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The Design and Testing of a Compacted Clay Barrier Layer to Limit Percolation Through Landfill Covers

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ABSTRACT: The design and testing of a compacted clay barrier layer to restrict vertical percolation through landfill covers is discussed. General relationships between compaction water content, dry unit weight, and permeability related to changes in soil fabric due to varying compaction conditions are reviewed. Laboratory testing programs to evaluate the degree of imperviousness capable of being achieved in the field for a given soil type are outlined, and a case study of the design and testing of a compacted clay barrier over a landfill is presented. Based on the results of the laboratory testing program prior to construction, it was determined that a design permeability of from 1 to 5×10^{-8} cm/s could be achieved by controlling the minimum dry unit weight to greater than 95% of the standard Proctor dry density and the compaction water content to greater than 1% wet of the line of optimums. Results of laboratory permeability testing on undisturbed ring and block samples taken from the landfill barrier layer indicated that an average permeability of 2×10^{-8} cm/s had been achieved.

KEY WORDS: permeability, seepage, landfill, leachate generation, compacted clay, compaction water content, dry unit weight, compactive effort, line of optimums, laboratory testing, design methods

The incorporation of a properly designed final cover layer system over a completed landfill (Fig. 1) is the most effective method for limiting the amount of moisture percolation through waste materials and provides the first line of defense against the generation of significant quantities of leachate from a landfill [1-5]. The primary inhibitor with respect to the reduction of percolation through a soil cover is the compacted clay barrier layer. The overlying protective cover will serve to shield this barrier from the effects of weathering and erosion and will support a healthy vegetated cover. The leveling course beneath the barrier will serve to provide a graded work surface firm enough to permit satisfactory compaction of the barrier layer.

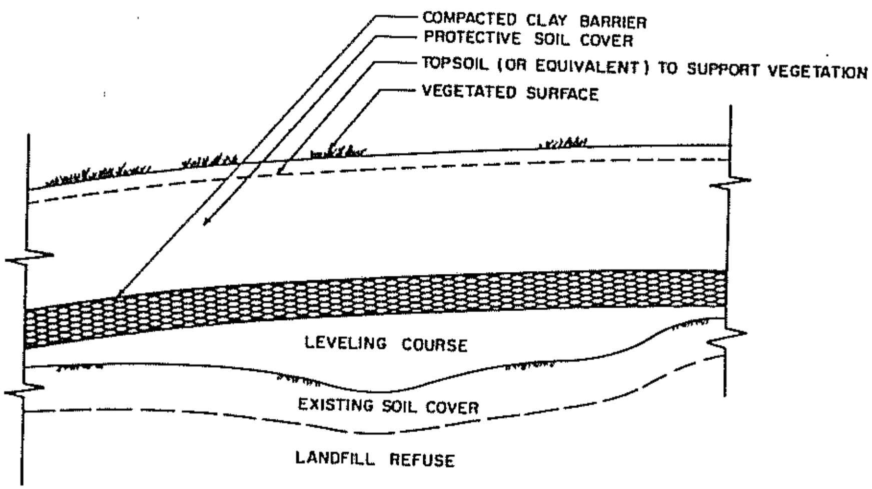

FIG. 1—*Typical landfill cover section.*

The amount of infiltration into the protective cover layer and any subsequent percolation down through waste materials will be controlled by the characteristics of the surface and the protective cover and by the climatological conditions of the site location. The type and thickness of the cover soil influence percolation by the soil's capacity to store water. The amount of available percolation through a cover is determined by performing water balance calculations [3,6,7] that involve assessing the seasonal variations in precipitation, surface runoff, infiltration, and evapotranspiration and their effect on soil moisture recharge and utilization. During those times of the year when water from precipitation is available in excess of the protective soil cover field moisture capacity after evapotranspiration and surface runoff losses, percolation through the compacted clay barrier can occur.

The seepage model shown in Fig. 2 can then be used to calculate vertical flow through the clay barrier. The total head loss, h, is taken equal to the barrier thickness, L, plus the field capacity of the protective cover (determined from the soil type) divided by its porosity. As illustrated, the seepage rate, q, is directly proportional to the permeability of the clay barrier

$$q = k\frac{h}{L} \qquad (1)$$

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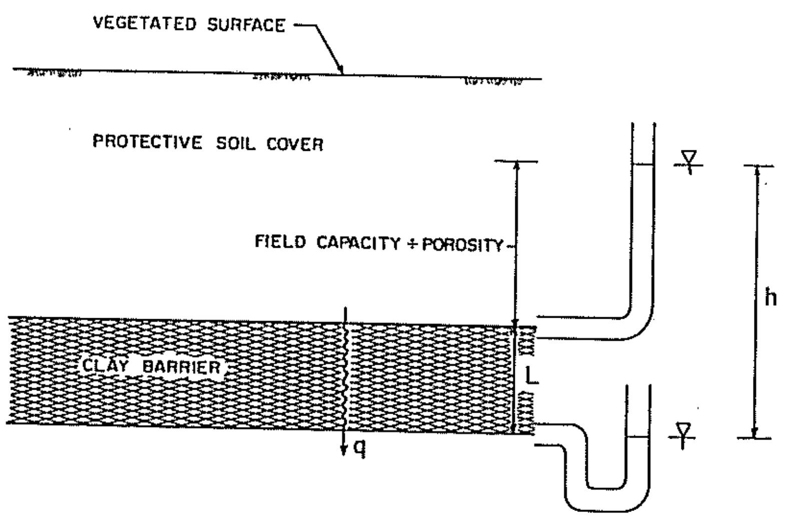

BARRIER SEEPAGE RATE: $q = k\frac{h}{L}$ PER UNIT AREA

FIG. 2—*Seepage model through cover.*

The total percolation quantity per year can then be calculated by multiplying the seepage rate by both the landfill area and the annual duration of flow (as determined by the water balance).

To regulate the potential amount of leachate which may be generated due to downward percolation, a design permeability of the compacted clay barrier can be selected which would limit vertical flow through the cover system. The estimated leachate quantities generated could then be used either in the design of a leachate collection system or for comparison with the attenuation capabilities of the underlying or adjacent soils or a combination of the two.

Permeability of Compacted Clay

General relationships between permeability and compacted characteristics (for example, compaction water content, dry unit weight, compactive effort) for fine-grained cohesive soils have appeared in the literature [*8–11*], and the general trends are shown in Fig. 3. It may be observed from the figure that at each compactive effort, the permeability values decrease dramatically at compaction water contents wet of the optimum water content. In addition, the higher the compactive effort, the lower the permeability value for a given compaction water content. The permeability of soil specimens compacted dry of optimum is generally 10 to 1000 times larger than the permeability of specimens compacted wet of optimum.

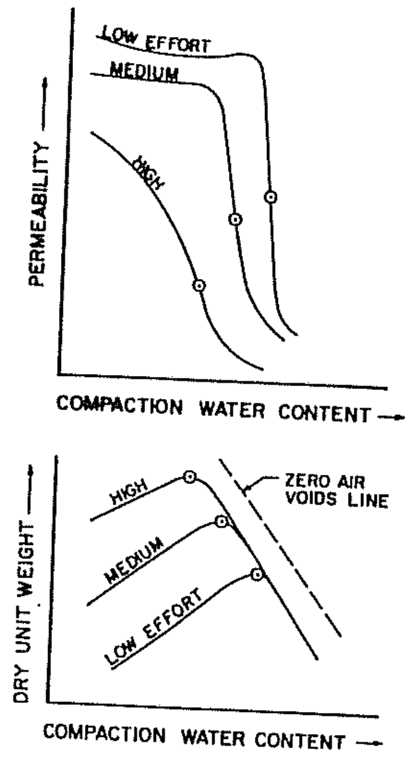

FIG. 3—*Permeability and compaction relationships.*

This behavior has been attributed to changes in the soil fabric and geometry of the porous network at varying water contents and dry unit weights [*9,10,13–15*]. Lambe [*12*] postulated that individual clay particles exist in a flocculated state dry of optimum and exhibit a more dispersed structure wet of optimum and that this difference controls the behavior of the soil mass. More recent investigations [*9,13,14*] have explained the behavior and characteristics of compacted clay using a deformable aggregate soil model in which the individual soil particles group together in agglomerations, and flow is controlled primarily by the size, frequency, and orientation of large interaggregate pores and to a lesser degree by a network of small intraaggregate pores. As the compaction water content increases, the aggregates decrease in strength and easily undergo large deformation during compaction, resulting in a decrease in the size of the interaggregate pore space and, in turn, a decrease in permeability.

Design and Testing Concepts

Several of the problems associated with predicting the field permeability of a compacted clay liner using laboratory prepared samples and permeability tests have been summarized by Daniel [*16*] and are again presented in Table 1. In general, for compacted clay barrier layers over landfills, the two sources of error which appear to be the most common and which yield the greatest magnitude of error on the unconservative side are the first two listed in the table.

If the field compaction water content is lower than that used in the laboratory testing program for the same compactive effort, the field permeability will be much larger than estimated in the laboratory. In addition, if the compactive effort in the field is less than that used in the laboratory, the field permeability will be much higher than expected due to the shift in the optimum water content for the lesser degree of compaction, as shown in Fig. 4.

The effect of landfill settlements also has to be considered in the design of cover systems. Large differential movements, characteristic of landfill surfaces, can contribute to significant cracking of otherwise low-permeability clayey barrier layers. Leonards and Narain [*17*] performed tests which indicated that clayey soils compacted above optimum water content were significantly more flexible and thus more resistant to cracking than if compacted dry of optimum.

Based on the preceding discussion, it is possible to develop a laboratory testing program which is capable of determining the degree of impermeability that can reasonably be achieved in the field for a given fine-grained clayey soil and the range of field conditions (compactive effort and field compaction water content) to achieve a desired design permeability. The initial portion of the testing program includes a complete series of classification tests (for example, natural water content and dry unit weight, Atterberg limits, specific gravity, grain-size analysis) on the range of expected soil types from the proposed borrow area which may be used in the compacted clay barrier layer.

TABLE 1—*Sources of error in estimating field permeability of compacted clay liners from laboratory tests.*[a]

Potential Source of Error	Possible Number of Orders of Magnitude of Error	Laboratory Permeability Compared to Actual Field Permeability
1. Compaction at a higher water content in laboratory than in field	1 to 3	low
2. Use of more compactive effort in the laboratory than in the field, resulting in optimum water content higher in field than in laboratory	1 to 3	low
3. Deleterious substances present in the field but not in laboratory samples	1 to 3	low
4. Maximum size of clay chunks smaller in laboratory than in field	1 to 2	low
5. Use of static (impact) compaction rather than kneading compaction to prepare laboratory specimens	0 to 1	high
6. Air in laboratory samples	0 to 1	low
7. Use of excessive hydraulic gradients causing particle migration	0 to 1	low
8. Steady-state seepage not attained	0 to 1	high
9. Sample size too small in laboratory test	0 to 3	low
10. Dessication cracks in field	no data	low

[a]After Daniel [*16*].

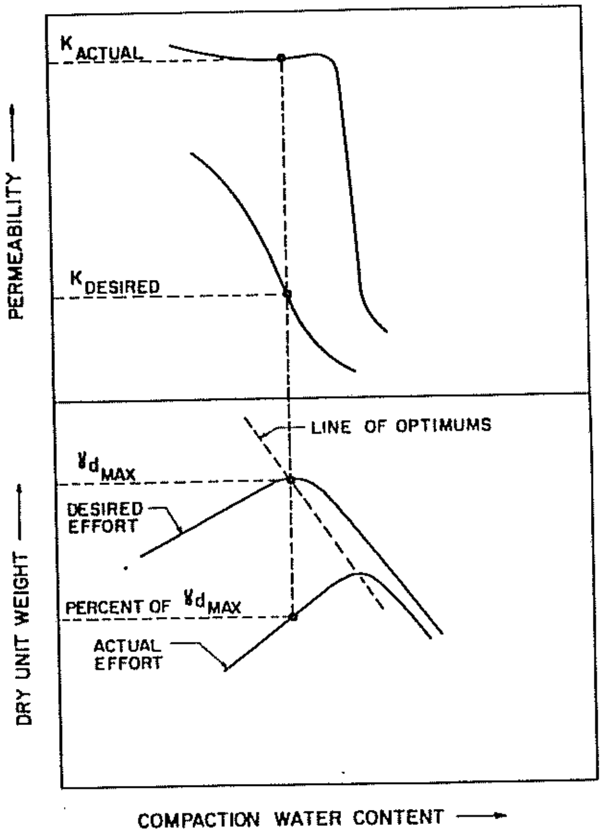

FIG. 4—*Error in estimation of field permeability (after Daniel* [16]*)*.

Figures 5 and 6 illustrate a procedure that may be used to define the range of lower permeability values that can exist for a given soil type. As shown, three compactive efforts (high, medium, low) are used to define the possible range of compactive efforts that may be used or achieved in the field. The highest effort curve (*C*) generally corresponds to the standard Proctor effort [ASTM Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures, Using 5.5-lb (2.49-kg) Rammer and 12-in. (304.8-mm)

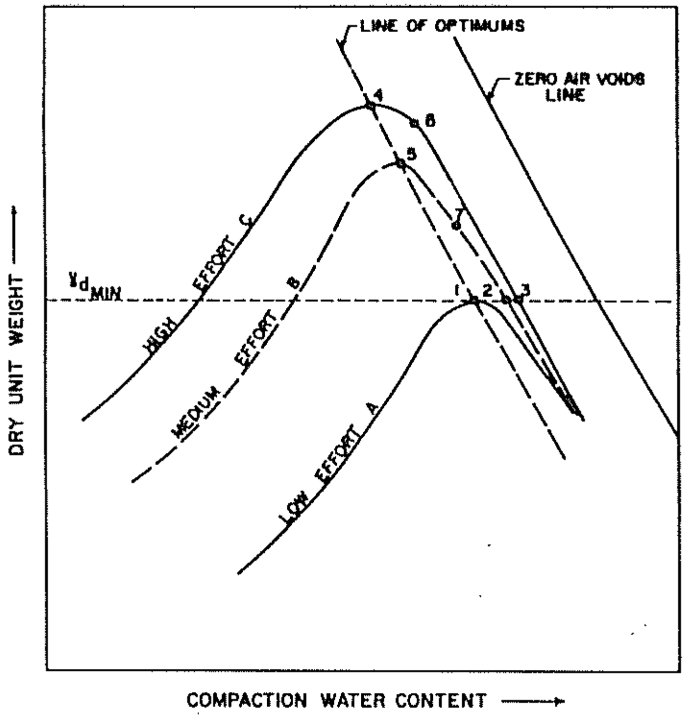

FIG. 5—*Laboratory testing to evaluate field permeability.*

Drop (D 698-78)]. The lowest effort curve (*A*) corresponds to the effort necessary for the maximum dry unit weight to equal the expected minimum dry unit weight requirement specified during the field construction. This may vary between 90 to 95% of the standard Proctor value, depending on the degree of compaction necessary to achieve the design permeability value. Points labeled 1 through 7 correspond to the water content, dry unit weight, and compactive effort conditions considered for the preparation of seven specimens for permeability testing. At Point 1, the minimum dry unit weight is achieved at the lowest selected compactive effort possible with the water content at optimum. The permeability of the specimen prepared at this point will be the greatest of all seven points. Conversely, a specimen at Point 3 compacted at the greatest water content using the highest effort will generally yield the lowest permeability of the seven points.

After the permeability tests have been performed, the resulting values are plotted on a graph of percent wet of compactive effort optimum versus dry unit weight as shown in Fig. 6. From these seven points, the design permeability line may be determined by interpolating between the permeability test results K_1 through K_7. For conditions to the right of the line, the as-

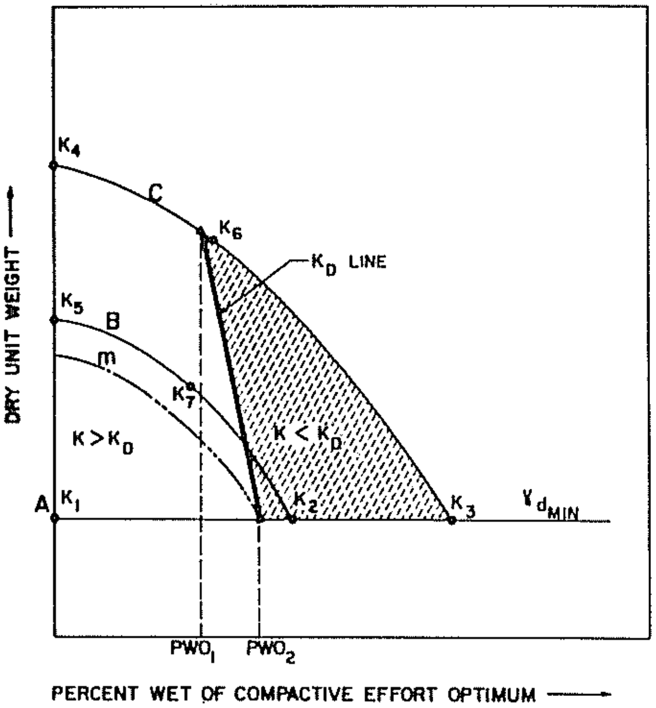

FIG. 6—*Determination of design permeability line.*

compacted permeability of the barrier will be less than the selected design permeability. To the left of the line, the compaction conditions will yield higher (and therefore unsuitable) permeability values. The two end points of the design permeability line, Control Points PWO_1 and PWO_2 (percent wet of compactive effort optimum), provide the control points which define the compaction conditions (shaded area in Fig. 7) necessary to achieve a permeability value less than the selected design permeability.

To illustrate this procedure, test data from Mitchell [*11*] have been plotted in Fig. 8 showing permeability values obtained for three different compactive efforts, curves *A, B,* and *C,* at compaction water contents above the optimum value for a silty clay. These points numerically illustrate how the permeability decreases with increased compactive effort and with increased compaction water content. Curves of equal permeability values (dashed lines) are approximately parallel for this soil.

It may be observed from Fig. 7 that a design permeability may be achieved by specifying a minimum dry unit weight with compaction water contents a given percentage wet of the line of optimums as defined by Control Point PWO_2. The construction criterion then becomes a vertical line through Con-

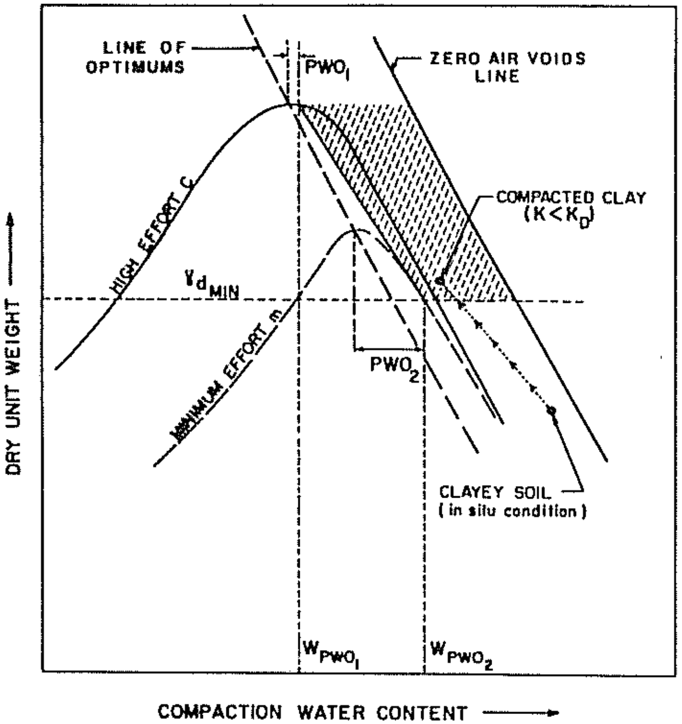

FIG. 7—*Control area to achieve design permeability.*

trol Point PWO_2 on Fig. 6 rather than the K_D line. If variations in soil types or soil plasticity are indicated from the borrow area testing, this procedure would be repeated for each soil type such that a water content/dry unit weight control area is developed for each soil type as shown in Fig. 9. The control area for a given soil type could be minimally estimated by running at least three permeability tests corresponding to Points K_1, K_2, and K_3 in Fig. 6.

Field Control

To adequately control the construction of a compacted clay barrier to achieve permeability values less than the selected design permeability, a continuous evaluation of the soil used for the barrier layer is necessary as well as careful monitoring of the compacted moisture and density conditions. Subsequent to the laboratory testing program, standard Proctor curves generated for the various soil types evaluated from the proposed borrow area should be available and the compaction criteria necessary to control the permeability of the compacted clay barrier established (see shaded area in Fig. 7). As soil is brought to the landfill site from the borrow area, the soil is visually classified and compared to the soils previously tested. When differences in soil types are observed, one-point standard Proctor tests and Atterberg limits are run to determine the variability of the soils. As shown in Fig. 9, if an untested soil type falls between two of the soil types tested, the line of optimums for that particular soil type can be estimated by interpolating between the two known soils. A shaded control area (in which the permeability will be less than the design permeability) can then be estimated for that soil type based on the results of the laboratory testing program. It should be emphasized that the water content at which a one-point field compaction test is run should be at or slightly dry of optimum so as to yield a distinct interpretation of maximum dry unit weight and optimum water content for the soil. The wet of optimum family of curves are generally so close together that there is much greater uncertainty in the interpretation in this area.

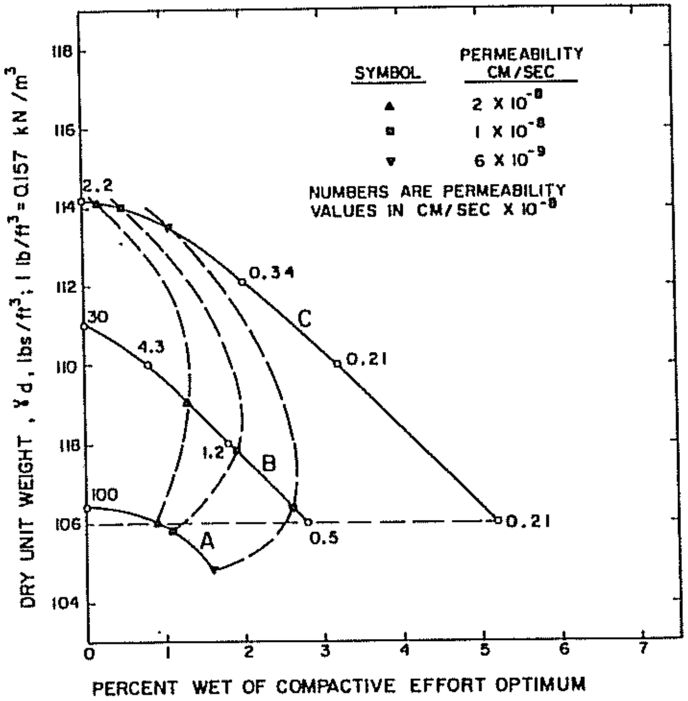

FIG. 8—*Design permeability line concept example (from Mitchell et al* [11]*).*

During placement and compaction of the barrier layer, periodic field density tests (on a random grid pattern) using the sand cone and nuclear moisture/density tests can be performed to continuously monitor and maintain control of the compaction process.

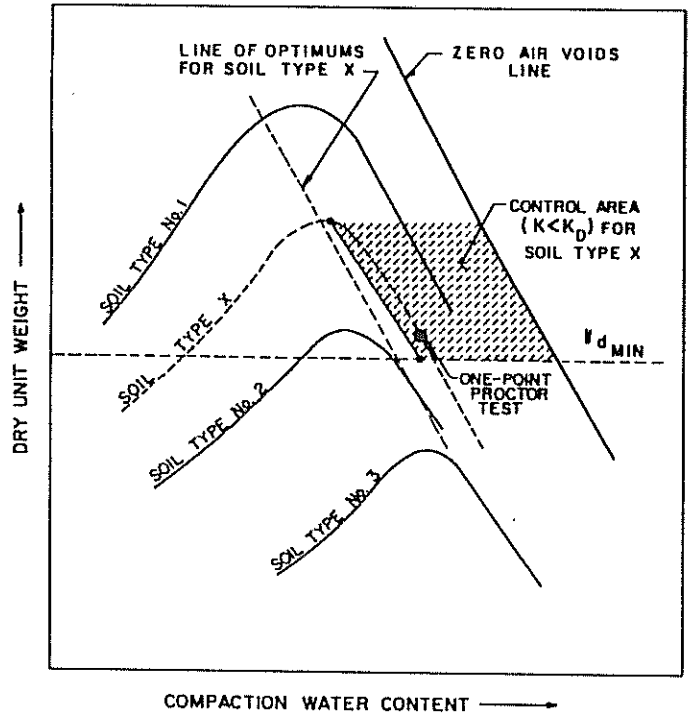

FIG. 9—*Field control area for intermediate soil type.*

Case Study

The closure plan for a waste disposal facility in the midwestern United States included the placement of an engineered final soil cover barrier system over the landfilled area in order to limit vertical percolation and subsequently reduce the potential amount of leachate generated. The landfilled wastes were generally of limited thickness, and the site had been inactive and covered with silty soils for several years. Thus, excessive postconstruction settlements were not expected. Although regulations called for a permeability of 1×10^{-7} cm/s or less for the cover system, it was determined from water balance calculations that an effective barrier design permeability on the order of 2 to 5×10^{-8} cm/s would limit percolation to an acceptable level.

A laboratory testing program was directed toward establishing the character and variability of soils encountered within a nearby borrow area selected as the source for landfill cover materials. A summary of the results of classification tests performed on the range of soils anticipated for use in the compacted clay barrier is shown in Table 2.

Based on these test results, two soil types were selected for extensive permeability testing: Soil 1, a gray to brown, mottled silty clay judged to be of average plasticity for the cohesive soils in the borrow area and Soil 2, a light brown, mottled, lower plasticity silty clay which was expected to provide an indication of some of the more marginal fine-grained borrow soils to be used in the barrier cover layer. Classification tests for these two soils are shown in Table 3.

TABLE 2—*Results of general classification testing on borrow soils.*

Parameter	Average	Range
Natural moisture content, %	25.5	17.7 to 29.2
Natural dry unit weight, lb/ft^3[a]	98.2	93.8 to 104.6
Atterberg limits		
Liquid limit	38.6	32 to 45
Plastic limit	18.3	17 to 20
Plasticity index	20.3	12 to 28
Clay content, %[b]	23.8	17.5 to 28.5
Specific gravity	2.71	2.68 to 2.75
Unified soil classification	CL[c]	CL

[a] 1 lb/ft^3 = 0.157 kN/m^3.
[b] Less than 0.002 mm.
[c] CL = Inorganic clays of low to medium plasticity.

As shown in Fig. 10, a series of compaction tests at three different compactive efforts were performed on Soil 1 to establish guidelines for preparing samples for permeability testing and to determine the location of the line of optimums. Samples were compacted in three layers into a standard 101.6-mm (4-in.)-diameter mold with the number of blows per layer varying from 10 (low compactive effect) to 25 (standard Proctor, ASTM D 698). The line of optimums was observed to be very nearly parallel to the zero air voids line, as expected.

Based on the results of these tests, two specimens were prepared at water contents of 19.0 and 20.3%, respectively, and compacted using 14 blows per layer in order to achieve a dry unit weight above 95% of the standard Proctor

TABLE 3—*Results of general classification testing on soil 1 and soil 2.*

Soil No.	Maximum Dry Unit Weight, lb/ft^3[a]	Optimum Water Content, %	Atterberg Limits[c]			Particle Size Gradation, %			Specific Gravity
			LL	PL	PI	Sand	Silt	Clay[b]	
1	110.9	16.0	39	18	21	2.4	73.1	24.5	2.69
2	112.3	15.1	32	20	12	3.3	79.2	17.5	2.68

[a] 1 lb/ft^3 = 0.157 kN/m^3.
[b] Less than 0.002 mm.
[c] LL = liquid limit; PL = plastic limit; PI = plasticity index.

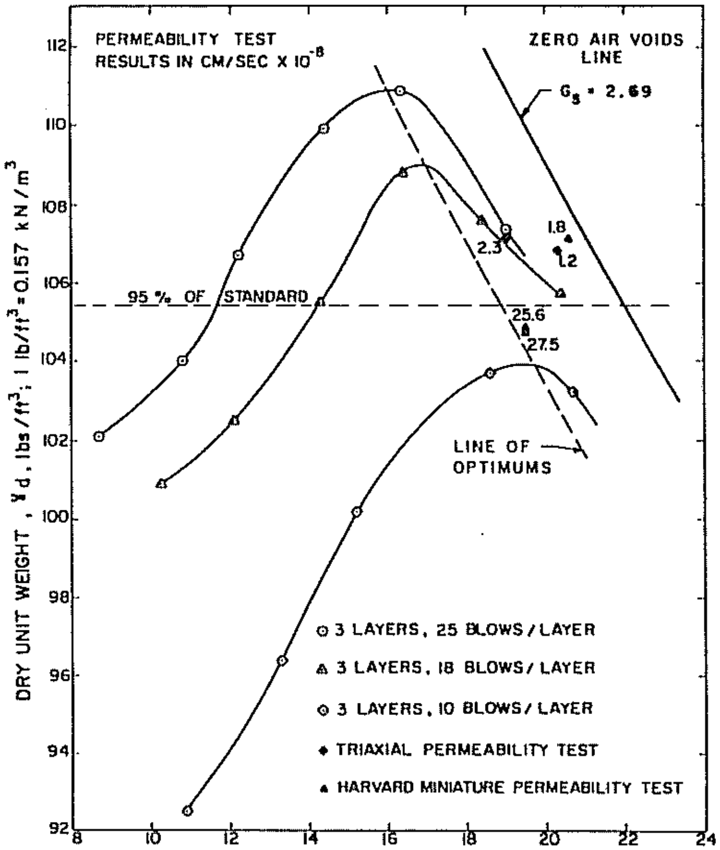

FIG. 10—*Laboratory test results—Soil 1.*

maximum and wet of the line of optimums. These specimens were trimmed from the mold, placed in a triaxial cell, and back-pressure saturated with a confining pressure of 345 to 552 kPa (50 to 80 psi). A constant-head permeability test was then performed with a pressure differential of 20.7 kPa (3 psi) maintained across the specimens to encourage flow at a measurable rate. Another specimen prepared in a similar manner using 12 blows per layer at a water content of 20.6% was trimmed into a Harvard miniature permeameter and a constant-head permeability test was performed. Two additional specimens were compacted directly into Harvard miniature molds (five layers, five blows per layer) at dry unit weights slightly below 95% standard and near the line of optimums.

The results plotted in Fig. 10 indicate that the permeability values ranged from 1.2 to 2.3 × 10^{-8} cm/s for specimens with water contents at least 1% wet of the line of optimums and greater than 95% of standard, and from 25.6 to 27.5 × 10^{-8} cm/s for specimens with water contents less than 1% wet of the line of optimums and dry unit weights slightly less than 95% of standard.

Similarly, for Soil 2 (Fig. 11), four specimens compacted to 94.0 to 96.5% of standard Proctor with water contents at least 1% wet of the line of optimums yielded permeability value between 3.1 to 4.4 × 10^{-8} cm/s for permeability tests performed in both the triaxial cell and the Harvard miniature permeameter.

From the results of the limited laboratory testing program, it was decided to compact the natural silty clay borrow soils to at least 95% of the standard Proctor maximum dry unit weight at water contents at least 1% wet of the line of optimums to achieve a coefficient of permeability in the range of 1 to 5 × 10^{-8} cm/s.

During the construction of the compacted clay barrier layer, field quality control testing and inspection was performed on a continuous basis. Daily activities included determination of the suitability of the borrow soils (by visual classification and Atterberg limits tests), nuclear moisture/density tests to establish the degree of compaction, check field density tests by the sand cone method, and one-point Proctor tests (see Fig. 12) to maintain control of the compaction process with respect to the line of optimums.

To assess the overall degree of imperviousness of the compacted clay bar-

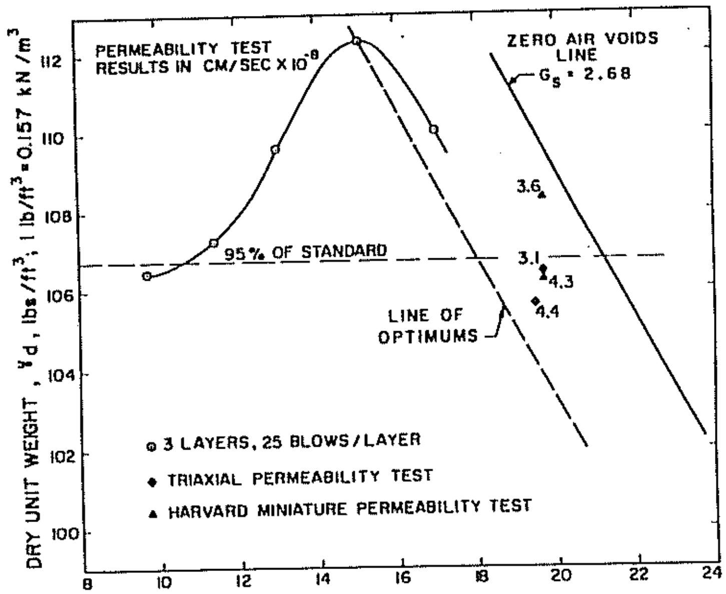

FIG. 11—*Laboratory test results—Soil 2.*

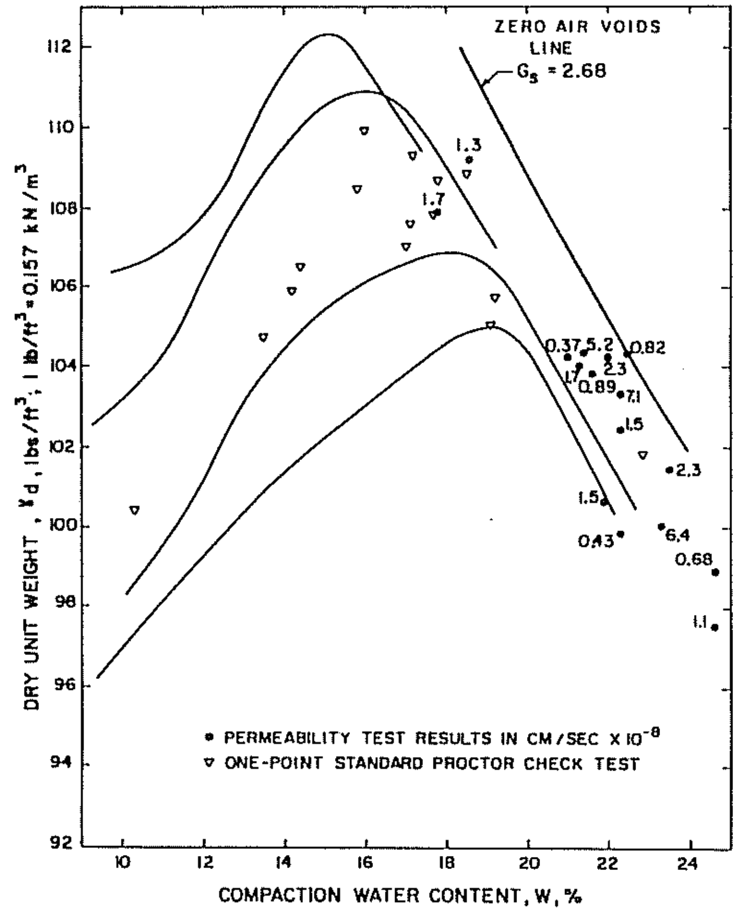

FIG. 12—*Summary of field one-point proctor and as-compacted permeability tests.*

rier layer covering the landfill during construction of the final cover section, the as-compacted permeability of the barrier layer was determined from 18 specimens trimmed from samples of the barrier layer taken from selected random locations across the landfill area. Samples were obtained either by manually driving a 101.6-mm (4-in.)-diameter metal ring sampler into the compacted clay or by cutting large undisturbed block samples from the barrier layer. The results plotted in Fig. 12 indicate that the permeability values from constant-head, back-pressure saturated tests performed in the triaxial cell ranged from 3.7×10^{-9} to 7.1×10^{-8} cm/s with an average value of about 1.8×10^{-8} cm/s. One sample which exhibited a higher permeability value (2.1×10^{-7} cm /s) was found to contain a continuous vertical silt seam and judged to be a localized condition based on additional testing and field inspection.

Conclusions

The generation of leachate quantities from landfills is dependent on the amount of percolation that passes through the final cover layer system. The primary inhibitor with respect to the reduction of percolation through the cover layer is the compacted clay barrier layer. Based on the general relationships between compaction water content, dry unit weight, and permeability for compacted clay soils, a laboratory permeability testing program can be used to determine the field compaction conditions necessary to achieve a design field permeability value for a clay barrier layer. From this testing program, construction specifications can be developed requiring that the clay barrier be compacted to minimum dry unit weight wet of the line of optimums by a given percentage in order to meet the design permeability.

Results from a case study indicate that an average permeability of 2×10^{-8} cm/s had been achieved for a disposal facility by controlling the minimum dry unit weight to greater than 95% of the standard Proctor value and the compaction water content to greater than 1% wet of the line of optimums. Field control procedures included performing classification and one-point Proctor compaction tests to determine the position of the line of optimums so that the compaction moisture content and dry unit weight would fall within the design permeability range.

Acknowledgments

The authors' interest in the permeability of compacted clays has been developed by their involvement in numerous projects relating to sanitary and hazardous waste disposal facilities while employed by ATEC Associates, Inc. The laboratory testing of the soils referenced in the text was performed by Diane Garrison, Gordon Pickett, and Jim Taylor. Audrey Smith and David Haupt contributed to the field control and undisturbed sampling of the compacted clay barrier.

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Desiccation Cracking of Soil Barriers

REFERENCE: Kleppe, J. H. and Olson, R. E., **"Desiccation Cracking of Soil Barriers,"** *Hydraulic Barriers in Soil and Rock, ASTM STP 874*, A. I. Johnson, R. K. Frobel, N. J. Cavalli, and C. B. Pettersson, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 263-275.

ABSTRACT: Compacted soil liners have been used to retard leakage of fluids from burial sites. If allowed to desiccate, such liners may shrink, crack, and lose their integrity. As a result of the expense and control problems associated with field tests, an initial laboratory study was made of shrinkage, cracking tendency, and hydraulic conductivity of various compacted clay/sand mixtures. The study showed that desiccation shrinkage increased linearly with compaction water content and was unaffected by density. Soaking prior to desiccation increased strains markedly for specimens compacted dry of optimum. Shrinkage strains greater than 10% should cause serious problems in the field. Clay/sand mixtures were prepared which were crack resistant and which had low hydraulic conductivities.

KEY WORDS: impermeable liners, clays, compaction, shrinkage, desiccation, cracking, hydraulic conductivity, permeability

Compacted cohesive soils are often used alone as "impermeable" barriers or ~~as~~ backups to synthetic liners at sites where wastes are buried in the ground. Laboratory tests, using compacted samples, may indicate that the soil is relatively impervious. However, compacted clay liners may fail to function satisfactorily because of

1. Chemical attack from retained fluids.
2. Development of cracks and holes due to differential settlement, penetration by plant roots and animals, freeze-thaw cycles, and desiccation.

This paper is concerned with desiccation cracking. Desiccation cracking occurs when the compacted soils are exposed to the atmosphere. Pore water evaporates, causing development of negative pore water pressures in the soil. The negative pore water pressures cause increases in effective stress and a consequent reduction in volume. Because the pore water pressure acts in all directions, the soil tends to shrink in all directions and cracking results. If the

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