Effect of Soil Structure and Thixotropic Hardening on the Swelling Behavior of Compacted Clay Soils

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Basic concepts of soil chemistry, soil physics, and soil structure as related to the expansive behavior of compacted clays are examined. A model of the swell pressure mechanism is presented. Equations are derived for the vertical and horizontal components of swell pressure in compacted clay soils with flocculated and dispersed structures in terms of average particle orientation and net interparticle swell pressure.

It is shown that theoretical values of swell pressure based on the proposed swell pressure model agree closely with experimental values, and that the concepts of soil structure as presented in the paper offer a reasonable explanation for the swelling behavior of a compacted clay. Thixotropic hardening is shown to be one of the most important factors determining the swelling behavior of undisturbed and remolded clays. The results of the investigation are related to the fundamental aspects of clay colloid chemistry and soil structure. Practical implications of the results are pointed out with particular reference to the fundamental physicochemical and engineering properties of clay soils.

IN THE western and southern parts of the United States and many parts of the world, cohesive soils are encountered which exhibit swelling or expansive characteristics. Lambe (8), Redus (12), Kassiff and Zeitlen (6), and Dawson (3) cite examples of damage to buildings, canals, highway and airport pavements, retaining walls, and pipelines as a result of expansive soils becoming saturated and swelling.

The first comprehensive study of the engineering, physicochemical and mineralogical properties of expansive soils was conducted by Holtz and Gibbs (5). Their findings indicated that expansiveness was primarily dependent on the amount of montmorillonite present in the soil and its exchange ions. Volume change was found to correlate well with colloid content, liquid limit and shrinkage limit. They also found that for a given initial moisture content, swelling and swell pressure increased as the initial dry density increased, and that for a given initial dry density, swelling and swell pressure increased as the initial moisture content decreased.

Encouraged by the success of Bolt, Miller and Warkentin (1, 2, 17) and Hemwall and Low (4) in determining the nature and magnitude of the forces between clay particles, Ladd (7) used the concepts of the electric double layer to explain the swelling mechanisms in compacted clays.

Seed, Mitchell and Chan (14) conducted tests on the swelling behavior of compacted sandy clays and found that swelling is dependent on stress history, and that at all initial moisture contents and initial dry densities, samples compacted statically produced...
higher swell pressures and swelled more than samples compacted by kneading. They attributed this to differences in soil structure, but presented no mechanism to explain the phenomena.

Results of a study to relate soil structure and swelling were published by Parcher and Liu (11). These investigators measured the vertical and horizontal components of free swell independently in a triaxial device, and attempted to relate the results to soil structure and clay colloid chemistry.

The investigation reported herein was conducted to study the effect of soil structure and thixotropic hardening on the swelling behavior of compacted clay soils. The scope of the paper is limited to (a) presenting a proposed model of the swell pressure mechanism based on soil structure and clay colloid chemistry; (b) utilizing this model to predict theoretical values of vertical swell pressure for Vicksburg Buckshot clay, and comparing them to experimental values; and (c) investigating the effect of thixotropic hardening on the swelling behavior of compacted samples of Vicksburg Buckshot clay and relating the results to clay colloid chemistry.

THEORETICAL PRELIMINARIES

Interparticle Repulsive Pressure

The interparticle swell pressure between clay particles is given by the osmotic pressure midway between the particles with respect to that of the equilibrium solution. This can be approximated by the van't Hoff equation

\[ P_s = RTC_0 \left( \frac{C_c + C_0}{C_0} - 2 \right) \]

where

- \( P_s \) = interparticle swell pressure,
- \( R \) = the universal gas constant,
- \( T \) = absolute temperature,
- \( C_0 \) = cation concentration in the equilibrium solution, and
- \( C_c \) = cation concentration in the central plane.

Bolt (1) has shown that the ion concentration midway between the particles can be computed approximately, using the Gouy theory of the electric double layer. From double layer theory, an expression is obtained relating the cation concentration midway between the particles and the distance between the particles

\[ \nu \sqrt{\beta C_0 (X_0 + d)} = 2 \sqrt{\frac{C_0}{C_c}} \int_0^{\pi/2} \frac{d\Phi}{\sqrt{1 - \left( \frac{C_0}{C_c} \right)^2 \sin^2 \Phi}} \]

where

- \( \nu \) = valence of exchange ions;
- \( \beta = \frac{8e^2}{kT} = 8.48 \times 10^{14} \) cm/millimole at 25°C;
- \( X_0 = \frac{4}{\nu \beta T} \), a constant dependent upon the surface charge on the clay particles:
  - \( \frac{1}{\nu} \) Å for illite,
  - \( \frac{2}{\nu} \) Å for kaolinite,
  - \( \frac{4}{\nu} \) Å for montmorillonite;
\[ \Gamma = \text{surface charge on clay particles in milliequivalents/cm}^2; \]
\[ 2d = \text{distance between particles; and} \]
\[ \Phi = \text{a variable whose value is not needed to evaluate this complete elliptic integral of the first kind.} \]

Interparticle swell pressure is not the only force acting between parallel clay particles. To be more complete, van der Waals attractive forces and surface hydration forces should also be included. However, as a first approximation all other forces will be neglected.

**Structure of Compacted Clays**

Soil structure is the relative arrangement of particles in a soil mass plus the nature and intensity of the electric forces acting between adjacent particles (9). The factors which determine the structure of a compacted clay soil are the type and amount of clay present, the moisture content of the soil when compacted, the valence and concentration of electrolyte in the soil water, the pH of the soil-water system, the type of compaction, and the amount and intensity of compaction. The arrangement of the particles is determined largely by the moisture content and the type and amount of compaction, while the physicochemical properties of the soil are the major factors determining the nature of the electric forces between adjacent particles.

In the moisture content range at which clay soils are compacted, the individual particles will be aggregated in parallel orientation. Therefore, a description of soil structure must begin with the relationship between the individual particle aggregations and their orientation relative to some datum such as the horizontal plane. The particle aggregation may be randomly oriented in a structure similar to salt flocculation (Fig. 1), or may be parallel in a structure similar to a dispersed state (Fig. 2). The average orientation of the particles may range from horizontal to vertical.

Cross links are edge-to-face and/or edge-to-edge contacts between individual particles which frequently occur between particle aggregations (16). The amount of cross-linking is influenced by moisture content, structure, electrolyte concentration, temperature, pH and time.

The structure of compacted clays is very closely related to their moisture-density relationship. Figure 3 shows the general shape of a moisture-density curve. The moisture content at which the maximum dry density is achieved under given compaction conditions is called the optimum moisture content.

At moisture contents less than the optimum, the soil crumbs are only loosely packed together (Fig. 3). They are too hard to be deformed and squeezed together to fill the air spaces between them. This results in a generally flocculated structure with a small amount of preferred horizontal orientation due to the vertical compaction.

As the moisture content is increased, the soil crumbs become softer and are more readily squeezed together. This results in a denser and more dispersed structure.

At moisture contents greater than optimum, kneading compaction produces a dispersed structure with most of the particles being horizontally or vertically aligned because of the deep penetration of
the compactor. Impact compaction also produces a dispersed structure on the wet side of optimum; however, the particles are more horizontally aligned than with kneading.

**Thixotropy of Dilute Clay Suspensions**

Thixotropy can be defined as a softening or thinning of a flocculated suspension caused by stirring, followed by a time-dependent return to the original stiffer state (10). If a flocculated clay suspension is disturbed by mixing, the edge-to-face contacts between the particles will be disrupted and the relatively stiff "gel" will be transformed into a dispersed suspension which is very fluid. As soon as the mixing is stopped, the suspension will begin to flocculate at a rate depending upon the physicochemical properties of the suspension.

Figure 4 shows interaction energy as a function of distance between the edge and face of adjacent particles in suspension for high and low electrolyte concentrations. In the low-electrolyte suspension, if the average edge-face distance is less than $x$, the suspension will flocculate as soon as the suspension comes to rest. However, if the average edge-face distance is greater than $x$, Brownian motion of the clay colloids will bring them close enough to flocculate at a rate depending upon the energy barrier to be crossed. From the figure it can be seen that increasing the salt concentration increases the rate of flocculation by lowering the energy barrier.

**Thixotropy of Compacted Clays**

Skempton and Northey (15) and Seed and Chan (13) present data which illustrate the increase in strength of compacted or remolded clays aged at constant moisture content.
The mechanism is believed to be essentially the same as thixotropic hardening of dilute suspensions. Figure 5 illustrates the mechanism by which cross links are believed to occur.

The increase in strength of clays with time has been found to increase with moisture content up to a certain moisture content, after which it decreases with further increases in moisture. The reason for this is that at low moisture contents particle mobility is low, and the rate of cross link formation is also low. As the moisture content increases, particle mobility and the rate of cross link formation increases. However, increased moisture content also increases the average particle separation and net energy barrier to be crossed (Fig. 4). Hence, a moisture content will be reached where further increase in moisture content will result in a decreasing rate of strength increase.

SWELL PRESSURE MECHANISM IN COMPACTED CLAYS

When a compacted clay soil is allowed to imbibe water, it swells until its internal forces are in equilibrium with its surroundings. If the soil is confined and allowed free access to water, the swell pressure developed is a function of the interparticle swell pressure, cross link forces between particle aggregations and individual particles, and structural arrangement and orientation of individual particle aggregations.

Interparticle Swell Pressure

Assuming that van der Waals attractive forces and surface hydration forces can be neglected, the interparticle swell pressure or simply swell pressure can be estimated from Eqs. 1 and 2 for each clay mineral in the soil, if the exchange ions and the electrolyte concentration are known. A curve representing swell pressure vs average particle spacing can easily be calculated, if the surface area of the clay mineral present in the soil is known, or can be estimated. The average distance between particles at various moisture contents can be approximated quite accurately if all the surface area of the soil is assumed to be associated with the flat sides of the clay particles. Then, if all the soil water is assumed to be distributed over the surface of the clay particles, we obtain

\[
\frac{d}{2d} = \frac{\text{Moisture content in percent}}{100 \times \text{Specific surface in sq cm/gm}} \tag{3}
\]

where \(2d\) = Average spacing of flat particles in cm.

Cross Link Forces

Cross link forces develop as a result of coulombic and van der Waals attractive forces between the edges and sides of nonparallel particles. The shear strength and rigidity of a clay soil are a direct function of the number of cross links. The net swell pressure of a clay soil is also a function of the number of cross links. As the number of cross links increases, the net swell pressure of the clay will decrease. Under constant moisture content conditions, cross links form due to the Brownian motion of the
particles; hence, the potential swell pressure of a compacted clay soil will decrease with time if it is maintained at a constant moisture content before being given free access to water.

The magnitude of the cross link force can be estimated quite simply, by allowing compacted samples to swell freely in the presence of an unlimited supply of water. The average particle spacing and the swell pressure between the particles can be estimated from the final moisture content, and since there are no outside forces acting on the specimen, the swell pressure equals the internal pressure due to cross links.

Effect of Structural Arrangement and Orientation of Particle Aggregations

The total pressure acting across a plane in a compacted clay soil is equal to the sum of the forces per unit area acting normal to the plane. If all of the clay particles were horizontally aligned, the total vertical swell pressure would very nearly equal the net swell pressure. In a compacted clay, however, the particles are not all horizontally aligned, and the effect of structure and orientation must be taken into account.

There are two fundamental arrangements of particle aggregations—flocculated and dispersed. In a flocculated soil, as shown in Figure 6, the vertical swell pressure is equal to the sum of the vertical components of net swell pressure. Letting \( \alpha \) equal the average particle orientation with respect to the horizontal,

\[
p_{v}^{f} = \cos \alpha (P_{s} - P_{l})
\]

where

- \( p_{v}^{f} \) = vertical swell pressure for a flocculated clay,
- \( P_{s} \) = interparticle swell pressure, and
- \( P_{l} \) = internal pressure due to cross links.

Next, assuming that the two horizontal components of swell pressure are equal, and using the relationship

\[
\cos^{2} \alpha + \cos^{2} \beta + \cos^{2} \gamma = 1
\]

where

- \( \cos \alpha \) = direction cosine with Z axis,
- \( \cos \beta \) = direction cosine with X axis, and
- \( \cos \gamma \) = direction cosine with Y axis,

we obtain

\[
p_{h}^{f} = \sqrt{\frac{1 - \cos^{2} \alpha}{2}} (P_{s} - P_{l})
\]

where \( p_{h}^{f} \) = horizontal swell pressure for a flocculated clay.

The average particle orientation with respect to the horizontal, \( \alpha \), can be estimated from the horizontal and vertical components of swell in a three-dimensional free swell test:

\[
\alpha = \tan^{-1} \frac{e_{H}}{e_{D}} = \tan^{-1} \frac{\Delta H}{\Delta D}
\]
where
\[ \Delta H = \text{change in height}, \]
\[ \Delta D = \text{change in diameter}, \]
\[ H = \text{initial height}, \]
\[ D = \text{initial diameter}. \]

A dispersed soil is shown in Figure 7. A large percentage of the particles can be assumed to be either horizontal or vertical. Therefore, the vertical component of swell pressure is approximately equal to the net swell pressure multiplied by the horizontal component of surface area divided by the total surface. In equation form,

\[ P_v^d = \frac{S_H}{S_T} (P_s - P_i) \]  

(7)

where
\[ P_v^d = \text{vertical swell pressure for a dispersed clay}, \]
\[ S_H = \text{horizontal component of surface area}, \]
\[ S_T = \text{total surface area}. \]

Assuming that in a dispersed clay the particles are either horizontal or vertical, we can write

\[ \frac{S_H}{S_T} = \lim_{\epsilon_H \to 0} \frac{\epsilon_H}{\epsilon_V} \]  

(8)

where
\[ \epsilon_V = \frac{(V + \Delta V) - V}{V} \]
and
\[ \Delta V = \text{volume change}, \]  
\[ V = \text{initial volume}. \]

Writing \( \epsilon_H/\epsilon_V \) in terms of \( H, D, \epsilon_H, \) and \( \epsilon_D \), we obtain

\[ \frac{\epsilon_H}{\epsilon_V} = \frac{\epsilon_H}{(1 + \epsilon_D)^2 (1 + \epsilon_H) - 1} \]  

(9)

By making the substitution, \( f\epsilon_D = \epsilon_H \), Eq. 9 becomes

\[ \frac{\epsilon_H}{\epsilon_V} = \frac{f\epsilon_D}{(1 + \epsilon_D)^2 (1 + f\epsilon_D) - 1} \]  

(9a)

Substituting Eq. 9a into Eq. 8, and taking the limit of both sides as \( \epsilon_H \to 0, \epsilon_D \to 0, \epsilon_V \to 0 \), we obtain
\[
\frac{S_{H}}{S_{T}} = \frac{f}{f + 2}
\] (10)

Substituting Eq. 10 into Eq. 7 gives
\[
P_{v}^{d} = \frac{f}{f + 2} (P_{S} - P_{I})
\] (11)

Next, assuming that the vertical particles have no preferred orientation with respect to the horizontal axes, we find
\[
P_{h}^{d} = \frac{\sqrt{2}}{(f + 2)} (P_{S} - P_{I})
\] (12)

where \(P_{h}^{d}\) = horizontal swell pressure for a dispersed clay.

**EXPERIMENTAL**

Tests and Materials

Four types of tests were performed in the investigation:

1. Three-Dimensional Free Swell Test—Compacted samples 2.500 in. in diameter and 0.500 in. thick were placed on a blotter 3.5 in. square. The sample and blotter were placed on a perforated porcelain plate in a large evaporating dish. The dish was then filled with distilled water to a depth which just covered the blotter, and was maintained at that depth for the duration of the test. At the end of four days, the samples were measured and weighed to determine the changes in height, diameter and volume, and the final moisture content.

2. Shrinkage Test—Compacted samples 2.500 in. in diameter and 0.500 in. thick were air-dried overnight and oven-dried at 110 C for one day. After cooling in a desiccator, the samples were measured and weighed to determine the volume change and the final void ratio.

3. One-Dimensional Swell Test—This test was performed in a standard consolidometer with a fixed ring, 2.500 in. in diameter and 1.000 in. high. To allow for swelling, the samples were trimmed to an initial height of 0.500 in. To reduce the amount of air entrapped in the samples, distilled water was allowed to enter the samples only through the bottom. The tests were run with a 1-psi surcharge, and readings were taken of sample height until swelling ceased. At the end of the test, usually less than four days, the samples were removed and weighed, then oven-dried and reweighed to determine the final moisture content and degree of saturation.

4. Swell Pressure Test—The Federal Housing Administration Potential Volume Change Meter (FHA-PVC Meter) was used to measure the swell pressure (8). As in the one-dimensional swell tests, distilled water was only allowed to enter the sample from below. Pressure readings were taken until equilibrium was reached, after which the final degree of saturation was determined.

The soil used in the experimental portion of the research was Vicksburg Buckshot clay. The sample was obtained from the Waterways Experiment Station, U.S. Corps of Engineers, Vicksburg, Mississippi. Its properties are as follows:

1. Specific gravity = 2.70
2. Atterberg limits
   - Liquid limit = 60
   - Plastic limit = 27
   - Plasticity index = 33
3. Particle size distribution
   - 97 percent minus 0.074 mm
   - 40 percent minus 0.001 mm
4. Approximate mineralogical composition (percent by weight)
   Illite = 25
   Montmorillonite = 25
   Quartz and feldspar = 50

5. Exchange cations (meq/100 grams)
   Calcium = 24.3
   Potassium = 0.8
   Sodium = 0.3
   Magnesium = 7.8
   Exchange Capacity = 33.2

6. Specific surface = 210 sq m/gm

7. Soluble salts = 0.4 meq/100 grams

8. pH = 5.7

Preparation and Treatment of Specimens

The procedure employed in performing the tests described previously was as follows:

1. The Vicksburg Buckshot clay was air-dried, ground to pass a No. 40 sieve, mixed with the desired amount of distilled water and allowed to equilibrate in a closed container for 48 hours prior to compaction.

2. The clay was then compacted in a 2.500-in. diameter consolidometer ring, or a 2.750-in. diameter PVC meter ring. Two types of compaction were employed—impact and kneading. The compactive effort for the impact compaction was 55,000 ft-lb per cu ft, using a standard 5.5-lb Proctor hammer. The kneading compactor used was a Harvard miniature compactor with a 40-lb spring. The kneading compaction was done in two layers with 60 tamps per layer for the 2.500-in. ring, and 72 tamps per layer for the 2.750-in. ring.

3. The samples were then either tested immediately, or stored for one, three, or seven days and then tested. The samples to be stored had plastic fillers and caps taped over the ends of the rings in which they were compacted. The capped samples were then sealed in polyethylene bags and stored in a humid chamber until ready for testing.

After the samples had been uncapped, and before they were tested, they were measured and weighed. This was done to determine if there had been any change in initial moisture content and initial height of the samples during the aging period.

DISCUSSION OF EXPERIMENTAL AND THEORETICAL RESULTS

Test Results

Effect of the Time on the Swelling Process—When a compacted clay is exposed to water, a certain amount of time is required for equilibrium to be reached. Water must flow into the sample before the particles can expand their double layers and before the negative pore pressures in the soil can be relieved. Figure 8 shows several typical swell time curves and Figure 9 shows swell pressure vs time curves for samples compacted by kneading and impact. The curves show that the rate of swelling and swell pressure development decreases with increasing initial moisture content. The time required to reach equilibrium was approximately four days for the swell tests and less than two days for the swell pressure tests. These results indicate that the rate and time of swelling and swell pressure development are a function of the initial moisture content and the amount of expansion.

Effect of Initial Moisture Content and Density on Swell Behavior—The results of the three-dimensional free swell tests (Figs. 10 and 11) and the one-dimensional swell tests (Fig. 12) indicate that swelling decreases as initial moisture content increases. The results of the swell pressure tests (Fig. 13) show that swell pressure also decreases as initial moisture content increases, but only at moisture contents higher than optimum (see Fig. 14). At moisture contents lower than optimum, initial dry density and structure determine whether there is an increase or a decrease in swell pressure as the initial moisture content decreases.
Figure 8. Swelling-time curves, impact and kneading compaction.

Figure 9. Swell pressure vs time.
Figure 10. Free swell tests, impact and kneading compaction.

Figure 11. Vertical and horizontal components of free swell tests.
Figure 12. One-dimensional swell test with a one-psi surcharge.

Figure 13. Swell pressure test, impact and kneading compaction.
Figure 14. Moisture-density curves for impact and kneading compaction.

The moisture-density curves for kneading and impact compaction in Figure 14 indicate the reason for the decrease in swell pressure for kneaded samples at moisture contents less than the kneading optimum, and the increase in swell pressure for samples compacted by impact at moisture contents less than the impact optimum. At moisture contents less than 20.5 percent, the density of the kneaded samples is much lower than that of the impact-compacted samples. Hence, in kneaded samples at low initial water contents, as the soil imbibes water the soil crumbs swell and fill the voids between them. This results in an increase in the average particle spacing and a reduction in swell pressure. As the moisture content approaches the optimum, the density increases, resulting in less internal swelling and an increase in swell pressure. Since the densities resulting from impact compaction at low moisture contents are relatively high, there is little or no internal swelling when the soil is exposed to water. This results in higher swell pressure in the impact-compacted samples than in the kneaded samples at low initial water contents.

Effect of Soil Structure on Swell Behavior—There are several characteristics of swell behavior that can only be explained by considering the effect of soil structure together with the effect of initial moisture content and density.

Soil structure varies with the type and amount of compaction and the moisture content of the soil. The basic variables that must be considered in describing the soil structure are (a) the structural arrangement of the particle aggregations, which varies
from flocculated to dispersed; (b) the orientation of the particle aggregations; and (c) the internal attractive pressure resulting from cross links. The three-dimensional free swell tests (Figs. 10 and 11), and the shrinkage tests (Fig. 15) were used to study the structure of the compacted samples.

Although there is no way to determine the structural arrangement of the particle aggregations precisely, a qualitative indication can be obtained from shrinkage tests (Fig. 15). The small volume changes at low moisture contents show that the samples compacted by impact and kneading both have flocculated structures. At moisture contents higher than optimum, however, the relatively large volume changes and low final void ratios show that both kneading and impact compaction produce a dispersed structure (9).

In Figure 11 the vertical and horizontal components of free swell are plotted against initial moisture content. In the lower portion of the figure, curves of the vertical to horizontal swell ratio $e_V/e_H$ are plotted against initial moisture content.

Study of the curves in Figures 11 and 15 reveals that, at low moisture contents, the particle aggregations in the kneaded samples are flocculated with an average orientation approaching horizontal. As the moisture content increases, the particle aggregations assume a dispersed arrangement, and the particle orientation becomes almost evenly distributed between horizontal and vertical. The particle aggregations in the impact-compacted samples also become dispersed with increasing moisture content, but the orientation becomes more horizontal as moisture content increases.

![Figure 15. Shrinkage test.](image-url)
Figure 16 shows curves of final moisture content vs initial moisture content for the free swell tests. The curves show a general decrease in final moisture content with increasing initial moisture content for both kneaded and impact-compacted samples. This implies a decrease in interparticle swelling and an increase in internal pressure resulting from cross links between particles and particle aggregations. The increased number of cross links is a result of the greater mobility of the particles at high moisture contents.

Figure 12 illustrates the effect of soil structure on swelling behavior. The curves show that at moisture contents between 16 and 20.5 percent, samples compacted by kneading swell more than samples compacted by impact, while at moisture contents lower than 16 percent and greater than 20.5 percent, samples compacted by impact swell more than kneaded samples. Figure 14 shows that at moisture contents below 20.5 percent, the impact-compacted samples are denser than kneaded samples, while at moisture contents greater than 20.5 percent, they are the same. This swelling behavior can be explained by referring to Figures 11, 15, and 16. Figure 16 shows that at moisture contents less than about 21 percent, the impact samples have greater internal cross link forces; hence, for a given density and particle orientation, impact-compacted samples should not swell as much as kneaded samples. Below initial moisture contents of 16 percent, however, the impact-compacted samples are so much denser than the kneaded samples that they swell more than the kneaded samples despite the effect of cross link forces. The curves in Figures 11 and 15 show that at moisture contents greater than 21 percent both types of compaction produce dispersed structures, but the impact-compacted samples have a greater horizontal component of surface area.
and less internal pressure from cross links, which results in the greater amount of swelling in the impact samples.

Effect of Thixotropic Hardening on Swell Behavior—The three-dimensional free swell tests, one-dimensional swell tests, and swell pressure tests were performed on impact and kneading-compacted samples immediately after compaction, and on samples three days after compaction. In addition, three-dimensional free swell tests were performed on kneaded samples seven days after compaction.

The results of these tests show a reduction in swelling and swell pressure by samples stored at constant moisture content before testing. The three-dimensional free swell tests on kneaded samples (Fig. 10) indicate that there was little or no further reduction in swelling after three days. The reductions in swell behavior increased with increasing moisture content. This was probably a result of the greater particle mobility at high moisture contents which allowed cross links to form at a faster rate.

The figures show that at all moisture contents, samples compacted by impact exhibited a greater net reduction in swell behavior than the kneaded samples.

The observed effect of thixotropic hardening on swell behavior of a compacted clay is consistent with the increase in shear strength due to thixotropy reported by Mitchell (10) and Seed and Chan (13), and the increase in swelling characteristics by undisturbed clays after remolding observed by Parcher and Liu (11). Parcher and Liu found that undisturbed samples of a Permian red clay swelled less than one-fourth as much as did kneaded samples of the soil at the same initial water contents.

All these phenomena can be explained by the disruption of cross link bonds caused by remolding, followed by a time-dependent formation of new cross link bonds. Remolding disrupts the cross links in a natural clay, which results in a decrease in shear strength and an increase in swelling behavior. With time new cross links form, resulting in an increase in shear strength and a decrease in swelling behavior.

Results of the Swell Pressure Prediction Studies

Using the proposed swell pressure mechanism, theoretical vertical swell pressures were calculated for Vicksburg Buckshot clay compacted by kneading and impact. The effect of thixotropic hardening was included by predicting the swell pressure for samples tested immediately and for samples aged three days before testing.

In Figure 17, swell pressure is plotted against the half distance (d) for divalent montmorillonite and illite in $10^{-3}$N and $3 \times 10^{-3}$N divalent salt solutions. The electrolyte concentration was $10^{-3}$N for the free swell tests, and $3 \times 10^{-3}$N for the swell pressure tests. The curves were computed by assuming values for $C_C/C_0$ in Eqs. 1 and 2 and solving for the corresponding values of swell pressure and half distance.

The specific surface of Vicksburg Buckshot clay is approximately 210 sq m/gm. Montmorillonite has a specific surface approximately 10 times that of illite. Hence, the montmorillonite component of the clay was estimated to contain 190 sq m/gm of surface area, and the illite component was estimated to contain 20 sq m/gm of surface. The moisture contents at various swell pressures were computed by multiplying the corresponding half distance (d) for montmorillonite and illite by their respective surface areas per gram. The resulting curves of moisture content vs swell pressure are shown in Figure 18.

Since the change in structure from flocculated to dispersed occurs in a very indefinite manner, vertical swell pressures were computed for both flocculated and dispersed structures, using the particle orientation data in Figure 11. For moisture contents greater than the optimum, the initial moisture content was used to determine $P_S$ in Eqs. 4 and 11 for both impact and kneading compaction. For initial moisture contents less than the optimum, the swelling of the soil crumbs was assumed to increase the effective moisture content to the corresponding moisture content on the wet side of optimum. This higher moisture content was then used to determine the corresponding values of $P_S$. Because of the greater density of the impact-compacted samples, it was felt that the soil crumbs might not be able to swell; hence another set of values of $P_S$ was calculated using the initial moisture contents on the dry side of optimum.

Values of $P_1$ in Eqs. 4 and 11 were determined (for samples tested immediately and for samples aged three days before testing) from the final moisture contents of the free
Figure 17. Interparticle swell pressure vs particle separation for montmorillonite and illite for different electrolyte concentrations.

Figure 18. Moisture content vs interparticle swell pressure for Vicksburg Buckshot clay for different electrolyte concentrations.
Figure 19. Theoretical and experimental swell pressure for Vicksburg Buckshot clay compacted by kneading.

Figure 20. Theoretical and experimental swell pressure for Vicksburg Buckshot clay compacted by impact.
swell tests (Fig. 16) and the moisture content vs interparticle swell pressure curves (Fig. 18). The resulting swell pressures are shown in Figure 19 for kneaded compaction and in Figure 20 for impact compaction. On the same figures, the experimental results are plotted against corrected moisture contents. The initial moisture contents were corrected for the small amount of expansion that occurred in the samples because of the deflection of the proving ring.

Study of the figures shows remarkable correlation between theoretical and experimental results. At low moisture contents the experimental points correspond to the theoretical curves for flocculated structure, and at high moisture contents the experimental points correspond to the theoretical curves for dispersed structure.

SUMMARY AND CONCLUSIONS

An analytical and experimental study of the relation between swelling behavior of compacted clays and soil structure and thixotropic hardening was presented. Based on the concepts of soil structure and clay colloid chemistry, a model of the swell pressure mechanism was developed. Using this model, equations were derived for the vertical and horizontal components of swell pressure in terms of average particle orientations and net interparticle swell pressure.

An experimental investigation consisting of three-dimensional free swell tests, shrinkage tests, swell tests, and swell pressure tests was conducted on a compacted clay to (a) study the effects of soil structure and thixotropic hardening on swell behavior; (b) determine the variation of soil structure and particle orientation with moisture content for kneading and impact compaction; and (c) check the theoretical values of swell pressure experimentally.

The conclusions that may be drawn from the results of the investigations are summarized as follows:

1. The swell pressure developed by a compacted clay when it is exposed to water can be accounted for very well by considering interparticle swell pressure and soil structure.

2. Thixotropic hardening is a very important factor affecting the swelling characteristics of Vicksburg Buckshot clay. At initial moisture contents greater than optimum for kneading and impact compactions, thixotropic hardening reduced the swelling and swell pressure by as much as 50 percent in three days. The effect of thixotropic hardening is of particular importance for two reasons: (a) many natural clays are thixotropic, and weeks or even months may elapse before the soil is exposed to water, and (b) it explains the tremendous increase in swelling and swell pressure exhibited by undisturbed clays when they are remolded.

3. The difference in swell behavior exhibited by Vicksburg Buckshot clay when compacted by different methods can be explained satisfactorily in terms of the basic concepts of soil structure and clay colloid chemistry.

REFERENCES


Discussion

KALANKAMARY P. GEORGE, Associate Professor, Civil Engineering Department, University of Mississippi—The laboratory investigation into the relation between swelling behavior of a compacted clay and structure has been well executed and clearly presented. Such an imaginative approach to this highly complex problem will surely help to stimulate progress toward a rational theory of compacted soil structure.

The authors in their concluding remarks state that many natural clays are thixotropic. In a series of experiments, still in progress, the writer has found that kaolinite clays, unlike montmorillonite, do not exhibit thixotropic characteristics (18). Illustrated in Figure 21-b is the relation between strength increase and particle orientation for an artificial mixture (1:1 ratio) of commercially pure kaolin and Ottawa sand. In order to compare the magnitude of strength increase, the term "thixotropic-strength ratio" was introduced (13). This is defined as the ratio of the strength of a specimen tested after time t to the strength of an identical specimen tested immediately after compaction. The preferred orientation ratio, as shown in Figure 21-a, is an index to indicate the degree of orientation of clay platelets; the higher this index the more the clay is dispersed. The preferred orientation ratio was determined by techniques similar to those described by Mead (19).

The results in Figure 21 clearly indicate that synthetic kaolinite soil shows a decreasing thixotropic strength ratio and an increasing particle orientation ratio. The results are even more pronounced when these properties are evaluated at optimum moisture, namely, 19.3 percent. This is exactly opposite to the changes in the synthetic montmorillonite (Volclay¹ and Ottawa sand in 1:3 ratio; optimum moisture, 12.4 percent), the results of which are shown in Figure 22. Skempton and Northey (15) reported that kaolinite shows almost no thixotropy and illite shows only a small effect.

¹Sodium bentonite, supplied by American Colloid Company of Chicago.
Figure 21. Kaolinite and Ottawa sand in 1:1 ratio: (a) preferred orientation ratio and time; (b) thixotropic strength ratio and time.

Figure 22. Montmorillonite and Ottawa sand in 1:3 ratio: (a) preferred orientation ratio and time; (b) thixotropic strength ratio and time.
Bentonite, on the contrary, shows a remarkable regain of strength in a very short time interval.

A partial explanation for the inert behavior of kaolinite could be based on its particle size in comparison with that of the montmorillonite. Particles of kaolinite clay are large compared to those of montmorillonite. A kaolinite particle has a diameter of 10,000 Å and a thickness of 1000 Å. The dimensions of montmorillonite are 1000 Å and 10 Å, respectively. The specific gravity of kaolinite is 2.64 compared to 2.4 for montmorillonite (20). Therefore, the kaolinite particle would be several times heavier than the montmorillonite particle. It would appear, therefore, that the body forces would control kaolinite particles as would surface forces in montmorillonite. Being relatively heavy, the tendency for the kaolinite particles to assume flocculated arrangement would be decreased, or perhaps would not exist.

Further, the correspondence between the strength increase and particle reorientation toward a random arrangement validates Mitchell's theory (10) of thixotropy in that he attributes the regain of strength with time to the time-dependent particle movement.

References