Nature and Magnitude of Swell Pressure

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The mechanism and nature of swell are discussed from an engineering viewpoint. Criteria for judging the swell capacity of a soil and the probable magnitude of the swell pressure are presented. Conventional laboratory methods of measuring swell pressure are discussed and are shown to be conservative. The desirable features of a measuring device are put forward and a device conforming to them is presented. The operation of the new device is described and typical swell pressure curves obtained from it are shown.

• AN UNDERSTANDING of the phenomenon of swelling of soils is important in pavement design. The stability characteristics of a compacted subgrade can be empirically assessed by various laboratory techniques and used to estimate a satisfactory thickness of pavement structure. This thickness, however, remains satisfactory only as long as the subgrade properties remain at least as good as those in the "as compacted" state.

Unfortunately, the properties of clayey subgrades deteriorate after compaction unless special precautions are taken in the design. Water is absorbed into the structure of such subgrades and leads to swelling and reduced stability. To guard against this undesirable swelling of soils, one must be able to recognize the soils which have the inherent capacity to absorb water and swell and should be able to measure the generated swell pressure if the swelling is to be effectively restrained in any way. The swell pressure may be defined as the unit pressure that a soil can exert in the presence of available water.

MECHANISM OF SWELLING

Two explanations of the swelling of clay soils are presented. One is based on the physical and chemical properties of the clay particles, the other on the physical properties of a soil-water structure. The physico-chemical explanation reveals how water may be absorbed into a soil mass even when it is already saturated, gives a qualitative explanation of experimental results, and suggests remedial measures. The physical explanation gives a purely engineering interpretation to the mechanism of swelling. Conclusions drawn from both theories are presented.

Physico-Chemical Theory

The colloidal clay fraction of a clayey soil is responsible for the absorption of any available water. This is shown by Figures 1 and 2. A clay silt with a liquid limit of 33 percent and a plastic limit of 20 percent was mixed with various percentages of bentonite, a highly colloidal material. The liquid limit and the hygroscopic moisture content was obtained for each of the mixtures. Both are good indexes of the ability of a soil to absorb water.

The clay fraction of most soils may be almost entirely reduced to the colloidal condition when fully dispersed. Thus, it is felt that for engineering purposes, where interest is focused on the soil mass rather than on the soil colloids themselves, material smaller than 0.002 mm may be considered the active clay fraction.

Analyses of inorganic soil colloids indi-

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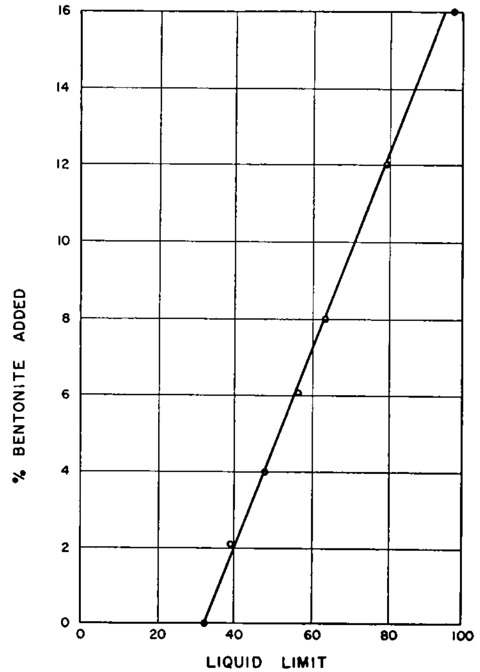

Figure 1. Liquid limit *vs* percent bentonite.

cate that they are composed primarily of silica, alumina, and water. It has been shown by X-ray analysis and by electron microscope studies that the clay fraction of soils consists of distinctly crystalline minerals. Two principal groups of clay minerals, kaolinite and montmorillonite, have been recognized. The kaolinite minerals, with fixed crystal lattices, do not display vigorous hydration and adsorption properties. The montmorillonite minerals, on the other hand, with a weak bond between the silica sheets, allow absorption on the inner surfaces of the crystal and exhibit high hydration.

Clay particles are characteristically, either plate-shaped or elongated. This shape, coupled with the colloidal size of the particle, provides an enormous surface area within a soil mass. At the surface of the particles and at the corners and edges the valences of the atoms are not satisfied completely. This means that there exists on the surface of a clay particle a residual electric charge, which has been shown to be negative.

The clay particle with its resultant negative charge is in effect an anion. Adsorbed cations of Na, H, K, Mg and Ca are found on the surfaces of these particles. The molecule of water is dipolar and its negative pole is attracted by the positive charge of the adsorbed cations. In this way, water is oriented around the cations. In a similar manner, water is also oriented around the clay anion because of the attraction between the negative charge on the clay particle and the positive pole of the water molecule. Water will continue to be absorbed into the system until a balance is achieved between the electrical and static forces on the system.

Two conclusions may be inferred from the foregoing discussion, as follows:

1. The volume change experienced by a saturated soil during swelling is not equal to the volume of water absorbed. In fact, because of the orientation mentioned, and the pressures of adsorption, the volume of swell will be less.
2. The amount of water that can be

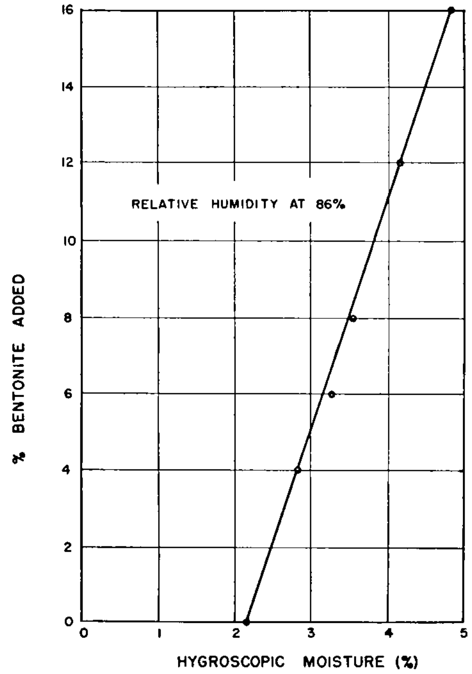

Figure 2. Hygroscopic moisture *vs* percent bentonite.

adsorbed by a clay due to adsorption on the clay anion is fixed for the particular clay, but the amount of water absorbed by adsorption on the cations may be modified. It can be reduced by replacing the adsorbed cations by cations with lower hydration characteristics by base exchange methods.

In other words, the attraction that the negatively charged clay mineral crystals and their positively charged adsorbed cations exert on the dipolar molecules of water results in the swelling of clay soils when such free water is available, until an equilibrium with the environment is reached.

Locked Pressure Theory

The following theory, which may be called the locked pressure theory, is presented in an effort to give an explanation of swelling from an essentially engineering viewpoint. It is based on rebound phenomena observed during triaxial and consolidation testing.

Consider a sample of a given saturated clay soil of height *h*, as shown in Figure 3. The sample is uncompressed.

A load *P* is applied to the sample and full consolidation is allowed to take place. The sample will compress a distance *dh*. If all surface moisture is removed and then the load *P* is also removed, the sample will retain its height *h-dh*, neglecting slight elastic rebound. Should the sample have access to water it will rebound to its former height *h*. This phenomenon may be explained as follows. While surface moisture is present load *P* maintains the sample in active compression. On removal of surface moisture and load *P*, since the sample remains compressed, the negative pressure is introduced into the water system. The application of free water relieves the negative pressure and the sample rebounds. The negative pressure is essentially a precompression phenomenon.

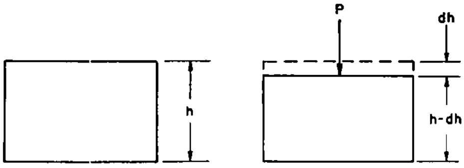

Figure 3. Symbols used in locked pressure theory.

In the field negative pressures are caused by compacting equipment; and can also be caused by any natural phenomenon like dessication, which tends to compress the soil. Because of the negative pressures introduced in the soil-water system by compaction, any free water available will be attracted into the system. This additional moisture will relieve the negative pressures and, as in the case of the laboratory sample mentioned, lead to rebound. The rebound results in reduced density and stability.

In a saturated clay mass the rebound pressure in the presence of free water will equal the precompression pressure. In a non-saturated soil mass, since the grains can carry some of the precompression pressure and since moisture distribution can take place, the rebound pressure will be less than the precompression pressure, and in general, there will be no well-defined relation between them. This is the case in a highway subgrade where the rebound pressure is equal to the negative pressure imparted to the water by compaction.

To summarize, a soil swells in the presence of free water until the negative pressure imparted to the water distributed in the soil mass is reduced to zero or to a value equal to the applied overburden pressure. This concept will be applied later to the measurement of swell pressure.

NON-ABSOLUTE NATURE OF SWELL PRESSURE

Both theories presented here explain the phenomenon of swell, but one important point, indicated by both theories must be emphasized.

The swell pressure of a mass of a given soil at a given moisture content is not a constant quantity, but can vary from zero to a maximum value when the soil is saturated at that water content. The physico-chemical theory demonstrates that water will be attracted into the soil until the electrical fields around each particle are made negligible by the thickness of water film. This definitely implies that for a given soil and a given moisture content, a specific quantity of water must be introduced to satisfy the electric field attraction. Swelling takes place to accommodate this moisture. In an infinitely loose soil mass no volume change in the over-all soil mass is necessary to accommodate the excess water. In a saturated soil mass the only way the water can be accommodated is by swelling. The amount of swelling, and hence the swell pressure, therefore depends also on the void ratio and degree of saturation of the soil. In general, it may be deduced that the higher the degree of saturation at a given water content the greater the swell pressure if swelling of the soil is inhibited.

Hence, any measurement of swell pressure which ignores the effect of variations in void ratio and degree of saturation will not be representative of field conditions where variations in void ratio and degree of saturation are the rule rather than the exception.

DIRECT MEASUREMENT OF SWELL PRESSURE

One of the more rational ways of coping with the swelling of pavement subgrades is to provide a thickness of pavement structure that will be sufficient for stability and will also prevent the swelling of the soil beyond limits of the required stability. In cases where swell is a dominating factor the pavement thickness will be influenced strongly by it. This makes it imperative that the swell pressure be measured with reasonable accuracy and facility.

The boundary conditions on a laboratory experiment should approximate as closely as possible those on the soil mass in the field. Any laboratory experiment should measure the generated swell pressure of a restrained soil-water sample. This rules out any method which primarily measures the attraction of the individual clay particles for water. Only in the case of a fully saturated soil will this attractive force equal the generated swell pressure, as was discussed earlier.

The only production line method in use today for the measurement of swell pressure is the California method. It is felt, however, that this method does not measure the absolute swell pressure, but gives an empirical index of its value, which when incorporated in the empirical Californian design procedure leads to structurally adequate pavements. In this method, friction in the mold reduces the measured swell pressure. Considerable increases in swell pressure can be recorded if the soil has access to water on both faces instead of just one (see Fig. 4). An increase in the time of testing can result in significantly higher swell pressures (Fig. 4).

Although the amount of expansion permitted in this test is insignificant for low swelling soils, it can have an appreciable effect on the recorded swell pressure for high swelling soils. This is shown in Figure 5, where an expansion of 0.001 in. reduces the swell pressure by as much as 0.17 psi, or 24.5 psf.

In preparing a test specimen by the California procedure, the soil is compressed until water is exuded; the rapid loading imposed for practical considerations leads to negative pressures in the soil sample and so tends to increase the swell pressure, as shown in Figure 6. The amount of this increase will depend on the magnitude of the exudation pressure.

The swell pressure is also affected by the degree of tempering of the soil with water prior to testing. Prolonged tempering reduces the swell pressure (Fig. 7).

In an attempt to assess the effect of friction, expansion, and time of testing, a swell pressure curve was developed for a given soil, a clay silt with a liquid limit of 43 percent, by the consolidation test. The swell pressures were deduced by the locked pressure theory. The results are shown in Figure 8. No swell pressure was recorded by the California procedure for water contents in excess of 27 percent for this clay.

All samples except those for consolidation were fabricated at the same com-

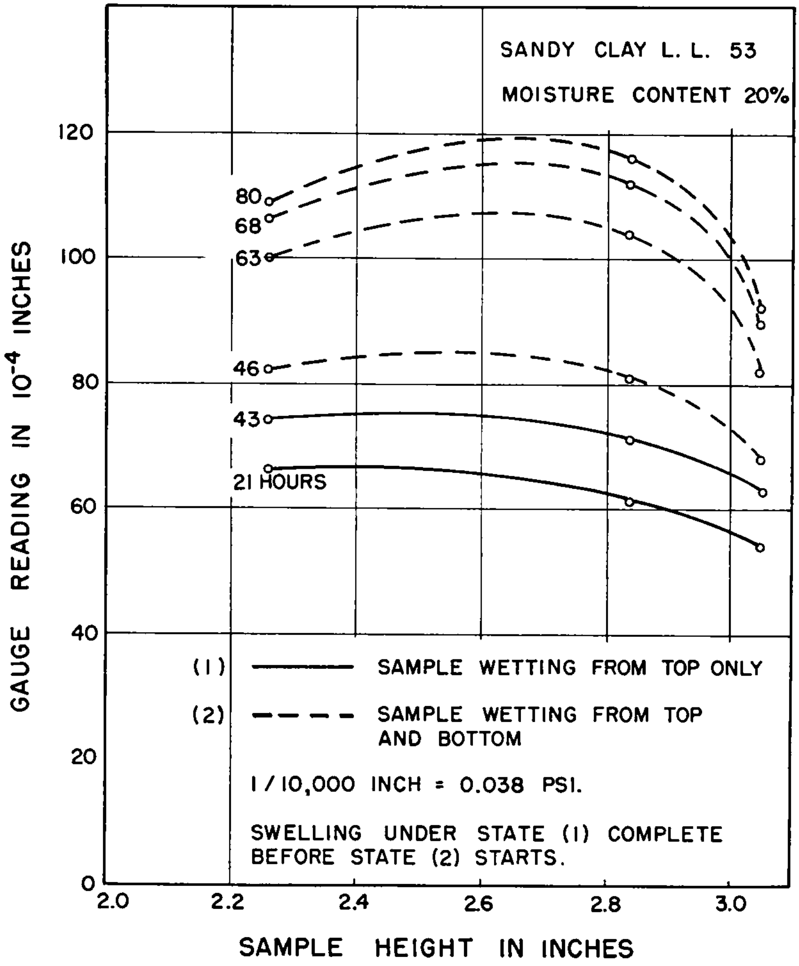

Figure 4. Effect of sample height and time of wetting.

pactive effort, where possible, by the Triaxial Institute kneading compactor.

Although the consolidation method seems more accurate and sensitive than the California method, it is too time consuming for routine investigations. Therefore, a new device was developed.

The new device (Fig. 9) consists of a pressure container, a base plate, a top plate, and a rubber membrane shaped like a top hat. The pressure container has a pressure gage, a tire valve, and a pipe plug. The hole where the pipe plug fits may be used to connect the chamber to an air supply. The bottom is open and is pressed down on the bottom plate with the flange of the rubber membrane in between, as shown in the sketch.

The base plate is about 8 in. square. It contains a porous stone, 3½ in. in diameter, which is set down into the plate flush with the surface. Two channels through the base plate lead to the porous stone. A wye made from ⅝-in. plastic tubing is connected to these channels. There are four studs in the base plate for clamping down the pressure chamber, providing a pressure-tight connection.

The rubber membrane was fabricated from 0.012-in. thick dental dam and two

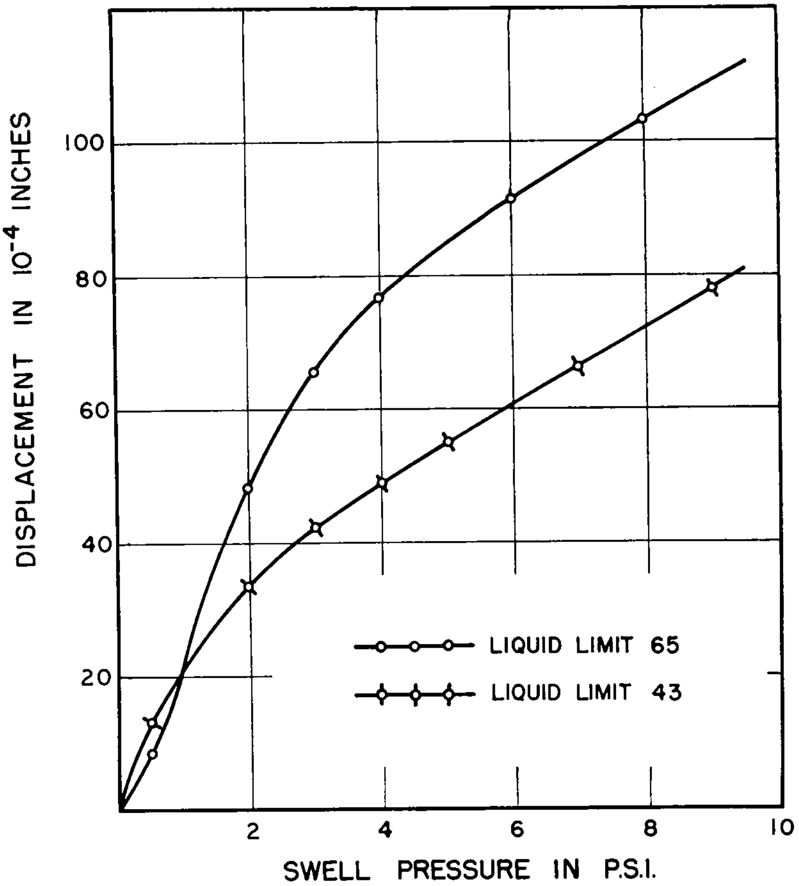

Figure 5. Displacement *vs* swell pressure.

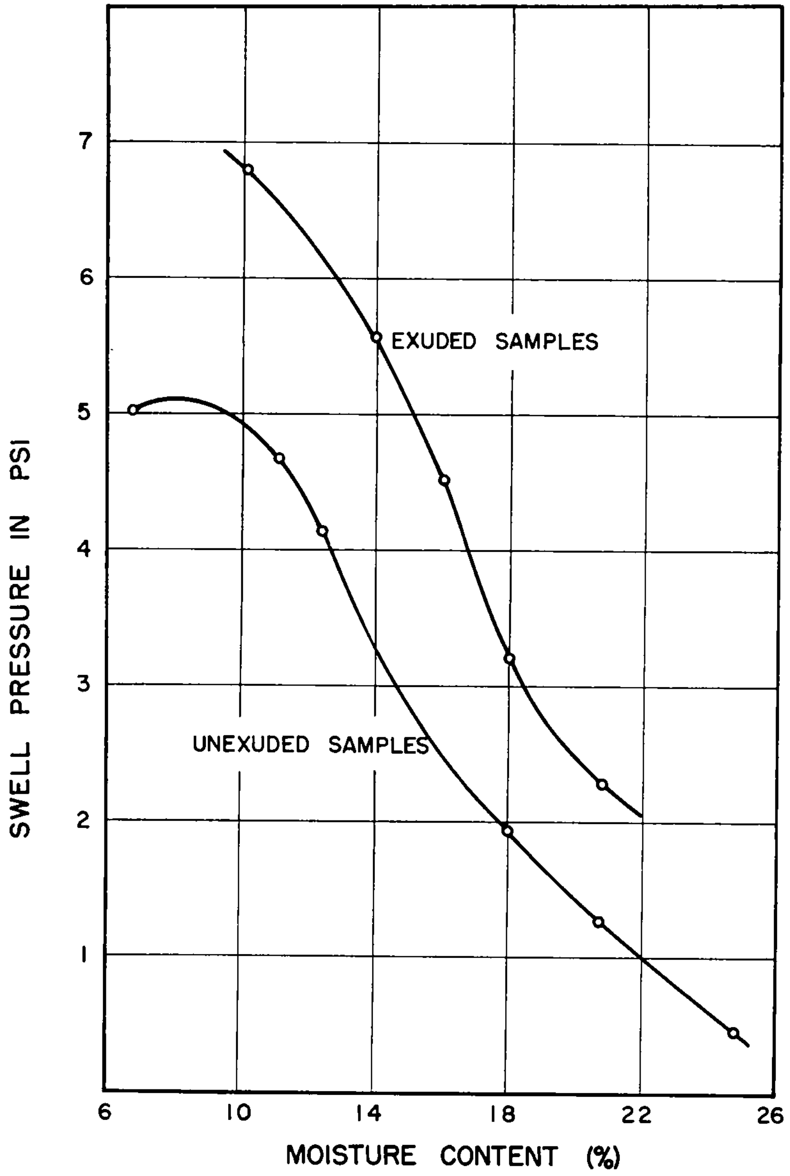

Figure 6. Swell pressure *vs* moisture content.

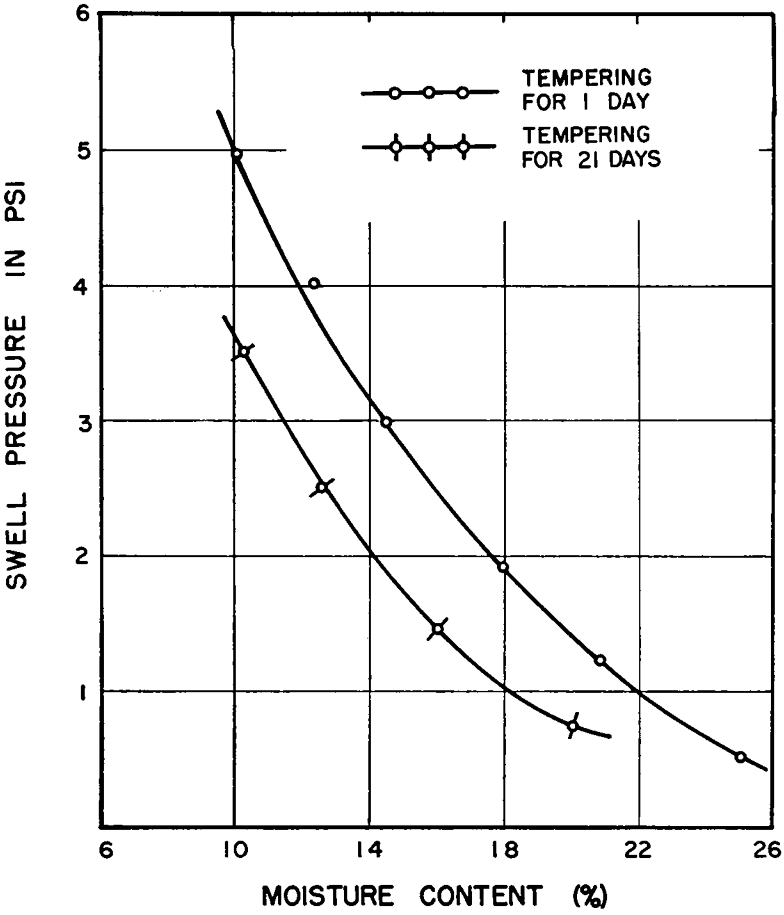

Figure 7. Effect of tempering at 12 percent moisture content.

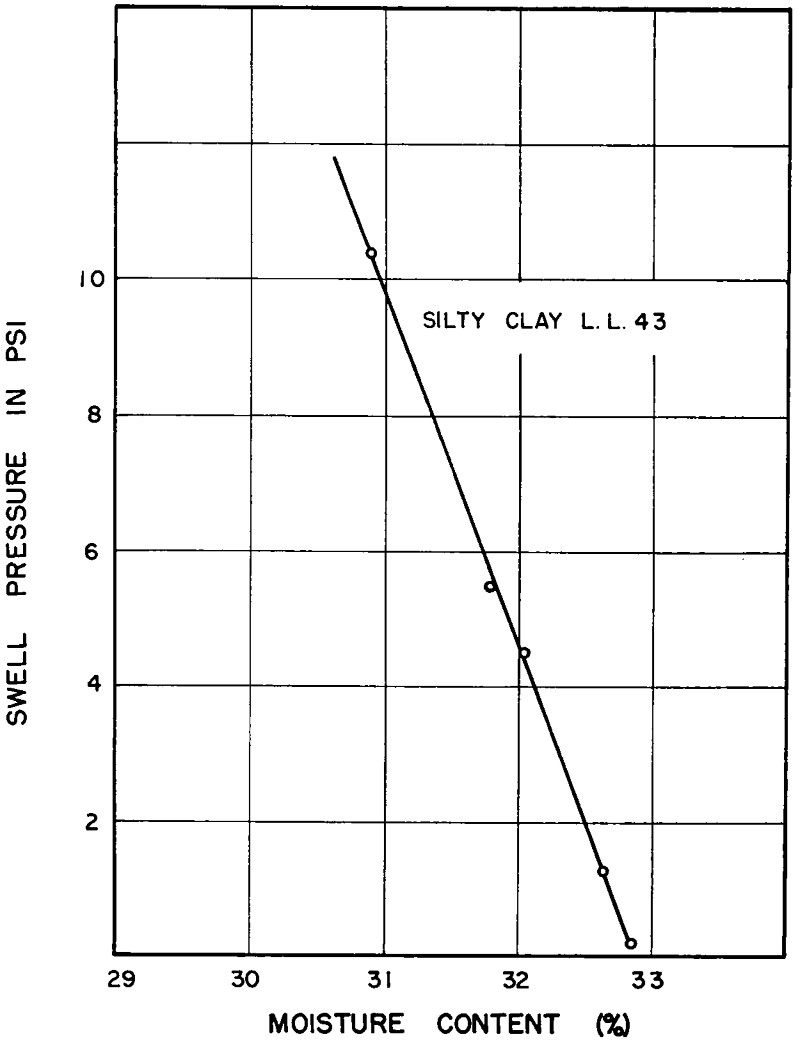

Figure 8. Swell pressure *vs* moisture content by consolidation procedure.

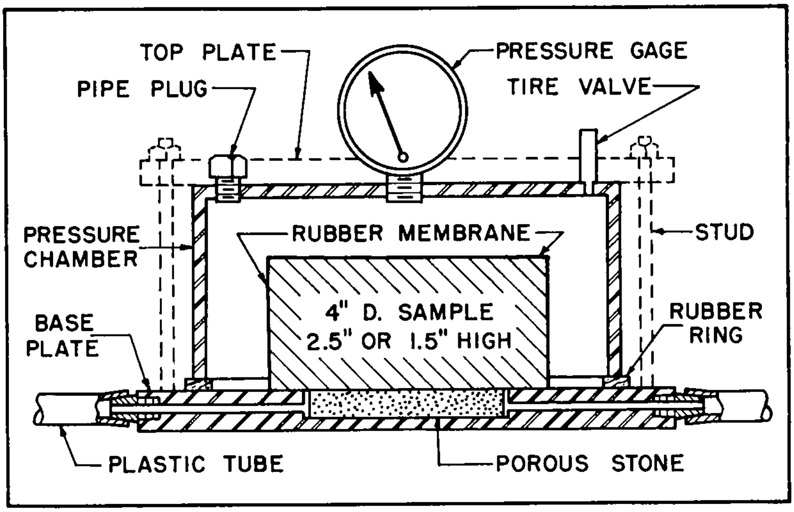

Figure 9. New device for measuring swell pressure.

⅛-in. thick rubber rings. The dental dam was doubled, and glued together with rubber cement.

The procedure for using the new apparatus is as follows:

1. Mix soil sample with the desired amount of water.
2. Temper sample for 24 hr.
3. Compact sample and extrude it from the compaction mold.
4. Pull the rubber membrane down over sample.
5. Place sample and membrane on the base plate, centered over the porous stone.
6. Clamp pressure chamber down on base plate so that the flange of the membrane acts as a gasket.
7. Fill pressure chamber with water.
8. Fill wye with water.
9. Read the pressure after 16 hr.

Although the samples generally used in the new method are of the same dimensions as the ones used in the California method, the swell pressures obtained with the new one are much higher. Figure 10 compares the two techniques applied to the same soil. The difference between them is of such magnitude that there is little doubt that there are some quite fundamental differences between the devices. The maximum swell pressure obtained by the new apparatus is about twice that obtained by the other. The initial moisture content at which the maximum swell occurred is also higher.

To find the factors causing the difference, several tests were performed with the new device. Two sizes of sample were tested for the same compaction and the same soil, and two different pressure chambers were used. By varying the chambers it was found that practically all the volume change on the part of the apparatus takes place in the membrane. The two chambers used were widely different both in size and in elastic properties. One measured 6 in. in inside diameter, 4 in. high, and was made with ⅛-in. walls and ¼-in. top, all brass. The other, a steel chamber, measured 4¾ in. in inside diameter and 3 in. in height. It had ⅜-in. walls, and ¼-in. top. The results obtained by using these two different chambers were practically identical, indicating that the volume change of the sample is taken up by the rubber membrane rather than by the chamber, the water being incompressible.

Comparison of the swell pressures measured for small and large samples furnished some information about the

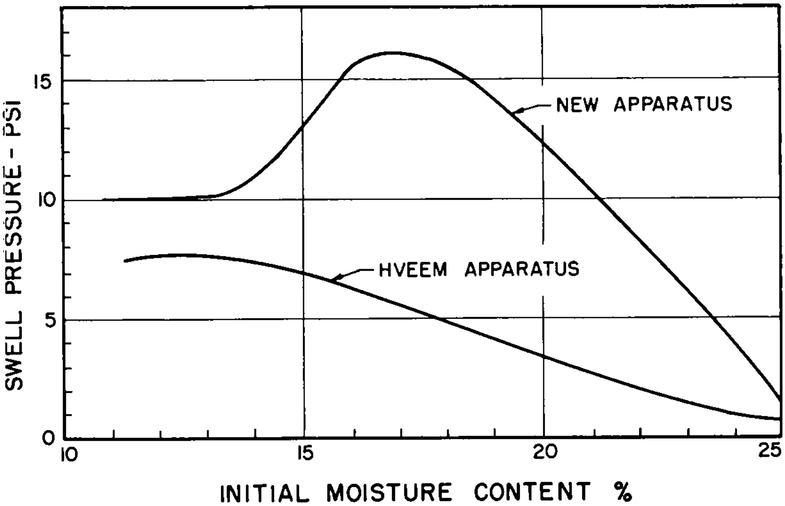

Figure 10. Comparison of swell pressure determined by California (Hveem) apparatus and new apparatus.

effect of varying the confinement. By confinement is meant the lack of freedom for the sample to expand. The volume change allowed a sample at different pressures was measured by the use of a dummy sample for different combinations of large and small sample, and large and small chamber. It was found that the allowed expansion was about the same for the two chambers when the sample size was the same. It was also found that the small sample was allowed about four times as great an expansion as the large one at the same pressure.

Figure 11 gives some indication of the effect of varying the degree of confinement. The small samples that could expand more than the large ones had a lower swell pressure. There seems to be some type of inverse proportionality.

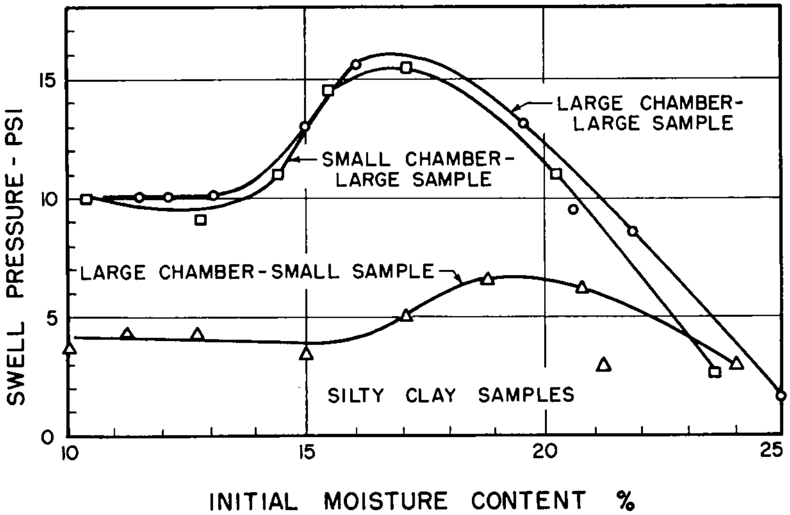

Figure 11. Comparison of swell pressures determined with large and small chambers and large and small samples.

It seems that one may safely assume that one of the main reasons for the difference between the measured swell pressures of the California method and the new method is the difference in the confinement. The California device allows about 6 percent expansion at 7.5-psi pressure, whereas the other only allows about 0.6 percent at the same pressure.

Another major factor is probably the wall friction. The force required to push some of the samples out of the 4-in. compaction mold was measured and plotted against the initial water content of the samples. The highest values of the extruding force occurred in the range of initial water content where the difference between the measured swell pressures was the greatest.

The wall friction effect is not easily analysed. Wall friction is affected by the degree of compaction, the type of soil, and the mold. It is a boundary phenomenon, and does not affect every part of the sample along the diameter to the same extent. The center part of the sample may swell almost independently of the friction, whereas the soil along the rim is greatly affected. The effect of the wall friction also varies vertically. The soil on top will tend to move more than the soil at the bottom of the mold, and it seems likely that some part of the sample will have no vertical movement.

By superimposing the effect of friction on the swell pressure curve for the new device, one gets a curve that resembles the California curve but lies higher. Removing the effect of the difference in the freedom to expand of the two methods would bring the two curves quite close together.

It seems that there is available an apparatus that differs from the California method in two major respects. This may be an improvement of the swell pressure technique. However, the California method is somewhat easier and quicker to use.

The pressure chamber of the new device may easily be modified to allow greater expansion by connecting it to different air-filled tubes through the hole where the pipe plug is. The California device may be modified much in the same way by changing the restraining beam. To obtain realistic swell pressures this versatility should be utilized. If, say, 2 percent of swell can be tolerated, the soil samples tested should be allowed about the same expansion.

This new apparatus offers the same lateral and axial restraint to the sample. This is a disadvantage when dealing with a large area of the same type of soil, because in such an area the soil is rigidly restrained horizontally by the surrounding swelling soil except near the boundaries. However, when dealing with differential swelling, where a relatively small area is underlain by swelling soil, the lack of rigid lateral restraint helps give realistic swell pressures. The swelling soil in this situation may expand as much horizontally as vertically if there is a substantial overburden. The new device seems capable of giving quite realistic results in the case of differential swelling, inasmuch as the field conditions are fairly closely reproduced by it for this type of swelling. The swelling soil, when surrounded by non-swelling or moderately swelling soils, is subjected to an elastic restraint much the same as the restraint in the apparatus. For swelling over a large area it seems unlikely that any of the present methods gives very realistic pressures.

It is not to be expected that any laboratory method of measuring swell pressure will closely duplicate field conditions. The problem still remaining is to approximate average field conditions in the laboratory as nearly as may be justified by the degree of uniformity that properly can be expected to prevail in the field.

ACKNOWLEDGMENTS

The research forming the basis of this paper was undertaken as a contribution to the program of investigation outlined by the Triaxial Institute in 1955. The authors thank R. G. Hennes, Professor of Civil Engineering, University of Washington, for his able direction and sincere cooperation. They also express their gratitude to the Engineering Experiment Station, University of Washington, under the direction of Professor F. B. Farquharson, for sponsoring the project.

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