Effect of Temperature on Some Engineering Properties of Clay Soils

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The engineering properties of soils are generally measured in the laboratory at room temperature. However, seasonal changes modify the thermal environment of the soils in the field and therefore a concern as to the type and degree of influence of the temperature changes on the engineering properties of soils is justifiably expressed.

In an attempt to assess this influence, laboratory studies were conducted on four clay soils—a kaolinitic, an illitic, a montmorillonitic, and a montmorillonitic-illitic—at temperatures of 35, 70, and 105 F with ± 2 F deviation. The standard laboratory tests were run on remolded specimens of soils compacted at their maximum density and optimum moisture content, and included those tests necessary to evaluate the very fundamental properties of liquid limit, plasticity index, unconfined compressive strength, and consolidation.

In all four soils the liquid limit decreased with an increase in temperature. The plasticity index followed the same trend with the exception of the kaolinitic soil, in which the plasticity index showed a slight increase with temperature increase. The unconfined compressive strength data, contrary to other established data, indicated an increase in strength with an increase in temperature. The illitic soil, however, deviated from this tendency by showing a parabolic type behavior with the highest value at 72 F. The void ratio-pressure relationships resulted in a family of somewhat parallel curves. For the kaolinitic and montmorillonitic soils the curves at low temperature were found to be above those at high temperature. On the other hand, for the illitic and montmorillonitic-illitic soils the void ratio-pressure curve at 105 F was between the 72 F and 35 F curves, with the 72 F curve occupying the lowest level.

It is concluded that since slightly higher densities were observed with temperature increases, the thermal energy effects were overcompensated.

•IN ENGINEERING practice, design values used for soil properties are those determined either in the field or the laboratory without due regard to temperature. However, in testing for research into fundamental soil behavior, it has become apparent that temperature is an important parameter. To bridge this gap interest has recently (1, 2, 4, 5, 6, 7, 8, 9) been shown in assessing the influence of temperatue on soil engineering properties.

The present study is an attempt to further help in evaluating temperature effects on soils. It is limited to clay soils primarily because clay plays an especially energetic role in soil behavior.

METHODS OF INVESTIGATION

Materials

Four C-horizon soils varying primarily in type and amount of clay were selected. Their properties are given in Table 1.

Laboratory Tests

The standard laboratory tests performed on all four soils were the liquid limit, the plastic limit, the unconfined compressive strength, and the consolidation tests. All specimens were tested at 35, 70, and 105 F with ± 2 F deviation. While this selection seems rather arbitrary, it reflects the range within which construction in the field takes place. The two extreme values of the temperature range and control of temperature were maintained by a heating and cooling unit (Therm-o-Rite Products Co.).

As indicated in Figure 1, the liquid limit and plastic limit tests were run in a small chamber. The equipment and materials were placed in the chamber 3 hours in advance of testing to bring them to the desired temperature.

The unconfined compressive strength test was performed in a closed Lucite cylinder on remolded specimens compacted to maximum density at optimum moisture content using the Harvard miniature compaction apparatus. The soil, water, and equipment had been maintained at the respective desired temperature, but compaction took place at room temperature. Consequently, it will be logical to assume that the 35 F specimens were prepared at a temperature slightly higher than 35 F and the 105 F specimens at a temperature slightly less than 105 F. As soon as the specimens were prepared, they were stored in the chamber having the desired temperature and kept for 2 hours prior to being tested. The test densities were also recorded.

The consolidation test was performed on remolded specimens compacted statically in the consolidometer ring (2.5 in. in diameter, 1 in. high) to maximum density at optimum moisture content. In the preparation of specimens, the same temperature control was exercised as in the unconfined compressive test with the exception that the compacting machine was at room temperature. As soon as the specimens were prepared, both the ring and the specimens were immersed and maintained in water for 24 hours to obtain saturation at the designated appropriate temperature. The standard consolidation test was run in a box (Figs. 2, 3), containing water whose temperature

TABLE 1

PROPERTIES OF SOILS

Sample designation	N. Carolina clay	Illinois clay	Texas clay	Oklahoma clay
Sampling location	Durham Co., N. C.	Livingston Co., Ill.	Harris Co., Tex.	Payne Co., Okla.
Soil series	White Store	Clarence	Lake Charles	Renfrow
Laboratory designation	A	B	C	D
Textural composition, percent				
Gravel (above 2 mm)	0.0	0.0	0.0	0.0
Sand (2-0.074 mm)	13.0	10.0	3.0	2.0
Silt (0.074-0.005 mm)	22.0	38.0	36.0	24.6
Clay (below 0.005 mm)	65.0	52.0	61.0	73.4
Clay (below 0.002 mm)	50.0	34.0	40.0	5.0
Physical properties				
Liquid limit, percent	54	32	65	50
Plastic limit, percent	25	17	18	22
Plasticity index	29	15	47	26
Chemical properties				
C.E.C.[a], m.e./100 g	36.2	10.8	27.3	18.5
Carbonates	0.9	22.5	16.6	10.2
pH	5.4	8.3	8.2	7.5
Organic matter	0.3	0.7	0.1	0.2
Non-clay minerals[b]	Quartz, feldspar	Quartz, feldspar	Quartz, feldspar	Quartz, feldspar
Clay minerals[b]	Kaolinite-halloysite	Illite	Montmorillonite	Montmorillonite-illite
Classification				
Textural	Clay	Clay	Clay	Clay
AASHO	A-7-6 (20)	A-6 (11)	A-7-6 (20)	A-7-6 (17)
Unified	CH	CL	CH	CL

[a] Cation exchange capacity determined by the ammonium acetate (pH = 7) method on soil fraction less than 0.42 mm.

[b] X-ray diffraction analysis.

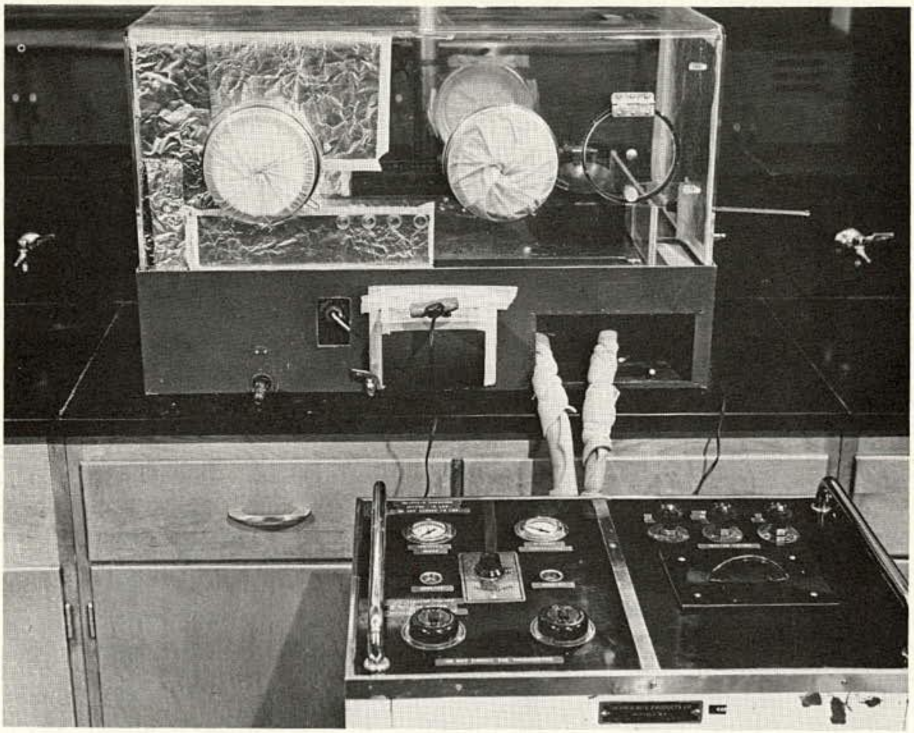

Figure 1. Incubator type chamber used for liquid limit and plastic limit test. Heating and cooling unit in the foreground.

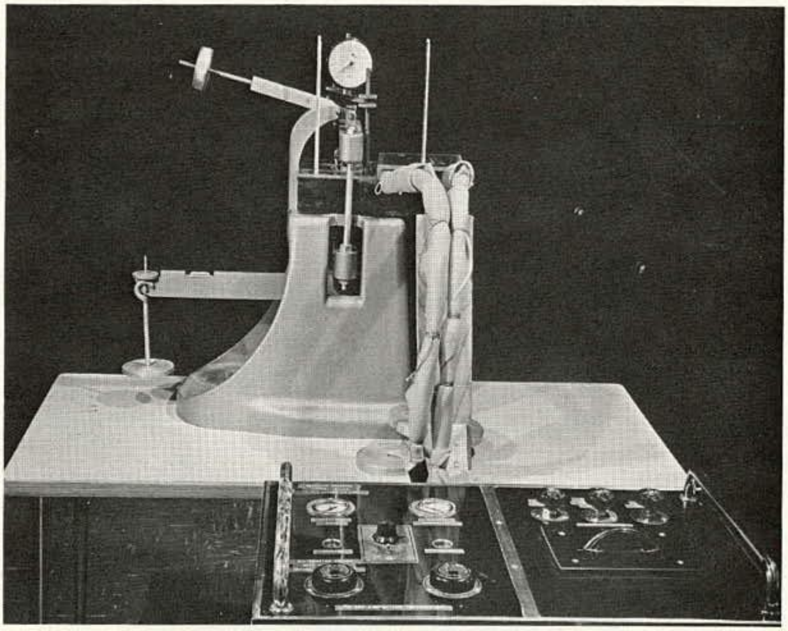

Figure 2. Consolidation test apparatus.

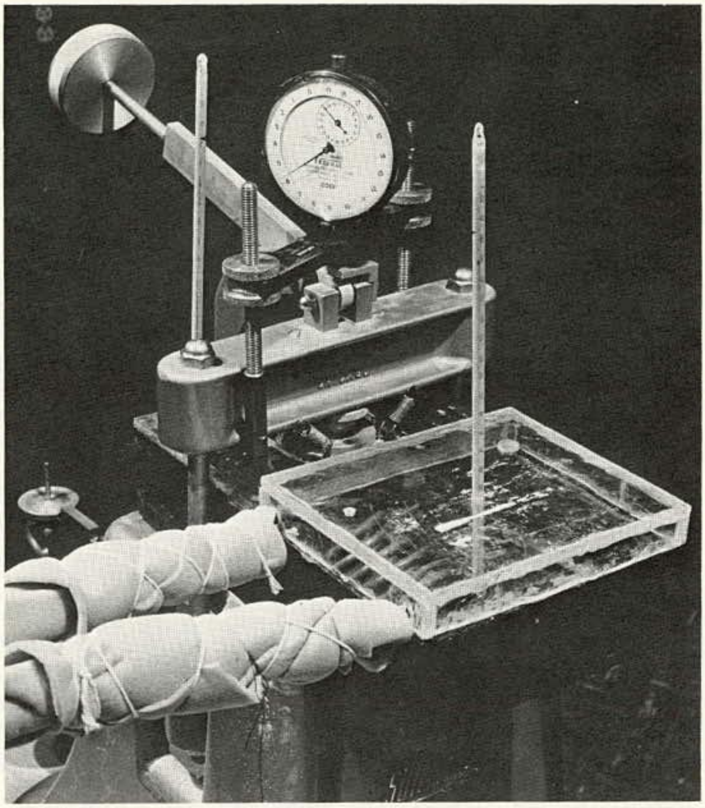

Figure 3. Temperature control during consolidation test.

was controlled by the heating unit. In the consolidation measurements the Levermatic soil test equipment (C-224) was used.

In following the one-dimensional two-way drainage procedure, 0.25, 0.50, 1.00, 2.00, 4.00, and 8.00 kg per sq cm load intensities were applied through a dead weight lever-type loading system. For each consolidation pressure, readings at total elapsed times of 0, 0.25, 0.50, 0.75, 1.00, 2.25, 4.00, 6.25, 9.00, 12.25, 16, 25, 36, 49 minutes, etc., were taken for a period of 24 hours. The consolidation response was measured in terms of the coefficient of consolidation, C_v, where

$$C_v = \frac{Th^2}{t}$$

and T = time factor, h = longest drainage path, and t = elapsed time. In calculating C_v, T_{90}, and t_{90}, the "square root of time" fitting method was used. For the liquid limit, plastic limit, and unconfined compressive strength tests, three determinations were used whereas only two were used for the consolidation test.

From the foregoing it becomes evident that the preparation of specimens did not take place at exactly the test temperatures specified. However, for the type of unsophisticated equipment used, thermometric measurements indicated that test temperature variation was limited to ± 2 F of the designated temperature of the test. Therefore, temperature effects should be interpreted with these limitations in mind and they should be looked upon as indicating a trend rather than exact quantified conclusions.

TABLE 2

SOIL ENGINEERING PROPERTIES AT VARIOUS TEMPERATURES

Soil Type Lab Designation	Temperature (F)	Liquid Limit (percent)	Plasticity Index (percent)	Uc[1] (psi)	Max. Dry Density[2] (pcf)	Optimum Moisture Content[2] (percent)	Cv[3] $(10^{-4}\ cm^2/sec)$
A (kaolinitic)	35	54	25	49	97.1	25.8	32.6
	70	54	29	52	97.7		30.7
	105	46	30	55	98.0		25.2
B (illitic)	35	35	16	87	111.7	18.2	11.5
	70	32	15	89	111.7		10.9
	105	31	5	83	111.5		11.2
C (montmorillonitic)	35	80	54	60	102.2	22.3	4.1
	70	65	47	64	102.9		2.5
	105	56	33	66	103.2		1.4
D (montmorillonitic-illitic)	35	60	30	67	105.2	21.1	3.5
	70	50	28	71	105.3		2.7
	105	48	28	72	106.1		2.9

[1] Unconfined compressive strength. [2] Harvard miniature compaction. [3] Coefficient of consolidation.

RESULTS

The summary of test results is given in Table 2.

In all four soils the liquid limit decreased with an increase in temperature (Fig. 4). Whereas in soils A and C the decrease was pronounced, in soils B and D the decrease was small, which, in view of the nature of the test, indicates a tendency rather than a decisive decrease. The plasticity index values (Fig. 5) show a definite decrease with temperature increase except for soil A; again it may be argued that this displays a tendency rather than a definite increase.

The unconfined compressive strength of the soils, as depicted in Figure 6, increased with increases in temperature. Soil B constitutes an exception in that it shows a parabolic tendency, the highest strength being observed at 70 F.

The consolidation e-log p curves for the four soils, shown in Figures 7 through 10, displayed two distinct patterns. At low temperature, soils A and C have curves above those at high temperature, whereas soils B and D deviated slightly from this trend in that the 105 F curve lies above the 70 F curve but below the 35 F curve. The same

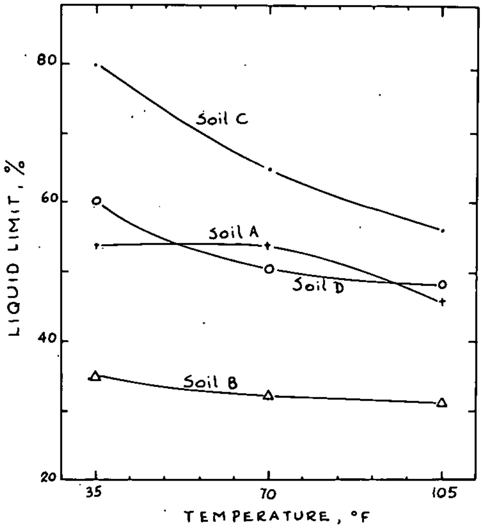

Figure 4. Effect of temperature on liquid limit.

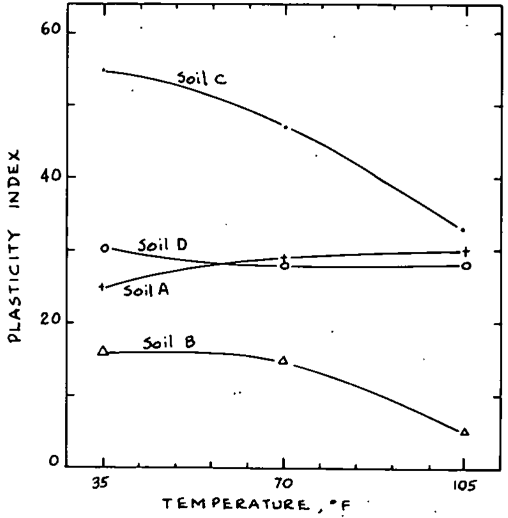

Figure 5. Effect of temperature on plasticity index.

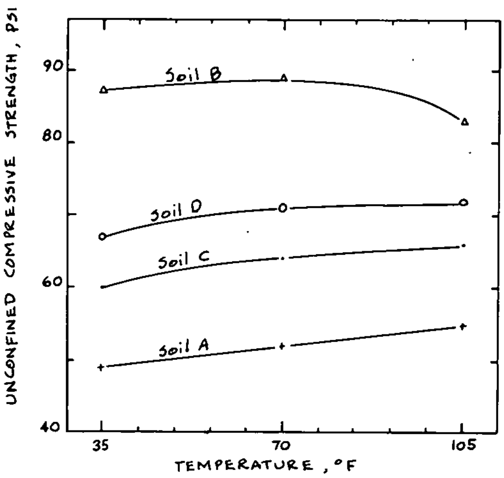

Figure 6. Effect of temperature on strength.

phenomenon was observed for the coefficient of consolidation, C_v, which decreased with higher temperatures for the A and C soils, whereas C_v values at 70 F were the lowest for the B and D soils (Fig. 11).

In reviewing previous studies in this area, it is possible to summarize the temperature effects as in Table 3. The explanations for these changes are based on the Gouy-Chapman mechanism of double layer, the modification of water viscosity, and the accompanying effects on the geometric arrangement of the soil particles.

In this study the lowering of the liquid limit with high temperatures is a manifestation of the low void ratio and of the water easily draining out; the same reasoning holds true for the plasticity index. That soil A did not obey this rule, insofar as the PI is concerned, may be ascribable, if at all, to the plastic limit test during which there has probably taken place an exchange of heat between the soil and the operator's hand to such a degree that it upset equilibrium conditions.

The unconfined compressive strengths generally indicated an increase with temperature increases. This contradicts data from earlier work (1) wherein low strength at high temperatures was attributed to pore pressure increase and attendant effective stress decrease. The soils studied in this case displayed slightly higher densities (Table 2) at higher temperatures. Admittedly, the density variations are small and their dependability may be questioned in view of the experimental error. But the

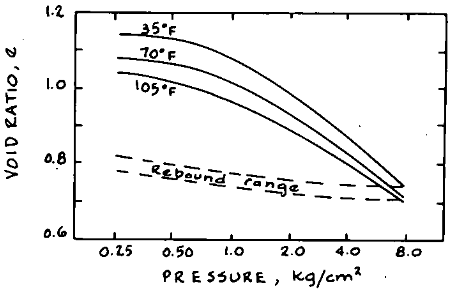

Figure 7. Consolidation curves for soil A.

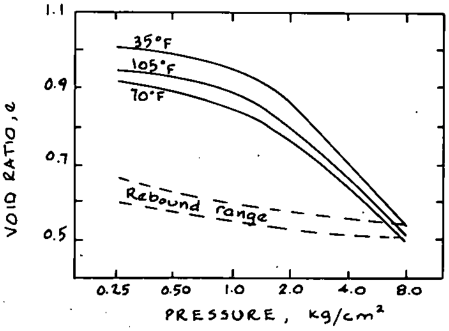

Figure 8. Consolidation curves for soil B.

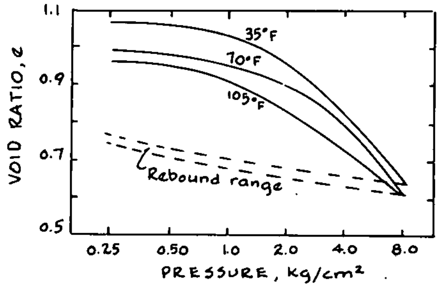

Figure 9. Consolidation curves for soil C.

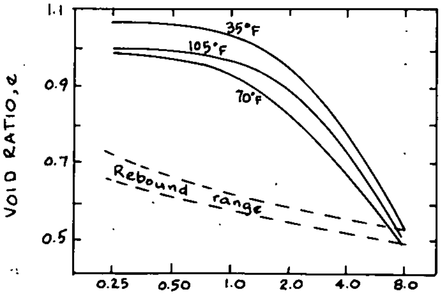

Figure 10. Consolidation curves for soil D.

TABLE 3

TEMPERATURE EFFECTS ON SOILS

Temperature	Diffuse Ion-Layer Thickness (net effect)	Soil Structure	Volume	Void Ratio	Pore Pressure	Water	Shear Strength
High	Increase	Dispersion	Compression	Low	Increase	Drains out	Low
Low	Decrease	Flocculation	Swelling	High	Decrease	Absorbed	High

density trend may be helpful in explaining the paradox of strength increase with temperature increase. The increase in thermal energy produces an interparticle bond strength decrease but at the same time there is a lowering of the void ratio. It is likely that, in the cases studied, the void ratio decrease overcompensated the bond strength decrease. That soil B behaved differently is not surprising because this illitic soil has shown peculiar behavior (3). Among the four soils used in this study, soil B had the lowest coefficient of hydraulic conductivity, 3.5 x 10^{-6} cm/sec (3); this may help account for the building up of uniform and nonuniform pore pressures at high temperatures that cannot be dissipated easily, and thus low shear strengths resulted.

The application of the criteria indicated in Table 3 to the consolidation characteristics of clay soils leads to two predictions. First, at high temperatures low pressures suffice to cause the same amount of consolidation as high pressures do at low temperatures; second, at low temperatures consolidation is more rapid than at higher temperatures. Both predictions seem to hold true for soils A and C. At high temperatures the occurrence of the lowering of the void ratio implies that consolidation begins at an initially lower void ratio, and it becomes evident that at high consolidating pressures the curves tend to converge, thereby minimizing the difference in temperature effects. Unfortunately, the test was not carried out beyond 8 kg/cm^2 and therefore it cannot be stated at this time whether or not the curves intersect. A similar, but somewhat less pronounced, relationship appears to exist among the coefficients of consolidation for the A and C soils. Implicit in the picture of voids ratio change is the change in soil structure. However, void ratio is not adequate to describe soil structure and it should be regarded as only a rough measure of soil structure. Soils B and D, which contain illite, departed slightly from the aforementioned description of consolidation behavior. To define what happens at 105 F is complex; it can only be traced to the peculiarity resulting from the presence of illite.

The rebound curves in all four soils present an interesting observation in that they fall, for all three temperatures, within a narrow band formed by intersecting lines. A possible explanation offered is that, once the soil is compressed to a pressure of 8 kg/cm^2, temperature effects in the decompression phase are so minimized that delineation becomes difficult.

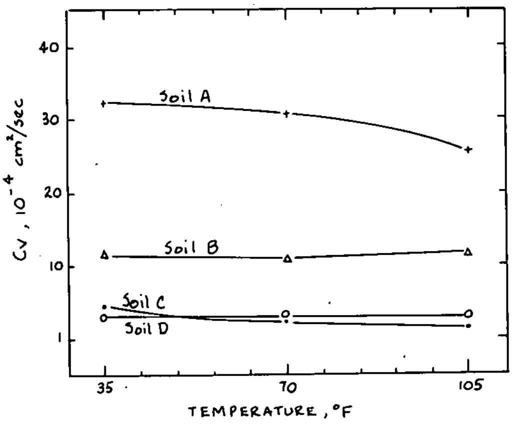

Figure 11. Effect of temperature on C_V.

To attempt to interpret and project the test data in terms of practical or field behavior of these clay soils, one is forced to accept that at high temperatures the soils display higher shearing strength and subside more, but the rate of consolidation is slower than at low temperatures. This, given the test conditions, should be looked upon as a tentative conclusion.

To substantiate and verify these findings, it will be necessary to dwell more extensively on density studies and on such other factors as activity, pH, and adsorbed ions, in addition to the type and amount of clay mineral, in order to offer more precise explanations of the paradoxical behavior of the clays studied.

REFERENCES

1. Campanella, R. G., and Mitchell, J. K. Influence of Temperature Variations on Soil Behavior. Jour. Soil Mech. and Found. Div., ASCE, Vol. 94, No. SM3, May 1968.
2. Finn, F. M. The Effect of Temperature on the Consolidation Characteristics of Remolded Clay. Symposium on Consolidation Testing of Soils, ASTM Publ. No. 126, 1951.
3. Laguros, J. G. Response Differences in the Stabilization of Clayey Soils. Paper presented at the Second Highway Research Symposium, Rio de Janeiro, Sept. 1966.
4. Lambe, T. W. The Structure of Inorganic Soil. Proc. ASCE, Vol. 79, Proc. Sept. No. 315, Oct. 1953.
5. Lambe, T. W. Compacted Clay. Trans. ASCE, Vol. 125, 1960.
6. Lambe, T. W. Residual Pore Pressures in Compacted Clay. Proc. Fifth Internat. Conf. on Soil Mech. and Found. Engr., Vol. 1, 1961.
7. Mitchell, J. K., and Campanella, R. G. Creep Studies on Saturated Clays. Symposium on Laboratory Shear Testing of Soils, ASTM-NRC, Spec. Tech. Publ. No. 361, Ottawa, Sept. 1963.
8. Mitchell, J. K., Campanella, R. G., and Singh, A. Soil Creep as a Rate Process. Jour. Soil Mech. and Found. Div., ASCE, Vol. 94, No. SM1, Jan. 1968.
9. Paaswell, R. E. Temperature Effects on Clay Soil Consolidation. Jour. Soil Mech. and Found. Div., ASCE, Vol. 93, No. SM3, May 1967.