	50 D698	18.5 - 23.7	12.1-15.6 (77.0-99.2)
592 (12,375) Standard	D698	15.5 - 22.0	12.6-16.2 (80.2-103.2)
2,693 (56,250) Modified	D1557	14.4 - 22.0	13.9-17.0 (88.8-108.4)

These variations are largely attributed to differences in retorting mode, variability of the unprocessed shale, gradation, and particularly the amount of fines.

Shown in Figure 4.1 are results of large scale [30.5 cm (12 in.) dia] compaction tests using 60 percent of standard, standard, and modified compactive efforts on minus 5 cm (2 in.) dia PARAHO material performed by WES. Companion tests performed on scalped and replaced minus 2 cm (3/4 in.) material using a 15 cm (6 in.) dia mold are shown in Figure 4.2. Using a 28 cm (11 in.) dia mold, vibrating table method maximum-minimum density tests were also performed on minus 5 cm (2 in.) and minus 2 cm (3/4 in.) dia material. Table 4.1 presents a summary of the compaction test data.

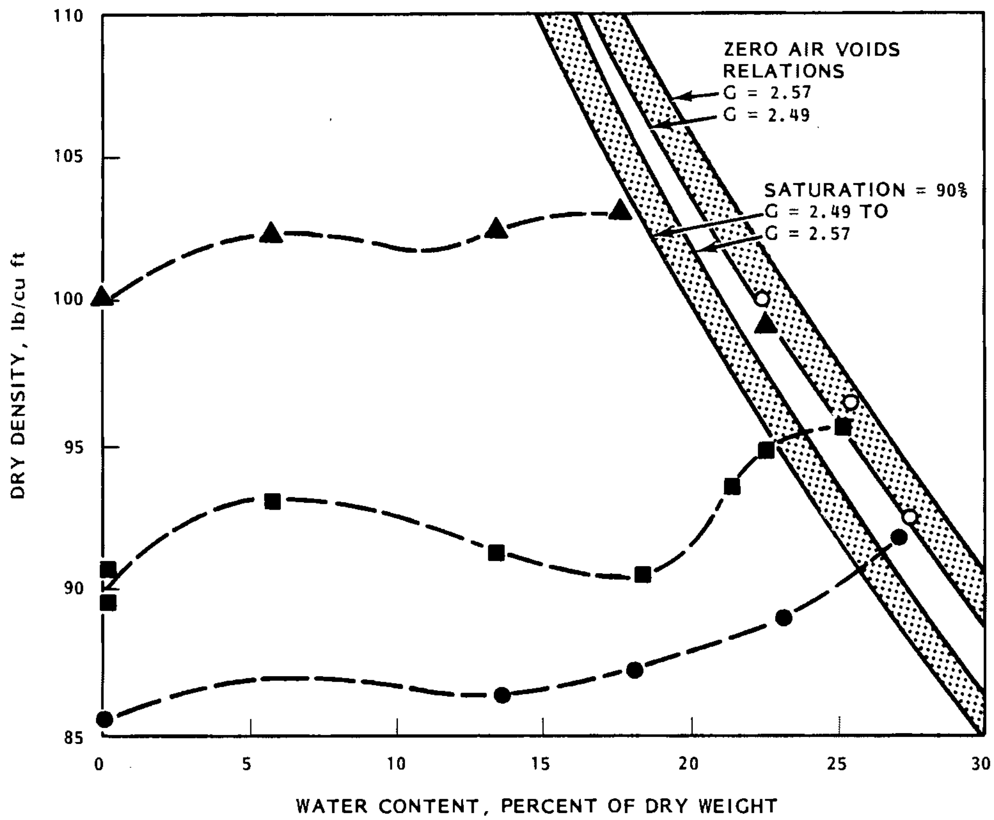


SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	G	LL	PL	% > NO. 4	% > 3/4 in.
		"AS BATCHED"	2.48		NP	72.5	33.5
●		60% STANDARD EFFORT	2.51		NP	63.0	28.5
■		STANDARD EFFORT	2.52		NP	58.0	25.5
▲		MODIFIED EFFORT	2.54		NP	49.0	19.5

SAMPLE NO.				
NATURAL WATER CONTENT, PERCENT				
OPTIMUM WATER CONTENT, PERCENT				
MAX DRY DENSITY, lb/cu ft				

REMARKS G_s = 2.67	PROJECT OIL SHALE (PARAHO)	
G_a = 2.42 NOTE: COULD NOT	12-in.-DIAM COMPACTION TESTS	
COMPACT MODIFIED EFFORT	AREA	
SAMPLE @ w = 23%	BORING NO.	DATE MARCH 1977
* FREE WATER	COMPACTION TEST REPORT	

FIGURE 4.1. Water Content-Density Relationship for 30.5 cm (12 in.) dia Compaction Test on PARAHO Retorted Oil Shale (Townsend and Peterson 1979)



SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	G	LL	PL	% > NO. 4	% > 3/4 in.
		"AS BATCHED"	2.49		NP	72.0	0
●		60% STANDARD EFFORT	2.53		NP	52.0	0
■		STANDARD EFFORT	2.54		NP	50.0	0
▲		MODIFIED EFFORT	2.57		NP	38.5	0

SAMPLE NO.				
NATURAL WATER CONTENT, PERCENT				
OPTIMUM WATER CONTENT, PERCENT				
MAX DRY DENSITY, lb/cu ft				

REMARKS G_s = 2.67	PROJECT OIL SHALE (PARAHO)	
G_a = 2.42	6-in.-DIAM COMPACTION TESTS	
* FREE WATER	AREA	
+NOTE: TEST DATA MAY BE	BORING TEST	DATE MARCH 1977
QUESTIONABLE.	COMPACTION TEST REPORT	

FIGURE 4.2. Water Content-Density Relationships for 15 cm (6 in.) dia Compaction Tests on Modeled PARAHO Retorted Oil Shale (Townsend and Peterson 1979)

TABLE 4.1. Summary of Compaction Test Results on PARAHO Oil Shale (Townsend and Peterson 1979)

Gradation Size	Compaction Effort	Maximum Dry Density $\gamma_{d_{max}}$ pcf	Minimum Dry Density $\gamma_{d_{min}}$ pcf	Water Content w, %	Relative Density D_r, %
Original (-2 in. fraction)	Vibration	89.2	66.0	---	---
	60% of standard	94.6	---	23.3	116.2
	Standard	97.5	---	22.2	124.2
	Modified	104.4	---	18.4	141.4
Scalped and replaced (-3/4 in. fraction)	Vibration	81.8	62.9	---	---
	60% of standard	91.9	---	27.2	136.6
	Standard	95.7	---	25.2	148.3
	Modified	103.1	---	17.7	168.8
Parallel (-3/4 in. fraction)	Standard	88.9		0.2	
		88.0		22.8	
Scalped (-3/4 in. fraction)	Standard	88.7		0.2	
		92.5		23.1	

The results presented in Figures 4.1 and 4.2 indicate that both full scale and scalped and replaced materials produced significantly higher densities with increased compaction effort. A comparison of results in Table 4.1 also shows that the scalping and replacement procedure underestimates the maximum dry density and overestimates the optimum water content. Others have also observed that scalping and replacement modeling fails to achieve results comparable to full scale (Snethen et al. 1978).

Table 4.2 compares results between the WES and WCC study. These comparisons show that the material tested at WES produced greater densities due to its greater amount of coarse particles for both the minus 5 cm (2 in.) and minus 2 cm (3/4 in.) gradations than did the finer grained WCC minus 4 cm (1 1/2 in.) and minus 2 cm (3/4 in.) gradations.

TABLE 4.2. Comparison of Compaction Results on PARAHO (Townsend and Peterson 1979)

	WES -2 in. Material Breakage			WCC -1-1/2 in. Material Breakage			WES -3/4 in. Material Breakage			WCC -3/4 in. Material Breakage		
Compaction Effort ft-lb/ft^3	w_{opt}[a] %	$\gamma_{d_{max}}$ pcf	B	w_{opt} %	$\gamma_{d_{max}}$ pcf	B	w_{opt} %	$\gamma_{d_{max}}$ pcf	B	w_{opt} %	$\gamma_{d_{max}}$ pcf	B
6,200[b] or 7,425[c] (50% or 60% of standard)	23.3	94.6	11	22	87.5	19	27.2	91.9	20	27.2	85.5	10
12,375 (standard)	22.2	97.5	16	22	94.8	22	25.3	95.7	24	25.2	90.2	17
56,250 (modified)	18.4	104.4	25	22	98.9	25	17.7	103.1	34	22.0	96.4	20

(a) w_{opt} = optimum water content
(b) WCC
(c) WES

The extent of particle breakage during compaction for tests performed by WES on full scaled and scalped and replaced gradations of PARAHO material are shown in Figures 4.3 and 4.4, respectively. Little difference in the magnitude of particle breakage exists for 60 percent of standard and standard compaction effort. Considerable breakage occurs, however, when modified effort is applied. Table 4.3 summarizes the breakage factor B, for the full scale and scalped and replaced compaction tests. These B values show a progressive increase with compaction effort.

Similar results were obtained by PNL where full scale compaction tests, using a 15 cm (6 in.) dia mold, were performed under standard, 50 percent modified, and modified compaction effort. Sieve analyses were performed after each compaction test and the results are summarized in Figure 4.5.

For materials containing less than 12 percent fines ASTM criteria recommend using a vibratory table method to obtain the maximum dry density. The maximum dry density achieved by vibration was only 14.0 and 12.8 KN/m^3 (89.2 and 81.8 pcf) for full scale and scalped and replaced gradations, respectively, for the WES "as batched" gradations containing only 3 percent fines. These results are considerably lower than the maximum dry density achieved by 60 percent of standard compaction effort shown in Table 4.1.

WCC also presented results showing that vibratory densification produced lower densities than those achieved by impact compaction. Hence, it might be concluded that retorted PARAHO shale does not respond favorably to vibratory compaction. This, however, is contrary to field compaction test which showed that the most economical compaction of PARAHO material could be obtained using a vibratory drum roller (Holtz 1976, Snethen et al. 1978).

4.2 CONSOLIDATION

Settlement properties are very important in assessing the stability of an embankment constructed of retorted shales. Further, the total volume required in a disposal site, its permeability, and strength characteristics are influenced by consolidation of retorted shale.

Snethen et al. (1978) reported settlement properties on retored shale. Summarized in Table 4.4 are the percent settlement for the various applied loads (ASTM D698 energy).

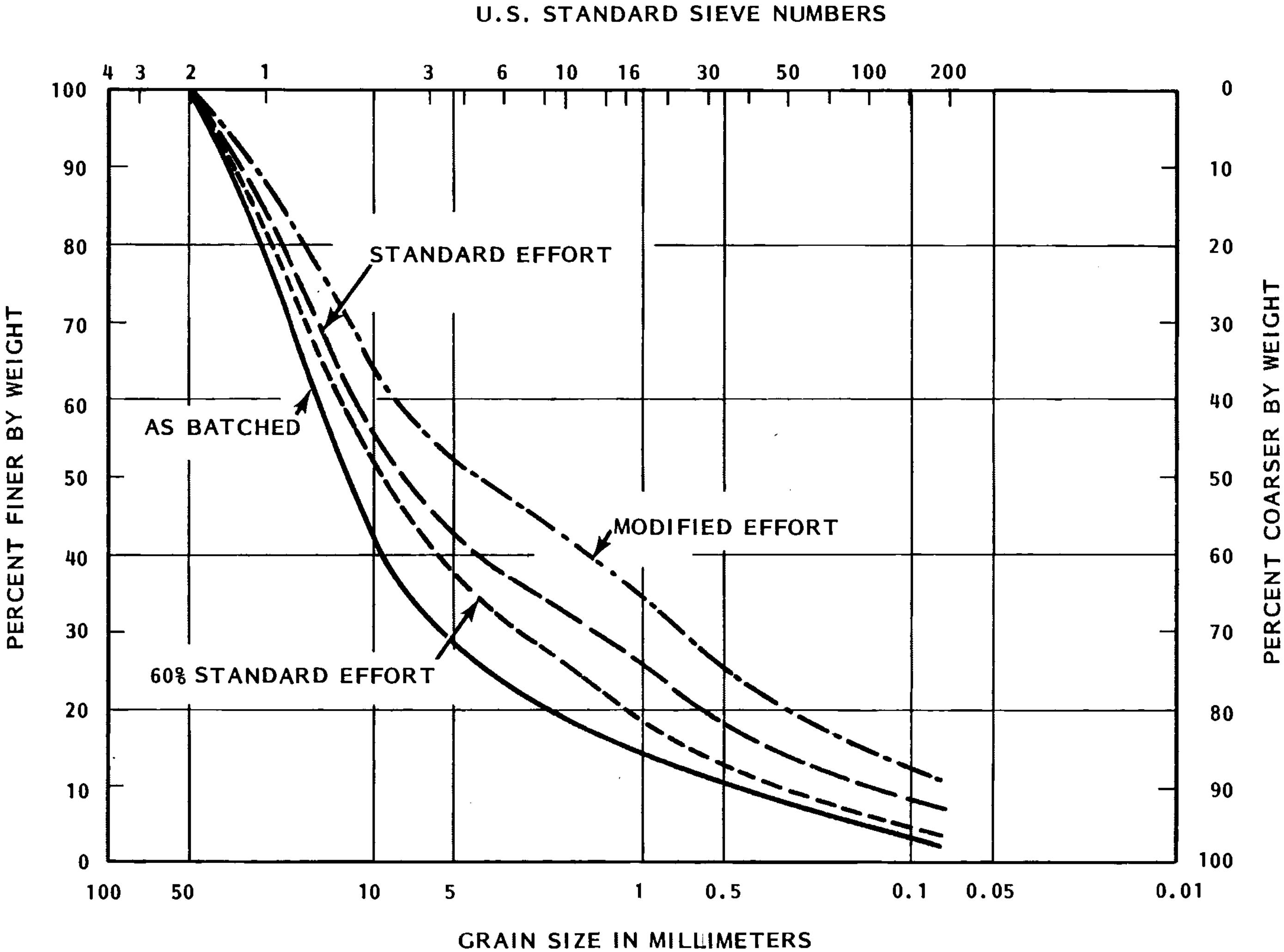


FIGURE 4.3. Effects of Compaction Effort on Gradation for 30.5 cm (12 in.) dia Compaction Tests on PARAHO Retorted Oil Shale (Townsend and Peterson 1979)

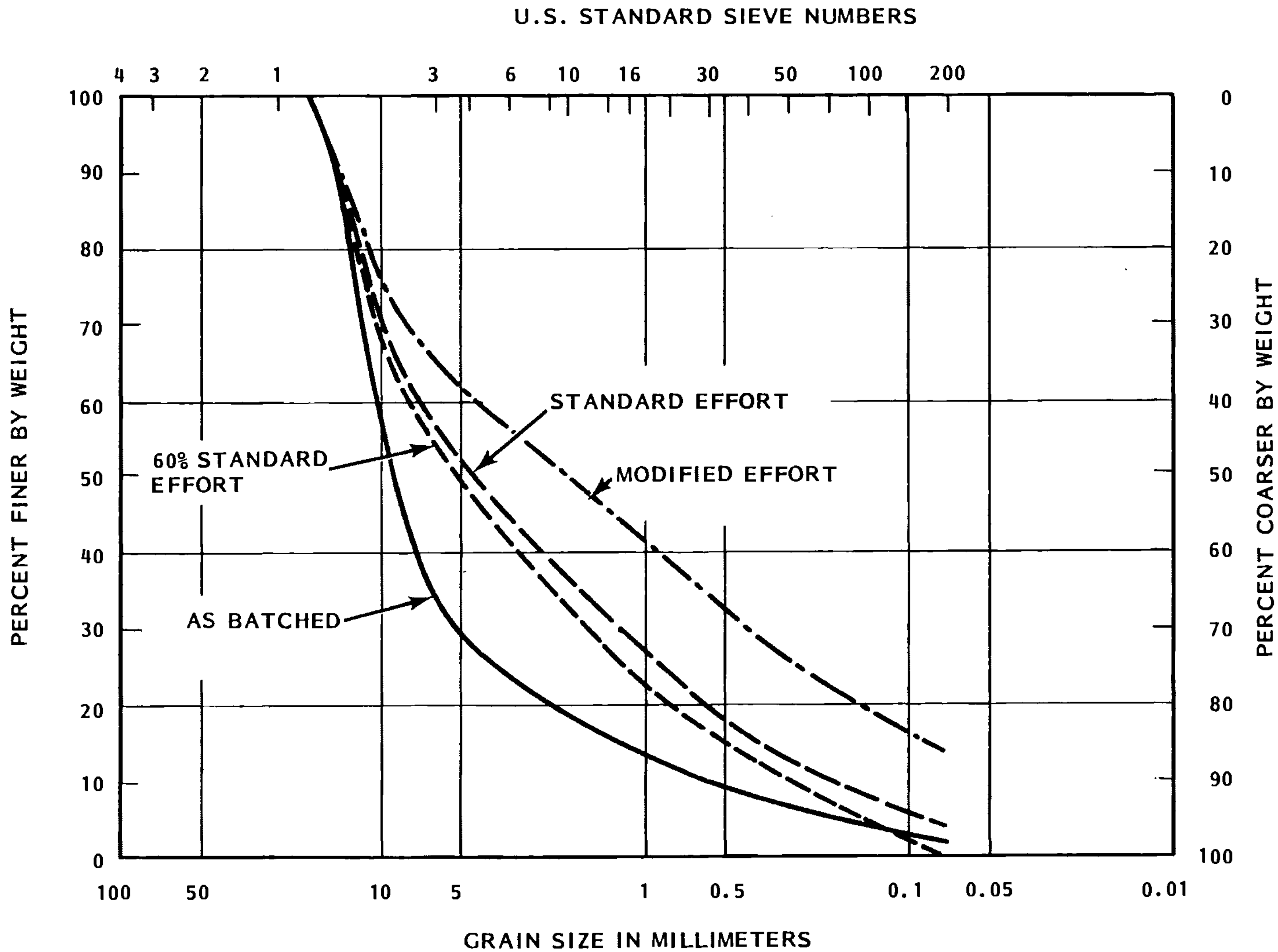


FIGURE 4.4. Effects of Compaction Effort on Gradation for 15 cm (6 in.) dia Compaction Tests on PARAHO Retored Oil Shale (Townsend and Peterson 1979)

TABLE 4.3. Breakage Factors Due to Compaction of PARAHO Material (Townsend and Peterson 1979)

	Original											Scalped and Replaced										
	Initial		60% of Standard			Standard			Modified			Initial		60% of Standard			Standard			Modified		
Sieve Size	% Pass	% Retain	% Pass	% Retain	Diff Δ	% Pass	% Retain	Diff Δ	% Pass	% Retain	Diff Δ	% Pass	% Retain	% Pass	% Retain	Diff Δ	% Pass	% Retain	Diff Δ	% Pass	% Retain	Diff Δ
2+	100	0	100			100	0		100	0												
2 to 1-1/2	93	7	95	5	-2	96	4	-3	97	3	-4											
1-1/2 to 1	80	13	82	13	0	85	11	-2	90	7	-6											
1 to 3/4	67	13	73	9	-4	77	8	-5	82	8	-5	100	0	100	0		100			100		
3/4 to 1/2	50	17	58	15	-2	63	14	-3	71	11	-6	70	30	83	17	-13	83	17	-13	84	16	-14
1/2 to 3/8	40	10	51	7	-3	55	8	-2	63	8	-2	52	18	67	16	-2	70	13	-5	74	10	-8
3/8 to 4	27	13	37	14	+1	43	12	-1	52	11	-2	28	24	48	19	-5	52	18	-6	62	12	-12
4 to 10	18	9	27	10	+1	33	10	+1	42	10	+1	19	9	33	15	+6	37	15	+6	52	10	+1
10 to 20	13	5	17	10	+5	24	9	+4	32	10	+5	12	7	22	11	+4	24	13	+6	39	13	+6
20 to 40	9	4	13	4	0	17	7	+3	23	9	+5	8	4	13	9	+5	17	7	+3	30	9	+5
40 to 100	5	4	7	6	+2	11	6	+2	15	8	+4	4	4	5	8	+4	8	9	+5	19	11	+7
100 to 200	3	2	3	4	+2	8	3	+1	10	5	+3	3	1	4	1	0	5	3	+2	14	5	+4
		3		3	0		8	+5		10	+7		3		4	+1		5	+2		14	+11
"B" factor					11			16			25					20			24			34

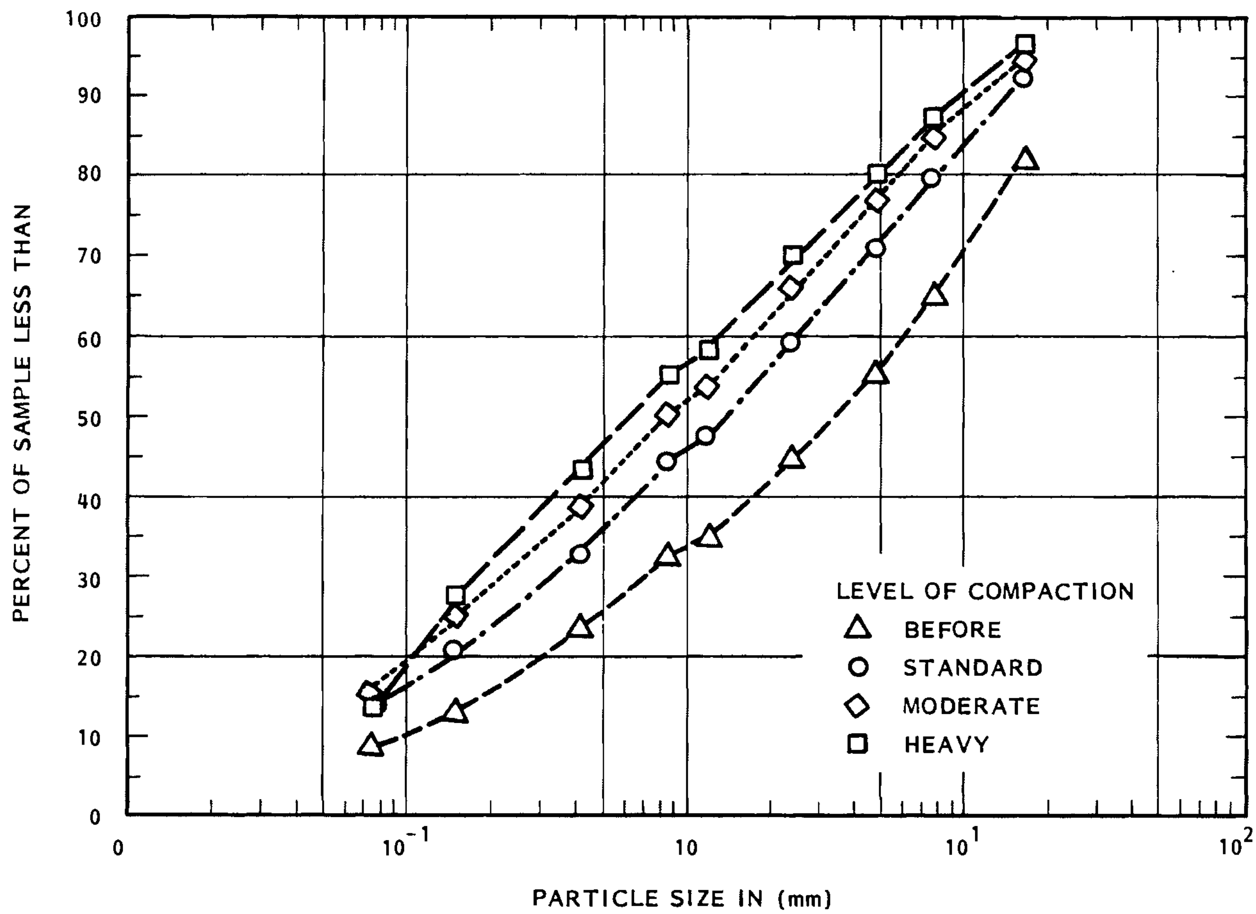


FIGURE 4.5. PARAHO Shale Particle Size Distribution After Compaction

TABLE 4.4. Percent Settlement Versus Applied Load for Retorted PARAHO Shale (Snethen et al. 1978)

Material	Applied Load psi	Applied Load KN/m^2	Settlement percent	Dry Density pcf	Dry Density KN/m^3
PARAHO	50	345	0.7 - 2.8	95.5 - 88.0	15.0 - 13.8
	100	689	0.8 - 3.4	95.5 - 98.3	15.0 - 15.4
	200	1379	0.8 - 4.8	95.5 - 98.3	15.0 - 15.4
	70	483	0.4 - 3.4	88.8 - 102.5	13.9 - 16.1
	145	1000	0.7 - 4.8	85.0 - 97.4	13.4 - 15.3
	300	2068	0.8 - 5.6	85.0 - 97.4	13.4 - 15.3
	1000	6895	5.3 - 10.7	80.2 - 96.6	12.6 - 15.2

The total vertical strains in the WES study varied from 4.7 to 10.0 percent when the vertical stress was 5,516 KN/m^2 (800 psi) and the maximum dry density around 15.3 KN/m^3 (97.5 pcf) for standard compaction energy. WCC obtained settlement values ranging from 2.2 to 11.3 percent with a vertical stress of 6,895 KN/m^2 (1000 psi) and a maximum dry density of 14.2 KN/m^3 (90.2 pcf). These results agree quite well with each other, as well as the results presented by Snethen et al. (1978).

The compressibility of compacted PARAHO material is comparable to that of dense rockfill or sands. Approximately 28 percent particle breakage during consolidation can be experienced for standard effort densities consolidated to 5,516 KN/m^2 (800 psi) normal stress.

4.3 STRENGTH

The stability or load carrying capacity of retorted oil shale is determined by its strength characteristics. Strength has been quantified using several parameters and tests, i.e., compressive strength, modulus values, and triaxial shear strength.

4.3.1 Unconfined Compression Test

The self-cementing characteristics of spent shale are well documented (Farris 1979, Holtz 1976, Snethen et al. 1978, Townsend and Peterson 1979) and have been tested by the unconfined compression test. Summarized in Figure 4.6 and Table 4.5 are unconfined compression results for PARAHO material performed by WES. Comparisons between these results and previous test results by WCC are given below.

Unconfined Compressive Strength, psi

Compaction Effort	WES		WCC
	0d	28d	28d at 123°F
60% of Standard	5.7	27.4	150 to 175
Standard	8.2	66.8	150 to 175
Modified	61.3	194.8	175 to 200

d - days
psi = 6.894 KN/m^2

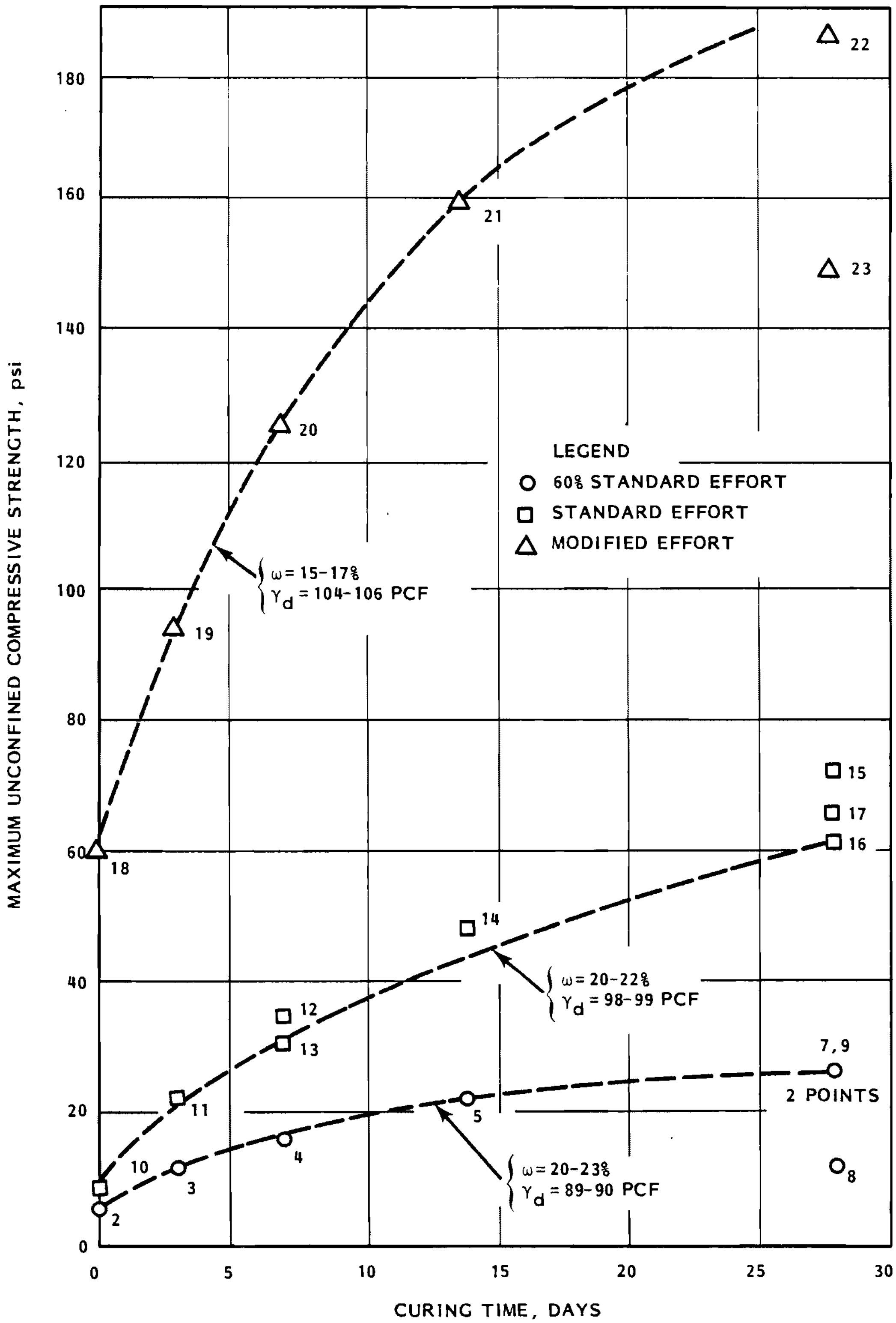


FIGURE 4.6. Effect of Curing Time on the Unconfined Compressive Strength for Compacted PARAHO (1 psi = 6.9 kPA) (Townsend and Peterson 1979)

TABLE 4.5. Summary of Unconfined Test Results on PARAHO Oil Shale (Townsend and Peterson 1979)

Symbol Number on Figure	Test No.	Compaction Effort	Curing Time days	As Tested: Water Content w, %	As Tested: Dry Density γ_d, pcf	Maximum Unconfined Strength psi	Maximum Unconfined Strength tsf	Secant Young's Modulus to 1/2 Maximum Unconfined Strength psi	Secant Young's Modulus to 1/2 Maximum Unconfined Strength tsf	Remarks
1	UC-L-0-9	60% standard	0	22.8	89.2	--	--	--	--	Questionable results
2	UC-L-0-9A		0	22.5	89.8	5.7	0.41	720	51.5	
3	UC-L-3-10		3	21.6	89.3	11.9	0.86	650	46.5	
4	UC-L-7-11		7	21.5	90.3	16.3	1.17	1,560	112.0	
5	UC-L-14-12		14	20.5	90.4	22.8	1.64	Not available		Initial strain data are questionable
6	UC-L-28-13		28	20.2	97.1	51.3	3.69	2,730	196.5	
7	UC-L-28-13A		28	23.0	93.0	27.4	1.97	1,180	85.5	Soaked overnight before test conducted
8	UC-L-28-13B		28	20.4	82.9	12.5	0.90	1,130	81.5	
9	UC-L-28-13C		28	20.4	90.5	27.4	1.97	1,840	132.5	
10	UC-S-0-5	Standard	0	20.7	99.6	8.2	0.59	510	37.0	
11	UC-S-3-6		3	21.4	99.0	22.4	1.61	890	64.0	
12	UC-S-7-1		7	21.3	98.0	35.6	2.56	950	68.5	Mellowed 16 hr before compacting
13	UC-S-7-4		7	21.3	98.2	31.1	2.24	1,430	103.5	
14	UC-S-14-7		14	20.3	100.9	49.3	3.55	2,230	160.5	
15	UC-S-28-2		28	20.4	98.3	73.6	5.30	3,640	262.0	Mellowed 16 hr before compacting
16	UC-S-28-3		28	22.1	98.1	62.3	4.49	2,740	197.0	Mellowed 16 hr before compacting; soaked overnight before test conducted
17	UC-S-28-8		28	19.5	101.2	66.8	4.81	2,630	189.0	
18	UC-M-0-14	Modified	0	17.2	104.4	61.3	4.41	4,100	295.0	
19	UC-M-3-15		3	16.6	105.8	95.6	6.88	4,240	305.0	
20	UC-M-7-16		7	15.6	105.2	127.0	9.14	8,170	588.0	
21	UC-M-14-17		14	15.7	105.5	161.6	11.64	12,000	864.0	
22	UC-M-28-18A		28	17.4	107.2	194.8	14.03	11,818	850.9	Soaked overnight before test conducted
23	UC-M-28-18B		28	15.1	106.5	151.4	10.90	11,818	850.9	

Considering differences in curing temperatures, percent fines and gradation differences, and the amount of time between retorting and compaction (all affecting cementing reactions) the variance between the two studies for the 60% of standard and standard compaction effort may be explained. The comparisons are fairly close for the modified compaction effort, however.

The time between mixing and compaction, "mellowing time", is an important construction consideration for stabilized soils. The results presented in Table 4.5 shows that mellowing times up to 16 hours had no effect on resulting unconfined compressive strengths. If self-cementing is desired several important design and construction guidelines are evident based upon these considerations (Snethen et al. 1978):

1. PARAHO satisfies recommended criteria for lime stabilized soils, hence, would be judged as a suitable stabilized material.
2. Increased density produces higher strengths.
3. Mellowing times up to 16 hours have little effect on self-cementing of PARAHO. This time should be kept to a minimum, however. Increased compaction effort can be substituted to obtain greater strengths, if the expense of increased compaction effort is justified.
4. The self-cementing components do not deteriorate significantly due to exposure to air after retorting. To maximize self-cementing, exposure time between retorting and placement should be minimized.
5. Self-cementing characteristics of PARAHO are retained.
6. Cementing reactions under normal curing conditions for PARAHO are slow. Additional strength gains are indicated after 28 days. Heavy equipment should be restricted from tracking compacted areas at least 7 to 14 days following compaction.

An equation to estimate the 3 to 8 fold increase in compressive strength from the cementation has been proposed by Farris (1979) and given below.

$$CS^* = \frac{A}{1 + De^{-KT}} \tag{4.1}$$

where,

CS = compressive strength, psi

A = coefficient related to ultimate compressive strength, psi

D = coefficient related to initial compressive strength, 1/psi

K = coefficient related to rate of cementation, 1/days

T = curing time, days

* Considerable variability in the results was observed; the predictive equation above fits the results to within approximately 345 KN/m^2 (50 psi) (Farris 1979).

With an assumed safety factor of 3, a design loading value of 572 KN/m^2 (83 psi) can be considered when using PARAHO materials for construction of waste disposal dams and embankments (Farris 1979). Inconsistent quality of the material would require careful considerations of its properties and variability for engineering design use, however.

4.3.2 Triaxial Compression Test

Presented in Table 4.6 is a summary of consolidated-drained (S) and undrained ($\overline{R}$) triaxial compression tests on PARAHO material performed by WES. Interpretation of shear strength parameters based on total stresses from $\overline{R}$ test envelopes is influenced by several factors:

1. curved failure envelopes,
2. negative pore pressures, and
3. criteria selecting maximum deviator stress.

Typically the failure envelope is curved, based upon total stresses, thus the angle of internal friction (ϕ) and cohesion (C) are often only for the higher confining stresses.

WCC provided strength parameters of C' = 1.95 kg/cm^2 (27.7 psi) and ϕ' = 34.2 degrees for S triaxial compression tests on 15 cm (6 in.) dia specimens of 4 cm (1 1/2 in.) maximum particle sized PARAHO material at standard density (Holtz 1976). Where ϕ' and C' are the effective angle of friction and effective cohesion, respectively. These values agree quite well with those observed in the WES investigation.

TABLE 4.6. Summary of Consolidated-Drained (S) and -Undrained ($\bar{R}$) Triaxial Compression Tests on PARAHO Material (Townsend and Peterson 1979)

Test No.(a)	Compaction Effort(b)	Specimen Conditions, Initial: Water Content w, %	Initial: Dry Density γ_d pcf	Initial: Saturation S, %	Initial: Void Ratio e	After Consolidation: Dry Density γ_d pcf	After Consolidation: Void Ratio e	Maximum B Before Consolidation $B = \Delta u/\Delta\sigma_3$	Permeability cm/sec	At Maximum Effective Stress Ratio, $\bar{\sigma}_1/\bar{\sigma}_3$: Principal Stress Difference $\sigma_1 - \sigma_3$ kg/cm²	Induced Pore Pressure $u - u_{o_2}$ kg/cm²	Volumetric Strain $\Delta V/V_o$ %	Effective Minor Principal Stress $\bar{\sigma}_3$ kg/cm²	Effective Stress Ratio $\bar{\sigma}_1/\bar{\sigma}_3$	Pore Pressure Parameter, A $A = \frac{u - u_o}{\sigma_1 - \sigma_3}$	Strain ε %
S-P-9-L-20-1	(1)	17.0	90.1	57.8	0.738	90.9	0.724	0.97	1.5×10^{-2}(c)	6.23	N/A	2.65	1.66	4.75	N/A	15.02
S-P-9-L-40-1		18.3	89.3	62.2	0.753	91.4	0.714	0.97	1.0×10^{-2}(c)	8.95	N/A	4.81	3.04	3.94	N/A	13.2
S-P-9-L-80-1		23.3	89.2	79.1	0.756	92.2	0.700	0.97	5.8×10^{-3}	14.29	N/A	6.29	5.86	3.44	N/A	14.2
S-P-9-L-160-1		17.8	88.7	60.6	0.765	95.4	0.643	0.96	2.7×10^{-3}	27.54	N/A	7.61	11.35	3.43	N/A	15.2
$\bar{R}$-P-9-S-20-1	(2)	18.7	95.1	72.8	0.654	95.9	0.640	0.97	4.6×10^{-3}	4.03	0.68	N/A	0.80	6.02	0.17	1.5
$\bar{R}$-P-9-S-40-1		17.3	95.1	67.2	0.654	96.6	0.629	0.98	1.9×10^{-3}	6.13	1.59	N/A	1.38	5.45	0.26	2.0
$\bar{R}$-P-9-S-160-1		17.5	95.2	68.2	0.652	98.1	0.604	0.96	5.2×10^{-4}	10.61	8.65	N/A	2.73	4.89	0.81	5.1
S-P-9-S-80SR-1		18.1	96.5	70.6	0.629	98.0	0.618	0.97	6.8×10^{-4}	18.79	N/A	1.80	5.72	4.28	N/A	7.8
S-P-9-S-80-2		18.6	94.6	72.7	0.662	97.0	0.622	0.97	6.2×10^{-4}	14.81	N/A	4.20	5.69	3.60	N/A	14.24
S-P-9-M-20-1	(3)	13.1	98.7	51.5	0.606	99.5	0.594	0.98	5.9×10^{-4}	10.34	N/A	0.48	1.57	7.58	N/A	1.5
S-P-9-M-40-1		12.9	100.3	50.6	0.581	101.2	0.567	0.97	7.6×10^{-4}	14.35	N/A	0.57	2.95	5.86	N/A	1.8
$\bar{R}$-P-9-M-80-1		13.0	100.3	51.2	0.581	101.8	0.558	0.97	4.6×10^{-4}	12.32	3.56	N/A	2.22	6.55	0.29	1.0
S-P-9-M-160-1		12.8	98.5	50.4	0.601	101.7	0.559	0.99	5.7×10^{-4}	32.23	N/A	2.24	11.33	3.84	N/A	7.0

(a) S = consolidated-drained; $\bar{R}$ = consolidated-undrained; P = PARAHO; SR = scalped and replaced gradation; 9 = 9-in. dia; 6 = 6-in. dia; L, S, and M = low, standard, or modified compaction effort; 20, 40, 80, or 160 = confining pressure; 1 or 2 = specimen number. Example: S-P-9-L-20-1 = 9-in.-dia PARAHO specimen, low compaction effort, 20 psi confining pressure, test specimen No. 1.
(b) (1) indicates 60% of standard (G_s = 2.51); (2) standard (G_s = 2.52); and (3) modified (G_s = 2.54).
(c) Permeability data may be questionable.

Figures 4.7 and 4.8 present the effective stress paths, Mohr's circles based on maximum effective principle stress ratio, and the total and effective stress envelopes for PARAHO materials. The following tabulation summarizes and compares the total and effective stress parameters (Townsend and Peterson 1979).

Material and Compaction Effort	Maximum Particle Size, in.	Total Stress		Effective Stress	
		ϕ, deg	c, kg/cm^2	ϕ', deg	c', kg/cm^2
PARAHO					
9-in.-diam, 60% of Standard	1-1/2			33.0	0.9
Standard	1-1/2	14.5	1.3	32.7	0.8
Modified	1-1/2	31.0[a]	0	32.3	1.9
Modeled PARAHO					
9-in.-diam, Standard[a]	3/4			38.0	0
6-in.-diam, Standard	3/4	17.1	1.7	37.9	1.1
PARAHO Fines					
1.4-in.-diam, Standard		23.2	1.7	33.6	2.3

(a) Based upon single test.

For these confining stresses typically well graded compacted gravels have effective angles of internal friction ranging from 40 to 45 degrees. It may be concluded that PARAHO is slightly weaker than similarly graded gravels even though it possess adequate strength. Further, increased compaction effort does not noticeably improve PARAHO's shear strength parameters.

4.4 PERMEABILITY

Figure 4.9 presents results of permeability measurements, preceding shear of triaxial compression tests, on specimens of PARAHO materials compacted to densities comparable to 60 percent of standard, standard, and modified compaction efforts performed by WES. Also shown are permeability values based upon consolidation tests by WES. Both sets of data are consistent and show decreasing permeabilities with decreasing void ratios. For 60 percent of standard effort densities the permeabilities for PARAHO decreased from 10^{-3} cm/s to 10^{-4} cm/s for modified effort densities. The permeabilities determined from consolidation tests reflect lower values due to lower void ratios achieved from higher consolidation stresses.

TEST NO.	AFTER CONSOLIDATION γ_d, PCF	AFTER CONSOLIDATION e	COEFFICIENT OF PERMEABILITY K, cm/sec	MATERIAL GRADATION	REMARKS
R-P-9-S-20-1	95.9	0.640	4.6×10^{-3}	ORIGINAL	UNDRAINED
R-P-9-S-40-1	96.6	0.629	1.9×10^{-3}	ORIGINAL	UNDRAINED
R-P-9-S-160-1	98.1	0.604	5.2×10^{-4}	ORIGINAL	UNDRAINED
S-P-9-S-80SR-1	98.0	0.618	6.8×10^{-4}	SCALPED + REPLACED	DRAINED
S-P-9-S-80-2	97.0	0.622	6.2×10^{-4}	ORIGINAL	DRAINED

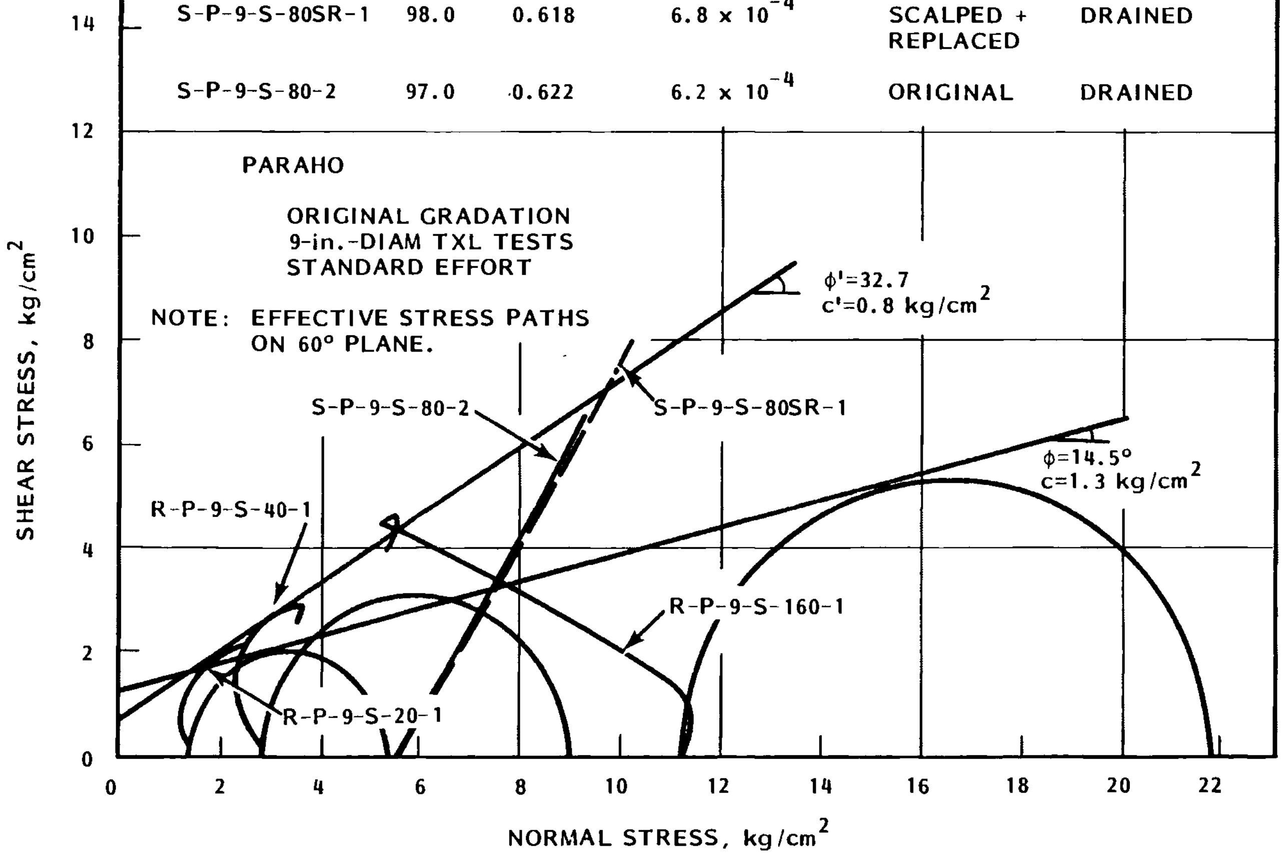


FIGURE 4.7. Total and Effective Stress Envelopes for PARAHO Compacted to Standard Effort Density (Townsend and Peterson 1979)

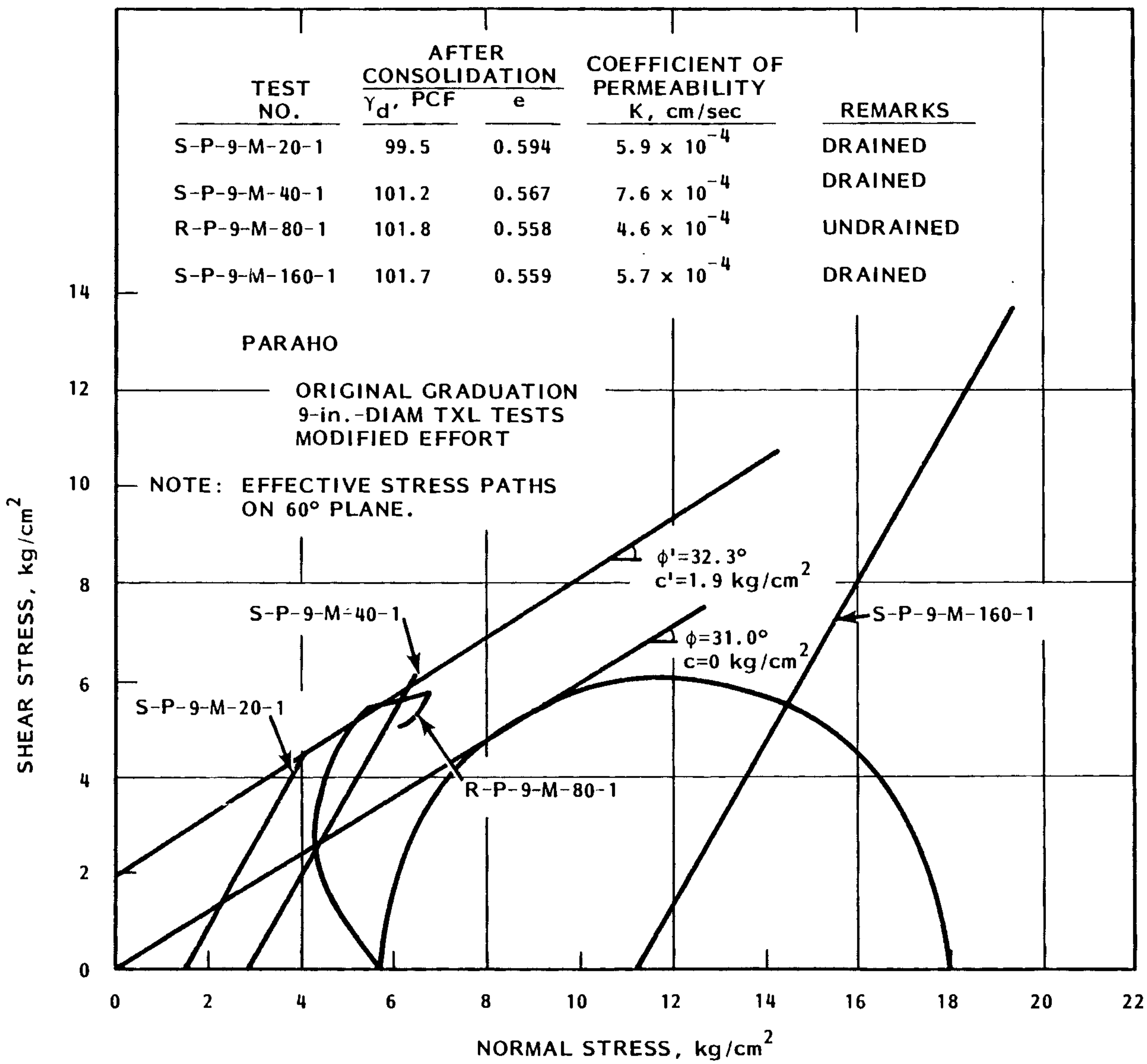


FIGURE 4.8. Effective Stress Envelope for PARAHO Compacted to Modified Effort Density (Townsend and Peterson 1979)

Permeability values determined by WCC on 20 cm (8 in.) dia specimens of 4 cm (1 1/2 in.) PARAHO material are also presented in Figure 4.9 for comparison. This comparison shows considerably lower permeabilities for comparable void ratios due to the greater amount of fines for WCC material than the WES material.

Using two different sampling apparatuses, permeability data were collected for full size PARAHO material at PNL and the results shown in Table 4.7. A 18 cm by 18 cm (7 in. by 7 in.) square column, 2 m (6 ft) high was used along with a 15 cm (6 in.) dia cylindrical cell, 15 cm (6 in.) high for comparison. Both apparatuses were packed with a low density and a high density pack. The permeability range between the two apparatuses is shown in Figure 4.10 for each respective packing.

The results of Townsend and Peterson (1979) are also shown in Figure 4.10 for comparison. The variance between results are due to differences in packing conditions (density) and the amount of fines present.

4.5 SOUNDNESS

The soundness of an aggregate material is a measure of its ability to resist degradation from an applied force. Soundness is quantified using the Los Angeles Abrasion test (LAA). Shown below is a summary of Los Angeles Abrasion tests on PARAHO shale. With LAA values of 79.7, 80.1, and 66.7 percent for the various gradations the PARAHO retorted shale is quite susceptible to abrasion. All of the values exceed the maximum acceptable value of 40 percent for base coarse materials.

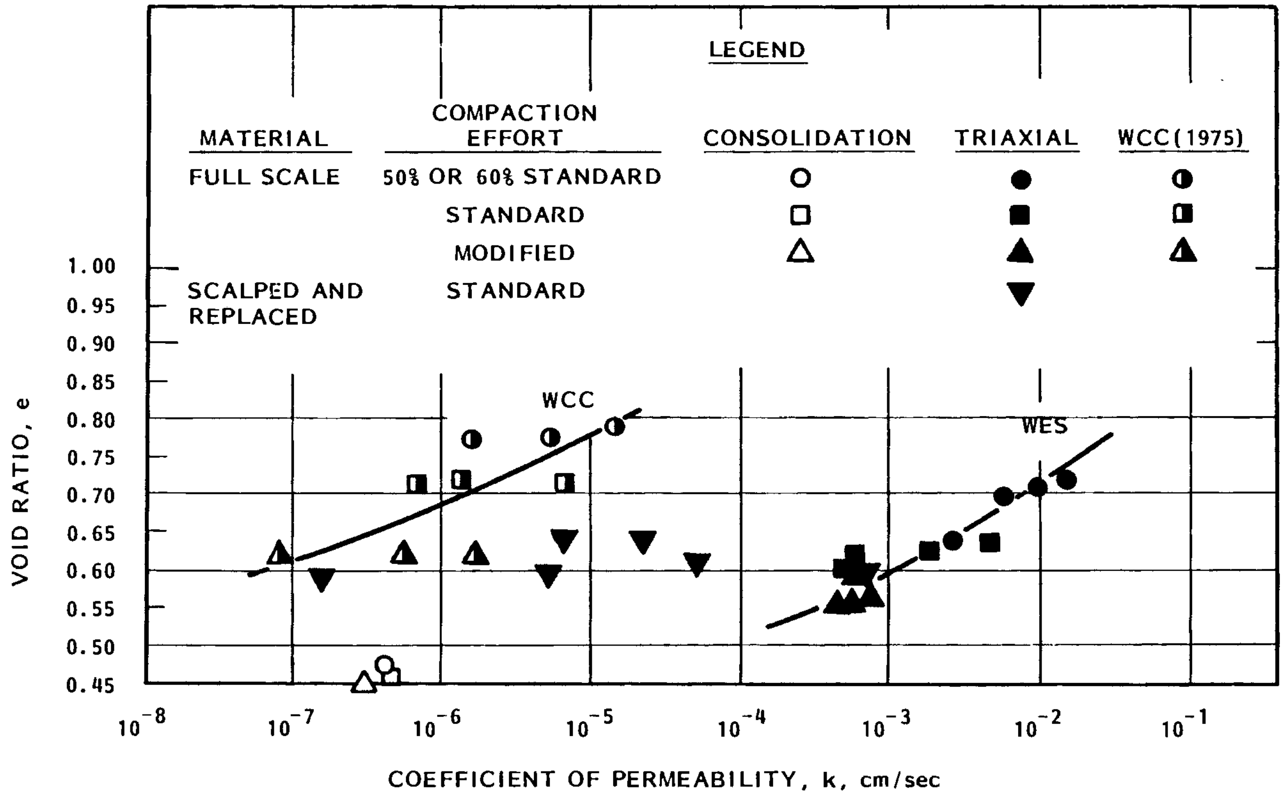


FIGURE 4.9. Permeability-Void Ratio Relationships for Compacted PARAHO Retorted Oil Shale (Townsend and Peterson 1979)

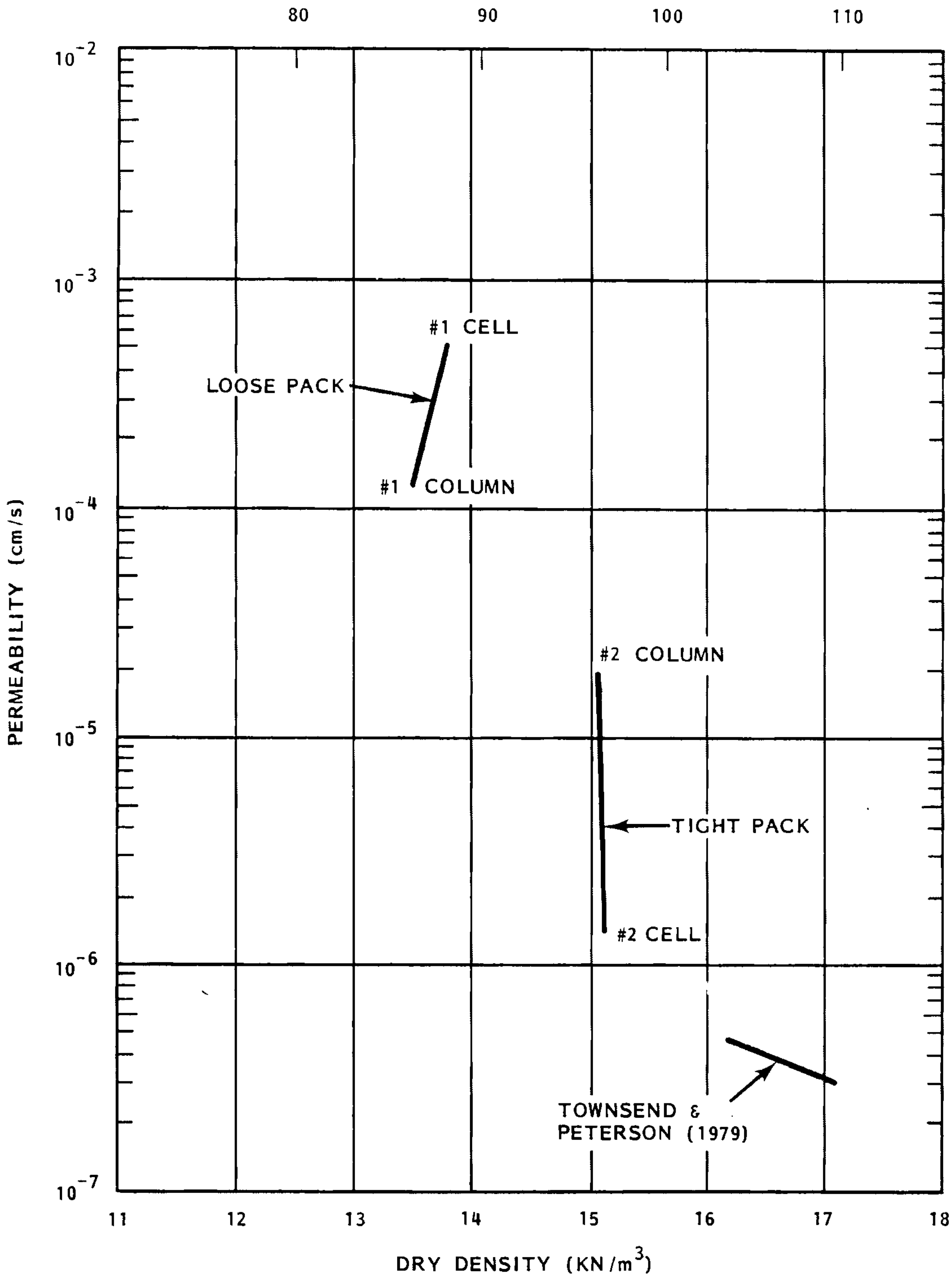


FIGURE 4.10. Permeability Values for Full Size PARAHO Material

TABLE 4.7. Permeability of PARAHO Shale at Different Dry Bulk Densities

Sample	Dry Bulk Density (g/cm3)	Permeability (cm/s)
Column No. 1 (Loose Pack)	1.32	1.2×10^{-4}
Column No. 2 (Tight Pack)	1.53	2.0×10^{-5}
Cell No. 1 (Loose Pack)	1.41	5.0×10^{-4}
Cell No. 2 (Tight Pack)	1.54	1.4×10^{-6}

TABLE 4.8. Summary of Los Angeles Abrasion Test Results on PARAHO Shale (Townsend and Peterson 1979)

Material	ASTM Designation	Grading	Sieve Size, in.	Percentage Wear
PARAHO	C131-76	A	- 1-1/2 to + 1	79.7
			- 1 to + 3/4	
			- 3/4 to + 1/2	
			- 1/2 to + 3/8	
PARAHO	C131-76	C	- 3/8 to + No. 3	80.1
			- No. 3 to + No. 4	
PARAHO	C535-69	2	- 2 to + 1-1/2	66.7
			- 1-1/2 to + 1	

5.0 OTHER PROPERTIES

Properties not specifically covered under physical or engineering properties will be covered below.

5.1 DROP HEIGHT TESTS

To determine densities achieved when processed oil shale is dropped from various conveyor heights, tests were conducted by WES and the results presented in Table 5.1 and Figure 5.1. Major increase in density occurs within the initial 1.5 m (5 ft) of drop for PARAHO, where a relative density of 67 percent was achieved. Only a small amount of densification (79 percent) was achieved by increasing the drop height to 5.0 m (16.5 ft).

TABLE 5.1. Summary of Drop Height Tests on PARAHO Shale (Townsend and Peterson 1979)

Material	Height of Drop		Density[(a)]	
	m	ft	KN/m^3	pcf
PARAHO (-2 in. fraction)	0.2	0.7	11.6	73.8
	0.4	1.5	11.6	74.1
	1.4	4.5	12.5	79.8
	3.2	10.5	12.9	82.0
	5.0	16.5	13.0	83.0

(a) Air dry material (the water content of the PARAHO fractions are less than 1 wt percent)

5.2 WATER RETENTION CHARACTERISTICS

Water retention characteristics for PARAHO shale were measured by PNL over a range from saturation to air dry conditions. Water retention data from 20 to 100 cm (8 to 39 in.) were collected by direct gravimetric sampling of 1.8 m (6 ft) permeability columns (Table 5.2) and a pressure plate extractor method

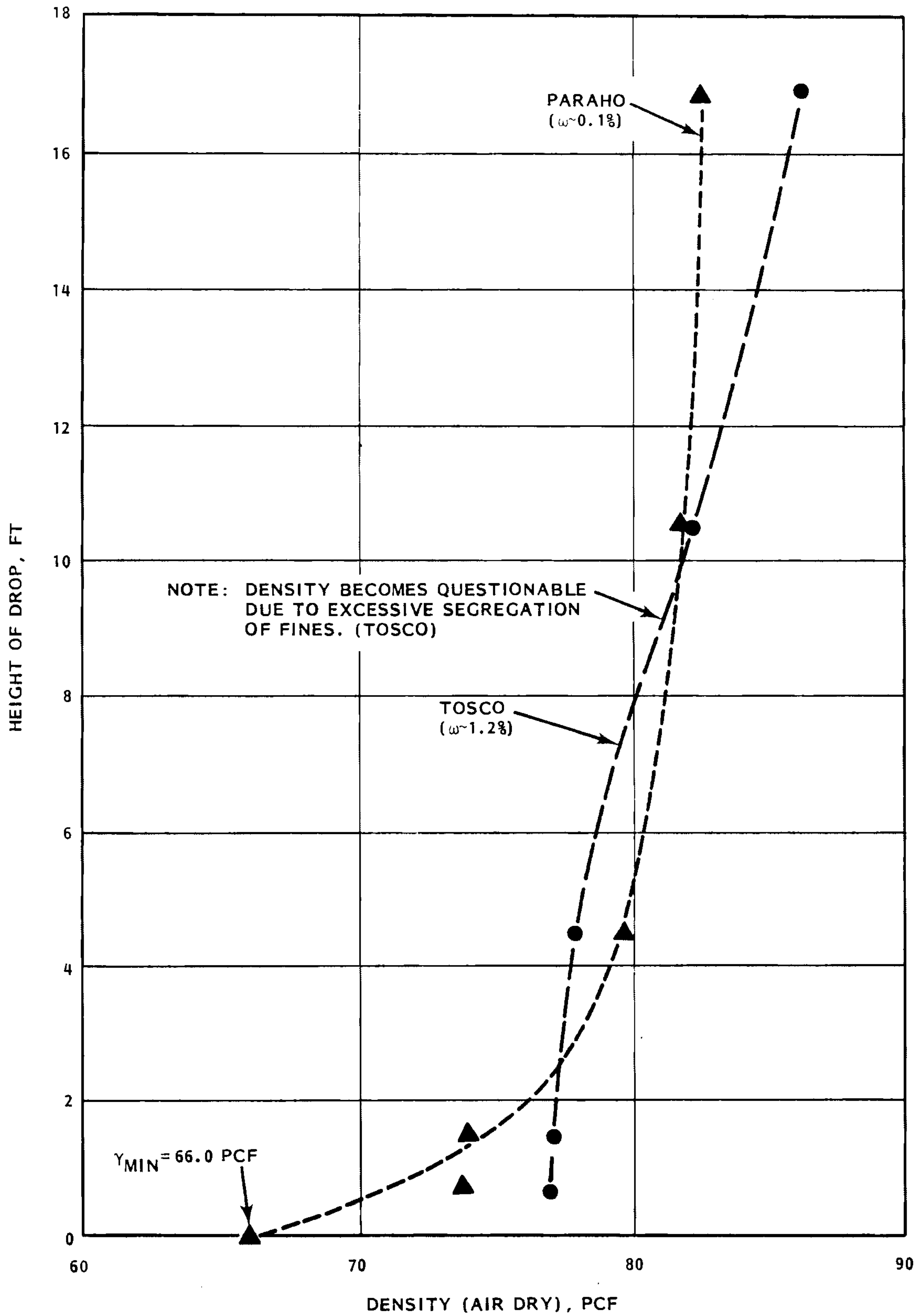


FIGURE 5.1. Effect of Drop Height on Dry Density for PARAHO and TOSCO Retorted Oil Shales (Townsend and Peterson 1979)

TABLE 5.2. Water Retention Characteristics by Large Column

Loose Pack		Tight Pack	
Head (cm)	Volumetric Water Content (cm^3/cm^3)	Head (cm)	Volumetric Water Content (cm^3/cm^3)
8.0	0.412	15.5	0.381
28.0	0.401	35.5	0.394
48.0	0.362	55.5	0.359
68.0	0.344	75.5	0.365
88.0	0.348	95.5	0.349
108.0	0.340	115.5	0.362
128.0	0.337	135.5	0.342
148.0	0.322	155.5	0.320
Dry Bulk Density (KN/m^3)	12.9	15.0	
Porosity[a] (cm^3/cm^3)	0.511	0.433	
Void Ratio	1.045	0.764	

(a) Assumes a particle density of 2.70 g/cm^3

used for collecting water retention over the range of 100 to 3,000 cm (3.25 to 98.4 ft) (Table 5.3). Summarized in Figures 5.2 and 5.3 are water retention characteristics for PARAHO shale loose and tight packed, respectively.

Water retention characteristics values determined by Bloomsburg and Wells (1978) on PARAHO material packed at densities of 12.6 KN/m^3 (80.0 pcf) and 15.0 KN/m^3 (95.0 pcf) are also shown in Figures 5.2 and 5.3, respectively, for comparison. This comparison shows considerable variance between the two studies, the result of the PARAHO material used during testing. Bloomsburg and Wells (1978) tested samples dry packed with retorted oil shale sieved to 2 mm and finer, where PNL used "as received" full scale material.

5.3 FIELD CAPACITY

To determine the "field capacity" of retorted oil shale, estimates were made by PNL using the technique of Kemper and Walker (1978). Field capacity measurements were determined to be 13.83% (dry wt) for the loose pack [dry bulk density of 11.8 KN/m^3 (75 pcf)] and 12.71% (dry wt) for the tight pack [dry bulk density of 16.1 KN/m^3 (102.5 pcf)]. Based on these measurements, little seepage should occur even in relatively deep piles when conditioned at moisture contents less than 13 or 14% (dry wt), for these compacted PARAHO materials. At a semi-arid disposal site, where annual deep infiltration is expected to be small or negligible, dry PARAHO treated shale could be moisturized with waste water to at least 0.1 MT (metric ton) retort water per MT of shale without significant drainage from 30 to 50 m thick piles (Bond et al. 1982). However, moisturization of the pile to optimum water contents [15 to 22% (dry wt)] will result in drainage. This kind of information will assist in properly engineering the pile for optimum stability as well as minimizing environmental degradation which may result from contaminant seepage from large spent shale piles.

TABLE 5.3. Water Retention Characteristics by Pressure Plate Extractor

Loose Pack		Tight Pack	
Head (cm)	Volumetric Water Content (cm^3/cm^3)	Head (cm)	Volumetric Water Content (cm^3/cm^3)
100	0.383	100	0.374
300	0.286	300	0.364
1,000	0.224	1,000	0.306
3,000	0.156	3,000	0.233

	Loose Pack	Tight Pack
Dry Bulk Density (KN/m^3)	12.2	16.0
Porosity[(a)] (cm^3/cm^3)	0.537	0.394
Void Ratio	1.160	0.650

(a) Assumes a particle density of 2.70 g/cm^3

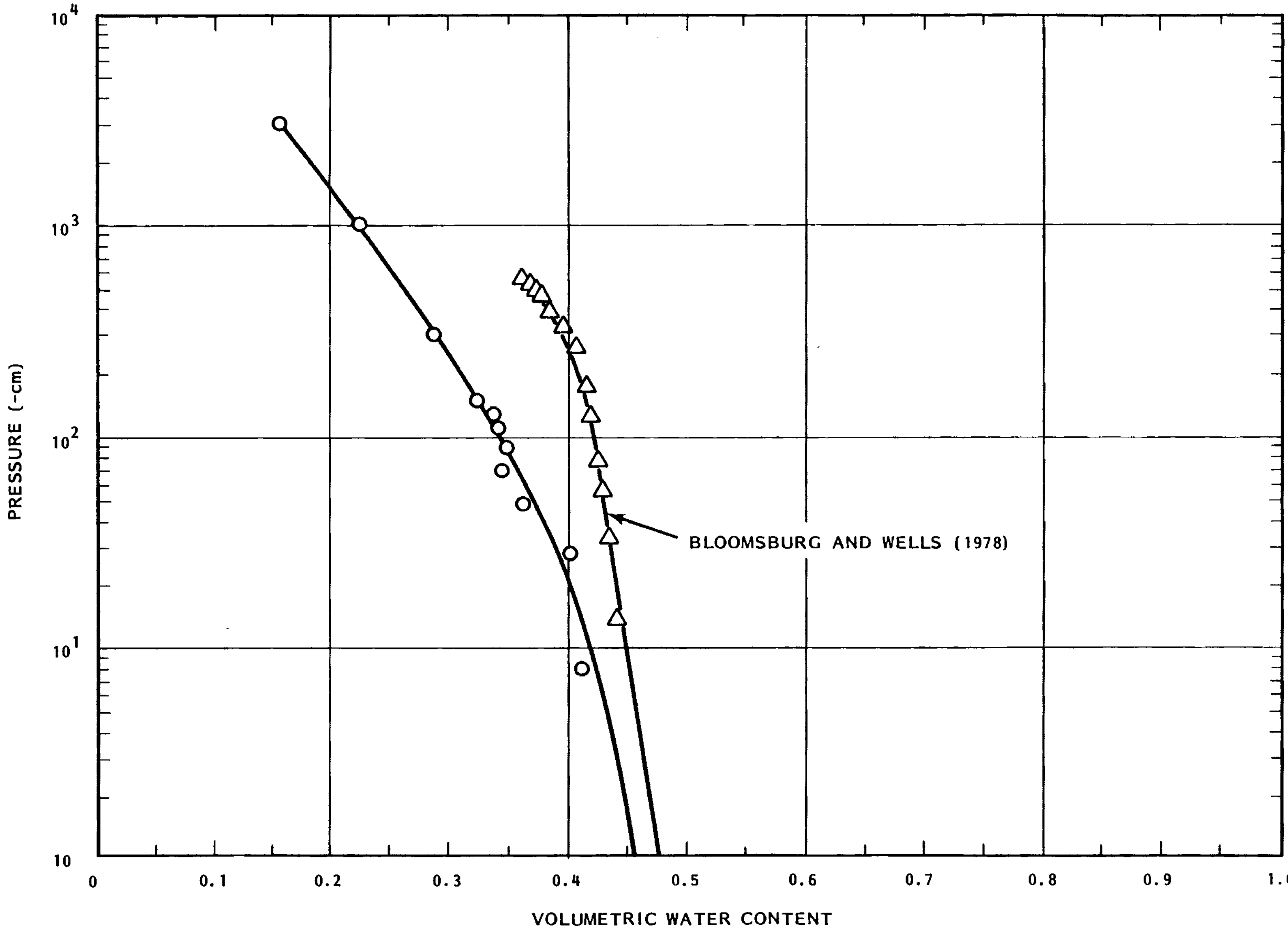


FIGURE 5.2. Water Retention PARAHO Shale "Loose Pack"

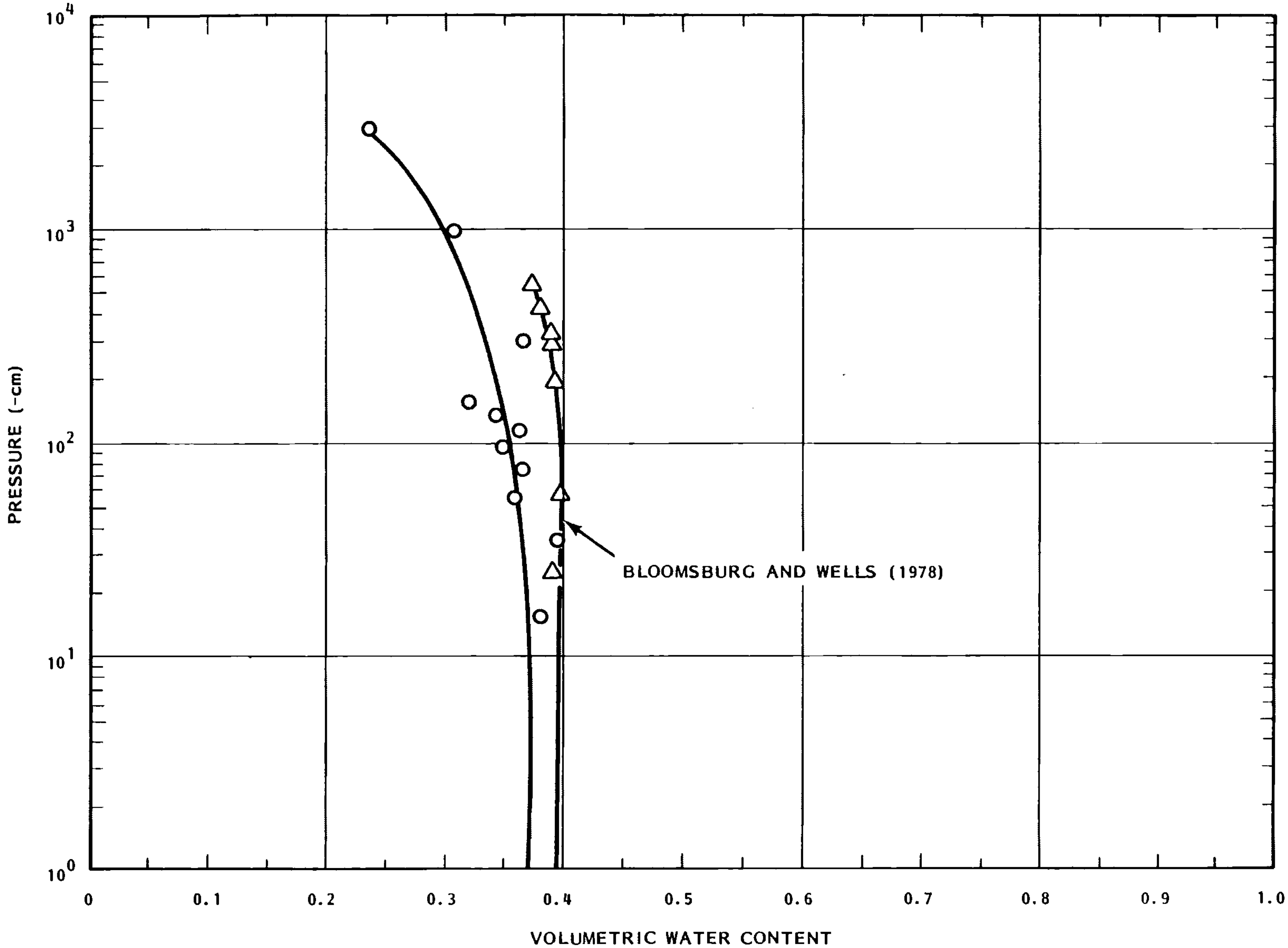


FIGURE 5.3. Water Retention PARAHO Shale "Tight Pack"

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