Mechanisms of Swelling by Compacted Clay

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The mechanisms believed to cause swelling in saturated clay-water systems are first reviewed. These concepts, drawn primarily from soil chemistry and soil physics, are extended to compacted natural clays. Test data are presented to show the effects of the ion concentration in the pore fluid on the swelling behavior of a highly plastic clay. These data consist primarily of heaving and fluid pickup measurements on samples molded with pure water and soaked in solutions of varying salt concentrations.

For the clay investigated, it is concluded:

1. For samples compacted wet of optimum water content, swelling can be explained by osmotic repulsive pressures arising from the difference in ion concentration in the double-layer water between interacting clay particles and that in the free pore water.

2. For samples compacted dry of optimum water content, swelling is influenced by factors in additions to osmotic pressures. These other factors may be: the effect of the negative electric and London van der Waals force fields on water, cation hydration and the attraction of the particle surface for water, elastic rebound of particles, a flocculated particle orientation, and the presence of air. The relative importance of these other factors is not known.

● IN SEVERAL areas of the world the differential heaving of foundations due to the swelling of highly plastic clays has resulted in severe damage to buildings. Swelling of clay also changes the engineering properties of strength, compressibility, and permeability. For many earth structures, such as road subgrades and embankments, a loss of strength or an increase in compressibility will be of greater concern to the soil engineer than the heaving per se. As the use of clay, and especially highly plastic clay, for earth structures increases, the need for a better understanding of the swelling phenomenon becomes greater, since the soil engineer must not only know the "as-compacted" properties of clay, but also know how these properties change with time.

The swelling behavior of a compacted clay will be governed primarily (but not solely) by the following factors:

1. Composition of the clay—composition and amount of clay minerals, nature and amount of exchangeable cations, proportions of sand and silt in the clay, and presence of organic matter and cementing agents.
2. Compaction conditions—molded water content, dry density, degree of saturation, and type of compaction.
3. Chemical properties of the pore fluid—both that during compaction and that which is imbibed during swelling.
4. Confining pressure applied during swelling.
5. Time allowed for swelling.

This paper is an effort to explain the swelling phenomenon in compacted clays. This

work is part of a fundamental study of the behavior of fine-grained soils that is currently being carried on by the Soil Engineering Division at MIT.

Data are presented to show the effects of salt content in the pore fluid on the swelling characteristics of a compacted natural clay. The data consist primarily of heaving and fluid pick-up measurements on samples molded with pure water and then soaked in solutions of varying salt concentration. The idea for this study came from research in soil physics and soil chemistry by such workers as Bolt (3) and Hemwall and Low (5). These workers ran consolidation-rebound tests on fractionated samples of pure clay minerals and showed that an osmotic repulsive pressure is developed between clay particles that causes rebound or swelling when the effective stress (total pressure minus pore pressure) on the sample is reduced. This repulsive pressure is proportional to the difference in salt content in the water between the clay particles and that in the "free" pore water.

The author's data indicate that osmotic repulsive pressures play an important role in the swelling of a compacted natural clay since an increase in the salt content of the soaking solution was found to reduce the amount of swelling by the soil. It was found, however, that swelling is influenced by factors in addition to osmotic pressures. Other possible swelling mechanisms are discussed.

Since principles of physical and colloidal chemistry and related fields are important to an understanding of swelling, the first portion of the paper summarizes those physiochemical properties of saturated clay-water systems which are thought to influence swelling. These concepts are then extended to compacted natural clays. Only inorganic clays are considered. While the theoretical considerations are somewhat oversimplified and the experimental data and conclusions admittedly incomplete, it is hoped that the reader may at least gain a better insight into the causes of swelling by compacted clay.

THEORETICAL CONSIDERATIONS

Swelling in Saturated Clays

Swelling of saturated clay is considered first, since its behavior is somewhat simpler and better understood than that for a partially saturated soil such as compacted clay. An excellent example of the swelling behavior of the former is the rebound portion of a standard consolidation test on a saturated clay for which any volume increase in the clay sample is accompanied by an equal (neglecting changes in the density of water) increase in the volume of water in the clay.
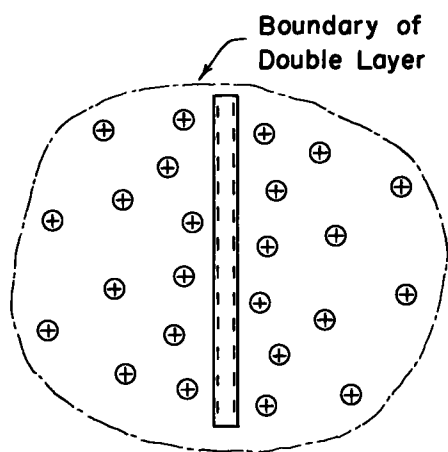
The Clay Micelle. — Figure 1 represents schematically a clay particle immersed in pure water. Sufficient exchangeable cations (the effect of the hydrogen and hydroxide ions in water are not considered in this paper) surround the particle and are attracted to it by a net negative charge in the clay particle in order that the cations plus the particle constitute an electrically neutral system. This system is designated the clay "micelle." The ions and water within the micelle constitute the "double layer." If the clay particle were immersed in a salt solution instead of pure water, then anions would also be present in the double layer, but the number of cations would be increased accordingly in order that the micelle still remain electrically neutral. In other words, the double layer includes that portion of the water surrounding the particle in which there is a negative electric field requiring an excess of positive charges relative to negative charges.

Figure 1. The clay micelle in pure water.

The variation in cation and anion concentration with distance from the clay particle surface for suspensions of clay in water can be calculated from principles of colloidal chemistry, the Gouy-Chapman theory being an example (8). Calculations based on such theories are quantitatively correct for the ideal systems for which the theories were developed; however, most natural soils are far from these ideal systems so that one can only use such theories in a qualitative manner when dealing with soils.

Figure 2. Forces between two clay particles.

Forces Between Clay Particles. — The magnitude of rebound in a standard consolidation test is, of course, directly related to the decrease in effective stress. In turn, the effective stress $\bar{\sigma}$ can be related to physicochemical forces acting between clay particles, and it is these latter forces that are basically responsible for swelling. Lambe (11) represents this relationship between forces by the expression (Fig. 2)

$$\bar{\sigma} = R - A$$

for parallel particles at an equilibrium interparticle spacing of 2d (this relationship and the following discussion of the forces involved apply to interparticle spacings of greater than 10 to 20 Å.) where: (assuming unit area)
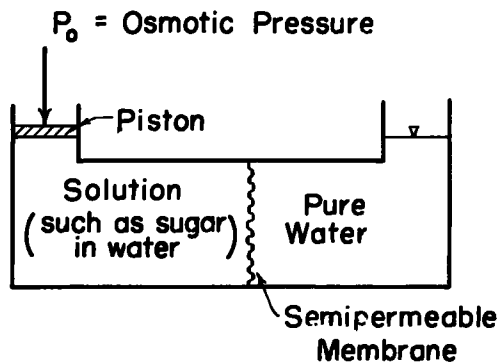

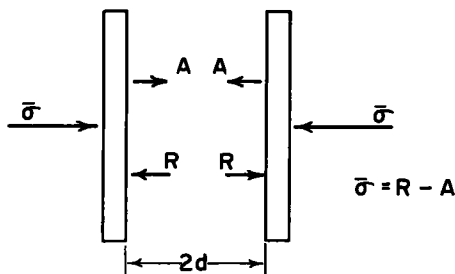Figure 3. The osmotic pressure of a solution.

1. A = the attractive pressure which is usually considered to be caused by London van der Waals secondary valence forces of attraction between the adjacent clay particles. (This secondary valence force is primarily a function of particle thickness and interparticle spacing and decreases rapidly with increasing interparticle spacing (8).)

2. R = the repulsive pressure which arises from the interaction of the double layers associated with the two clay particles. This pressure will be discussed.

A parallel particle alignment is assumed in order to simplify the concept of interparticle forces. "Edge effects" arising from electrical charges at the edges of the particle are neglected. These edge effects may cause an additional attractive force between particles that can lead to a nonparallel particle orientation (11).

All natural clays will swell or rebound when the effective stress $\bar{\sigma}$ is reduced and many, particularly if remolded (remolding tends to align clay particles into a more nearly parallel orientation and also tends to break attractive bonds that may have existed between particles at points of contact prior to remolding, Lambe (11)), will even slake completely if $\bar{\sigma}$ is reduced to zero (for example, the result of immersing an unsupported chunk of clay in water). Hence, for these clays R must be greater than A for at least some of the particles, and the mechanism of swelling can be studied by investigating the nature of the repulsive pressure R.

It is generally believed, Low and Deming (12), that this repulsive pressure has several components. One of the most important components is thought to be caused by an osmotic pressure (This osmotic pressure is the "electricl repulsion" referred to by other writers such as Lambe (10, 11). The higher ion concentration causing osmotic pressures arises, after all, from the electric field in the double layer.) arising from
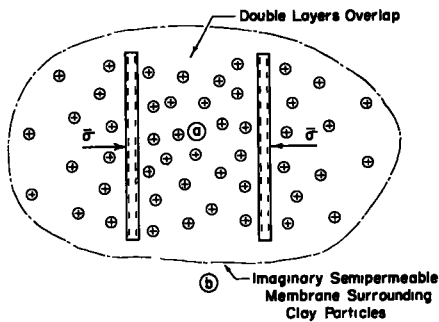
Figure 4. Osmotic pressure between two clay particles immersed in water.

the higher ion concentration in the double-layer water of the clay micelle than in the "free" pore water, that is, that water outside of the micelle. The nature of the other components will be presented after a discussion of osmotic pressures.

Osmotic Repulsive Pressure (Principle). —When an aqueous solution is separated from pure water by a semi-permeable membrane, that is, a membrane that permits the passage of water but not that of the substance dissolved (solute) in the solution, water tends to pass through the membrane into the solution, thereby diluting it. This phenomenon is called "osmosis." The pressure that must be applied to the solution in order to prevent the flow of water into the solution through the semipermeable membrane is called the "osmotic pressure" of the solution. This is shown diagramatically in Figure 3.

Although a mechanistic picture has not yet been developed to explain fully osmosis, there are formulas for calculating osmotic pressures. One of the simplest of these is the van't Hoff equation which yields

$$p_o = \bar{R}Tc$$

where p_o = osmotic pressure (g per sq cm), $\bar{R}$ = gas constant, T = absolute temperature ($\bar{R}T = 2.5 \times 10^7$ g cm per mole for 20 C), and c = concentration of solute (moles per cc of solution). (The van't Hoff equation as presented is only strictly applicable to very dilute solutions of nonelectrolytes. Measured osmotic pressure values exceed calculated values for most other cases, Prutton and Marion (17).) Osmotic pressures can reach very large magnitudes. For instance, 130 gm of sugar per liter of aqueous solution exerts an osmotic pressure of about 10 tons per sq ft. Osmotic pressures can, of course, be developed between two solutions of unequal concentration so that

Figure 5. An illustration of pore water tensions in compacted clay.

$$p_o = \bar{R}T (c_a - c_b)$$

where c_a and c_b refer to the solute concentrations on either side of a semi-permeable membrane.

Osmotic Repulsive Pressure (in Clays). —Osmotic pressures can act in clays since: (a) there exist differences in solute concentrations (in this case ions are the solute), and (b) the electric field around the negatively charged clay particle acts as a semipermeable membrane. This can be illustrated by picturing two clay particles that have been immersed in a beaker of pure water and pushed under an effective stress $\bar{\sigma}$ to an interparticle spacing of 2d, as shown in Figure 4. (Pure water is used to simplify the illustration, because in this case the only ions in the double layer will be the exchangeable cations.) Because of the exchangeable cations, the concentration of ions in the double-layer water is larger than the concentration of ions in the free water. The exchangeable cations are attracted to the clay particles by the negative electric field arising from the negative charge on the particles. Hence the electric field acts as a semi-permeable membrane in that it will allow water to enter the double layer but will not allow the exchangeable cations to leave the double layer. The dashed line in Figure 4 depicts figuratively this "semi-permeable membrane." One can see that due to the difference in ion concentrations between points such as "a" and "b", water would like to flow from "b" to "a" and that an effective stress $\bar{\sigma}$ (plus the attractive pressure A)

is required to prevent an increase in inter-particle spacing, that is, swelling. If $\bar{\sigma}$ is reduced, then water flows from "b" to "a", thus decreasing the ion concentration at "a" (in other words, the double layer is expanded) until the correspondingly lower osmotic pressure is again in equilibrium with the effective and attractive pressures.

At this point one might re-examine the meaning of the term "pore water pressure" as used in soil engineering. When the soil engineer measures pore pressures, as for instance with a piezometer, he measures the pressure in the "free pore water" (that water outside of the double layer). For a particle arrangement as shown in Figure 4,

$$p \approx \frac{2Ts}{r} \cos \alpha$$

where: Ts = surface tension in water
        r = radius of capillary tube
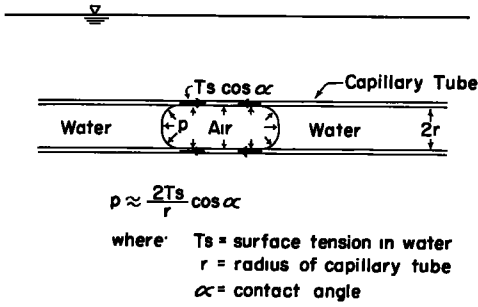 α = contact angle

Figure 6. Air pressure in capillary tube.

the pore pressure u as used in soil engineering is, therefore, the pressure in the water as a point such as "b". The total pressure in the double-layer water (to mean water plus ions) at a point such as "a" midway between clay particles is, however, greater than u by a pressure equal to the developed osmotic pressure (and possibly other pressures to be mentioned) and this pressure increase is counterbalanced by $(\bar{\sigma} + A)$. This assumes that the pore pressure u also acts between particles. For a detailed discussion of variations in water pressures throughout a clay-water system, see Low and Deming (12).

Osmotic Repulsive Pressure (Factors Influencing). — The ion concentration differential that determines the osmotic repulsive pressure between particles is the ion concentration at the midplane between particles (that is, point "a" in Fig. 4) minus the ion concentration in the water outside of the double layer (the free pore water). Thus, based on the van't Hoff equation, the osmotic pressure becomes

$$p_o = \bar{R}T (c_c - c_o)$$

where c_c and c_o refer to the total ion (both cations and anions) concentration (moles per cc) at the midplane and in the free pore water, respectively. (The reader is referred to Bolt (3), Kruyt (8), Low and Deming (12), Hemwall and Low (5) and Lambe (11), for a more detailed presentation and discussion of these and other factors and for additional reference material.)

Whereas the ion concentration in the free pore water c_o can be easily measured, the midplane concentration c_c must be computed from a theory relating ion concentration with distance from the clay particle surface. For certain ideal cases, the Gouy-Chapman theory has been used and the calculated osmotic pressures checked experimentally. Bolt (3) and Warkentin, et al. (22) ran consolidation-rebound tests on samples of fractionated (minus 0.0002 mm) montmorillonite and illite with various exchangeable cations and pore water ion concentrations over a pressure range of from 0.1 to 50 tons per sq ft. Their data show that the compression-swelling curves based on osmotic pressures computed from the Gouy-Chapman theory agreed qualitatively and in some cases almost exactly with the observed curves, and in all cases the observed trends corresponded with theory. (Bolt and Warkentin, et al. (22) hypothesize that unknown variations in particle shape and spacing can account for much of the discrepancy between the computed and measured curves.)

Of main interest, the Gouy-Chapman theory tells us (as does intuition) that for a given clay:

1. For a constant interparticle spacing, p_o decreases with increasing ion concentration in the free pore water.
2. p_o decreases with increasing interparticle spacing.

Furthermore, the data by Bolt and others indicate that variations in osmotic pressures, and hence swelling, as predicted by the Gouy-Chapman theory, should also apply in a qualitative sense to natural clays for interparticle spacings exceeding 10 to 20 Å. A quantitative treatment of natural clays is, of course, impossible because the extreme

variations in particle size, shape, composition, orientation, and spacing preclude any realistic computation of interparticle forces.

Other Repulsive Pressures and Swelling Mechanisms. — The previous discussion has shown that an osmotic pressure can reasonably account for a repulsion between clay particles which results in swelling, or in other words, an expansion of the double-layer, when the effective stress on a clay sample is reduced. Other factors may also contribute to swelling. One of these is the effect of secondary valance or London van der Waals forces on the water surrounding clay particles, Hemwall and Low (5) and Low and Deming (12). Another is the effect of the negative electric field on the double-layer water. Both of these force fields are believed to attract water to the soil particles, although the latter force field is not thought to contribute to R for particles at equilibrium, Low and Deming (12). Whereas there are fairly extensive data indicating that osmotic pressures play a very important role in swelling, at least for certain clay-water systems, there are no known data from which definite conclusions can be drawn relative to the magnitude of influence of the above two factors on swelling.

As previously noted, the foregoing discussion has been restricted to interparticle spacings, 2d, greater than 10 to 20 $\overset{o}{A}$. (The double-layer thickness would then be 5 to 10 $\overset{o}{A}$.) For smaller spacings, the nature and interrelationship of $\bar{\sigma}$, R, and A may change radically. (At these small interparticle spacings, such as one might expect in a highly compressed clay, the likelihood of having A greater than R may be increased for many of the interacting particles, Lambe (11), p 1655-20.) For these smaller spacings (among other things):

1. Osmotic pressures may not be developed; in other words, the "normal" double-layer is not formed, MacEwan (13) and Norrish (15).

2. Water adsorption is generally thought to be governed primarily by hydration of the exchangeable cations and the attraction of the clay particle surface for polar molecules like water, Barshad (2), MacKensie (14) and Norrish (15).

Mention should be made of swelling due to elastic rebound and "unbending" of soil particles. It is felt, Lambe (11), that this phenomenon, while important in coarse-grained soils and in soils containing relatively large platey shaped particles (like mica), is of little importance for most clays. Bolt (3) discusses the importance of these "mechanical" effects versus the "physicochemical" effects for natural soils.

Swelling in Compacted Clays

In attempting to utilize the foregoing swelling concepts to explain the swelling behavior of a compacted clay, one is confronted with the following complications. As the molded water content changes (the reader is referred to Holtz and Gibbs (7) for extensive data on the swelling characteristics of compacted clays) for a given compactive effort:

1. The dry density of the soil and thickness of the double-layer water around clay particles vary.

2. The particle orientation varies.

3. The pore water tensions vary.

4. The degree of saturation, and hence the amount of air in the sample, varies. The pressure in the air may also vary.

The above factors are discussed relative to their possible effects on swelling behavior and the mechanisms involved.

Effect of Molded Water Content on Dry Density and Double-Layer Thickness. — The thickness of the double-layer water on compacted clay particles is nearly always less than that which the particles would like to have if given free access to water. (Silt and sand size particles also have "double-layer water." However, these particles have a relatively small specific surface area that is, surface area per unit weight of soil, so that the effect on the over-all volume change of an expansion of the double layer around these particles is small compared to that for clay size particles where the specific surface area is large.) For instance, many plastic clays under zero confining pressure

will imbibe water until they reach a water content approximating the liquid limit, whereas the clays may be compacted at water contents less than the plastic limit. The difference between these two water contents has been termed the "double-layer deficiency" Lambe [11]. This deficiency is thought to be caused by the same factors causing swelling, that is, a double-layer expansion, in saturated clays (for example, osmotic pressures, effect of force fields on double-layer water, etc.). If the thickness of double-layer water is less than 5 to 10 Å (corresponding to a 2d spacing of 10 to 20 Å) the double-layer deficiency may in part be due to cation hydration, etc., as previously mentioned. A double-layer thickness of 5 to 10 Å is approximated by the water content of the soil at 99 percent relative humidity. This water content, even for extremely plastic soils, seldom reaches 10 to 15 percent (pure montmorillonite is an exception) and is usually only a few percent for most lean clays. Hence for many clays, the water content used for compaction may be sufficient for a double-layer thickness of greater than 5 to 10 Å.

The thickness of the double-layer is roughly proportional to the molded water content (assuming all water to be in the double-layer, the average thickness of the double-layer is then equal to the water content divided by the specific surface area). Hence the lower the molded water content (other things being equal), the greater is the water uptake required to satisfy the double-layer deficiency; and for a constant molded water content, an increase in dry density would lead to an increase in the amount of swelling.

Effects of Molded Water Content on Particle Orientation. —There is evidence, Pacey [16], to show that the orientation of clay particles changes with molded water content. These data indicate that compaction dry of optimum water content leads to a nonparallel or flocculated orientation while compaction wet of optimum leads to a parallel or dispersed orientation of clay particles. Different methods of compaction may also yield different particle orientations, even at the same density and water content. One might expect different particle orientations to cause a difference in swelling behavior. Seed's [18] data suggest that a flocculated particle orientation will swell more than a dispersed orientation.

Effects of Molded Water Content on Pore Water Tensions and Degree of Saturation. — Pore water tensions (water pressures less than atmospheric) undoubtedly exist in compacted clay, particularly if compacted dry of optimum water content where the initial degree of saturation is well below 100 percent, Aitchison [1], Soil Mechanics for Road Engineers [19] and Hilf [6]. Tensions are caused by the double-layer deficiency in the clay micelles. (As previously pointed out, one should also include the larger size particles since they also desire water.) In other words, all the particles in the soil are competing for the limited supply of water in order to expand their double-layers. Capillarity may also enter the picture if the voids in the soil contain both air and "free" water.[1] The desire of the clay micelles to imbibe this free water would be resisted by the surface tension at the air-water interface in the void.[2] An illustration of this phenomenon is shown in Figure 5 which depicts clusters of clay particles compacted between silt particles. The inflow of water to the clay is restrained by the menisci in the pores between the silt particles. This illustration is only one example of the many possible situations that might occur, since a compacted clay will contain a wide variation in the size and shape of particles and voids.

In summary, then, pore water tensions in a compacted clay represent a balance between double-layer deficiencies and surface tensions at air-water boundaries. Another way one might look at pore water tensions is to say that they exert an effective stress

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[1] Capillarity in the same sense as the capillary rise of water in a glass tube. The author, when using this term, is referring in general to relatively large pores in the soil (for example, diameters of several thousand Å or larger) where the amount of double-layer water is relatively small compared to the "free" pore water. Although the fundamental cause of capillarity may originate from the electrical nature of the soil particles, the term capillarity is a widely used concept which seems applicable in this case.

[2] Calculations based on the capillary equation, Taylor [20], relating pressure, surface tension, and pore diameter show that a 3,000 Å diameter pore can resist a tension of about 10 atmospheres. Bolt's [3] data for Na montmorillonite show that a swelling pressure of 10 atmospheres corresponds to a particle spacing of only about 30 Å (double-layer thickness of 15 Å).

on the compacted clay mass which prevents the particles from imbibing water and swelling. This effective stress is more of an "effect" than a "cause."

When a compacted clay sample is put in contact with water, any air-water menisci at the surface of the sample are broken. Water will flow into the clay because of the pore water tensions within the sample, these tensions having been caused by a combination of double-layer deficiencies and capillarity. With time, the pressure in the pore water increases to atmospheric with a resultant lowering of the effective stress within the sample. Concurrently, the clay micelles expand their double-layers and swelling occurs between clay particles, just as for the saturated clays, until the repulsive pressure minus the attractive pressure between particles is in equilibrium with any applied effective stress. Over-all swelling of the sample can, of course, be prevented by applying an effective stress to the soil equal to the "swelling pressure."

The Role of Air in Swelling. —Previous discussion has mentioned that the presence of air can influence the magnitude of the pore water tensions that are developed in compacted clay. Air may also influence the swelling behavior in another manner. Swelling data, Holtz and Gibbs (7), Figures 8, 10 and 11, usually show that the total volume of air in a compacted sample decreases during the soaking process, particularly for samples compacted dry of optimum water content, although the final degree of saturation is still less than 100 percent. Thus, during the soaking process, some of the air initially in the soil voids must either escape from the soil, be dissolved by water, or be compressed by capillary forces. Most likely a combination of these conditions occurs. If a nonspherical pocket of air is compressed in a soil void during the soaking process, the pressure in the air may produce tensile stresses in the soil skeleton forming the void in which the air resides ($_0$a long, initially air filled pore having a relatively large diameter of several thousand $\overset{\circ}{A}$ or larger is visualized). These tensile stresses could cause an increase in the volume of the void, and hence an expansion of the soil.

An analogous situation is shown in Figure 6. An initially air filled capillary tube is immersed horizontally in water. As water enters the tube from both ends by capillarity, the air in the tube becomes compressed. An analysis of the stresses on a cross-section of the tube through the air pocket (there must be enough air in the tube so that the air pocket does not become spherical) shows that both axial and hoop tensions act in the tube at this location; in other words, the pressure in the air tends to expand the tube. If the capillary tube were brittle and could not withstand these tensions, it would ultimately break at the center. If the capillary tube were flexible at the center, a bulging would occur. The maximum air pressure that can be attained in a capillary tube of a given radius (assuming a sufficient amount of air) is proportional to the tensile strength of the tube or the surface tension of water, whichever is smaller.

In a similar manner, it is believed that air in a soil void, if under pressure, can cause an enlargement of the void if the soil skeleton cannot resist this pressure. These air pressures could be quite large. For example, theoretically, air could be compressed by capillary forces to a pressure of 6 atmospheres in a void having a diameter of 0.5 microns (5,000 $\overset{\circ}{A}$). Such a pore size is not unlikely in a compacted clay.

One can probably best visualize this swelling phenomenon occurring in a soil where: (a) There are many interconnected tubular air voids; (b) the air pressure is initially atmospheric, and (c) water enters the soil from all directions during soaking. These conditions (except possibly for the shape of the voids) are met when a dry sample of clay is immersed without confinement in water. The rapid slaking of such a sample is said, Terzaghi and Peck (21), p. 129, to be caused at least in part, by the air pressure that is built up within the sample. Data will be presented which suggest that air pressures may contribute to the swelling of clay if compacted dry of optimum water content.

The above discussion dealt with the presence of air in the larger voids of a compacted clay. The presence of air in the double-layer water between interacting clay particles would also affect swelling. For example, if air were present, it would tend to expand the double layer, since it is displacing water and ions. In other words, for a given interparticle spacing, the presence of air would increase the repulsive pressure; or for a given effective stress, the interparticle spacing would be larger. The magnitude of influence on swelling of this air is, however, not known. Even the amount

of air to be expected in the double layer is a matter of conjecture.

Only two "types" of air have been discussed, that is, large, fairly continuous voids of air that extend throughout the clay mass, and minute bubbles of air that exist in the double-layer water. While air undoubtedly exists in many forms in compacted clay, the above conditions are thought to represent two extreme cases which can be used for a consideration of the major effects of air on the swelling behavior of compacted clay.

EXPERIMENTAL DATA

Swelling data are presented in which compacted samples of a clay are soaked in aqueous solutions ranging from pure water to a 5 molar salt solution. According to the previously developed theory, the samples which are soaked in salt solutions should swell less than the samples soaked in pure water, since an increase in ion concentration in the water outside of the double layer reduces the osmotic repulsive pressure between clay particles. In other words, the salt solution will reduce the double-layer deficiency in the clay micelles. Data are also presented relative to the distribution and pressure of air in as-compacted samples of clay.

Description of Soil

The soil, Vicksburg Buckshot clay, was supplied to the MIT Soil Stabilization Laboratory by the Waterways Experiment Station, Vicksburg, Mississippi. The Atterberg limits, specific gravity, grain size distribution, mineralogical composition, and certain other properties are presented in Table 1. Of particular interest are: (a) The highly plastic characteristics of the soil, although only 36 percent of the soil is clay size; (b) the presence of montmorillonite, a clay mineral known to be very expansive;

TABLE 1

PROPERTIES OF VICKSBURG BUCKSHOT CLAY

1. Specific gravity[a] = 2.74

2. Atterberg limits[a]
   Liquid limit = 63 percent
   Plastic limit = 25 percent
   Plasticity index = 38 percent

3. Grain size distribution
   94 percent minus 0.074 mm; 36 percent minus 0.002 mm

4. Mineralogical composition in percent by weight[b]

Illite	} Interstratified	25 ± 3[c]
Montmorillonite		25 ± 3
Quartz		20 ± 3
Feldspar		20 ± 10
Fe_2O_3		1.1 ± 0.1
Organic matter		1.1 ± 0.1

5. Other properties[b]
   Soluble salts (meg. NaCl/100 g) = 0.3
   Cation exchange capacity (meg./100 g) = 30; 52 (minus 0.002 mm)
   Glycol retention (mg/g) = 65; 135 (minus 0.002 mm)
   pH = 4.9

Note: Items 4 and 5 obtained by R. T. Martin, Research Associate, MIT Soil Engineering Division.

[a] On air-dried and ground soil.
[b] Unless otherwise specified, data shown for soil passing 0.074 mm.
[c] ± indicates probable uncertainty in percentages given.

and (c) the high glycol retention by the soil. Multiplying the glycol retention by 3.22 to obtain the specific surface area yields values of 210 and 435 sq m per g of clay, respectively, for the two soil fractions (by comparison Na montmorillonite has a surface area of 800 sq m per g). The exchangeable cations are believed to be predominantly calcium.

Test Procedure

The test procedure employed for the compaction-soaking tests was as follows:

1. The clay was air-dried, ground to pass a No. 20 sieve, and equilibrated for at least two days at the desired water content. Distilled water was used as the molding fluid.
2. The clay was compacted dynamically in 2.75-in. diameter by 0.85-in. consolidometer rings (fixed ring type) at an effort of 28,000 ft-lb per cu ft and trimmed to a height of 0.6 in. A surcharge of 200 lb per sq ft was applied, followed by immersion of the sample in an aqueous solution. The test set-up is shown schematically in Figure 7. Note that the soaking solution enters both ends of the compacted sample.
3. Three different aqueous solutions were used for soaking. These were: (a) Distilled water; (b) a 0.5 molar $CaCl_2$ solution (55 g $CaCl_2$ per 1,000 cc of solution. $CaCl_2$ was used to prevent ion exchange); and (c) a 5.0 molar $CaCl_2$ solution. The solubility of $CaCl_2$ in water at room temperature is approximately 5.2 molar. Hence, a 5 molar $CaCl_2$ solution is very strong.
4. Measurements of the amount of heave were taken over a four day period.
5. At the end of four days the weight of the sample was measured. The weight of solution in the sample was divided by the estimated unit weight of the solution to obtain a volume of solution. The volume of solution was treated as if it were pure water for computing water contents after soaking. (That is, if 10 g of initially dry soil imbibed 1.5 g of a salt solution with a unit weight of 1.5 g per cc, the recorded "water content" change would be 10 percent. For initially moist samples, however, the exact unit weight of solution in the sample after soaking was unknown and had to be estimated.)

TABLE 2

WATER ADSORPTION AND IMBIBITION DATA ON VICKSBURG BUCKSHOT CLAY

A. Water vapor adsorption[a]

Relative Humidity (%)	Equilibrium Water Content (%)
50	6
~ 99	13.5

B. Water imbibition under "Free-Swell" condition[b]

Initial Water Content (%)	Equilibrium Water Content (%)
3.6	64
4.7	68
4.7	67
4.7	60
8.2	55
32.4	53
50.2	51
51.0	54

[a] On loose samples of initially oven-dried clay.
[b] On 1.5 mm thick samples of clay spread over a porous stone whose top surface was slightly above a water surface which was enclosed in a sealed container. Equilibrium content taken after 24 hr.

Swelling Data

Data on water adsorption and water imbibition under a "free-swell" condition are presented in Table 2. The data indicate that: (a) At water contents in excess of 13.5 percent (the equilibrium water content at 99 percent relative humidity), it is reasonable to assume that the exchangeable cations are hydrated and that the normal double layer is formed; and (b) under zero confining pressure, the double layer will imbibe approximately 60 percent water. (Assuming that all the water is associated with the clay-size fraction of the soil and that the surface area of this fraction is 435 sq m per g, the average thickness of water around the clay particles in $\mathring{A}$ is approximately one-half of the water content in percent; for example, a water content of 60 percent corresponds roughly to an average water thickness of 30 $\mathring{A}$.) The molded water contents used for the compaction soaking data presented below range from 14 to 24 percent with optimum water content at 19 percent.
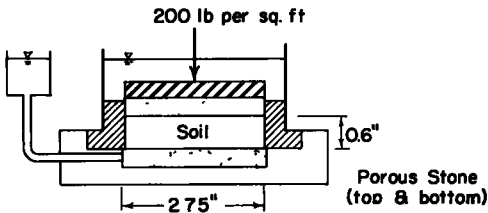
Figure 7. Compaction-soaking test apparatus.

The effects of salt concentration on swelling are shown in Figure 8 in which the molded dry density, the percent heave (change in height divided by initial height times 100), and the "water content" increase are plotted against the molded water content. The effect of salt content on the rate of swelling for samples compacted wet and dry of optimum water content are presented in Figure 9. Dry density and water content curves before and after soaking are plotted in Figure 10 for samples immersed in both pure water and in the 5 molar $CaCl_2$ solution. Figure 11 shows the relationship between volume change (cc) and water pickup (g) for samples soaked in water (since the swelling data were obtained on soil samples of unequal volume prior to soaking—variations of up to 15 percent—the observed data have been adjusted to correspond to initial samples volumes of 100 cc).

The data show that:

1. The amount of heaving and water pickup decreases with increasing molded water content.

2. The degree of saturation after soaking is less than 100 percent. The volume of water pickup also exceeds the volume of expansion, particularly for samples compacted dry of optimum water content.

3. The soaking of compacted samples in salt solutions produces a marked decrease in the amount of fluid pickup and heaving. Figure 8 shows that the absolute magnitude of this reduction in fluid pickup and heaving is fairly uniform, particularly for the strongest salt solution, over most of the molded water content range. Furthermore, the 5 molar salt solution prevents swelling for a sample compacted 2 percent wet of optimum water content.

4. The initial rate of swelling is practically unaffected by the salt concentration in the soaking solution. (A 5 molar $CaCl_2$ solution has a viscosity 10 times and a surface tension 1.3 times that of pure water so that one might expect a net decrease in the rate of swelling due to the large increase in viscosity.)

The data show that the salt content in the pore fluid has a decided effect on the swelling behavior of this compacted clay. Hence it would appear that osmotic repulsive pressures play an important role in swelling, since osmotic pressures depend upon the difference in ion concentration in the water between the clay particles and that in the free pore water. Furthermore, it would seem that the osmotic pressure concept can satisfactorily explain, at least in a qualitative sense, the observed swelling of samples compacted wet of optimum water content, since the addition of salt prevented swelling. This does not necessarily mean, however, that an osmotic pressure is the only component of the repulsive pressure R. For example, even for the sample that did not swell when immersed in the 5 molar $CaCl_2$ solution, there must be a repulsive pressure

between particles in order to counterbalance the effective stress (that is, the 200 lb per sq ft surcharge) plus any attractive stresses that may act. If this strong salt solution reduced osmotic pressures to zero, then some other mechanism of repulsion must be operative even though the magnitude of its influence is small.

While it is evident that some of the swelling of samples compacted dry of optimum water content can be explained by osmotic pressures, there are certainly other factors which influence the swelling behavior. One might assume that the reduction in swelling due to the 5 molar CaCl₂ solution is approximately equivalent to the "osmotic" swelling
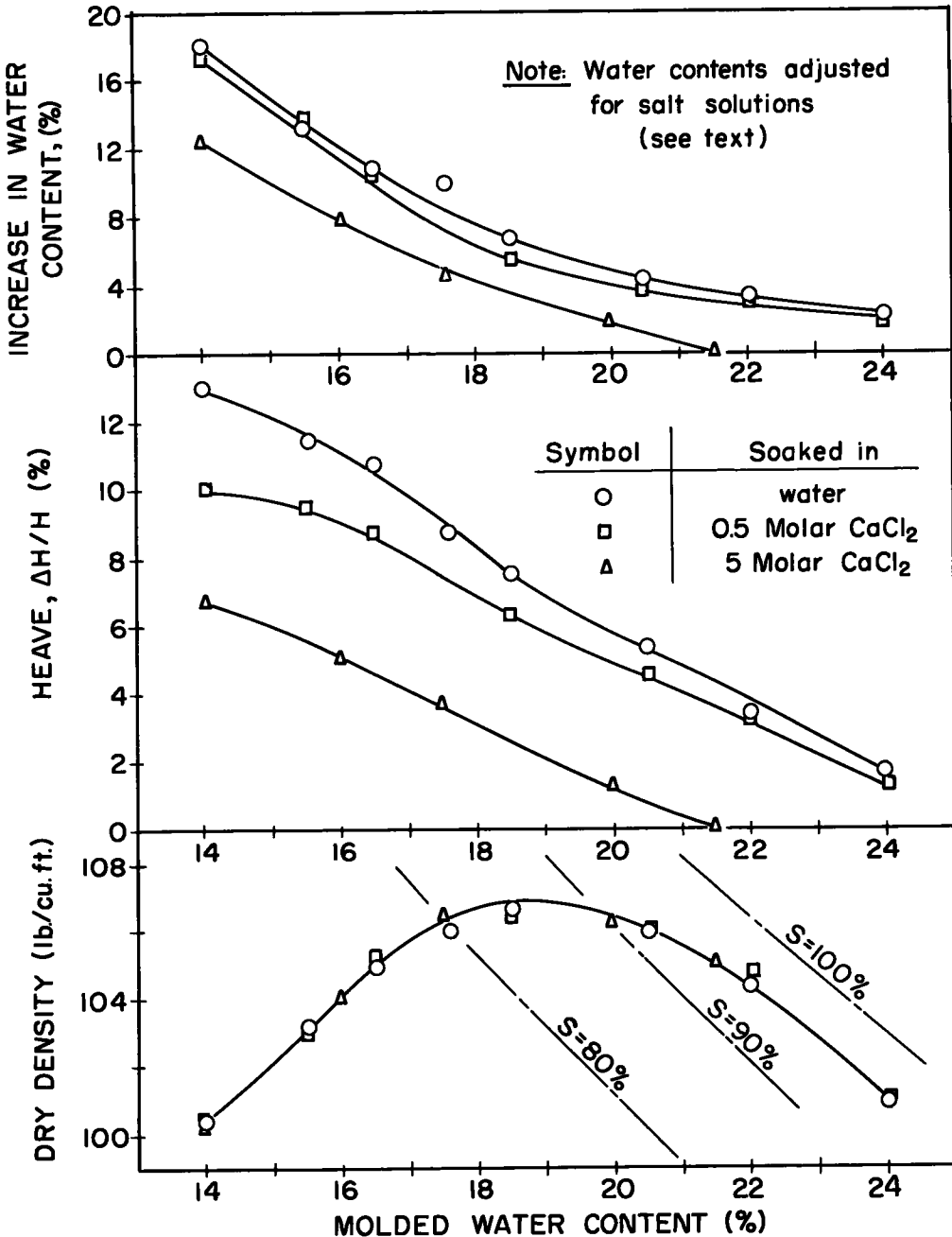
Figure 8.   Effect of salt concentration on swelling behavior.
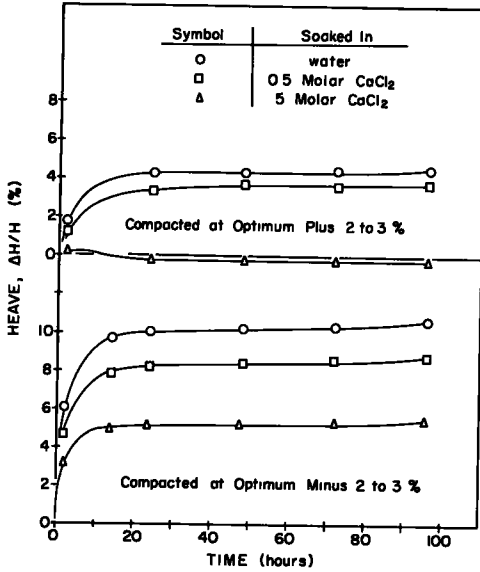
Figure 9. Effect of salt concentration on rate of swelling.
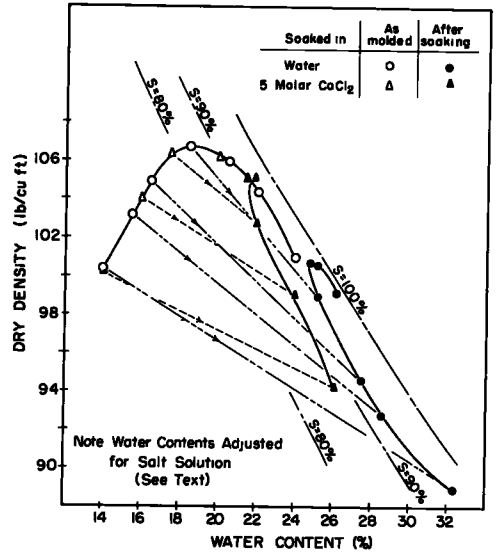
Figure 10. Effect of salt concentration on density and water content after soaking.

that occurs when the samples are soaked in pure water. However, an increase in salt concentration may also influence other interparticle forces besides osmotic pressures. A better assumption would be that the 5 molar salt solution reduces swelling due to osmotic pressures to a negligible amount, since rough calculations show that the concentration of ions in a 5 molar $CaCl_2$ solution far exceeds the concentration of the exchangeable cations between clay particles. (For a monomolecular thickness of water on the
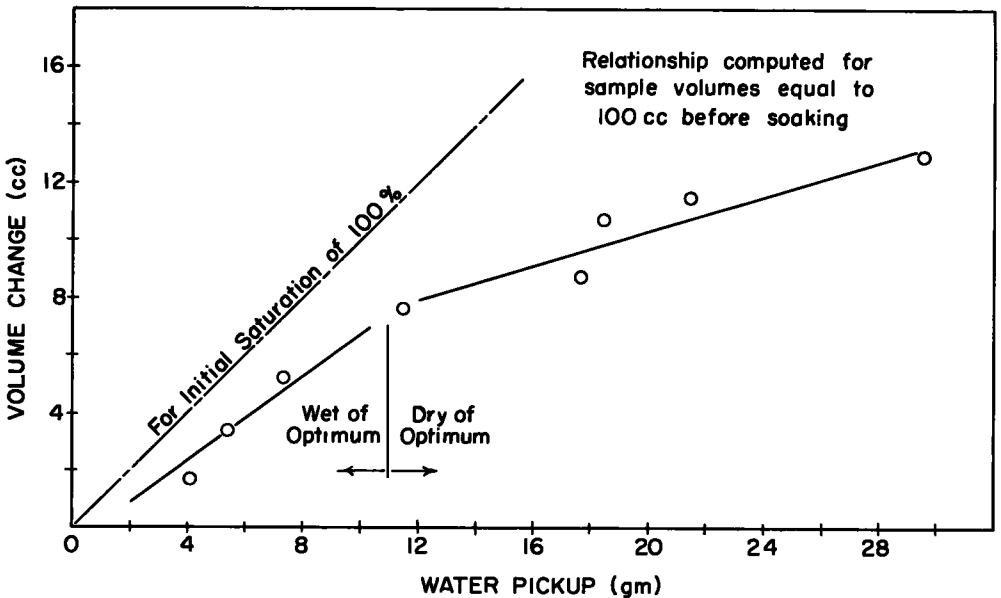
Figure 11. Relationship between volume change and water pickup for samples soaked in water.

clay, the average concentration of exchangeable cations, assumed to be calcium, around the particles is only about 2 molar. Reducing the surface area by a factor of two still only yields a 4 molar concentration. Hence the total ion concentration in a 5 molar CaCl₂ solution far exceeds the concentration of exchangeable cations in the soil for all water contents.)
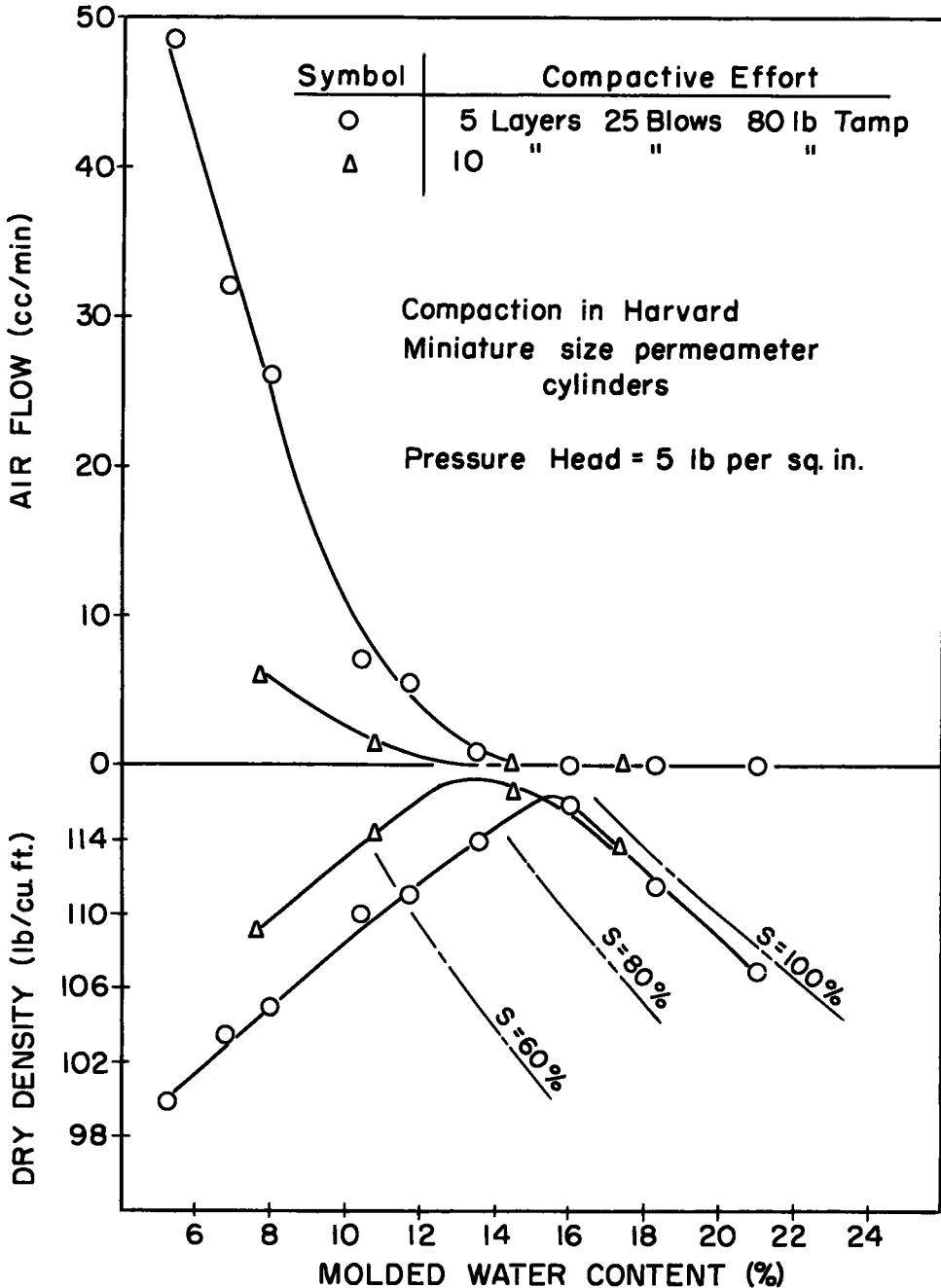

Figure 12. Air flow data.

The increased swelling dry of optimum over and above that which might be attributed to osmotic pressures may be due to a number of factors. As previously mentioned under Theoretical Considerations, there are mechanisms other than osmotic pressures by which clay particles can imbibe water. These were: (a) The effect of the negative electric and London van der Waals force fields on water; and (b) the effect of cation hydration and the attraction of the particle surface for water, at least for small double-layer thicknesses. The relative importance of the first factor is unknown; the second factor should be relatively important for the molded water content range investigated, since the molded water contents exceeded the equilibrium water content of the soil at 99 percent relative humidity. Elastic rebound and a flocculated particle orientation may contribute to the increased swelling dry of optimum; the magnitude of their influence is not definitely known. Finally, there is the role of air in swelling. The increase in volume of fluid pickup with decreasing molded water content can be partially explained by the decreasing initial degree of saturation (increasing volume of air voids). The following data suggest that a buildup of air pressures within soil voids during the soaking process may contribute to the increased swelling dry of optimum water content.

Data Relative to the Role of Air

Figure 11 has shown that the volume of air in the compacted clay samples decreases upon immersion, particularly dry of optimum water content, since the volume of water pickup exceeded the total volume increase of the samples during soaking. It seems possible that some of this decrease in the volume of air voids is caused by a compression of air by capillary forces. An increase in the air pressure (preliminary attempts to measure the pressure in the air voids after soaking proved unsuccessful) within entrapped nonspherical pockets of air, as previously discussed, is thought to cause swelling of soil.

One would expect swelling due to air pressures to be of greatest importance in compacted samples containing numerous interconnected air voids prior to soaking. With decreasing molded water content dry of optimum, the volume of air voids in the compacted clay increases. Data are presented in Figure 12 which indicate that at least some of the air in the samples compacted dry of optimum is also continuous (and therefore at atmospheric pressure), whereas the air in samples compacted wet of optimum appears to be discontinuous. Clay samples were compacted at two compactive efforts in a constant head permeability apparatus, an air pressure applied at the top of the sample, and the quantity of air flow measured with a rotameter at the outlet. For both compactive efforts the quantity of air flow decreased rapidly with increasing molded water content, and at optimum water content the flow became too small to measure (less than 1 cc per minute).

The data thus show that the samples having the greatest amount of swelling also initially have the greatest amount of interconnected air voids. While this fact supports the air pressure hypothesis, the author has no data to prove its validity. Further experimentation is planned.

Reliable data have not been obtained relative to the amount of air present in double-layer water.

CONCLUSIONS

The data have shown that the salt content in the pore fluid has an important effect on the swelling behavior of Vicksburg Buckshot clay. Furthermore, it appears that the osmotic pressure concept can satisfactorily explain a good portion of the swelling that occurs when this clay is soaked in water, particularly for samples compacted wet of optimum water content. Dry of optimum water content, however, swelling is influenced by factors in addition to osmotic pressures. These other factors may be: the effect of negative electric and London van der Waals force fields on water, cation hydration and the attraction of the particle surface for water molecules, elastic rebound, particle orientation, and the presence of air. The relative importance of these other factors is not known.

Although the experimental data are limited to one clay, the theoretical considerations

indicate that many of the same concepts can be extended to other compacted soils. With other soils, however, the relative importance of the different swelling mechanisms may be altered.

An understanding of some of the factors which influence swelling may help the soil engineer predict, at least in a qualitative sense, the swelling behavior of compacted clays, and it may even enable him to alter swelling behavior to better suit his needs. This is illustrated by the following examples:

1. Fat clays, with their relatively large surface area and hence greater proportion of double-layer water, almost always swell more than lean clays.

2. Clays compacted at low water contents, where the water deficiency in the double layer is high and the degree of saturation is low, will often swell more than clays compacted at high water contents.

3. The replacement of low valency exchangeable cations by higher valency cations (for example, calcium for sodium) can reduce swelling, since the number of exchangeable cations in the double layer is reduced.

4. The mixing of salt with a compacted clay can reduce swelling, since the ion concentration in the pore water is increased. This may partially explain why the treatment of road subbases and subgrades with salt often improves stability.

5. Leaching compacted clays with salt solutions will result in less expansion and hence less strength loss than leaching with pure water. Salt leaching might be employed to increase the stability of a dam or to reduce heaving at the bottom of an excavation.

ACKNOWLEDGMENTS

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