SOME SWELLING CHARACTERISTICS OF COMPACTED AND UNDISTURBED CLAYS

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SOME SWELLING CHARACTERISTICS OF COMPACTED

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CHAPTER I

INTRODUCTION

General

Many studies have been conducted relative to the prediction of one-dimensional and volumetric swelling characteristics of expansive clays. No parameter has been found to describe the relationship of vertical to horizontal swelling. For further investigation into the three-dimensional swelling characteristics of soils, a triaxial swelling apparatus had been developed in the school of Civil Engineering, Oklahoma State University by R. B. Fost (1, 1962) under the direction of Professor James V. Parcher. The apparatus is able to measure the vertical and horizontal rate and magnitude of swelling and the rate of water absorption. Seven new apparatuses have been made for this first stage of the study (Plate I shows some of these). A total of 190 samples have been tested, of which 177 are compacted samples prepared using three different methods of compaction--kneading, static and dynamic. The remainder are undisturbed samples taken from depths of about 9 feet and about 18 feet at the same location as some of the soils used in the compacted samples. All the tests were carried out under zero confining pressure. The main purposes of the investigation were to find the change in the swelling and swelling ratios corresponding to various initial conditions and modes of treatment, and to

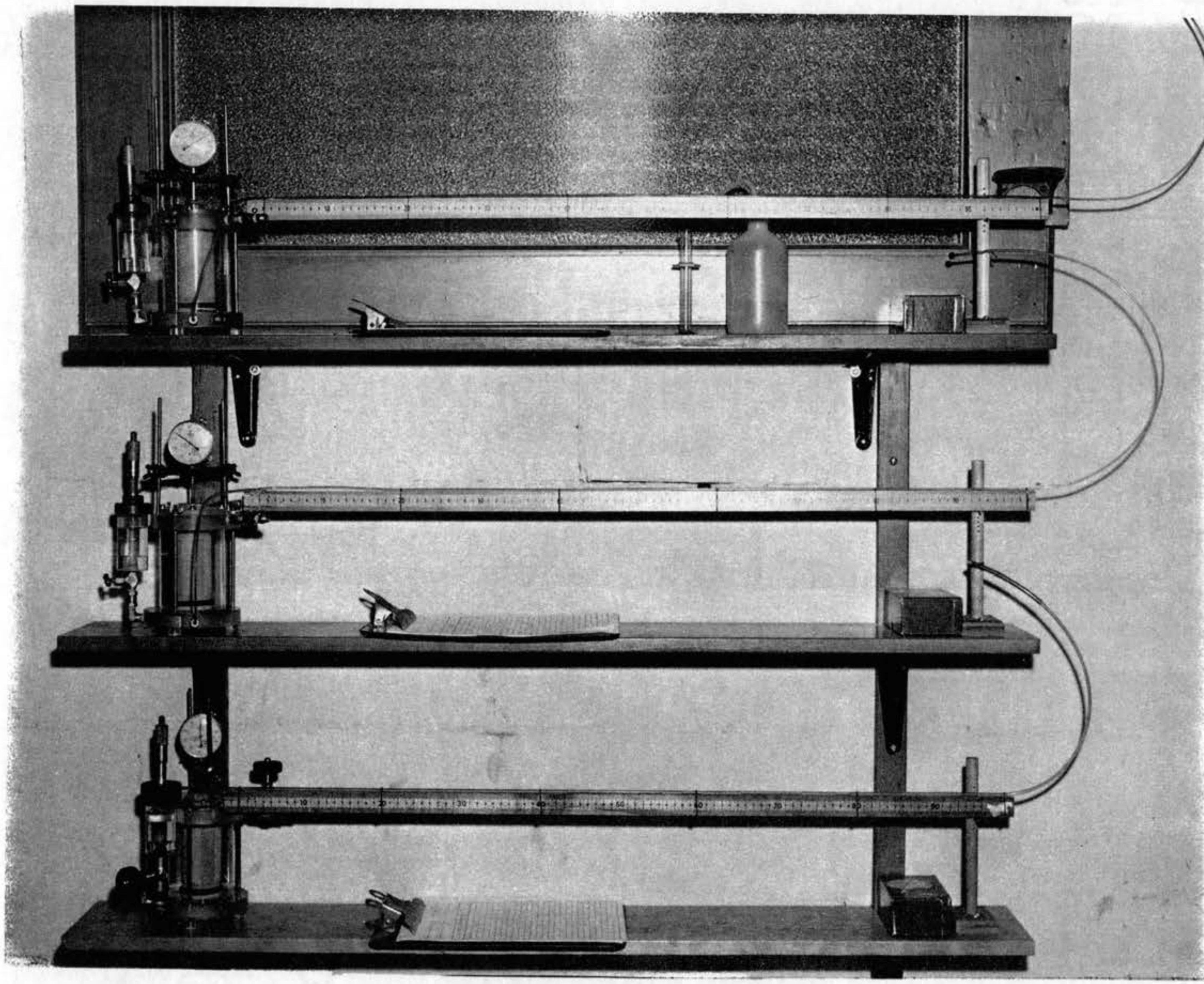


PLATE NO. I THREE TRIAXIAL SWELLING APPARATUSES compare the difference in the swelling characteristics of clay in the undisturbed and remolded states.

Origin of Investigation

From consulting experience in the expansive clay areas, Professors Means and Parcher have observed that the structural damage produced by the clays is not only caused by vertical swelling, but also by horizontal swelling. The effect of horizontal swell has been especially evident in buildings that have shallow broad continuous footings and foundation walls. In a one-story building in South Central Oklahoma, the outside foundation wall was rotated and displaced by uplift and horizontal swelling pressures, and a 4 inch horizontal crack was produced between partition and exterior wall (Means, 2, p. 177). In a college building in South Central Oklahoma, due to similar causes, a pipe tunnel running parallel to the exterior wall was forced outward and upward wrecking the panel wall to such an extent that it had to be completely torn out and replaced (2, p. 179). In an institutional building in southern Oklahoma, lateral expansion of clay fill had pushed the grade beams outward causing cracks about one-half inch wide between the floor and the beams (2, p. 180). It is hard properly to explain and analyze these phenomena without a complete understanding of the three-dimensional swelling characteristics of soils. In belled footing design, the clearance between drilled hole and the cast pile is the space reserved for horizontal swelling of the surrounding clays. Estimation of the amount of space to be provided lacks experimental and theoretical confirmation. When clay absorbs water it swells, a large portion of the absorbed water becoming double layer water. The condition of the adsorbed water on the particle edges is not clear. It is believed that correlations of particle size, particle shape, particle structure, degree of saturation and the swelling ratios can shed some light on this question. If so, the role of double layer water in the swelling process could be conceived a step further.

Historical Background

According to Terzaghi (3) the first law of swelling was derived by Katz in 1918. When Katz analyzed the relations existing between swelling-pressure, heat of swelling, relative vapor-pressure and volume contraction, he concluded that swelling is due entirely to physico-chemical reactions within the system. In 1931, Terzaghi (3) pointed out the importance of pure physical factors as contrasted to Katz' theory. Terzaghi shows that the pure physical factors such as elasticity, capillary force, hydrostatic pressure, and permeability have a decisive influence on the swelling process. These theories have provided the basis for further studies which have led to a deeper understanding of the swelling characteristics of clays by many scientists and engineers.

For the purpose of providing mental tools with which to analyze the volume changes of clay, physical concepts of clay expansion were also developed by Casagrande (4), Means (5), and Lambe and Whitman (6).

After an extensive study on the nature of the electric double layer on clay surfaces, Bolt (7) compared the theoretical and experimental results and emphasized the relative importance of the physical and physico-chemical factors which affect swelling. He pointed out that osmotic swelling (physico-chemical factor) will occur if the ionic distribution is favourable in a pure clay system. Mechanical swelling, if it occurs, will take place in addition to the osmotic swelling. Seed, Mitchell and Chan (8), from the effect of concentration of absorbed solution on the swell of sandy clay, found a definite amount of swelling which is most likely caused by mechanical factors.

Lambe (9, 10), from the standpoint of interparticle forces and the arrangement of particles has given a detailed criticism of the factors affecting the volume change of compacted clays. The effects of the ion concentration in the pore fluid on the behavior of compacted clay were studied by Ladd (11). He recognized a difference in the mechanisms of swelling for compacted clays having various initial moisture contents. Holtz and Gibbs (12) analyzed 28 kinds of clay and correlated the amount of volume change to colloid content, plasticity index, shrinkage limit and some other properties of clays. They suggested that relative swelling characteristics of clays might be predicted by the use of clay content, plasticity index, and shrinkage limit as indicators of expansion characteristics. Extending the work which had been done by Holtz and Gibbs, Seed, Woodward and Lundgren (13) developed a more reliable means of predicting the potential expansion characteristics of compacted clays. The influence of soil structure on swell and swell pressure, and the influence of kneading and static compaction on swell and shrinkage were studied by Seed and Chan (14). Compacted clay with a flocculent structure is found to have greater swelling tendency than does clay having a dispersed structure. The vertical swell pressure exerted by a statically compacted specimen is higher than that of specimens compacted by kneading.

The significant effect of soil structure on the engineering properties of soils was first recognized by Terzaghi. With almost the same physical concept of soil structure, Casagrande (4) presented a theory of honeycomb structure and was among the first to explain the difference of physical properties of clay in the natural and remolded states. According to Rosenqvist (15), the unstable card-house structure of highly sensitive clays was expressed by Goldschmidt in 1926 from the geochemical point of view. An open structure similar to Goldschmidt's card-house structure was advanced by Lambe in 1953. In 1957, T. K. Tan presented a schematic picture of a clay network dominated by contacts between a corner of one particle and the face of another. Using electron microscopy, Rosenqvist (1959) proved that the mineral particle arrangement in undisturbed marine clays really corresponds to the card-house structure, and in fact exactly corresponds to the imaginative drawing of Tan.

Mitchell (16, 17) by special petrographic microscopy investigated relations of soil structure and physical properties of both marine and fresh water clays. Pacey (18), using techniques similar to those of Mitchell, clarified the change in particle orientation of compacted clay produced by variations in the molding moisture contents.

CHAPTER II

SWELLING CHARACTERISTICS OF CLAYS

In order to understand the swelling characteristics of compacted and undisturbed clays (including vertical and horizontal swelling ratios) the factors which affect the swelling characteristics will be summarized according to the literature reviewed. Since the engineering properties of clay in the remolded and undisturbed states are basically different, the swelling characteristics pertaining to those states will be discussed separately.

Swelling Characteristics of Compacted Clay

The swelling characteristics of compacted clays are mainly governed by the following factors.

1. Composition of clay
2. Initial moisture content
3. Soil structure
4. Availability of water, and its chemical properties
5. Effect of confining pressure on swelling
6. Curing period
7. Time period required for swelling
8. Temperature

Composition of Clay

So-called expansive soil generally contains sand, silt and clay. The sand and silt size particles have only a minor effect on the swelling. The clay size particles are largely responsible for swelling, both from the physico-chemical and the purely physical points of view.

Most of the clay minerals have sheet or layered structures. Some of them have elongated tubular or fibrous structures. Generally, clay particles possess negative charges on their broad surfaces, while the edges of the particles are positively charged. The over-all, or net, particle charge, however, is negative. The exchangeable cations which accompany the clay particles are attracted to the particle as a result of the negative charge. These cations and their water of hydration, together with the system of adsorbed water molecules, take up space and thus tend to keep particles apart. Osmotic pressure is created by the difference in ionic concentration in the vicinity of clay particle and in the free water. Osmotic pressure causes water to flow from the point of low concentration to the point of high concentration. Swelling due to osmotic pressure difference is called osmotic swelling. When soil is compacted, the soil particles may be deformed due to elastic compression of solid particles, or by bending of the flaky grains. The soil particles may be held in their deformed positions by either external loading or by negative pore pressure effects. Swelling due to the release of the stresses causing such elastic deformations is purely mechanical.

There are many different kinds of clay minerals having a variety of physico-chemical properties. About 15 minerals are ordinarily classed as clay mineral (Karr, 19). These belong to four main groups: Kaolin, Montmorillonite, Illite and Polygorskite. The major differences in the physico-chemical properties and crystalline structure of the first three groups will be reviewed according to Grim (20) and Leonards (21).

a. Kaolin -- The kaolinite structural unit is an alumina octahedral layer with a parallel superimposed silica tetrahedral layer. This unit is about 7 Å thick, and may extend indefinitely in the other two directions. The kaolinite mineral grains are stacks of such 7 Å sheets. The structure is like that of a book with each leaf 7 Å thick in thickness. Successive 7 Å layers are held together with hydrogen bonds. There is substantially no substitution of one cation for another within the kaolinite structure. It forms very stable clays because the tight inexpandible crystalline structure resists the introduction of water into the lattices.

b. Montmorillonite -- The montmorillonite structural unit is an octahedral sheet sandwiched between two silica sheets. The thickness of the unit is about 9.5 Å, and as in the case of kaolinite, the dimensions in the other two directions are indefinite. The octahedral sheet may contain aluminum, iron, magnesium, or a combination of these atoms. There are a considerable number of isomorphous substitutions within the structure, always producing a net positive charge deficiency. This deficiency is balanced by adsorbed cations which are held on the outside of the sheets, and which in general are readily exchangeable.

The 9.5 Å sheets are stacked one above the other like the leaves of a book. There is very little bonding force between successive sheets; and thus an unstable mineral results, especially in the presence of water. In fact, the attached water molecules easily insert themselves between the sheets causing swelling. In such cases, individual montmorillonite flakes are enclosed in water films. The soils containing substantial amounts of montmorillonite will exhibit high shrinkage and swelling characteristics, depending on the nature of exchangeable cations present.

c. Illite -- The structure of illite is similar to that of montmorillonite except that there is always considerable replacement of silicon by aluminum atoms in the silica sheet (20% $\pm$), resulting in a residual negative charge somewhat larger than that of the montmorillonite unit. However, a substantial fraction of this negative charge is balanced by nonexchangeable potassium (K^+) ions. The bonds with the nonexchangeable K^+ ions are weaker than the hydrogen bonds that link the units of the kaolinite crystal, but they are much stronger than the exchangeable ionic bonds present in the montmorillonite crystal. Accordingly, the illite structure does not swell because of the movement of water between the sheets, as is the case for montmorillonite.

The bonds between soil particles composed of clay minerals will be greatly affected by the magnitude of the net residual negative charge on the minerals, and by the type, concentration, and distribution of cations that are available to balance this charge.

In soils and clays the usual adsorbed cations are calcium, magnesium, sodium, potassium, hydrogen, aluminum, and iron. Calcium, in the presence of an abundance of water tends to develop very well oriented water to a thickness of about four molecular layers with any additional water being unoriented. In general, Mg^{++} exerts about the same influence as Ca^{++}. The sodium ion tends to develop a very thick layer (probably 10 molecular layers) under the same conditions. Obviously,

Na^+ clays have very high swelling potential. K^+, H^+, Al^{++}, and Fe^{++} in nature form tight bonds between particles, with a very small potential for the growth of thick oriented water layers (Grim, 22). A single molecular layer of water is about 2.55 Å in thickness (Grim, 23, p. 170).

Soils containing montmorillonite swell much more than soils containing illite. The total expansion observed by Bolt in a sodium montmorillonite suspended in 10^{-3} molar sodium chloride over the pressure range of $0.1 \sim 100$ atmospheres was about six times larger than that for a sodium illite in a similar environment (7, 24, 25). As with adsorbed water, the double layer water is thicker on kaolinite than montmorillonite because of higher charge density on kaolinite. The thickness of the double layer water for a particular kaolinite particle (10,000 Å by 1,000 Å) and a particular montmorillonite particle (1,000 Å by 10 Å) is 400 Å and 200 Å respectively (Lambe, 10). Thus for unit thickness of the particle, the double layer of the montmorillonite is 50 times thicker than that of a kaolinite particle.

Initial Moisture Content

Under a specified compaction method, the most important factor which will affect the density of compacted soil is the initial moisture content. The relations of initial moisture content, dry density and percentage of expansion are introduced by Holtz and Gibbs. Figure 1 shows the results of load-expansion tests (using the consolidometer) on "Porterville clays" from the Delta-Mendota Canal. The effects of initial moisture content on dry density, double layer thickness, particle orientation, pore water tension and degree of saturation are

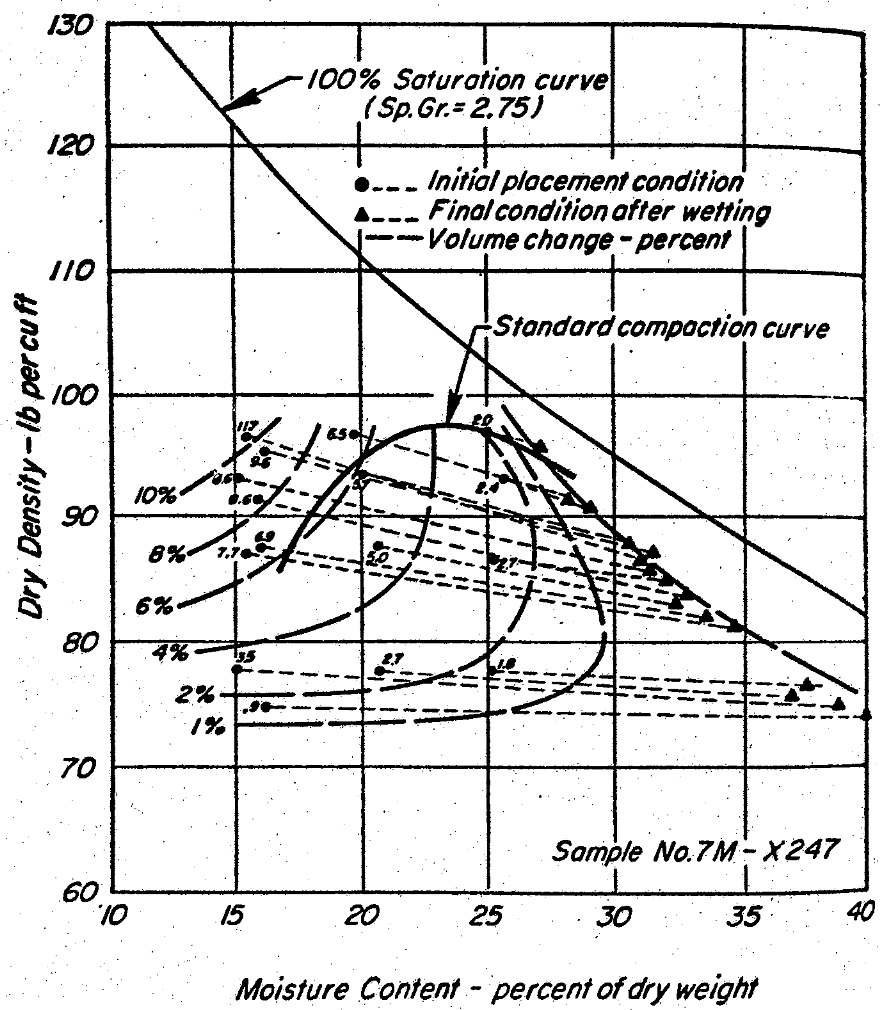


FIGURE 1. PERCENTAGE OF EXPANSION FOR VARIOUS PLACEMENT CONDITIONS WHEN UNDER 1 LB PER SQ. IN. LOAD (From Holtz and Gibbs, after Seed, Woodward and Lundgren, 13)

thoroughly discussed by Ladd (11). In general, the effects of initial water content on the swelling characteristics of clays are as follows:

a. For a constant moisture content, the higher the dry density, the greater the amount of swell. The effect is more pronounced at the lower moisture contents.

b. For a constant dry density, the lower the moisture content, the greater the amount of swell. The effect is more pronounced at higher densities.

c. For samples compacted wet of optimum water content, swelling can be explained by osmotic repulsive pressure arising from the difference in ion concentration in the double layer water between interacting clay particles and that in the free pore water. And for samples compacted dry of optimum water content, swelling is influenced by factors in addition to osmotic pressures. These other factors may be: the effect of negative electric and London-van der Waals force fields on water, cation hydration and the attraction of the particle surface for water, elastic rebound of particles, a flocculated particle orientation, and the presence of air (Ladd, 11).

Soil Structure

In compacted clay the structure will be affected by changing the initial moisture content, compaction method or compactive effort. The arrangement of the clay particles in a compacted soil, as originally conceived by Lambe (10), is illustrated in Fig. 2. The change in arrangement at different stages of the density-water content relationship are explained as follows by reference to Figure 2. At point A there is not sufficient water for the diffuse double layers of the soil

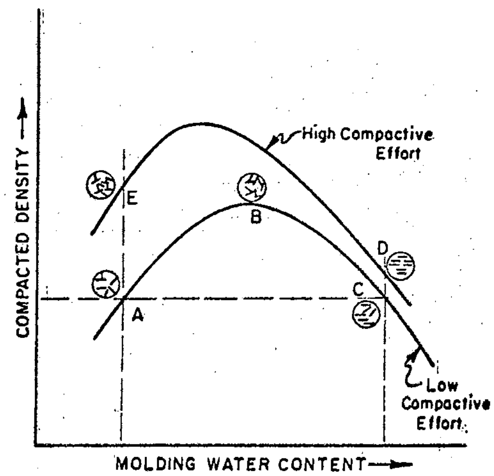


FIGURE 2. EFFECT OF COMPACTION ON SOIL STRUCTURE (From T. W. Lambe) (After Seed and Chan, 14)

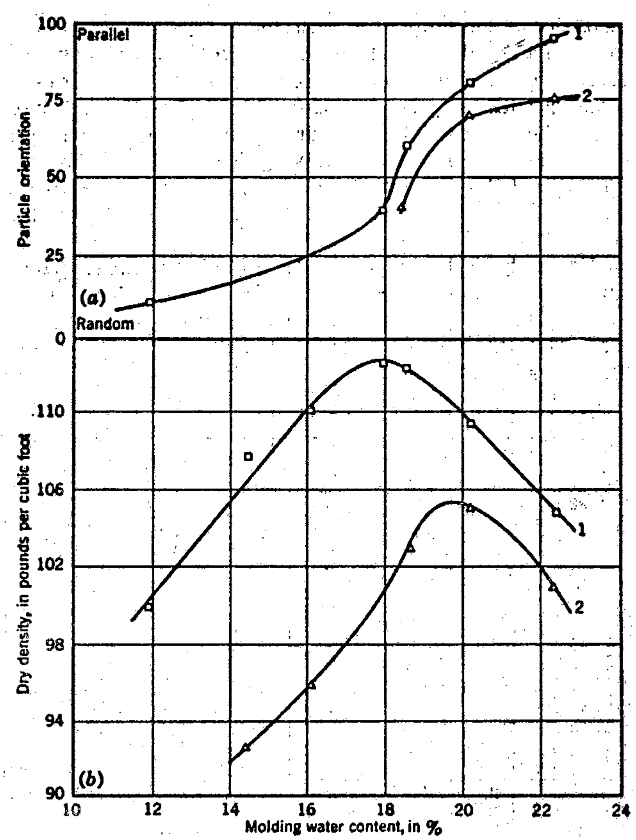


FIGURE 3. ORIENTATION VERSUS WATER CONTENT FOR BOSTON BLUE CLAY (After Lambe, 10)

colloids to develop fully. Actually, the small amount of water present at A gives a very high concentration of electrolyte which depresses the double layer. The double layer depression reduces the interparticle repulsion, causing a tendency toward flocculation of the colloids. Increasing the molding water from point A to B expands the double layers around the soil particles and also reduces the electrolyte concentration. The reduced degree of flocculation permits a more orderly arrangement of particles and a higher density. A further increase of water from point B to C results in a further expansion of the double layer and a continued reduction in the net attractive forces between particles. Even though a more orderly arrangement of particles exist at C than B, the density of C is lower because the added water has diluted the concentration of soil particles per unit of volume. The greater the compactive effort the more nearly parallel are the clay particles.

The change in the degree of particle orientation corresponding to various initial moisture contents, as originally measured by Pacey (18), is shown in Fig. 3. The relationships indicate that the degree of particle orientation is increased as the initial moisture content or the compactive effort increases. These conclusions are in agreement with Lambe's explanations.

The influence of particle arrangement on the swelling of compacted clay has also been studied by Seed and Chan (14). Their conclusions follow:

a. Samples compacted dry of optimum exhibit higher swelling characteristics and swell to higher water content than do samples of the same density compacted wet of optimum. Thus the increased swell might be interpreted as a manifestation of the greater swelling tendency of soils having a flocculated structure than those having a dispersed structure.

b. Different compaction methods will create different soil structures for the same initial moisture content and dry density. The results of swelling pressure tests show that the pressures exerted by statically compacted specimens exceed those of specimens of equal densities and water contents prepared by kneading compaction, indicating a greater degree of flocculation in the specimens prepared by static compaction (Fig. 4).

Availability of Water and its Chemical Properties

Clay will swell, or shrink, only if there is a change in moisture content. In clay-chemical mixes (such as the mixture of permian clay and sodium hydroxide), the volume expansion due to the growth of new crystals also requires water as a medium. When a compacted clay sample is put in contact with water, any air-water menisci at the surface of the sample are broken. Water will flow into the clay because of pore water tensions within the sample, these tensions having been caused by a combination of double-layer deficiencies and capillary effects. If water is continuously available during the swelling process, the clay will swell continuously and the thickness of double-layer water increase, until the repulsive force minus the attractive force between particles is in equilibrium with any applied effective stress.

That the chemical properties of the pore fluid have a decided effect on the swelling behavior of compacted clay has been proved by Ladd (11) and by Seed, Mitchell and Chan (8). Their conclusions are

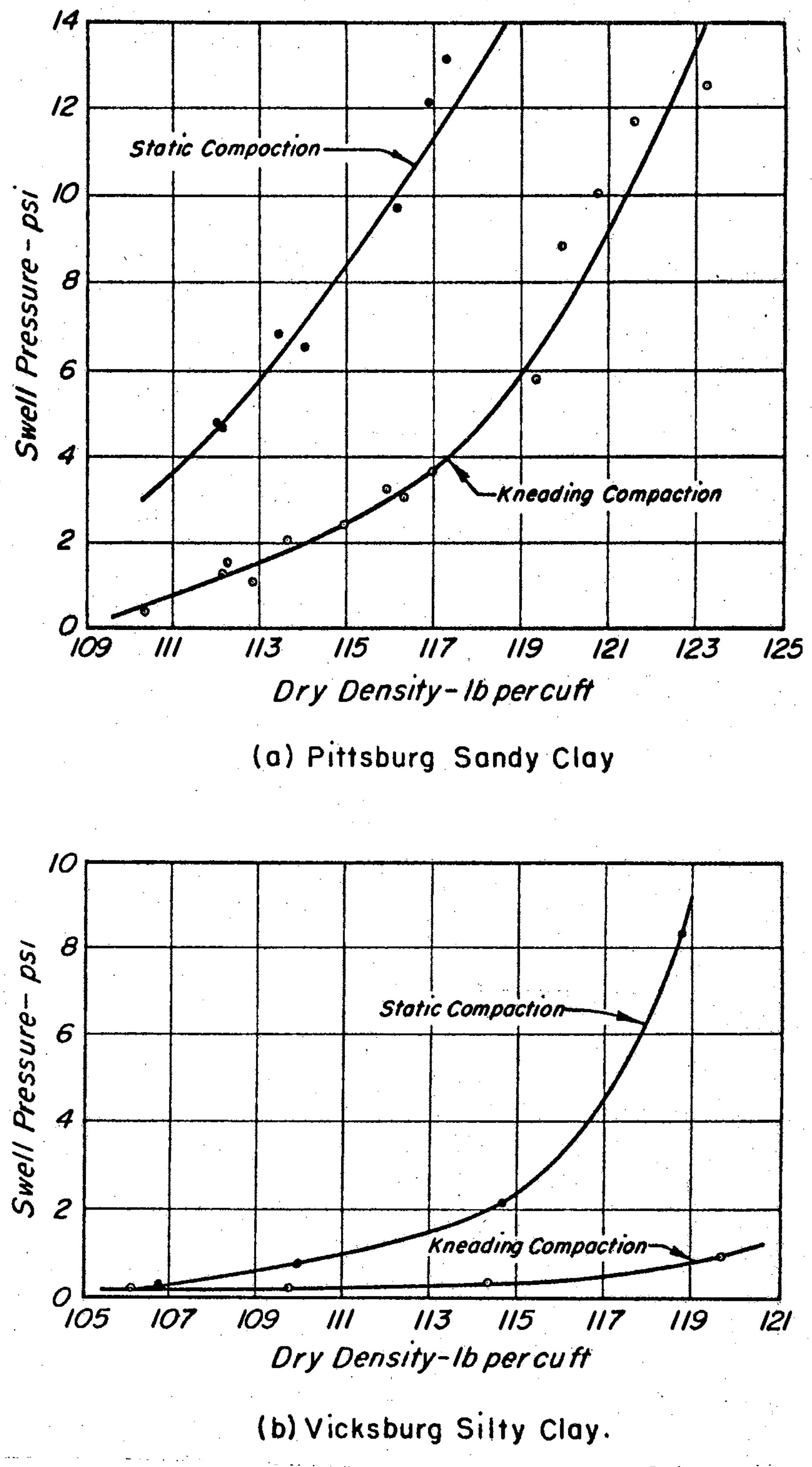


FIGURE 4. EFFECT OF METHOD OF COMPACTION ON SWELL PRESSURE FOR SAMPLES COMPACTED TO HIGH DEGREE OF SATURATION. (After Seed, Mitchell and Chan, 8).

presented in the following paragraphs.

a. The soaking of compacted samples in salt solutions (calcium chloride) produces a marked decrease in the amount of fluid pickup and heaving. The absolute magnitude of this reduction in fluid pickup and heaving is fairly uniform, particularly for the stronger salt solutions.

b. The initial rate of swelling is practically unaffected by the salt concentration in the soaking solution.

c. The amount of swell decreased as the electrolyte concentration increased, but it appears to reach a constant value of about 1.1 percent above a concentration of about 1.5 Normal (for 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).

Hemwall and Low's data (26) also show that an increase of electrolyte concentration in the pore fluid is more effective in decreasing the volume change when the confining pressure is low.

Effect of Confining Pressure on Swelling

The swelling pressure of the system results from those physico-chemical and mechanical factors which compel the liquid phase to enter the system. The swelling pressure can be balanced by applying an equal confining pressure to the sample when it is subjected to conditions which initiate swelling. Seed, Mitchell and Chan (8) showed that the final swelling pressure will be rapidly decreased as the specimen is allowed to swell.

Curing Period

According to Barber's data (27) the effect of curing period on the swelling pressure is as shown in Fig. 5 (after Seed etc.). It shows that the swelling pressure decreases as the time interval between compaction and testing increases. Similarly, we may expect that the amount of swell will be proportionally decreased with longer curing periods.

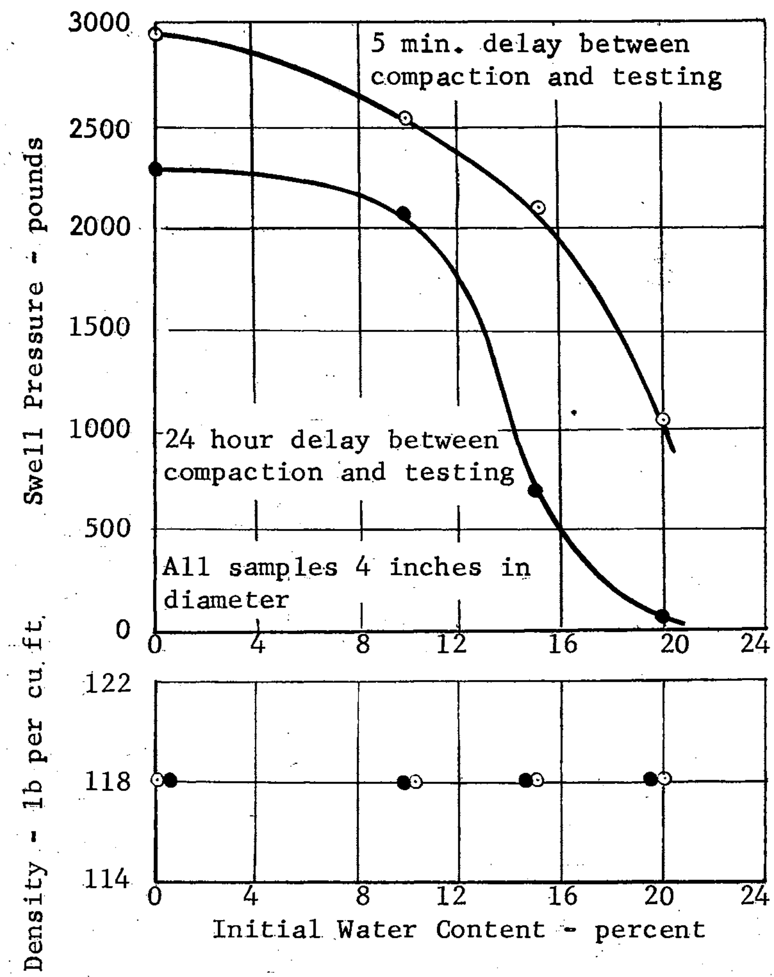


FIGURE 5. EFFECT OF INTERVAL BETWEEN COMPACTION AND TESTING ON SWELL PRESSURE RECORDED AT CONSTANT VOLUME. (Values from E. S. Barber, 1956.) (After Seed, Mitchell and Chan, 8.)

Time Period Required for Swelling

When a compacted soil is supplied with water, time is required for the movement of water into the sample and consequent swelling. The degree of swelling depends upon the amount of water available, and upon the ability of the soil to absorb water. The time required for water to enter into a swelling clay system is analogous to that required for water to escape from a consolidating system. The time is proportional to the permeability of soil. For a given soil and permeant, factors affecting the permeability can be expressed by the Kozeny-Carman equation,

$$K = \frac{1}{R_o S^2} \frac{e^3}{1+e}$$

where, K = Absolute permeability

R_o = Constant depending on pore shape and tortuosity of flow

S = Specific surface

e = Void ratio

According to Lambe (10) soil compacted on the dry side of optimum has a much higher permeability than that on the wet side (Fig. 6 and 7). Since the sample compacted dry of optimum has a more random orientation of particles, it has more large pores than does the sample with the more nearly parallel arrangement of particles resulting from wet-side compaction. The larger the individual pores for any given total pore volume, the greater is the flow, since permeability varies as a power function of the opening size. On the dry side, permeability is rapidly reduced as the molding water content increases. The minimum permeability is likely created at optimum moisture content. After reaching this

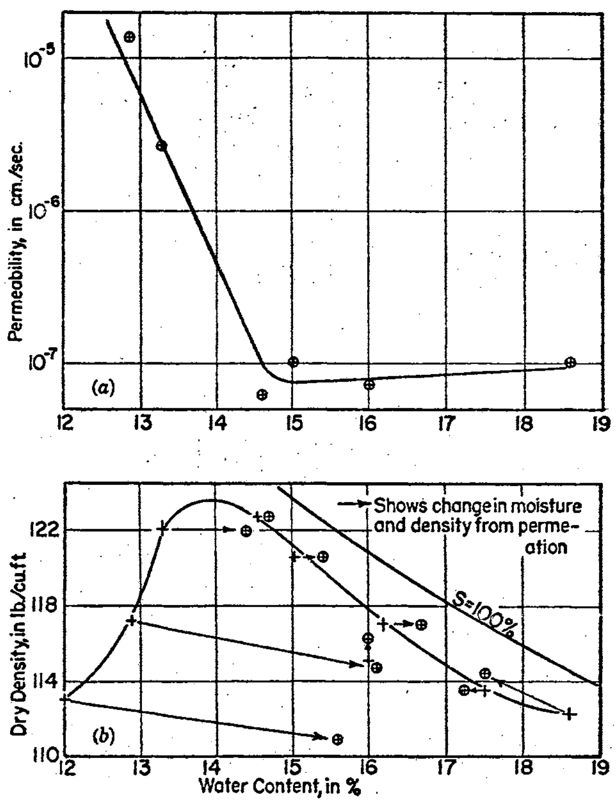


FIGURE 6. COMPACTION-PERMEABILITY TESTS ON JAMAICA SANDY CLAY (After Lambe, 10)

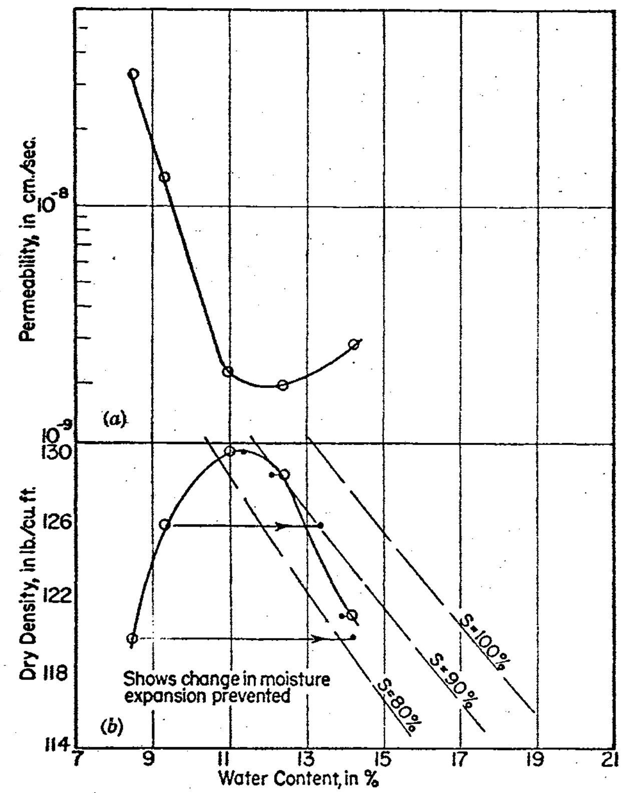


FIGURE 7. COMPACTION-PERMEABILITY TESTS ON SIBURUA CLAY (After Lambe, 10)

minimum point the permeability has only a slight increment.

Temperature

The effect of temperature on clay expansion was investigated by Lambe (10, p. 725). A sample of Boston blue clay was consolidated at a temperature of 20°C; the temperature was then raised to 41°C while the load was held constant; and finally the temperature was lowered again to 20°C under constant load. The results showed that under constant load, the clay compressed with a temperature increase and expanded with a temperature decrease. This illustrates that an increase in temperature will depress the double layer, and a decrease in temperature will expand the double layer.

Swelling Characteristics of Undisturbed Clay

General

When Casagrande (4) presented his paper "The Structure of Clay and Its Importance in Foundation Engineering" one of his valuable conclusions was "Do not disturb the natural structure of the clay; if you do, no human-being is able to restore its original strength." Before petrographic and electron microscopes were used for studying soil structure, the particle arrangement of clays was envisioned according to certain assumptions. The importance of the influence of soil structure was proved experimentally. The development of improved investigative tools has largely verified what before had been only imagined or arrived at by inference. It has been disclosed that the particles of a clay exist in a card-house structure arrangement (Fig. 8 and 9).

The formation of natural clay is complicated. Due to such factors

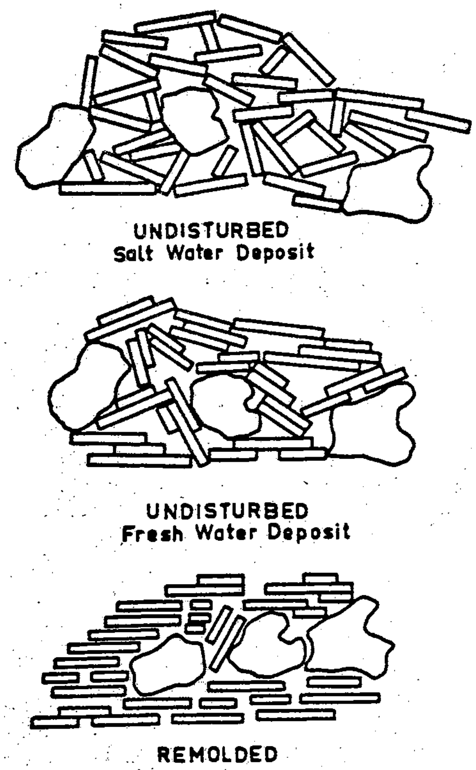


FIGURE 8. THE GOLDSCHMIDT-LAMBE CONCEPT OF CARDHOUSE STRUCTURE, REDRAWN FROM T. WILLIAM LAMBE: THE STRUCTURE OF INORGANIC SOILS. (After Rosenqvist, 15.)

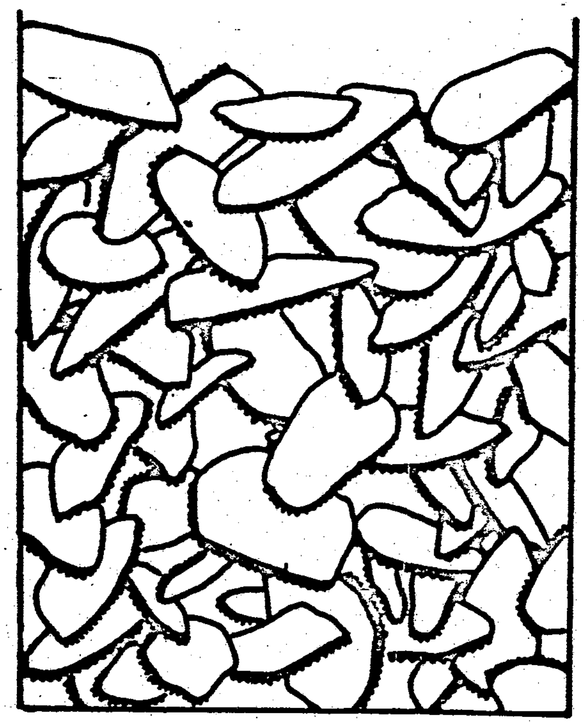


FIGURE 9. SCHEMATIC PICTURE OF CLAY (T. K. Tan, 1957) (After Rosenqvist, 15.)

as long stress history and diagenetic cementation of soil particles, the natural clay structure can never be reconstructed once it has been disturbed. It was mentioned earlier that the evident change of engineering properties of clay in the natural and remolded states has been recognized for a long time. Some causes of these differences are discussed in the following sections.

Stress History

In natural clay deposits which have existed for thousands of years, one can easily imagine that there have been great variations in the stresses which have acted on the soil. Although the effect of the stress history on the swelling potential of natural clays is probably incapable of prediction, Seed, Mitchell, and Chan (8) have investigated these effects in the case of compacted clays.

During long period of consolidation, or desiccation, the contact surfaces of the particles may become closer. Whether the particles in the undisturbed clay ever completely touch is not known; however, they probably approach to within about 3 Å (Lambe, 9) of each other which is many times less than the average particle spacing given by the water content divided by the specific surface (Mitchell, 16).

Diagenetic Cementation

Natural clay particles may be recombined or rearranged due to compression under their own weight, or due to high temperatures which may arise.

In such a way, smaller crystalline grains may form a larger grain; or particles may become stronger and more closely attached.

According to Mitchell (16) cementation between particles may also be formed by cementing agencies such as carbonates and oxides. It is found that some clays have at least 1 percent by weight of free iron oxide, and some clays have significant carbonate mineral contents. In the case of iron oxide it is quite likely that all the material is present as particle coatings and cement at contact points. Carbonate, however, may be present both as a cementing agent and as mineral particles (calcite, dolomite, magnesite).

CHAPTER III

LABORATORY PROCEDURES AND DATA

Physical Properties of Permian Clay

A natural permian clay obtained on the O.S.U. campus, Stillwater, was used in all tests. Two origins from which soils for compaction purpose were obtained are: (a) Life Science Building -- from a depth of about 3 feet at center portion of its basement, or about 11 feet below the original ground surface; (b) New Engineering Building -- from depths about 9 and 18 feet near its northeast corner. The two buildings are about 200 feet apart. The undisturbed samples were taken at same locations as (b). The soils used for compaction were dried, pulverized, and screened through a No. 30 sieve. The physical properties of soils were determined and the results were as shown in Table I. Figure 10 shows the grain size distribution obtained from a hydrometer analysis of the soil.

TABLE I

PHYSICAL PROPERTIES OF SOILS

Origin	(a) Life Science Building	(b-1) Engineering Bldg. (9 ft. depth)	(b-2) Engineering Bldg. (18 ft. depth)
Liquid limit	40.5	51.0	41.0
Plastic limit	15.0	19.0	15.1
Plastic index	25.5	32.0	25.9
Specific gravity	2.72	2.78	2.72
Clay content	24.5	26.0	36.0
Activity	1.04	1.23	0.72

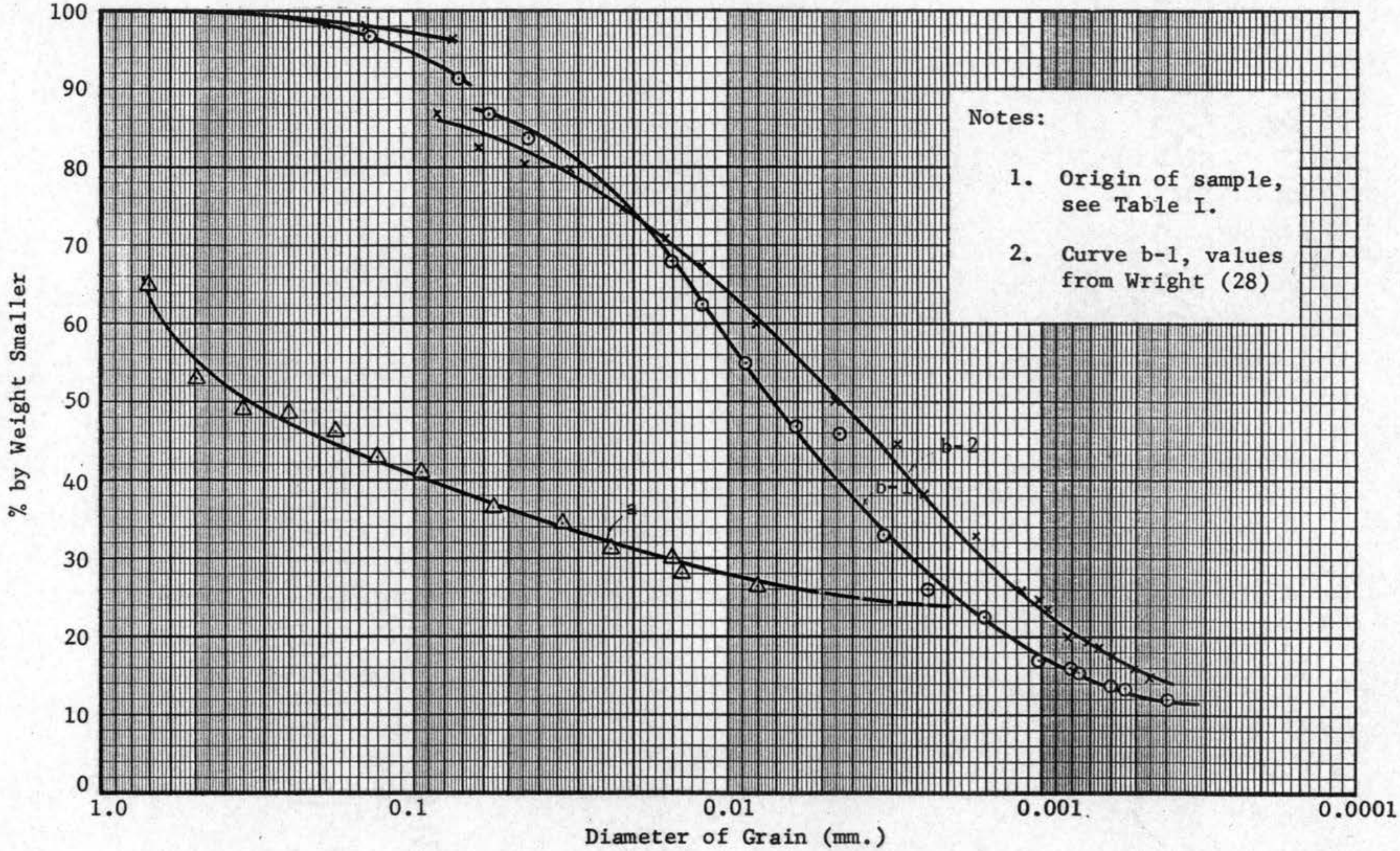


FIGURE 10. GRAIN SIZE DISTRIBUTION CURVES

Triaxial Swelling Apparatus

The triaxial swelling apparatus permits the magnitute of one-dimensional or three-dimensional swelling to be estimated either with or without the presence of confining pressure. This study involved only the case of free triaxial swelling.

The apparatus is made principally of plexiglas. One of the characteristics of plexiglas--water absorptivity--has an influence on the results of swelling measurements. Three plexiglas plates (1.0 x 1.0 x 0.2 inch) each with a different surface roughness were tested for water absorptivity (Fig. 11). When the plates are submerged in water, the rate of water absorption is proportional to their surface roughness; and when they are dried in the air after being wetted, the rate of evaporation is also proportional to their surface roughness. However, the difference in the rate due to surface roughness is not very significant. By rough estimation, the maximum water absorption of the plexiglas is 0.6 percent by weight. During swelling measurement the influence of water absorptivity of the plexiglas is eliminated by a correction value from a calibration curve (Figs. 12 to 17). ΔR_H in the figures represents the correction to be applied to measurements of horizontal swelling. No correction is needed for vertical swelling. The rate of water absorption of plexiglas varies with time according to its degree of saturation (Fig. 11), and the calibration value therefore varies with respect to the time. Consequently, the correction value for horizontal swelling is chosen according to the time of test and the time required for swelling.

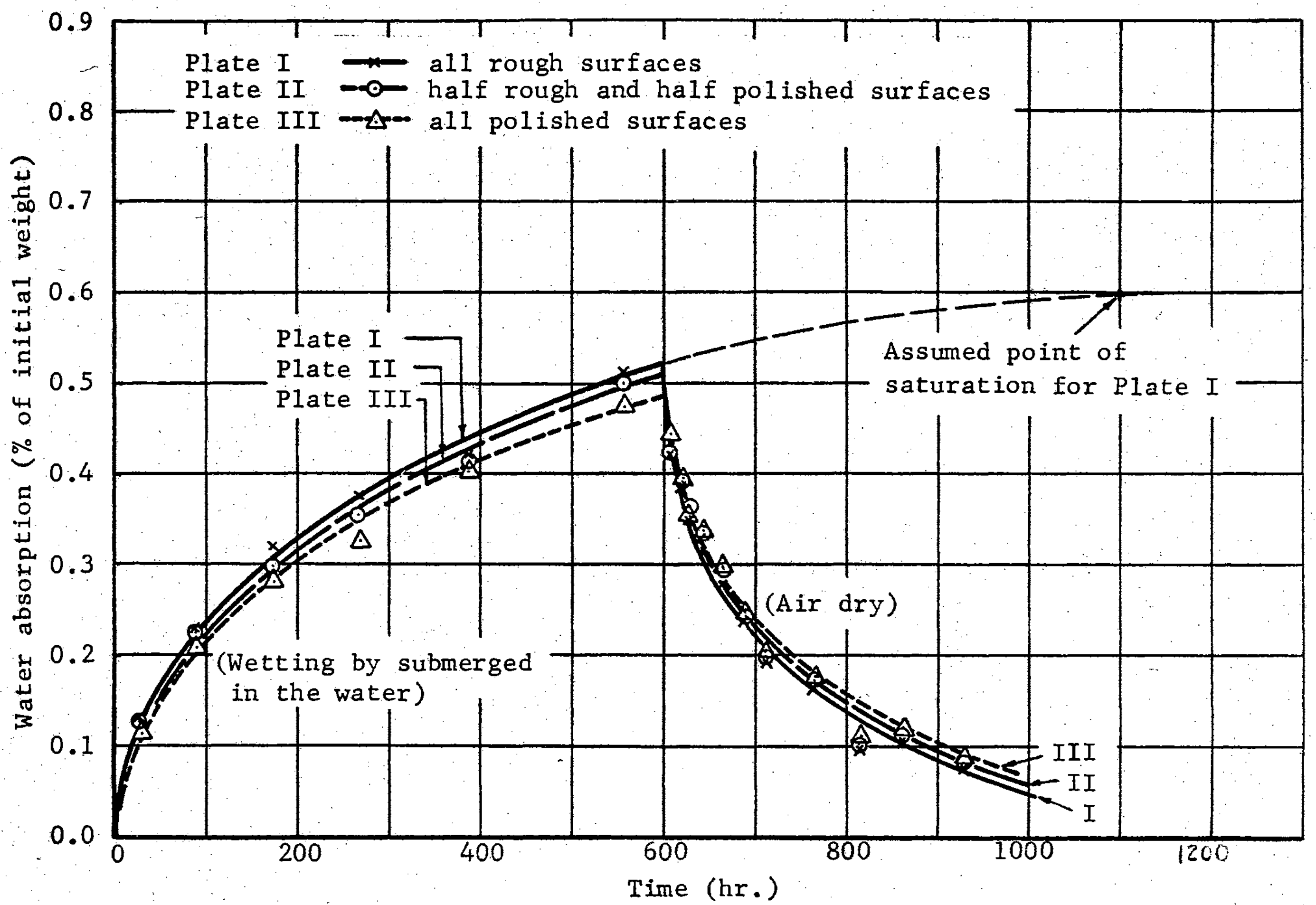


FIGURE 11. WATER ABSORPTIVITY CURVES FOR PLEXIGLAS

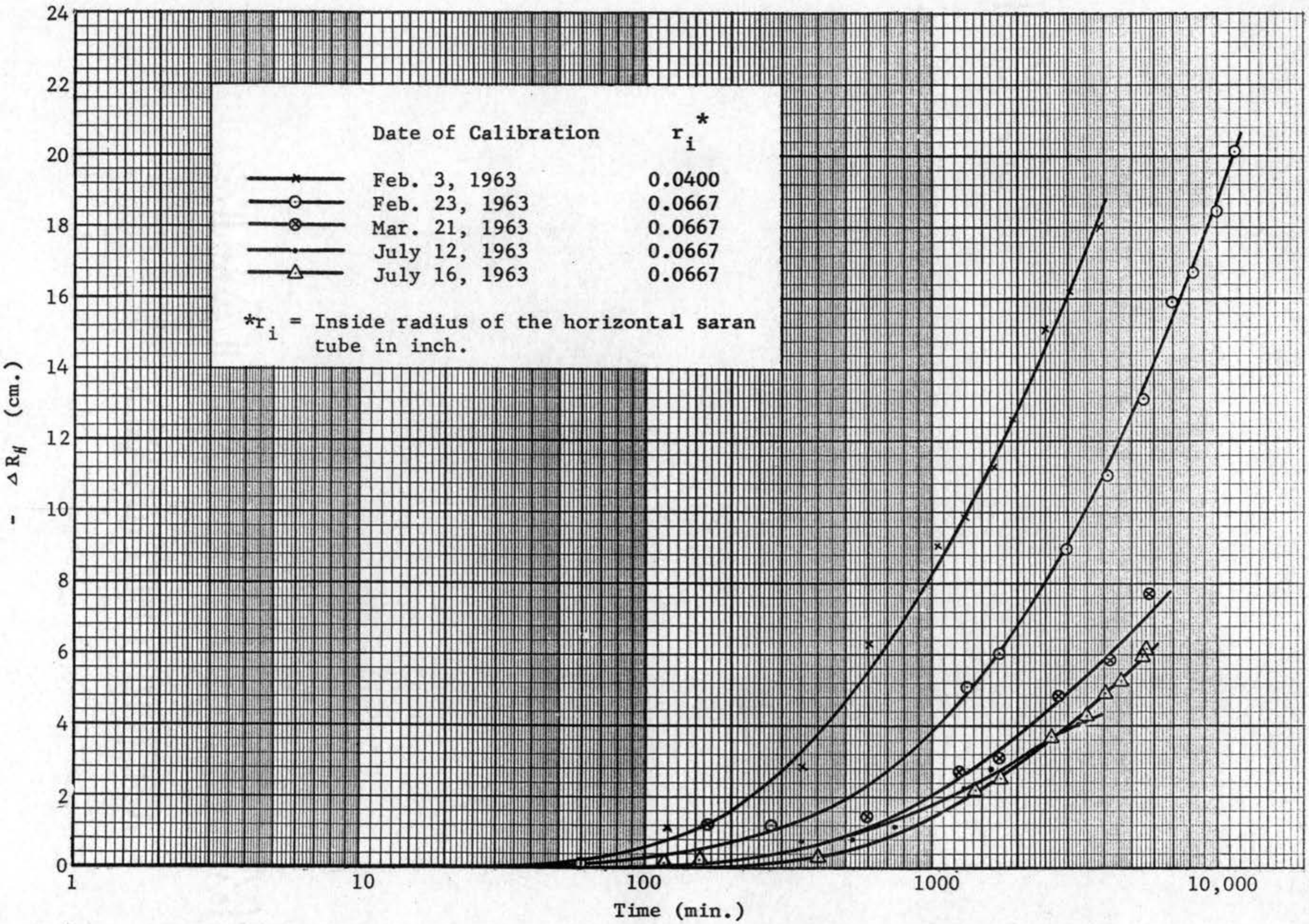


FIGURE 12. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 1

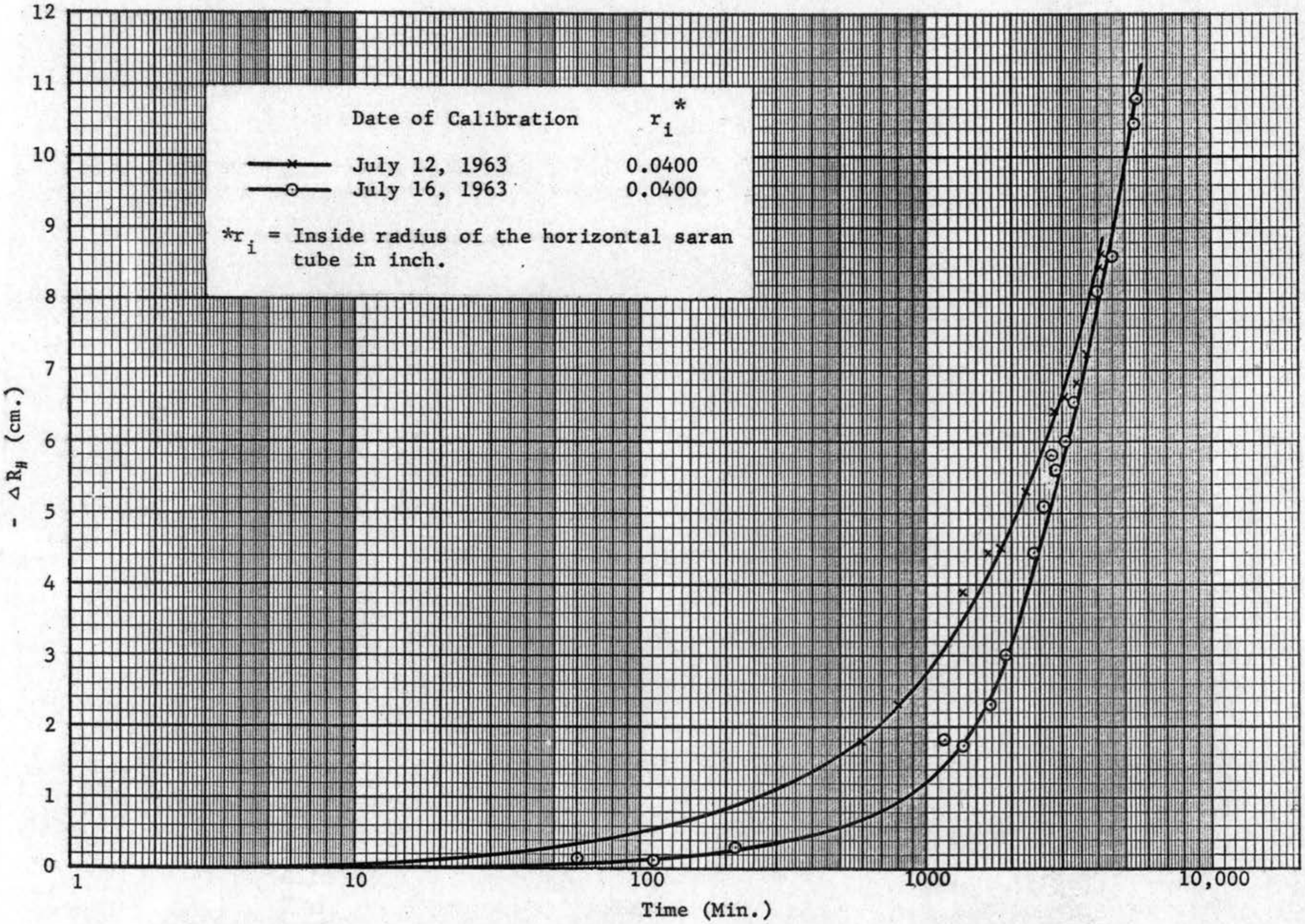


FIGURE 13. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 2

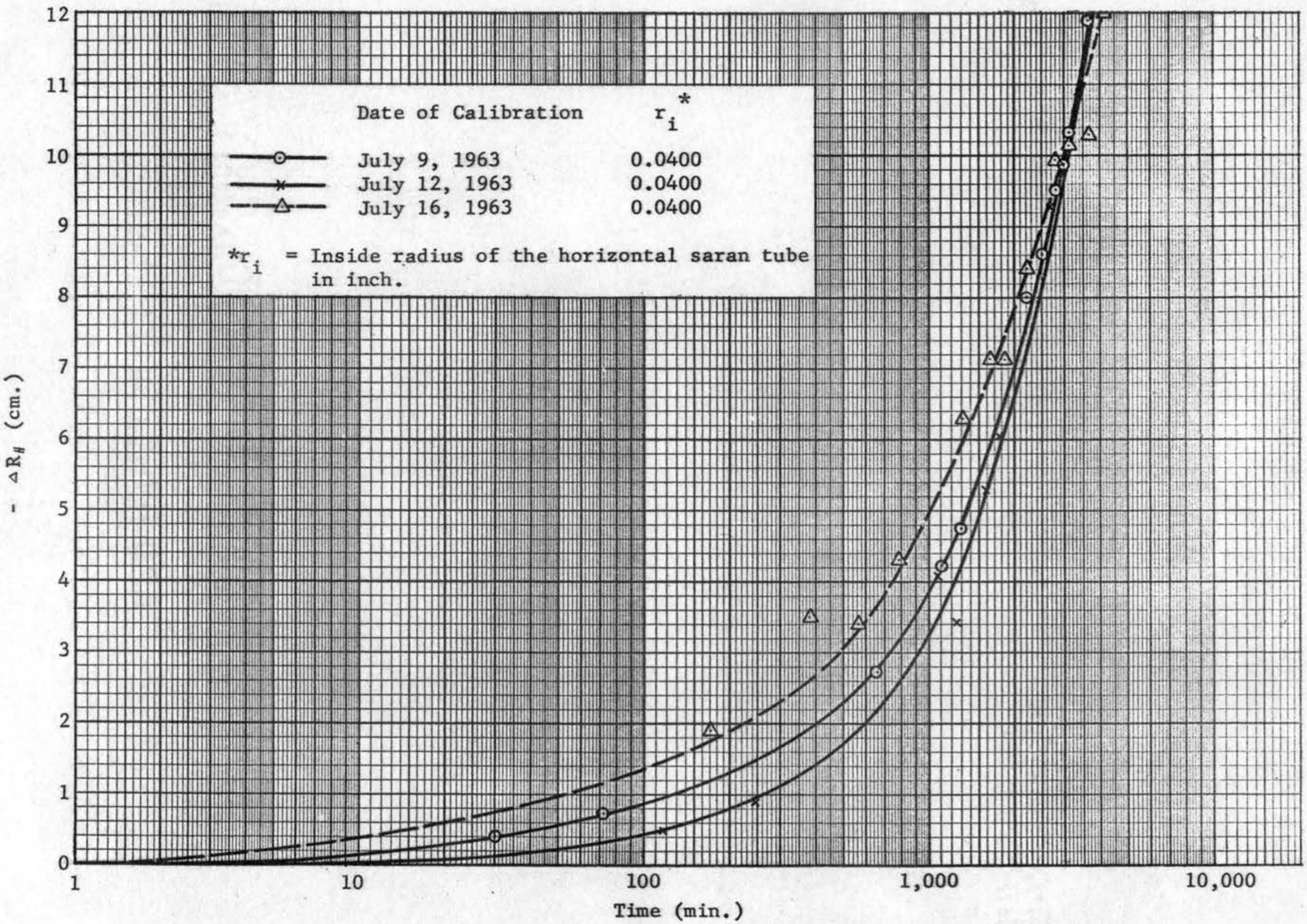


FIGURE 14. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 3

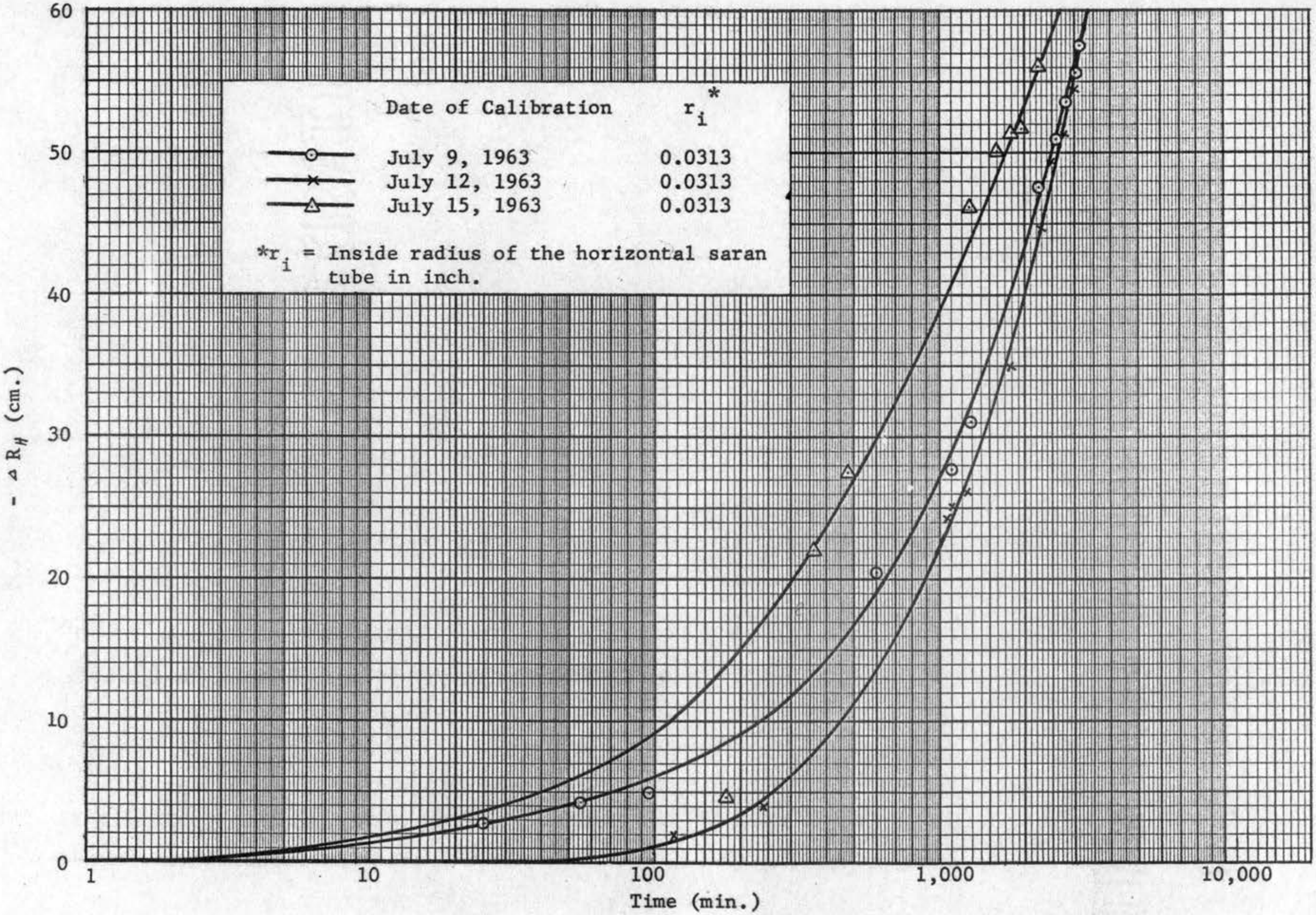


FIGURE 15. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 4

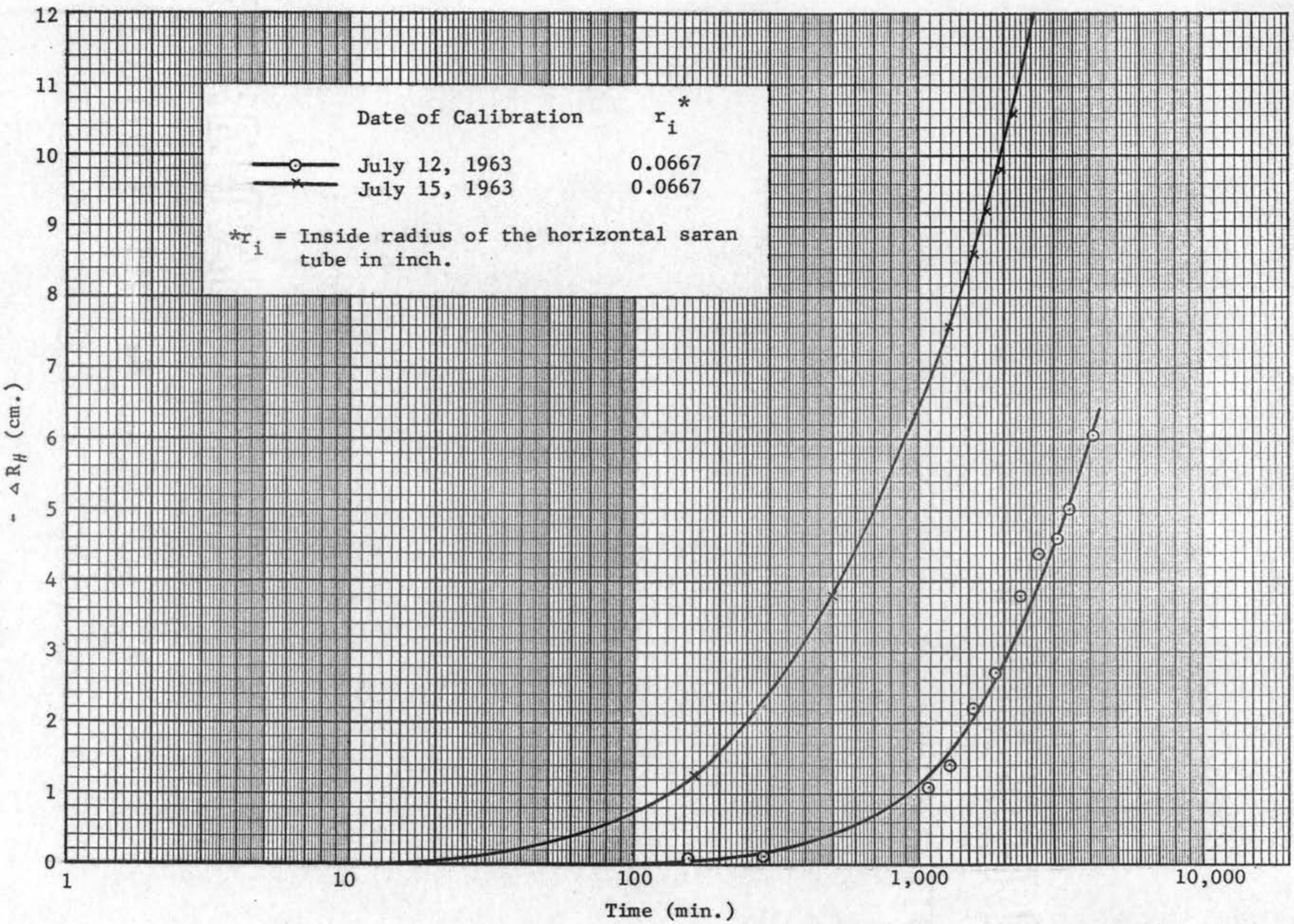


FIGURE 16. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 5

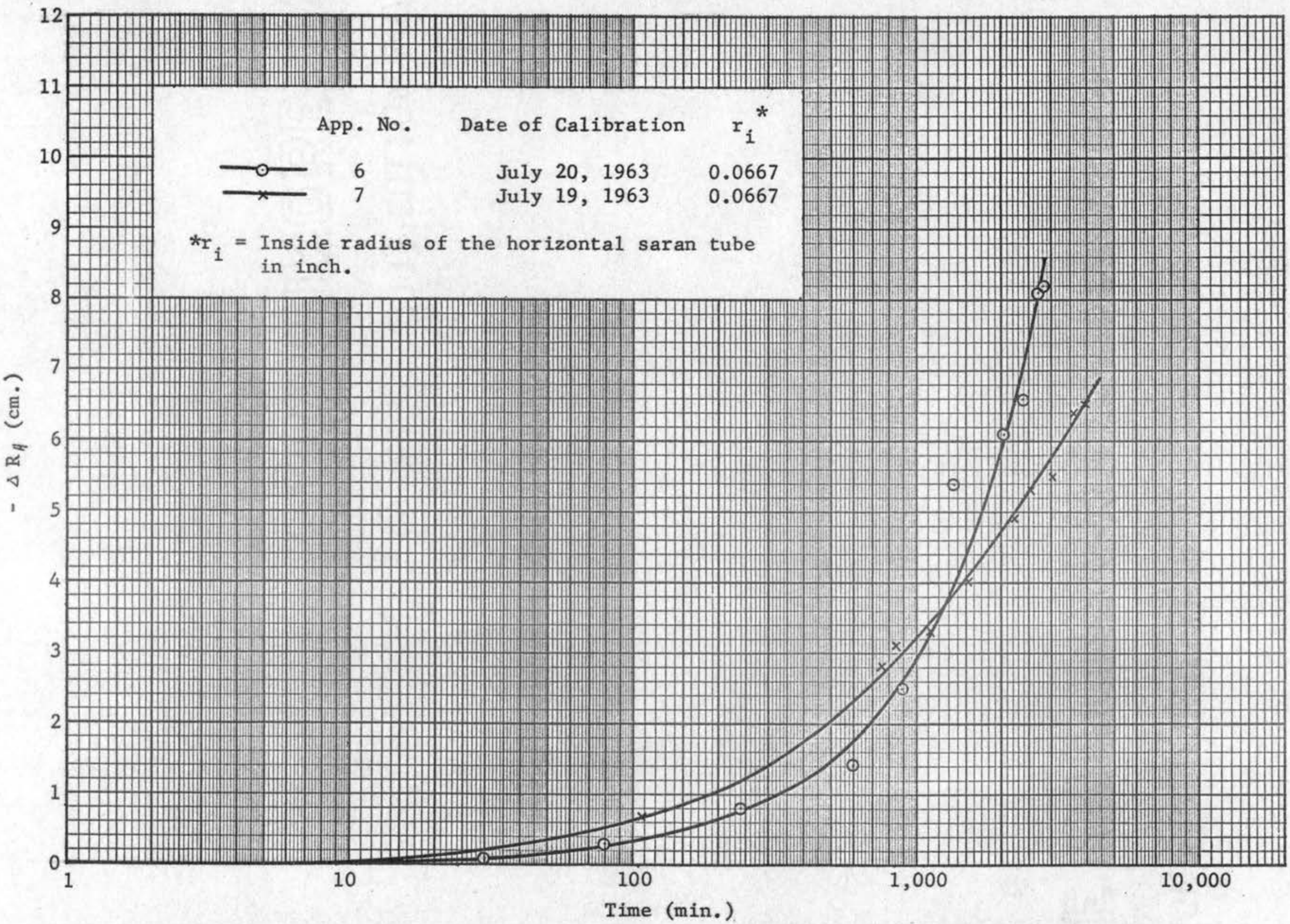


FIGURE 17. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 6 AND NO. 7

Kneading Compaction Method

The kneading compaction specimens were compacted in a cylindrical mold 1.4 inches in diameter and 2.8 inches long, using the Harvard miniature compaction equipment. Soils were moistened with distilled water. The initial moisture content was varied in a series of samples prepared using constant compaction energy. An effort was made to have at least three different initial moisture contents in the series -- one about equal to the optimum moisture content of the permian clay, another about three percent higher, and another about three percent lower than optimum. The tamping forces used were 20, 40 and 60 pounds. Generally, a specimen was compacted in three layers, using 25 tamps for each layer. The number of layers was increased to 5 for one special series. For better control in the uniformity of samples, all samples of a given series were compacted at the same time. After compaction and extrusion, the specimens were immediately wrapped in saran sheeting and aluminum foil and dipped in molten microcrystalline wax to form a wax coating about 1/16 inch thick. Identifying labels were attached to the specimens which were then stored in a room in which a high humidity was maintained. The samples were then tested as soon as possible. In this study, the effect of curing period on swelling is not considered.

For comparison of the swelling characteristics of samples prepared using different compaction methods, equivalent samples having practically the same initial water content and dry density were made by both kneading and static compaction methods, and dynamic and static compaction methods. For comparison of the swelling characteristics of clay in the undisturbed and remolded states, a remolded sample equivalent in moisture content and density to an undisturbed sample was prepared using kneading compaction. The undisturbed sample was taken from a depth of 9 feet near the northeast corner of New Engineering Building, and it has an initial moisture content of 22.1 percent and a dry density of 1.680 grs./cu. cm. Utilizing trimmings of the undisturbed sample, an equivalent sample was compacted by a spring-tamper of 20 pounds strength, using a total of 25 layers with 25 tamps on each layer. The equivalent sample had an initial moisture content of 22.1 percent, and a dry density of 1.688 grm./cu. cm.

Static Compaction Method

The static compaction apparatus shown in Plate II was designed and manufactured at Oklahoma State University. A hydraulic compression machine used for static compaction is shown in Plate III. The compaction apparatus shown in Plate II is made of plexiglas. It includes a compaction cylinder 1.4 inches in inside diameter and 5.6 inches long, two compression pistons, and an extrusion rod. The soil is compacted inside the compaction tube from both ends by the two pistons. The pistons are pressed gradually into the tube using the hydraulic compression machine, and 2.8 inches of clearance between top and bottom pistons exists when the pistons reach their final positions. After the final positions are reached, the pistons are kept stationary for more than a minute to allow the compressed air to escape from inside the cylinder.

The sample was made equivalent to a sample prepared using kneading or dynamic compaction by using an equal amount of soil from same batch.

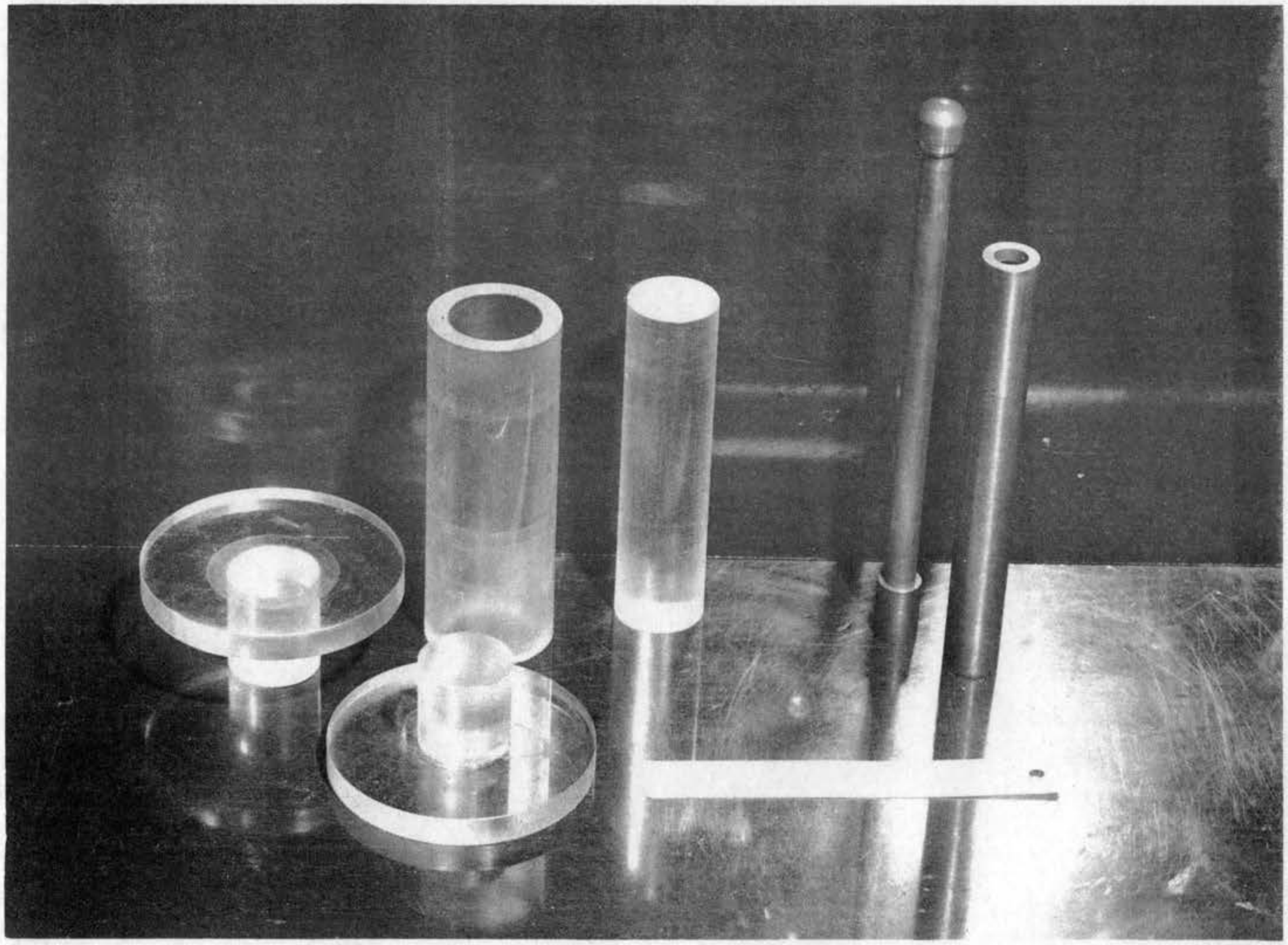


PLATE NO. II STATIC COMPACTION APPARATUS AND A DROP HAMMER FOR DYNAMIC COMPACTION

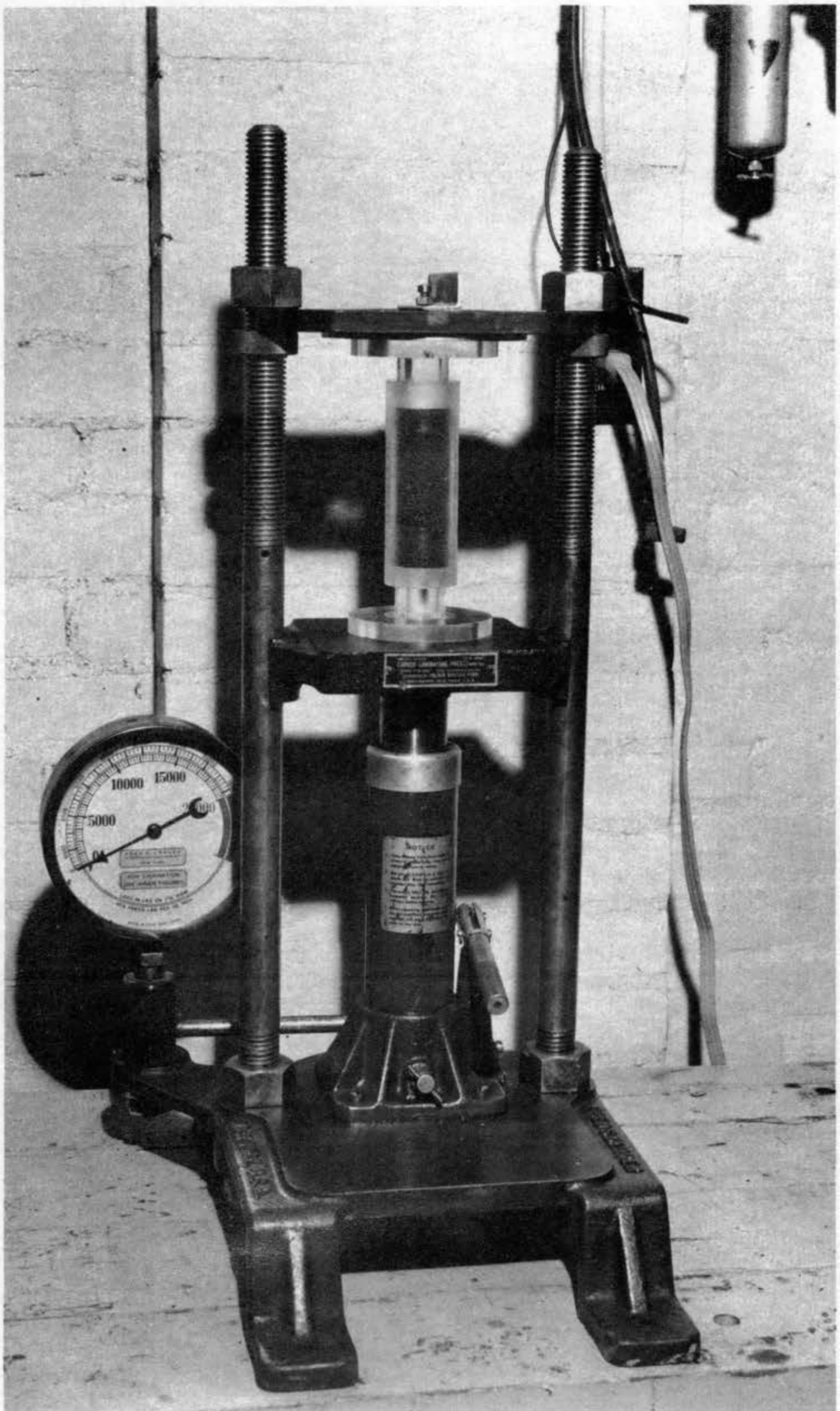


PLATE NO. III HYDRAULIC COMPRESSION MACHINE USED IN THE STATIC COMPACTION

The work was carried out as rapidly as possible in an air conditioned laboratory. The maximum deviation of the initial moisture content between equivalent samples was 0.5 percent, although simple precautions against evaporation were taken.

Dynamic Compaction Method

For the purpose of utilizing the same compaction mold as was used in the kneading compaction method, a small drop hammer was designed and manufactured at Oklahoma State University (Plate II). The drop hammer will deliver the same compaction energy to a unit volume of soil as is used in the standard AASHO compaction test. The miniature compaction apparatus consists of a mold having a volume of 1/400 cu. ft. The drop hammer was made of brass having a milled face 0.7 in. in diameter and weighing 0.825 lbs. An arrangement is provided for lifting the hammer 6 in. and allowing a free fall to the surface of the soil.

Different compaction efforts were applied to two groups of samples. In one group the soil was compacted in three lifts using 25 blows for each lift. In the other group the soil was placed in three lifts using 50 blows for each lift. For the latter group equivalent static compaction samples were made. The treatment after compaction was the same as described for kneading compaction.

Triaxial Swelling Test Procedures

The procedures for triaxial swelling tests were originally suggested by Professor Parcher, and were further delineated by Fost (1). The following procedures were adopted for the work described here (refer to Fig. 18).

1. Deair the connection system between water reservoir (a) and the base plate (c), and pedestal (d) by flushing with distilled water. Place a porous stone (e), which has been previously deaired, in the recess provided in the top of the pedestal.

2. While the distilled water is still flowing from the reservoir through the porous stone, close the lower valve (b). Remove the excess water standing on the porous stone.

3. Four strips of filter paper of 1.5 cm. wide, and 8.0 cm. long, are applied on the side and bottom surfaces of specimen to accelerate the water flow during swelling.

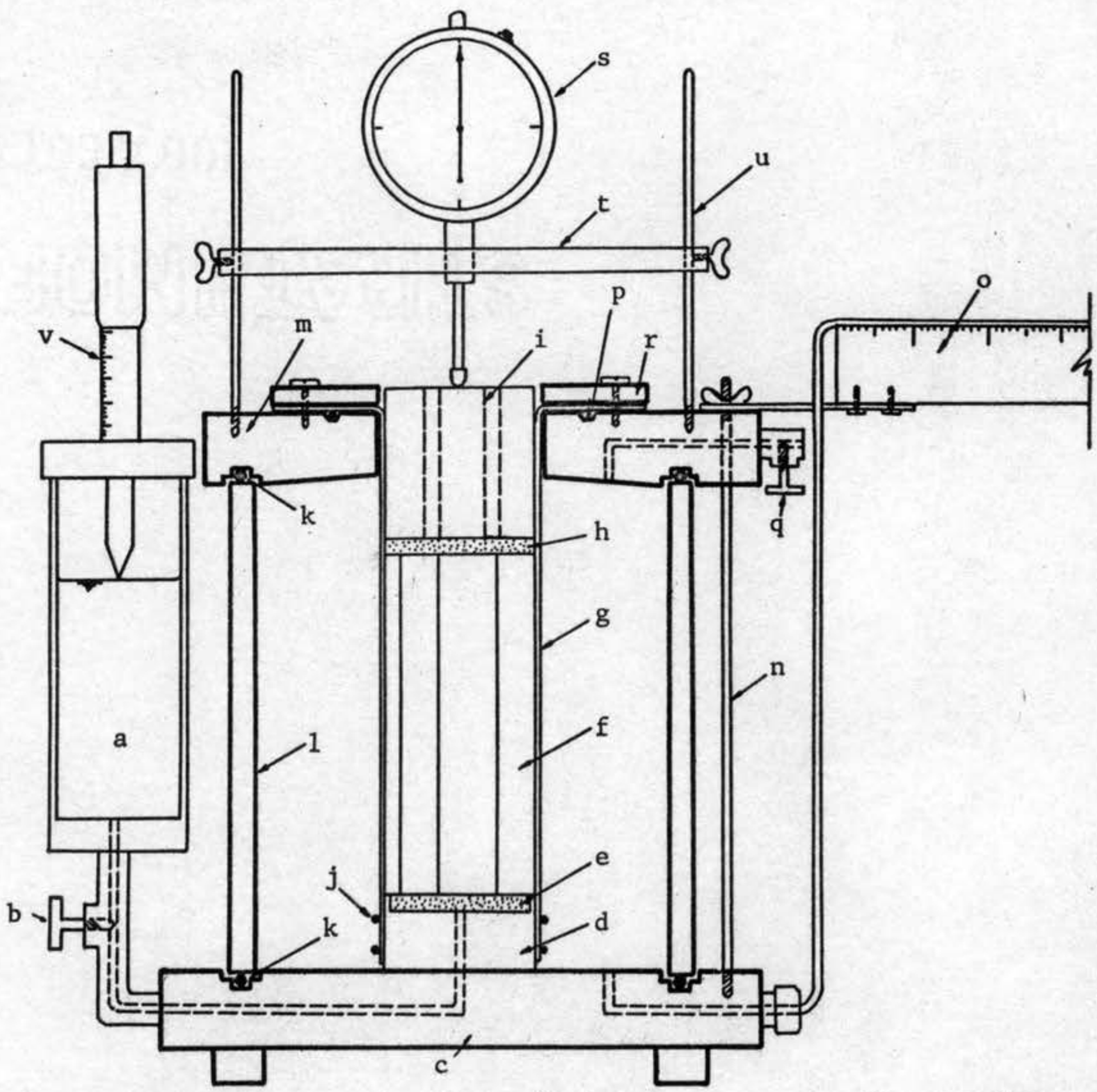
4. Enclose the specimen within the flanged membrane (g) by using a membrane stretcher. Place the specimen atop the pedestal, lapping the end of the membrane over the pedestal.

5. Place a dry porous stone (h), and the cap (i) on top of the specimen, then lap the upper end of the membrane over the cap.

6. Using the metal O-ring expander to expand and pass the O-rings down around the specimen, place two O-rings (j) over the bottom end of the membrane which overlap the pedestal.

7. Place the chamber sealing O-rings (k) into position. Set the chamber (l) into the centering groove in the base plate. Using the centering grooves as a guide, center the top plate (m) on the chamber, taking care not to jostle the cap as the top plate passes down around the cap. The flange of the membrane should be lying on top of the top plate upon completion of this step.

8. Insert the three vertical tie rods through the top plate and screw them into the base plate until finger tight. Next, after placing



a. Water reservoir
b. Lower valve
c. Base plate
d. Pedestal
e. Porous stone 1
f. Specimen
g. Flanged membrane
h. Porous stone 2
i. Cap
j. Lower O-ring membrane seal
k. O-ring chamber seal (top and bottom)
l. Chamber
m. Top plate
n. Vertical tie-rods
o. Meter stick
p. O-ring flange seal
q. Upper valve
r. Cover plate
s. Dial gage
t. Gage holder
u. Gage holder rods
v. Needle point micrometer water level gage

FIGURE 18. APPARATUS ASSEMBLED FOR TRIAXIAL SWELLING TEST

the meter stick hook over one of the rods, tighten all wing nuts until finger tight. Place the uppermost O-ring (p) in place on top of the top plate.

9. Fill the chamber with de-aired water through the base plate chamber connection until the water starts to seep from the top plate under the flange of the membrane. Close the upper valve (q), and at the same time stop the de-aired water supply.

10. Press the membrane flange to the top plate with the cover plate (r). Tighten the cover plate screws one-half turn at a time until the O-ring seal is effected. No air bubbles should remain inside the chamber system.

11. Remove the de-aired water supply line which is connected through the saran tube attached to the meter stick (o). Then adjust the liquid-air interface within the saran tube by discharging the water from the chamber using the upper valve (q). When the desired initial position of the interface is attained, close the upper valve.

12. Add distilled water to the water reservoir until it is about three-fourths full. With the needle-point micrometer water level gage affixed tightly over the reservoir, determine the initial level of the water.

13. Tightly screw the dial holder rods into the top plate and install the dial holder and dial gage (s) for measuring vertical deflection. Adjust the dial holder until the plunger is in contact with the cap. Take the initial dial reading.

14. Open the lower valve (b) to start the test.

15. Take readings of reservoir water level, vertical expansion, displaced chamber fluid, and time.

16. Readings are discontinued when the last 8 hours swelling is less than 1 percent of the magnitude of total swelling.

17. Drain the chamber fluid after closing open valves. This is done through the base plate chamber connection. Disassemble the apparatus.

18. Weigh the specimen, and also weigh after it is oven-dried at 105°C. Finally, the initial and final moisture content, dry density, swelling ratio, and volumetric swelling are calculated.

Swelling Ratio

The swelling ratio, as used in this study, is defined as the ratio of vertical to horizontal swelling of a specimen. According to the results of a triaxial swelling test, the swelling ratio is determined as following:

a. Vertical swelling

$$\mathcal{E}_v = \frac{\Delta H}{H} \times 100 = 14.08 \ \Delta H \ (\%)$$

where, $\mathcal{E}_v$ = Vertical swelling (%)

H = Initial sample height = 2.8 in. = 7.11 cm.

ΔH = Incremental vertical dial reading (cm.)

b. Horizontal swelling

When a sample swells, the part of incremental volume due to the horizontal swelling (ΔV_1) is equal to the volume of water that has been forced from the chamber (ΔV_2).

If, H' = Total sample height after swell (cm.)

r = Initial radius of the sample = 0.7 in. = 1.778 cm.

Δr = Incremental radius due to swelling (cm.)

ΔR_H = Incremental horizontal reading in the saran tube (cm.)

C = Capacity of the saran tube (c.c./cm.)

$\mathcal{E}_H$ = Horizontal swelling (%)

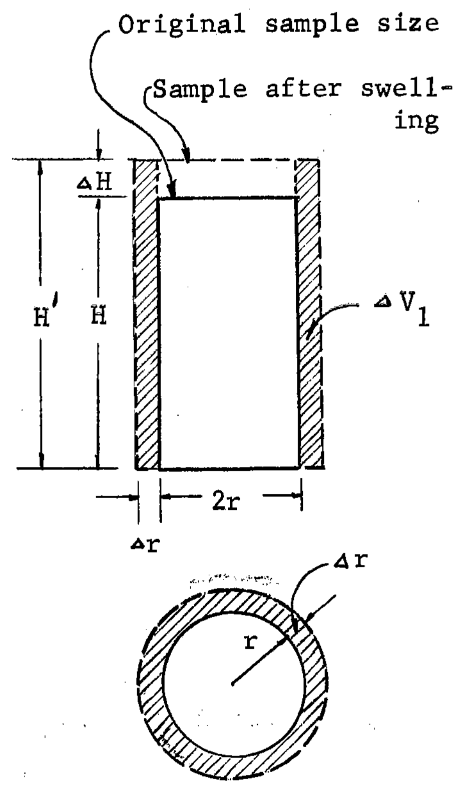


FIGURE 19. CROSS SECTIONS OF A SAMPLE

And, $\Delta V_1 = 2\pi(r + \frac{\Delta r}{2})\ \Delta r\ H'$

$\Delta V_2 = C\ \Delta R_H$

Setting $\Delta V_1 = \Delta V_2$, and neglecting the Δr term of second degree, we have

$$\Delta r = \frac{C\ \Delta R_H}{2\pi r H'}$$

Since, $\mathcal{E}_H = \frac{\Delta r}{r} \times 100$

$$H' = H + \Delta H = H\ (1 + 0.01\ \mathcal{E}v)$$

By substitution and solving for the horizontal swelling,

$$\mathcal{E}_H = \frac{C\ \Delta R_H}{2\pi r^2 H\ (1 + 0.01\ \mathcal{E}v)} \times 100$$

$$\mathcal{E}_H \doteq \frac{C\ \Delta R_H}{2\ \pi\ r^2\ H} \times 100$$

Saran tubing of three different sizes were used. The inside radii of the tubes are 0.0313, 0.0400, and 0.0667 in., and their capacities are 0.018, 0.049, and 0.091 c.c./cm. respectively.

Therefore,

$\mathcal{E}_H = 0.0128\ \ \Delta R_H$ (%) , for r_i = 0.0313 in.

$\mathcal{E}_H = 0.0348\ \ \Delta R_H$ (%) , for r_i = 0.0400 in.

$$\varepsilon_H = 0.0645 \ \Delta R_H \ (\%), \quad \text{for } r_i = 0.0667 \text{ in.}$$

where, r_i = Inside radius of the saran tube.

Volumetric Swelling

The volumetric swelling η is estimated according to the magnitude of vertical and horizontal swelling. As shown in Figure 20, the incremental swelling volume includes two parts ΔV_A, and ΔV_B.

$$\Delta V_A = \pi r^2 \Delta H$$

$$\Delta V_B = 2\pi(r + \frac{\Delta r}{2}) \Delta r \ H'$$

The total incremental volume,

$$\Delta V = \Delta V_A + \Delta V_B$$

And,

$$\eta = \frac{\Delta V}{V} \times 100 \ (\%)$$

$$= \frac{100}{V}\left[\pi r^2 \Delta H + 2\pi(r + \frac{\Delta r}{2}) \ (H + \Delta H) \ \Delta r\right]$$

where, V = Volume of original sample

η = Volumetric swelling (%)

Since, $V = \pi r^2 H$

$$\Delta H = H \ (0.01 \ \varepsilon_v)$$

$$\Delta r = r \ (0.01 \ \varepsilon_H)$$

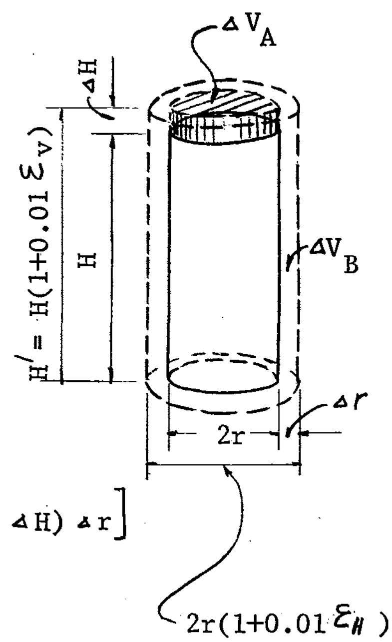


FIGURE 20. SKETCH OF SAMPLE SWELLING

By substitution and solving for the volumetric swelling,

$$\eta = \varepsilon_v + 2 \ (1 + 0.01 \ \varepsilon_v) \ (1 + 0.005 \ \varepsilon_H) \ \varepsilon_H$$

Water Absorption

The water absorbed by a sample during swelling is estimated from its initial and final moisture content. The rate of water absorption is estimated according to the change in water elevation of the reservoir. And the amount of the reservoir discharge is equal to that of absorbed water.

$$V_w = 20.95 \Delta R_\ell$$

where, V_w = Volume of absorbed water (c.c.)

ΔR_ℓ = The relative change in water elevation in the cylindrical reservoir of which the inside diameter is 3.24 cm. (1.275 in.)

CHAPTER IV

DISCUSSION OF LABORATORY TEST RESULTS

Time Period Required for Swelling

The time period required for swelling is related to the availability of water, and is proportional to the permeability of a specimen. In the beginning of the study, the triaxial swelling tests were carried out without filter strips. Later, filter strips were applied on the surfaces of the specimen to accelerate water flow during swelling. As shown in Figure 21, for two equivalent samples, the time period required for swelling without filter strips is at least 4 times longer than is required when filter strips are used. A test in which filter strips are used is generally accomplished in about 3 days. With the use of filter strips the test becomes more practical from the standpoint of time, and is also more reliable due to the lesser influence by environmental factors, such as temperature, humidity, and apparatus characteristics (Refer to the calibration curves, Figures 12-17).

Effects of Initial Water Content on Swelling and Swelling Ratio

The initial water content was varied in a series of compacted samples which were prepared using the same method of compaction and equal compaction energy. The results of this series of tests show that

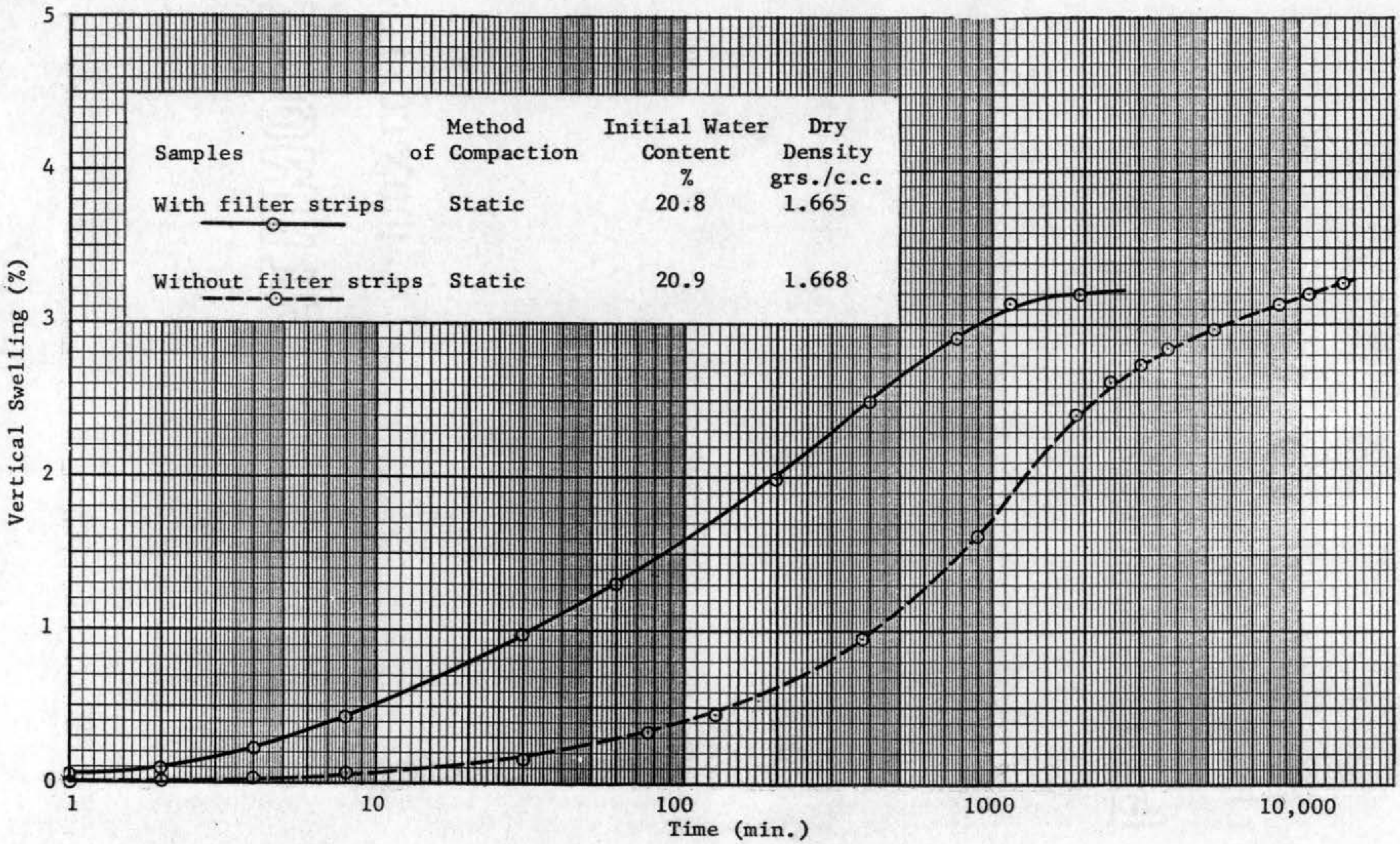


FIGURE 21. TIME PERIOD REQUIRED FOR SWELLING

a sample compacted dry of optimum swells more than a sample compacted wet of optimum. Generally, the horizontal swelling is larger than the vertical swelling (see tables of swelling ratio, at the end of Chapter IV).

The results for a series of samples which were prepared using kneading compaction are shown in Figures 22-28. The soil has an optimum moisture content of 17.5 percent, and a maximum dry density of 1.740 grs./c.c. (108.7 lbs/cu. ft.). Swelling-time and swelling ratio-time curves are illustrated by the test results for three representative samples which had different initial water contents. As shown in Fig. 23, the rates of vertical and horizontal swelling are about equally affected by variation of the initial moisture content. Therefore, the rate of volumetric swelling is directly proportional to both the rate of vertical and the rate of horizontal swelling. As shown in Figure 24, the swelling ratio and time relationship is affected by the initial water content. A sample compacted on dry side of optimum starts to swell with a higher swelling ratio ($\varepsilon_v/\varepsilon_H > 1$) which however rapidly decreases with increasing time. A sample compacted at about optimum, or on the wet side of optimum has a lower initial swelling ratio ($\varepsilon_v/\varepsilon_H < 1$) which is not much influenced by time. A comparison of vertical and horizontal swelling for various initial water contents is shown in Figure 25. The difference in magnitude of final vertical and final horizontal swelling reaches a minimum when the initial water content is equal to the optimum. Thus the swelling ratio becomes maximum at optimum. However, a study of results obtained using other methods of compaction shows that this tendency is comparatively evident only for the case of kneading compaction.

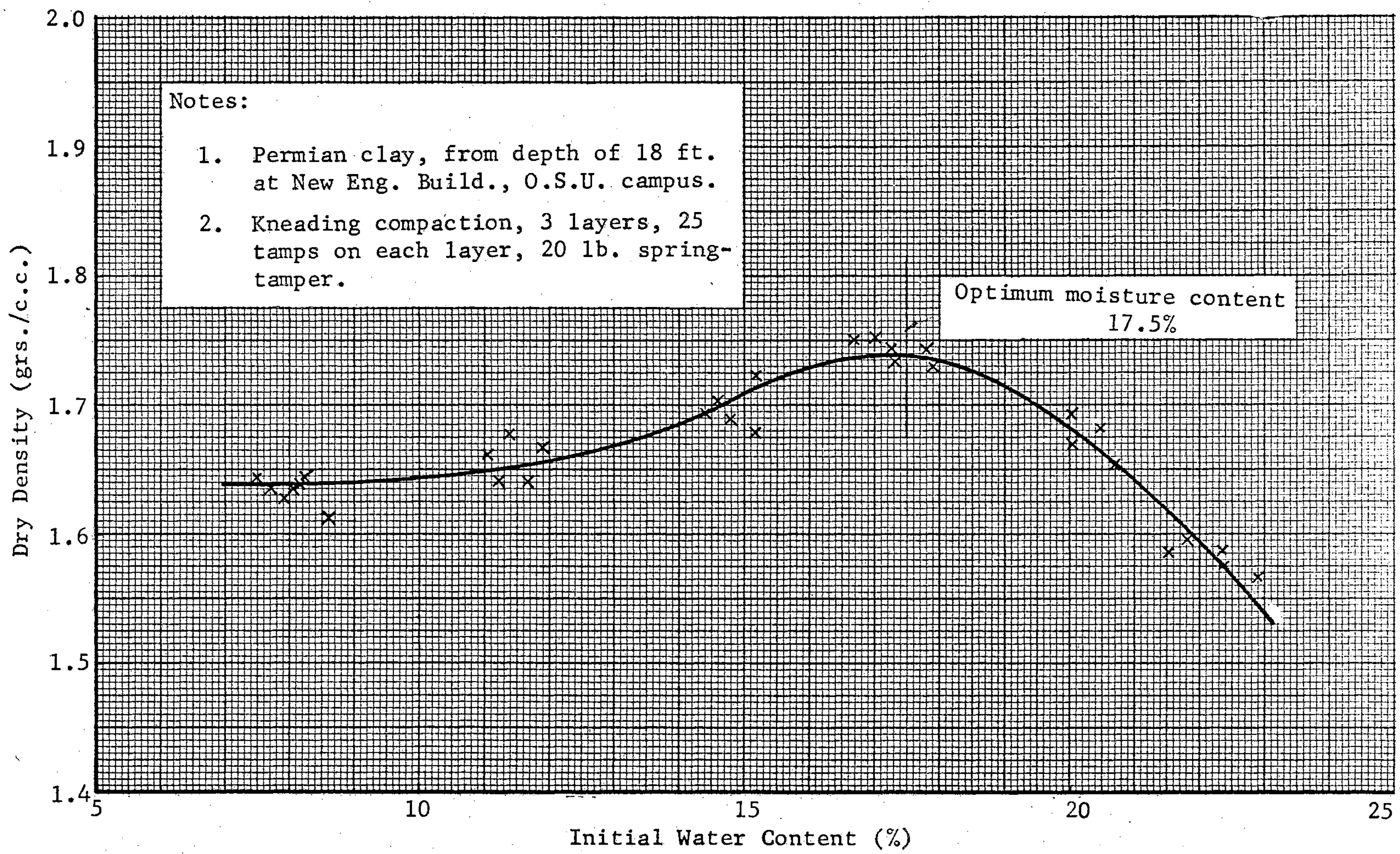
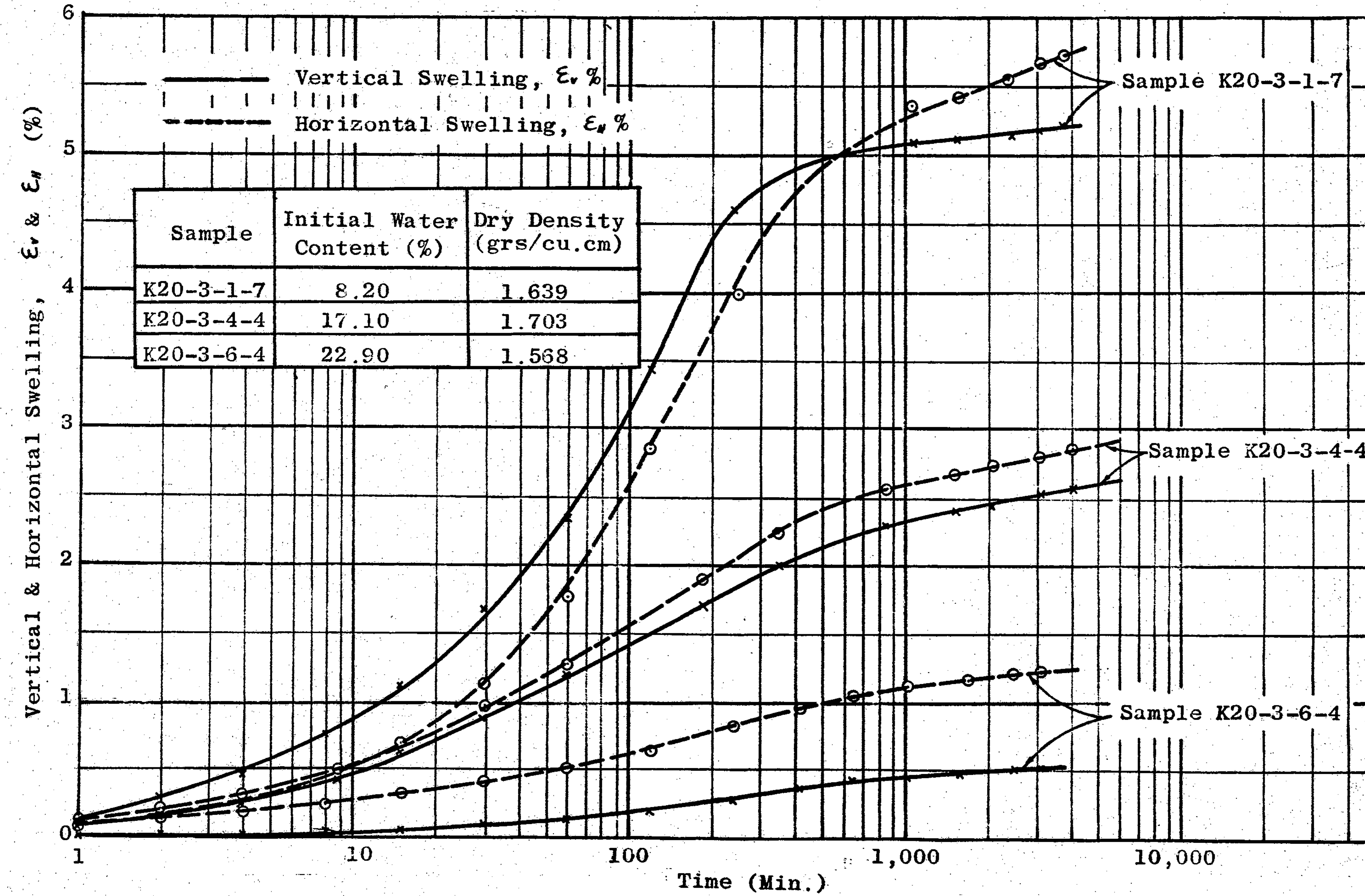


FIGURE 22. INITIAL MOISTURE AND DRY DENSITY RELATIONSHIP OF PERMIAN CLAY AT N.E.B.



Sample	Initial Water Content (%)	Dry Density (grs/cu.cm)
K20-3-1-7	8.20	1.639
K20-3-4-4	17.10	1.703
K20-3-6-4	22.90	1.568

FIGURE 23. SWELLING TIME CURVES - KNEADING COMPACTION SAMPLES WITH VARIOUS INITIAL WATER CONTENTS

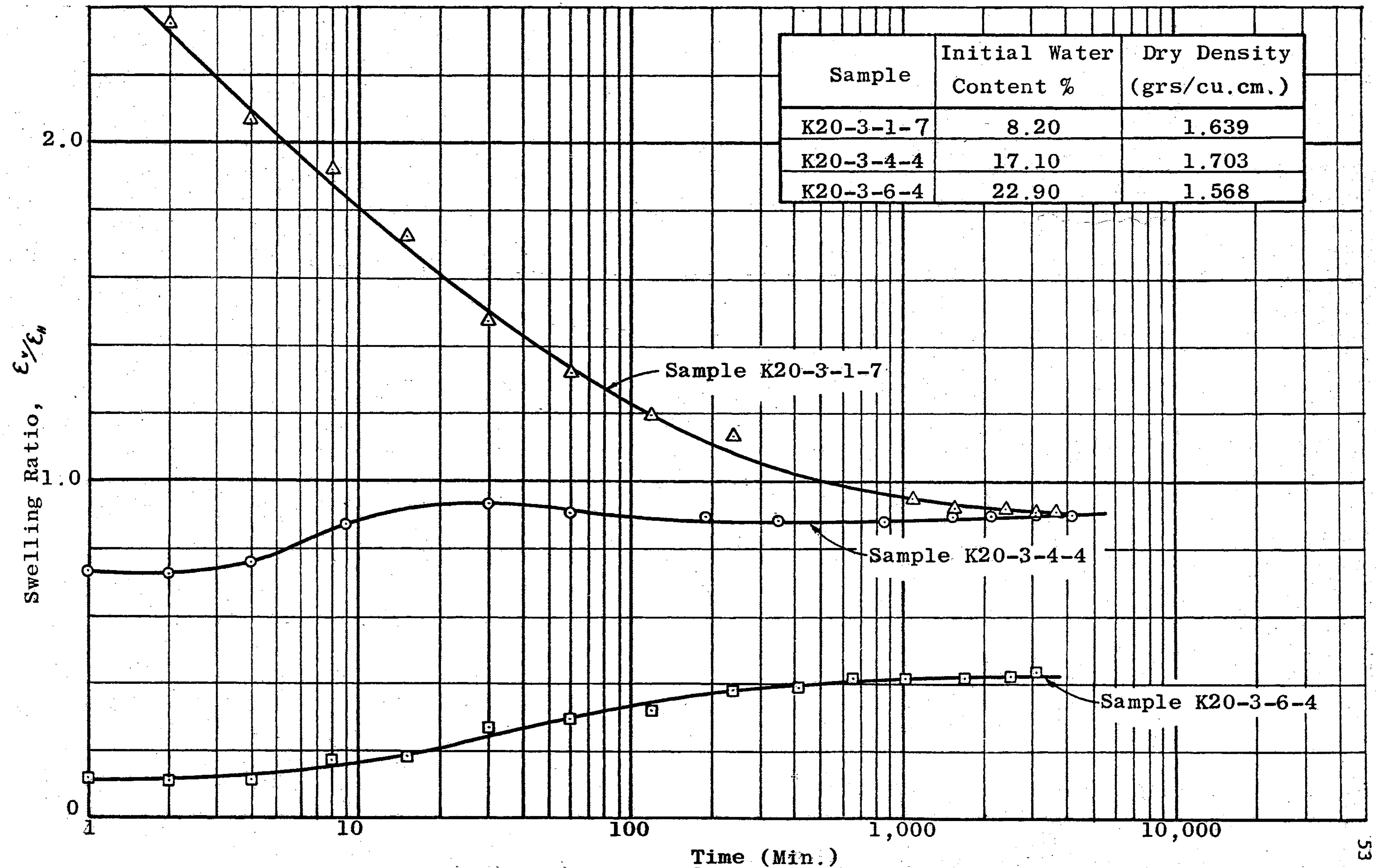


FIGURE 24. SWELLING RATIO - TIME CURVES - KNEADING COMPACTION SAMPLES WITH VARIOUS INITIAL WATER CONTENTS

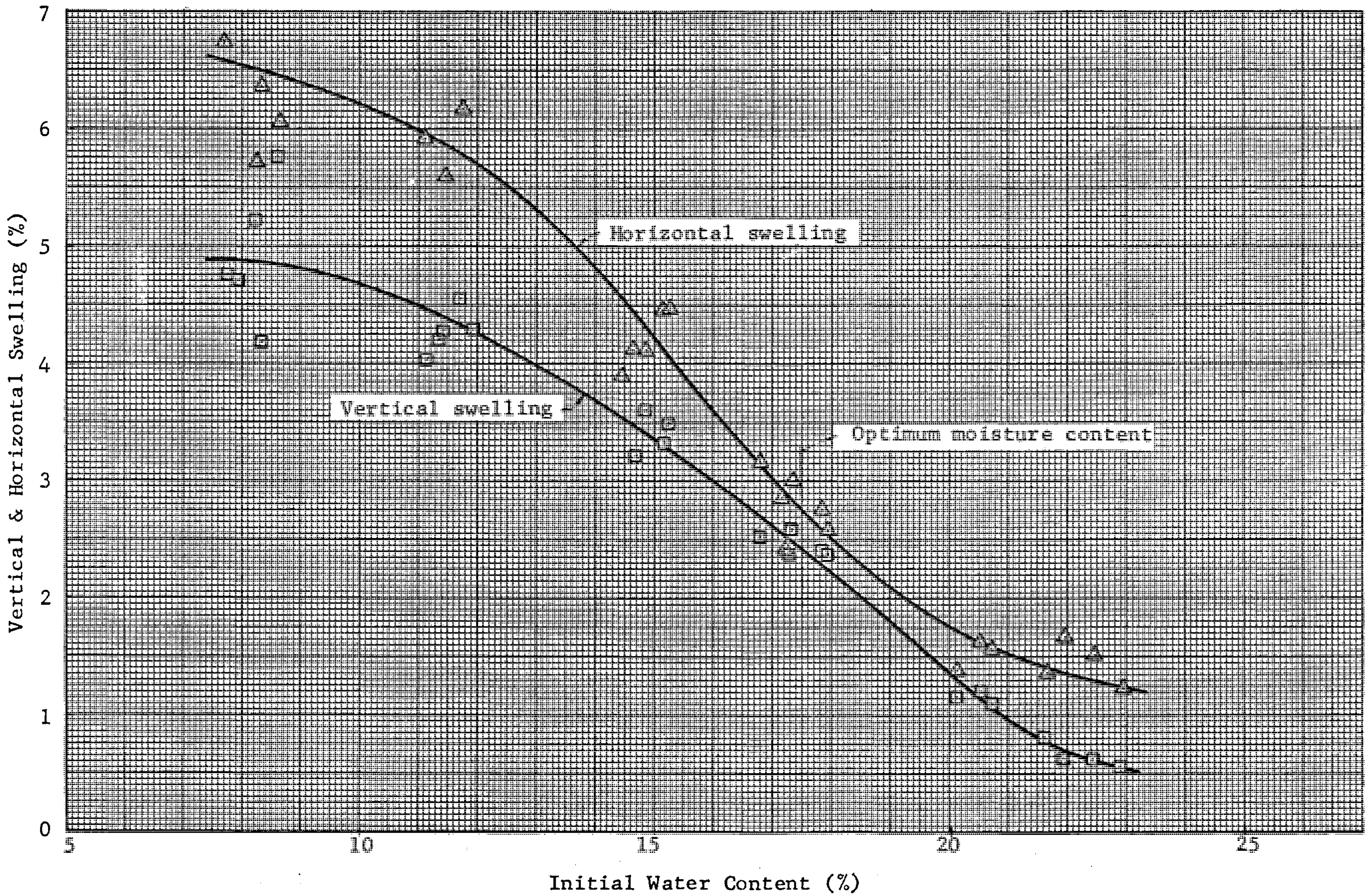


FIGURE 25. EFFECT OF INITIAL WATER CONTENT ON SWELLING

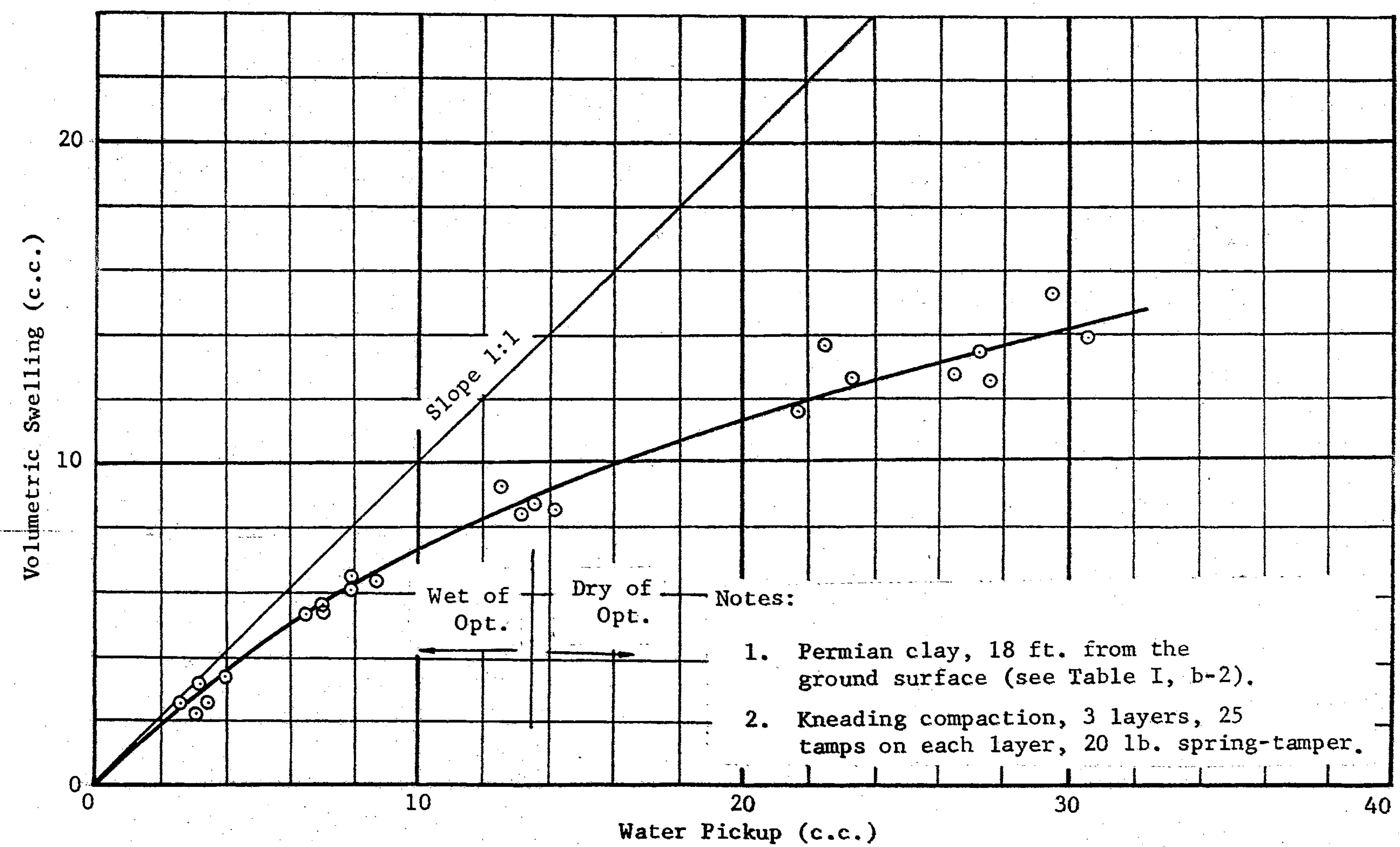


FIGURE 26. RELATIONSHIP BETWEEN VOLUMETRIC SWELLING AND WATER PICKUP OF COMPACTED CLAY

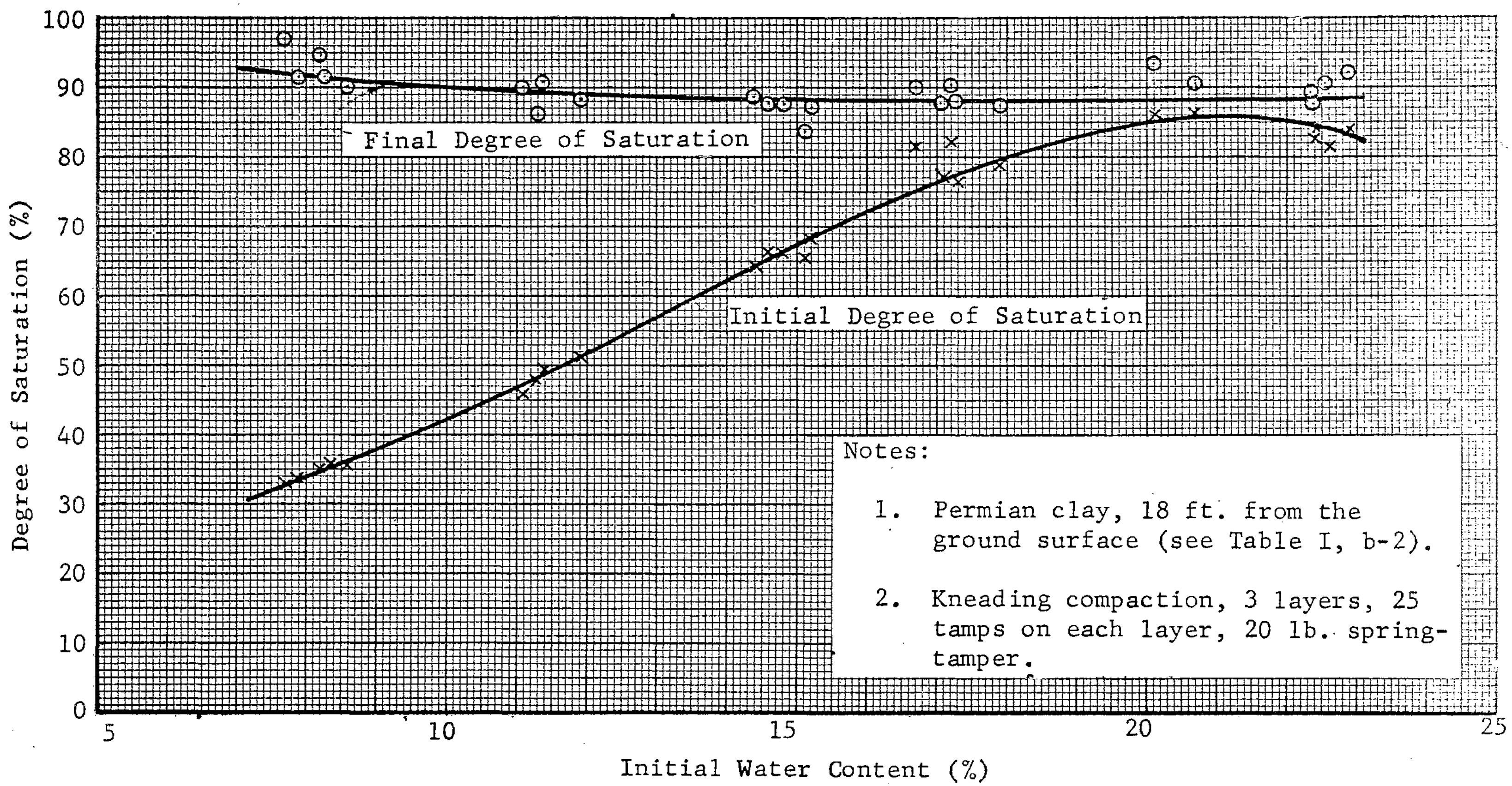


FIGURE 27. INITIAL AND FINAL DEGREES OF SATURATION

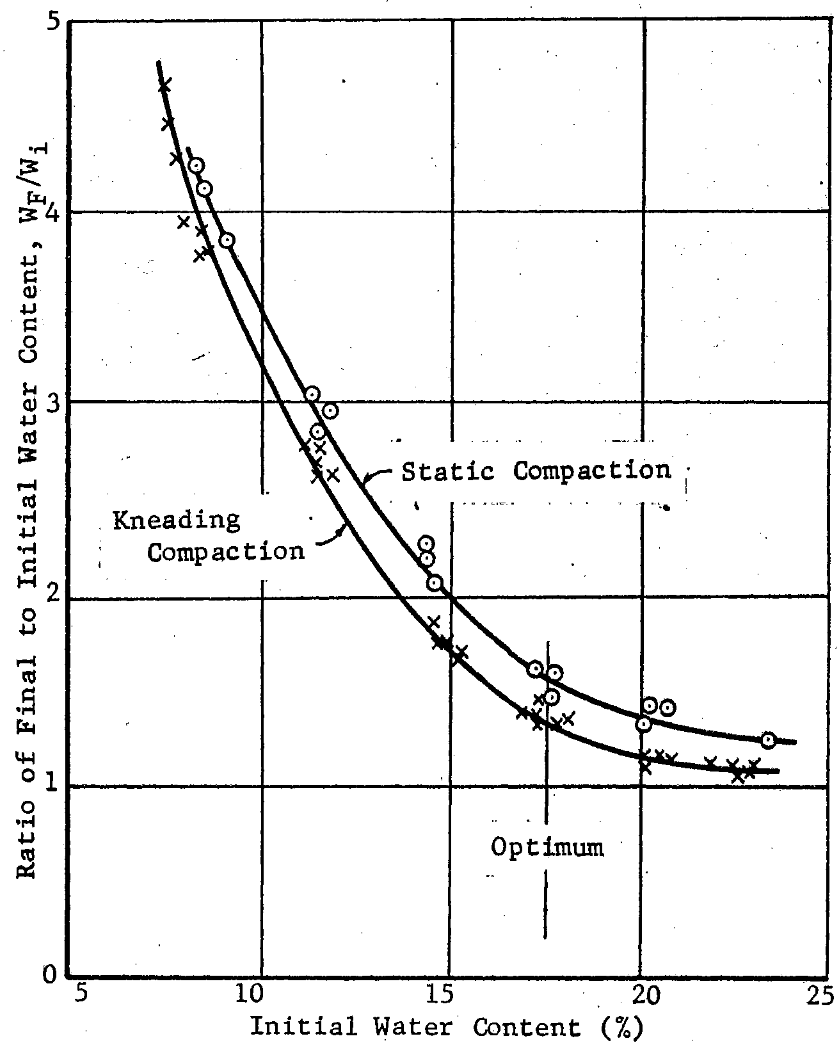


FIGURE 28. RATIO OF FINAL TO INITIAL WATER CONTENT Comparison of Kneading and Static Compaction

The relationship between volumetric swelling and water pickup is shown in Figure 26. It may be seen that for all samples the swelling volume is less than the volume of imbibed water. The higher the initial water content of a sample the smaller is the difference between the volume of swelling and the volume of the imbibed water. Evidently, the difference is related to the difference in the initial and final degrees of saturation in the various cases. In Figure 27 it is shown that the difference in the initial and final degree of saturation varies according to the initial water content. Although samples start to swell from different degrees of saturation, they attain practically the same degree of saturation after swelling. The final degree of saturation is always less than 100 percent. Figure 28 illustrates the variation of the ratio of final to initial water content for various initial water contents. It may be observed that the ability of the compacted soil to imbibe water is inversely proportional to the initial water content. The ratio of final to initial water content for a sample compacted on dry side of optimum may be as much as 4 times greater than that of one compacted at optimum.

Effects of Compaction Energy on Swelling and Swelling Ratio

Using the soil obtained at the location of the Life Science Building, kneading compaction samples were prepared using three different compaction energies. The effects of compaction energy on swelling and swelling ratio are shown directly in Figure 30. The magnitude of vertical and horizontal swelling is proportional to the magnitude of compaction energy. The effect is somewhat more evident for the vertical

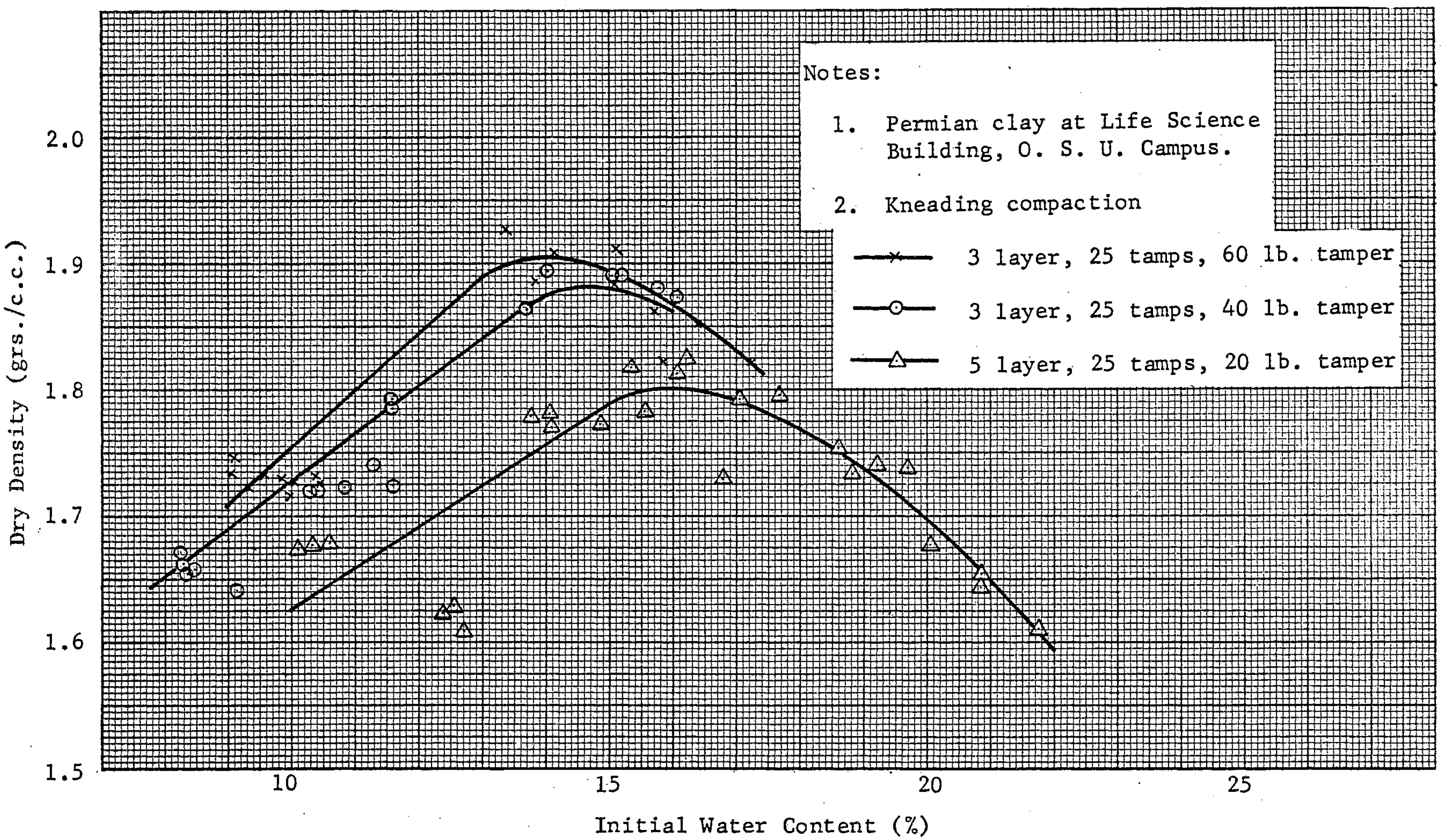


FIGURE 29. OPTIMUM MOISTURE CURVES OF PERMIAN CLAY AT L.S.B.

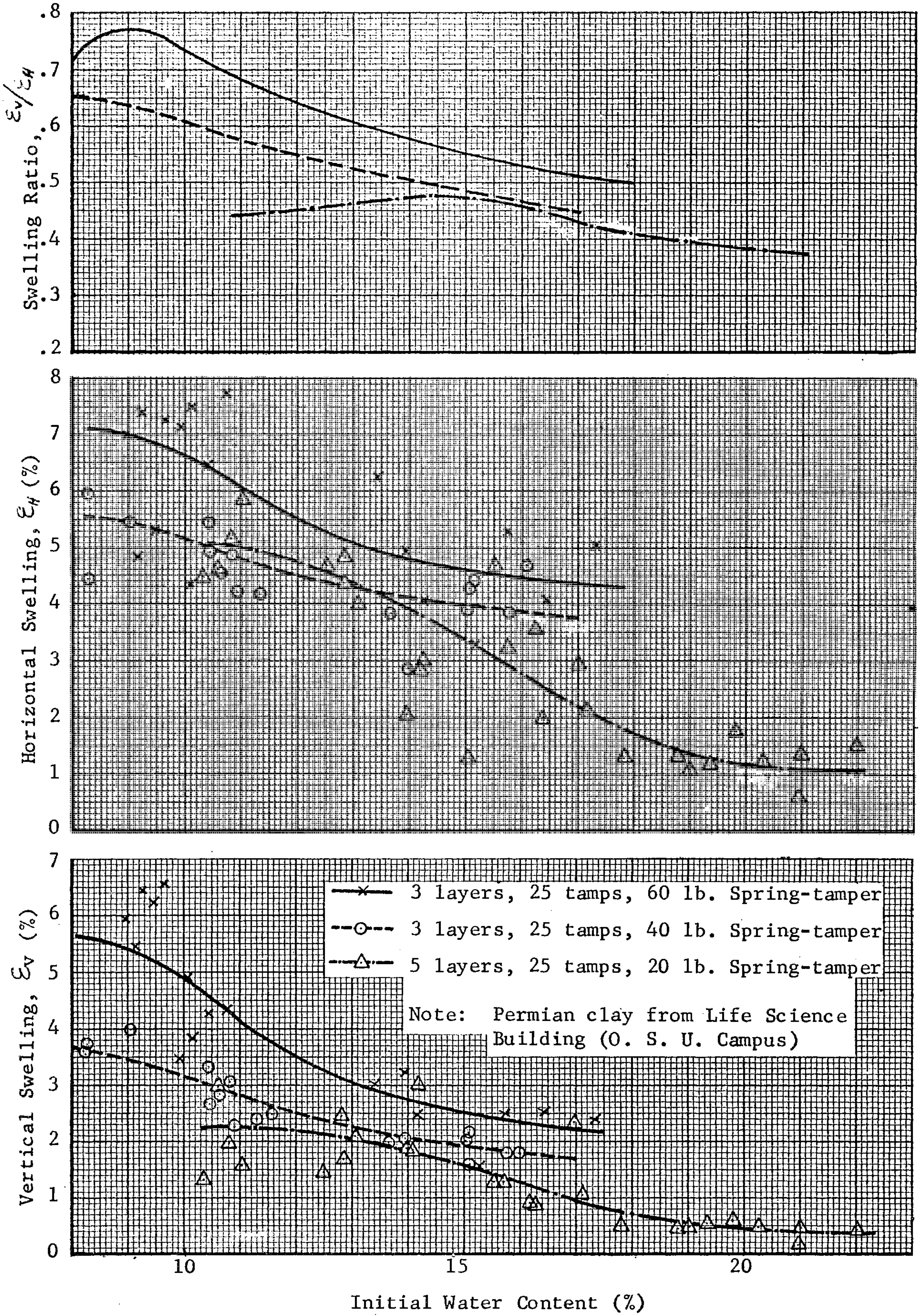


FIGURE 30. EFFECT OF COMPACTION ENERGY ON SWELLING

swelling. The swelling ratio is also proportional to the magnitude of the compaction energy. The variation in swelling ratio may be analyzed from the aspect of change in soil structure. It was shown by Pacey (18) that the degree of particle orientation increases as the compactive effort, or initial water content increases (Chapter II). For samples compacted with the same initial water content, the magnitude of swelling is directly proportional to the dry density. The swelling ratio of a group of samples having equal initial moisture contents but different dry densities should be the same unless there are differences in the structural arrangement of the soil grains. As the degree of particle orientation is improved by compaction, the magnitude of swelling increases more vertically than horizontally; therefore, the swelling ratios of a series of samples which were compacted with greater compaction energy are higher. For a series of samples compacted using constant energy, the swelling ratio decreases with increasing initial moisture content for samples wetter than optimum. (Figures 24, 29, and 30). The degree of water deficiency is reduced by the addition of water during compaction because the thickness of the double-layer water increases. According to Lambe (10), with increasing initial water content the degree of particle orientation increases rapidly for samples on wet side of optimum (Figure 3). Because the degree of particle orientation and the double-layer water thickness increase proportionally on the wet side of optimum, the degree of water deficiency may become comparatively lesser along a vertical section than along a horizontal one when there is an increase of initial water content. This could be the reason that the swelling ratio decreases on the wet side of optimum as the initial water content increases. No direct observation of the change in soil structure was made in this study; therefore, additional studies are needed to provide data which would support the foregoing hypothesis.

Effects of Compaction Method on Swelling, and Swelling Ratio

By using equivalent samples which are equal in initial water content and dry density, the effects of compaction method on swelling were studied. For purposes of comparison the test specimens were divided into two groups. In one group the effects of kneading and static compaction are compared, while in the other group dynamic and static compaction are compared.

Figure 31 shows the swelling times curves for two samples which are practically identical initially, except that they were molded using different methods of compaction. The one formed by static compaction swells about twice as much both vertically and horizontally as the one formed by kneading compaction. The swelling processes of both samples are accomplished during nearly equal periods of time.

Figures 32 and 33 are presented for the purpose of permitting a direct comparison of the results achieved using various initial water contents. As shown in Figure 31, statically compacted samples swell much more, for all initial water contents, than do samples compacted by kneading. On the other hand, Figure 33 indicates that there is not very much difference in the magnitude of swelling of samples compacted by static and dynamic methods, except for samples at very high initial water contents. The total volumetric swelling of each series was estimated according to the data from Figures 32 and 33, and the

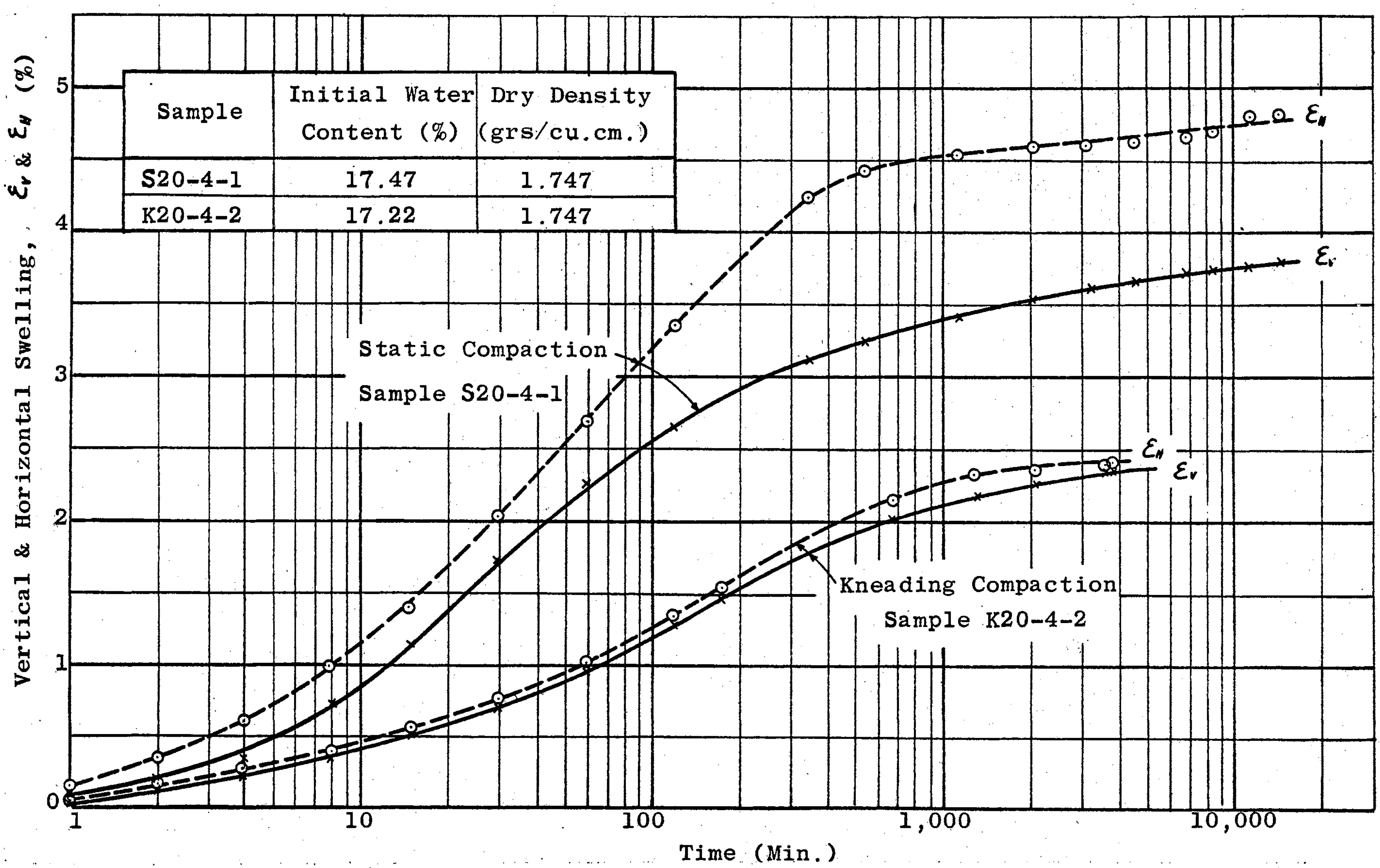


FIGURE 31. SWELLING TIME CURVES
Comparison of Kneading and Static Compaction

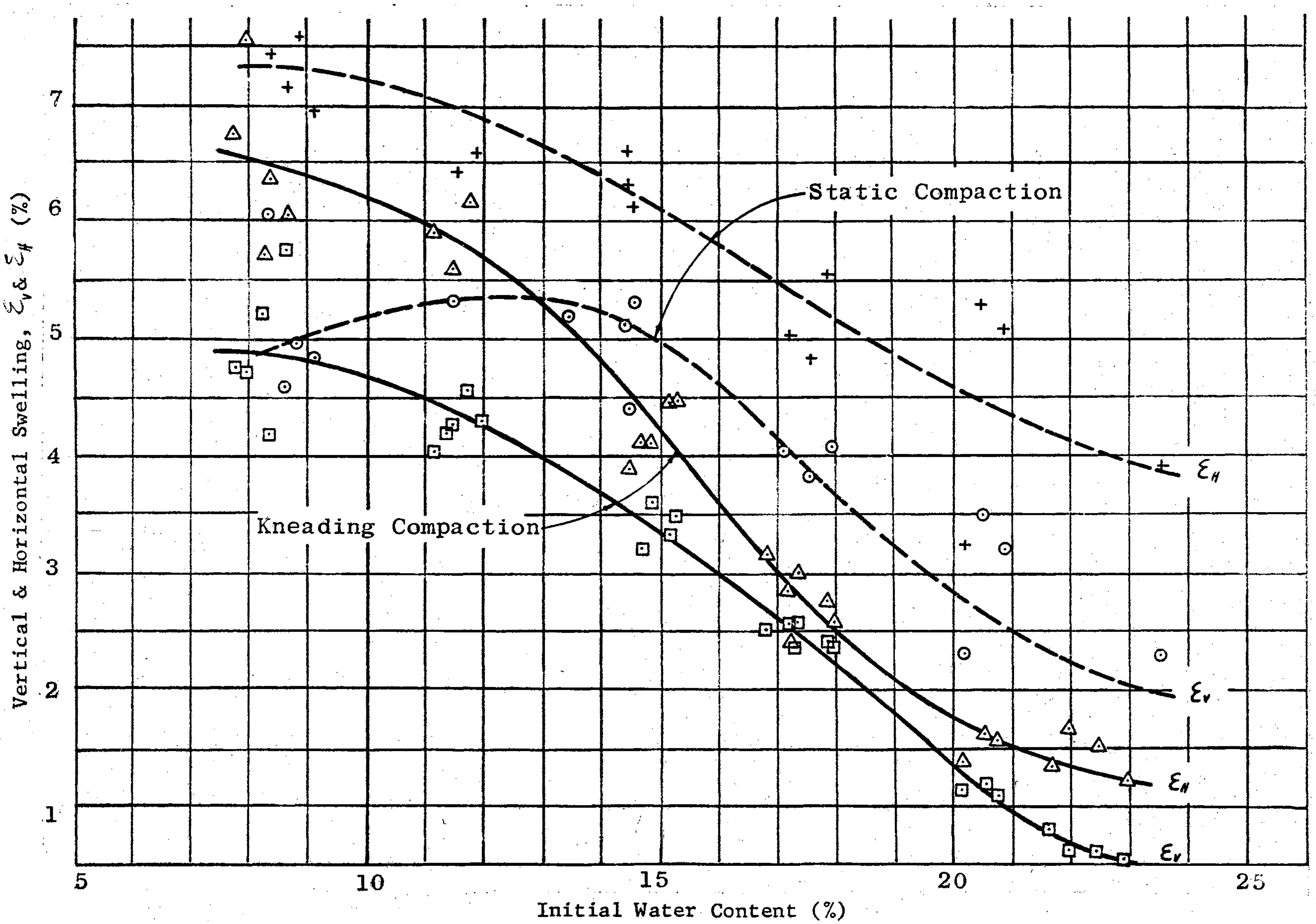


FIGURE 32. EFFECT OF INITIAL WATER CONTENT ON SWELLING
Comparison of Kneading and Static Compaction

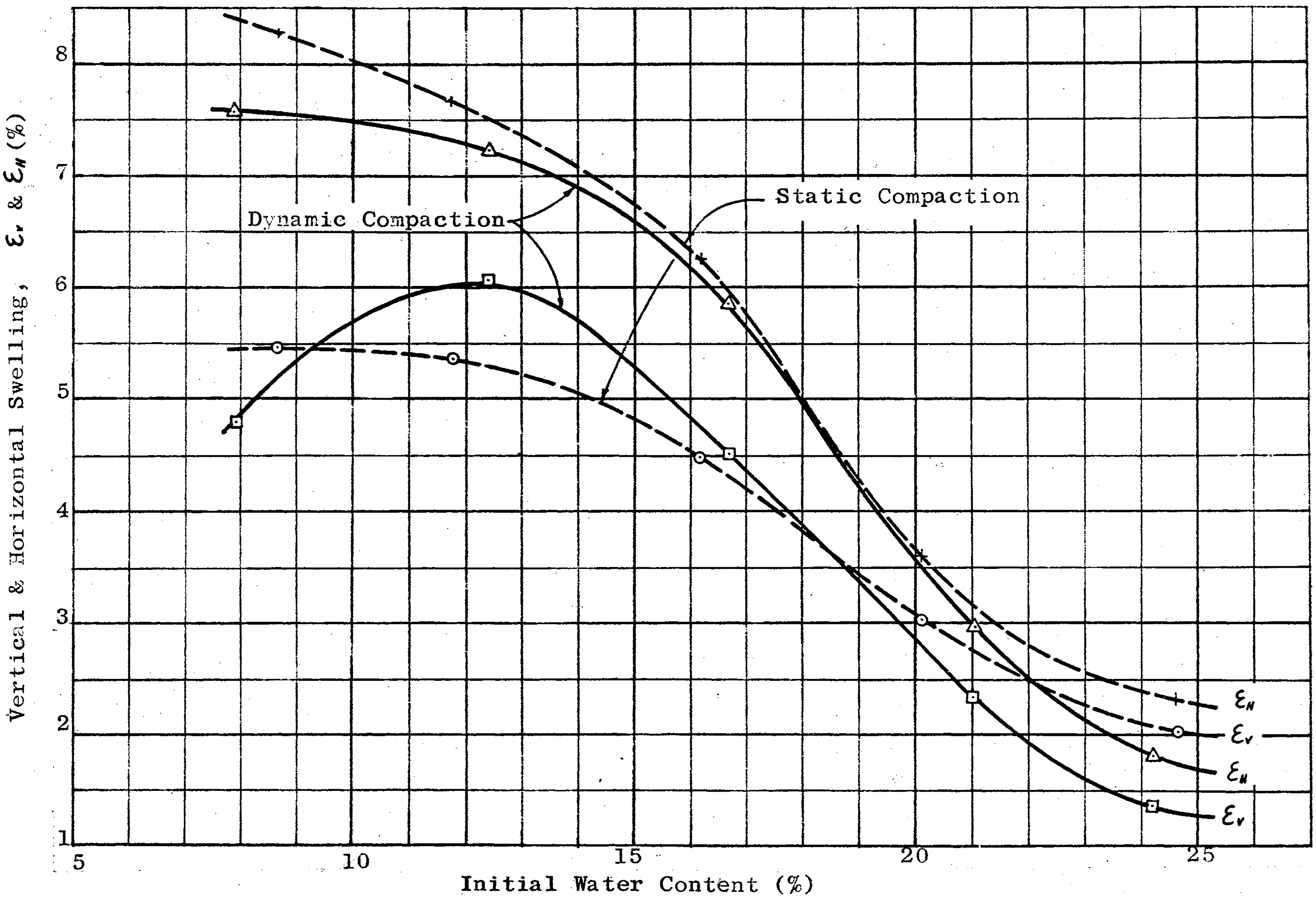


FIGURE 33. EFFECT OF INITIAL WATER CONTENT ON SWELLING
Comparison of Dynamic and Static Compaction

results are shown in Figures 34 and 35. It is evident that static compaction always produces samples possessing higher swelling potential than is present when the other two compaction methods--kneading and dynamic are used. The difference in swelling volume of statically and dynamically compacted samples is slight, but those compacted by kneading swell much less--perhaps only one-fourth as much when the initial water content is high. Seed and Chan (14) believe that the difference in swelling characteristics of static and kneading compaction samples is mainly due to the difference in their structure. Those compacted statically have a greater degree of floccuration than do those prepared by kneading compaction. The more flocculent samples swell more than those with a lower degree of floccuration (more highly dispersed structure). According to the conclusions of Seed and Chan, a clear relationship of the soil structure may be found among the three compaction methods. Thus, a sample prepared by the static compaction method is always more flocculent in structure than equivalent sample prepared by kneading or dynamic compaction, and the variation is more evident between static and kneading compaction. In other words, kneading compaction results in a higher degree of particle orientation than is produced by the other two methods.

The effect of compaction method on swelling ratio is shown in Figure 36 for two different groupings of compaction methods. All swelling ratios are smaller than unity, indicating that, for all samples, the magnitude of swelling is larger vertically than horizontally. In the first group, comparing kneading and static compaction, the peak swelling ratio appears on the dry side of optimum for static compaction, but corresponds to the optimum moisture content for kneading compaction.

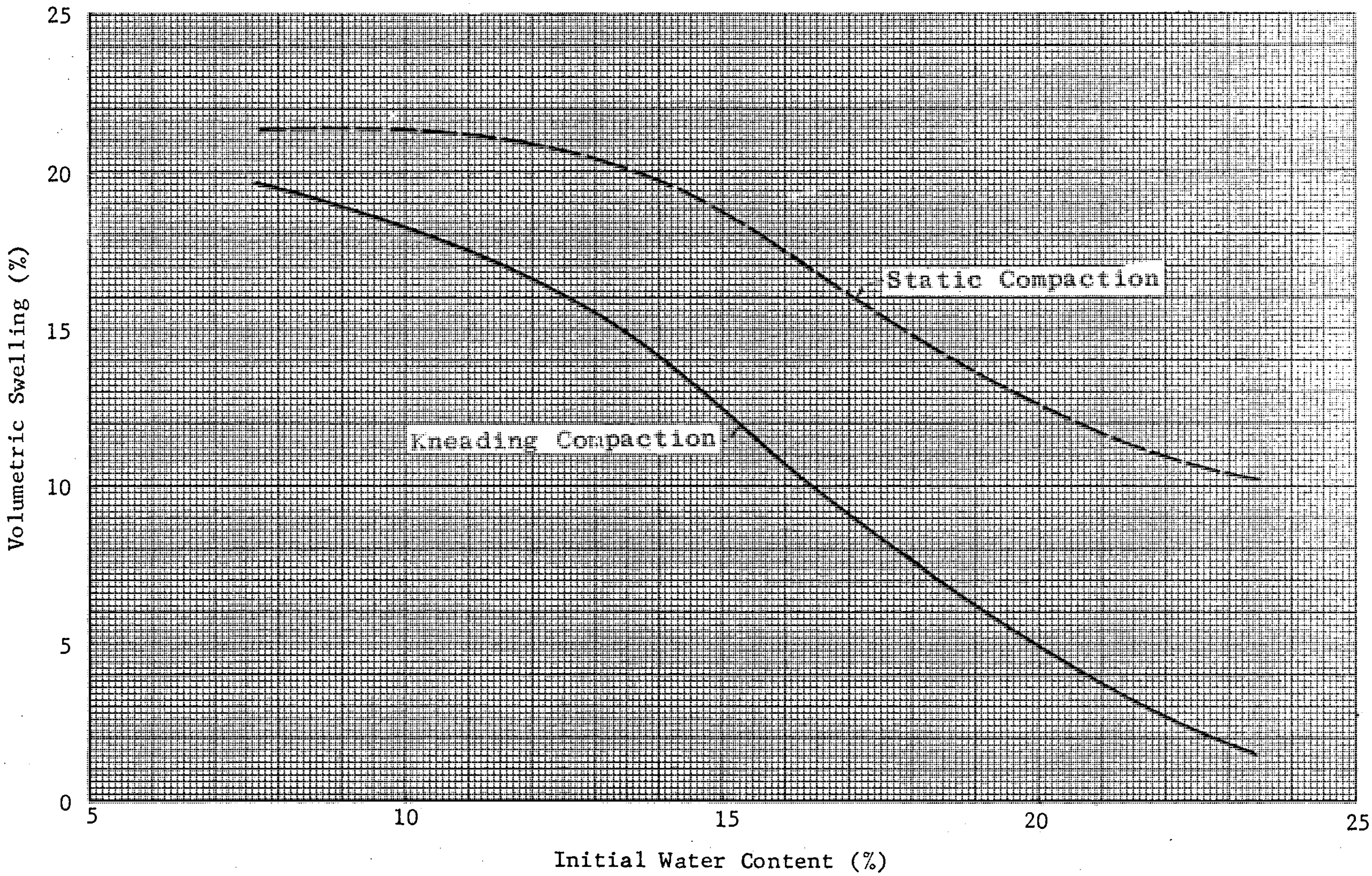


FIGURE 34. EFFECT OF COMPACTION METHOD ON VOLUMETRIC SWELLING
Comparison of Kneading and Static Compaction

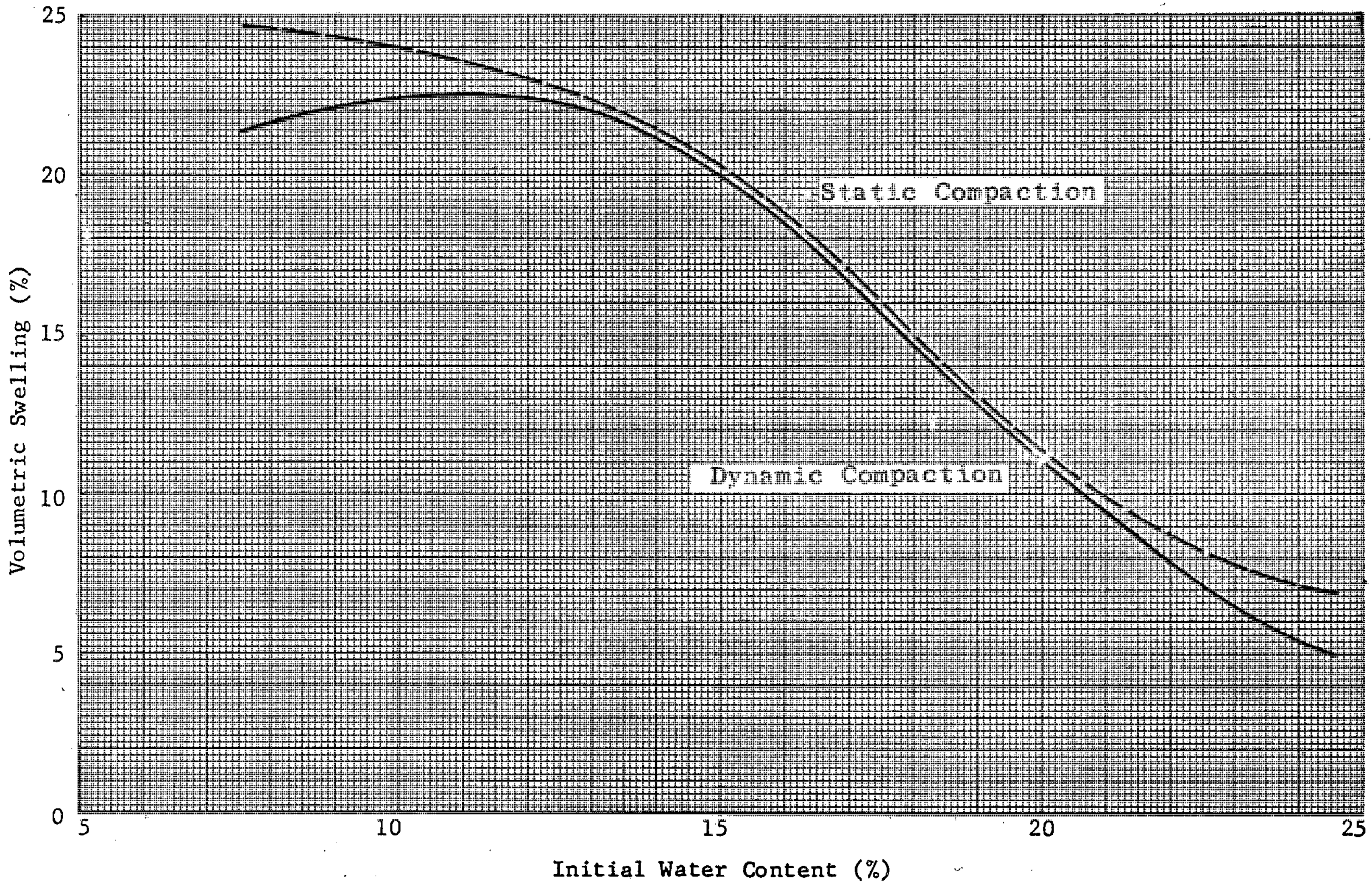


FIGURE 35. EFFECT OF COMPACTION METHOD ON VOLUMETRIC SWELLING
Comparison of Dynamic and Static Compaction

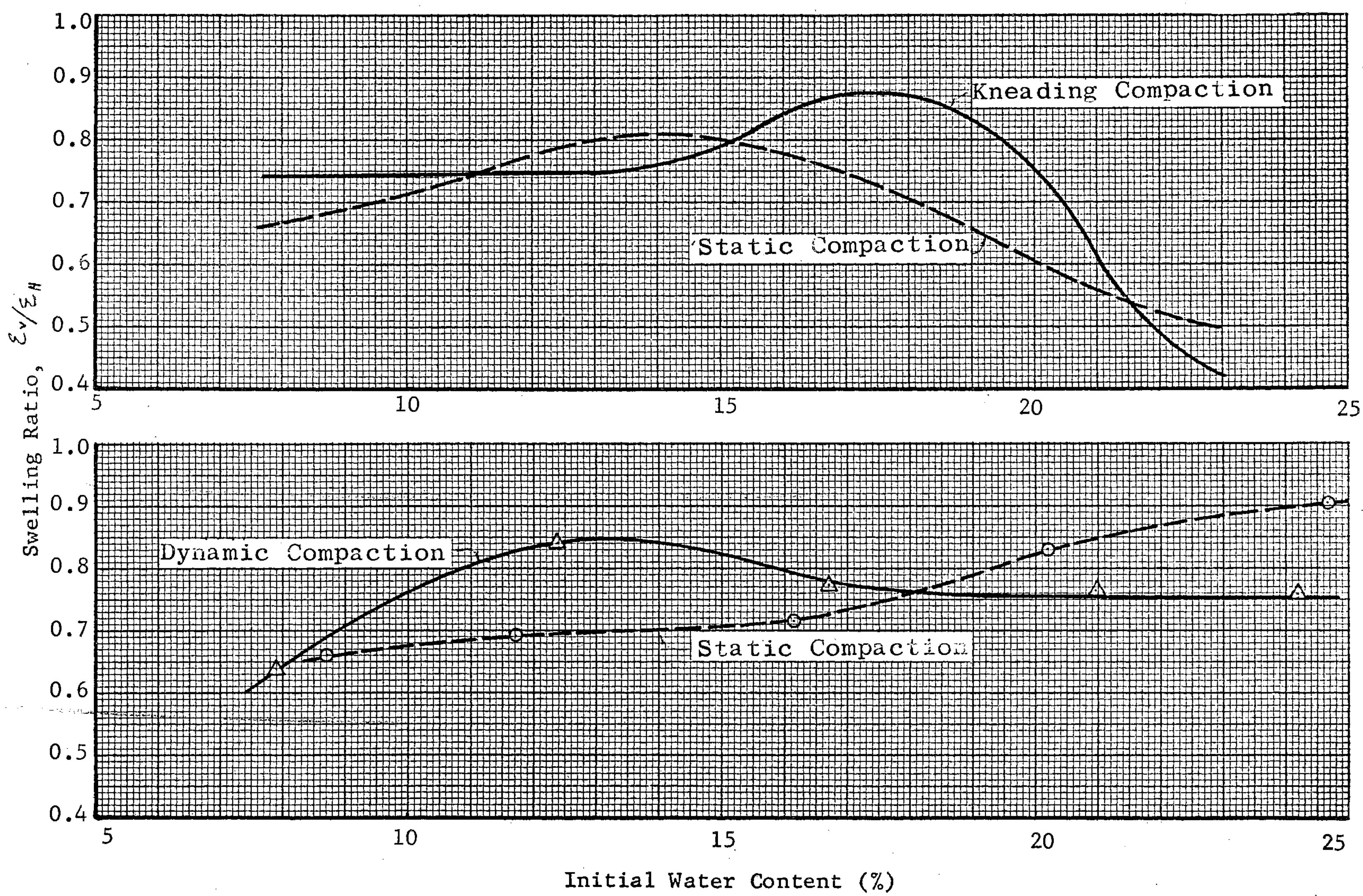


FIGURE 36. EFFECT OF COMPACTION METHOD ON SWELLING RATIO
Comparison of kneading and Static Compaction,
and Dynamic and Static Compaction

The swelling ratio curve for kneading compaction resembles the optimum moisture curve shown in Figure 22. Apparently, for kneading compaction, the swelling ratio is closely related to the dry density and/or the initial water content. In the second group using dynamic and static compaction, the swelling ratio for dynamic compaction is higher at lower water contents, but is reversed for higher water contents. The swelling ratio curves for the two static compaction groups do not much resemble each other (Fig. 36). The difference is probably due to the fact that samples at same initial water content in the two groups actually differ in dry density because of the difference in compaction effort.

The ratio of final to initial water content is also affected by the method of compaction. As shown in Figure 28, the ratio is higher for all initial water contents for statically compacted samples as compared to equivalent samples formed by kneading compaction. Therefore, it is concluded that more water is imbibed by samples possessing higher swelling potential.

Swelling Characteristics of Clay in the Undisturbed and Remolded States

The swelling test results of 13 undisturbed samples are presented in Table XII. Those samples were taken from depths of about 9 and 18 feet near the northeast corner of New Engineering Building. The average initial water content and dry density for those from 9 feet depth were 21.92 percent and 1.680 grs./c.c.(105 lbs/cu. ft.) respectively; and for those from 18 feet depth were 13.66 percent and 2.008 grs./c.c. (125 lbs./cu. ft.) respectively.

It was explained in the last chapter that an equivalent sample had been prepared using the kneading compaction method. The difference in the magnitude of swelling and the variation of swelling ratio for samples in the undisturbed and remolded states is shown in Figures 37 and 38. The remolded sample swells about 4 times more than the undisturbed sample in either the vertical direction or horizontal direction. When an undisturbed soil is remolded its original structure is destroyed, and the bond stresses between individual soil particles are also greatly reduced, depending on the degree of remolding. Those bond stresses may exist as a result of diagenetic cementation (Chapter II). The individual soil particle is allowed to move more freely after the soil is remolded, and this contributes to a larger swelling.

The average swelling ratios for the undisturbed samples from depths of 9 and 18 feet are about 0.50 and 0.46, respectively. As shown in Figure 37, two of the equivalent samples are not much different in the final swelling ratio (0.629 for undisturbed sample, 0.570 for remolded sample); but the variation of the swelling ratio during the swelling process is quite different in the two cases. The swelling ratio of the undisturbed sample is more nearly constant during the swelling period than that of the remolded one. A steady swelling ratio may represent one of the swelling characteristics of undisturbed clay, which is characterized by a soil structure in which the individual particles are joined by strong bonding forces, making it possible to treat the whole sample as a single structural unit. This kind of structure may be regarded as a "linked" structure, whereas remolded soils may be thought of as having a "free" structure.

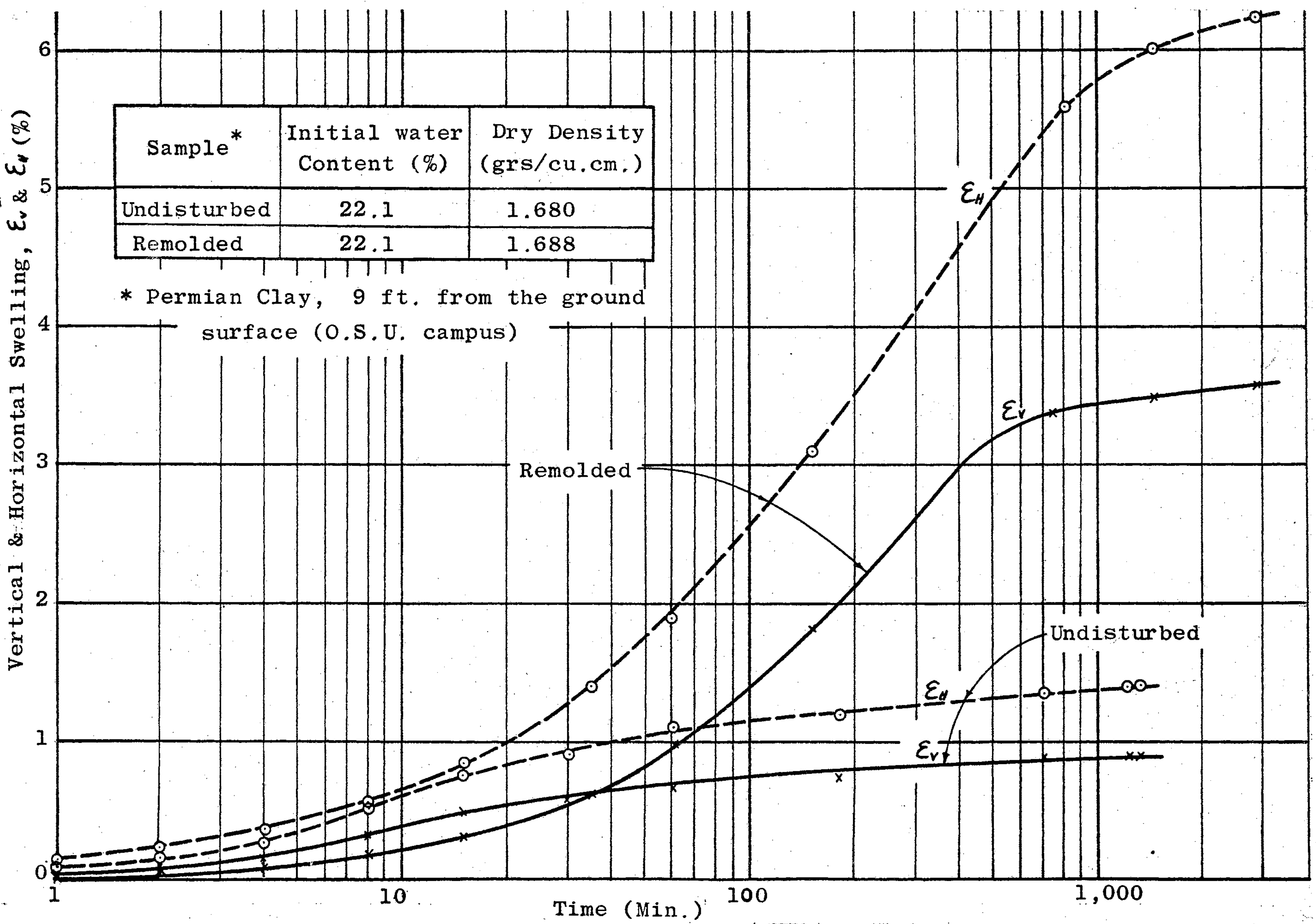


FIGURE 37. SWELLING TIME CURVES — Comparison of Undisturbed and Remolded State

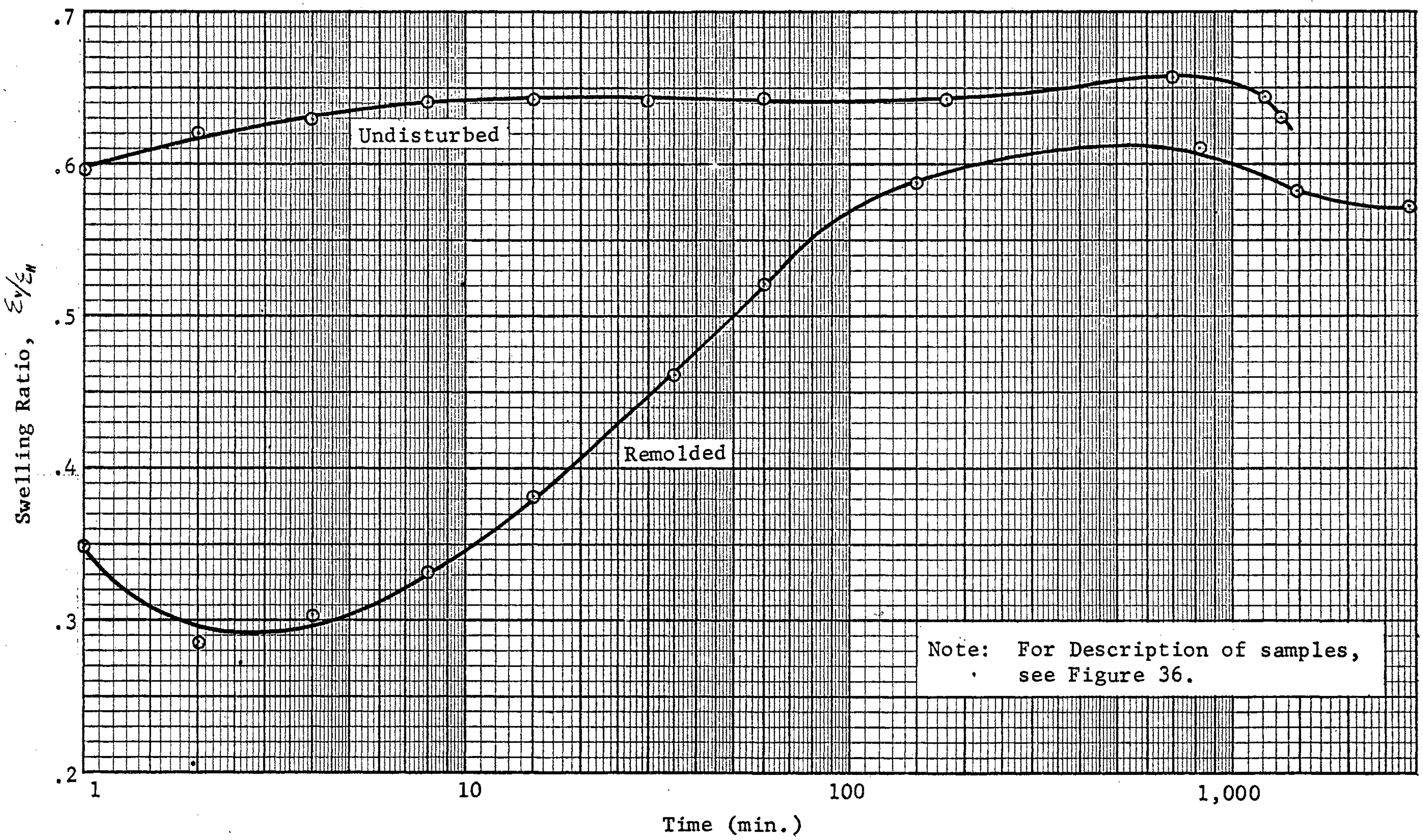


FIGURE 38. SWELLING RATIO - TIME CURVES
Comparison of Undisturbed and
Remolded State

For the purpose of controlling swelling in a structural foundation, the suggestion made by Casagrande (4) may be paraphrased to read "do not disturb a natural soil structure; if we do, the structure can never be reconstructed and the magnitude of swelling is increased as the degree of disturbance increases."

The relationship between volumetric swelling and water pickup for undisturbed soil is shown in Figure 39. The relation is the same as for compacted clay. Thus for all samples tested the swelling volume is less than the volume of imbibed water (Refer also to Figure 26).

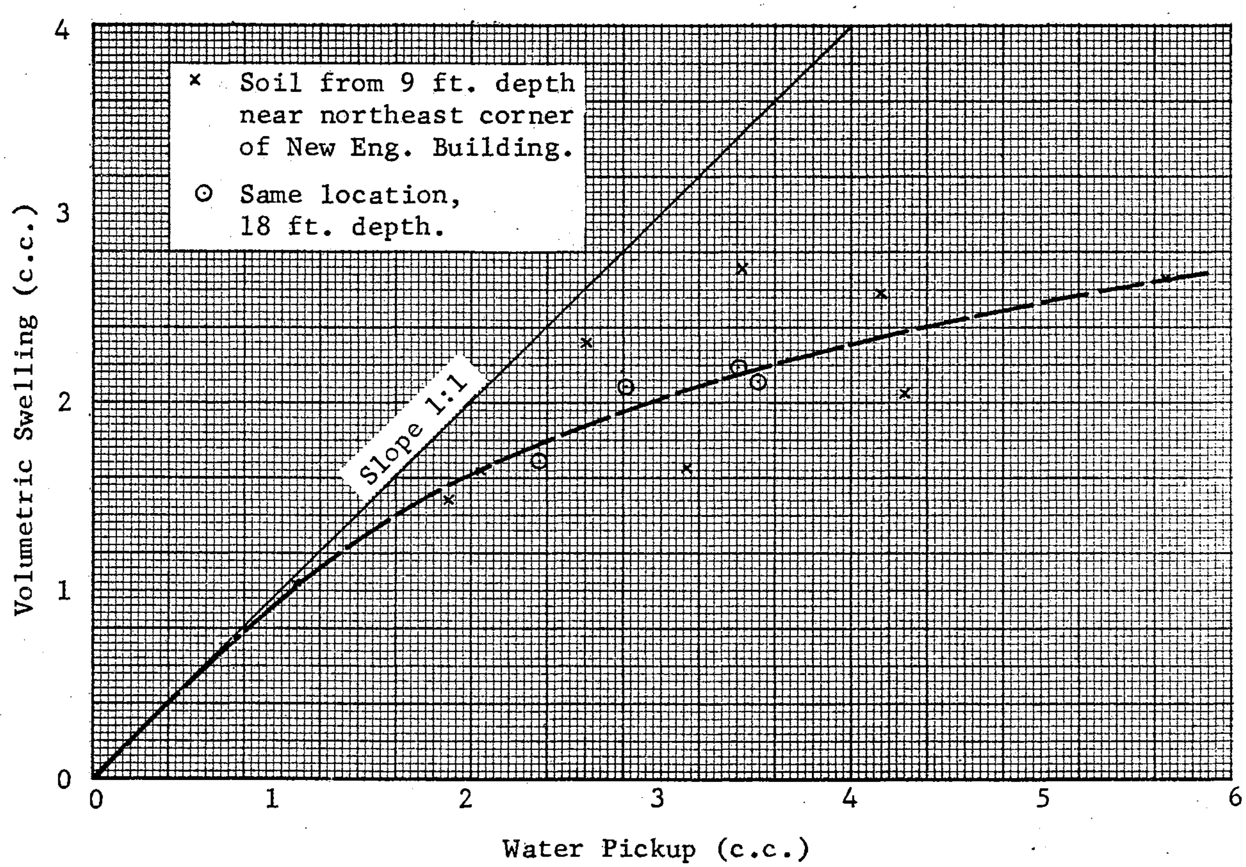


FIGURE 39. RELATIONSHIP BETWEEN VOLUMETRIC SWELLING AND WATER PICKUP OF UNDISTURBED CLAY

TABLE II

SWELLING RATIO

Description of Samples: PRC from L. S. B., a (See Table I)

Method of Compaction: Kneading compaction, 5 layers, 25 tamps, 20 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
15.06	-	1.770	1.537	1.290	1.191
13.92	21.00	1.787	1.870	2.085	0.897
14.18	20.90	1.793	1.722	2.800	0.615
14.20	23.00	1.780	1.480	2.970	0.498
17.00	24.50	1.736	2.310	2.900	0.796
19.00	20.40	1.748	0.451	1.076	0.419
19.33	20.50	1.753	0.514	1.143	0.449
19.80	20.65	1.752	0.606	1.735	0.350
18.80	20.60	1.770	0.486	1.304	0.372
13.09	28.50	1.602	2.055	3.990	0.514
12.50	27.55	1.627	1.444	4.670	0.309
12.82	28.35	1.632	2.435	4.800	0.507
12.85	28.05	1.614	1.632	4.350	0.375
17.83	20.00	1.808	0.494	1.288	0.384
16.36	19.45	1.832	0.900	1.832	0.491
17.13	20.40	1.802	1.057	2.180	0.489
10.80	26.85	1.682	1.948	5.170	0.377

TABLE II (Continued)

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
10.31	25.50	1.680	1.337	4.490	0.298
10.59	27.20	1.681	2.980	4.700	0.634
11.02	28.80	1.651	1.530	5.86	0.261
16.20	20.55	1.825	0.910	3.56	0.256
15.73	20.25	1.793	1.243	3.22	0.386
15.50	20.00	1.830	1.335	4.70	0.284
20.30	21.45	1.693	0.534	1.215	0.440
22.00	24.05	1.632	0.408	1.550	0.263
21.00	22.80	1.667	0.473	1.370	0.345
20.95	23.30	1.655	0.152	0.530	0.283

TABLE III

SWELLING RATIO

Description of Samples: PRC from L. S. B.

Method of Compaction: Kneading compaction, 3 layers, 25 tamps, 40 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_v$ %	$\mathcal{E}_H$ %	$\mathcal{E}_v/\mathcal{E}_H$
9.03	29.20	1.640	3.99	5.45	0.733
8.25	29.60	1.662	3.58	5.93	0.603
8.27	27.60	1.673	3.73	4.40	0.847
11.63	22.60	1.722	2.82	4.53	0.622
10.40	24.60	1.740	3.34	5.45	0.612
10.91	27.20	1.723	2.29	4.22	0.543
10.47	24.60	1.720	2.66	4.97	0.535
11.58	17.40	1.783	2.50	6.65	0.376
11.30	21.40	1.739	2.40	4.13	0.582
11.57	18.23	1.792	-	-	-
10.83	22.70	1.765	3.10	4.87	0.635
16.03	21.25	1.871	1.87	4.68	0.400
15.77	20.30	1.879	1.83	3.85	0.475
15.03	20.30	1.885	2.02	3.90	0.517
15.08	20.85	1.883	2.14	4.30	0.498
15.14	21.65	1.832	1.57	4.40	0.356
13.97	19.12	1.891	2.04	2.86	0.713
13.67	19.10	1.865	1.96	3.82	0.512

TABLE IV

SWELLING RATIO

Description of Samples: PRC from L. S. B.

Method of Compaction: Kneading compaction, 3 layers, 25 tamps, 60 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_v$ %	$\mathcal{E}_H$ %	$\mathcal{E}_v/\mathcal{E}_H$
9.45	28.50	1.726	6.25	5.30	1.180
9.62	30.50	1.736	6.57	7.25	0.906
9.14	25.50	1.736	5.42	4.85	1.120
9.23	29.60	1.750	6.46	7.39	0.874
8.95	29.40	1.742	5.95	6.99	0.852
10.41	29.15	1.737	4.25	6.48	0.653
10.78	31.15	1.726	4.32	7.75	0.558
10.07	30.30	1.722	4.88	4.34	1.126
10.13	29.70	1.730	3.82	7.51	0.509
9.92	28.80	1.734	3.48	7.14	0.487
13.40	21.15	1.936	3.03	6.28	0.478
13.91	22.35	1.896	3.22	4.96	0.650
16.42	22.80	1.862	2.52	4.08	0.618
15.72	23.55	1.872	2.48	5.30	0.468
17.30	20.00	1.835	2.40	5.06	0.767
15.13	19.03	1.920	1.68	3.27	0.515
14.15	19.68	1.929	2.49	4.06	0.613

TABLE V

SWELLING RATIO

Description of Samples: PRC from L. S. B. (second time sampling)

Method of Compaction: Kneading compaction, 3 layers, 25 tamps, 20 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
6.03	31.5	1.622	3.71	4.47	0.830
6.51	33.4	1.610	3.19	6.85	0.465
6.44	34.1	1.603	3.66	7.26	0.505
6.76	31.7	1.615	3.47	4.67	0.743
11.02	30.2	1.593	3.24	5.40	0.600
11.22	29.7	1.566	3.27	4.38	0.747
11.72	30.7	1.593	3.25	5.25	0.619
11.20	31.6	1.597	3.00	4.99	0.600
11.10	30.5	1.609	2.64	5.70	0.463
13.10	26.3	1.678	3.25	5.14	0.632
13.60	25.9	1.638	2.88	4.56	0.632
13.70	25.2	1.664	2.82	4.16	0.680
13.33	24.5	1.640	2.66	4.25	0.625
13.80	25.5	1.646	2.95	3.71	0.795
14.96	21.9	1.713	2.09	3.38	0.618
17.10	20.7	1.750	1.46	2.02	0.724
16.80	20.2	1.772	1.20	-	-
16.30	18.4	1.790	1.21	2.18	0.556
16.10	19.5	1.770	1.47	1.84	0.798

TABLE VI

SWELLING RATIO

Description of Samples: PRC from depth of 9 ft. at N.E.B., b-1 (see Table I)

Method of Compaction: Kneading compaction, 3 layers, 25 tamps, 20 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
14.00	40.10	1.476	4.63	6.37	0.727
14.68	40.60	1.450	4.65	6.28	0.740
13.95	38.20	1.451	4.56	5.92	0.769
15.30	41.00	1.436	4.16	6.18	0.672
13.93	41.70	1.425	3.65	5.70	0.642
19.42	42.60	1.429	-	-	-
16.68	41.20	1.445	3.81	5.91	0.645
20.10	40.10	1.425	2.31	5.58	0.414
18.44	41.30	1.445	3.54	6.42	0.552
18.75	39.10	1.460	3.21	-	-
24.40	34.20	1.566	3.29	4.32	0.762
23.20	33.40	1.550	2.28	4.47	0.510
24.60	36.40	1.510	3.16	4.61	0.687
24.80	35.00	1.522	3.12	4.53	0.688
22.80	36.00	1.540	3.45	4.82	0.716

TABLE VII

SWELLING RATIO

Description of Samples: PRC from depth of 18 ft. at N.E.B., b-2 (see Table I)

Method of Compaction: Kneading compaction, 3 layers, 25 tamps, 20 lb. spring-tamper

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
8.1	31.9	1.635	-	-	-
7.7	34.2	1.637	4.77	6.75	0.707
7.9	33.5	1.630	4.73	7.55	0.627
7.5	35.1	1.645	-	-	-
8.2	32.2	1.639	5.22	5.73	0.912
8.3	31.0	1.643	4.16	6.35	0.654
8.6	32.5	1.612	5.77	6.06	0.954
11.9	31.1	1.668	4.31	6.82	0.632
11.4	29.8	1.679	4.28	5.57	0.767
11.1	30.9	1.663	4.04	5.92	0.683
11.3	31.4	1.640	4.22	-	-
11.7	30.6	1.640	4.58	6.17	0.743
15.2	25.4	1.722	3.50	4.49	0.779
14.6	25.6	1.703	3.20	4.12	0.777
14.8	26.2	1.690	3.62	4.12	0.878
15.1	25.7	1.677	3.31	4.47	0.740
14.4	26.2	1.696	3.83	3.88	0.987
17.8	23.5	1.745	2.42	2.76	0.877
17.2	22.5	1.745	2.36	2.40	0.984

TABLE VII (Continued)

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_v$ %	$\mathcal{E}_H$ %	$\mathcal{E}_v/\mathcal{E}_H$
16.7	23.1	1.751	2.52	3.17	0.795
17.1	23.7	1.703	2.58	2.86	0.902
17.3	24.7	1.685	2.58	3.00	0.860
17.9	23.9	1.682	2.38	2.55	0.933
20.5	23.9	1.682	1.20	1.63	0.737
20.7	23.5	1.652	1.08	1.57	0.688
20.1	23.3	1.692	-	-	-
20.1	23.2	1.668	1.15	1.37	0.841
22.4	24.6	1.576	0.60	1.51	0.398
22.4	25.0	1.588	-	-	-
22.9	25.7	1.568	0.54	1.23	0.439
21.9	24.6	1.596	0.62	1.69	0.368
21.6	24.2	1.587	0.80	1.33	0.603

TABLE VIII

SWELLING RATIO

Description of Samples: PRC from depth of 18 ft. at N.E.B.

Method of Compaction: Static Compaction

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
8.3	34.9	1.645	6.05	7.42	0.815
8.6	35.2	1.633	4.54	7.14	0.645
8.8	-	-	4.91	6.02	0.815
9.1	34.8	1.622	4.77	6.92	0.690
11.5	32.4	1.651	-	-	-
11.4	36.4	1.620	5.20	7.58	0.687
11.8	34.8	1.640	5.34	6.55	0.817
11.4	34.4	1.647	5.28	6.40	0.825
14.6	30.2	1.695	5.32	6.10	0.872
14.3	31.4	1.700	4.39	6.60	0.667
14.3	31.7	1.700	5.12	6.30	0.813
17.5	25.4	1.747	3.80	4.83	0.787
17.1	27.6	1.750	4.05	5.03	0.805
17.9	28.6	1.737	4.09	5.54	0.738
20.1	26.5	1.673	2.34	3.22	0.727
20.4	29.5	1.670	3.51	5.30	0.663
20.8	30.0	1.665	3.20	5.06	0.633
23.6	29.9	1.550	2.32	3.90	0.595

TABLE IX

SWELLING RATIO

Description of Samples: PRC from depth of 18 ft. at N.E.B.

Method of Compaction: Dynamic compaction, 3 layers, 25 impacts on each layer

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	ε_V %	ε_H %	$\varepsilon_V/\varepsilon_H$
11.24	34.2	1.640	5.42	7.00	0.775
10.79	34.7	1.632	5.40	7.42	0.728
14.47	34.2	1.618	5.41	7.83	0.690
14.27	31.7	1.642	4.75	7.06	0.673
17.18	30.8	1.651	4.31	5.62	0.766
17.07	31.3	1.628	4.16	5.95	0.698
19.76	30.9	1.600	3.12	5.41	0.577
19.59	29.6	1.622	3.14	4.60	0.682
23.2	31.2	1.567	2.32	4.17	0.557
22.5	29.4	1.581	2.10	3.88	0.542

TABLE X

SWELLING RATIO

Description of Samples: PRC from depth of 18 ft. at N.E.B.

Method of Compaction: Dynamic compaction, 3 layers, 50 impacts on each layer

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_v$ %	$\mathcal{E}_H$ %	$\mathcal{E}_v/\mathcal{E}_H$
7.9	31.1	1.736	4.80	7.60	0.632
12.4	30.7	1.750	6.08	7.20	0.845
16.7	29.0	1.759	4.54	5.87	0.774
21.0	26.7	1.680	2.32	3.00	0.773
24.2	28.0	1.597	1.39	1.82	0.765

TABLE XI

SWELLING RATIO

Description of Samples: PRC from depth of 18 ft. at N.E.B.

Method of Compaction: Static compaction

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_v$ %	$\mathcal{E}_H$ %	$\mathcal{E}_v/\mathcal{E}_H$
7.7	33.0	1.722	5.47	8.28	0.660
11.8	31.0	1.759	5.34	7.67	0.695
16.1	29.8	1.770	4.49	6.25	0.718
20.5	27.1	1.692	3.01	3.60	0.833
24.7	29.2	1.595	2.05	2.26	0.911

TABLE XII

SWELLING RATIO

Description of Samples: Undisturbed samples from b-1, and b-2 (*), see Table I

Initial Moisture %	Final Moisture %	Dry Density grs./c.c.	$\mathcal{E}_V$ %	$\mathcal{E}_H$ %	$\mathcal{E}_V/\mathcal{E}_H$
22.10	24.80	1.648	0.334	1.042	0.320
23.20	25.00	1.617	0.282	1.010	0.279
22.05	24.20	1.713	0.525	1.372	0.382
20.10	21.00	1.698	0.376	0.540	0.687
22.80	24.40	1.659	0.494	0.804	0.615
23.00	27.80	1.680	0.702	1.530	0.458
21.00	24.40	1.730	0.942	1.350	0.698
22.10	25.00	1.680	0.920	1.460	0.629
20.90	24.50	1.696	0.469	1.202	0.391
13.20	15.60	2.015	0.465	1.250	0.372*
13.23	15.70	2.015	0.503	1.235	0.407*
13.98	15.65	2.020	0.434	1.110	0.391*
14.24	16.25	1.982	0.730	1.097	0.666*

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions

In the preceeding pages an attempt has been made to throw some light on the further understanding of swelling characteristics of clay. By using a new triaxial swelling apparatus, and Stillwater permian clay, free triaxial swelling tests were performed on 190 samples. Involved in the tests were compacted samples with various initial conditions and different mode of treatments, and undisturbed samples. Based on the data and discussions presented in previous chapters, it may be concluded that:

1. Samples compacted using the same method and compaction energy swell more when compacted at low initial water contents than when compacted at higher initial water contents. Generally, their horizontal swelling ($\mathcal{E}_H$) is larger than their vertical swelling ($\mathcal{E}_v$); or their swelling ratios ($\mathcal{E}_v/\mathcal{E}_H$) are smaller than unity.

2. A sample compacted on the dry side of optimum usually starts to swell with a higher swelling ratio ($\mathcal{E}_v/\mathcal{E}_H > 1$) which rapidly decreases with increasing time; and a sample compacted at about optimum, or on the wet side of optimum usually starts to swell with a lower swelling ratio ($\mathcal{E}_v/\mathcal{E}_H < 1$) which is not much affected by time (Figure 24).

3. For all compacted and undisturbed samples, the volume of swelling is always less than the volume of water imbibed during swelling (Figures 26, and 38).

4. Using the kneading compaction method, the magnitude of swelling is found to be proportional to the magnitude of compaction energy. This relation is more evident in vertical swelling. Therefore, the swelling ratio is increased with increasing compaction energy (Figure 29).

5. For samples having the same initial water content and dry density, those prepared using static compaction swell more than those formed by kneading compaction or dynamic compaction. The volume of swelling of statically compacted samples is large compared to that of samples compacted by kneading; but there is little difference in the volume of swelling of statically and dynamically compacted samples. (Figures 33 and 34). Their swelling is accomplished at rates which are proportional to their swelling potentials (Figure 30).

6. According to the preceding samples prepared using static compaction have a higher degree of floccuration than samples compacted by other methods. The difference is more evident between static and kneading compaction than between static and dynamic compaction.

7. Remolded samples of Permian clay swell more than undisturbed samples, both in the vertical and horizontal directions. For samples which are equal in initial water content and dry density, remolded ones swell about 4 times as much as undisturbed ones in both directions (Figure 36).

8. The average swelling ratios for the undisturbed samples from depths of 9 and 18 feet are about 0.50 and 0.46 respectively, indicating that their vertical unit swelling is about one-half their horizontal

unit swelling.

9. The new triaxial swelling apparatus was found to be satisfactory for studies of the swelling ratio, and it may be recommended as a very practical apparatus which can provide dependable and useful quantitative measurements.

Recommendations for Future Research

Much additional research is necessary in order to gain a complete understanding of the swelling characteristics of compacted and undisturbed clays, and to define swelling characteristics in terms of the engineering properties of soils. The following are recommendations which may be profitable for future research:

1. Investigations similar to those described in this thesis should be made for clays from different locations, mixtures of known clay minerals, and for soils to which salts have been added.

2. Investigations of the structure of soil before and after swelling.

3. Investigations of the swelling properties of soils under confinement.

4. Investigation of the effects of curing period and stress history on swelling and swelling ratio of samples with or without confining pressure.

5. Further studies for the purpose of obtaining quantitative data concerning the charges and characteristics of the adsorbed water existing on particle edges.

6. Through the study of additional natural clays, correlate the swelling and swelling ratio to the engineering properties of soils.

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