Studies of Swell and Swell Pressure Characteristics of Compacted Clays

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Factors affecting the values of swell and swell pressure developed by compacted samples of an expansive soil on exposure to water under controlled condition are examined.

Data are presented and discussed to illustrate such factors as:

1. The effect of time on swell pressure. It is shown that considerable periods of time are required before a sample develops its full swell pressure after exposure to water.
2. The effect of sample shape on measured swell pressures. It is shown that sample faces must be perfectly plain if reliable measurements are to be made.
3. The effect of volume change on measured swell pressures. It is demonstrated that volume expansions of as little as 0.1 percent during swell pressure measurement may cause an error of large magnitude in the values of swell pressure observed.
4. The relation between soil structure, as determined by compaction method, and the amount of swell and the swell pressure.
5. The effect of stress history on swell and swell pressure.
6. The relationship between swell and swell pressure. It is shown that the magnitude of the swell pressure cannot be reliably predicted from a knowledge of the amount of swell.

Explanation of the results is offered, where possible, in terms of the fundamental aspects of the system composition and structure. Practical implications of the results are pointed out with particular reference to pavement design.

● ENGINEERING PROBLEMS and failures resulting from the swelling of clays have been encountered in many areas of the world in connection with highway fills, highway subgrades, building foundations, canal linings, and other structures. When a swelling soil is encountered, the engineer may have available several courses of action for the solution of the associated problems. Among the solutions to be considered are the following:

1. By-pass the site.
2. Remove the expansive soil and replace it with a nonexpansive soil.
3. Prevent access of water to the swelling soil.
4. Make the soil nonexpansive by appropriate chemical treatment.
5. Allow expansion to occur under selected loading conditions and design the structures in such a manner that they are able to withstand displacement without distress.
6. Prevent swelling by appropriate surcharge loading and design structures to withstand the swell pressures that may develop.

The relative merits of each solution must be judged, of course, with respect to each particular project. In cases where some swelling is allowed to occur, satisfactory engineering will require reliable estimates of the probable magnitude of the swell and swell pressures developed.

During the past decade, numerous studies have been conducted to investigate the swelling characteristics of clay soils; yet, because of the complexity of the problem, considerable difficulty has been encountered in the development of satisfactory procedures. One of the primary reasons for this has been the lack of information concerning the many factors that might influence swell and swell pressure measurements in soils. In the absence of an understanding of all factors involved, accurate evaluations of swelling characteristics cannot be reasonably expected.

Much progress has in fact been made, however, in reporting on swelling studies, a number of investigators have pointed out, from time to time, procedural changes influencing the test data and, in conducting studies on soils for pavement design purposes, the authors have noted a number of other factors affecting the results of swelling tests. Recent developments in understanding the structure of compacted clays have provided a basis for explaining the influence of many of these factors, and thus it would seem that an appropriate stage has been reached when a presentation and analysis of available data might usefully contribute to an improved understanding of the subject.

CAUSES OF SWELL AND SWELL PRESSURES IN COMPACTED CLAYS

The fundamental factors causing swelling have been studied by many investigators. The influence of mechanical factors in swelling was illustrated a number of years ago by Terzaghi (1), while Bolt (2) has obtained data on the role of physicochemical effects in clay expansion. More recently Lambe (3), Ladd (4), and Lambe and Whitman (5) have outlined the causes of clay expansion in some detail.

It is generally agreed that expansion of a soil on exposure to water and/or external load reduction is attributable to the combined effect of several factors. The fact that a soil takes in water on exposure to free water or on load release is, of course, a direct consequence of a water pressure difference inside and outside the sample. Free water can only enter under the influence of a hydraulic gradient. The factors responsible for water pressures less than those in free water are the fundamental factors controlling swelling and the development of swelling pressures. Conditions within a fine-grained soil that give rise to a swelling tendency may be classified into two general categories — physicochemical and mechanical.

Physicochemical Components of Swelling

The surface structure of the clay minerals is such that water molecules are strongly attracted to them. This adsorptive effect is responsible for a portion of the water required to satisfy the swelling tendency of a soil. In addition to the unique surface structure of clay minerals, the particles usually possess a net negative electrical charge and, in order to achieve electrical neutrality in the soil, cations are attracted to the surfaces. These cations and their water of hydration take up space and thus tend to keep particles apart. More important from a swelling standpoint, however, is the fact that in the vicinity of the clay particles the cationic concentration is much higher than in the free water with which the soil communicates. The difference in ionic concentrations gives rise to an osmotic pressure difference that causes water to flow from the point of low concentration to the point of high concentration (i.e., into the soil), unless this osmotic pressure is balanced by applying a tension stress to the free water or applying a pressure to the water of high ionic concentration.

In partially saturated soils the affinity of the soil for water, as a result of the adsorptive and osmotic properties, acting in conjunction with the surface tension of water, gives rise to curved air-water interfaces. The pressure differential across these interfaces is given by $2t/r$ where t is the surface tension of water and r is the radius of the meniscus. Water deficiencies arising from mechanical effects in partially saturated systems will also be reflected through curved air-water interfaces. The relationships between radius of curvature, osmotic, adsorptive, pore air, and hydrostatic pressures in partially saturated soils have been recently analyzed by Mitchell (6).

Mechanical Components of Swelling

Though the effects to be considered below may appear purely physical in nature, it is important to keep in mind that they often depend on the affinity of water for soil surfaces and on water surface tension, both of which are physicochemical in origin. Particles within a soil mass may be deformed under load in two ways. The first, an actual elastic compression of solid particles, is probably insignificant within the practical range of loadings. In the second, volume changes resulting from the bending of platy clay particles may be appreciable. Particles could be held in bent positions by either external loading or through water surface tension effects. Release of the stresses by unloading or exposure to free water could result in expansion of the soil mass. Terzaghi (1) has demonstrated that the compression-expansion curve of almost any clay soil may be duplicated by a properly chosen sand-mica flake mixture. Physicochemical effects in such mixtures may be assumed negligible. By making reasonable assumptions concerning moduli of elasticity, it may be shown that a typical clay plate, acting as a simple beam between other particles, may be held by menisci in a deformed state where the deflection is about 10 percent of the span.

A mechanical component of swelling that may be of importance in compacted clays (partially saturated clays) arises from the compression of the air in the voids as water enters the soil during swelling. If there are many interconnected tubular air voids and the air is initially at atmospheric pressure, water entering the soil from all directions will cause the air to be compressed and exert a disruptive pressure along the walls of the tubular voids. If the soil structure is too weak to withstand these pressures, then expansion may occur. Such a phenomenon has been suggested as the cause of slaking when a dry sample is immersed in water without confinement.

In compacted clays both physicochemical and mechanical factors may be significant contributors to the swell or swell pressure that develops on exposure to water. A typical example of the influence of both types of factors is provided by the results of tests on an expansive sandy clay soil having a liquid limit of 35 percent, a plastic limit of 19 percent, 25 percent by weight finer than 2 microns and montmorillonite as the dominant clay mineral. Several samples of the soil were prepared by kneading compaction at a water content of 17.3 percent to a density of 111.3 pcf. The samples were then permitted to swell in solutions of calcium acetate under a surcharge pressure of 0.1 kg per sq cm. The results, plotted as percent swell vs calcium acetate concentration in Figure 1, show that the amount of swell decreases as the electrolyte concentration increases, but that it appears to reach a constant value of about 1.1 percent above a concentration of about 1.5 Normal. The higher swells at low electrolyte concentrations are attributable to osmotic pressure differences between the swelling solution and the fluid between clay particles. Evidently the concentration at the midplane between particles was of the order of 1.5 Normal.[1/] Since some 1.1 percent swell appears to be independent of electrolyte content, it seems reasonable to attribute it to factors other than osmotic pressure. It is unlikely that water adsorptive forces would be significant at a water content of 17.3 percent (this soil has been observed to absorb water freely from the atmosphere to a water content of only about 5 percent). The basic swell of 1.1 percent is more likely due to a combination of the mechanical factors already outlined.

FACTORS AFFECTING THE SWELL AND SWELL PRESSURE OF COMPACTED CLAY AND THEIR MEASUREMENT

The brief summary of swelling mechanisms presented in the previous section would tend to indicate that a great variety of factors might influence the swell and swell pressure characteristics of a given soil. In the case of compacted clays, the molding water content and density would obviously be expected to be of paramount importance. The data in Figure 1 show that the nature of the imbibed fluid plays an important role. Somewhat less obvious but perhaps of equal importance is the method of compaction used for sample preparation. As illustrated by Seed and Chan (7), this is due to the fact that the method of compaction determines the structure of a compacted clay, and the structure influences the behavior of exposure to water. All of these factors may be considered under the general category of the influence of compositional factors on swell and swell pressure.

In order to evaluate properly the influence of the compositional factors, however, reliable and interpretable methods of measurement must be used. Studies have indicated that accurate determination of the expansion characteristics of a soil, in particular the swell pressure, is not always a simple task and that carefully controlled test conditions must be main-

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[1/] The actual concentration is a function of the clay exchange capacity, particle spacing, pore fluid electrolyte content, and other factors. It cannot be measured directly.

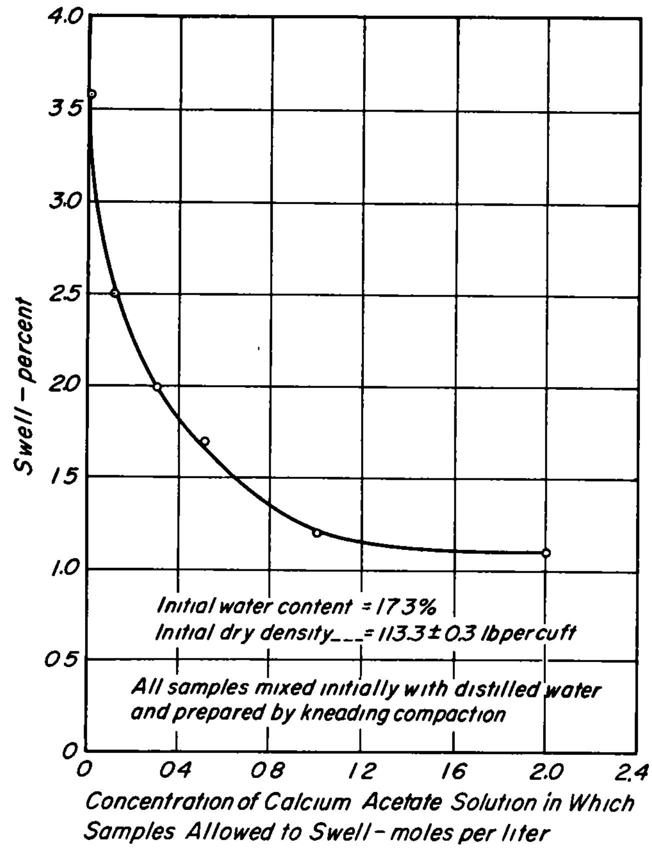


Figure 1. Effect of concentration of absorbed solution on swell of sandy clay

tained. Although, at the present stage, the effects of all of the variables in test condition that might reasonably be expected to influence the test results have not been evaluated, the influence of many factors has been reliably established. Included in the latter category are the effect of time on swell pressure development, the effect of sample shape on swell pressure, the effect of volume change on swell pressure, the effect of temperature on swell readings, and the influence of stress history on swell. All of these factors may be considered under the general category of the influence of measurement methods on swelling characteristics, and their effects are considered in the next section. Test results illustrating the influence of compositional factors are discussed in the following section.

THE INFLUENCE OF TEST CONDITIONS ON SWELL AND SWELL PRESSURE MEASUREMENTS

The Effect of Time on the Development of Swell and Swell Pressure

When a compacted soil is exposed to water, time is required for the movement of water into the sample under the hydraulic gradient set up by the negative water pressures within the soil relative to free water. The process is in many ways analogous to the process of consolidation wherein the movement of water in a loaded clay is retarded by the low permeability. A typical swell vs log time curve for a sample of compacted sandy clay is shown in Figure 2. It may be noted that for this relatively thin sample of 0.63-in. initial thickness, a considerable period is required for full expansion to occur. It may also be seen that the shape of the curve is essentially the reverse of a typical curve for consolidation.

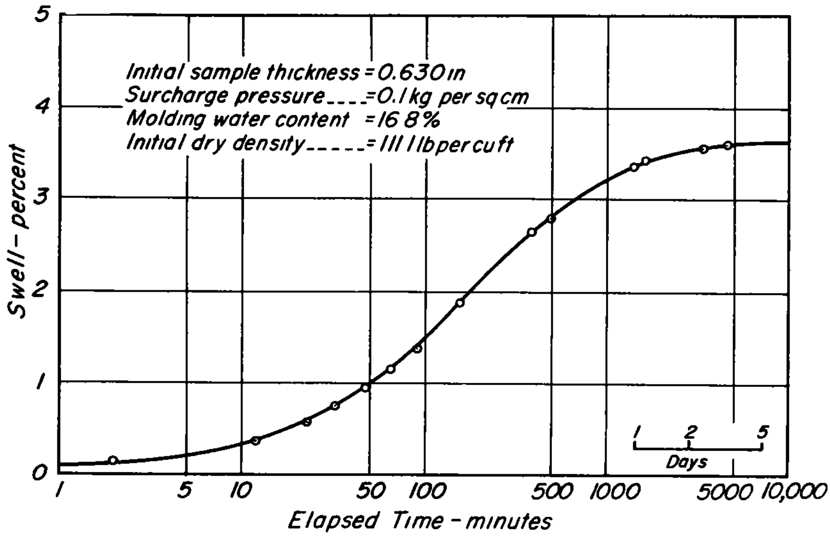


Figure 2. Increase in swell with time for thin sample of compacted sandy clay

The development of swell pressure on exposure of an expansive soil to water proceeds in much the same manner. A typical test result showing the rate of development of swell pressure for a sandy clay soil is shown in Figure 3. The procedure used for the measurement of the pressures shown in Figure 3 and for the other swell pressures obtained in this investigation was, unless otherwise indicated, as follows: Samples were mixed to the desired water content and compacted in 4-in. diameter molds, using a kneading compactor to form specimens approximately 2.5-in. high. The samples were then subjected to static pressure until moisture was exuded. The pressure was then released and the sample allowed to stand for half an hour. A perforated plate with a vertical stem was placed on top of the sample, and the mold containing the sample was placed in an expansion pressure device (see Fig. 4) so that the stem of the plate firmly contacted the center of a horizontal proving bar fixed at each end.[2] A dial gage was mounted to record subsequent deflections of the proving bar. Water was poured on the upper face of the specimen and the pressure that developed as the sample tended to expand was observed by noting the deflection of the proving bar. Calibration of the proving bar permitted computation of the expansion pressure. It may be noted that this is the same procedure used by a number of State Highway Departments in connection with the design of pavements.

[2] A seating load of 0.4 psi was used.

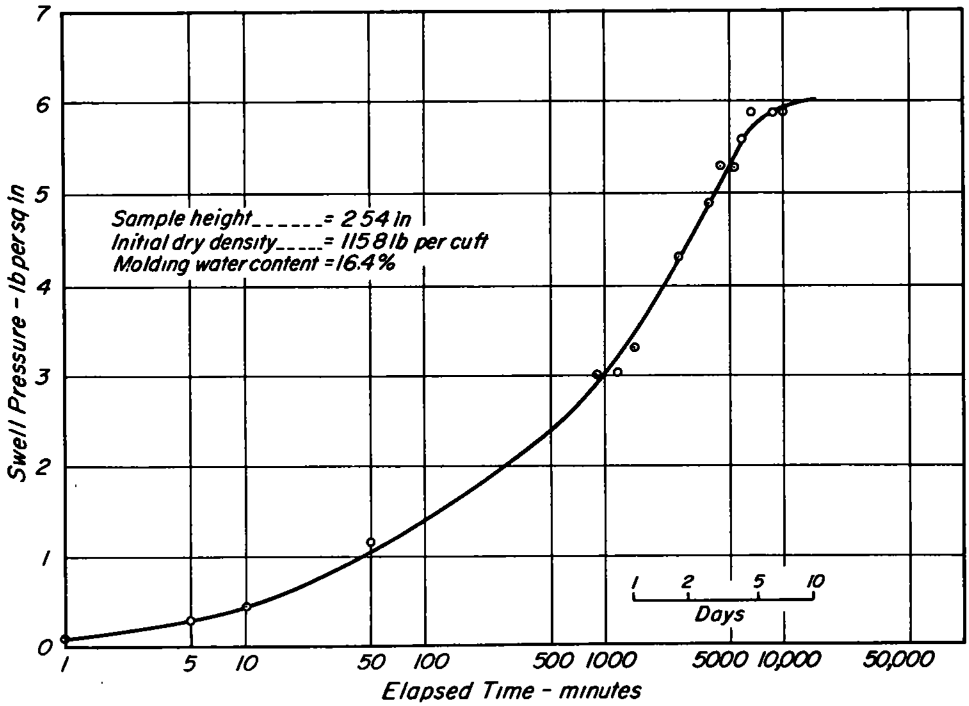


Figure 3. Increase in swell pressure with time after exposure to water for compacted sample of sandy clay

It should also be noted, however, that in this procedure the sample is not maintained at constant volume, inasmuch as the proving bar must deflect upwards to measure the expansion pressure, and the sample is thus allowed to expand by an amount equal to the deflection of the proving bar. Thus, while the actual sample expansion is quite small (0.003 in. per psi or less depending on the thickness of the proving bar used), the true swell pressure at zero volume change is not measured, but rather an expansion pressure corresponding to some small amount of swell is determined. The marked effect of very small volume increases on the observed pressures will be illustrated in a subsequent section.

From Figure 3 it may be seen that the expansion pressure increased relatively rapidly for the first day but that the rate of increase was very low after this time. At the end of one week, however, the pressure had reached a value significantly higher than after one day. Figure 5 shows the results of a series of tests on the same sandy clay conducted over a range of water contents likely to be of greatest practical interest for pavement design considerations (expansion pressures less than 1.5 psi). The pressure developed after 7 days was at least 100 percent greater than the pressures developed after 1 day. This would seem to indicate that even when samples are compacted to a condition approaching full saturation, considerable periods of time are still required to determine ultimate values of swell pressure if samples of 2.5-in. thickness are employed.

Similar time effects have been reported by DuBose (8) for the development of swell in samples of highly plastic clay. For samples 5 in. in thickness, full swell was not developed even after 50 days.

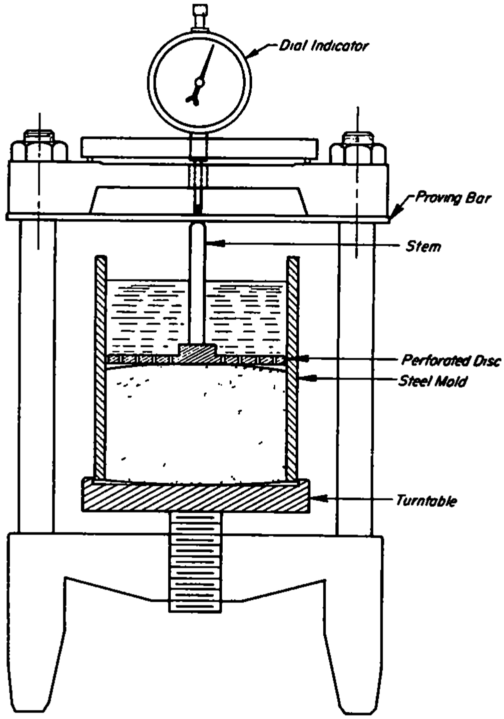


Figure 4. Sample curvature in expansion pressure test

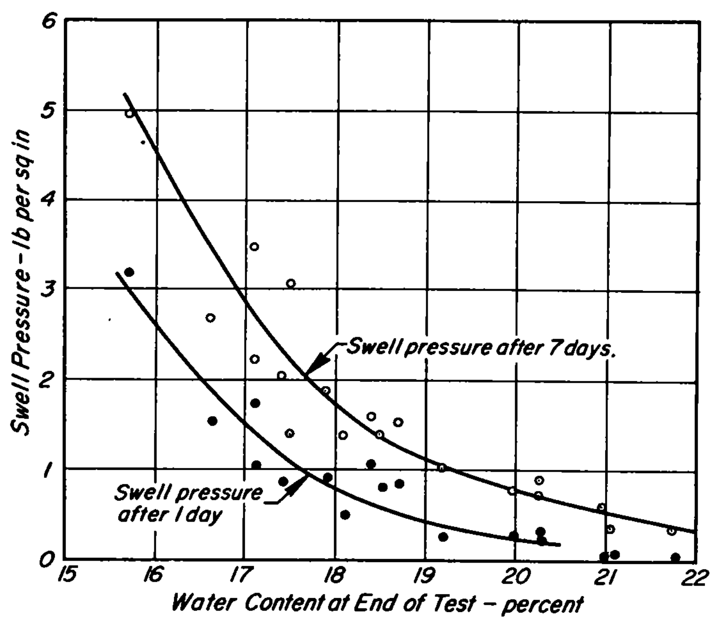


Figure 5. Effect of time on expansion pressures developed by samples of sandy clay

The long time required for the development of full swell or swell pressure is a result of the time required to effect the stress transfer in the water from a large negative value existing before exposure of the sample to water up to the zero value that must exist throughout the system at equilibrium. The pore-water-pressure change requires the flow of water into the partially saturated soil in order to flatten menisci and satisfy water adsorptive forces. The process is slow due to the low permeability of compacted clays; and the rate decreases with increasing time because of the continually decreasing gradient tending to draw water in. Unfortunately, after about 24 hours the rate of change of swell or swell pressure may become so slow that observers are tempted to conclude that the process is completed; yet considerable swelling may still develop after the initial 24-hour period. Considerable care is required to determine the maximum values for any given test.

The Effect of Sample Shape on Swell Pressures

It was observed, using the procedure previously described, that in some cases the deflection of the proving bar decreased rather than increased following the addition of water to the sample — a confusing result in view of the extremely light seating load to which the samples were subjected. These results remained unexplained until it was noticed that these samples developed considerable curvature of their upper and lower surfaces in the half-hour waiting period following the release of the static compactive load. This curvature is likely to occur in all samples but more particularly with those exhibiting considerable rebound after static compaction, because friction between the sample and walls of the mold will tend to restrict the rebound at the edges of the sample. At the center, greater rebound is possible because of the absence of edge effects.

It was concluded that for these samples the perforated plate was not in contact with the full surface of the sample, as shown in Figure 4, and that the decrease in proving-bar deflection was due to a progressive decrease in curvature caused by the seating load (the expansion of the sample due to the addition of water being insufficient to offset this effect). Thus it would seem reasonable to conclude that even in cases where expansion pressures were recorded, the sample actually expanded appreciably to fill the gaps between the original curved surfaces of the specimen and the horizontal base plate and the perforated plate before any expansion pressure could be developed near the edges of the specimen. As a result, the observed pressures would be appreciably less than those that would be developed by a sample in contact with its restraining boundaries over its entire surface area.

To check the validity of these conclusions, samples of sandy clay were prepared using the procedure previously described, and curvature was allowed to develop during the period following static compaction. Just before placing the samples in the expansion pressure device, the soil at the curved ends was trimmed off to form plane surfaces. The expansion pressures developed by these trimmed samples are compared with those of identical untrimmed samples in Figure 6. The similar compositions of both trimmed and untrimmed samples are indicated by the plot of dry density vs water content at the bottom of Figure 6.

The results indicate that the samples whose ends were trimmed prior to testing developed considerably higher pressures than did the untrimmed

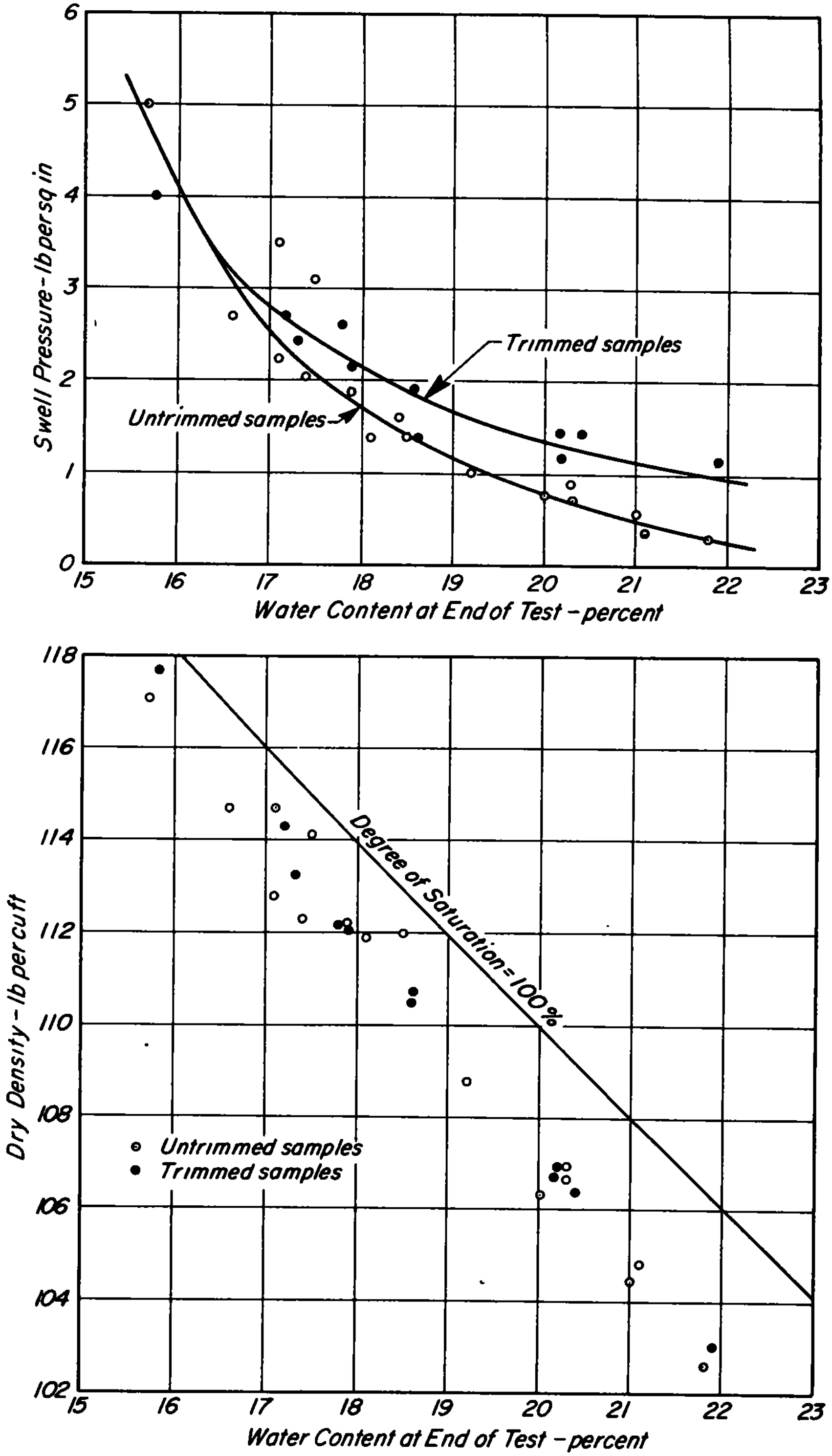


Figure 6. Effect of trimming on swell pressures developed by compacted samples of sandy clay

specimens. The difference between the expansion pressures developed by trimmed and untrimmed specimens increases with water content within the range investigated, and in some cases was as great as 100 percent. The effect is greatest at the higher water contents. This is apparently due to the fact that at the lower water contents there is little rebound of the sample after removal of the static pressure and, thus, little tendency for curvature of the ends to develop. This lack of curvature in the drier samples was evident during the tests. Similar results have been obtained for samples of silty clay prepared in the same manner.

It is thus apparent that the determination of reliable swell pressures is dependent on insuring perfectly plane sample surfaces and is particularly important for statically compacted samples or any samples subjected to static pressures. Unfortunately, however, trimming the ends of a thick sample prepared in this way may not be the proper procedure for obtaining satisfactory results, because the removal of material from the center part of the sample will result in a specimen of nonuniform density, and the swell pressure exerted by the edges may then exceed that exerted by the center portion; furthermore, some pressure may result from the expansion of the soil due to the gradual release of friction forces between the sample and the walls of the mold.

The problem of curvature at sample ends is not the only difficulty encountered in making reliable determinations of swell pressures for compacted samples. Barber (9) has presented data illustrating the marked differences in results that may be obtained due to variations in the interval of time between compaction and the start of the test. Typical results are presented in Figure 7. It is apparent that this factor needs careful consideration in the correct interpretation of swell pressure data.

The Effect of Volume Change on Swell Pressure

The significant effects of volume change on the swelling pressure developed by compacted soils has been recognized for some time. Barber (9), Dawson (10), and DuBose (8), among others, have presented data illustrating the marked reduction in swell pressures caused by volume changes of even a fraction of 1 percent. Typical results reported by Dawson (10) for samples of silty clay compacted by the standard Proctor procedure are presented in Figure 8.

It is apparent that a careful assessment of the amount of expansion permitted in any test is required in the evaluation of the test data, and that comparative test results can only be obtained where volume changes are the same for all soils. Probably the most convenient and often the most significant standard of comparison is that in which samples are maintained at constant volume. However, many test procedures do not satisfy this requirement, and it is of interest to compare swell pressure data for samples maintained at constant volume with those obtained using proving bar procedures. The proving-bar method of swell pressure measurement must necessarily permit some sample expansion, because the deflection of the bar forms the basis for evaluation of the pressure. Though only a very slight expansion of samples occurs by this or other usual methods of swell pressure measurements, the measured pressures are likely to be somewhat lower than those that would be developed if constant volume were maintained.

To investigate the influence of such effects on the expansion pressures developed by samples of sandy clay, three series of tests were run,

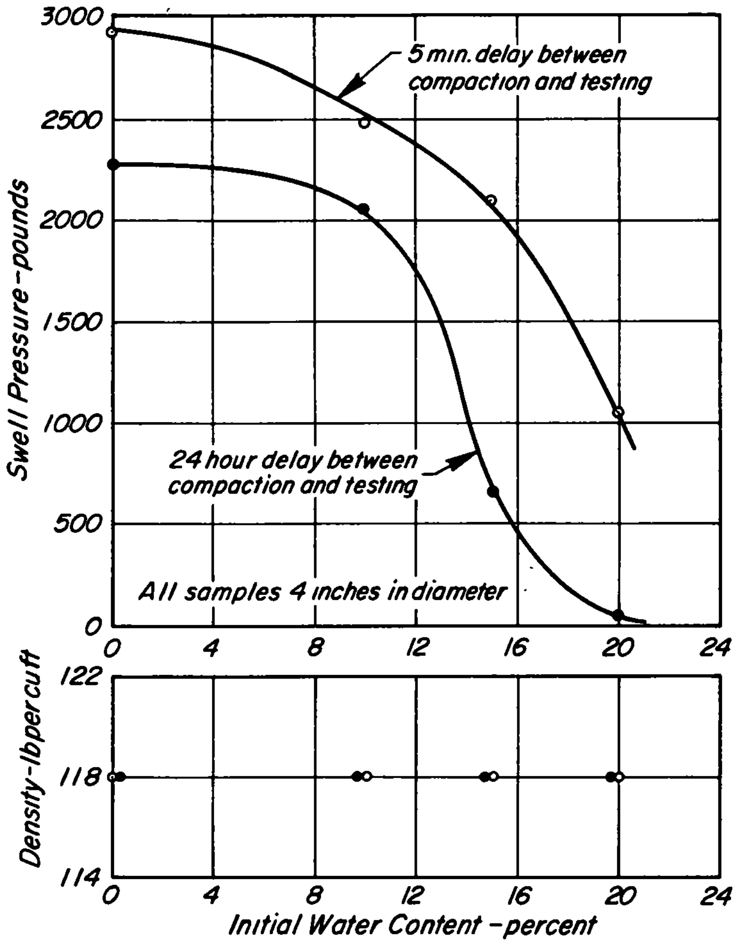


Figure 7. Effect of interval between compaction and testing on swell pressure recorded at constant volume. (Values from E. S. Barber, 1956.)

using the swell pressure device shown in Figure 4 with proving bars of 1/8-in. thickness and 1/4-in. thickness and using a loading yoke instead of a proving bar over the stem of the perforated plate to maintain constant volume. For the series maintained at constant volume, the sample faces were trimmed prior to the addition of water; data were obtained for both trimmed and untrimmed specimens using the 1/8-in. proving bar; and data on untrimmed specimens only were obtained with the 1/4-in. proving bar. With the 1/8-in. bar an expansion pressure of 1 psi caused a deflection of 0.003 in.; with the 1/4-in. bar the deflection was 0.0004 in. per psi; and using the loading yoke, constant volume was essentially maintained by application of appropriate loads. A slight volume increase is possible with the loading yoke due to the elastic compression of the vertical stem above the perforated plate. Compression of the stem was computed to be 0.000376 in. per 10 psi expansion pressure exerted by the 4-in. diameter samples.

Figure 9 shows the relationship between swell pressure at the end of 7 days and water content for the four conditions of test. It may be seen

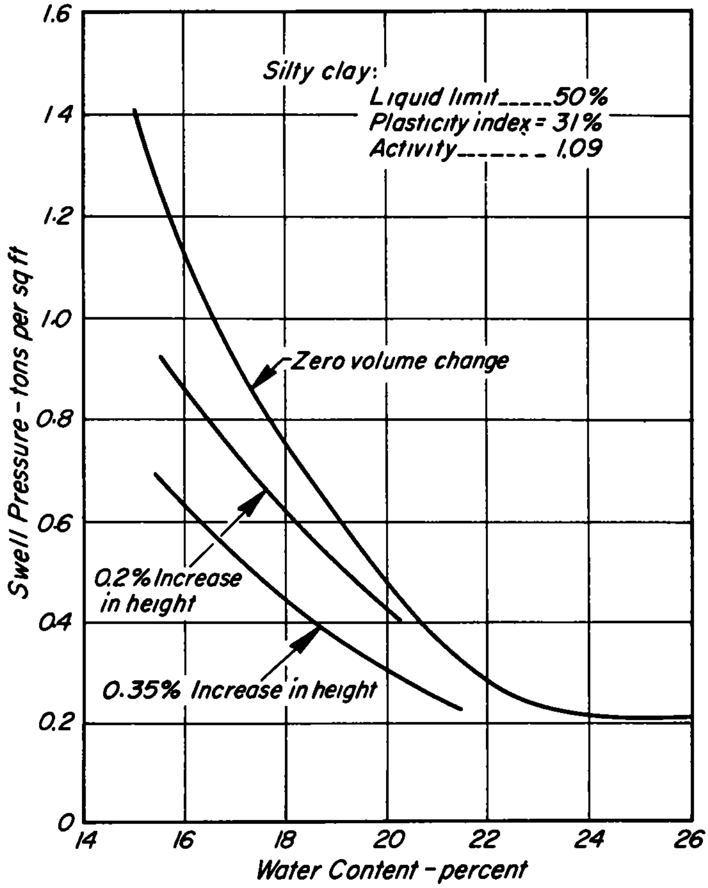


Figure 8. Effect of volume change on measured swell pressures. (After R. F. Dawson, 1956.)

that the measured swell pressure is very sensitive to the amount of volume change actually allowed to take place during the measurement. It is evident that the measured pressures, even in a relatively stiff system (e.g., with a 1/8-in. proving bar) are much lower than the pressures measured under constant volume conditions.

In cases where the relationship between amount of swell and swell pressure is desired, suitable results can be obtained using the proving-bar type of equipment with bars of different thicknesses in conjunction with the loading yoke apparatus. Typical data obtained in this way for samples of sandy clay, prepared by kneading compaction at various water contents using a constant compactive effort, are presented in Figure 10. The density vs water-content curve for the samples studied is shown in the lower part of the figure.

The soil was compacted in 4-in. diameter molds to form samples 4.5 in. in height; after compaction, the samples were trimmed off to leave a specimen with a height of 2.5 in. in the mold. Three sets of samples were tested. In the first, the samples were given access to water with a 3/16-in. thick proving bar used to measure expansion pressures; in the second, a 3/8-in. thick proving bar was used; and in the third, the samples were confined between the base plate and a loading yoke with a lucite piston. In the third set, sufficient pressure was applied to the yoke to prevent

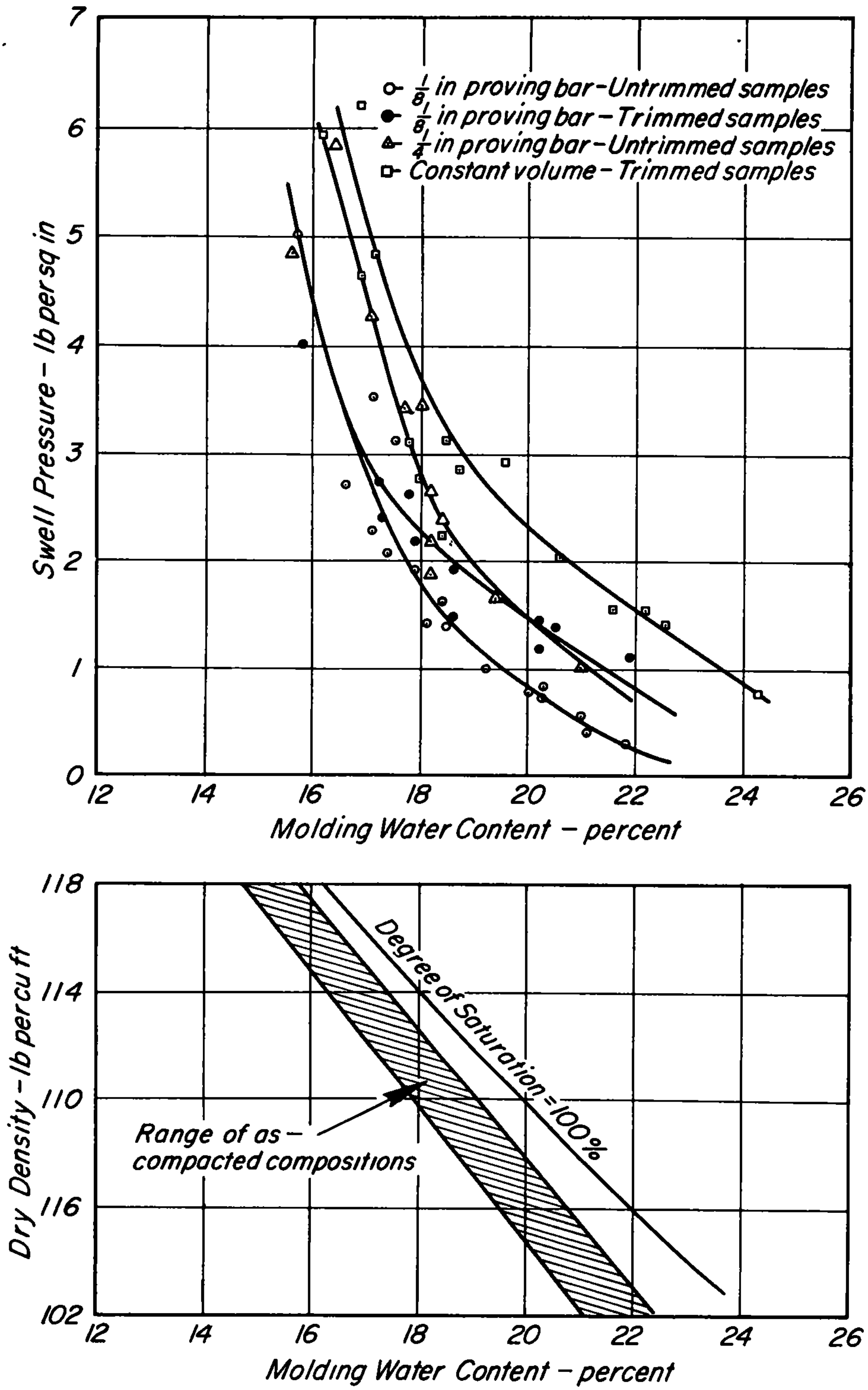


Figure 9. Effect of sample restraint and trimming on the swell pressures developed by compacted samples of sandy clay.

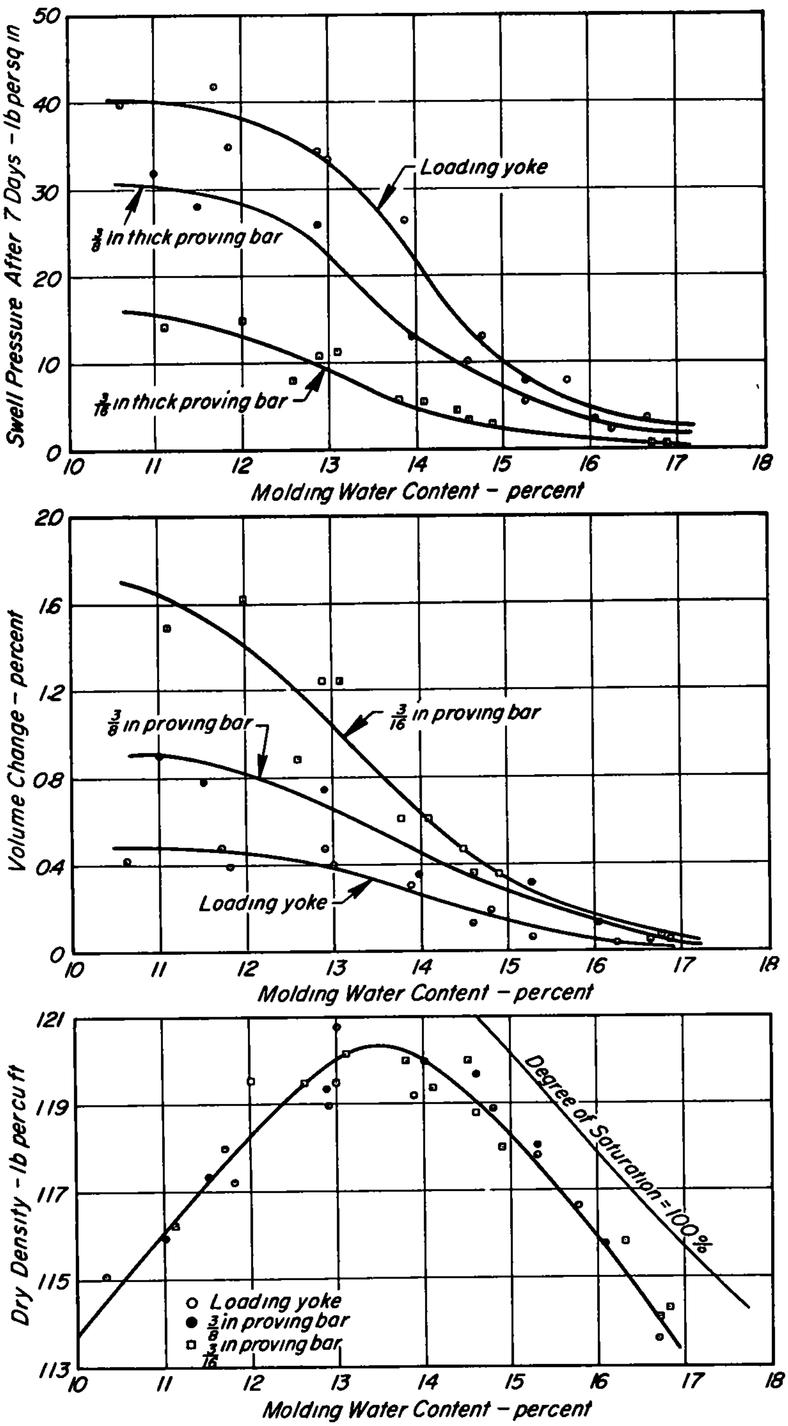


Figure 10. Effect of volume change on swell pressure of compacted sandy clay.

apparent expansion of the specimen as indicated by a dial gage mounted on the yoke. Actually, however, a slight volume change could occur due to compression of the lucite piston. The magnitude of this volume change could be evaluated and is included in consideration of the test results.

The expansion pressure after 7 days and the volume change in percent for each of the samples are shown in Figure 10 as functions of molding water content. It may be seen that the samples having the lowest water content at compaction had the highest expansion pressures, and the greater the expansion that is permitted during the test, the lower is the measured pressure.

The results in Figure 10 have been used to prepare Figure 11, which shows the expansion pressure as a function of volume change at different compaction water contents and densities. Presentation of the data in this form provides a convenient means for assessing the magnitude of swell pressure for any degree of expansion and would be useful in practical situations where, very often, the swelling pressure against a structural member and the deflection of the members are mutually dependent.

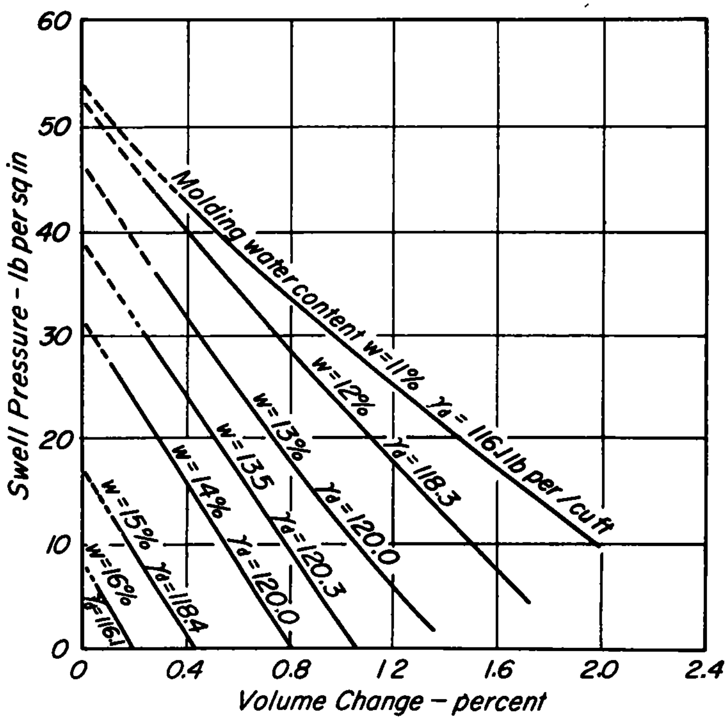


Figure 11. Effect of volume change on swell pressure developed by samples of sandy clay prepared using constant compactive effort.

<u>Effect of Temperature on Swell and Swell Pressure Measurements</u>

An additional factor affecting the results of swell pressure measurements is temperature variation during the test. The magnitude of swell and swell pressure is a function of temperature for purely physicochemical reasons, as the interparticle forces and pore water pressures are known to be temperature sensitive. Exclusive of the influence of physicochemical factors, however, temperature effects are also important through their influence on the volume of the components of the measuring system.

It has been found, for example, that temperature variations of 10 to 15° F can cause a change in observed swell up to 0.5 percent in sample of 1/2-in. thickness. Differences of this magnitude may be intolerable if the specimens being investigated only swell 1 or 2 percent. While reliable data have not yet been obtained concerning the effect of temperature variations on swell pressure, it might be expected to be rather large, because as shown in Figure 11, very small volume changes lead to large changes in swell pressure.

Effect of Stress History on Swelling of Compacted Soils

The relationships between the amount of swell that will develop when a compacted sample is exposed to water and the surcharge pressure resisting expansion is often of interest in practical problems. The labor involved in determining such a relationship could be appreciably reduced if the same sample could be used for determination of several points on the percent swell vs surcharge pressure curve by means of successively reducing the surcharge load after equilibrium has been reached under the previous load. However, test results show that the amount of swell is significantly influenced by the stress history of a sample, and no such simple procedure can be used.

The effects of stress history in this type of test are demonstrated by the results of the following study: Three compacted specimens of 4-in. diameter all having the same initial composition of 13.1 percent water content and dry densities of 122.5 to 122.8 pcf were trimmed to a thickness of 3/4 in. and placed between porous discs. Surcharge pressures were applied and measurements made of the amount of swelling when the samples were immersed in water. Specimen No. 1 was tested under an initial surcharge of 10 psi. After equilibrium had been achieved, the surcharge pressure was reduced to 5 psi; after a second equilibrium was attained, the pressure was further reduced to 1 psi and swell measurements continued for an additional 28 days to insure ultimate equilibrium. Specimen No. 2 was subjected to an initial surcharge pressure of 5 psi, and, when no further swell appeared likely, the surcharge was reduced to 1 psi. Specimen No. 3 was maintained under 1 psi throughout the test.

Figure 12 summarizes the changes in thickness occurring in each of the samples throughout the test period. It may be seen that the amount of swell of Specimen No. 1, on which the load was reduced in stages from 10 to 1 psi, was less than that of Specimen No. 2, on which the stress was reduced from 5 to 1 psi, and that both of these specimens swelled less than Specimen No. 3 which was subjected to only 1 psi throughout.

The results of a similar series of tests reported by Barber (9) for a clay of low plasticity are presented in Figure 13. For these studies, compacted samples were placed under initial pressures of 8,000, 1,000, 500, 200, and 20 psf and allowed to swell to equilibrium conditions; the pressure on all samples was then reduced to 20 psf and the final equilibrium conditions determined. The marked differences in final expansion resulting from the use of different initial pressures are readily apparent.

It is clear from these results that stress history does have a significant effect on the amount of swell of a compacted soil and that erroneous results may be obtained if the equilibrium conditions of compacted specimens after swelling are predicted from measurements made by progressively reducing the surcharge pressure on a single specimen. The results also indicate that if a sample is used to measure swell pressure it cannot then

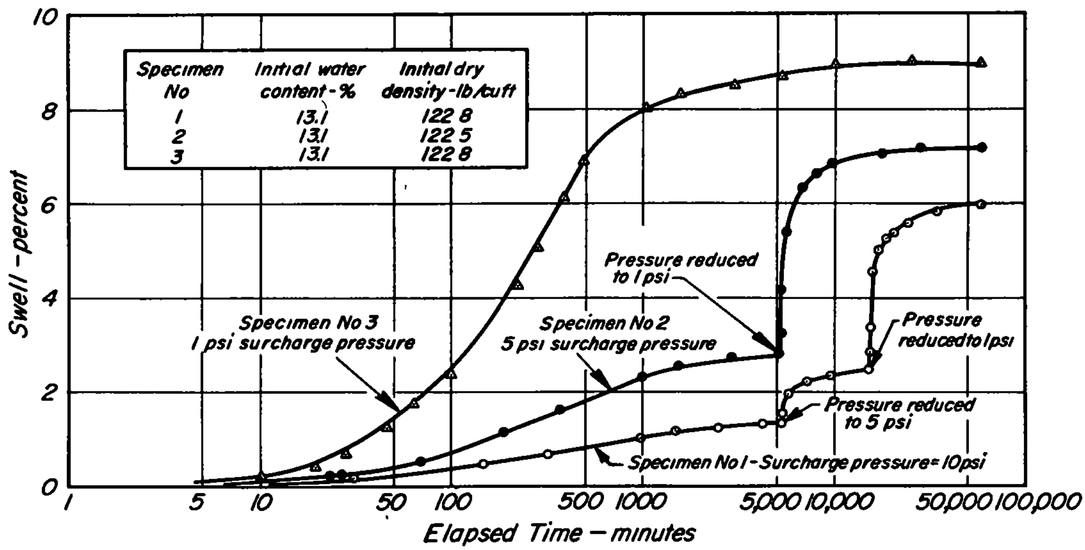


Figure 12. Effect of stress history on swell of compacted samples of sandy clay.

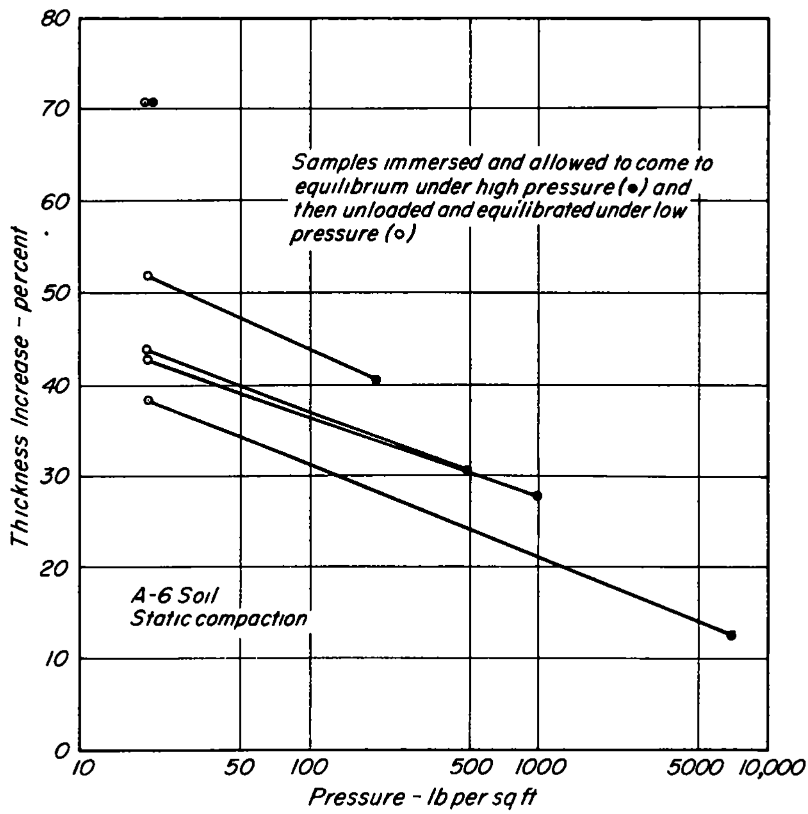


Figure 13. Swell vs pressure relationships for different initial loads. (Data from E. S. Barber, 1956.)

be unloaded and allowed to swell in the hope of determining the swelling characteristics of the soil. Separate samples are required for swell pressure and swell measurements.

Recent developments in the study of the structure of compacted clays provide a possible explanation for this type of behavior. It has been shown, Lambe (3), Seed and Chan (7), that samples compacted dry of optimum, as were the samples used to obtain the data in Figure 12, exhibit flocculent structures; i.e., the clay particles are more or less randomly oriented. The pore-water pressures are negative and of rather large magnitude in such soils, and it is likely that many of the platy particles are held in a deformed state by menisci. On exposure to water, the relief of these high water tensions enables deformed particles to straighten, water adsorptive forces to be satisfied, and double layer osmotic pressures to be balanced. It is reasonable to assume also that some rearrangement of the internal structure of the soil will take place as water is imbibed and the tensions in the water are released. As water moves in, deformed particles tend to straighten and effective particle spacings tend to increase. The form of the structure adjustment will be a function of the restraints applied to the sample and could reasonably be expected to take the path of least resistance.

When sample expansion can take place with ease, as in the case of low surcharge pressures, then large over-all volume increase of the specimen may occur and a relatively high swell may result. When vertical expansion is restrained by the application of high surcharge pressures it is likely that internal particle reorientations occur such that the initial structure, which could be considered to consist of clusters or aggregates of randomly oriented particles, shifts in the direction of a more dispersed or parallel structure as the dissipation of stresses and the movement of particles proceed. The tendency for particle orientation to become more parallel in a direction normal to the direction of stress application when saturated clays are subjected to high pressure has already been discussed by Lambe (3), while Seed and Chan (7) have shown that parallel particle orientations exhibit lower swelling characteristics than random orientations. Thus, it seems likely that the subsequent swelling characteristics of samples previously subjected to high pressures are less than those of identical samples subjected directly to low pressures because of the increased degree of particle orientation induced by the high pressure application.

If the above mechanism were correct, it would be expected that the initial structure of a compacted clay would influence the magnitude of the stress history effect. It would be further anticipated that the stress history effect would be more pronounced in samples having flocculent structures than in samples having dispersed structures, because internal particle adjustments in dispersed systems might be expected to be fairly small.

THE ROLE OF COMPOSITIONAL FACTORS IN DETERMINING THE SWELL AND SWELL PRESSURE CHARACTERISTICS OF COMPACTED CLAYS

As pointed out at the outset of this paper, the swelling characteristics of a compacted soil are dependent on several fundamental factors. The relative influence of these factors for a given soil is, in most cases, determined by more or less controllable conditions that are imposed on the composition of the compacted soil. By composition of a compacted soil is meant the water content, density, and structure of the material in the

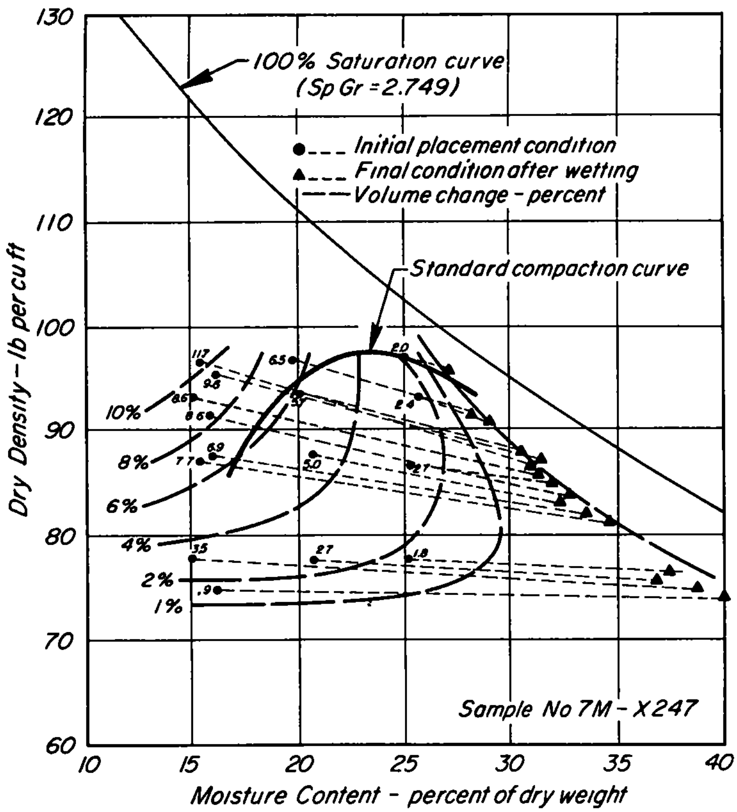


Figure 14. Percentage of expansion for various placement conditions when under 1-psi load. (After W. G. Holtz and H. J. Gibbs.)

as-compacted state. The composition of the fluid to which the compacted soil is exposed during swelling is a further important variable as shown by Ladd (4) and Mitchell (6). The structure is, in many cases, determined by the method of compaction and the molding water content, as illustrated by Seed and Chan (7) and Lambe (3). The influence of these various compositional factors is illustrated in the following paragraphs.

Influence of Density and Water Content on Swelling Characteristics

The influence of compacted density and molding water content on the swell and swell pressure of compacted clays has been studied by numerous investigators in recent years. Probably the most convenient way of presenting the results of such studies is that of plotting contours of equal expansion effects on a standard dry-density vs water-content plot. Typical examples of such plots, obtained by Holtz and Gibbs (11), are presented in Figures 14 and 15. These data were obtained from studies of the relationships between compacted density, water content, and swelling characteristics of samples of a highly plastic clay prepared by impact compaction. It is readily apparent that for this method of compaction an increase in molding water content at any given density causes a decrease in swell and swell pressure; however, an increase in density at any given water content may increase or decrease the swell depending on the range of densities involved. This latter effect is due to the fact that changes

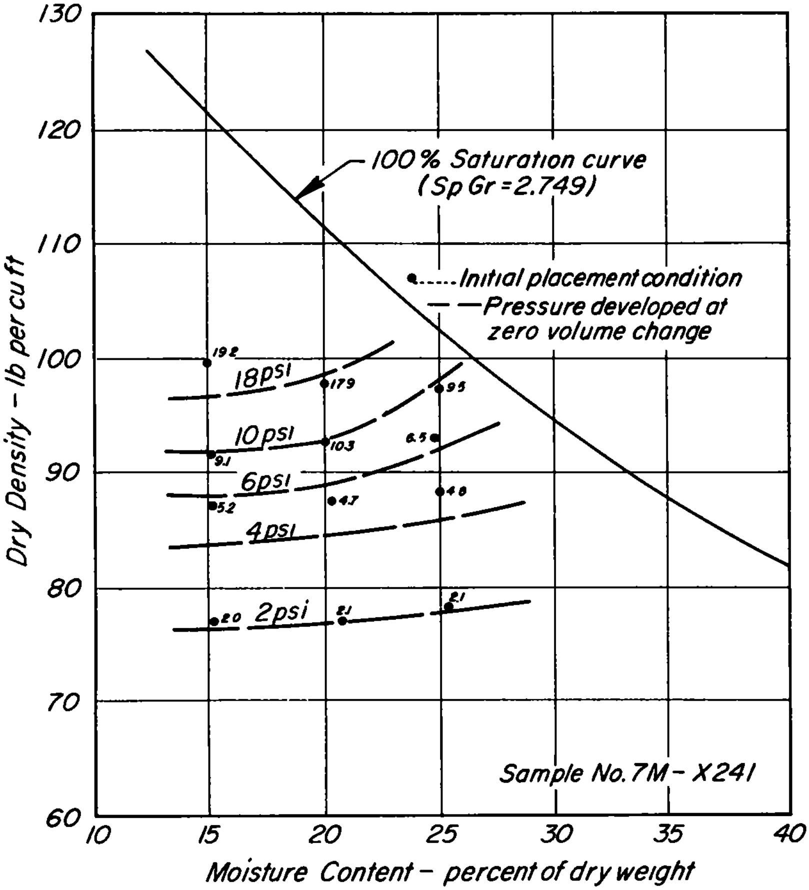
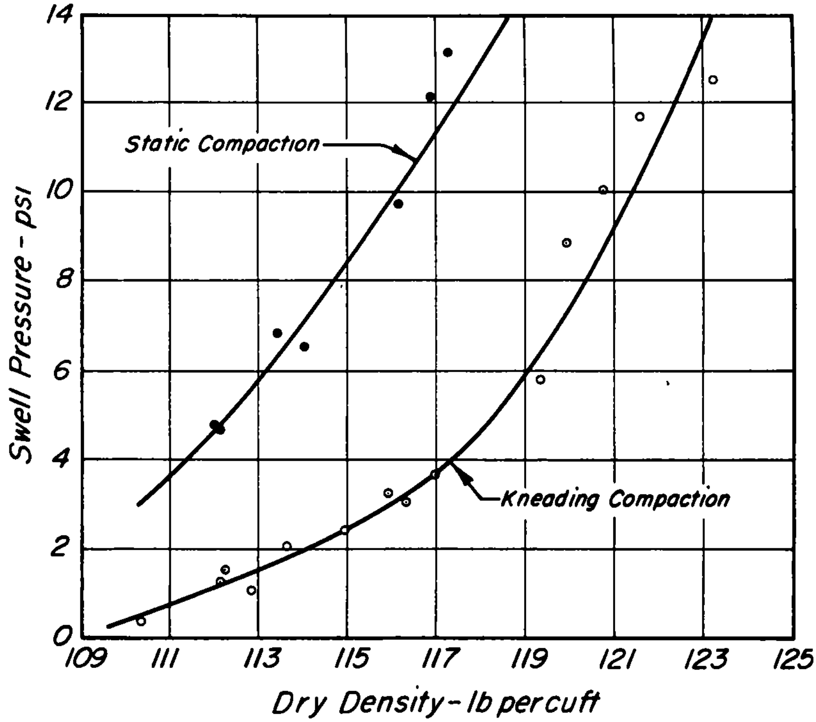


Figure 15. Total uplift pressure caused by wetting — for various placement conditions. (After W. G. Holtz and H. J. Gibbs.)

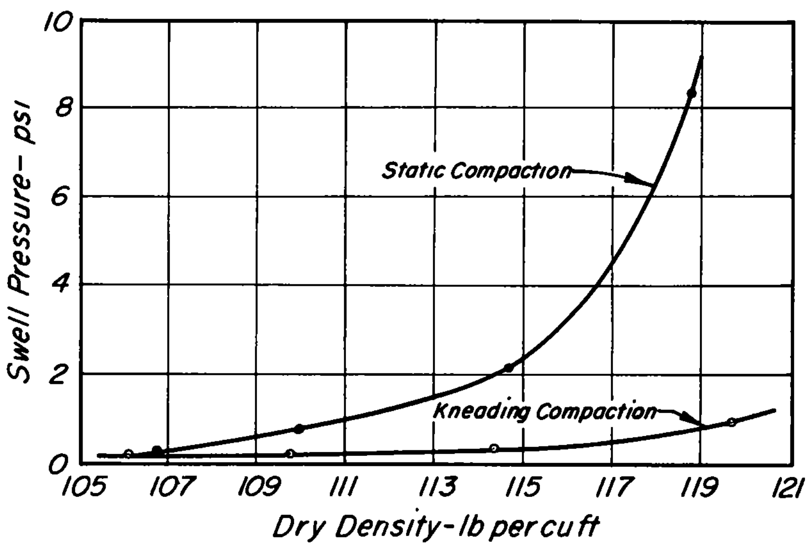
in density, at high degrees of saturation, are accompanied by changes in soil structure, and the swelling characteristics reflect the effects of both density and structural changes.

The Effect of Soil Structure on Swelling Characteristics

In addition to the initial density and water content, the swell and swell pressure of compacted samples are greatly influenced by their initial structures. As shown by Seed and Chan (7), for many soils the method of compaction provides a simple method for the inducement of different structures in compacted samples at identical water contents and densities. However, such structural variations generally can only be obtained at water contents greater than optimum for the compactive effort and procedure used. Under those conditions it has been shown that kneading compaction tends to create a dispersed structure and static compaction a flocculent structure in many clays. The influence of such structural differences on the swell of samples of sandy clay is shown by the data in Figure 16. It may be seen that for samples compacted dry of optimum, the swell is relatively insensitive to method of compaction, because both methods yield flocculent structures. Wet of optimum, however, the flocculent sample prepared by



(a) Pittsburg Sandy Clay



(b) Vicksburg Silty Clay.

Figure 16. Effect of method of compaction on swell pressure for samples compacted to high degree of saturation.

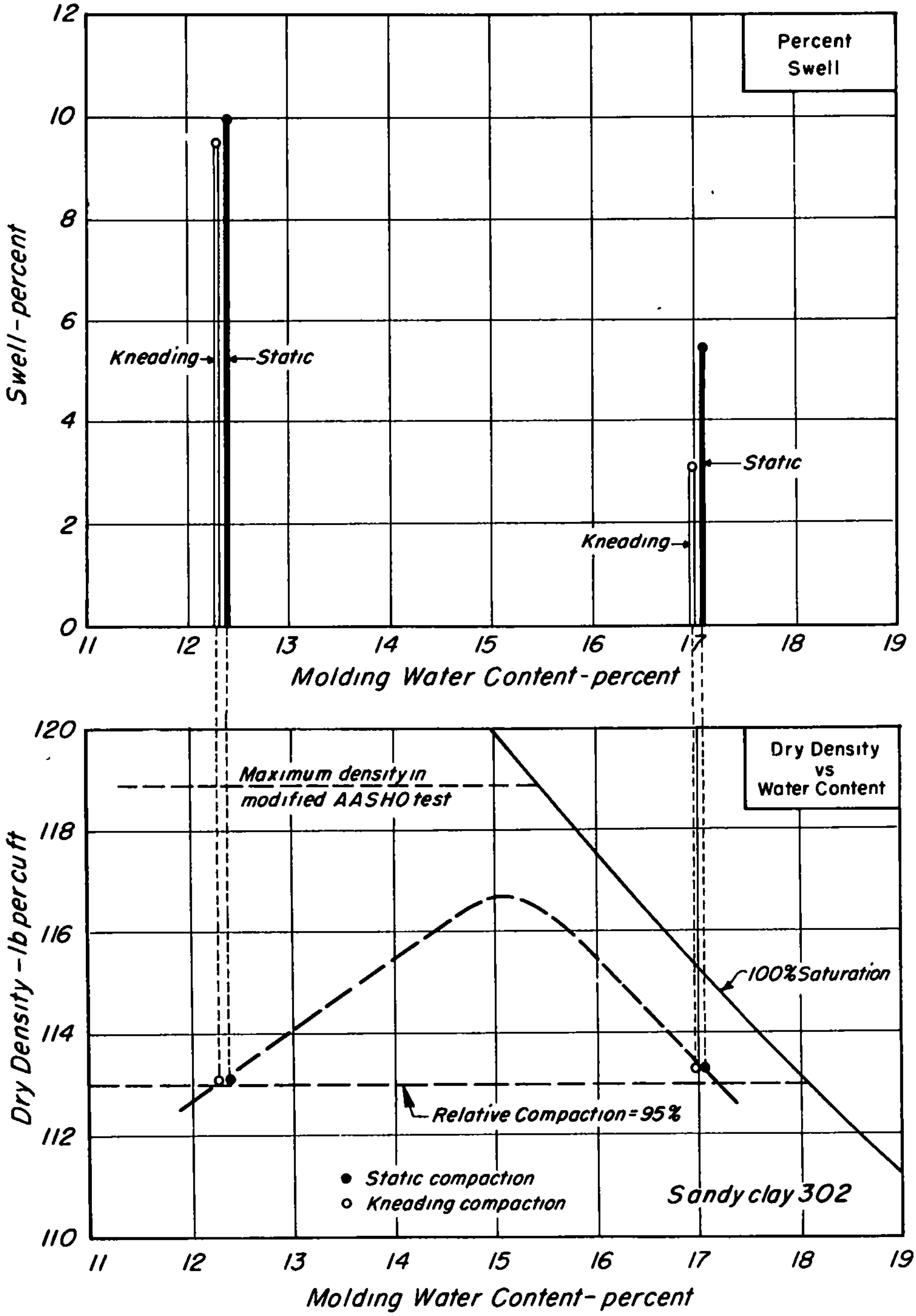


Figure 17. Swell characteristics of samples of sandy clay prepared of kneading and static compaction.

static compaction swells considerably more than the sample with a dispersed structure prepared by kneading compaction. That the swell pressure is similarly affected by structure is illustrated by Figure 17, which presents data for samples of two clays prepared at various densities wet of optimum by kneading and static compaction. The swell pressures of the statically compacted samples are greater than those for the kneading compacted samples at the same molding water content over the entire range of densities investigated.

The Effect of Swelling Solution Composition on Swell

The effect of the composition of the solution to which a compacted soil is exposed on the swelling characteristics has been discussed in connection with swelling mechanisms and Figure 1. Similar measurements have been reported by Ladd (4). Such behavior (i.e., decreased swell with increased electrolyte content) might be expected with any soil in which physicochemical components, particularly osmotic pressures, are significant contributors to the swell. Figure 1 presents data for samples prepared by kneading compaction. These data are compared in Figure 18 with the results of similar tests on samples prepared by static compaction to the same

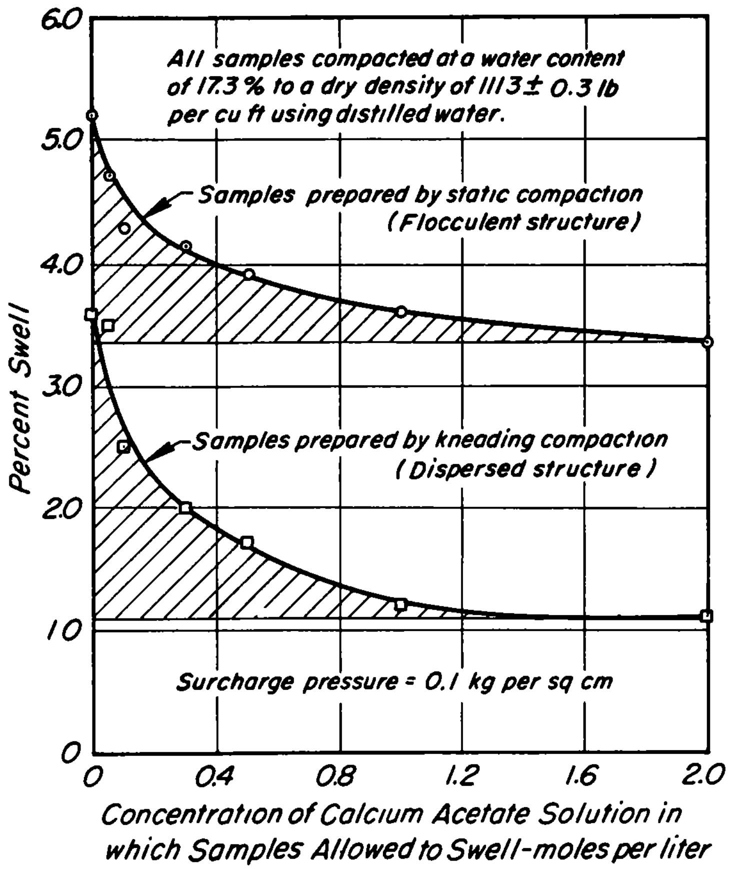


Figure 18. Effect of structure and electrolyte concentration of absorbed solution on swell of compacted sandy clay.

density and water content. It may be noted that the effect of solution composition, shown by the shaded areas, is about the same for each method of compaction, suggesting that the electrolyte-sensitive factors influencing swell are relatively insensitive to structure. The greater overall swell of the statically compacted samples is readily apparent.

Discussion of the Relationships Between Composition and Swelling Characteristics

The behavior summarized in Figures 14 through 18 appears to form a consistent picture relative to the known characteristics of compacted clays, physicochemical principles, and soil structure. Structure appears to be one of the major variables governing swelling behavior. The data in Figures 16, 17, and 18 show that flocculent structures consistently swell more and develop higher swell pressures than dispersed structures. Study of Figure 18 and of data presented by Ladd (4) indicates that the proportion of the swell that is insensitive to the electrolyte content of the solution to which the sample is exposed is much greater for flocculent than for dispersed samples. If it is assumed that the effect of the electrolyte content is a measure of the physicochemical components of the swell, then it would seem that mechanical factors are primarily responsible for the difference between the swelling characteristics of the two structures. Compaction to a flocculent structure might be expected to give a greater number of deformed particles and higher internal stresses because of the random particle arrangements and the inability of particles to slide into unstressed parallel positions, as is the case by kneading compaction.

The increase in swell and swell pressure with increase in density at a given water content is a logical consequence of several factors. In low density samples, the particle deformations would be expected to be less than in high density samples in the as-compacted state. The average interparticle spacing of low density samples is greater than in high density samples; thus, interparticle repulsive forces due to interacting double layers would be less, and, therefore, the samples would require less water to reach an osmotic equilibrium. Furthermore, structural adjustment within the samples could take place more easily in low density samples.

Both swell and swell pressure decrease with increasing molding water content because structures are generally more dispersed at higher water contents for any method of compaction, and the natural desire for the soil to imbibe water to satisfy adsorptive and double layer pressures decreases with increasing water content.

The form of the relationship between swell pressure or swell and molding water content for samples prepared at constant compactive effort is the result of variations in the combined effects of density, water content, and structure. At water contents a few percent below optimum, the swell is reasonably insensitive to changes in molding water content. This is because the density increases with increasing water content, and the effects of the two variables tend to cancel each other out. At water contents in the vicinity of optimum, the density is not changing rapidly and the effects of water content and structure predominate. Structure undergoes a marked shift towards greater dispersion as optimum water content is reached. Thus the swell and swell pressure decrease rapidly as the water content changes from just below to just above optimum for the compactive effort being used. When water contents considerably wet of optimum are reached, further structural changes have more or less ceased and physical interaction between particles becomes low. Physicochemical effects and the effects of decreased density are probably the important factors influencing the swelling characteristics in this range, and their influence is shown by a gradual decrease in swell and swell pressure as the water content increases.

SUMMARY AND CONCLUSIONS

The factors responsible for the swelling characteristics of compacted clays have been briefly reviewed. These factors may be conveniently considered to be of two types: physicochemical factors, which are functions of interparticle electrical forces, particle surface structure, pore fluid composition, the surface tension properties of water, and the composition of the water to which the soil is exposed; and mechanical factors, which include the effects of elastically deformed particles or particle groups and the compression of air in the voids during imbibition of water.

Some of the factors affecting the results of swell and swell pressure measurements have been examined. It was shown that considerable attention to detail is necessary if meaningful values of swell pressure characteristics are to be determined. Periods up to a week or longer are often necessary for the determination of equilibrium swell and swell pressure in compacted samples of appreciable thickness (2.5 in.), even if the initial degree of saturation is over 90 percent. Data have been presented that show that, for samples prepared by static compaction, curved surfaces may develop during the period between the end of compaction and the beginning of a swell pressure determination as a result of the rebound of the central portion of the sample. The effect of the curved surface is to give a swell pressure less than the true pressure. Furthermore, changes in the interval between compaction and testing may also influence the results.

The extreme sensitivity of measured swell pressure to volume change was illustrated. For the samples studied, for example, the measured pressure may be as much as 100 percent too low if as little as 0.1 percent expansion occurs, depending on the initial conditions. The combined effects of sample surface curvature, insufficient time of test, and expansion can lead to observed values of swell pressure that are several hundred percent too low, as shown by the test results in Figure 19.

The effect of stress history on the swell of a compacted sandy clay has also been shown to be large. If a sample is first exposed to water under a high surcharge and allowed to swell, and the sample is later unloaded to a low surcharge, the ultimate swell will be significantly less than if the sample had been subjected to a low surcharge on initial exposure to water. Such behavior precludes the use of the same sample for the determination of more than one point on a swell vs surcharge pressure curve or the prediction of swell from swell pressure data.

Finally, the roles of density, water content, soil structure, and the nature of the solution to which the soil is exposed in influencing the swelling characteristics of compacted clay were summarized. It was shown that swell and swell pressure increase with increasing density, decreasing water content, increasing randomness of structure (flocculent structure), and decreasing electrolyte concentration in the absorbed water. The data

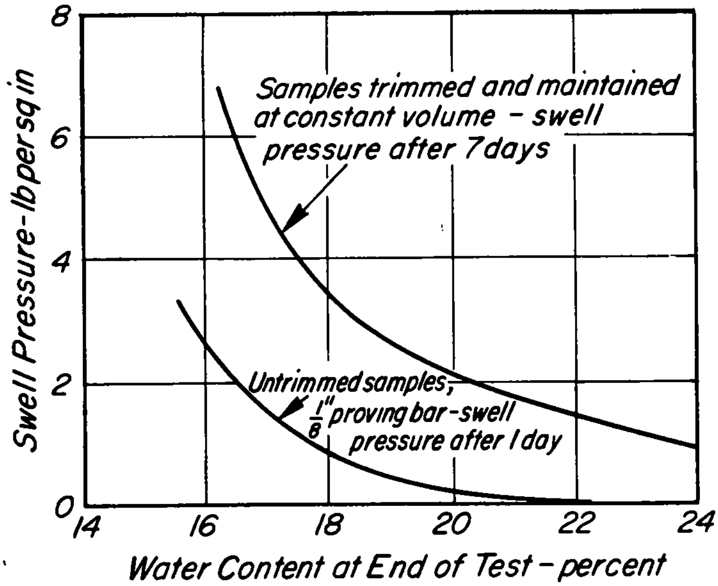


Figure 19. Range of observed swell pressures for similar samples of sandy clay tested under different conditions.

all appear consistent with known characteristics of compacted clays, physicochemical principles, and soil structure.

It is believed that recognition of the importance of the many factors controlling swell and swell pressure may aid in the selection of appropriate compaction conditions and in improved methods of predicting the effects of swelling in engineering practice.

ACKNOWLEDGMENTS

The test results summarized in this paper were obtained in the University of California, Soil Mechanics Laboratory over a period of several years and include the efforts of numerous former and present staff members and laboratory employees. The authors are particularly indebted to Professor C. L. Monismith, Mr. F. N. Finn, Mr. D. Clark, and Mr. D. R. Hooper for their assistance in performing many of the tests.

The appreciation of the authors is also extended to Mr. George Dierking who prepared the figures.

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