plus water is pushed back into the reservoir and stability is retained. There may come a time, however, when the compression goes forward so rapidly that the surplus water cannot be carried off fast enough. When that point is reached (if it is reached), there will tend to be an excess of water in the interstices and that excess will transmit some of the pressure that was before carried only by the bearings of solid particles, and the frictional resistance of the material will be less, and perhaps much less, than it was before.

"The thought has occurred to the writer, in looking at the material that slid in the Calaveras Dam, that something of this kind may have happened on a large scale—800,000 cu yd of fill flowed for a brief space, and then became solid. It was, in fact, so solid that in examining it afterward, by samples and by borings, it was difficult to see how the material could have flowed—as it certainly did flow.

"It may be that after the first movement there was some readjustment of the material in the toe which resulted in producing temporarily this condition of quicksand, and which destroyed for a moment the stability of the material and facilitated the movement that took place.

"This will not account for the initial movement; but the initial movement of some part of the material might result in accumulating pressure, first on one point, and then on another, successively, as the early points of concentration were liquefied and in that way a condition comparable to quicksand in a large mass of material may have been produced."

From the "Summary" of his paper, the following paragraph is particularly pertinent:

"Stability is increased by compactness. It is worth while to watch voids closely, and to make every effort to hold them at a minimum. The extra weight is advantageous, but security against compression and re-arrangement with resulting temporary quicksand conditions, can be best reached in this way."

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PERMEABILITY OF COMPACTED CLAY

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and Richard G. Campanella[3]

INTRODUCTION

Although the hydraulic permeability of clay soils is of great importance in connection with problems of seepage, settlement, and stability, it has not been studied to the same extent as other major soil engineering properties, such as strength and compressibility. However, significant contributions to our understanding of the permeability of saturated clays, have been made recently by Michaels and Lin,[4] Schmid,[5] Hansbo,[6] Olsen,[7] and Miller and Low.[8]

Note.—Discussion open until December 1, 1965. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 91, No. SM4, July, 1965.

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[4] Michaels, A. S., and Lin, C. S., "The Permeability of Kaolinite to Various Fluids," Industrial and Engineering Chemistry, Vol. 46, June, 1954, pp. 1239–1246.

[5] Schmid, W. E., "The Permeability of Soils and the concept of a Stationary Boundary Layer," Proceedings, Amer. Soc. for Testing and Materials, Vol. 57, 1957, p. 1195.

[6] Hansbo, S., "Consolidation of Clay, With Special Reference to Influence of Vertical Sand Drains," Proceedings, Swedish Geotech. Inst., No. 19, Stockholm, Sweden, 1960.

[7] Olsen, H. W., "Hydraulic Flow Through Saturated Clays," Clays and Clay Minerals, Vol. 9, Pergamon Press, New York, N. Y., 1962.

[8] Miller, R. J., and Low, P. F., "Threshold Gradient for Water Flow in Clay systems," Proceedings, Soil Science Soc. of Amer., Vol. 27, No. 6, 1963, pp. 605–609.

Lambe,[9,10] and Bjerrum and Huder[11] have made recent contributions to our understanding of the permeability behavior of compacted clays. Lambe[9] devised a simple apparatus wherein a soil specimen was compacted in a lucite mold and then tested using a constant head procedure. Although the procedure did not allow for either the precise control or measurement of saturation during permeation, the test was rapid, reliable, and convenient. Fig. 1 presents data typical of those obtained by Lambe. The great influence of molding water content on permeability is readily apparent. As shown by Lambe[10] and Seed and Chan,[12] many clay soils compacted dry of optimum by kneading compaction have a more random particle orientation (flocculent structure) and a larger average pore size than when compacted wet of optimum where the shear strains induce more nearly parallel particle arrangements (dispersed structure). It may be seen from Fig. 1 that this effect of structure outweighs the opposing influence of saturation, because the specimens compacted dry of optimum come to equilibrium at a considerably lower degree of saturation than do the specimens compacted wet of optimum; and, ordinarily, other conditions being equal, the higher the degree of saturation the greater the permeability. It is also apparent from Fig. 1 that density plays a role that is minor relative to the effect of molding water content and structure.

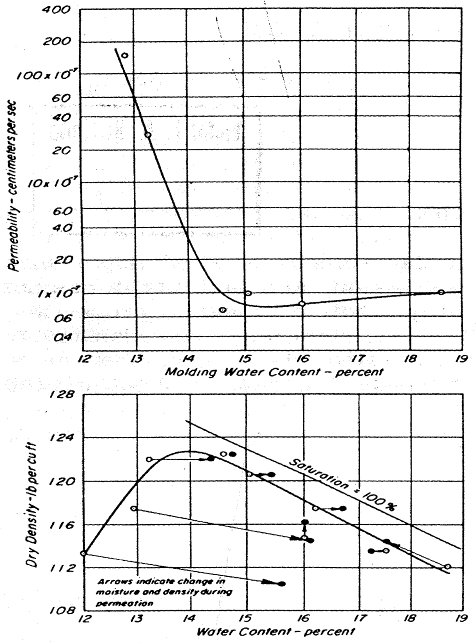

FIG. 1.—COMPACTION—PERMEABILITY BEHAVIOR OF JAMAICA SANDY CLAY

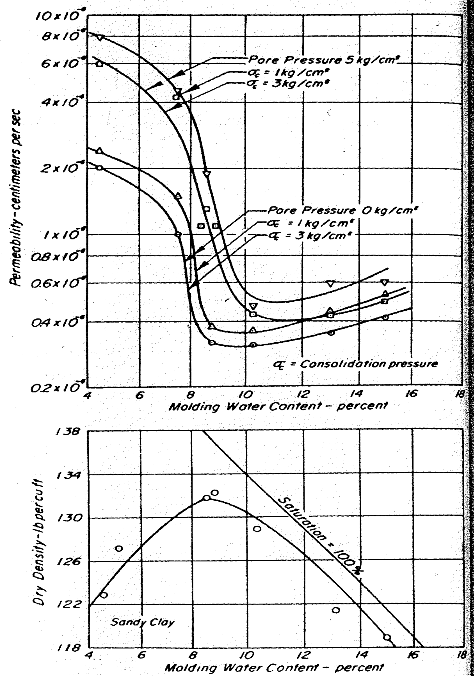

FIG. 2.—EFFECT OF SATURATION USING BACK PRESSURE AND CONSOLIDATION PRESSURE ON PERMEABILITY

Bjerrum and Huder[11] describe a method for the measurement of compacted clay permeability wherein a back pressure is used for saturation. Their tests were performed in a triaxial cell. Fig. 2 illustrates the influence on permeability of both the saturation and consolidation of the specimens. Increased permeability of higher degrees of saturation is clearly indicated because, for these tests, higher degrees of saturation are associated with higher pore pressures.

Studies of the permeability of compacted clays have been in progress at the University of California for several years in an effort to clarify further the roles of such factors as soil structure, density, method of compaction, method of test, thixotrophy, and degree of saturation. It is the purpose herein to outline the test procedures, to present significant findings, and to point out the practical implications of the results of these studies.

Notation.—The letter symbols adopted for use in this paper are defined where they first appear and listed alphabetically in the Appendix.

EXPERIMENTAL PROCEDURES

A permeability test apparatus was developed which permits the utilization of saturating back pressures and the precise determination of flow both in and out of the sample. The basic elements of the apparatus are shown schematically in Fig. 3. Air pressure is applied through regulators (1) to the water reservoirs (2) "Nylon" pressure tubing of two different diameters (3,4) connects to the inflow and outflow sides of the permeameter cell through non-displacement control valves (5). Red-dyed carbon tetrachloride in the lower parts of the U-tubes provides a well-defined interface with the water. Because the U-tubes are calibrated with respect to volume of contained fluid, observation of the rate of travel of the interface along the meter sticks (6) provides a direct measure of flow rates. The small diameter U-tube is used for measurements on samples of lower permeability, while the larger tube is used for samples of higher permeability. The reservoirs (7) permit the recharging of the U-tubes as needed. A pressure gage (8) may be switched into either side of the system through valves (9).

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[9] Lambe, T. W., "The Permeability of Compacted Fine-Grained Soils," Special Technical Publication No. 163, ASTM, 1954, pp. 56-67.

[10] Lambe, T. W., "The Engineering Behavior of Compacted Clay," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 84, No. SM2, Proc. Paper 1655, May, 1958.

[11] Bjerrium, L. and Huder, J., "Measurement of the Permeability of Compacted Clays," Proceedings, Fourth Internatl. Conf. on Soil Mechanics and Foundations Engrg., London, Vol. I, 1957, pp. 6-10.

[12] Seed, H. B., and Chan, C. K., "Structure and Strength Characteristics of compacted Clays," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 85, No. SM5, Proc. Paper 2216, October, 1959.

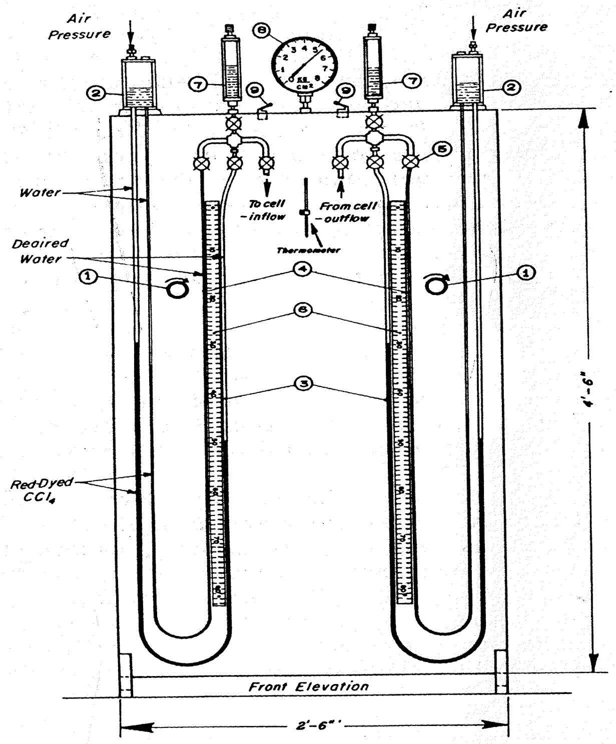

FIG. 3.—SCHEMATIC DRAWING OF PERMEABILITY TEST APPARATUS

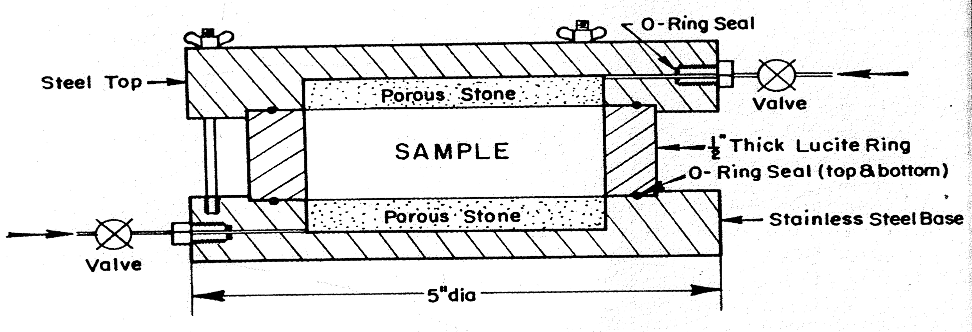

FIG. 4.—SECTIONAL ELEVATION OF TYPICAL 2.8 IN. DIAMETER BY 1 IN. HIGH PERMEABILITY CELL

A lucite sample holder of either 1.4 in. or 2.8 in. inside diameter, 1/2 in. walls, and 3.5 in. or 1.0 in. height, respectively, contained within brass or stainless steel top and base plates (Fig. 4) has been used for most of the tests. Samples could be compacted directly in the lucite molds and tested without the necessity of further manipulation of the specimen. This procedure has been found considerably easier and more rapid than testing specimens within a triaxial cell.

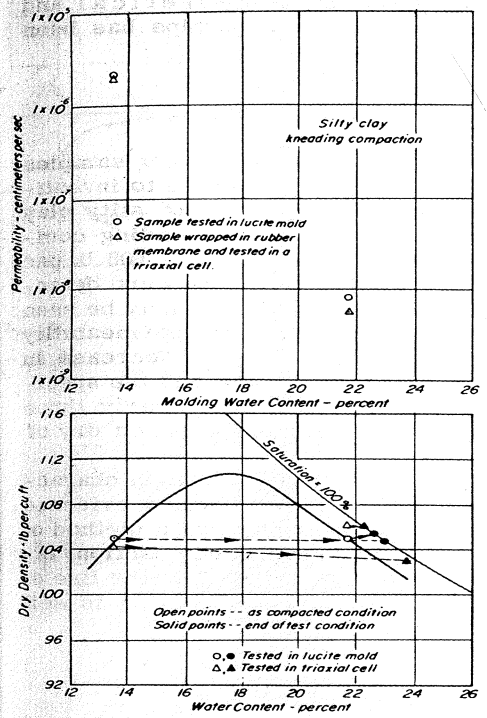

FIG. 5.—COMPARISON OF PERMEABILITY VALUES FOR SAMPLES TESTED IN LUCITE MOLDS AND IN A TRIAXIAL CELL

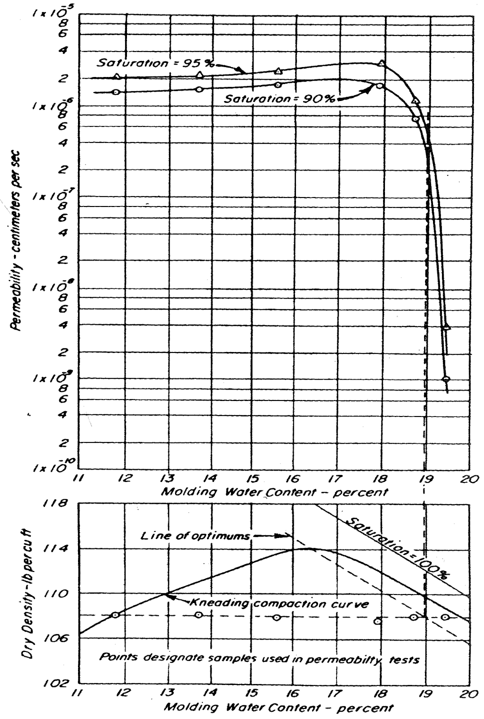

FIG. 6.—PERMEABILITY AS A FUNCTION OF MOLDING WATER CONTENT FOR SAMPLES OF SILTY CLAY PREPARED TO CONSTANT DENSITY BY KNEADING COMPACTION

An uncertainty arises in connection with tests in the lucite molds, however, as a result of the possibility of undetected excess flow along the contact between the sample and the mold. To provide positive evidence that no boundary leakage took place, sets of essentially identical specimens of silty clay were prepared—one sample of each set to be tested in a triaxial cell where the rubber membrane prevents leakage along the side of the specimen, and the other to be tested in a lucite mold in the usual manner. The results of these tests are shown in Fig. 5, from which it may be seen that nearly the same values of permeability were determined for each method of test. It was concluded, therefore, that reliable tests could be performed on samples compacted in lucite molds and that leakage between the sample and mold was not taking place.

Because back pressure saturation was used so extensively in the permeability tests and back pressure saturation is now commonly used on a routine basis for triaxial testing of soils, a comparison between theoretical and experimentally measured back pressure-saturation relationships has been made. The results of this study are presented in Appendix I.

INFLUENCE OF STRUCTURE ON PERMEABILITY

The data shown in Figs. 1 and 2 represent permeability values for samples of different density, degree of saturation, and structure. In order to investigate the effect of structure alone on permeability, samples of silty clay (liquid limit = 37%, plastic limit = 23%) were prepared using kneading compaction over a range of water contents but to a constant density of 108 lb per cu ft, as shown in the lower part of Fig. 6. Permeability values were determined and compared at values of saturation of 90% and 95%. It may be seen that for specimens compacted dry of the line of optimums, the permeability increases slightly with increasing water content. An abrupt decrease in permeability is observed at about optimum moisture content, and the specimen prepared wet of the line of optimums had a permeability nearly three orders of magnitude less than the permeability of samples prepared dry of optimum.

Seed and Chan[12] have studied in detail the structure and strength characteristics of the silty clay used for these tests. They have provided evidence that this soil is extremely structure sensitive in the sense that a method of compaction including large shear strains, such as kneading compaction, induces a dispersed structure in soil compacted on the wet side of the line of optimums. The great influence of this dispersion on permeability is well illustrated by the data in Fig. 6.

PERMEABILITY BEHAVIOR OF SAMPLES DRY OF OPTIMUM

The slight increase in permeability accompanying an increase in molding water content for samples prepared dry of the line of optimums, Fig. 6, is contrary to the steadily decreasing values of permeability accompanying an increase in molding water content, as found by Lambe[9,10] and Bjerrum and Huder[11] and shown in Figs. 1 and 2. It might be argued that the behavior of Fig. 6 is caused by the fact that the compactive effort required to obtain a density of 108 lb per cu ft decreased with increasing molding water content for specimens prepared dry of the line of optimums, as shown in Fig. 7. The decreased tendency towards dispersion of the structure because of reduced compactive effort may outweigh the tendency for increased dispersion at increased water content and lead to a slight increase in permeability.

This explanation, however, is untenable as the sole cause of such behavior, as may be seen from the test data in Fig. 8, which show the permeability

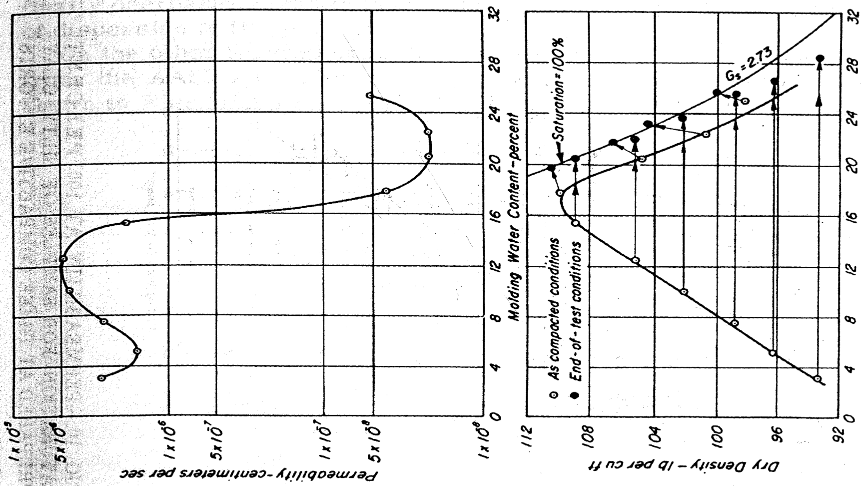

FIG. 8.—PERMEABILITY VERSUS MOLDING WATER CONTENT RELATIONSHIP FOR SILTY CLAY-KNEADING COMPACTION

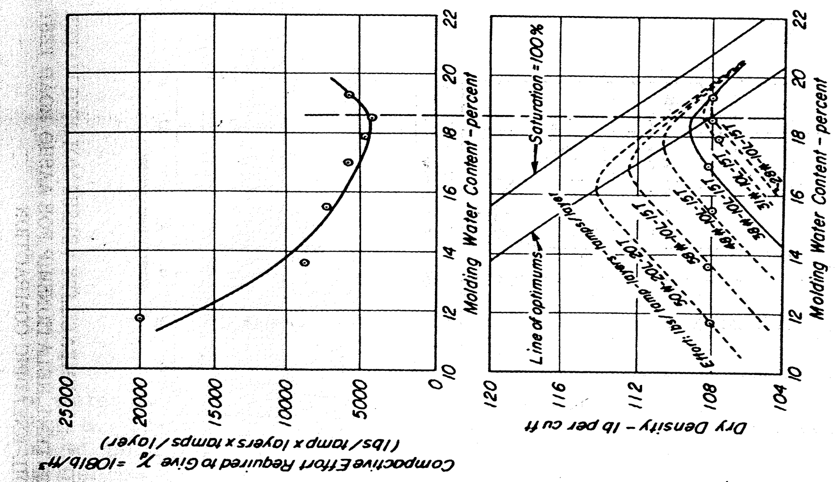

FIG. 7.—MOISTURE-DENSITY-COMPACTIVE EFFORT RELATIONSHIPS FOR SAMPLES OF SILTY CLAY PREPARED BY KNEADING COMPACTION TO CONSTANT DENSITY

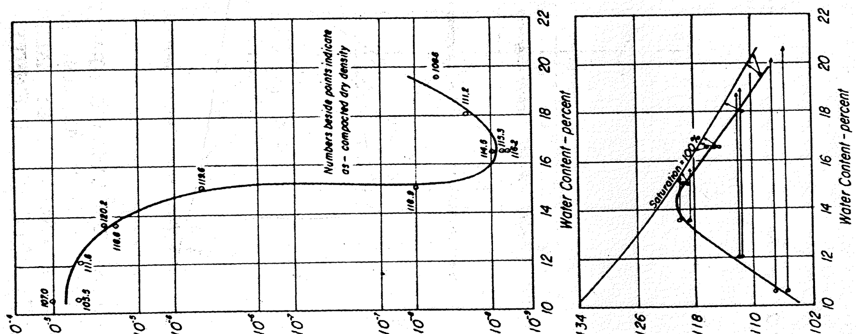

FIG. 9.—PERMEABILITY VERSUS MOLDING WATER CONTENT RELATIONSHIP FOR AASHO ROAD TEST SOIL-KNEADING COMPACTION

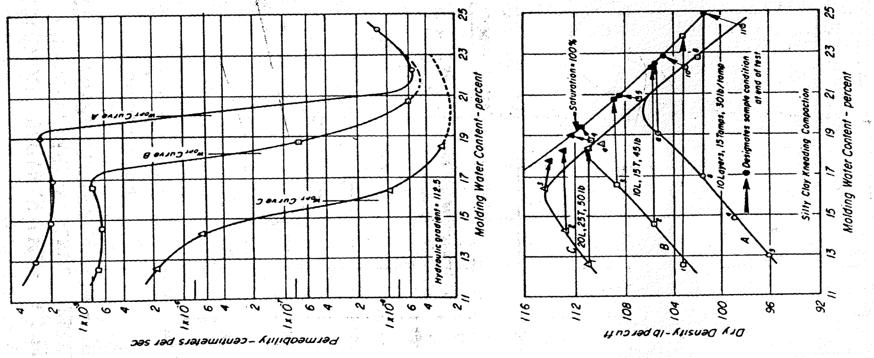

FIG. 10.—PERMEABILITY AT 100 PERCENT SATURATION FOR SAMPLES OF SILTY CLAY PREPARED AT THREE COMPACTIVE EFFORTS

versus molding water content behavior for specimens prepared over a wide range of water contents using the same compactive effort for each specimen. Fig. 8 shows that the permeability passes through a minimum at a low water content (5.2%), then increases to a maximum at a water content of 12.5%, and finally decreases abruptly at a water content of approximately 13% as a result of dispersion of the structure.

On the other hand, similar tests on samples of a different soil, a silty clay from the AASHO road test site, Ottawa, Ill., gave results similar to those shown in Figs. 1 and 2 (see Fig. 9). It should be noted however, that the range of water contents dry of optimum is considerably less in Fig. 9 than it is in Fig. 8. Thus, the actual behavior of specimens prepared dry of optimum might be a function of soil type and would appear to reflect the combined influences of compactive effort, a tendency towards increased dispersion with increased molding water content, and possibly the effects of nonuniform saturation of the sample under a back pressure and the migration of fine particles under the action of relatively large hydraulic gradients. Hydraulic gradients used for the tests reported herein were in general in the range of

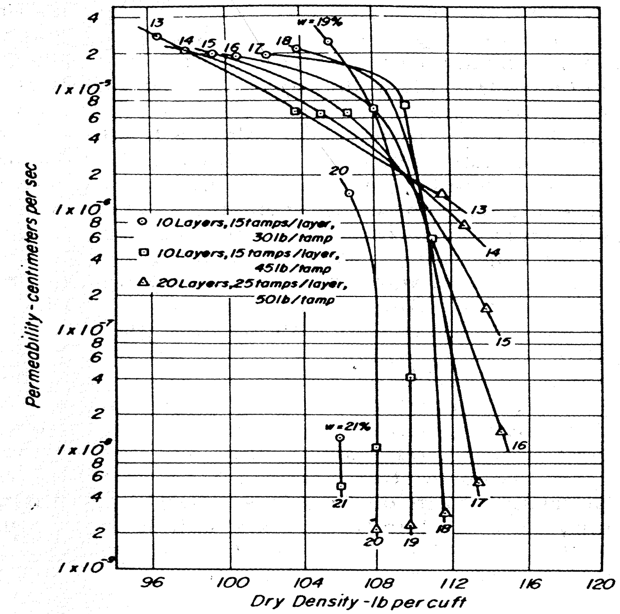

FIG. 11.—PERMEABILITY AS A FUNCTION OF DENSITY AT SEVERAL CONSTANT WATER CONTENTS FOR SAMPLES PREPARED BY KNEADING COMPACTION

50 to 120, which, while not unusually high for laboratory permeability testing, nonetheless produce substantial seepage forces within the clay.

INFLUENCE OF COMPACTION CONDITIONS ON PERMEABILITY

In order to develop more fully the interrelationships between permeability, structure, molding water content, and density, three series of silty clay specimens were prepared using three different compactive efforts to give the compaction curves shown in the lower part of Fig. 10. Permeability values determined after saturation, using back pressure, are shown in the upper part of Fig. 10. The curves showing permeability as a function of molding water content for specimens prepared at the lower two compactive efforts (curves A and B) are similar to the curves in Fig. 6. Curve C, corresponding to the highest compactive effort is similar to the curves shown in Figs. 1, 2, and 9, for different soil types. Thus the behavior illustrated by Figs. 6 and 8 and curves A and B of Fig. 10 cannot be solely a function of soil type.

The data from Fig. 10 have been replotted in Fig. 11 to show the variation of permeability with dry density for various constant values of molding water content. The curves clearly show the pronounced decrease in permeability that accompanies an increase in density at any given water content.

Perhaps of greater importance, however, is the great difference in permeability of samples at the same water content and density, but prepared using different compactive efforts. Reference to the curves in Fig. 11 for molding water contents of 18%, 19%, and 20% shows that the permeability may be decreased more than 100-fold, without change in density or moisture content, simply by increasing the kneading compactive effort. The effect of the increased compactive effort is to increase the degree of particle dispersion. The increased dispersion reduces the number of large flow channels and results in smaller average pore sizes, and, because permeability varies directly with the pore cross-sectional area, the permeability decreases. The great influence of shear strain on the stress-strain and shrinkage characteristics of the silty clay used in these tests had been previously studied by Seed and Chan[12] (Fig. 12). The permeability characteristics shown in Figs. 10 and 11 are in accord with the general pattern of behavior established by Seed and Chan.

The water content, permeability, and density data in Fig. 11 have been replotted in Fig. 13 in the form of contours of equal permeability on a plot of dry density versus molding water content. The extremely great variation in permeability with water content and density for compaction conditions wet of optimum is clearly shown. Fortunately, permeability values are low in this region so that essentially impervious embankments could be constructed with this soil. Selection of an appropriate value of permeability for use in a seepage, drainage, or rate of pore pressure dissipation analysis would be difficult, however.

INFLUENCE OF METHOD OF COMPACTION ON PERMEABILITY

It would be expected that permeability would be greatly influenced by the method of compaction because, for the silty clay used in these studies, (1) the permeability has been shown to be influenced more by structure than any

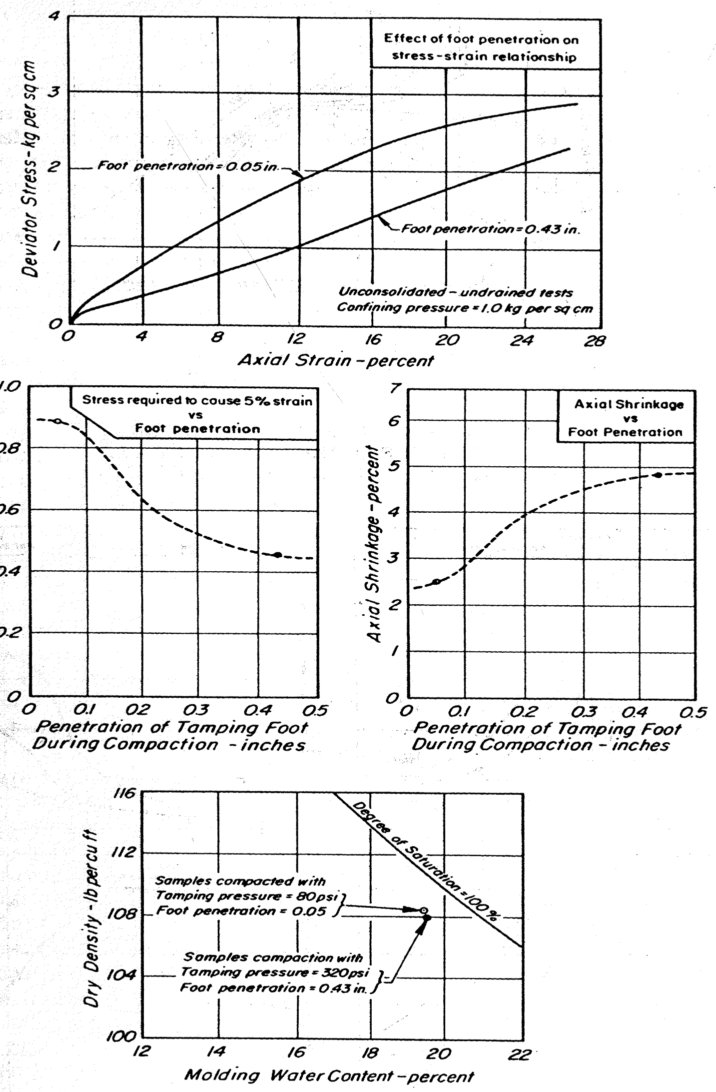

FIG. 12.—EFFECT OF STRAIN DURING COMPACTION ON DEFORMATION AND SHRINKAGE CHARACTERISTICS FOR SILTY CLAY

Consider the line
dry of
of optimum

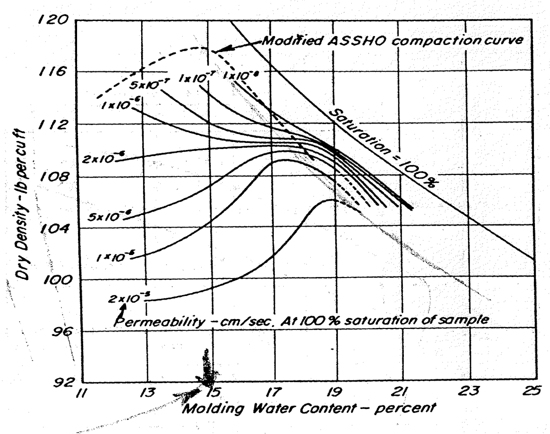

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FIG. 13.—CONTOURS OF EQUAL PERMEABILITY FOR SAMPLES OF SILTY CLAY PREPARED BY KNEADING COMPACTION

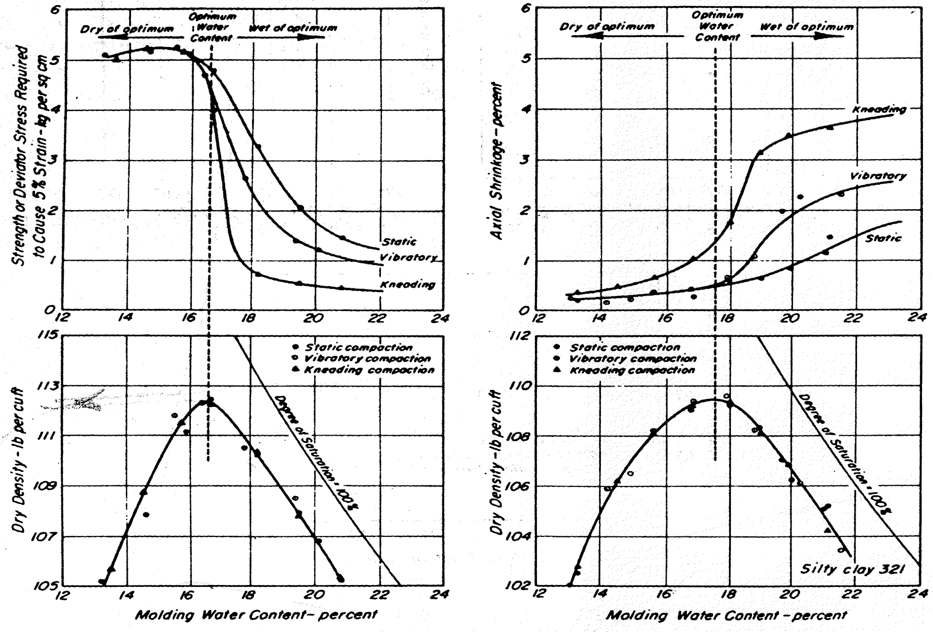


FIG. 14.—INFLUENCE OF METHOD OF COMPACTION ON STRENGTH AND SHRINKAGE OF SILTY CLAY

approx 96% Modified

other single variable, (2) structure is greatly influenced by shear strains associated with compaction wet of the line of optimums, and (3) different methods of compaction induce different amounts of shear strain. Seed and Chan[12] have studied the influence of the compaction method on the swelling, shrinkage, and stress-strain characteristics of compacted clays. The test data shown in Fig. 14 show the effects of the compaction method on the strength and shrinkage characteristics of silty clay. The shear strain and, therefore, the degree of dispersion, increases for the different compaction procedures in the following order: static, vibratory, and kneading. Fig. 14 shows that, for specimens prepared wet of optimum, where it is possible to disperse the structure under the action of shear strain, strengths increased and shrinkage decreased with the method of compaction in the following order: kneading, vibratory, and static.

It is anticipated that permeability should be similarly influenced by the method of compaction, with samples prepared by kneading compaction having lower permeabilities than samples prepared by static compaction for molding water contents greater than optimum. As for shrinkage and strength, Fig. 14, the method of compaction should have little effect on the permeability of specimens prepared dry of optimum because no method of compaction induces appreciable shear strains in such specimens.

In order to test these predictions, samples of silty clay were prepared by using both static and kneading compaction. Because of side friction, homogeneous specimens could not be prepared by static compaction using lucite molds 1.4 in. in diameter and 3.5 in. high. The sample ends were at a significantly greater density than the center and reliable density measurements could not be made. Consequently, samples were prepared using a 2.8 in. diameter by 1 in. high mold and were found to have satisfactory uniformity. In addition, two tests were made on samples prepared by kneading compaction in the 3.5 in. high molds.

The results shown in Fig. 15 verify the predictions given previously and show that for samples prepared dry of optimum moisture content, the method of compaction has little effect. When wet of optimum water content, statically compacted samples are significantly more pervious than samples prepared by kneading compaction. The differences were not as great as originally anticipated, however. To account for the permeability behavior of several structural clays, the significant drop in permeability wet of optimum water content, for samples prepared by static compaction, even in the absence of significant local shear strain during compaction, might be interpreted in the light of the cluster concept of soil structure proposed by Olsen[7] to account for the permeability behavior of several saturated clays.

It was observed that the clay particles were randomly flocculated into aggregates or clusters that formed even during carefully controlled hand mixing of the soil and water prior to compaction. The resistance to deformation of such clusters could be expected to decrease with increasing water content. Olsen has shown that the permeability of a cluster structure is controlled largely by flow through intercluster pores, rather than through the clusters themselves. At low water contents, the clusters have high strength and should be able to resist the static compaction pressure without appreciable distortion. Thus intercluster spaces may be large because of the difficulty in deforming a given cluster to the contours of adjacent clusters.

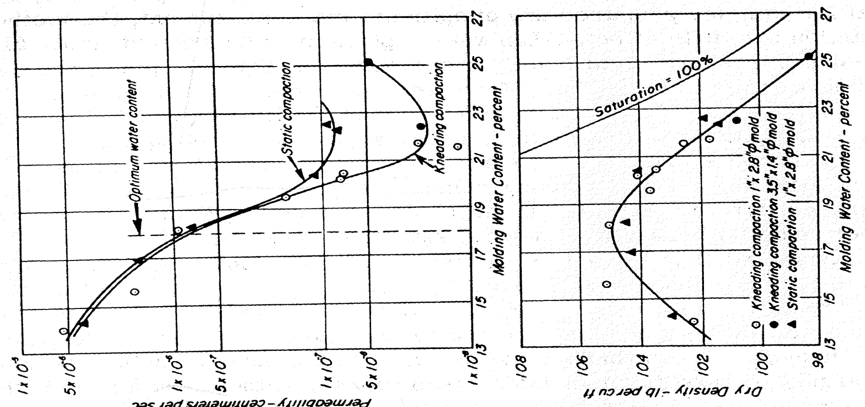
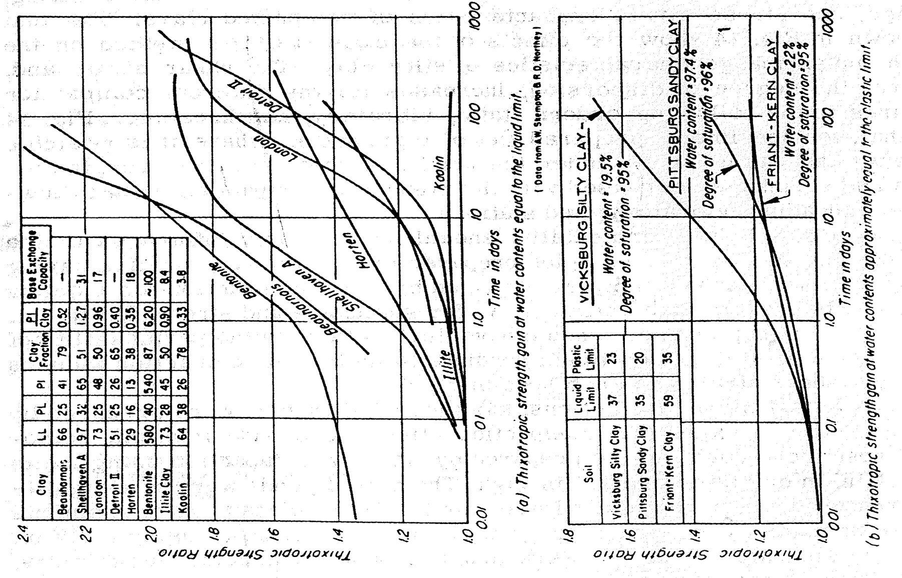


FIG. 15.—INFLUENCE OF METHOD OF COMPACTION ON THE PERMEABILITY



Clay	LL	PL	PI	Clay Fraction	PI/Clay	Base Exchange Capacity
Beauharnois	66	25	41	79	0.52	—
Shellhaven A	97	32	65	51	1.27	31
London	73	25	48	50	0.96	17
Detroit II	51	25	26	65	0.40	—
Horten	29	16	13	38	0.35	18
Bentonite	580	40	540	87	6.20	~100
Illite Clay	73	28	45	50	0.90	8.4
Kaolin	64	38	26	78	0.33	3.8

(a) Thixotropic strength gain at water contents equal to the liquid limit.

(Data from A.W. Skempton & R.D. Northey)

Soil	Liquid Limit	Plastic Limit
Vicksburg Silty Clay	37	23
Pittsburg Sandy Clay	35	20
Friant-Kern Clay	59	35

(b) Thixotropic strength gain at water contents approximately equal to the plastic limit.

FIG. 16.—SUMMARY OF THIXOTROPIC STRENGTH GAIN DATA

As molding water content increases, however, the cluster should become weaker. Furthermore, they will probably be of a smaller size prior to compaction due to the disruptive effects of mixing. Because the clusters are weaker, they may be more easily distorted to fit efficiently with surrounding clusters, thus resulting in smaller intercluster void spaces. The smaller cluster size will also tend to reduce intercluster pore size. At water contents wetter than optimum, the structure retains its basic flocculent nature after static compaction, as evidenced by the swell, shrinkage, and strength properties studied by Seed and Chan.[12] The weakening effect of the higher water content, however, has enabled floc or cluster distortion to the point that average pore size has been significantly reduced.

INFLUENCE OF THIXOTROPY ON PERMEABILITY

Compacted clays may exhibit appreciable thixotropic effects; i.e., the ability to gain strength with time of rest after compaction while at constant water content and density (Seed and Chan[13] and Mitchell,[14]). Fig. 16 shows typical data for strength gain as a function of time for three compacted clays. Mitchell[14] has suggested that compacting a thixotropic clay creates a somewhat dispersed structure that is compatible with the compacting energy. The natural tendency may be for the clay to flocculate, however, so that on completion of compaction, the clay structure may undergo a small but significant, time-dependent transition to a more flocculated state. At the same time, changes in adsorbed water structure probably take place, because measurements have shown pore water pressure to decrease with time after compaction (Bishop, et al., 1960).[15] Both of these effects tend to create a stronger material. If a transition to a more flocculent structure takes place to cause thixotropic hardening, it would be expected that the permeability should increase as well, because the more flocculent structure should have a larger effective pore size.

In order to investigate the effect of aging on the permeability of a trixotropic silty clay, two sets of specimens were compacted to a dry density of 108 lb per cu ft over a range of water contents. One set of specimens was tested immediately after compaction, and the other was aged at constant water content and density for 21 days and then tested. The test results shown in Fig. 17 show that aging did lead to an increase in permeability. The relative magnitude of the effect is shown in Fig. 18, where the ratio of permeability after aging to permeability immediately after compaction is plotted as a function of molding water content. Fig. 18 shows that the importance of thixotropic effects on permeability increases with increasing molding water

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[13] Seed, H. B., and Chan, C. K., "Thixotropic Characteristics of Compacted Clays," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 83, No. SM4, Proc. Paper 1427, November, 1957.

[14] Mitchell, J. K., "Fundamental Aspects of Thixotropy in Soils," Transactions, ASCE, Vol. 126, 1961, pp. 1586-1626.

[15] Bishop, A. W., Alpan, I., Blight, G. E., and Donald, I. B., "Factors affecting the Strength of Partly Saturated Cohesive Soils," ASCE Research Conf. on the Shear Strength of Cohesive Soils, Boulder, Colo., 1960.

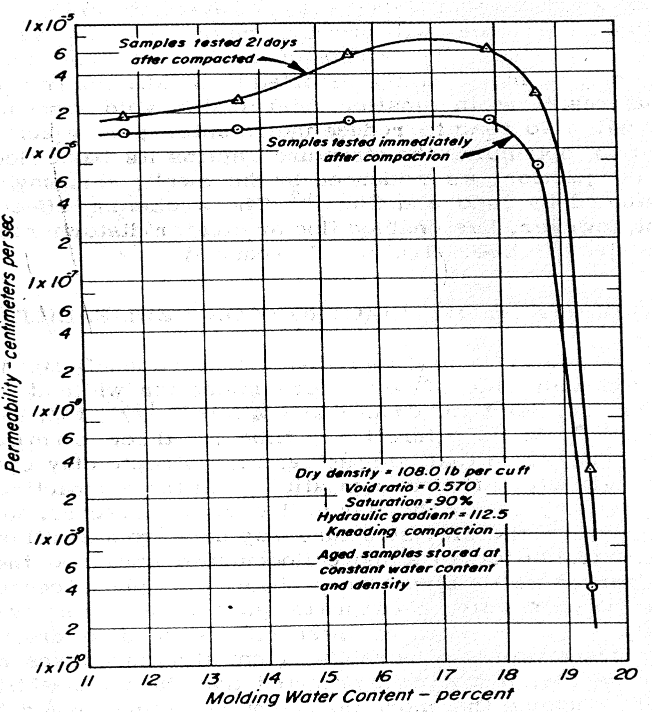

FIG. 17.—EFFECT OF AGING ON PERMEABILITY OF COMPACTED SILTY CLAY

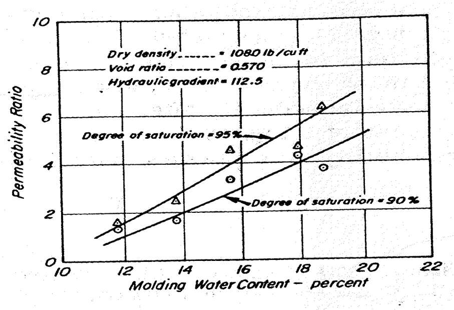

FIG. 18.—RATIO OF PERMEABILITIES OF SAMPLES OF SILTY CLAY TESTED 21 DAYS AFTER COMPACTION TO PERMEABILITIES OF SAMPLES TESTED IMMEDIATELY AFTER COMPACTION

content—a result consistent with previously observed effects of molding water content on thixotropic strength gain (Seed and Chan[13] and Mitchell,[14]).

INFLUENCE OF DEGREE OF SATURATION ON PERMEABILITY

Because the apparatus used for permeability testing permitted the accurate determination of flow both into and out of the sample, and because tests could be performed under a range of back pressure, it has been possible to determine the variation of permeability with the degree of saturation. It would be anticipated that an increase in the degree of saturation in a sample maintained at constant void ratio would lead to an increase in hydraulic permeability because of the increased pore volume through which water can flow. An approximate theoretical estimate of the effect of variation in saturation may be made as follows.

From Poiseuille's law for flow through a capillary, it may be shown that for any geometrical cross section of tube, the flow rate is given by Taylor.[16] Thus,

$$q_c = C_s \frac{\gamma_w R_H^2}{\mu} i a \quad \dots\dots\dots\dots\dots (1)$$

in which C_s is a shape constant, independent of size; γ_w denotes the unit weight of water; R_H refers to the hydraulic radius of the tube; μ represents the viscosity of permeant; i is the hydraulic gradient; and a denotes a cross-sectional area of flow passage.

If an unsaturated soil mass may be treated as a bundle of capillary tubes, and if the gas phase is uniformly distributed along the direction of flow, then the area of flow passages at any cross section is given by S n A, in which S is the degree of saturation, n represents the porosity, and A is the total cross-sectional area of the soil mass. Thus the total flow rate through the soil mass will be

$$q = C_s \left(\frac{\gamma_w}{\mu}\right) R_H^2 \, S \, n \, i \, A \quad \dots\dots\dots\dots\dots (2)$$

The hydraulic radius, R_H, is, by definition, the flow area divided by the wetted perimeter, A/P, but it may be interpreted also as

$$R_H = \frac{A}{P} = \frac{A\,L}{P\,L} = \frac{\text{volume available for flow}}{\text{wetted area}} \quad \dots\dots (3)$$

in which L is the length of flow path.

By definition,

$$S = \frac{V_w}{V_v} = \frac{V_w}{e\,V_s} \quad \dots\dots\dots\dots\dots\dots (4)$$

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[16] Taylor, D. W., "Fundamentals of Soil Mechanics," John Wiley & Sons, Inc., New York, N. Y., 1948.

in which V_w is the volume of water; V_v denotes the volume of voids; V_s rep- resents the volume of solids; and e is the void ratio. Therefore, the volum available for flow is

$$V_w = S\ e\ V_s \qquad (5)$$

Denoting the wetted area by A_s gives

$$R_H = \frac{S\ e\ V_s}{A_s} \qquad (6)$$

Using the fact that $n = \frac{e}{1+e}$ and substituting Eq. 6 in Eq. 2 yields

$$q = \left(\frac{\gamma_w}{\mu}\right) \frac{C_s\ V_s^2}{A_s^2} \frac{e^3}{1+e} S^3\ i\ A \qquad (7$$

If Darcy's law is assumed valid, then

$$q = k\ i\ A \qquad (8$$

in which k is the coefficient of permeability, and

$$k = \left(\frac{\gamma_w}{\mu}\right) \frac{C_s\ V_s^2}{A_s^2} \frac{e^3}{1+e} S^3 \qquad (9$$

Thus for a given soil the permeability should vary as the cube of the degree saturation. This conclusion can be accepted as a rough approximation onl however, because the use of a simple capillary model to describe flow throug fine-grained soils is subject to a number of limitations[17] and may, in fact, in considerable error.[7]

Experimental evidence of the variation of permeability with cube of degre of saturation is given in Fig. 19 for samples used for the tests described connection with Figs. 6 and 17. Saturation values less than 80% could n reliably be investigated during steady-state flow because the degree of satura tion increased immediately on the initiation of flow.

Fig. 19 shows that the actual variation of permeability with cube of degre of saturation is in excellent agreement with the prediction of Eq. 9. Th same data replotted in Fig. 20 show that the assumption of permeability vary ing directly with the degree of saturation gives as good a correlation as th theoretically derived cubic function. The reason for this is that in the rang of saturation from 80% to 100%, the relationship between saturation and th cube of saturation does not itself deviate appreciably from a straight line.

The slopes of the lines in Figs. 19 and 20 show that the increase in per meability with increase in saturation can be of practical significance, amount ing to a factor of as much as four or five over ranges of saturation from 85 to 98%. Thus it would appear desirable to take the saturation effects int account when performing seepage analyses on compacted earth structure

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[17] Leonards, G. A., "Foundation Engineering," McGraw Hill Book Co., Inc., Ne York, N. Y., 1962.

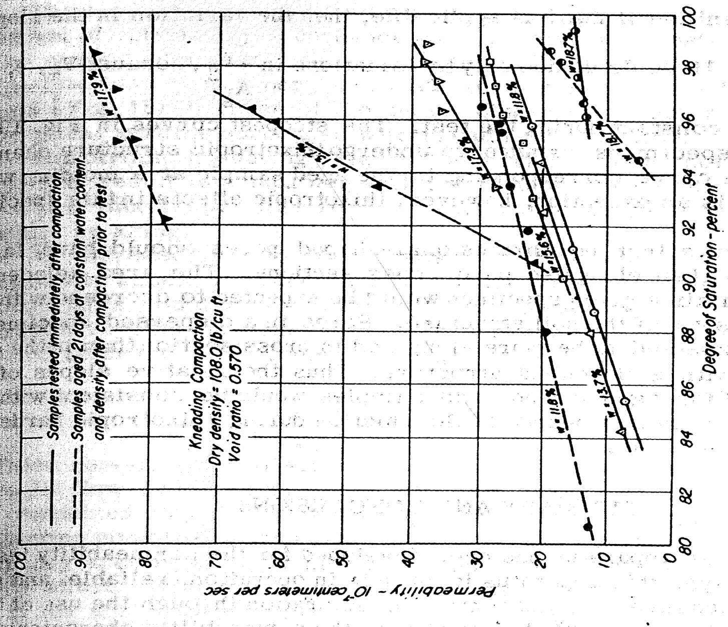

FIG. 20.—INFLUENCE OF DEGREE OF SATURATION ON PERMEABILITY OF COMPACTED SILTY CLAY

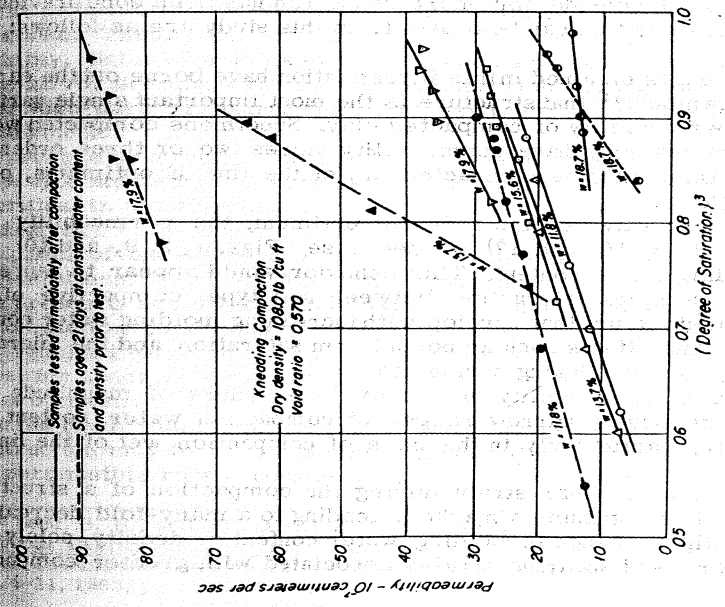

FIG. 19.—INFLUENCE OF DEGREE OF SATURATION ON PERMEABILITY OF COMPACTED SILTY CLAY

It may be seen that if Eq. 9 is applicable, then the variation in the slope o the lines in Fig. 19 could be due only to variations in $\frac{C_s}{A_s^2}$, because Vs, e, γ_w and μ remained constant during the test. The steepest curves in Fig. 19 ar associated with specimens permitted to undergo thixotropic structure changes The slope of the curve corresponding to the aged sample at a molding wate content of 11.8% is an exception; however, thixotropic effects in this specime were minor.

Taylor[16] shows that equidimensional-shaped pores should have large shape constants than elongated pore cross sections. The area adjacent t flowing water within a given specimen would be expected to decrease with de creasing dispersion of the soil structure. Pores in a dispersed specimen o clay could be expected to be more elongated in cross section than in the cas of a specimen with a flocculent structure. Thus the relative slopes of th lines in Fig. 19 for aged and nonaged samples would be consistent with th change towards a greater degree of flocculation during thixotropic hardenin as postulated previously.

SUMMARY AND CONCLUSIONS

In this study, an apparatus has been developed for the permeability testin of compacted clays; this apparatus is simple in operation, reliable, and per mits accurate measurement and control of saturation through the use of bac pressure. It has been possible to investigate the permeability characteristic of compacted clays in considerably more detail than has been done previously The major conclusions that can be drawn from this study are as follows:

1. The test results obtained in this investigation have borne out the earlie conclusions of Lambe[9,10] that structure is the most important single variabl influencing the permeability of compacted clay. Specimens compacted wet o the line of optimums may have permeability values two or three orders o magnitude less than samples compacted dry of the line of optimums, othe conditions being equal.

2. For molding water contents dry of optimum, the permeability ma increase (Figs. 6, 8, 10, and 17) or decrease (Figs. 1, 2, 9, and 10) wit increasing molding water content. This behavior would appear to represe the results of a complex interaction between soil type, compactive effor small changes in structure that develop with increasing molding water conte dry of optimum, and effects such as nonuniform saturation and the migratio of fines that may develop during permeation.

3. Variations in permeability of two to three orders of magnitude ma develop within relatively narrow ranges of compaction water content an density (Fig. 13), particularly in the case of compaction wet of the line o optimums.

4. The influence of shear strain during the compaction of a structure sensitive soil wet of optimum is marked, leading to a many-fold decrease i permeability, without change in molding water content or density, solely as result of the increased shearing strains associated with greater compacti efforts (Fig. 11).

5. The method of compaction influences the permeability of samples prepared wet of optimum in accordance with the previously established[12] effects of the method of compaction on structure. Samples prepared by kneading compaction have lower permeabilities than those prepared by static compaction (Fig. 15) because of the more dispersed structure induced by the larger shear strains associated with kneading compaction.

6. Thixotropic hardening (Figs. 17 and 18) led to an increase in permeability. This result is compatible with the results of previous work which suggested that thixotropic hardening involves a change to a more flocculent structure on aging.

7. An increase in saturation leads to an increase in permeability. The permeability appears to vary linearly with the cube of the degree of saturation, but correlates equally as well in terms of a direct variation with saturation. Saturation from the as-compacted conditions may lead to as much as a four to five-fold increase in the coefficient of permeability.

PRACTICAL ASPECTS

These results lead to some practical considerations in connection with hydraulic flow problems in soil mechanics. It is clear that the permeability of a compacted clay may vary over several orders of magnitude depending on compaction conditions; it is also clear that rather large changes in permeability may accompany very small changes in molding water content or compactive effort. Thus the selection of an appropriate value of permeability for use in the analysis of seepage problems in compacted clay is likely to be uncertain at best.

The permeability of compacted soils is likely to increase with time after placement. Thixotropic effects can lead to a several-fold increase in permeability. Saturation is likely to increase as a result both of the flushing out of the air by seeping water and by compression and solution of the air phase under high pore pressures that may exist, for example, at the base of an embankment.

Fortunately, however, the actual values of permeability for compacted clays of the type studied herein are sufficiently low as to make seepage problems noncritical in most instances, thus nullifying the need for knowledge of exact permeability values. On the other hand, problems involving drainage and dissipation of excess pore pressures can be vitally affected by permeability considerations. Seed and Mitchell[18] have shown how the time required for pore pressure equalization in triaxial tests on compacted clays is influenced by compaction conditions and their influence on permeability. The loading rate required for complete pore pressure equalization may be many times slower for specimens compacted wet of optimum than for specimens compacted dry of optimum.

In the field, dissipation of excess pore pressures during embankment construction may be of critical importance to the stability of the embankment. The permissible rate of construction may depend, therefore, on permeability.

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[18] Seed, H. B., and Mitchell, J. K., "Test Interpretations and Errors," ASTM Special Technical Publication No. 361, American Society for Testing Materials-National Research Council Canada Symposium on Laboratory Shear Testing of Soils, Ottawa Canada, Sept. 9-11, 1963, pp. 401-415.

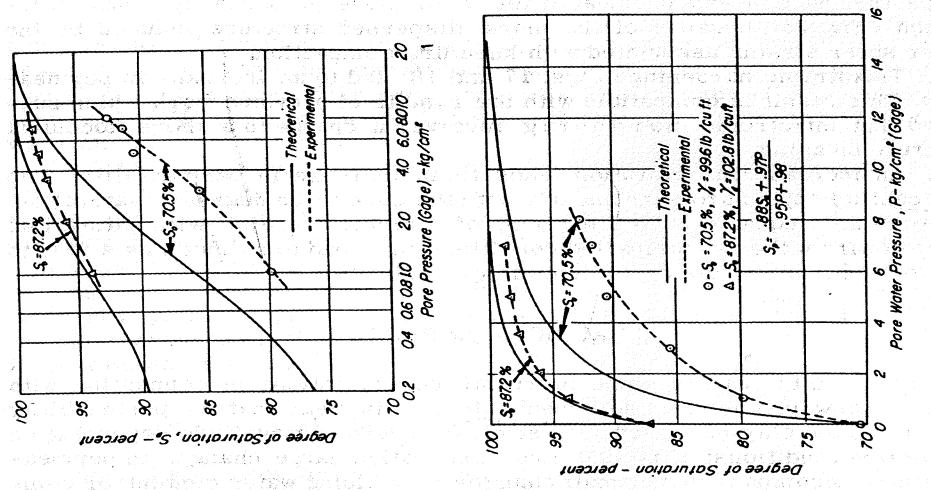

FIG. 22.—THEORETICAL AND EXPERIMENTAL

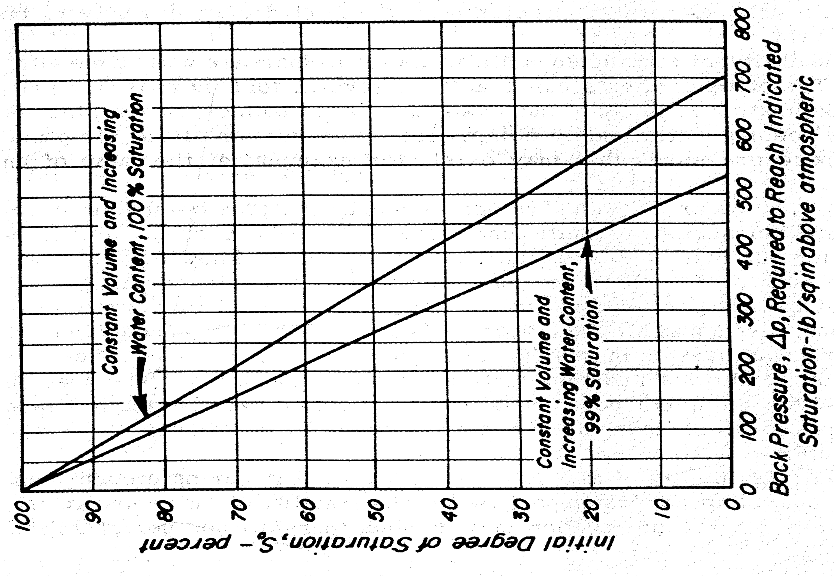

FIG. 21.—MAGNITUDE OF BACK PRESSURE REQUIRED

Clays of the type studied herein have permeabilities that are so sensitive to compaction conditions that in the field (where compaction cannot be controlled to the extent required to assure a specified permeability, even within a factor of 100%) such problems become nearly impossible to handle on a purely theoretical basis. Thus piezometers must be used to provide a record of the rate of pore pressure dissipation.

Finally, it should be borne in mind that all data presented in this paper have been obtained in the laboratory. There is need for data on the permeability of specimens actually compacted in the field. Laboratory testing subjects specimens to conditions, particularly with respect to hydraulic gradients, that are totally unrealistic with respect to the field where hydraulic gradients seldom exceed unity and are usually far less than unity.

ACKNOWLEDGEMENTS

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APPENDIX I.—SATURATION OF SOIL SAMPLES USING BACK PRESSURE

An increase of pore pressure in a partially saturated soil leads to an increase of saturation as a result of the (1) compression of pore air in accordance with Boyle's law, and (2) solution of air in the pore water according to Henry's law. In the usual application of back pressure, the soil specimen volume is maintained constant during saturation, while water is allowed to flow into the pores. Lowe and Johnson[19] give the relationship between pore water pressure (gage) and saturation as

$$P_1 = P_0 \left[\frac{1 - (1 - H)\, S_0}{1 - (1 - H)\, S_1} \right] \quad \ldots\ldots\ldots\ldots (10)$$

in which P_0 and S_0 refer to the initial pressure (absolute) and saturation, respectively; S_1 is the saturation corresponding to pressure, P_1; and H represents Henry's coefficient of solubility ≈ 0.02 at 20°C, measured as volume of air (at the given pressure) per volume of water.

Fig. 21 from Lowe and Johnson[19] presents the relationship between initial degree of saturation and the magnitude of back pressure required to reach both full saturation and 99% saturation according to Eq. 10. It may be seen that a significantly greater pressure is required to cause full saturation than to give 99% saturation.

In order to check the predictions of Eq. 10, samples of silty clay were compacted into lucite molds and water was permitted to flow into the specimens

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[19] Lowe, J., and Johnson, T. C., "Use of Back Pressure to Increase the Degree of Saturation of Triaxial Test Specimens," Proceedings, ASCE Research Conf. on the Shear Strength of Cohesive Soils, Boulder, Colo., 1960.

from each end until equilibrium was reached under a series of successively higher pressures. The amount of water inflow, as indicated by changes in U-tube readings (Fig. 3), in conjunction with the water content and density at the end of the test permitted calculation of the actual saturation at the various pressure levels used in the test.

The measured relationship between saturation and back pressure compared with the theoretical relationship as given by Eq. 10 for two specimens of dif-ferent initial degrees of saturation is given in Fig. 22. The calculation of the theoretical relationship was facilitated by rewriting Eq. 1 in the form

$$S_P = \frac{0.97\ P + 0.98\ S_o}{0.98 + 0.95\ P} \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

in which S_P is the saturation at pressure P; P denotes the back pressure (gage) in kg per sq cm; and S_o represents the initial degree of saturation under atmospheric pressure.

The data show that theory and experiment are in reasonably good agreement in the case of the specimen prepared to an initial degree of saturation o 87.2%. The agreement is not as good for the specimen prepared to an initial degree of saturation of 70.5%. It may be seen that the theoretical and experimental curves are generally similar in shape, and the experimental curves tend to become asymptotic to a degree of saturation considerably less tha 100%. Such an asymptote is not likely and it is suggested that the major caus of the discrepancies may have been an undetected compression during seepage Calculation has shown that a 2 mm compression of the 3.5 in. high specime would be sufficient to account for the difference between the theoretical an experimental curves.

Another cause for greater than predicted pressures being required fo saturation has been noted by Lowe and Johnson.[19] If the air present in th specimens before the application of back pressure is discontinuous, the initia air pressure will be greater than atmospheric caused by the presence o menisci.

On the basis of these considerations, Eq. 11 can be assumed to give onl an approximation of the back pressure required for complete saturation an should probably be used only for preliminary estimates. Measurement of th B pore pressure parameter probably provides the best check available fo complete saturation.

APPENDIX II.—NOTATION

The following symbols have been adopted for use in this paper:

A = total cross-sectional area of soil mass;
a = cross-sectional area of flow passage;
C_s = shape constant;
e = void ratio;
H = Henry's coefficient of solubility;

i = hydraulic gradient;
k = coefficient of permeability;
L = length of flow path;
n = porosity;
P = pressure;
q = microscopic flow rate;
q_c = flow rate through a capillary;
R_H = hydraulic radius;
S = degree of saturation;
V_s = volume of solids;
V_v = volume of voids;
V_w = volume of water;
γ_w = unit weight of water; and
μ = viscosity.