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HYDRAULIC CONDUCTIVITY OF THIRTEEN COMPACTED CLAYS

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Abstract—Hydraulic conductivity tests were conducted on thirteen compacted clayey soils being used for compacted clay liners at landfills throughout the United States. The soils were prepared to various molding water contents and then compacted and permeated in the laboratory. Results of the tests show that for all of the soils, zones exist in the compaction plane (i.e., dry unit weight vs. water content) where the hydraulic conductivity is similar. These zones fall roughly parallel to contours of constant initial saturation (degree of saturation at compaction), with lower hydraulic conductivities generally occurring for conditions corresponding to higher initial saturation. Wet of the line of optimums, lower hydraulic conductivity is also attained for soils that are more plastic and have a greater quantity of fines. A regression equation was developed from the data to estimate hydraulic conductivity given the initial saturation, compactive effort, plasticity index, and clay content.

Key Words—Clay liners, Compacted clays, Hydraulic conductivity.

INTRODUCTION

Compacted clay liners are an integral component of lining systems used for municipal and hazardous waste landfills. Because the primary purpose of a compacted clay liner is to impede the flow of fluids, the most significant factor affecting its performance is hydraulic conductivity (Daniel 1987, 1990). Soils rich in clay minerals are used for constructing compacted soil liners because they have low hydraulic conductivity and can attenuate inorganic contaminants. Most regulatory agencies in the United States require that the hydraulic conductivity of clay liners be less than or equal to 1×10^{-9} m/s.

Although the hydraulic conductivity of clayey soils is normally considered to be low, the hydraulic conductivity of compacted clays can vary tremendously depending on the soil composition and the conditions under which they are compacted (Lambe 1954; Mitchell *et al* 1965; Garcia-Bengochea *et al* 1979; Acar and Oliveri 1990; Benson *et al* 1994). For example, Benson and Daniel (1990) reported that the hydraulic conductivity of a highly plastic clay from the Gulf Coast of Texas varied by six orders of magnitude depending on the molding water content and degree of compaction. Smaller, yet significant changes in hydraulic conductivity also occur as a consequence of variations in soil composition (Benson *et al* 1994).

A review of factors influencing the hydraulic conductivity of compacted clays is contained in Benson *et al* (1994). In their study, the hydraulic conductivity of specimens collected from 67 compacted clay liners throughout the United States was examined. Results of hydraulic conductivity and index tests conducted on more than 2000 specimens are included in a database. They reported that the hydraulic conductivity of these specimens depends greatly on the molding water content and dry unit weight achieved during compaction. In particular, specimens compacted at combinations of water content and dry unit weight yielding higher initial saturation (degree of saturation at compaction) have lower hydraulic conductivity. Benson *et al* (1994) also reported that hydraulic conductivity is sensitive to the Atterberg limits and particle size distribution. Soils that are more plastic (higher liquid limit or higher plasticity index) or contain a greater quantity of fines (clay-size particles) have lower hydraulic conductivity.

This paper presents the results of hydraulic conductivity tests conducted on specimens of thirteen compacted clayey soils used for compacted soil liners at various sites in the United States. Specimens were prepared and tested for hydraulic conductivity in the laboratory under controlled conditions. Identical procedures were used for each test to eliminate ambiguities caused by testing variations. Results of the hydraulic conductivity tests are used to illustrate the significant factors affecting hydraulic conductivity of compacted clayey soils and to develop a regression equation for estimating hydraulic conductivity. Comparisons are also made to data previously published by Benson *et al* (1994).

MATERIALS AND METHODS

Index properties and mineralogy

ASTM procedures D422, D4318, D854, and D2487 were used to obtain the particle size distribution, Atterberg limits [liquid limit (LL), plastic limit, and plasticity index (PI)], specific gravity of solids, and Unified Soil Classification System (USCS) soil classification. Cation exchange capacity (CEC) was measured using the sodium saturation method described in *Methods*

Table 1. Index properties of clayey soils.

Soil	Deposit	LL	PL	PI	Activity	G_s	% Gravel	% Sand	% Fines	% Clay	CEC (meq/100 g)	USCS
A	mine spoil	70	32	38	0.58	2.80	0	6	94	65	8	CH
B	loess	49	23	26	0.65	2.70	0	6	94	40	23	CL
C	glacial till	27	12	15	0.54	2.75	2	24	76	28	22	CL w/sand
D	glacial till	35	16	19	0.46	2.80	3	8	89	41	27	CL
E	marine sediment	53	12	41	0.65	2.90	0	12	88	63	31	CH
F	marine sediment	67	21	46	0.87	2.80	0	6	94	53	39	CH
G	alluvial	29	13	16	1.00	2.68	0	48	52	16	8	Cl sandy
H	marine deposit	37	17	20	0.80	2.78	0	19	81	25	27	CL w/sand
I	glacial till	33	14	19	0.51	2.80	7	8	85	37	25	CL w/sand
J	glacial till	31	13	18	0.69	2.80	8	18	74	26	23	CL w/sand
K	alluvial	24	13	11	0.55	2.80	3	35	62	20	23	CL sandy
L	glacio-lacustrine	43	17	26	0.84	2.78	2	9	89	31	23	CL
M	glacial till	32	18	14	0.32	2.80	1	14	85	44	25	CL w/sand

Note: LL = liquid limit, PL = plastic limit, PI = plasticity index, G_s = specific gravity, USCS = Unified Soil Classification System, CEC = cation exchange capacity.

of Soil Analysis (ASA 1965). For the particle-size distribution tests, gravel was defined as particles larger than 4.8 mm (No. 4 sieve) and fines were particles smaller than 0.075 mm (No. 200 sieve); these are USCS definitions. Clay content was defined as the percentage of particles smaller than 2 μm (as determined using sedimentation analysis), which is the common definition used in geo-environmental engineering practice.

Results of the index tests are summarized in Table 1. The soils vary in plasticity ($24 \leq LL \leq 70$, $11 \leq PI \leq 46$), particle size distribution ($52\% \leq$ fines $\leq 94\%$, $16\% \leq$ clay content $\leq 65\%$), cation exchange capacity (8 to 39 meq/100 g of soil), and soil classification. All of the soils are naturally occurring soils with the exception of Soil A, which is a mine spoil from northern California.

Mineralogy of the soils was analyzed using X-ray diffraction. Results of the analysis are summarized in Table 2. For this paper, the soils are segregated into four groups based on their predominant mineral (excluding quartz): kaolinite/dolomite (Soils A, M), illite (Soils C, D, I, J, K), mixed-layer illite/smectite (Soils E, F, G), and smectite (Soils B, H, L).

Compaction tests

Specimens of each soil were compacted at various molding water contents and three compactive efforts. Prior to compaction, the soils were crushed to pass the U.S. No. 4 Sieve (4.8 mm openings) as suggested in ASTM D698 and D1557. Gravel and other particles too large to pass through the No. 4 sieve were discarded. In general, the percentage of gravel-size particles was small, being at most 8% and more commonly 0–2%.

The crushed and sieved soils were moistened to various water contents with Madison, Wisconsin tap water. The moistened soils were sealed in plastic bags and allowed to equilibrate for at least 48 hours. After hydration, the soils were compacted using one of three compactive efforts: modified Proctor (ASTM D1557), standard Proctor (ASTM D698), and reduced Proctor. The reduced Proctor procedure is identical to the standard Proctor procedure, except 15 blows per lift were applied as opposed to 25 (Daniel and Benson 1990). The reduced Proctor procedure is also known as the U.S. Army Corps of Engineers' "15-blow compaction test" (COE 1980). These compactive efforts are believed to simulate the range of efforts normally encountered in the field (Daniel and Benson 1990).

Hydraulic conductivity tests

The specimens were placed into flexible-wall permeameters for hydraulic conductivity testing. All tests were conducted using the falling-head method in accordance with procedures described in ASTM D5084. The influent, effluent, and average effective stresses were 5, 18, and 11.5 kPa, respectively. The cell pressure was 20 kPa and no backpressure was applied. These conditions resulted in a hydraulic gradient of approximately 12 (dimensionless). Testing was continued until no trend in hydraulic conductivity was apparent, the last four measurements of hydraulic conductivity varied by no more than 25%, and inflow was equal to outflow. Madison, Wisconsin tap water was used as the permeant.

Typical test results are shown in Figure 1 (Soil C). The results are similar to those reported by numerous researchers in the last four decades (Lambe 1954; Bjerrum and Huder 1954; Mitchell *et al* 1965; Garcia-Bengochea *et al* 1979; Acar and Oliveri 1990; Benson and Daniel 1990; Daniel and Benson 1990). Hydraulic conductivity is sensitive to molding water content and compactive effort. The lowest hydraulic conductivities generally occur at molding water contents 1–2% wet of

Table 2. Mineralogy of clayey soils.

Soil	Quartz (%)	Plag. Feldspar (%)	K Feldspar (%)	Calcite (%)	Dolomite (%)	Kaolinite (%)	Chlorite (%)	Illite/Mica (%)	Smectite (%)	Mixed-Layer Illite/Smectite (%)	Other[3] (%)
A	29	Tr[1]	Tr	0	0	37	4	2	22	6 (40–60)[2]	0
B	32	4	2	2	4	2	4	4	43	0	3
C	24	2	1	17	10	Tr	8	27	0	9 (70–90)	2
D	33	3	2	8	3	2	5	22	0	18 (70–80)	2
E	23	3	1	12	0	2	4	6	0	46 (10–20)	3
F	24	2	1	12	Tr	3	3	8	0	44 (10–20)	3
G	73	1	Tr	0	Tr	2	2	Tr	0	22 (20–40)	0
H	42	1	Tr	0	Tr	6	4	7	38	2	0
I	33	4	1	9	2	1	6	23	0	19 (70–80)	2
J	32	5	1	10	1	1	7	25	0	17 (70–80)	2
K	33	3	6	10	7	2	2	14	0	23 (50–60)	0
L	42	6	2	0	Tr	2	3	4	40	0	1
M	18	3	1	9	43	1	3	6	0	16 (20–30)	0

Notes: (1) Tr = Trace, (2) quantity in parenthesis is % illite in mixed-layer illite/smectite, (3) Other is siderite, pyrite, hematite, gypsum, and/or geothite.

the line of optimums for a given compactive effort. Furthermore, the sensitivity of hydraulic conductivity to molding water content is greater for specimens compacted with lower compactive effort. Similar results were obtained for all soils. Detailed test results are tabulated in Table 3 and described by Trast (1993).

RESULTS OF HYDRAULIC CONDUCTIVITY TESTS

Compaction conditions

The aforementioned procedures were used to prepare and permeate 193 specimens. The resulting hydraulic conductivities were used to construct a set of zones in the compaction plane (dry unit weight vs. molding water content), delineating combinations of water content and dry unit weight yielding similar hydraulic conductivity (Figure 2). The zones fall roughly parallel to contours of initial saturation (S_i), which is computed using:

$$S_i = \frac{w}{\left(\dfrac{\gamma_w}{\gamma_d} - \dfrac{1}{G_s}\right)} \qquad [1]$$

where w is molding water content, γ_d is dry unit weight, γ_w is the unit weight of water, and G_s is the specific gravity of solids. Zones of this type can be used to develop generalized acceptable zones for compaction control, defining combinations of water content and dry unit weight corresponding to hydraulic conductivities less than or equal to the maximum permissible hydraulic conductivity.

The similarity between the contours of initial saturation and the zones of similar hydraulic conductivity was expected, because contours of constant initial saturation generally fall parallel to the line of optimums (Mitchell *et al* 1965; Mundell and Bailey 1985; Boutwell and Hedges 1989; Benson and Boutwell 1992; Benson *et al* 1994; Othman and Luettich 1994). Combinations of water content and dry unit weight corresponding to low initial saturation (<70%) tend to fall dry of the line of optimums. For compaction dry of the line of optimums, the clods are stiff and difficult to remold (Benson and Daniel 1990) and the clay particles are flocculated (Lambe 1958). Consequently, large interclod pores exist as well as a more permeable micro-structure. These conditions result in higher hydraulic conductivity. Conversely, combinations of water content and dry unit weight corresponding to high initial saturation (>90%) tend to fall wet of the line of optimums. Compaction wet of the line of optimums permits greater remolding of clods, elimination of large interclod voids, and preferential re-orientation of clay particles, all of which result in lower hydraulic conductivity (Lambe 1958; Olsen 1962; Mitchell *et al* 1965; Garcia-Bengochea *et al* 1979; Acar and Oliveri 1990; Benson and Daniel 1990).

To further illustrate this behavior, hydraulic conductivity vs. initial saturation was graphed (Figure 3). A trend of decreasing hydraulic conductivity with increasing initial saturation exists. Those specimens compacted with higher compactive effort also generally have lower hydraulic conductivity. Based on the relationship shown in Figure 3, it is apparent that hydraulic conductivities less than 10^{-9} m/s, the common regulatory maximum hydraulic conductivity in the United States, can be achieved for all of the soils in this study by compacting to an initial saturation in excess of 85%.

The writers caution, however, that increasing initial saturation may not always result in lower hydraulic conductivity. For example, initial saturation may be increased by increasing the molding water content even

Table 3. Compaction and hydraulic conductivity data.

Soil	W (%)	γ_d kN/m^3	Comp. Effort	Si (%)	K (m/s)
Soil A	14.70	13.60	RP	40.36	7.0E-09
	19.40	13.80	RP	54.84	4.0E-09
	23.20	14.50	RP	72.63	2.5E-10
	33.00	13.50	RP	89.30	1.3E-10
	44.60	11.50	RP	89.94	1.2E-10
	14.60	14.40	SP	45.05	6.0E-10
	18.50	14.70	SP	59.64	5.5E-10
	24.10	15.40	SP	86.11	1.0E-10
	33.30	13.60	SP	91.44	1.3E-10
	43.60	11.80	SP	91.94	1.2E-10
	14.60	17.10	MP	67.42	6.0E-11
	18.40	17.10	MP	84.97	1.0E-10
	24.10	15.80	MP	91.38	6.0E-11
	33.10	13.50	MP	89.57	1.7E-10
Soil B	12.80	14.40	RP	39.49	1.5E-06
	15.40	14.70	RP	49.64	7.5E-06
	18.80	15.90	RP	72.35	1.0E-09
	19.30	16.30	RP	78.87	2.0E-09
	22.00	16.30	RP	89.91	4.1E-11
	26.60	14.60	RP	84.50	7.5E-11
	13.30	16.10	SP	52.74	1.1E-09
	14.70	16.50	SP	61.92	7.0E-10
	18.00	17.30	SP	85.75	3.0E-11
	19.60	17.20	SP	91.93	2.5E-11
	21.90	16.50	SP	92.25	1.6E-11
	26.50	15.00	SP	89.27	7.5E-11
	12.00	19.20	MP	78.03	9.0E-12
	15.10	18.70	MP	90.17	3.0E-11
	19.70	16.90	MP	88.21	5.0E-11
	21.90	16.10	MP	86.84	2.0E-11
	26.70	14.60	MP	84.82	7.5E-11
Soil C	9.00	17.80	RP	48.00	3.0E-09
	11.20	18.00	RP	61.75	3.0E-09
	13.20	18.60	RP	80.59	1.1E-09
	14.90	18.50	RP	89.42	1.6E-10
	20.20	16.70	RP	90.26	2.0E-10
	9.10	18.30	SP	52.78	1.9E-09
	11.90	19.00	SP	77.94	8.5E-10
	13.80	19.00	SP	90.39	1.5E-10
	14.80	18.50	SP	88.82	1.2E-10
	16.20	17.80	SP	86.41	2.0E-10
	7.30	20.50	MP	63.53	3.6E-10
	9.00	20.50	MP	78.33	1.6E-10
	11.10	20.30	MP	92.80	6.0E-11
	13.90	18.70	MP	86.36	1.2E-10
	16.10	18.10	MP	90.27	2.1E-10
Soil D	13.20	16.00	RP	51.57	1.0E-08
	15.30	16.30	RP	62.53	6.0E-09
	18.20	17.00	RP	82.76	4.0E-10
	18.60	16.60	RP	79.55	4.0E-10
	22.10	16.20	RP	88.96	2.0E-10
	11.80	16.50	SP	49.70	3.4E-09
	13.80	17.10	SP	63.73	5.0E-10
	18.10	17.40	SP	87.59	1.0E-10
	19.50	17.00	SP	88.67	1.5E-10
	10.60	19.00	MP	66.59	8.1E-11
	13.60	19.40	MP	91.57	5.5E-11
	14.70	19.00	MP	92.35	5.4E-11
	16.80	18.10	MP	90.89	7.8E-11
	19.20	17.20	MP	90.05	1.1E-10
Soil E	9.00	15.10	RP	29.52	3.0E-08
	13.00	16.00	RP	48.45	1.1E-09
	16.20	16.40	RP	63.94	1.5E-09
	18.70	16.70	RP	77.08	2.3E-11
	22.90	15.10	RP	75.12	1.7E-11
	9.20	15.80	SP	33.33	3.0E-08
	13.20	17.50	SP	61.18	2.6E-10
	16.00	17.90	SP	78.73	2.1E-10
	17.60	17.60	SP	82.80	1.0E-11
	18.40	17.30	SP	82.80	2.0E-11
	20.80	16.40	SP	82.10	2.0E-11
	10.20	19.30	MP	62.40	3.2E-11
	11.90	19.90	MP	80.33	3.9E-11
	13.50	19.40	MP	83.93	3.5E-11
	14.20	18.80	MP	80.23	2.2E-11
	18.20	17.50	MP	84.36	3.5E-11
Soil F	16.90	14.40	RP	52.14	1.1E-09
	21.60	15.70	RP	80.69	1.4E-10
	23.30	15.80	RP	88.34	1.9E-11
	25.60	15.10	RP	87.51	2.0E-11
	29.00	14.60	RP	92.13	2.7E-11
	13.10	15.20	SP	45.45	1.0E-09
	16.70	15.50	SP	60.56	9.0E-10
	18.03	16.00	SP	70.43	4.8E-10
	21.40	16.20	SP	86.15	1.6E-10
	26.20	15.00	SP	88.26	1.9E-11
	13.00	18.10	MP	70.33	1.5E-10
	16.00	18.40	MP	90.90	2.6E-11
	23.00	16.40	MP	95.42	1.3E-11
	26.30	15.20	MP	91.24	1.9E-11
Soil G	10.20	17.70	RP	55.47	1.0E-08
	11.30	18.40	RP	69.42	2.0E-10
	12.50	18.50	RP	78.17	3.0E-10
	16.30	17.60	RP	87.16	2.0E-10
	17.90	17.10	RP	88.04	2.0E-10
	4.80	15.70	SP	18.86	5.0E-07
	7.60	18.30	SP	45.87	6.0E-10
	10.20	18.90	SP	68.60	6.0E-10
	11.10	19.00	SP	76.06	6.0E-10
	13.60	18.70	SP	88.18	1.1E-10
	16.80	17.50	SP	88.33	1.0E-10
	5.60	19.30	MP	40.60	2.5E-10
	10.30	20.30	MP	91.25	3.5E-11
	12.40	19.80	MP	99.13	3.4E-11
	15.00	18.60	MP	95.51	3.3E-11
Soil H	10.50	15.00	RP	35.68	5.5E-09
	12.00	16.10	RP	48.08	6.0E-09
	15.10	16.80	RP	67.35	2.0E-10
	19.00	16.10	RP	76.12	1.0E-10
	21.70	15.80	RP	83.09	9.5E-11
	10.50	16.00	SP	41.43	1.5E-08
	12.10	16.90	SP	54.81	2.0E-09
	13.50	17.50	SP	67.21	2.0E-10
	16.20	17.30	SP	78.13	1.5E-10
	19.00	16.80	SP	84.74	1.4E-10
	10.50	19.40	MP	71.94	2.2E-10
	12.10	19.60	MP	85.94	2.3E-11
	14.40	18.60	MP	85.86	2.0E-11
	15.50	18.20	MP	86.45	2.0E-11
	8.30	18.80	MP	51.20	2.2E-10
	19.00	17.40	MP	93.10	2.2E-11
Soil I	16.04	16.40	RP	66.55	1.6E-08
	17.10	17.10	RP	78.97	5.5E-10
	19.63	16.90	RP	87.90	1.3E-10
	21.72	16.40	RP	90.11	1.5E-10
	12.98	17.20	SP	60.88	3.3E-09

Table 3. Continued.

Soil	W (%)	γd kN/m³	Comp. Effort	Si (%)	K (m/s)
	15.93	17.60	SP	79.55	1.3E-09
	16.91	17.70	SP	85.80	3.4E-10
	19.95	17.10	SP	92.13	2.4E-10
	9.75	19.00	MP	61.25	1.7E-10
	11.73	19.30	MP	77.61	1.0E-10
	13.77	19.20	MP	89.53	7.3E-11
	16.26	18.40	MP	92.38	6.7E-11
	18.48	17.40	MP	89.43	1.4E-10
Soil J	12.73	16.40	RP	52.82	4.8E-08
	17.23	17.20	RP	80.81	7.0E-10
	20.02	17.00	RP	91.03	3.3E-10
	11.38	17.10	SP	52.55	6.4E-09
	13.17	17.30	SP	62.74	3.4E-09
	15.09	17.70	SP	76.56	3.0E-10
	17.70	17.40	SP	85.65	1.9E-10
	19.98	16.90	SP	89.46	2.3E-10
	8.16	19.10	MP	52.15	1.0E-10
	9.82	19.30	MP	64.97	1.5E-10
	13.41	19.40	MP	90.29	6.0E-11
	14.11	19.20	MP	91.75	4.0E-11
	15.76	18.40	MP	89.54	9.5E-11
Soil K	8.00	16.90	RP	35.82	2.1E-08
	10.08	18.00	RP	53.66	7.5E-09
	13.31	18.60	RP	78.17	9.0E-10
	14.51	18.50	RP	83.81	1.7E-10
	16.65	17.70	RP	84.48	2.5E-10
	17.80	17.60	RP	88.89	2.0E-10
	5.40	19.50	SP	37.00	5.0E-09
	8.60	20.10	SP	65.69	3.0E-09
	11.30	20.00	SP	84.73	1.0E-10
	15.00	18.60	SP	88.09	2.0E-10
	5.97	20.40	MP	48.25	1.0E-10
	5.97	20.60	MP	50.14	1.0E-10
	11.38	20.90	MP	101.39	2.5E-11
	11.38	20.80	MP	99.40	3.0E-11
	11.38	21.00	MP	103.45	2.0E-11
Soil L	15.23	15.60	RP	56.05	3.8E-08
	17.92	16.30	RP	73.23	4.2E-09
	18.00	15.80	RP	68.25	1.9E-09
	20.06	16.50	RP	84.50	3.2E-10
	22.18	16.20	RP	89.29	7.0E-11
	16.30	15.40	SP	58.24	5.2E-09
	18.00	15.70	SP	67.24	2.5E-09
	19.80	16.00	SP	77.35	1.2E-09
	21.60	15.90	SP	83.13	6.7E-10
	23.80	15.50	SP	86.31	2.7E-10
	10.13	18.20	MP	55.70	8.8E-11
	14.04	18.60	MP	82.45	3.7E-11
	18.50	17.40	MP	89.52	1.3E-11
Soil M	6.80	16.30	RP	27.79	4.5E-08
	9.50	16.70	RP	41.25	2.0E-08
	15.90	17.70	RP	80.67	3.0E-09
	20.30	16.20	RP	81.72	2.5E-10
	22.10	15.70	RP	82.56	2.0E-10
	9.78	18.30	SP	54.66	5.0E-09
	11.47	18.50	SP	66.25	1.0E-09
	14.70	18.30	SP	82.16	1.0E-10
	16.67	17.40	SP	80.67	1.5E-10
	17.80	17.10	SP	82.20	2.0E-10
	7.59	20.20	MP	59.07	5.0E-10
	8.43	20.40	MP	68.13	1.5E-10
	10.17	20.60	MP	85.41	4.0E-11
	12.23	19.70	MP	86.84	5.0E-11
	14.28	18.90	MP	88.20	6.0E-11

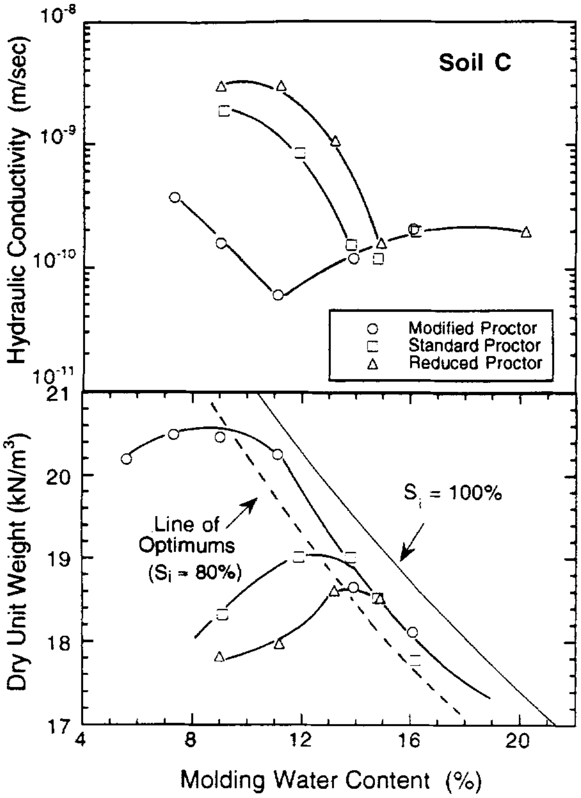

Figure 1. Relationship between hydraulic conductivity, molding water content, and compactive effort for Soil C.

if the compactive effort is decreased. Such a condition may result in an increase in both initial saturation and hydraulic conductivity (Benson *et al* 1994). However, in practice, increases in initial saturation generally occur as a result of increasing molding water content without changing compactive effort by using the same compactor and number of passes, increasing compactive effort without increasing molding water content, or increasing both compactive effort and molding water content. These conditions generally decrease the hydraulic conductivity.

Index properties

Composition of the soil can also significantly affect hydraulic conductivity, particularly for compaction wet of the line of optimums where flow is controlled by the size, shape, and connectivity of microscale pores (Acar and Oliveri 1990; Benson *et al* 1994). In particular, soils having a greater quantity of fines and clay, and more active clay minerals, generally have lower hydraulic conductivity because they contain clay particles that are smaller and have thicker double layers (Lambe 1954; Mesri and Olson 1971; D'Appolonia 1980; Daniel 1987; Kenney *et al* 1992; Benson *et al* 1994). To confirm that similar behavior was true for the soils in this study, relationships existing between

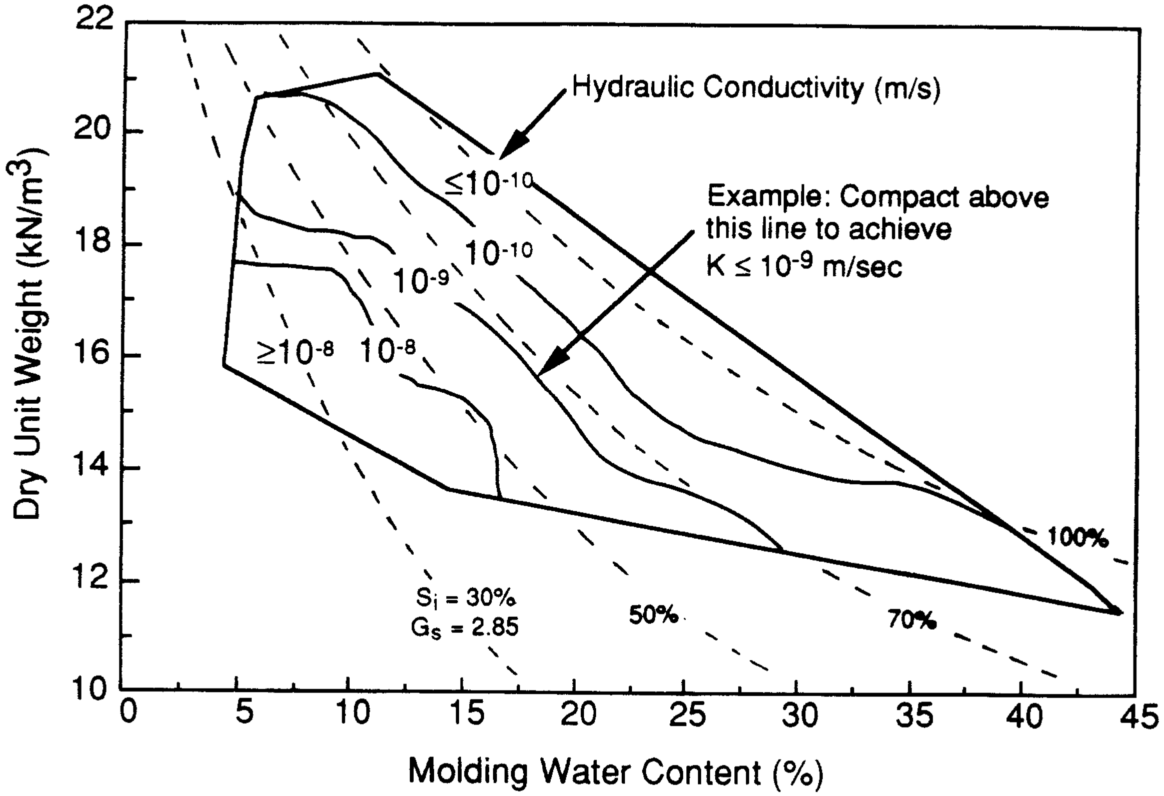

Figure 2. Zones of similar hydraulic conductivity in the compaction plane.

hydraulic conductivity wet of the line of optimums (molding water contents approximately 2% wet of optimum water content for each compactive effort) and index properties of the soils were examined. These hydraulic conductivities are listed in Table 4.

Atterberg limits

Hydraulic conductivity generally decreases with increasing liquid limit and plasticity index (Figures 4 and 5). These trends are expected, because the liquid limit and plasticity index are directly related to the mineralogy of the soil and the clay content (Figure 6). An increase in clay content or the presence of more active clay minerals generally corresponds to a decrease in the size of microscale pores, which control flow in soil compacted wet of the line of optimums. Consequently, lower hydraulic conductivity occurs. That is, soils having higher liquid limit and plasticity index generally contain more active clay minerals and/or greater clay content and typically have lower hydraulic conductivity. Soil A is the exception to this trend. It has very high liquid limit, plasticity index, and clay content, but moderate activity (A = PI ÷ 2 μm clay content) and low cation exchange capacity (Table 1). Its predominant clay mineral is kaolinite. This exception of Soil A serves to indicate that while the relationship between hydraulic conductivity and liquid limit, or plasticity index, is generally inverse, neither index may adequately reflect hydraulic conductivity wet of the line of optimums.

The trends shown in Figures 4 and 5 are also similar to those reported by Benson *et al* (1994) for specimens collected from actual compacted soil liners. That is, a rapid decrease in hydraulic conductivity occurs as the liquid limit is increased from 20 to 40 and the plasticity index is increased from 10 to 30. Thereafter, hydraulic conductivity is less sensitive to liquid limit or plasticity index. The writers note, however, that the hydraulic conductivities shown in Figures 4 and 5 are approximately one-half order of magnitude lower, on average, than those reported by Benson *et al* (1994). Although the cause for this discrepancy in hydraulic conductivity is not obvious, three possible reasons are offered. First, the field specimens described in Benson *et al* (1994) may have contained defects that are not likely to exist in the specimens described in this paper, which were prepared under controlled laboratory conditions. Second, the compactive effort applied in the field may have been less than was applied in the laboratory. It has been Benson's experience that in many field applications, the compactive effort actually delivered is slightly less than that corresponding to standard Proctor

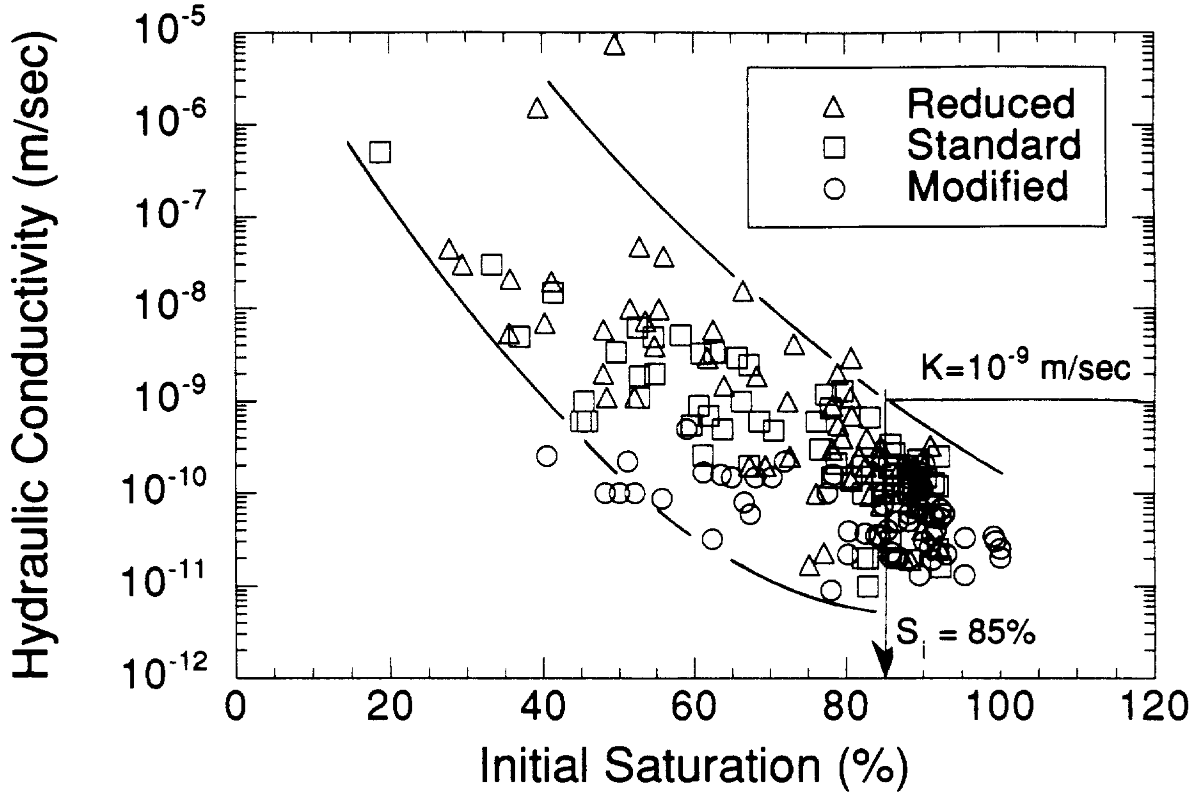

Figure 3. Hydraulic conductivity vs. initial saturation.

compaction. Third, backpressure saturation was used for many of the tests described by Benson *et al* (1994), whereas no backpressure was used in this study. Any of these factors, or a combination, could be responsible for the differences in hydraulic conductivity.

Particle size distribution

The influence that percentage fines and 2 μm clay content have on hydraulic conductivity wet of the line of optimums is shown in Figures 7 and 8. An increase in percentage fines generally results in a decrease of hydraulic conductivity, but the trend is relatively weak and exhibits significant scatter. No trend is evident for clay content. Similar behavior was reported by Benson *et al* (1994) for fines, but they found a strong relationship between hydraulic conductivity and clay content.

The weakness or non-existence of the trends suggests that neither percentage fines nor clay content are adequate to reflect hydraulic conductivity wet of the line of optimums for these soils. This is especially true when Soil A is considered. Soil A has the highest clay content, but also has one of the higher hydraulic conductivities. Soil A also appeared as an outlier in Figures 4 and 5.

Hydraulic conductivity should not be expected to be strongly related to percentage fines or clay content for the soils that were tested. All of the soils contain more than 50% fines, and therefore classify in the USCS as fine-grained soils. Furthermore, all of the soils classify as clays in the USCS (CL or CH, see Table 1). Because these soils contain a large quantity of fines and are sufficiently plastic to classify as clays, it is expected that the pore structure controlling flow should be affected more by mineralogical composition and less by particle size distribution. In fact, those soils categorized as

Table 4. Hydraulic conductivities approximately 2% wet of the line of optimums.

Soil	Hydraulic conductivity (m/s)		
	Modified	Standard	Reduced
A	9.9×10^{-11}	1.1×10^{-10}	1.5×10^{-10}
B	2.5×10^{-11}	2.3×10^{-11}	3.5×10^{-11}
C	6.0×10^{-11}	1.3×10^{-10}	2.0×10^{-10}
D	5.0×10^{-11}	1.0×10^{-10}	3.0×10^{-10}
E	2.0×10^{-11}	2.0×10^{-11}	2.0×10^{-11}
F	1.3×10^{-11}	1.8×10^{-11}	2.0×10^{-11}
G	3.0×10^{-10}	1.1×10^{-10}	2.0×10^{-10}
H	2.0×10^{-11}	1.5×10^{-10}	1.5×10^{-10}
I	8.0×10^{-11}	1.8×10^{-10}	2.1×10^{-10}
J	5.0×10^{-11}	2.0×10^{-10}	2.8×10^{-10}
K	3.0×10^{-11}	1.3×10^{-10}	2.1×10^{-10}
L	3.0×10^{-11}	5.0×10^{-11}	1.5×10^{-10}
M	4.0×10^{-11}	1.0×10^{-10}	2.5×10^{-10}

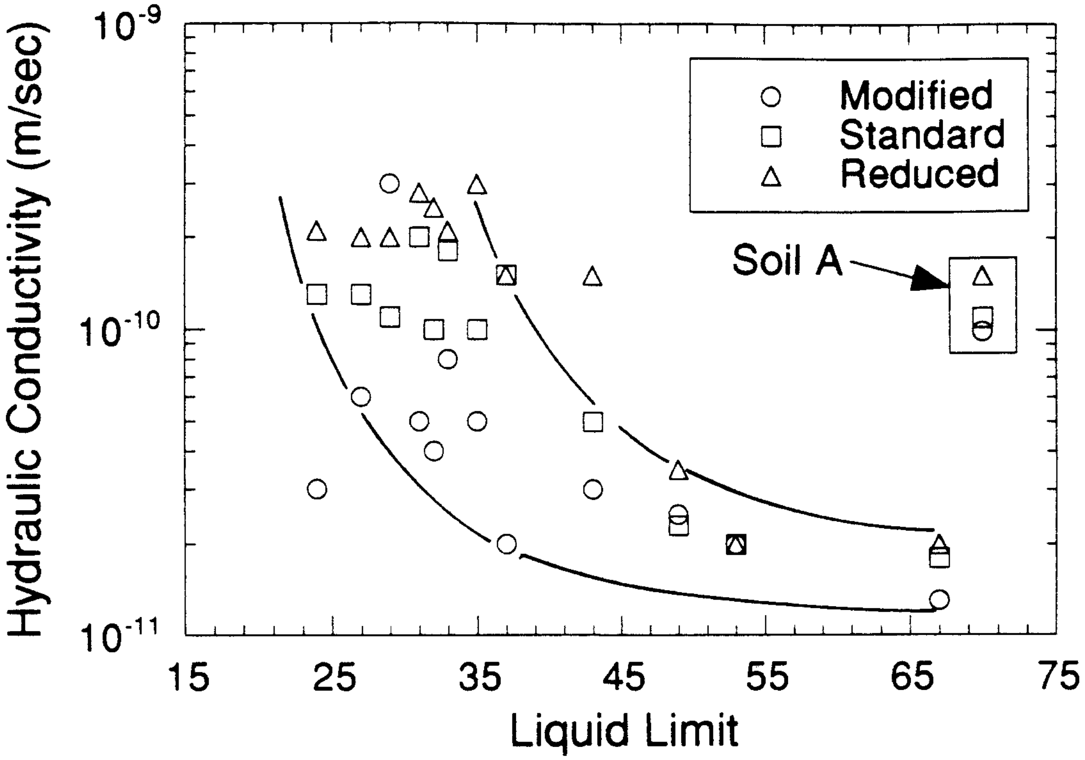

Figure 4. Hydraulic conductivity vs. liquid limit.

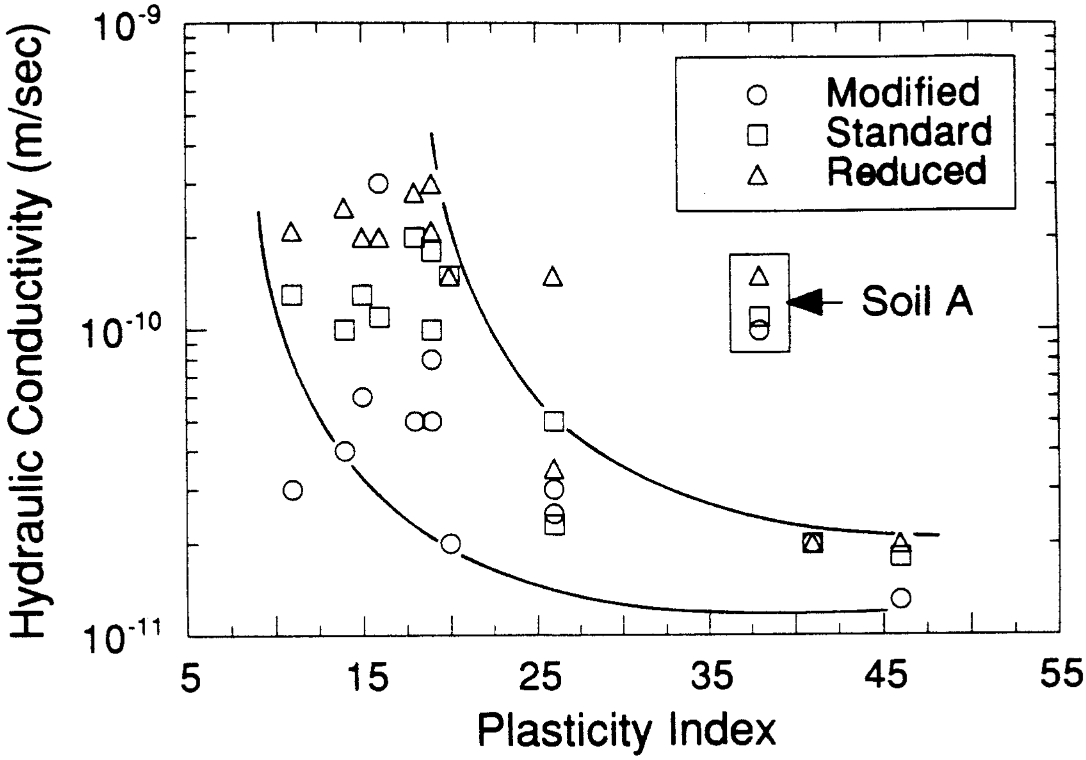

Figure 5. Hydraulic conductivity vs. plasticity index.

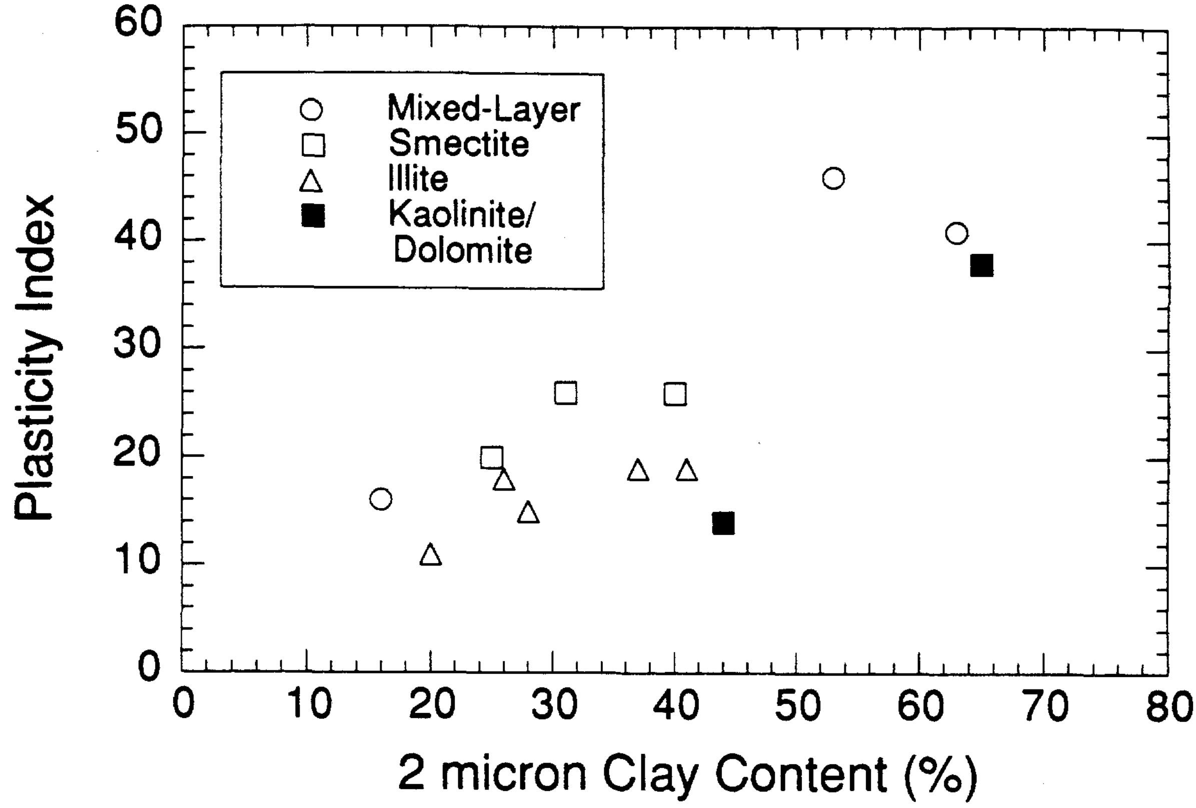

Figure 6. Plasticity index vs. 2 micron clay content.

smectitic and mixed-layer illite/smectitic on average tend to have slightly lower hydraulic conductivity (Figure 8).

ESTIMATING HYDRAULIC CONDUCTIVITY

Regression procedure

Stepwise linear regression was used to identify which compaction and compositional variables have the greatest influence on hydraulic conductivity and to develop an equation that could be used to estimate hydraulic conductivity. A detailed discussion of stepwise regression can be found in Draper and Smith (1981). A brief review of the procedure is provided herein.

Stepwise regression is conducted in a series of steps. In each step, a decision to include an independent variable (e.g., compaction or compositional variable) is made based on its correlation with the dependent variable, which in this case is ln K (natural logarithm of hydraulic conductivity, K). In the first step, a "partial-F" statistic is computed for each of the independent variables. The partial-F is a ratio describing the portion of the variance of the dependent variable that is described by the independent variable. Independent variables having a larger partial-F are more strongly correlated to the dependent variable and thus are more useful in describing the variation in the dependent variable. Moreover, the partial-F can be tested for statistical significance. In this study, the partial-F was required to exceed 4 for the independent variable to be deemed significant. A partial-F of 4 corresponds to a significance level of 5%, i.e., the probability of falsely rejecting significance.

After the partial-F's are computed in the first step, the dependent variable is linearly regressed on the independent variable having the largest partial-F. The residual variance (variability in dependent variable that still remains unexplained) is then computed. In subsequent steps, the procedure in the first step is repeated using the remaining independent variables and the residual variance computed from the immediately previous regression.

All of the data contained in Tables 1–3, except gravel content, were used in the regression analysis, which was performed using the program StatView (Abacus Concepts 1992). Gravel was not included because it was removed during preparation of the specimens by crushing the soil past the No. 4 sieve, as suggested by the ASTM procedures (D698, D1557) that were followed. Mineralogy (Table 2) was also included as a categorical variable defined by the predominant mineral in a given soil.

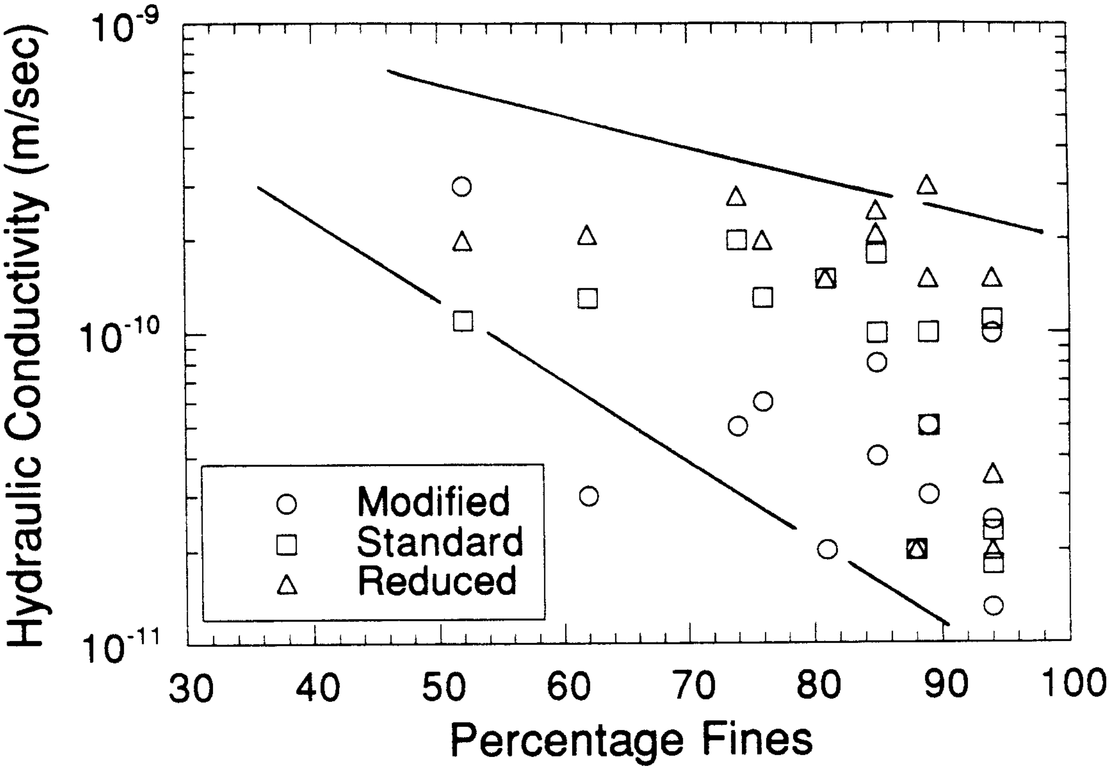

Figure 7. Hydraulic conductivity vs. percentage fines.

The resulting regression equation is:

$$\ln K = -15.0 - 0.087S_i - 0.054PI + 0.022C + 0.91E + \epsilon \qquad [2]$$

In Equation 2, K is in units of m/s, C is 2 μm clay content, E is the compactive effort index, and ϵ is a random error term. The compactive effort index is an integer categorical variable describing compactive effort; E was assigned as -1, 0, and 1 for modified, standard, and reduced Proctor compactive efforts. The partial-F's for the independent variables in Eq. 2 are 262 for S_i, 65 for E, 24 for PI, and 5 for clay content. The next largest F is for liquid limit (F = 1.5) and much smaller F's (<1) correspond to percentage fines, activity, CEC, and mineralogy. The residual variance is 1.2 (lnK units, K in m/s) and the coefficient of determination is 0.81.

These results indicate that for these soils, the most significant factors affecting hydraulic conductivity are (in decreasing order of importance): (1) initial saturation, (2) compactive effort, (3) plasticity index, and (4) clay content. Furthermore, the form of the regression equation is consistent with the data shown in Figures 3–8. That is, hydraulic conductivity decreases with increasing initial saturation (Figure 4), plasticity index (Figure 6), and compactive effort (Figures 1–7). The form of Equation 2 also suggests that hydraulic conductivity increases with increasing clay content, whereas no trend between hydraulic conductivity and clay content is present in Figure 8. However, the positive coefficient in Eq. 2 for clay content is reasonable. According to Eq. 2, hydraulic conductivity increases with increasing clay content provided all other variables in Equation 2 are held constant. Increasing clay content while maintaining the same plasticity index suggests that the clay fraction is composed of less active minerals, which generally corresponds to higher hydraulic conductivity (Figure 8).

It is also interesting to compare Equation 2 to a similar equation presented by Benson *et al* (1994) that was also developed using stepwise regression and a minimum partial-F of 4. Their equation is:

$$\ln K = -18.35 + \frac{894}{W} - 0.08PI + 0.0287S_i + 0.02C + 0.32\sqrt{G} + \epsilon \qquad [3]$$

where ln K is the natural logarithm of hydraulic conductivity (in cm/s), W is compactor weight (kN), and G is gravel content (%). The residual variance for Equation 3 was reported as 0.25 (ln K units, ln K in cm/s). Equation 3 is similar in form to Equation 2, even though

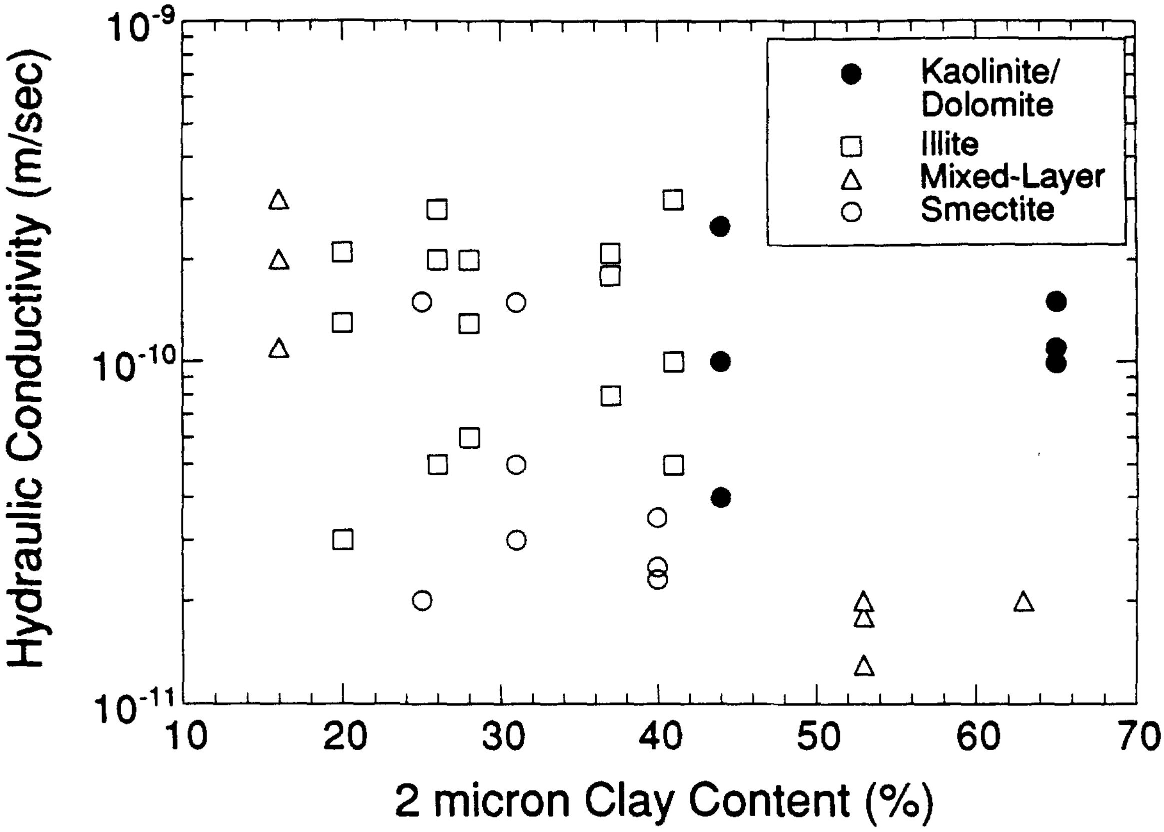

Figure 8. Hydraulic conductivity vs. 2 μm clay content.

it was developed using specimens collected from actual compacted soil liners and with a completely different set of soils. The coefficient for plasticity index is similar in Equations 2 and 3 and the coefficient for clay content is identical. Both equations also show the importance of compaction conditions by including initial saturation (reflecting water content and dry unit weight) and compactive effort, which is inferred by compactor weight in Equation 3. Furthermore, both equations show that hydraulic conductivity decreases with increasing plasticity index, but increases with increasing clay content, provided all other variables are held constant.

Practical application

A practical application of Equation 2 is using it to screen candidate borrow sources to quickly assess whether the soil being considered is likely to yield acceptably low hydraulic conductivity. For many soils, the initial saturation corresponding to the line of optimums is approximately 85% (Benson and Boutwell 1992). If $S_i > 85\%$ is assumed, then hydraulic conductivity can be quickly estimated if the plasticity index and clay content are known. Estimates of this sort used for screening candidate soils could eliminate costly hydraulic conductivity testing of soils unlikely to yield a specified maximum hydraulic conductivity. In contrast, the writers do recommend hydraulic conductivity testing of soils that would appear adequate based on estimates made using Equation 2.

Another application of Equation 2 is to estimate the shape of acceptable zones for use in compaction control (i.e., regions of acceptable water contents and dry unit weights that yield sufficiently low hydraulic conductivities). If the plasticity index and clay content are known, an acceptable zone could be constructed by first specifying the maximum permissible hydraulic conductivity (K_{max}) and then using Equation 2 to back-calculate the S_i necessary to yield $K \leq K_{max}$. A limited number of hydraulic conductivity tests corresponding to those combinations of water content and dry unit weight likely to yield the highest hydraulic conductivities could then be conducted to verify the shape of the estimated acceptable zone.

The writers also caution that Equation 2 should only be used for soils that have similar characteristics as those described in Table 1. In particular, Equation 2 should not be used for gravely clays, because gravel was removed from the soils in this study prior to testing. Furthermore, Equation 2 is not meant to be used as a substitute for hydraulic conductivity testing. Soils to be used for construction of compacted soil liners should always be tested to verify that adequately low hydraulic conductivity can be achieved.

SUMMARY AND CONCLUSIONS

Results of hydraulic conductivity tests conducted on thirteen compacted clayey soils have been presented. The soils were collected from compacted clay liners at various landfills throughout the United States. The soils were compacted and permeated in the laboratory using various molding water contents and three compactive efforts believed to span the range of compactive effort commonly employed in the field.

Examination of the hydraulic conductivities showed that a distinct set of zones exist in the compaction plane (dry unit weight vs. water content) that correspond to similar hydraulic conductivity for all of the soils. Such zones can be used to construct a generalized acceptable zone for use in compaction control. The zones of similar hydraulic conductivity fall roughly parallel to contours of constant initial saturation (degree of saturation at compaction), with lower hydraulic conductivities generally occurring at higher initial saturation. A graph of hydraulic conductivity vs. initial saturation confirmed this trend. It showed an inverse relationship between hydraulic conductivity and initial saturation and also illustrated that lower hydraulic conductivities are achieved for higher compactive effort.

Comparisons between index properties and hydraulic conductivities for water contents 2% wet of optimum for each compactive effort showed that hydraulic conductivity was sensitive to soil composition. In general, lower hydraulic conductivities were obtained for soils having a larger percentage of fines, higher liquid limit, and higher plasticity index. However, hydraulic conductivity was not uniquely related to any of the compositional variables, suggesting that a single index property is not sufficient to estimate hydraulic conductivity.

Stepwise linear regression was used to identify the compaction and compositional variables that are most useful in predicting hydraulic conductivity. The variables identified were initial saturation, compactive effort, plasticity index, and clay content. The resulting regression equation is strikingly similar to another equation previously published in the literature (Benson *et al* 1994) that was developed using hydraulic conductivities for specimens collected from actual compacted soil liners. These equations may prove useful when considering potential borrow sources, selecting compaction machinery, or estimating the shape of an acceptable zone for compaction control.

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