Some Temperature Effects on Soil Compressibility And Pore Water Pressure

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Data are presented to show that heating a cohesive soil increases its compressibility at low levels of applied stress and also produces volume decreases. The volume changes associated with temperature increases are shown to be related to the degree of overconsolidation of the soil, decreasing as the overconsolidation ratio increases. Cooling the soil alters its stress-strain characteristics and causes it to behave as if it were overconsolidated. Secondary compression rates are shown to be affected only slightly by heating and significantly by cooling. Temperature-induced pore water pressures in undrained triaxial specimens are shown to be related to the stress history of the specimen and, for some materials, predictable from the results of triaxial consolidation tests.

•THE BEHAVIOR of soils under a particular stress system and at a constant temperature is governed by the stress (or strain) history of the material and by the applied effective stresses. Altering the temperature of a soil specimen can produce effects similar to changes in stress history (2, 5, 7, 12, 13) and can produce changes in the pore water pressures within the material (2, 5, 12, 15).

Clearly, any such changes, if unrecognized, may have important engineering implications. For example, a sample of a marine sediment may have been subjected to a temperature increase of 20 C between the time it was recovered from the ocean floor and was brought to the laboratory for testing. Temperature changes of this magnitude can be expected to alter the mechanical behavior of the soil and complicate, or make impossible, a proper engineering solution to a submarine problem.

Large temperature changes, frequently of a cyclic nature, also occur in more conventional circumstances. Samples obtained at a building site during the winter are subject to temperature decreases upon removal from the ground and then to temperature increases when they arrive in the laboratory, unless considerable care in handling is exercised. The reverse can occur in summer or in hot climates where the air temperature exceeds that of the ground and the laboratory. Thus, soil samples are frequently subjected to large temperature changes, and engineers must be in a position to evaluate the way these changes affect the mechanical behavior of the material.

SUMMARY OF LITERATURE

There is experimental evidence to indicate that the heating of a cohesive soil will cause it to decrease in volume (4, 12, 13), to decrease in undrained shear strength, and, perhaps, to exhibit a decrease in shear strength parameters obtained from an effective stress analysis (10). The observations suggest that temperature increases do not alter significantly the compressibility of soil upon continuous loading although its void ratio at a given pressure declines with increasing temperature (2, 3, 4).

Lambe (7) explained the decrease in volume of cohesive soils on heating using the double layer equations presented by Marshall (10). The development of these equations includes the assumption that the dielectric constant of the pore water is unaffected by temperature. In this form, the equations suggest that an increase in temperature depresses the electric double layer and permits the soil particles to move together.

TABLE 1
SOIL INDEX PROPERTIES

Index Property	Soil	
	Illite	Newfield Clay
Liquid limit, percent	112	25
Plastic limit, percent	28	14
Plasticity index, percent	84	11
Specific gravity	2.76	2.74
pH	5.1	7.9
Percent clay (<0.002 mm)	96	32
Primary clay minerals	Illite	Hydrous Mica Chlorite

Direct measurement of changes in particle spacing with variations in temperature in a montmorillonite slurry subjected to low stresses were reported by Yong et al (17). They observed volume increases in sodium montmorillonite subjected to temperature increases at constant externally applied stresses of less than one atmosphere. One might expect that the increase in energy associated with heating a soil would cause the expansion of the electric double layer in accordance with Yong's observations rather than the decrease in thickness suggested by Lambe.

The observation that temperature increases cause a decrease in soil volume as long as the drainage of pore water is permitted and the fact that, when heated, water will expand more than soil, leads to the conclusion that excess pore water pressures will develop whenever drainage is restricted. Temperature-induced pore water pressures have been reported by a number of investigators (2, 4, 12, 14, 15).

Several expressions have been developed to permit prediction of the temperature-induced pore water pressures (2, 14, 15). These expressions account for the volume changes in soil and water due to temperature changes but do not consider any changes in soil compressibility with temperature or the effects of secondary compression.

The research on temperature effects in cohesive soils has established that temperature increases cause volume decreases and has suggested that the volume change is somewhat dependent on rate of temperature increase (13). It is not yet clear how the stress history, perhaps as defined by the overconsolidation ratio, affects the observed volume changes. Nor is it clear why the heating of a soil temporarily increases its compressibility (i.e., causes the soil to decrease in volume while under a constant applied stress) but no change in compressibility from the preheating condition is observed when loading is continued at the new, higher temperature. The investigation reported herein was performed in an attempt to clarify some of these points and to gain insight into the phenomenon of pore water pressure development due to temperature change.

MATERIALS AND EXPERIMENTAL OBSERVATIONS

Two remolded soils were used in the testing program. One was a fractionated illitic material of high liquid limit and the other a glacial lake clay obtained from Newfield, New York. The properties of the soils are given in Table 1.

Submerged, ¾-in. thick soil specimens were tested in a fixed ring consolidometer around which water was circulated at a constant temperature. The tests were performed at temperatures of 50 and 24 C. About 3 hours were required to change the temperature of the circulating water by 26 C. Maximum variations of less than 2 C from these fixed temperatures occurred during the testing program and were found experimentally to have virtually no effect on the readings.

Temperature Effects on Volumetric Strain

Samples of illite and Newfield clay were poured into consolidometer rings as slurries and were consolidated to a pressure of 1.7 psi at an initial temperature of 24 C before any heating was done. The initial water content of the illite was 180 percent and the initial water content of the Newfield clay was 44 percent. Consolidation was begun from a slurry in order to insure that the soil would be normally consolidated at very low pressure. Three tests were performed with each of the materials. In one test the soil was consolidated at a constant temperature of 24 C, in a second a temperature of 50 C was maintained, while in the third test the sample was loaded to 30 psi (New-

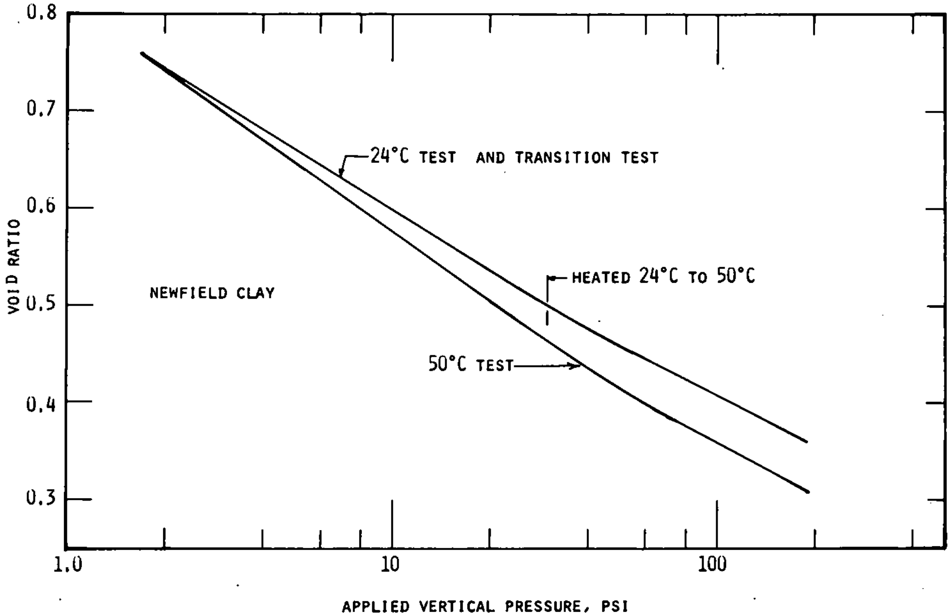

Figure 1. Consolidation test on Newfield clay.

field clay) or 40 psi (illite) at 24 C, then heated to 50 C and loading was continued. The results of these three tests on each of the materials are shown in Figures 1 and 2.

To facilitate comparison of the test results and to correct for small variations in the initial moisture content of the individual specimens, all of the test data have been normalized to a common void ratio at 1.7 psi of pressure. The curves in Figures 1 and 2

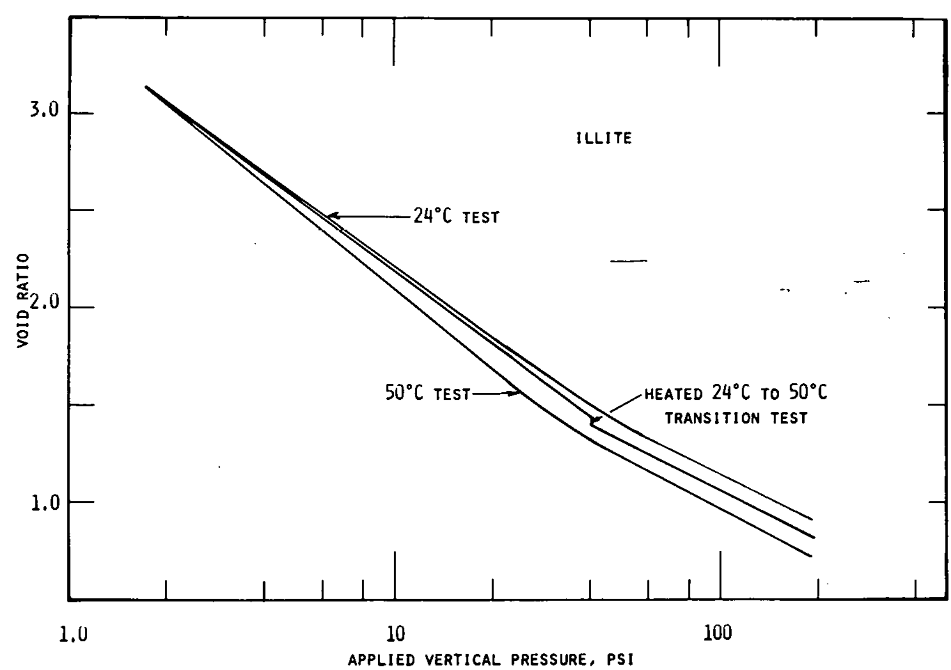

Figure 2. Consolidation test on illite.

TABLE 2

COMPRESSION INDEXES OF SOILS AT DIFFERENT TEMPERATURES

Test Temperature (deg C)	Illite		Newfield Clay	
	Low Pressure (<30 psi)	High Pressure (>30 psi)	Low Pressure (<30 psi)	High Pressure (>30 psi)
50	1.40	0.86	0.238	0.170
24	1.24	0.82	0.208	0.170
Transition Test				
50	–	0.84	–	0.170
24	1.23	–	0.204	–

indicate that at applied pressures smaller than about 30 psi both soils were more compressible when tested at 50 C than at 24 C. However, at pressures in excess of 30 psi, little difference in compressibility was apparent. In the transition tests, where the soil was first loaded to 30 psi before heating, the temperature change produced essentially no volume change of the inactive Newfield clay and about a 1 percent volumetric strain of the illite.

The slopes of the curves in Figures 1 and 2 are indicative of the compressibility of the soils and are defined as the compression indexes of the materials. Clearly, the compression index of each of the materials varies as a function of pressure and of temperature. This is in contrast with the observations of others (2, 3, 4). The compression indexes of the two materials at pressures above and below 30 psi and at temperatures of 50 and 24 C are given in Table 2.

The results of the transition tests (Figs. 1 and 2) showed that, after heating, both materials continued to behave as normally consolidated clays. The effect on the behavior of the material of heating to 50 C and then recooling to 24 C was investigated using the illitic material. Some of the results of this investigation are shown in Figure 3. Although recooling caused a slight expansion of the material, the volume change is too small to be shown on the figure. It can be seen that the cycle of heating and cooling

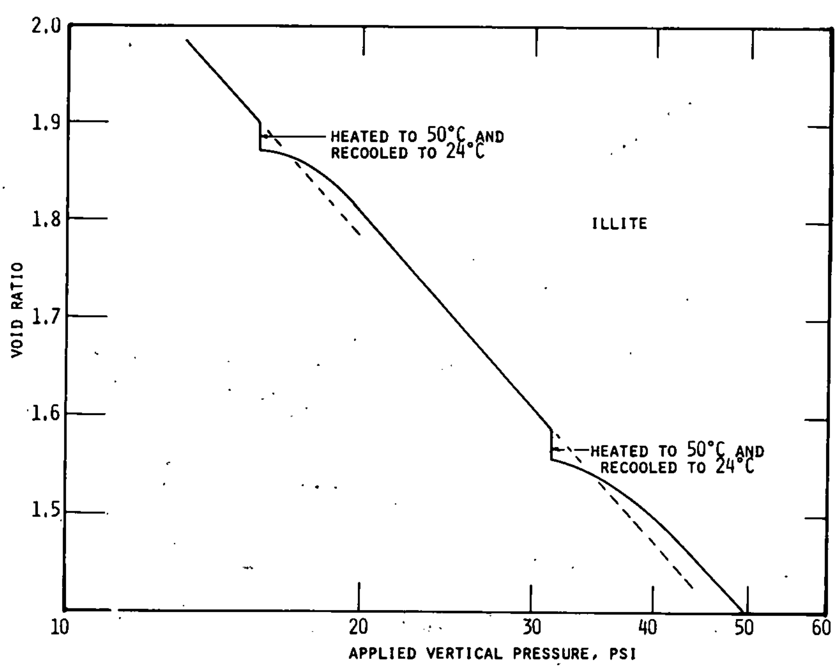

Figure 3. Effect on stress-strain behavior in consolidometer of heating and cooling illite.

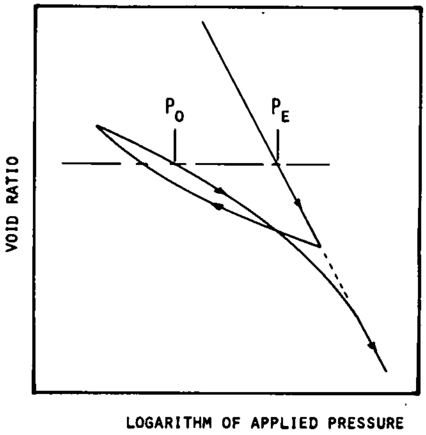

Figure 4a. Definition of overconsolidation ratio.

has caused the soil to behave as if it were overconsolidated. Furthermore, the new virgin portion of the consolidation curve, established by reloading after completing the cooling-reheating cycle, is displaced from the original virgin curve toward higher pressures. The reloaded soil appears to behave as if it were more overconsolidated than the volumetric strain associated with heating would suggest. Apparently a quasi-preconsolidation load similar to that found by Leonards and Rahmiah (8) was developed. This observation suggests that laboratory testing of natural soils that have been heated and recooled during the period of handling could lead to an incorrect evaluation of the maximum previous pressure to which the material had been subjected.

In assessing the effect of temperature changes on natural soils, it is of interest to investigate the relationship between the volumetric strain produced by heating and the overconsolidation ratio of material. When a soil is unloaded and then reloaded it arrives at the void ratio associated with the maximum previous pressure at a somewhat lower stress level and does not rejoin the virgin portion of the stress-strain curve until the maximum previous pressure has been exceeded. This is illustrated in Figure 4a. Because of this reloading behavior it is most convenient to define overconsolidation ratio as the ratio of the equivalent consolidating pressure p_e to the current pressure p_o at the time the soil is heated. The equivalent consolidation pressure is defined as the pressure required during the first cycle of loading to bring the material to the same void ratio it exhibited at the time it was heated. This definition is also illustrated in Figure 4a.

The relationship between the volumetric strain and the overconsolidation ratio p_e/p_o for the illitic material is shown in Figure 4b. It is evident that the volumetric strain associated with temperature increases decreases significantly as the soil is overconsolidated and is essentially zero at an overconsolidation ratio of the order of 1.7. These data suggest that volume change resulting from temperature cycling is considerably less important for overconsolidated soil than for normally consolidated soil.

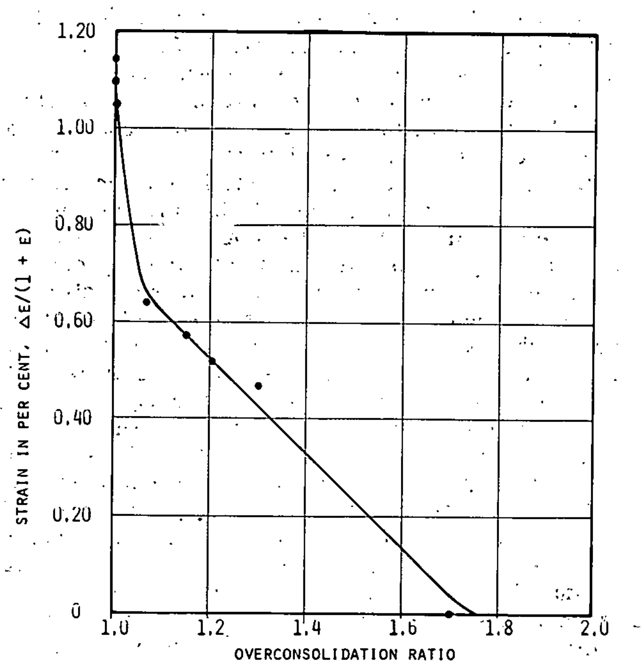

Figure 4b. Effect of overconsolidation ratio on volume change of illite heated from 24 C to 50 C.

Temperature Effects on Secondary Consolidation

Several investigators have reported that the heating of cohesive soils increases the rate of secondary consolidation (2, 9, 16). They also report thet secondary consolidation is of minor importance

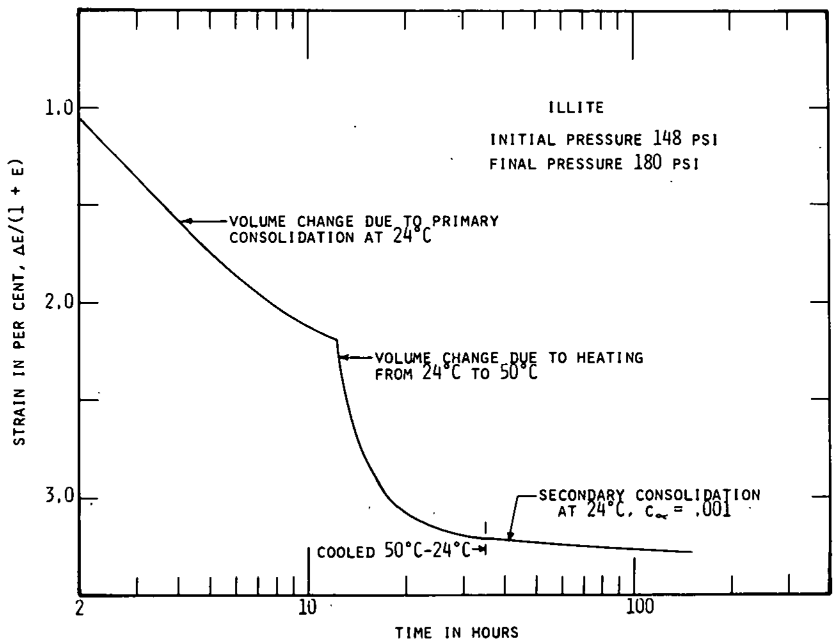

Figure 5. Effect of heating and cooling on secondary consolidation behavior of illite.

in overconsolidated soils. Two tests were performed with the illitic material in order to investigate these statements.

The illitic material exhibited a rate of secondary consolidation, defined by the slope of the consolidation curve on a plot of $\Delta e/(e + 1)$ vs logarithm of time in hours, of 0.005 when the temperature was 24 C. Figure 5 shows the results of a test in which a specimen of the same material was heated to 50 C after primary consolidation was completed and the volumetric strain due to heating was permitted to occur before the sample was cooled back to 24 C. After cooling, the volumetric strain of the specimen was observed for the next 5 days. It is important to note that about one day was required for the heating of the sample and for straining under the change in temperature. During the last 5 days, the relationship between volumetric strain and the logarithm of time was linear and had a slope c_α of 0.001. This is one-fifth of that exhibited by the normally consolidated material and suggests, once again, that the heating caused the sample to behave as if it were overconsolidated.

In a second test, the soil was consolidated at 24 C, heated to 50 C, and allowed to consolidate at this new temperature. As before, the heating caused a volumetric strain that required about one day to dissipate. Thereafter, the soil redefined a secondary consolidation curve with a slope c_α of 0.0053, which was only slightly larger than the slope of 0.0048 observed before heating.

It is of passing interest to note that the slopes of the secondary consolidation curves shown in Figure 6 increase by 10 percent due to heating and that the thermal energy, given by the ratio of the absolute temperatures of 323 C/297 C, was also increased by about 10 percent. Considered to be of greater significance, however, is the observation that increasing the temperature of the consolidating specimen of illitic material produced a rather small change in its secondary consolidation characteristics. However, this small change was only observable when the specimen was permitted to consolidate for a considerable time after the temperature change had occurred. It is considered possible, therefore, that the marked changes in secondary compression characteristics due to increases in temperature that have been reported by many investigators (2, 9, 16) have been confounded by the volumetric strains associated with heating. Further work in this area is apparently required.

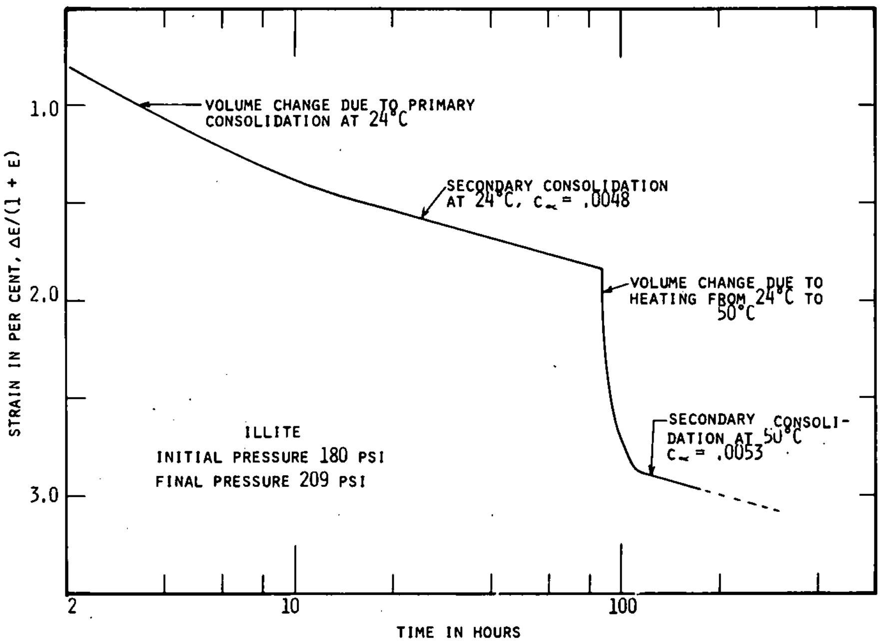

Figure 6. Effect of heating on secondary consolidation behavior of illite.

Temperature Effects on Pore Water Pressure

A lengthy discussion has been presented by Campanella and Mitchell (2) on whether or not the pore water pressures developed by changing the temperature of a soil specimen under undrained conditions should follow a closed hysteresis loop on temperature cycling as they observed (12) or should produce a pore water pressure that increases at a decreasing rate with each cycle to some maximum value. Their discussion indicated quite clearly that temperature cycling under undrained conditions was akin to repeated loading of the soil and suggests that in a soil like Newfield clay that exhibits no significant decrease in volume with increases in temperature, the pore water pressure developed by temperature changes should be directly predictable from the results of a triaxial consolidation test where the three principal stresses are equal.

Temperature cycling of Newfield clay remolded at a water content of 19 percent was done in a triaxial cell surrounded by a constant-temperature water bath. A backpressure of 30 psi was used to insure complete saturation of the soil, and pore water pressures were measured using a temperature-compensated pressure transducer. The temperature was varied between about 14 and 35 C, with some variation occurring in the actual end-points, at effective consolidating pressures of 20, 40, and 60 psi (cell pressures of 50, 70, and 90 psi). The results of the tests at 40 psi are shown in Figure 7 and indicated, as did the tests at 20 and 60 psi, that there was a gradual increase in pore water pressure for four cycles of temperature, after which no increase in pore pressure was observed with additional cycling.

The data in Figure 7 are similar to those presented by Campanella and Mitchell (2) for San Francisco Bay mud, Henkel and Sowa for Weald clay (5), and Sangrey for Newfield clay (15). They differ from the earlier data obtained by Mitchell and Campanella (12) in that they show the development of the hysteresis loop after four temperature cycles. This loop is not clearly defined in Figure 7 because the pore pressure measurements could only be obtained at the end of a temperature cycle after sufficient time had elapsed for temperature equalization throughout the system. The importance of these differences among the data can be discussed best after consideration is given to the results of a triaxial consolidation test to simulate temperature cycling.

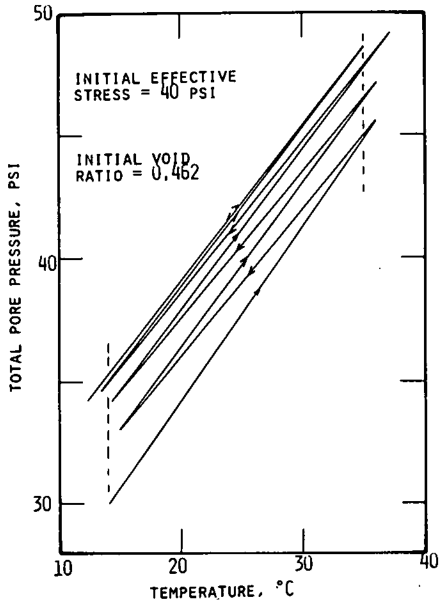

Figure 7. Pore water pressures resulting from undrained temperature cycling of Newfield clay.

Volume changes in the consolidation test were measured using a volume change gage that was calibrated and accurate to 0.0002 cc and was connected to the backpressure system and to the specimen. Stress cycling was done between two void ratios. The change in void ratio actually used corresponds to the volume expansion of the water in the sample when it is heated between 14 and 38 C. The results of this test in which cycling was done at effective consolidation pressures of 40 and 60 psi are shown in Figure 8. For clarity, only the unloading paths are shown in Figure 8 by single lines.

It required five stress cycles in the consolidation test to develop a closed hysteresis loop rather than the four cycles of temperature required before no further change in pore water pressure was observed. A portion of this difference may be the result of the nonuniformity of the temperature cycling, which is apparent from an inspection of Figure 7, and the rest may be associated with the somewhat too-large void ratio change used in the simulated temperature test (the consolidation test).

A comparison of the pore water pressures measured in the undrained tests (Fig. 7) with those predicted from the drained tests (Fig. 8) is given in Figure 9. The pore pressures given in Figure 8 were extrapolated or interpolated, as required, so that the comparison could be made for the temperature range of the consolidation test, i. e., for a temperature variation of 14 to 38 C.

The results of the triaxial consolidation and undrained triaxial tests in which the temperature was varied can be seen to be in good agreement when the specimen was reloaded or the temperature returned to its initial value and in poorer agreement at the higher pore pressures representing the unloading of the soil or the increasing of temperature. It is concluded that the drained consolidation test to simulate temperature cycling provides a reasonable representation of the stress changes produced by temperature changes, at least for materials that undergo minimal volume changes due to temperature increases.

The data in Figures 7 to 9 appear to substantiate the basic assumptions made in developing equations to predict pore pressure changes due to temperature fluctuations (2, 14, 15). Equally important, however, is the observation that it takes several cycles of loading and unloading or of temperature variation before a hysteresis loop can be expected.

The drained stress cycling of the Newfield clay between two fixed void ratios produced a material that was overconsolidated. It would appear that it is only when the material is somewhat overconsolidated that a closed hysteresis loop can and does develop. This could be the explanation for the observations of Campanella and Mitchell (2). The two materials they tested that exhibited a hysteresis loop almost immediately upon temperature cycling were overconsolidated. Their illitic soil and been overconsolidated by drained temperature cycling before the undrained tests were performed while their kaolinitic material was overconsolidated by initially cooling the sample before the temperature was raised and then cycling back to the cooled temperature.

Thus, the data included herein suggest an explanation for the hysteresis effect noted by some and not observed by others. They also suggest the validity of the approach used to predict pore water pressures in undrained specimens due to temperature changes (2). Newfield clay was an appropriate material to use in arriving at these conclusions because the test results reported earlier indicate that temperature increases cause

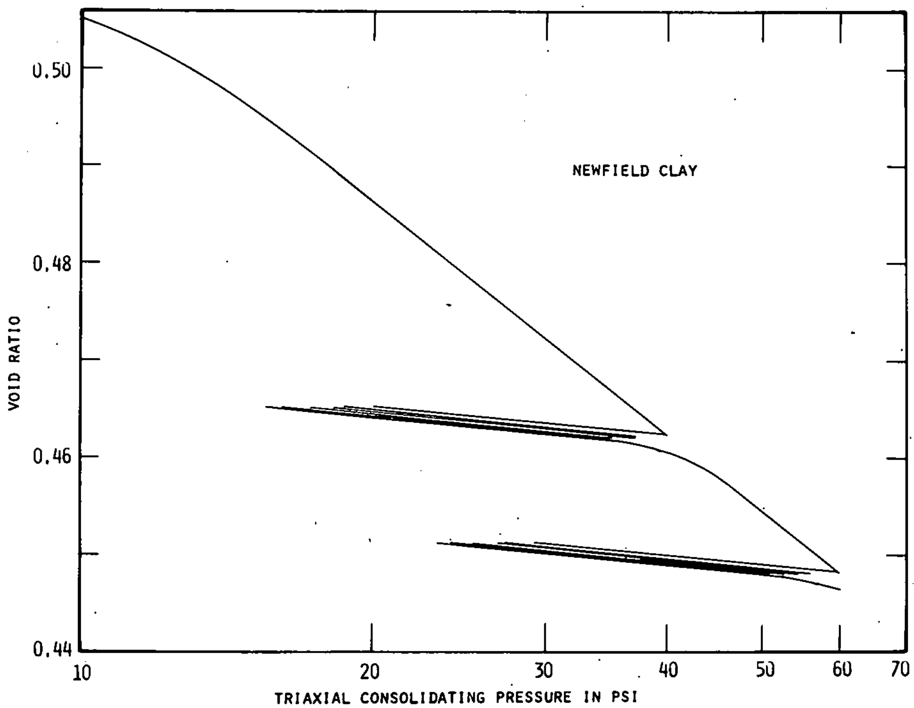

Figure 8. Triaxial consolidation test on Newfield clay to simulate temperature cycling.

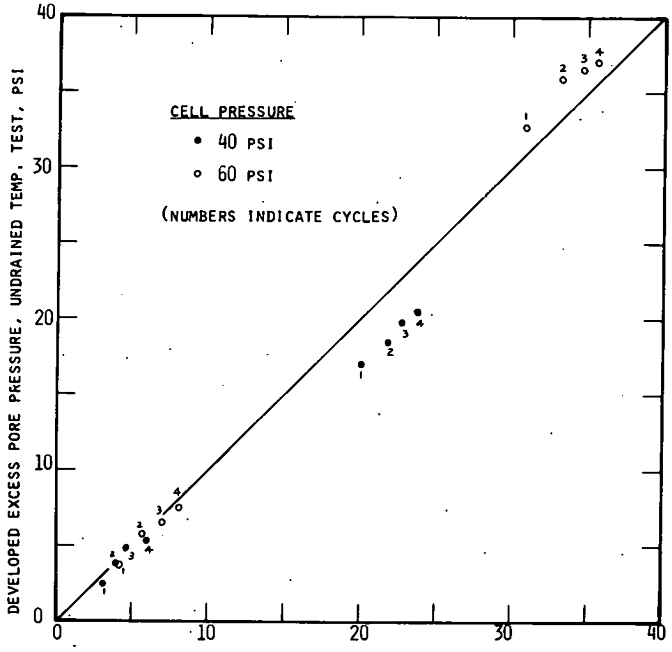

Figure 9. Comparison of undrained pore pressures and simulated pore pressure due to temperature cycling.

little volume change and virtually no change in compressibility within the pressure range of the investigation.

MECHANISTIC INTERPRETATION OF SOIL BEHAVIOR DUE TO HEATING

A cohesive soil may be considered to be composed of clay platelets of various shapes and sizes packed in some fashion dependent upon its manner of deposition (or artificial preparation) and its environment. Loads applied to the material externally are transmitted through the system at points of particle "contact." In this concept, the clay fabric is pictured as a complex three-dimensional truss with the contact points as the joints. The forces at the contacts are the Van der Waals forces of attraction, the repulsive forces due to the interaction of the electric double layers on the clay surfaces, and some portion of the externally applied forces. If the electric double layers are expanded and, as a result, the repulsive forces increased, readjustment of the soil structure under the applied loads can be expected.

Decreases in soil volume with expansion of the electric double layer have been reported by Kenney (6). While maintaining a constant, externally applied, axial force on a soil specimen in a consolidometer, Kenney leached salts from samples of noncemented Norwegian marine clays, thereby increasing the thickness of the electric double layer, and he observed a marked decrease in the volume of the specimen. The decrease in volume was pressure-dependent and was most pronounced at high pressures. Kenney explained this observation by reference to interparticle forces and to Lambe's (7) mechanistic model of soil behavior. He suggested that the expansion of the electric double layer decreased the effective stresses at the particle contacts, which permitted shear failures to occur at these contacts. Volume decrease (consolidation) is the manifestation of these shear failures.

By hypothesizing that heating expands the electric double layer, as the leaching of the salts is known to do, it is possible to explain the apparently contradictory observations of Lambe (7) and Yong (17), discussed earlier. The tests reported by Yong et al (17) were performed on sodium montmorillonite specimens consolidated from a slurry at pressures of less than 1 atmosphere. The concentrations of salts in the pore fluid were such that a reasonably dispersed structure (parallel clay plates) might be expected. Interparticle contact was probably small. Consequently, expansion of the electric double layer by heating would be expected to cause the observed volume increase.

The clays used in the tests reported by Lambe (7) and others were less active and interparticle contacts were important. Expansion of the electric double layer would, in this case, reduce the effective stresses at the points of contact and permit shear deformations and consolidation to occur. Mechanistically speaking, Lambe (7) and Kenney (6) suggested that the effective stress at the point of contact N' is related by Eq. 1 to the stress N associated with the externally applied loads, to the repulsion R of the electric double layers, and to the attraction A of the Van der Waals attractive forces:

$$N' = N - (R - A) \tag{1}$$

The resistance to sliding at the particle contact is assumed to be some function of N'. If some constant external force is assumed, then changes in interparticle effective stress are related to changes in the repulsive and attractive forces. It is commonly assumed that the respulsive forces decrease exponentially with interparticle distance while the attractive forces vary with the inverse third power of the interparticle spacing. In accordance with Eq. 1, an increase in the thickness of the electric double layer, which increases the interparticle repulsion when the particle spacing is essentially fixed, decreases N' and therefore decreases the shearing resistance at the particle contact. When the shearing resistance at the points of contact is reduced and the shearing stress is maintained sensibly constant, shear displacement can be expected. The displacement will continue until the particles are rearranged to a configuration that is stable under the new effective stresses.

The preceding argument suggests that the heating of a cohesive soil with a significant number of interparticle contacts should lead to the increase in compressibility observed at low pressures in the tests reported herein rather than produce no change as observed by others (2, 3, 4).

It is also of interest to note that Yossef et al (18) have shown that the liquid and plastic limits of soils decrease with increasing temperature. They explain their results by reference to the decreasing viscosity of water with increasing temperature. However, it is clear that both the liquid and plastic limit tests are measures of the shearing resistance of the soil and therefore their observations are considered to be in agreement with the mechanistic model proposed and to be explained better by reference to this model.

Tests by Burmister (1) also tend to confirm the foregoing hypothesis. Burmister's tests show that the maximum dry density that can be obtained from a Proctor compaction test is increased as the temperature increases. At 65 F, the dry density of a particular soil was found to be 104 pcf at the optimum moisture content. The same material achieved a dry density of only 90 pcf at 35 F.

The proposed model may also be used to explain the observation that decreasing the temperature of a consolidating soil mass causes it to behave as if it were overconsolidated. By decreasing the temperature, the electric double layer is compressed, the repulsive forces are reduced, and the shearing resistance at the points of contact is increased. Thus, a large increase in external stress is required before significant further consolidation is obtained.

SUMMARY AND CONCLUSIONS

Data have been presented to suggest that temperature increases do, indeed, cause changes in the compressibility of soils. However, the compressibility changes are most notable in soft soils consolidated under small stresses. At applied stresses in excess of about 30 psi, temperature increases appear to produce insignificant changes in compressibility.

Cooling a sample causes it to behave as if it were overconsolidated, as suggested by Campanella and Mitchell (2), and appears to produce a quasi-preconsolidation load. This temperature-induced alteration in stress history could be of consequence when the results of laboratory tests are applied to field problems.

The volume change of a specimen subjected to an increase in temperature is dependent on its degree of overconsolidation. At an overconsolidation ratio of 1.7, no apparent volume decrease occurred in the illitic material as a result of a temperature increase of 26 C.

Secondary compression rates appear to be only slightly affected by increases in temperature, provided that sufficient time is allowed for the volume change associated with the temperature increase to be dissipated. This conclusion is in sharp contrast to the conclusions reached by others (2, 9, 16). In agreement with the observations of others (2), the data indicate that overconsolidation of soil by decreasing its temperature reduces the rate of secondary consolidation dramatically. Consequently, for those soil problems in which secondary consolidation is an important consideration, great care must be exercised in obtaining, handling, and testing the specimens.

Temperature changes are known to induce pore water pressures in soils. The new data presented herein suggest that current techniques for the prediction of these temperature-induced pore water pressures are sound and that for some materials, at least, the pore water pressures can also be predicted from the results of consolidation tests in which the specimen is unloaded between two void ratios.

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