SWELLING CHARACTERISTICS
OF PERMIAN CLAY

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NOMENCLATURE

μ	Micron --- one thousandth of a millimeter.
Å	Angstrom --- one hundred millionth of a centimeter.
S_1	Swelling Potential.
C_1	Percentage of clay sizes finer than 0.002 mm.
K_1	A coefficient which varies with type of clay, used in determining the swelling potential.
A_1	Activity of Clay.
x	An exponent varying with type of clay, used in determining the swelling potential.
K	Absolute Permeability.
R_o	A constant that depends on pore shape and tortuosity of flow.
S	Specific surface.
e	Void Ratio.
ε_v	Vertical Strain.
H	Initial Sample Height.
ΔH	Incremental Vertical Dial Reading.
ΔV_1	Volume change due to horizontal swelling.
ΔV_2	Volume of water that has been forced from the Plexiglas chamber in swelling.
π	3.1416
r	Initial Radius of Specimen
Δr	Incremental increase in the radius due to horizontal swelling.
H'	Total Height of Specimen after completion of swelling.
C	Capacity of Saran Tube

CHAPTER I

INTRODUCTION

General

In many areas of the world and particularly in the middle-western and south-western parts of the United States, the volume increase of highly plastic clays has caused considerable damage to buildings, retaining walls, pipe lines, highways, etc. Therefore, the prediction and estimation of one-dimensional and volumetric swelling characteristics of expansive clays have been the subject matter of many studies. However, no effort was made to investigate directly the relationship between vertical and horizontal swelling. For this purpose, a triaxial swelling apparatus that can measure separately the rate and magnitude of both horizontal and vertical swelling of compacted or undisturbed clay samples was developed in the School of Civil Engineering at Oklahoma State University by Mr. R. B. Fost[1] under Professor James V. Parcher's direction.

To determine the swelling characteristics of permian red clay of Oklahoma, seven apparatuses have been made and used for various stages of the study. The study was divided into three distinct phases.

In the first phase of the study, the effects of the various compaction methods (kneading, static, dynamic) and the amount of compaction energy were investigated. In this study 177 compacted samples and thirteen undisturbed samples have been tested. Some of the soil that has been used in the preparation of the compacted samples was taken from the same location as that of the undisturbed samples.

The second phase of the study involved the investigation of the effects of gypsum addition to the mix of compacted clay samples. Gypsum contents of 5, 10, 20 and 30 per cent based on dry weight have been used in conjunction with various moisture contents. Furthermore, the curing effect has been investigated by direct comparison of samples that have been cured 1 and 28 days. In this phase a total of 85 compacted samples have been tested.

The effects of inorganic chemicals on the swelling properties of permian red clay have been investigated in the third phase of the study. The chemicals used were NaCl and $CaCl_2$. Chemical contents of 1 per cent and 2 per cent by dry weight of soil have been utilized. A total of 31 compacted samples have been tested and, in addition, the effect of curing has been investigated by direct comparison of samples that have been cured one and seven days.

In this study an attempt was made to find the effect on the swelling ratio, defined as the ratio of the vertical swelling to horizontal swelling, of the various modes of treatment and conditions, and to see whether the swelling potential of the expansive clays can be economically and feasibly reduced.

Origin of Investigation

Certain structures have been severely damaged not only by vertical swelling of the expansive clays upon which they rest, but also by the horizontal swelling. This has been observed several times by Professors J. V. Parcher and R. E. Means in various parts of the middle-west and south-west of the United States, where expansive clays have been a problem to civil engineers for some time. If a retaining wall is backfilled with an expansive clay, the swelling pressures exerted by this clay will be greater than the active earth pressure, which is usually taken as the basis of design. Because of this greater pressure, the wall may be damaged or will tilt slightly outward, particularly during wet seasons. However, when the dry season arrives, the clay will start to shrink and cracks will form at the surface, which may be filled with debris. If these cracks are filled with debris before the next wet season arrives, the expansive clay will exert full swelling pressures against the wall and tilt it some more. When this action continues for many years, the retaining wall may finally fail.

Horizontal swelling has greater significance in light buildings on shallow continuous footings and foundation walls. In one of the college buildings constructed recently in south-central Oklahoma, the horizontal as well as the vertical swelling of the clay caused severe damages. This particular building had a steel frame which was supported on a drilled and underreamed pier and grade beam foundation. In order to maintain vertical stability, the footings had been placed approximately 4 feet inside the exterior building line. The exterior wall of a pipe tunnel that ran parallel to the wall supported this panel wall. The pier and underreamed footings, which were at the same level as the footings under the main columns, carried this exterior tunnel wall.

As the clay outside the building was exposed to the sun and wind it became, after a certain period of time, relatively drier than the clay under the building, which at this time, unfortunately, was fed water by a broken water line. The swelling pressures of the clay inside the building forced the tunnel outward and upward, and finally wrecked the panel wall to such an extent that it became necessary to tear it down completely and replace it (Means, 2, p. 22).

A building in southern Oklahoma was constructed on a pier and belled footing and grade beam foundation. The clay in the bottoms of the trenches which were excavated for the cast grade beams had been loosened. By this method, an attempt was made to prevent the damaging effects of the expansion of the clay, for which the consolidation of the loose clay would compensate. Subsequent uplift on the bottom of the grade beams caused only small damages, but the lateral expansion of the clay was far more significant. Swelling of the clay in the horizontal direction exerted a pressure upon the grade beams, pushing them outward and causing cracks approximately one-half inch wide between the beams and the floor that was cast on a compacted fill. Furthermore, some additional cracking took place in the exterior brick walls (2, p. 23).

These particular examples serve as indications of the significance of the horizontal swelling of clays. In order to understand and perhaps remedy this situation, three-dimensional swelling characteristics have been investigated. In this respect the relationship between the magnitude and the rate of vertical and horizontal swelling of expansive clays becomes very important. Elimination of the damaging effects of the lateral swelling can only be achieved by analyzing the data of the triaxial swelling phenomena under different conditions. However, so far both the theoretical and empirical descriptions of this phenomenon are not sufficient. The attempt of this study, then, is to fill this gap as much as possible.

Historical Background

The founder of modern soil mechanics and foundation engineering, Karl Terzaghi (3), believes that it was R. J. Katz who analyzed for the first time relationships among swelling-pressure, heat of swelling, relative vapor pressure and volume contraction. Although he gives credit to Katz for providing a basis for an exploration of the nature of swelling, Terzaghi pointed out that in this first analysis only the physico-chemical reactions within the system were considered and the purely physical factors which might have significant effects upon swelling were completely ignored. Terzaghi asserted that even though the relative significance of the physico-chemical factors increases when one proceeds from coarse disperse systems to fine disperse systems, nevertheless, there is no reason to believe that purely physical factors such as porosity, elasticity, capillary force, permeability, and hydrostatic pressure become less effective in the swelling process. In his final analysis Terzaghi concluded that the process of swelling is due to the elastic expansion caused by a lowering of the capillary pressure. The physico-chemical reactions which take place in this process affect the swelling due to the fact that they change the elastic properties of the system. As adhesion at the points of contact is altered and stiffness of molecular links is modified, the elastic properties of the system undergo a change.

As all physical factors are influenced by the soil structure, it was Terzaghi who first recognized the significance of the soil structure in the swelling phenomenon. His physical concept of the volume change of expansive clays was supported by the studies of Arthur Casagrande (4). The influence of the effective stress as another physical factor in the behavior of expansive clays was studied by Smith and Redlinger (5) and Lambe and Whitman (6). Their studies showed that a relaxation of effective compressive stress cause an enlargement of capillary films and consequent swelling of clay soils. Means (2) contributed to the development of physical concepts of clay expansion by considering stress history, effective stress and climatic conditions.

Although the physical concept of clay expansion is a very important contribution to the understanding of the swelling phenomenon, a complete understanding is not possible unless physico-chemical factors are also considered.

In his extensive studies, Lambe (7) investigated almost all of the factors that influence the volume change in a clay mass and found that swelling properties can be altered by changing any of the following factors:

1. Composition of clay (minerals, exchangeable ions and impurities),
2. Nature of pore fluid (ions, PH, dielectric properties),
3. Structure of clay, and
4. Environmental factors (temperature, pressure, time).

Physico-chemical factors were investigated by Baver and Winterkorn (1936) (8). Their studies were concerned with the effects of exchangeable ions on the swelling magnitudes. They observed that when sodium is replaced by other univalent or by divalent and trivalent ions, the swelling of montmorillonite type clays decreases significantly. For Wyoming bentonite (sodium montmorillonite) the decrease in swelling conformed to the following sequence of ion substitution: sodium, lithium, potassium, calcium, magnesium and hydrogen.

Hendrik, Nelson and Alexander (1940) (9) studied the simultaneous effects of exchangeable ions and relative humidity on the expansion of montmorillonite clays and found out that at a relative humidity of 5 per cent the sequence of decreasing swelling is magnesium, calcium, lithium, strontium, barium, hydrogen, sodium, cesium and potassium. However, in the presence of excess water, lithium and sodium montmorillonites swell more than do montmorillonites with other cations.

The Missouri River Division of the United States Army Corps of Engineers (10) investigated the cation exchange capacity of expansive clays and they found that expansive properties can be significantly changed by the chemical nature of the seepage waters. When the seepage water contained exchangeable cations, the expansion of clay was reduced considerably. Goldberg and Klein's studies (11) showed that an admixture of 8 per cent calcium hydroxide to a sodium montmorillonite reduced the swelling pressure from approximately 9 to 5 psi.

Bolt (12) and Ladd (13) studied the effect of the chemical properties of the pore fluid, both that used during compaction and that which is imbibed during swelling. These studies indicated that when effective stress (total pressure minus pore pressures) on the sample is reduced, an osmotic repulsive pressure is developed between clay particles that causes swelling. Futhermore, this osmotic repulsive pressure is proportional to the difference in salt content in the water between clay particles and that in the free pore water.

R. K. Katti and A. G. Barve (14) studied the effects of inorganic chemicals on the consistency properties of expansive soils and found that in general $CaCl_2$, $MgCl_2$ and $BaCl_2$ lower the liquid limit and increase the plastic index. Na_2Co_3, $BaCo_3$ $MgCo_3$ and Na_2SiO_3 increase the plastic index of the soil and make the soil highly plastic. KoH, $Ca(OH)_2$ and NaOH change the soil from a plastic clay into a friable soil.

W. G. Holtz (15) has investigated the factors affecting the magnitude of volume change and has shown that the amount of volume change which can occur in a natural or remolded expansive clay depends upon six factors, which are as follows: (a) the amount and type of clay minerals, (b) initial density, (c) change in moisture, (d) load conditions, (e) soil structure, and (f) time.

Holtz and Gibbs (16) tried to determine the amount and type of minerals in any clay sample by using three petrographic tests: microscopic examination, X-ray diffraction and differential thermal analysis, in order to correlate identification tests with physical properties that affect the swelling of clays.

Mielenz and King (17) have shown that the magnitude of the swelling of clay minerals depends upon the kind and amount of clay minerals present, their exchangeable ions, electrolyte content of the aqueous phase, particle size distribution, void size and distribution, the internal structure, water content and the applied load.

Ladd (13) studied the mechanisms of swelling in compacted clay and established that the following factors governed this process: (a) composition of clay, (b) compaction conditions, (c) chemical properties of the pore fluid, (d) confining pressure applied during swelling, and (e) time allowed for swelling.

Low and Deming (18) investigated the forces acting between clay particles and found their components. The most important component is considered to be an osmotic pressure which was referred to as "electrical repulsion" by Lambe.

Seed, Woodward and Lundgren (19) studied the swelling of compacted clays and tried to determine the swelling potential in terms of plastic index. They found that if the plasticity indices of the various soils prepared from any one clay type were plotted against the percentage of clay sizes in the soils, the points approximate a series of straight lines. From this analysis they have concluded that there is a significant correlation between swelling potential and plasticity index for the compacted samples. Debruyn, Collins and Williams (20) studied the relationship among the specific surface of clay minerals, water affinity and potential expansiveness of clay and found that plastic index and per cent clay sizes may be considered in assessing the swelling characteristics of any soil.

The importance of soil structure was first pointed out by Terzaghi as mentioned previously. Casagrande's (4) theory of honeycomb structure helped to explain the difference between the physical properties of clays in the natural and remolded states. In 1926 Goldschmidt (21) suggested that highly sensitive clays have an unstable card-house structure. This geochemical representation of highly sensitive clays was further developed by Lambe (22), T. K. Tan (23) and Rosenqvist (24). In 1957 Tan gave a schematic picture of clay network in an imaginative drawing and showed that in this random arrangement contacts were established between the face of one particle and a corner of another one. Experimental studies of Rosenqvist in 1959 with the aid of an electron microscope, clearly indicated that Tan's conception of mineral particle arrangement was correct. The arrangement of mineral particles in undisturbed marine clays apparently corresponds to a card-house structure.

The significance of soil structure was further established by Seed and Chan's studies (25). Their investigations showed that clay materials with a flocculent structure swell more than clays that have a dispersed structure. Furthermore, it was their finding that the vertical swell pressure exerted by a specimen that was compacted statically is higher than that of a specimen compacted by the kneading method.

Although Terzaghi's physical concept of swelling of porous structures which led to various studies was extremely helpful in pointing out the effect of surface tension of the water in the system and the elasticity of the solid components, experimental results clearly indicate that swelling can best be explained in terms of colloidal chemistry of the surface of clay minerals, which takes into consideration the effects of both the inner and outer parts of electrical double layer. In this respect Katz's early contribution cannot be overlooked.

CHAPTER II

SWELLING CHARACTERISTICS OF CLAYS

A study of swelling characteristics of clay materials can best be approached by considering separately (a) compacted clays, and (b) undisturbed clays, as the engineering properties from one class to another change significantly. Swelling of clay changes those engineering properties such as strength, permeability and compressibility. Therefore, from an engineering point of view, an understanding of the swelling process is important in order to prevent or reduce certain severe damages that might occur because of swelling. For highway engineers in the construction of subgrades and embankments, and for hydraulic engineers in the construction of earth dams, this information becomes invaluable.

Swelling Characteristics of Compacted Clays

According to Seed, Woodward and Lundgren (19) the swelling of compacted clay is influenced by two groups of factors. In the first group there are those factors that depend upon the nature of clay particles. These control the swelling potential. In the second group are the factors that determine the amount of swell which will actually occur. This classification can be given by modifying the table given by Seed:

Factors Influencing Swelling of Compacted Clay Soils

Group I:

1. Type of clay in soil
2. Amount of clay in soil

Determine swelling potential

Group II:

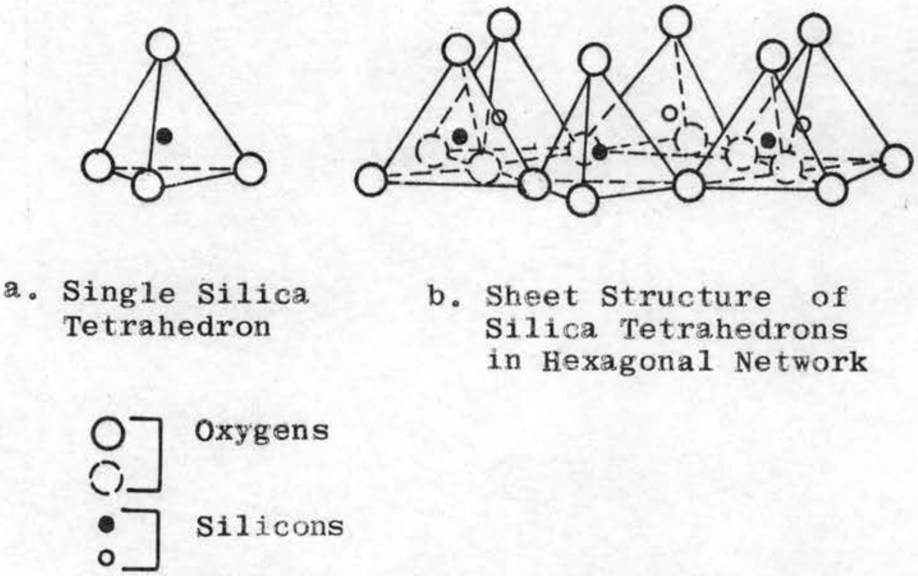
1. Initial water content
2. Method of compaction and soil structure
3. Availability of water and its chemical properties
4. Confining pressure
5. Period of curing
6. Time required for swelling
7. Temperature

Determine the magnitude of horizontal and vertical swelling

<u>Group I</u>

1. Type of Clay in Soil: Swelling is a phenomenon which is associated with only clay minerals, as silt and sand particles have but a very small influence on volume change. In the atomic structure of most common clay minerals two units are involved. The first one is a tetrahedral silica unit and the second one an octahedral aliminum oxide unit (gibbsite). The first unit has a silicon atom which is equidistant from four oxygens arranged in the form of a tetrahedron. These tetrahedrons are arranged in such a way that they form a hexagonal network. This network, whose structural formula is $Si_4O_6(OH)_4$, is repeated continuously to

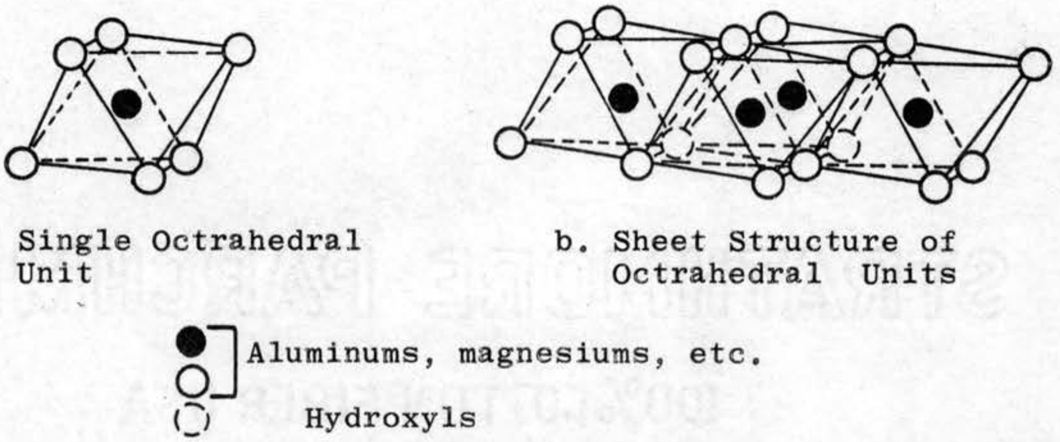
form a sheet. The tips of the tetrahedrons point in the same direction, and the bases are on a common plane, as shown in Figure 1. In this unit, for every silicon ion having four positive charges, there are three oxygen ions (each having two negative charges) that form the base of the silica unit and share their charges with another unit, and one oxygen ion at the tip of the tetrahedron. Thus, there remains five negative charges to balance four positive charges. Therefore, the tetrahedral unit has a -1 net charge.


a. Single Silica Tetrahedron

b. Sheet Structure of Silica Tetrahedrons in Hexagonal Network

FIGURE 1. (After Grim, 26.)

The second fundamental unit which is octahedral in form, and whose structural formula is $Al_2(OH)_6$, has 6 hydroxyl ions surrounding an aluminum, iron or magnesium atom. This aluminum atom is equidistant from 6 hydroxyl ions. The octahedral units are arranged in such a way that they form a sheet structure in which every hydroxyl ion is shared by 3 octahedral units, as shown in Figure 2. As an Al ion has +3 charges


a. Single Octrahedral Unit

b. Sheet Structure of Octrahedral Units

FIGURE 2. (After Grim, 26.)

and as each hydroxyl ion divides its -1 charge with two other units, each octahedral unit has a net charge of +1. It was mentioned above that each tetrahedral unit has a -1 net charge. Therefore, the opposite charges between silica and gibbsite units create a strong ionic bond. (See Figure 3.)

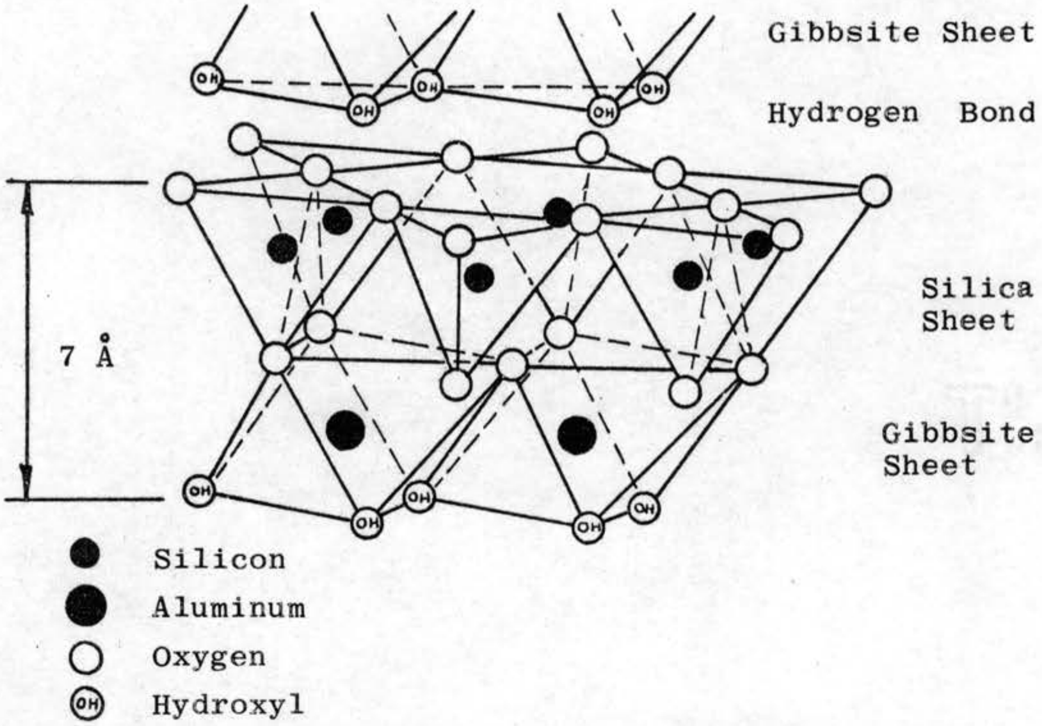


FIGURE 3. ELEMENTAL SILICA-GIBBSITE SHEET (After Grim, 26.)

In the silica-gibbsite sheet commonly there are more silica units than alimunum hydroxyl units which creates negative charges on the sheet. The elemental silica-gibbsite sheet has a thickness of 7 Å. The negative charges of the silica-gibbsite sheet attract the dipolar water molecules and some water molecules are bound by this electro-magnetic field to the surface of the clay particle. These water molecules are in the solid state. (See Figure 4.) This adsorbed water is adjoined by additional water of apparently viscous nature. The viscosity decreases as distance from the particle surface increases until finally at a sufficient distance from the particle surface the water possesses ordinary properties.

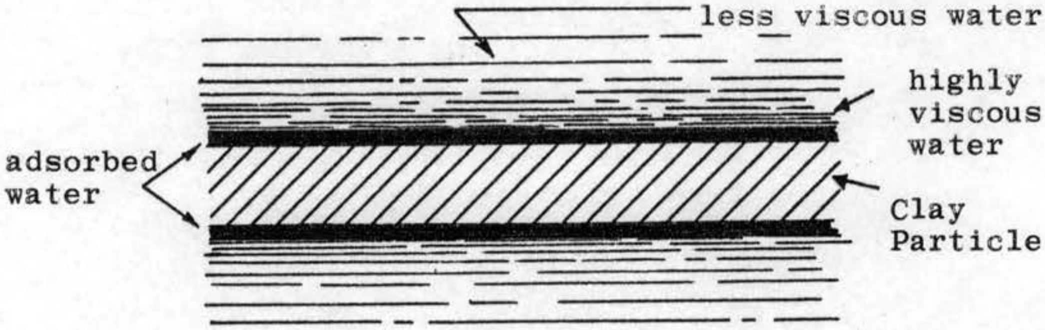


FIGURE 4. CLAY PARTICLE WITH ATTACHED WATER

The water molecules between elemental clay sheets may tend to keep particles apart. The concentration of ions in the vicinity of the clay particle is different from that in the free water, consequently, there result osmotic pressures which cause water to flow from points of low ionic concentration to points of high ionic concentration. This is known as osmotic swelling. Osmotic swelling is a physico-chemical phenomenon and is entirely different from the swelling due to the release of compressive stresses. This latter process is known as elastic rebound. If the pressure that causes consolidation of a clay material is removed, the deformed elastic particles try to return to their original position and through this purely mechanical process elastic rebound occurs.

The swelling process varies significantly from one type of clay to another. Therefore, it is important to classify certain clay types and investigate their volume changes separately. One of the best classifications is given by Grim (26) in which clays are divided mainly into nine groups which are as follows:

1. Allophane minerals
2. Kaolinite minerals
3. Halloysite minerals
4. Montmorillonite minerals
5. Illite minerals
6. Chlorite minerals
7. Vermiculite minerals
8. Altapulgite-Palygorskite-Sepiolite
9. Mixed layer minerals

In this study the author was primarily interested in the swelling characteristics of Kaolinite, Montmorillonite, and Illite clay minerals, as the clay soils used in triaxial swelling experiments contain mainly these minerals. Therefore, attention will be directed to these three types.

Kaolinite

The structure of Kaolinite, which was first suggested by Pauling (1930) (27) and developed by Gruner (1932) (28) and Brindley (1946) (29), is composed of two sheets, one of them being a tetrahedral sheet and the other one the alumina octahedral sheet. (See Figure 5.) The structural formula can be given as $(OH)_8Si_4Al_4O_{10}$ and in the theoretical composition the SiO_2 is 46.54 per cent, Al_2O_3 is 39.50 per cent and H_2O is 13.96 per cent. The thickness of Kaolinite units is about 7 Å. Unit layers of Kaolinite are held together by a hydrogen bond which is weaker than ionic or covalent bonds.

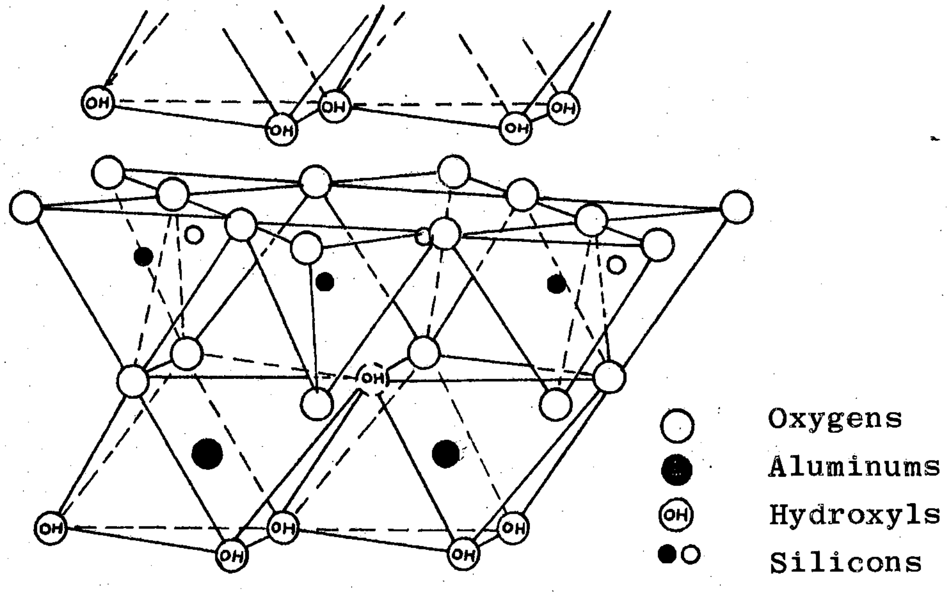


FIGURE 5. DIAGRAMATIC SKETCH OF THE STRUCTURE OF THE KAOLINITE LAYER (After Grim, 26.)

(See Figure 6.) Therefore, kaolinite crystals can be split into very thin sheets. However, these sheets generally are clustered together. As the sheets carry negative electromagnetic charges on their flat surfaces, the dipolar water

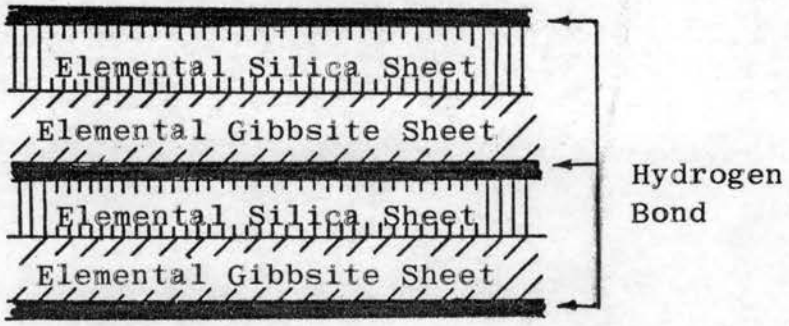


FIGURE 6. STRUCTURE OF KAOLINITE

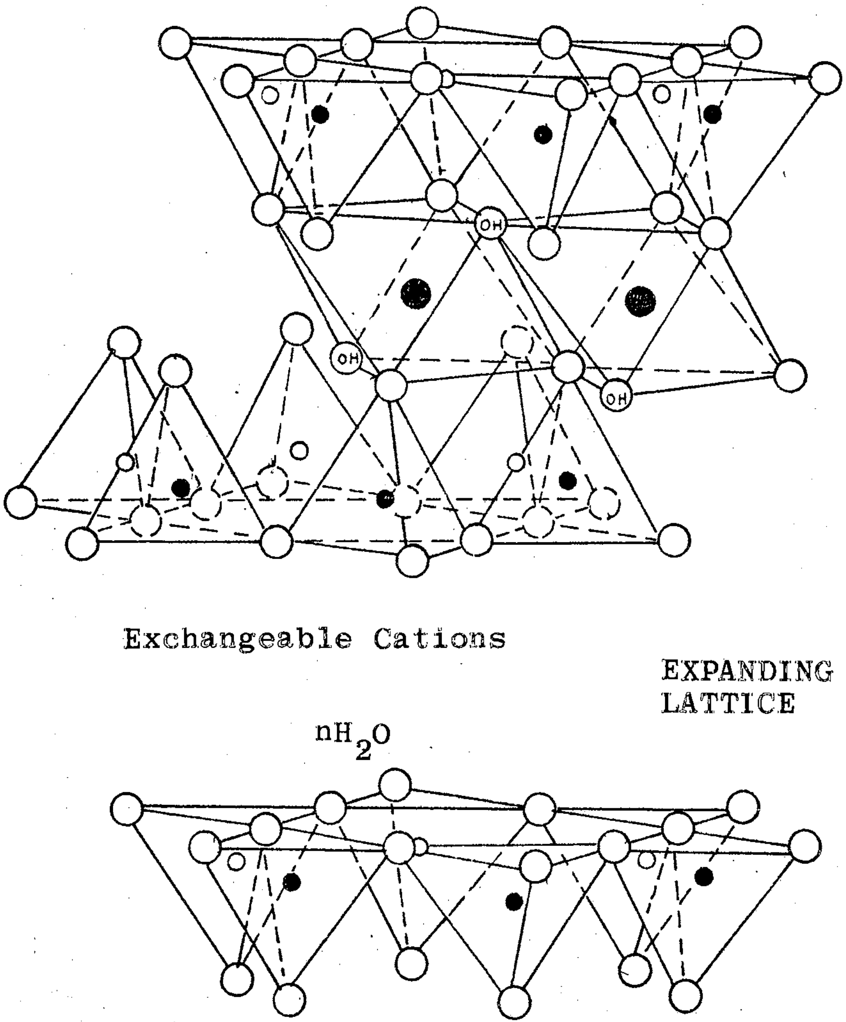
molecules are attracted to them. Lambe's (30) studies show that a Kaolinite crystal which is 1000 Å thick will have about 10 Å of solid water attached to its surface and about 400 Å of viscous water. Therefore, between the two kaolinite platelets there will be 800 Å of water. Consequently, in this combination, kaolinite will be 44 per cent water and 56 per cent solid by volume. Because of the hydrogen bond, the kaolinite mineral cannot be dispersed very easily in water to very small units. As the elemental sheets are very compact, they have no space between them for ions or small molecules. Because of this fact, colloidal properties are determined only by external surfaces.

Montmorillonite

The montmorillonite minerals are very small particles. This fact eliminates the use of the single crystal X-ray diffraction method to obtain data in order to develop an understanding of the structure of montmorillonite minerals. However, powder data can be used for this purpose. According to analyses developed by Hofmann, Endell, and Wilm (31) (1933), Marshall (1935) (32), Maegdefrau (1937) (33), and

Hendrix (1942) (34), the montmorillonite structural unit is composed of an octahedral alumina sheet sandwiched between two silica sheets, as shown in Figure 7. In this structure the octahedral and tetrahedral sheets are arranged in such an order that the tips of tetrahedrons of silica sheets and one of the hydroxyl layers of the octahedral sheet lie on a common plane. Furthermore, the tips of all tetrahedrons are oriented in the same direction, which is toward the center of the unit. In this arrangement of silica-alumina-silica units, there is a very weak bond that holds successive sheets together. Therefore, water and other polar molecules can enter between the layers and cause the lattice to expand, as shown in Figure 7. This phenomenon is known as an expanding lattice and it explains why the soils that contain significant quantities of montmorillonite minerals are subject to extreme volume changes. Shrinkage and swelling depend upon the amount of water available. The Montmorillonite group can further be divided into subgroups. These are montmorillonite, beidellite, notronite, and saponite. In montmorillonite Al in the octahedral sheet is replaced sometimes by Mg. In beidellite this replacement is done by Si. In notronite Fe replaces Al and in Saponite Al is replaced by Mg in the octahedral sheet and Si is replaced by Al in the tetrahedral sheet. Montmorillonite, whose structural formula is $Al_2O_3 \cdot 5\ SiO_2 \cdot 5\text{-}7\ H_2O$ consists of SiO_2, 66.7%; Al_2O_3, 28.3% and H_2O, 5%.

In 1940 Edelman and Favejee (35) introduced a different kind of structure and claimed that this new concept could



○ Oxygens

Ⓞ Hydroxyls

● Aluminium, iron, magnesium

○● Silicon, occasionally Aluminum

FIGURE 7. DIAGRAMATIC SKETCH OF THE STRUCTURE OF MONTMORILLONITE (After Grim, 26.)

explain the properties of montmorillonite minerals more precisely. According to their concept, every other silica tetrahedron in both silica sheets is inverted. Therefore, half of the tetrahedrons point in the opposite direction. Yet X-ray diffraction, chemical and dehydration analysis do not generally agree with this concept. On the other hand, the possibility that a small amount of silica tetrahedrons may be inverted is not refuted.

Montmorillonite minerals that occur in very thin flake-shaped units can be easily dispersed in water into very small particle sizes. The thickness of the montmorillonite unit is approxmiately 9.5 Å and the other dimensions are indefinite.

Illite Minerals

The basic structural unit of illites is similar to the units of montmorillonite with one exception, that some of the silicons are always replaced by aluminum atoms, consequently creating a residual negative charge which in turn is balanced by potassium ions. (See Figure 8.) Approximately 25 per cent of the silicons are replaced by aluminum atoms in some micas that have well-crystallized structures. The potassium bond is weaker than the hydrogen bond of kaolinites; however, it is stronger than the bonds that exist in montmorillonite minerals. Consequently there is no expanding lattice in illites as is observed in montmorillonites. In all these clay minerals the interlayer balancing cations are nonexchangeable.

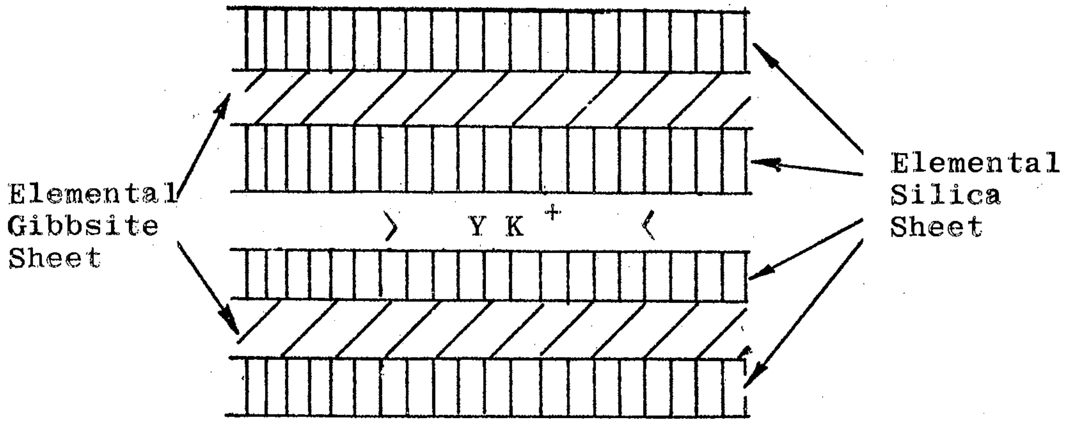


FIGURE 8. STRUCTURE OF ILLITE

If some of the potassium ions are removed from illite structure, the bonding force between the silica-alumina-silica layers would weaken, creating the possibility of an expanding lattice. This type of material is called degraded illite, yet it is not exactly similar to montmorillonites as it is not so readily dispersable and has a stronger capacity for adsorption of ions.

Studies done by electron microscopes demonstrate that illite minerals have small and not clearly defined flakes. These flakes generally are grouped in a random fashion. The diameter of most of the flakes ranges between 0.1 and 0.3 μ.

In summary, kaolinite minerals that have fixed crystal lattices have very small hydration and adsorptive capacities. In these minerals, cation adsorption or base exchange is not pronounced. However, in the case of montmorillonite minerals, the situation is completely different. Montmorillonites have expanding crystal lattices which is the main cause of considerable hydration and cation adsorption. Dipolar water molecules and available cations are adsorbed both on the exterior surfaces and on the interior surfaces of the montmorillonite crystal. The water adsorbed on the interior surfaces introduces relatively higher volume changes. In this respect illite minerals lie in between kaolinite and montmorillonite.

In quantitative comparison, this can be demonstrated more concretely. Kaolinite will have a double layer of water of 400 Å thickness on its surface when the pressure is zero, as mentioned previously. Therefore, between two kaolinite platelets there is 800 Å of water. The thickness of a kaolinite crystal, according to Lambe is approximately 1000 Å and considering also 10 Å of solid water adsorbed on its surface, under zero pressure and normal temperatures kaolinite minerals will contain 44 per cent water and 56 per cent solids by volume.

However, the thickness of a montmorillonite crystal sometimes may be as small as 10 Å and will have 10 Å of adsorbed water and 200 Å of double water layer. Therefore, if the montmorillonite mineral has a dispersed structure it will contain 97 per cent water and 3 per cent solids by volume. From these considerations it is obvious that the thinner the clay particle, the higher is the percentage of attached water by volume.

2. Amount of Clay in Soil: Following the suggestion of Holtz and Gibbs (16), Seed, Woodward and Lundgren (19) studied the relations between swelling potential and clay content, plasticity index and shrinkage limit. They have plotted the swelling potential for certain types of

clay soils, against the respective values of the factors mentioned above. (See Figure 9.) However, it is obvious from this Figure that it is very difficult to establish a correlation between swelling potential and these indicators. However, if the amount of swelling at maximum density and optimum water content is plotted against the percentage of clay sizes for different clay types, a definite correlation can be observed. From Figure 10 it can easily be observed that swelling increases with the amount of clay present in the soil, as expected. Observation of the curves in Figure 10 indicated to Seed, Woodward and Lundgren that a relationship in exponential form may exist between the swelling potential and percentage of clay size.

$$S_1 = K_1 C_1^x$$

In this formula S_1 represents the swelling potential defined as percentage of swell under 1 psi surcharge. For a sample compacted at optimum water content to maximum density in a standard AASHO compaction test, C_1 is the percentage of clay sizes finer than 0.002 mm., K_1 denotes a coefficient which varies with type of clay and x is an exponent varying also with the clay type. If such a relationship exists, then $\log S_1 = \log K_1 + x \log C_1$. Therefore, if $\log S_1$ is plotted against loc C_1, the points should fall on a straight line. This second relationship is shown in Figure 11. The slopes of the straight lines plotted on Figure 11 are the exponents, x, for different types of clay soils and the coefficients, K_1, can be found by reading the values that correspond to $C_1 = 1$. In Figure 11 all straight lines are approximately parallel,

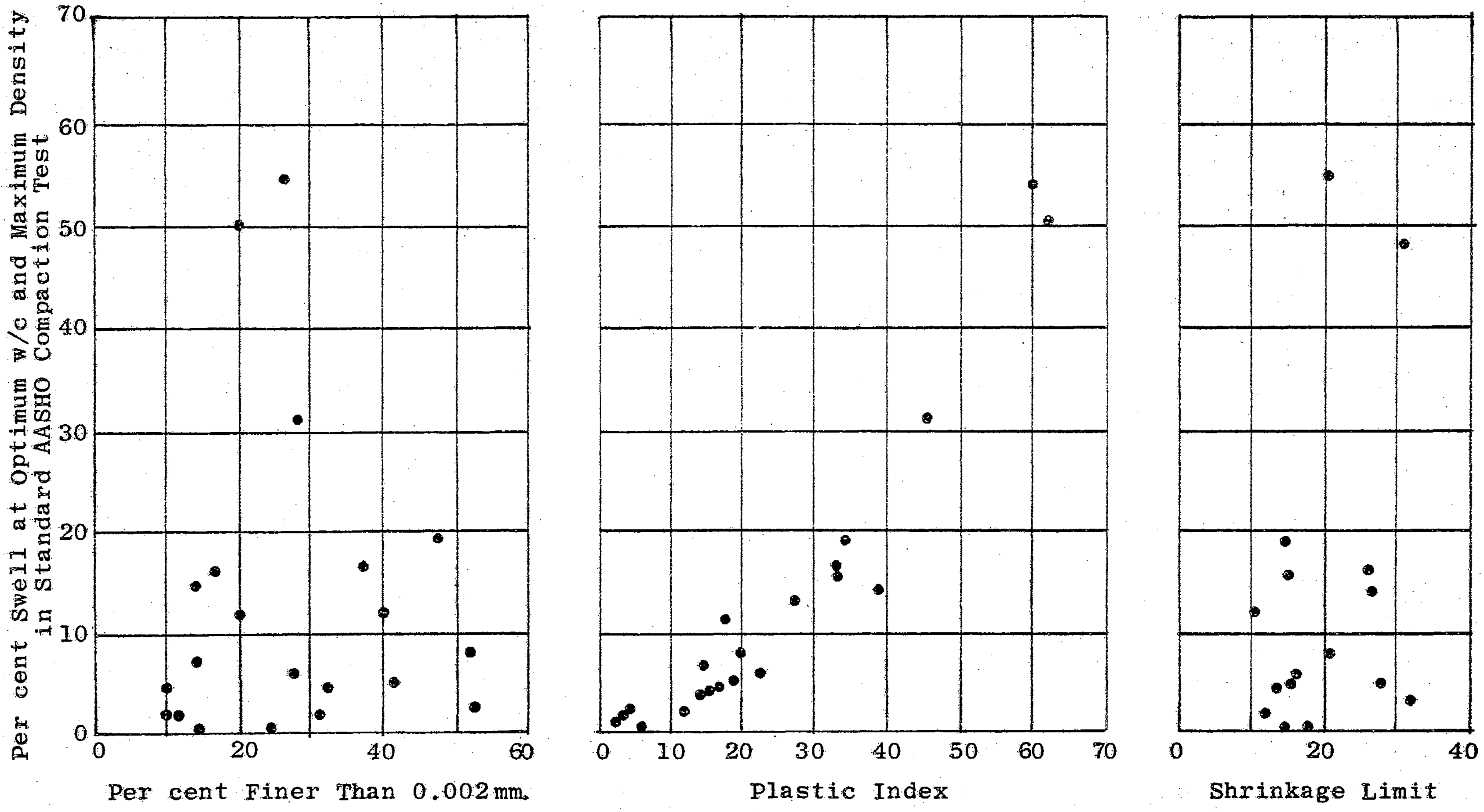
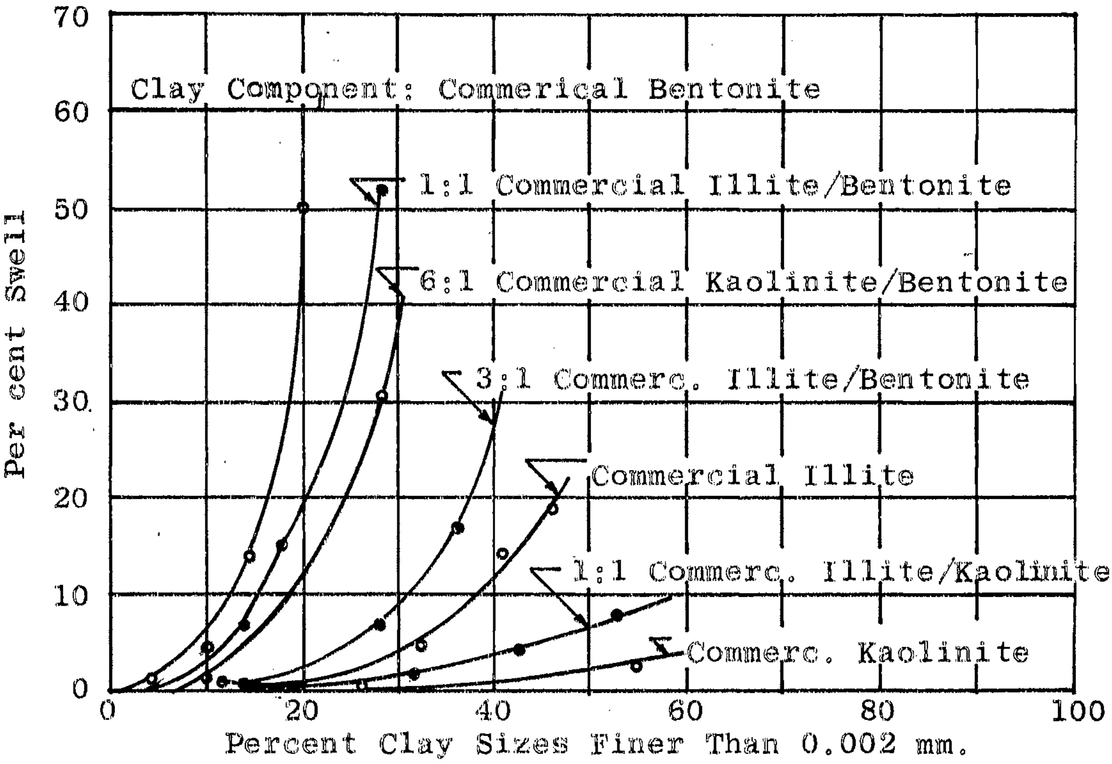


FIGURE 9. RELATION OF SWELL POTENTIAL TO PERCENTAGE OF CLAY SIZES, PLASTICITY INDEX, AND SHRINKAGE LIMIT FOR EXPERIMENTAL SOILS. (After Seed, Woodward and Lundgren, 19.)



Note: Percent swell measured under 1 psi surcharge for sample compacted at optimum water content to maximum density in standard AASHO test.

FIGURE 10. RELATIONSHIP BETWEEN PERCENTAGE OF SWELL AND PERCENTAGE OF CLAY SIZES FOR EXPERIMENTAL SOILS. (After Seed, Woodward, and Lundgren, 19.)

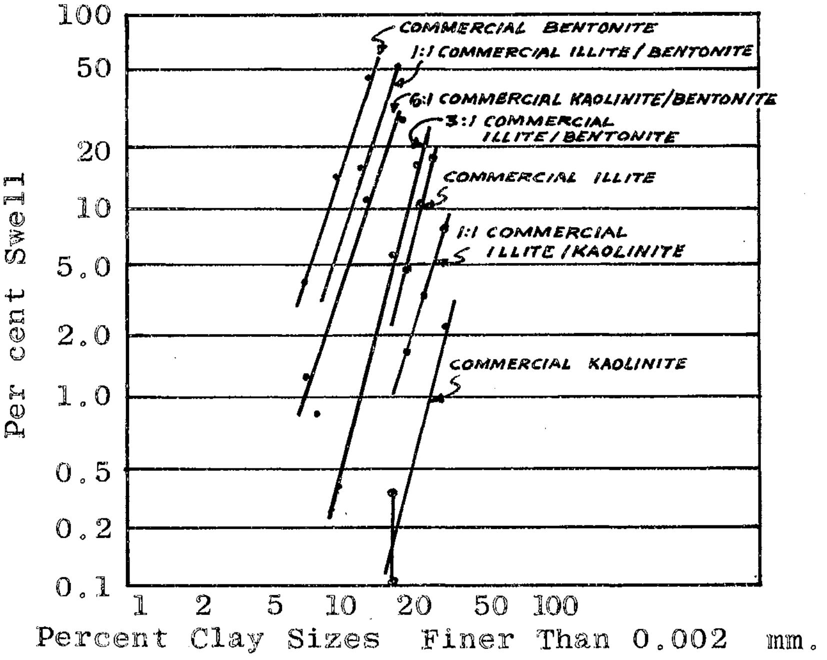


FIGURE 11. RELATIONSHIP BETWEEN PERCENTAGE OF SWELL AND PERCENTAGE OF CLAY SIZES FOR EXPERIMENTAL SOILS. (After Seed, Woodward, and Lundgren, 19.)

having a slope of about 3.44. Therefore, the first relationship can be given as $S_1 = K_1 C_1^{3.44}$. Seed, Woodward and Lundgren found that K_1 values are very different for different types of soils. These K_1 values are given in Table I. Then, for a given clay soil, if the percentage of clay sizes finer than 0.002 mm. is determined by laboratory procedures, swelling potential can be directly computed from the relation, $S_1 = K_1 C_1^{3.44}$.

TABLE I

THE RELATIONSHIP BETWEEN K_1 VALUES AND TYPE OF CLAY

(After Seed, Woodward and Lundgren, 19.)

Type of Clay	K_1	Activity, A_1
Bentonite	152×10^{-5}	5.20
1:1 Illite/Bentonite	78×10^{-5}	3.30
6:1 Kaolinite/Bentonite	31.6×10^{-5}	2.21
3:1 Illite/Bentonite	5.5×10^{-5}	1.25
Illite	3.47×10^{-5}	0.95
1:1 Illite/Kaolinite	1.12×10^{-5}	0.57
Kaolinite	0.28×10^{-5}	0.40

Group II

Initial Water Content: One of the most important factors that influences the swelling properties of compacted clays is the initial water content. For a given compactive effort, dry densities vary with initial water contents. The initial water content that corresponds to the maximum dry density, under a given compactive effort, is called the optimum water content. Generally its determination is a routine laboratory test procedure carried out by trial in the manner devised by R. R. Proctor (36) of the Bureau of Waterworks and Supply of Los Angeles, California. This test is known as the Standard AASHO (Proctor) Test. If it is desired to study the properties of a soil under a greater compactive effort than that used in the Standard Test, the Modified AASHO Test may be used. The relationship between the initial water content and the dry density for a given compactive effort is shown in Figure 12. As observed in Fig-12, points A and B have the same dry density, yet different initial water contents. The properties of the samples corresponding to points A and B are different. If two samples are compacted to the same dry density by a given compactive effort, yet with different initial water contents, the one that is compacted on the dry side of optimum will swell more. In other words, the sample corresponding to point A in Figure 12 swells more than does the sample corresponding to point B.

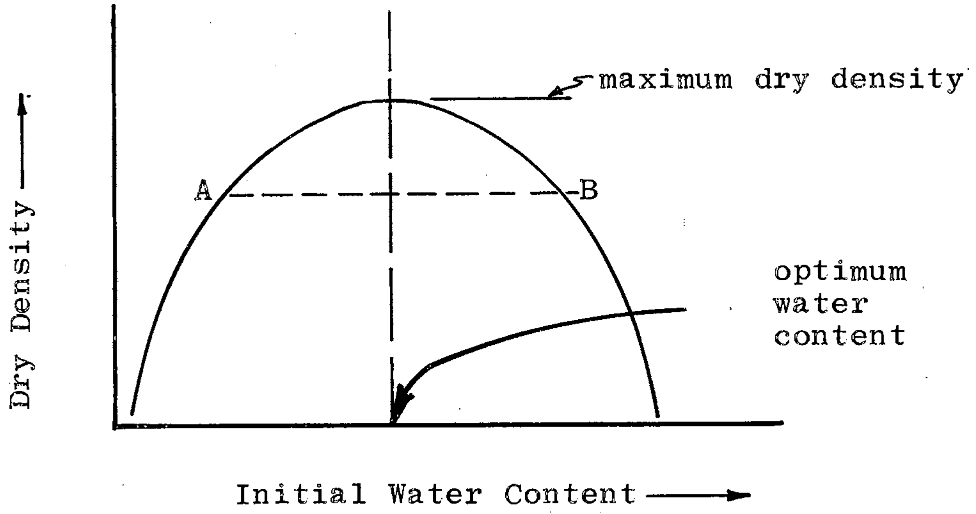


FIGURE 12. THE RELATIONSHIP BETWEEN INITIAL WATER CONTENT AND DRY DENSITY

When the compactive effort is increased, the optimum water content decreases and the maximum dry density increases for a given type of soil. This effect is shown in Figure 13 for a certain type of soil. Points 1, 2, and 3 are the optimum water contents for compactive efforts 1, 2 and 3. In this process three different compactive efforts with increasing magnitudes are applied. Looking at Figure 13, it can be observed that points A, B and C correspond to the same initial water content. However, the magnitude of swelling is different for these three points. It is generally observed that for a constant water content, the higher the dry density, the greater the magnitude of swell. In other words, the sample that corresponds to point C will swell more than the samples corresponding to points A and B.

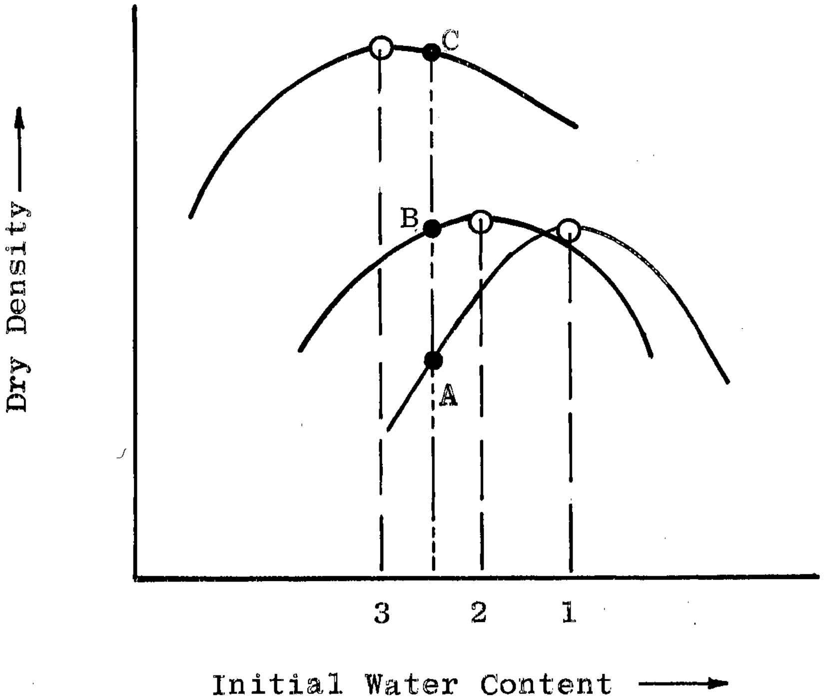


FIGURE 13. THE EFFECT OF VARIOUS COMPACTIVE EFFORTS AND INITIAL WATER CONTENT ON DRY DENSITY.

The volume change of compacted clays is due to increase of the double layer water. When clay samples are compacted on the dry side of optimum, the negative charges on the surfaces of clay particles are not completely satisfied. Therefore, if water is available, these particles will attract water molecules and create a volume change.

The optimum water content for a given compactive effort is different for different types of soils.

Soil Structure and Method of Compaction: The method of compaction and the amount of compactive energy applied have a direct effect on the soil structure. A clay in nature which has not been subjected to heavy overburden pressures may be in a loose state having generally a random structure. In this structure, clay particles that have attached solid adsorbed water and viscous double layer water on their surfaces will not have a preferred orientation. However, when compactive effort is applied this random structure is generally modified and clay particles tend to orient themselves parallel to each other. This type of structure is known as dispersed structure. Pacey (37) studied the effects of initial water content on particle orientation and found that compaction on the dry side of optimum water content causes a non-parallel or flocculent orientation in clay particles whereas compaction on the wet side of optimum water content leads to a parallel or dispersed orientation. This relation can be observed in Figure 14. Here the compacted dry densities are plotted against initial water contents. Two different

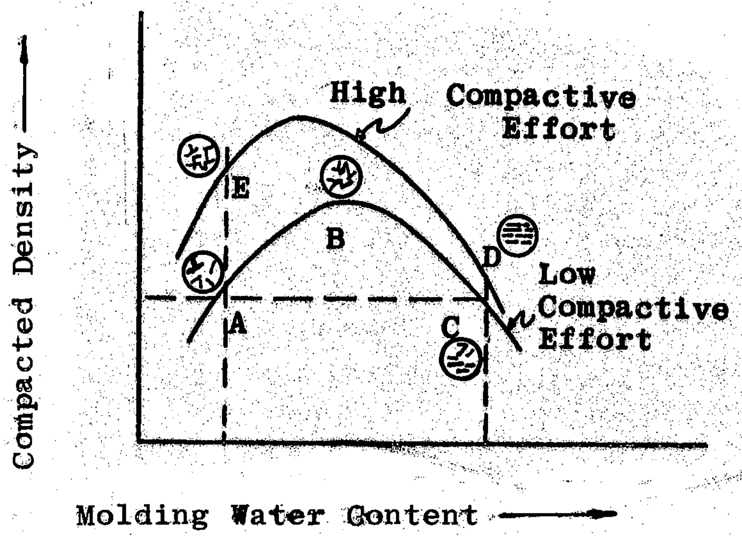


FIGURE 14. EFFECT OF COMPACTION ON SOIL STRUCTURE. (After Seed and Chan, 25.)

compactive efforts are applied. Point A is on the dry side of optimum. The double layers are not yet fully developed, as the high ionic concentration due to the lack of water depresses the double layers. As double layers are depressed, the inter-particle repulsion that might lead to a dispersed structure is reduced and finally a flocculent structure is created. However, when the initial water content is increased as indicated by point B, most of the negative charges on the surface of clay particles are balanced and the electrolyte concentration is reduced. As the double layers are not depressed significantly, the inter-particle attraction is reduced, which finally leads to a more dispersed structure and this arrangement gives a higher density. When initial water content is further increased, point C is obtained. At point C the double layers are expanded more than at the first two points and the attractive forces between clay particles are reduced significantly. Therefore, the clay sample corresponding to point C has a more dispersed structure than those represented by points A and B. However, the increased initial water content dilutes the concentration of soil particles per unit volume and, consequently, the dry density at point C is lower than dry densities corresponding to points B and A. When the compactive effort is increased the clay particles form a more dispersed structure, as seen in Figure 14.

It is then reasonable to expect a difference in swelling behavior due to the different particle orientations. The effects of particle arrangement on volume change of compacted clays have been investigated by Seed and Chan (25). According to their studies:

1. Clay samples that are compacted on the dry side of optimum swell more than the samples of the same density compacted on the wet side of optimum moisture content. However, it was pointed out previously that samples compacted on the dry side of optimum moisture content have a flocculent structure, therefore, it is possible to conclude that soils that have a flocculent structure possess higher swelling characteristics and swell more than soils that have a dispersed structure.

2. For the same initial water content and dry density, static compaction methods will tend to create a flocculent structure in clay samples, whereas kneading compaction produces a relatively more dispersed structure. Consequently, the samples compacted by static compaction tend to have higher swelling characteristics.

Liu's (38) studies confirm these points. As shown in Figure 15, vertical and horizontal swelling of clay samples that are compacted by static compaction are greater than those of the samples compacted by kneading compaction. In Figure 16 a comparison between dynamic and static compaction is made; however, the difference in swelling is not so pronounced here, except for samples at very high initial water contents.

The effect of compaction methods on volumetric swelling can be observed from Figure 17 and Figure 18, which show clearly that static compaction always leads to higher swelling characteristics and dynamic compaction falls in between the static and kneading compactions.

Availability of Water and Its Chemical Properties: A change in the water content of clay material will cause volume changes such as swelling or shrinkage, depending upon whether the water content is increased or decreased. It has been pointed out previously that even if the water is available and its chemical properties are the same, the magnitudes of swelling for different types of clay minerals will not be the same. However, it is generally observed in all types of clays that the amount of volume change decreases with increasing initial water content in compacted samples. When water is supplied, double layer deficiencies together with capillary effects will create pore water tensions within the clay sample causing water to be imbibed. If this process continues for a time the negative charges on the surfaces of

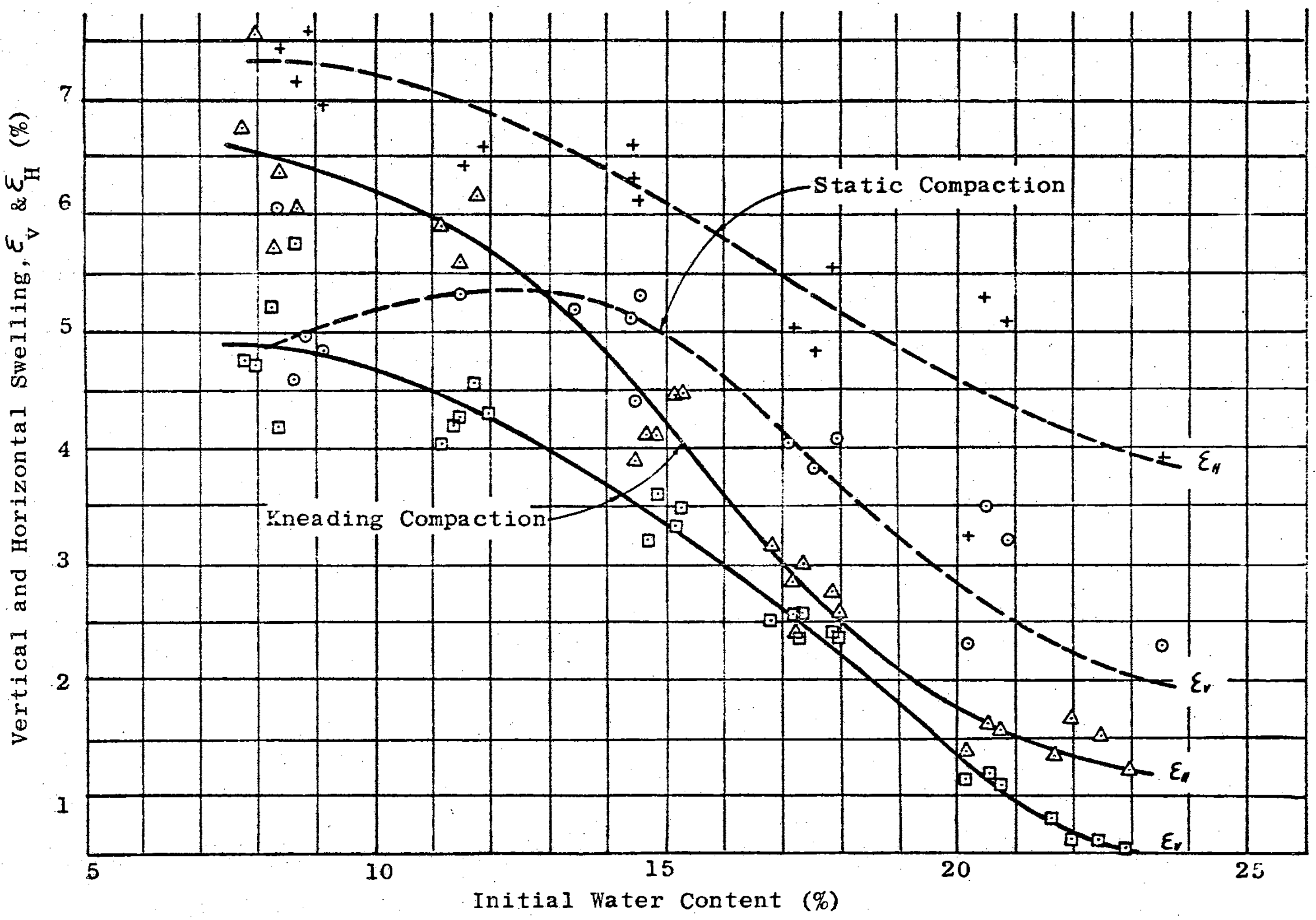


FIGURE 15. EFFECT OF INITIAL WATER CONTENT ON SWELLING
Comparison of Kneading and Static Compaction. (After Liu, 38.)

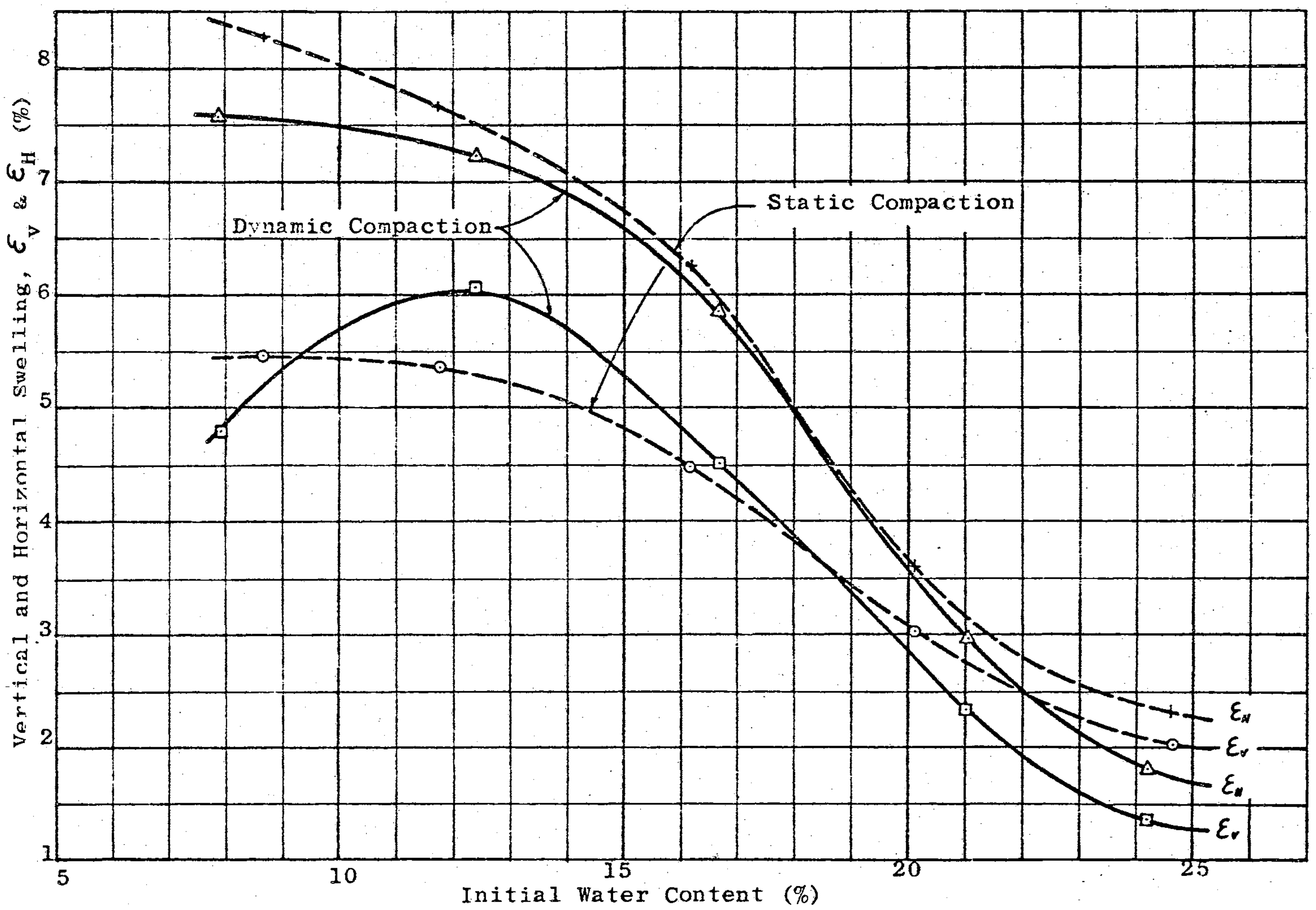


FIGURE 16. EFFECT OF INITIAL WATER CONTENT ON SWELLING Comparison of Dynamic and Static Compaction. (After Liu, 38.)

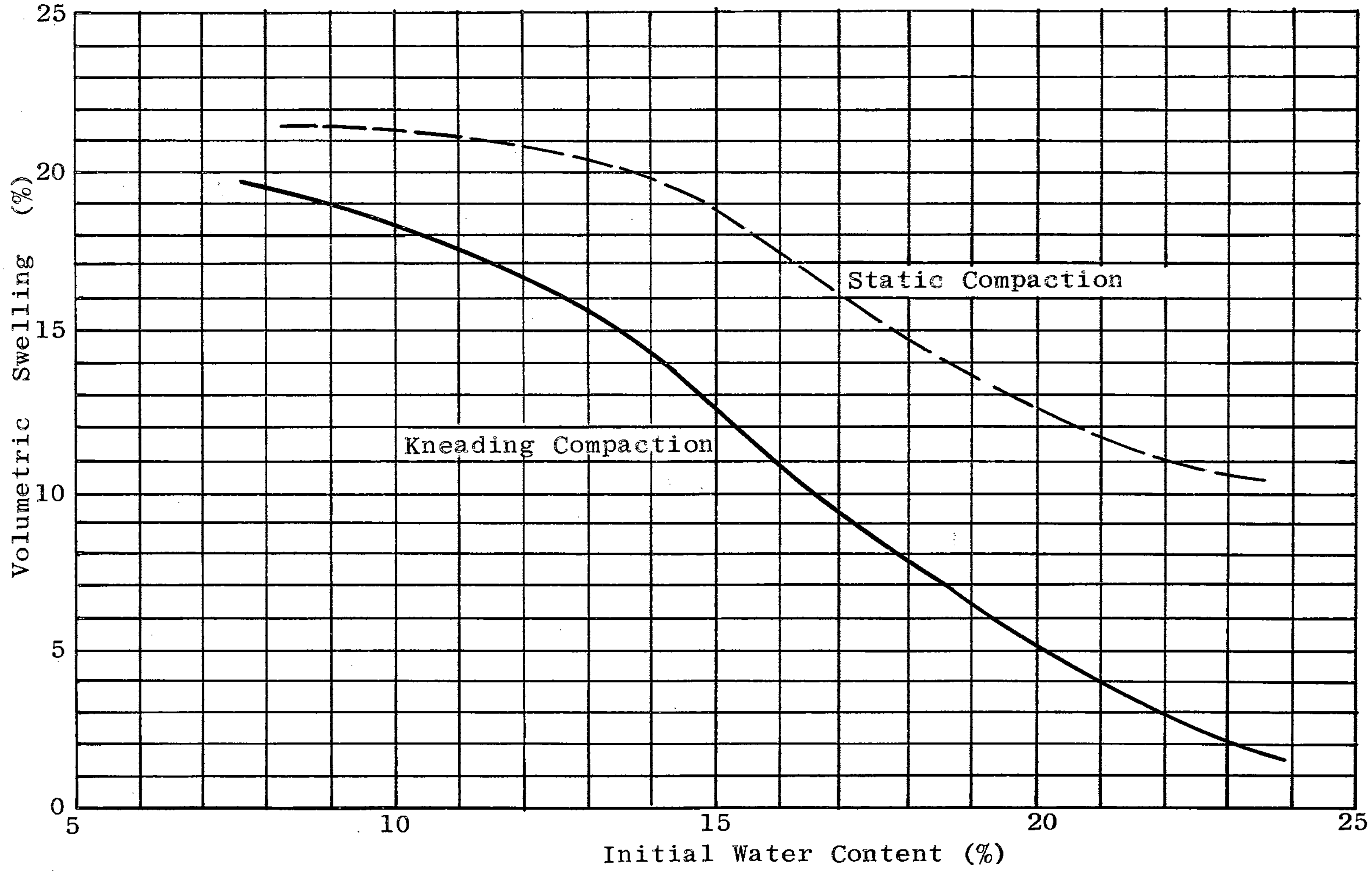


FIGURE 17. EFFECT OF COMPACTION METHOD ON VOLUMETRIC SWELLING, Comparison of Kneading and Static Compaction (After Liu, 38.)

FIGURE 18. EFFECT OF COMPACTION METHOD ON VOLUMETRIC SWELLING
Comparison of Dynamic and Static Compaction. (After Liu, 38.)

the clay particles will be satisfied, and the thickness of double layer water will increase until the difference between the repulsive and attractive forces between clay particles is in equilibrium with the effective stress that is exerted upon the clay sample.

According to Ladd's (13) studies the soaking of compacted clay samples in salt solutions results in a significant reduction in the amount of water pick-up and a reduction in swelling. Figure 19 shows this trend clearly. Ladd's data which pertain to only one dimensional (vertical) swelling indicate that the chemical properties of the pore water have a very important effect on the swelling behavior of the compacted clay samples. It appears that osmotic pressures are very significant in swelling, as this pressure depends upon the difference in ion concentration between the free pore water and clay particles. The strong salt solutions generally reduce the osmotic pressures and consequently decrease the volume change in swelling. Figure 20 shows the relationship between the salt concentration in the molding water and the rate of swelling. By the same consideration, if the low valency exchangeable cations in a clay mineral are replaced by higher valency cations, swelling can be reduced.

However, according to Ladd (13) the initial rate of swelling is practically unaffected by the salt concentration in the soaking solution. These findings were confirmed by the studies of Seed, Mitchell and Chan (39). They found that the amount of swell decreased when the salt concentra-

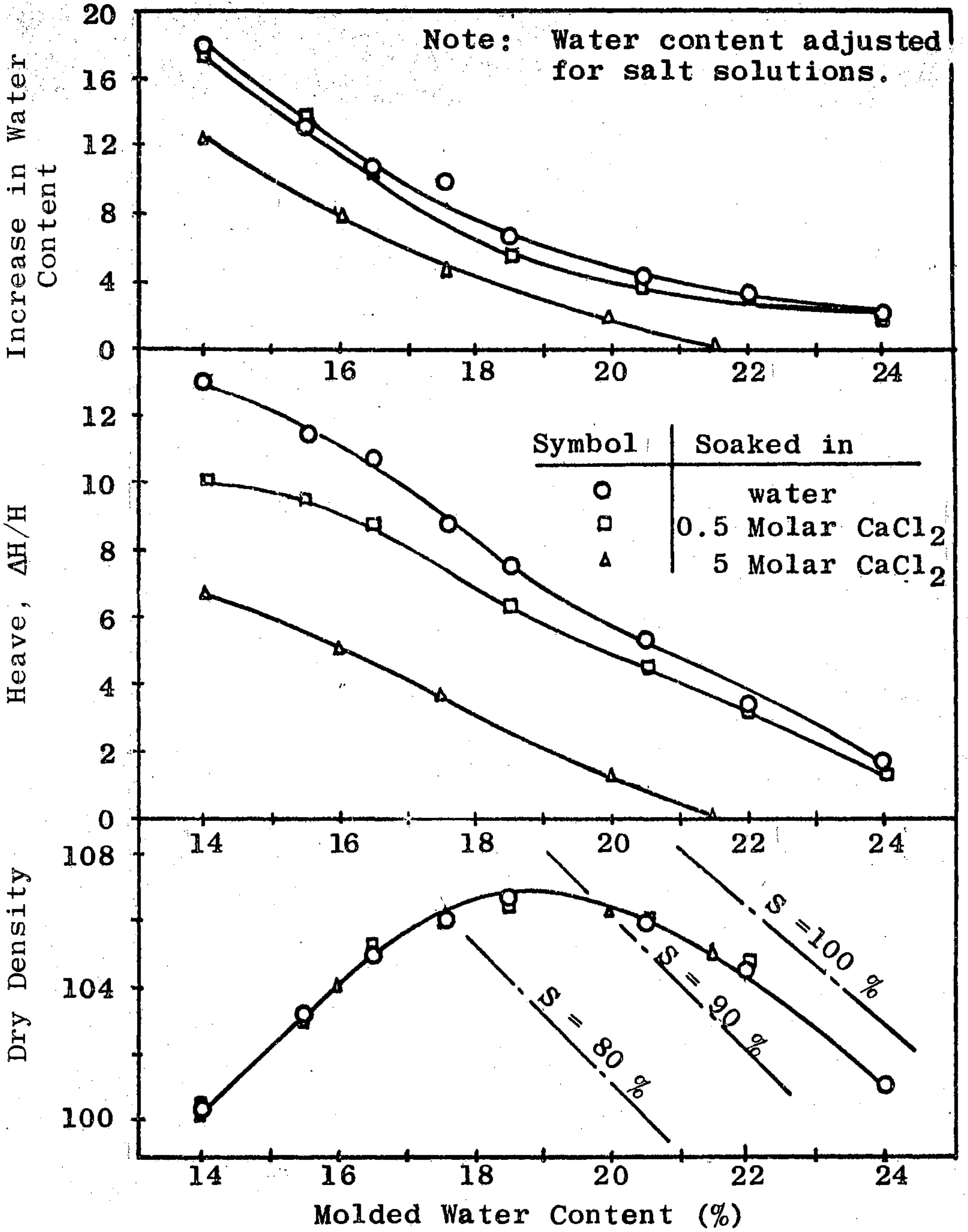


FIGURE 19. EFFECT OF SALT CONCENTRATION ON SWELLING BEHAVIOR OF CLAY. (After Ladd, 13.)

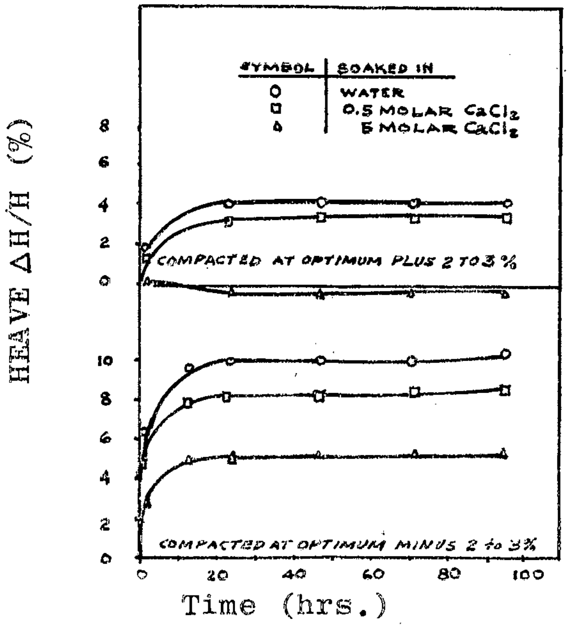


FIGURE 20. EFFECT OF SALT CONCENTRATION ON RATE OF SWELLING. (After Ladd, 13.)

tion is increased; however, above a concentration of approximately 1.5 normal, swelling seemed to reach a constant value of about 1.1 per cent. In their study the soil that was investigated was an expansive sandy clay which had a liquid limit of 35 per cent, a plastic limit of 19 per cent, and 25 per cent by weight finer than two microns. Montmorillonite was the dominant clay material.

The main conclusions of these studies can be summarized as follows:

1. Swelling of clay samples compacted on the wet side of optimum water content can be explained by osmotic pressures that are created by the difference in ion concentration between the free pore water and the double-layer water.

2. Swelling of clay samples compacted on the dry side of optimum water content cannot be explained only by osmotic pressures as it is also affected by the negative electric and London-Van der Waals force fields in water, elastic rebound of clay particles, cation hydration and the attraction of the particle surface for water, presence of air, and a flocculated particle orientation. The quantitative relations among these factors are not yet established.

Effect of Confining Pressure on Swelling: If a clay sample that is in the process of swelling is confined, swelling pressures will be exerted upon the object that confines the sample. Therefore, the application of confining pressures will reduce the magnitude of swelling. Because of this fact, heavy buildings constructed upon expansive clays are subject to less danger than light buildings with shallow footings. If the confining pressure is increased to such a degree that it is capable of reducing the void ratio of the saturated clay to that of the dry soil, then swelling will be prevented. However, this is a theoretical consideration. Seed, Mitchell and Chan (39) studied the effects of confining pressure upon the magnitude of swelling and established that the final swelling pressure rapidly decreases when the clay sample is allowed to swell.

Curing Period: Barber's (40) studies show that as the time interval between compaction and swelling test increases, the swelling pressure decreases. This may be associated with the elastic rebound of the clay particles. The effect of the curing period on the swelling pressure is shown in Figure 21. This figure clearly demonstrates the reduction in the swelling pressure as the curing period increases. Generally speaking, the greater the magnitude of potential swelling of a clay material, the stronger the swelling pressures. Therefore, it may be deduced from Barber's studies that increased curing periods will reduce the magnitude of swelling. However, the time period which is required to create maximum reduction in swelling is not yet established. This characteristic depends upon many factors such as clay type, magnitude of compactive effort, type of compactive effort, initial water content, etc.

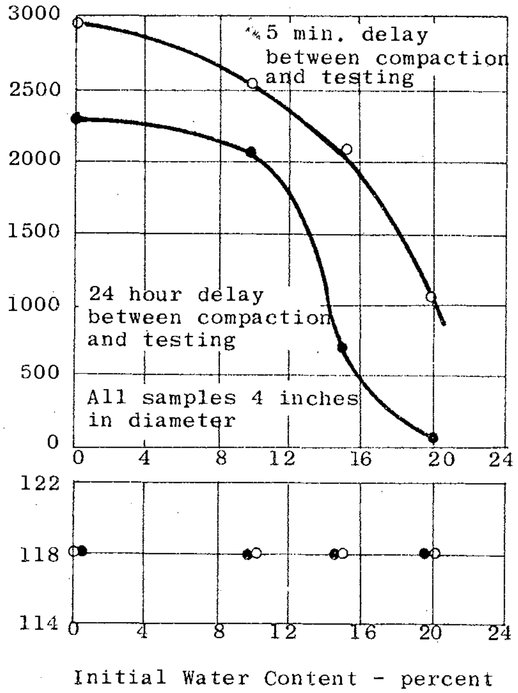


FIGURE 21. EFFECT OF INTERVAL BETWEEN COMPACTION AND TESTING ON SWELL PRESSURE RECORDED AT CONSTANT VOLUME. (After Seed, Mitchell, and Chan, 39.)

Time Period Required for Swelling: Swelling of compacted clay samples will occur if the clay particles have unbalanced negative surface charges, and if water is available. However, the movement of the water into the clay sample requires an amount of time inversely proportional to the permeability of the soil, and to the hydraulic gradient that exists. The permeability of the compacted clay samples is affected by the kind and magnitude of compactive effort, which creates different soil structures. The Kozeny-Carman equation gives the absolute permeability of a given soil in terms of pore shape and tortuosity of flow, specific surface and void ratio:

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

in which K = absolute permeability, R_o = a constant that depends on pore shape and tortuosity of flow, S = specific surface, and e = void ratio.

It has been previously stated that clays compacted to the same dry density on the dry side of the optimum water content have higher permeabilities than those of samples compacted on the wet side of optimum, due to the fact that compaction on the dry side creates a more random or flocculent structure. A flocculent structure will have more large pores than will a dispersed structure which is produced by compaction on the wet side of optimum water content. The permeability of a given soil depends on the opening size, and as the diameters of the individual pores are larger in samples compacted on the dry side of optimum, their permeabilities are higher. The higher the permeability, the greater is the flow of water in the clay sample.

Lambe (30) studied the time period required for swelling and found that the minimum permeability is produced at about optimum water content. Figures 22 and 23 show the relationship between permeability and initial water content.

Temperature: The temperature has an effect upon the thickness of the double layer water that exists under conditions of equilibrium. Lambe (30) studied this phenomenon in a sample of Boston blue clay which was consolidated at a temperature of 20° C. Then the load was held constant and the temperature was increased to 41° C, and after that the temperature was again lowered to the initial temperature of 20° C., hold the load constant. His findings show that if the load is held constant, an increase in the temperature compresses the clay sample and a decrease in the temperature creates expansion. This can be explained by the fact that an increase in temperature will depress the double layer, thus, creating compression, and that a decrease in temperature will expand the double layer water and produce swelling.

Swelling Characteristics of Undisturbed Clay: Holtz (15) states that the amount of volume change which can occur in a natural expansive clay material is generally affected by six factors: (a) the amount and type of clay mineral, (b) initial density, (c) change in moisture, (d) load conditions, (e) soil structure, and (f) time. See Figure 24.

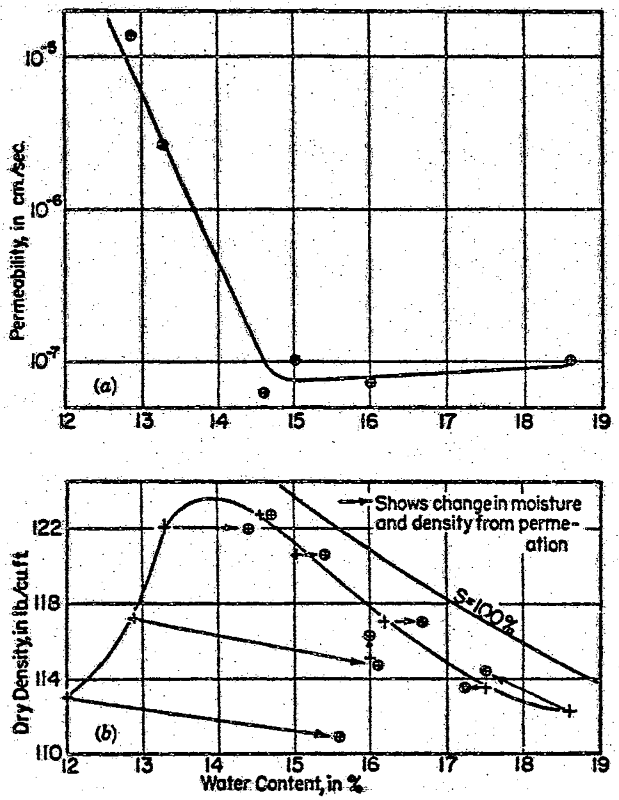


FIGURE 22. COMPACTION-PERMEABILITY TESTS ON JAMAICA SANDY SOIL (After Lambe, 30.)

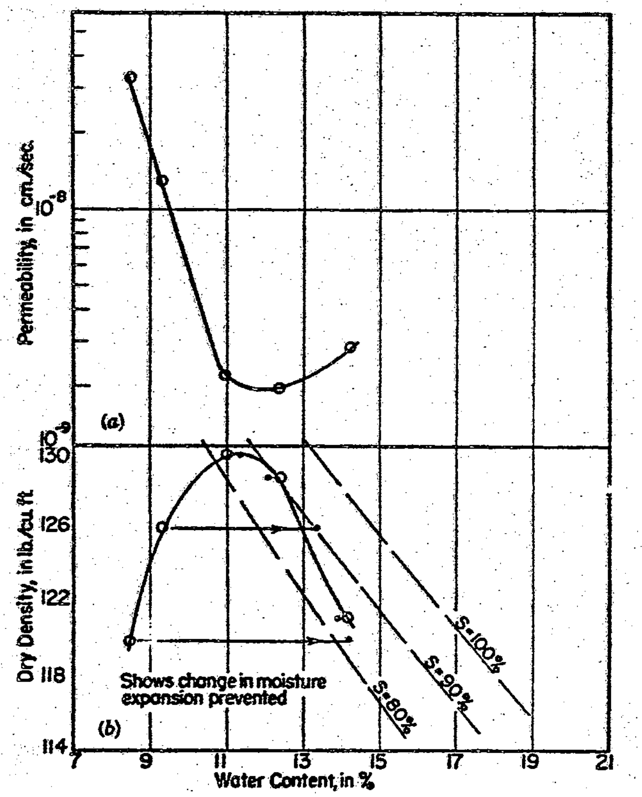


FIGURE 23. COMPACTION-PERMEABILITY TESTS ON SIBURUA CLAY (After Lambe, 30.)

The effects of the amount and type of clay minerals in compacted clay materials were given previously. The same facts and relations exist in natural clay materials.

The initial density of an expansive clay soil is important, because in denser soils, more clay particles are packed in a unit volume. Consequently, when the soil has contact with water, greater expansion will occur.

The effects of moisture and load conditions are the same as in compacted clay soils.

The most important factor in the swelling of natural clay soils is the structure. Laboratory investigations clearly show that when undisturbed and remolded specimens of the same type of soil having the same initial water contents and densities are tested in consolidometers the remolded specimens will swell considerably more than do the undisturbed samples. Figure 24 shows this effect.

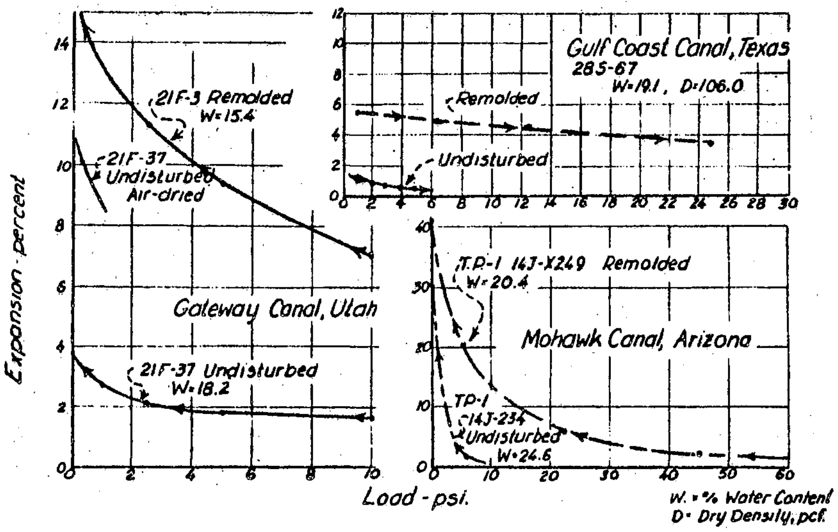


FIGURE 24. EFFECT OF LOADING AND REMOLDING ON EXPANSION. (After Holtz, 15.)

The importance of the initial structure of clay materials has been emphasized by Casagrande (4), who has concluded that if the natural structure of the clay is disturbed, the original strength of this material will be significantly reduced. This statement is particularly true in the case of "bond clays", as called by Casagrande. If a stream that carries both silt grains and colloidal clay particles discharges into a body of water that contains certain salts, the positive ions in the body of water are attracted by the negative charges on the surfaces of the clay particles and finally balance them. When neutralized particles come close to each other, they become attracted by gravity forces and finally form flocks that are composed of randomly arranged particles. These flocks settle in the suspension pulling silt grains down with them. This process results in the formation of loose honeycomb flocks and silt grain arches. Marine clays generally have this type of structure which is appropriately considered a honeycomb within a honeycomb structure. Even though this structure is generally loose, the arches can carry heavy loads. Figure 25 illustrates the flocculent structure of a marine clay. If this structure is destroyed, for example by pile driving, the bearing capacity of the material is significantly reduced. Through thixotropy, some strength characteristics can be repossessed in time.

The swelling characteristics of freshly deposited clays that have been consolidated under their existing overburdens are different from the swelling characteristics of clays

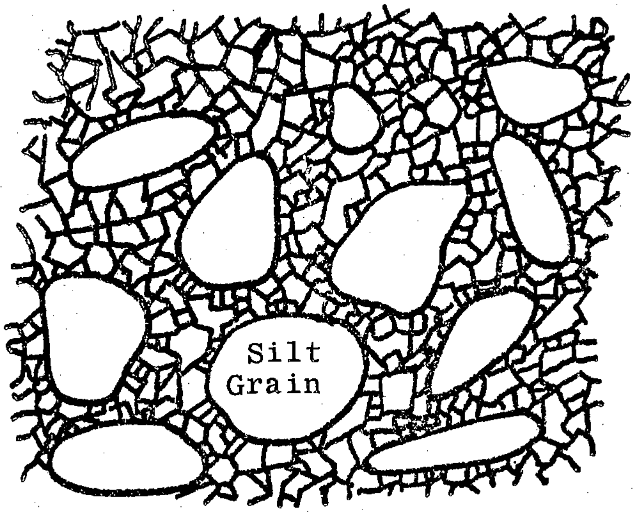


FIGURE 25. FLOCCULENT STRUCTURE OF MARINE CLAY.

that have been subjected to stresses much higher than their existing overburden pressures for hundreds of years. The latter ones are called overconsolidated clays, in which heavy pressures may have produced a nearly dispersed structure; whereas, the freshly deposited clays generally have a flocculent structure. This difference of structure explains different swelling characteristics. Lambe (22) states that the particles in the undisturbed clays may come as close as 3 Å to each other during long periods of dessication or consolidation.

Another factor that affects the structure of natural clays is the "diagenetic cementation". Clay particles may be cemented to each other either by high temperatures that cause smaller crystal grains to form a larger grain, or according to Mitchell (41) by cementing agencies such as oxides or carbonates. Some clays have considerable amounts of free iron oxide or carbonate mineral contents. The free iron oxide content may reach at least one per cent by weight and it is generally accepted that this material is distributed throughout the clay structure as cement at contact points or particle coatings. In this respect, carbonate may differ from iron oxides as they generally exist in two different forms --- as mineral particles (calcite, dolomite, magnesite) and as a cementing agent at contact points.

Time is also an important factor in the ultimate volume changes of the clay soils. As the permeabilities of these soils are very low, transmission of moisture and the consequent balancing of forces is slow. Soils that have considerable amounts of montmorillonites become tighter when they are wetted. This tightening effect reduces permeability. Therefore, sometimes days or even weeks are required to completely wet samples brought to laboratories. This explains why years are required to saturate a foundation soil or the water retained material that contains montmorillonite.

CHAPTER III

LABORATORY PROCEEDURES, EQUIPMENT AND MATERIALS

Physical Properties of Permian Clay

In all triaxial swelling tests of this study, a natural Permian Clay was used which was obtained on the Oklahoma State University campus in Stillwater, Oklahoma. Soils were obtained from two different locations which were: (a) Life Science Building --- from eleven feet below the original ground surface or a depth of approximately three feet below the center areas of the northeast corner of the building from depths of approximately nine and eighteen feet.

Location (b) was also used as a source of undisturbed soil samples. The distance between the two locations is approximately 200 feet. The soils that were obtained were dried, pulverized and screened through a No. 30 sieve for the first series of tests and through a No. 100 sieve for the second and third series. The physical properties of the soils such as liquid limit, plastic limit, clay content, activity, etc., were determined in the Soil Mechanics Laboratory of Oklahoma State University. The results of these tests are given in Table II. The grain size distribution of the Permian clay obtained from hydrometer analyses are shown in Figure 26.

TABLE II

PHYSICAL PROPERTIES OF SOILS

Origin	Life Science Building	Engineering Building (9 ft. depth)	Engineering Building (18 ft. depth)
Liquid limit	40.50	51.00	41.00
Plastic limit	15.00	19.00	15.10
Plastic index	25.50	32.00	25.90
Specific gravity	2.72	2.78	2.72
Clay content (%)	24.50	26.00	36.00
Activity Number	1.04	1.23	0.72

Triaxial Swelling Apparatus

The triaxial apparatus used in measuring the horizontal and vertical swelling of compacted clay samples was developed under the direction and supervision of Professor James V. Parcher. R. B. Fost (1) in his Master's Thesis has given a comprehensive description and explanation of the apparatus. With this apparatus, one dimensional as well as three dimensional swelling of cylindrical specimens can be measured. Confining pressure on clay samples can be applied if needed. In this study, the free triaxial swelling under zero confining pressure was investigated. (Refer to Plate I.)

The apparatus is made principally of Plexiglas. As one of the characteristics of Plexiglas is water absorptivity, which has an influence on horizontal and vertical swelling measurements, the apparatus must be calibrated. To find the water absorptivity of Plexiglas three Plexiglas plates (1.0"x 1.0" x 0.2"), each having a different surface roughness, were tested. The results as reported by Liu (38) are given in

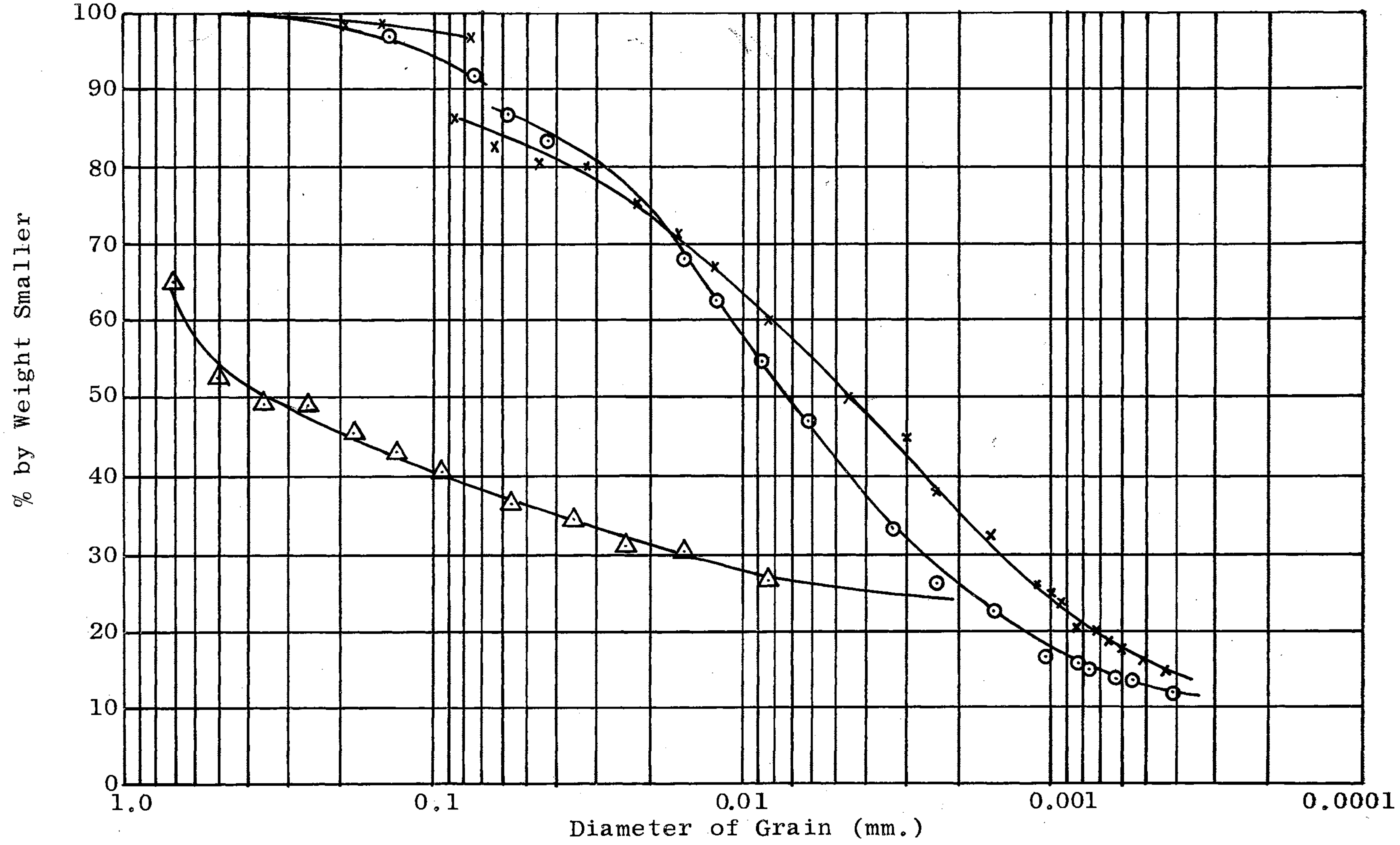


FIGURE 26. GRAIN SIZE DISTRIBUTION CURVES FOR PERMIAN CLAY.

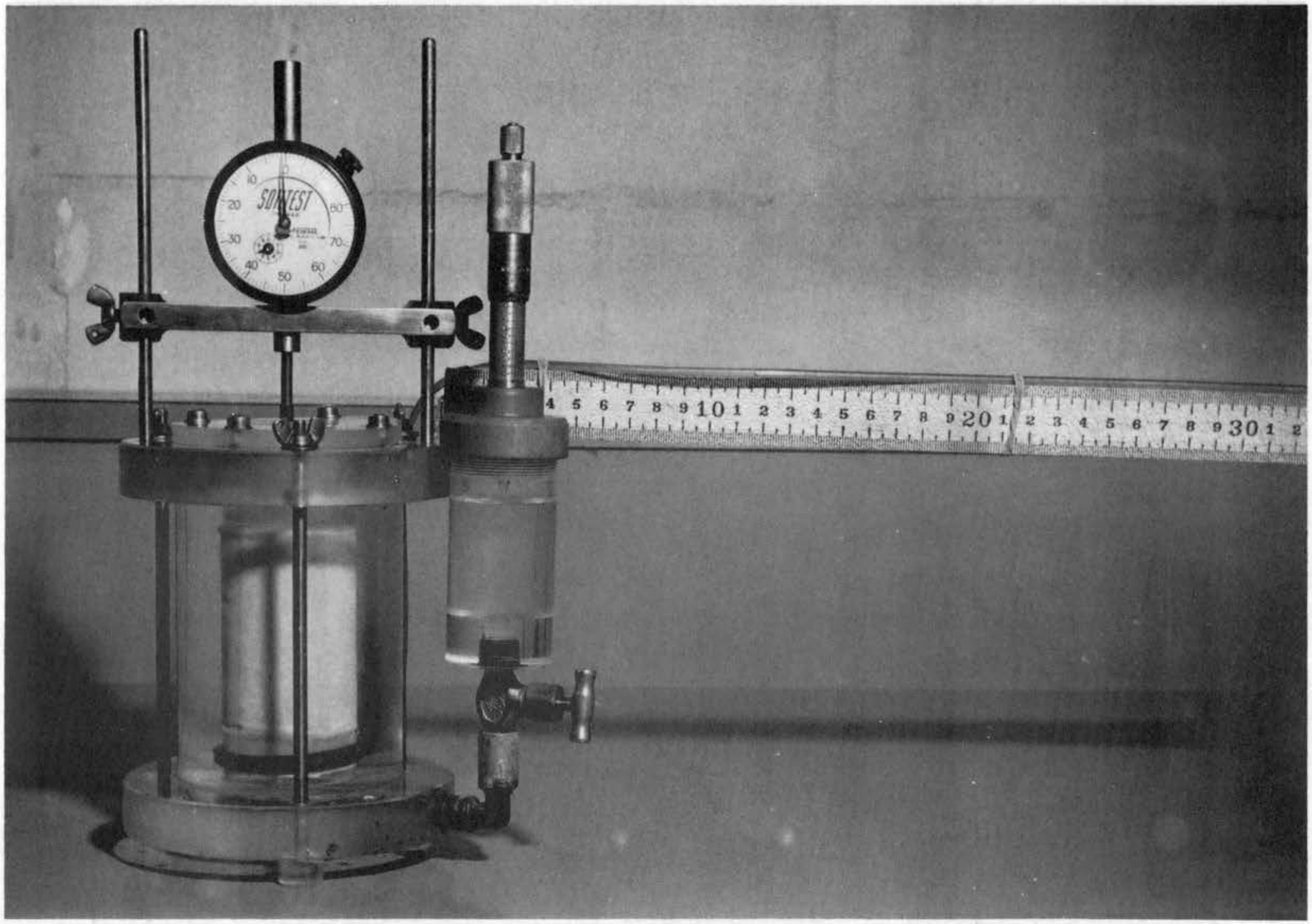


PLATE NO. I TRIAXIAL SWELLING APPARATUS

Figure 27. From this figure it can be observed that both the rate of water absorption of Plexiglas plates when they are immersed in water, and the rate of evaporation of the absorbed water during air drying depend slightly on the surface roughness. It was found that the maximum water absorption of Plexiglas is about 0.6 per cent by weight and that the difference both in the rate of water absorption or evaporation due to surface roughness is not very pronounced. To account for the water absorptivity of Plexiglas, calibration curves were developed for each apparatus that was used. The calibration curves are given in Figures 28 to 33. These figures were used to determine the correction to be added to horizontal swelling readings. This corrective amount is designated as ΔR_H. Due to the nature of the apparatus, no correction in vertical swelling reading was necessary. The ΔR_H values are dependent on time, and specific ΔR_H values should be taken from calibration curves corresponding to readings made at certain times. However, it can be assumed that after a period of time Plexiglas becomes saturated, making correction unnecessary if the apparatus remains constantly in use or is kept immersed when not in use.

Figure 34 shows the triaxial swelling apparatus. When this apparatus is used to measure the rate and the magnitude of vertical and horizontal swelling of compacted clay specimens the following procedures are used:

1. De-air 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

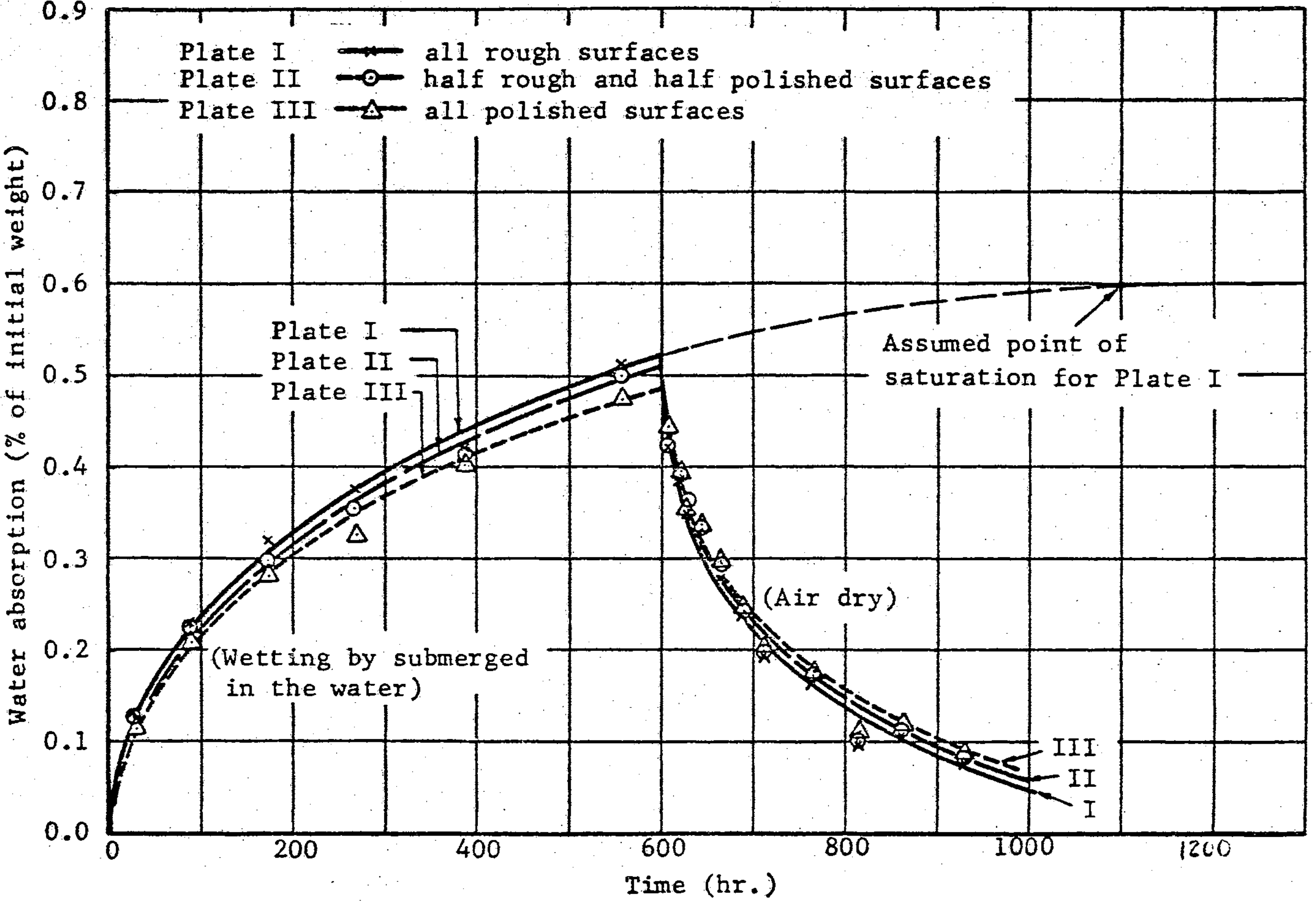


FIGURE 27. WATER ABSORPTIVITY CURVES FOR PLEXIGLAS

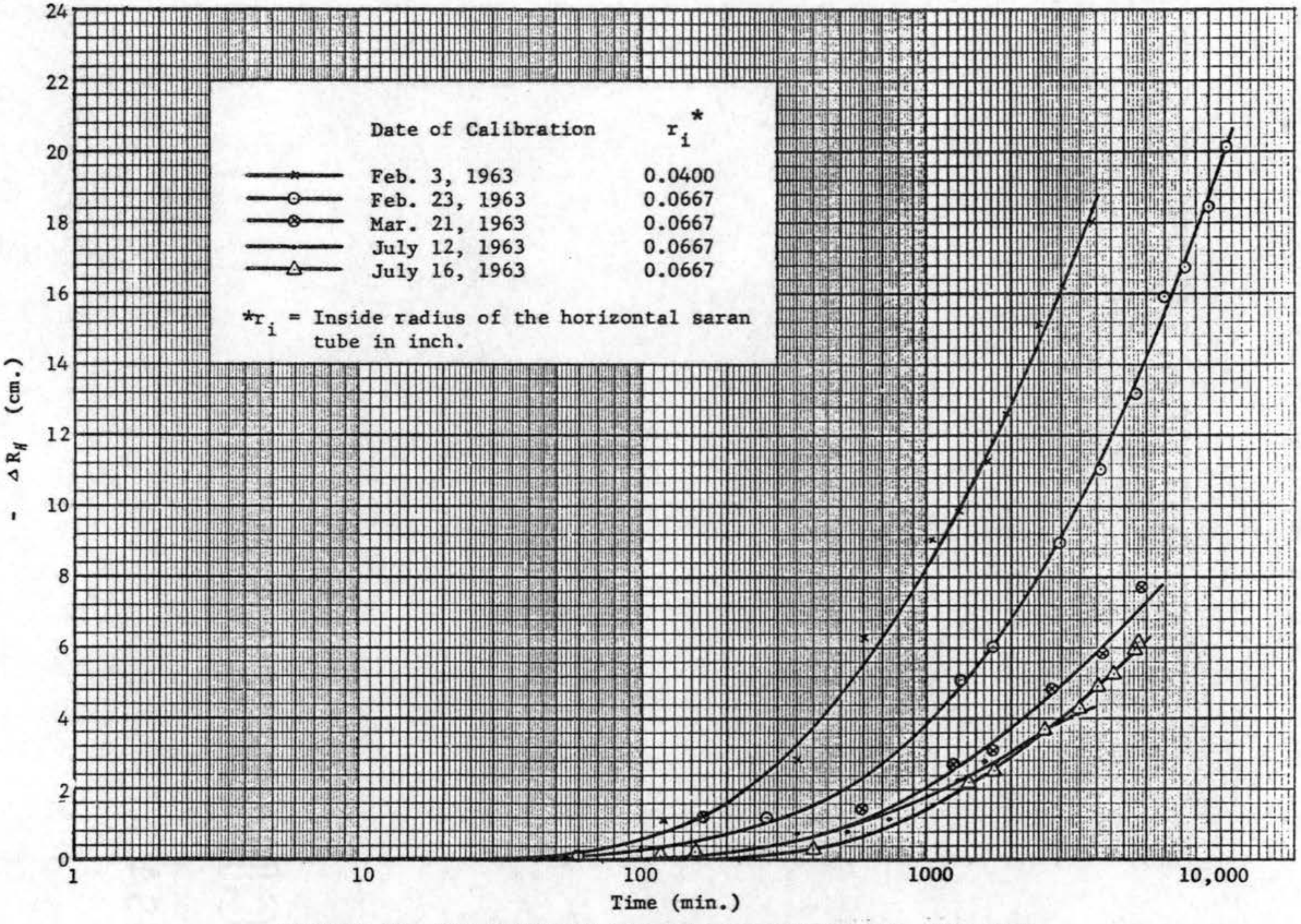


FIGURE 28. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 1.

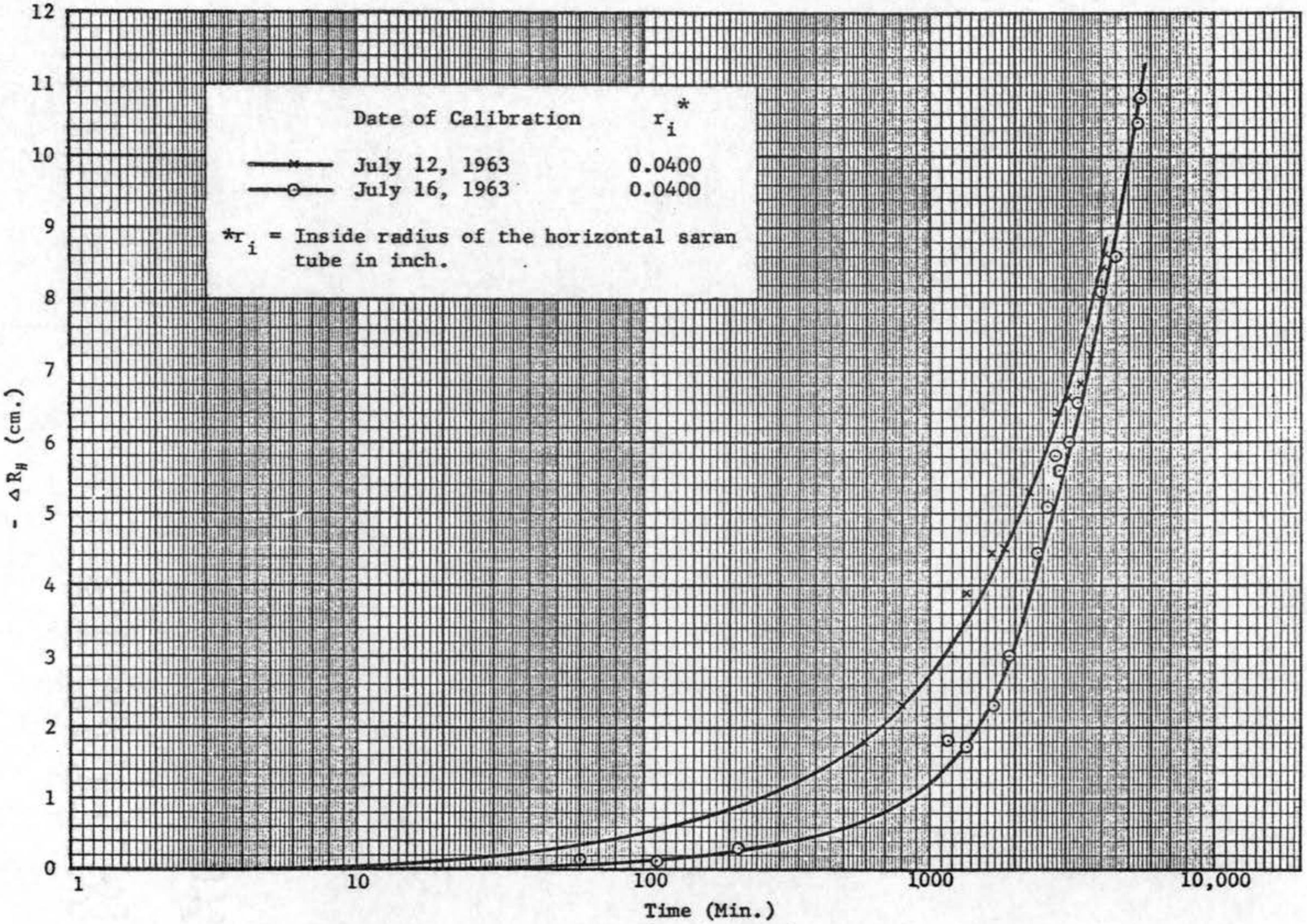


FIGURE 29. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 2.

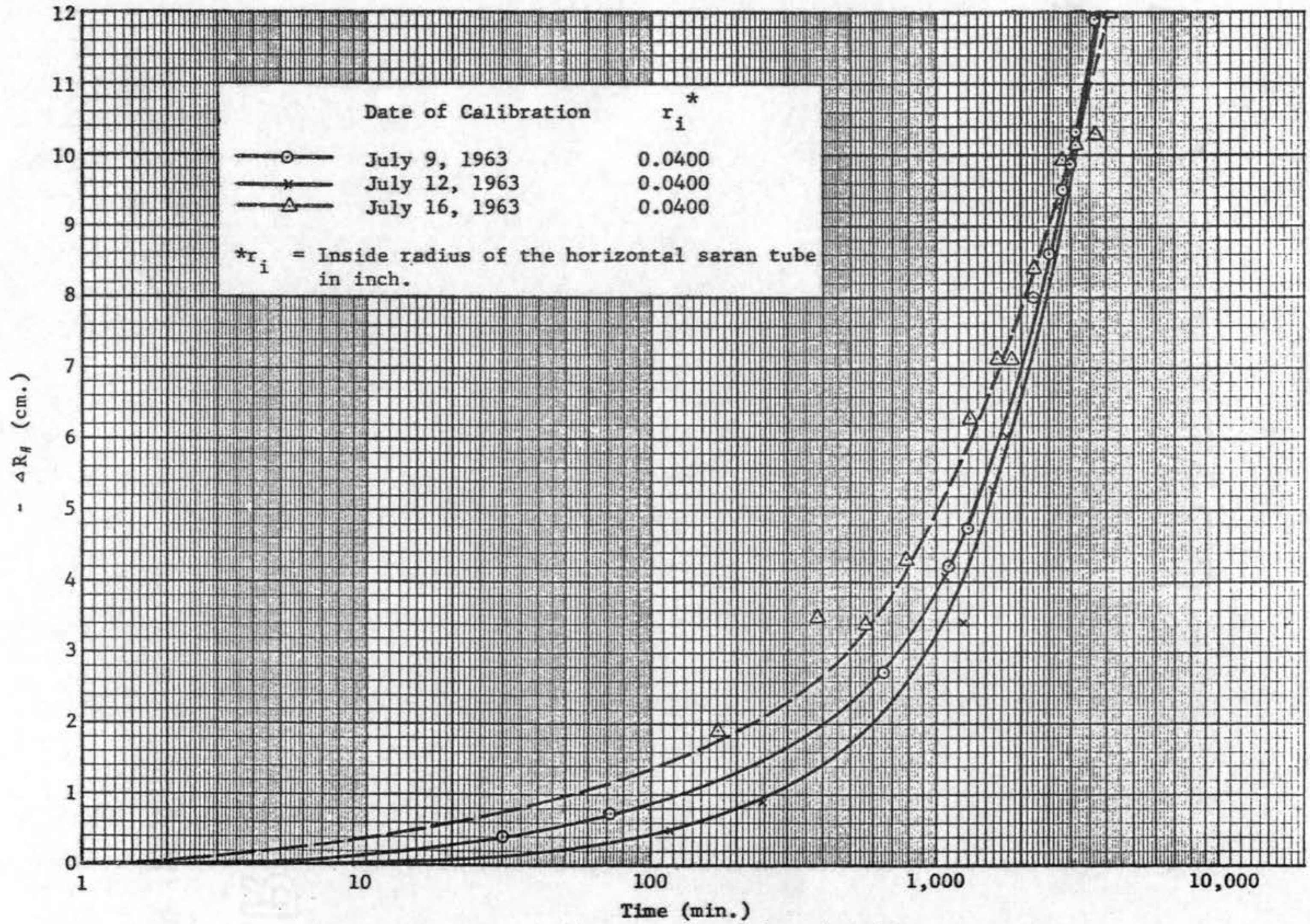


FIGURE 30. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 3.

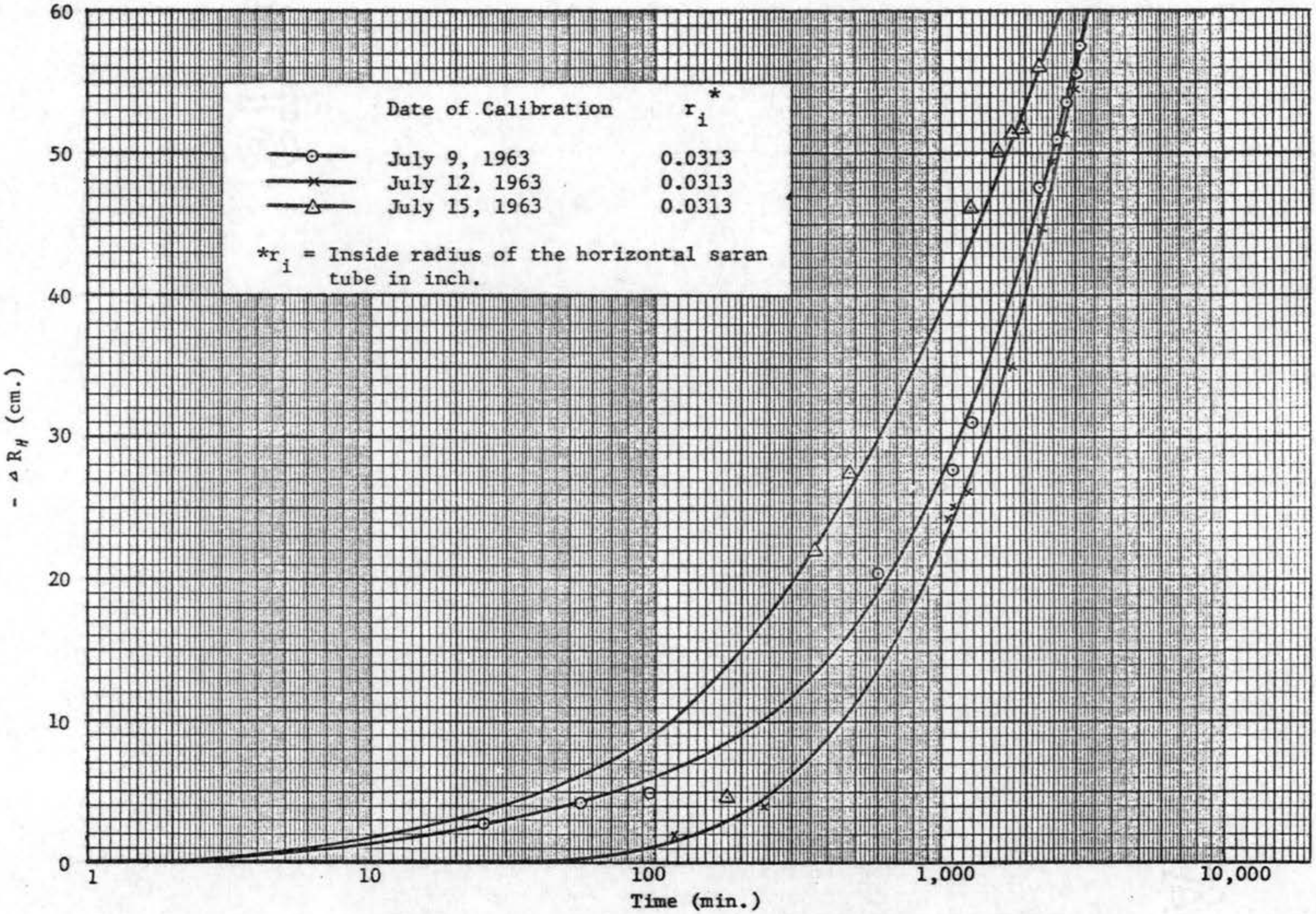


FIGURE 31. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 4.

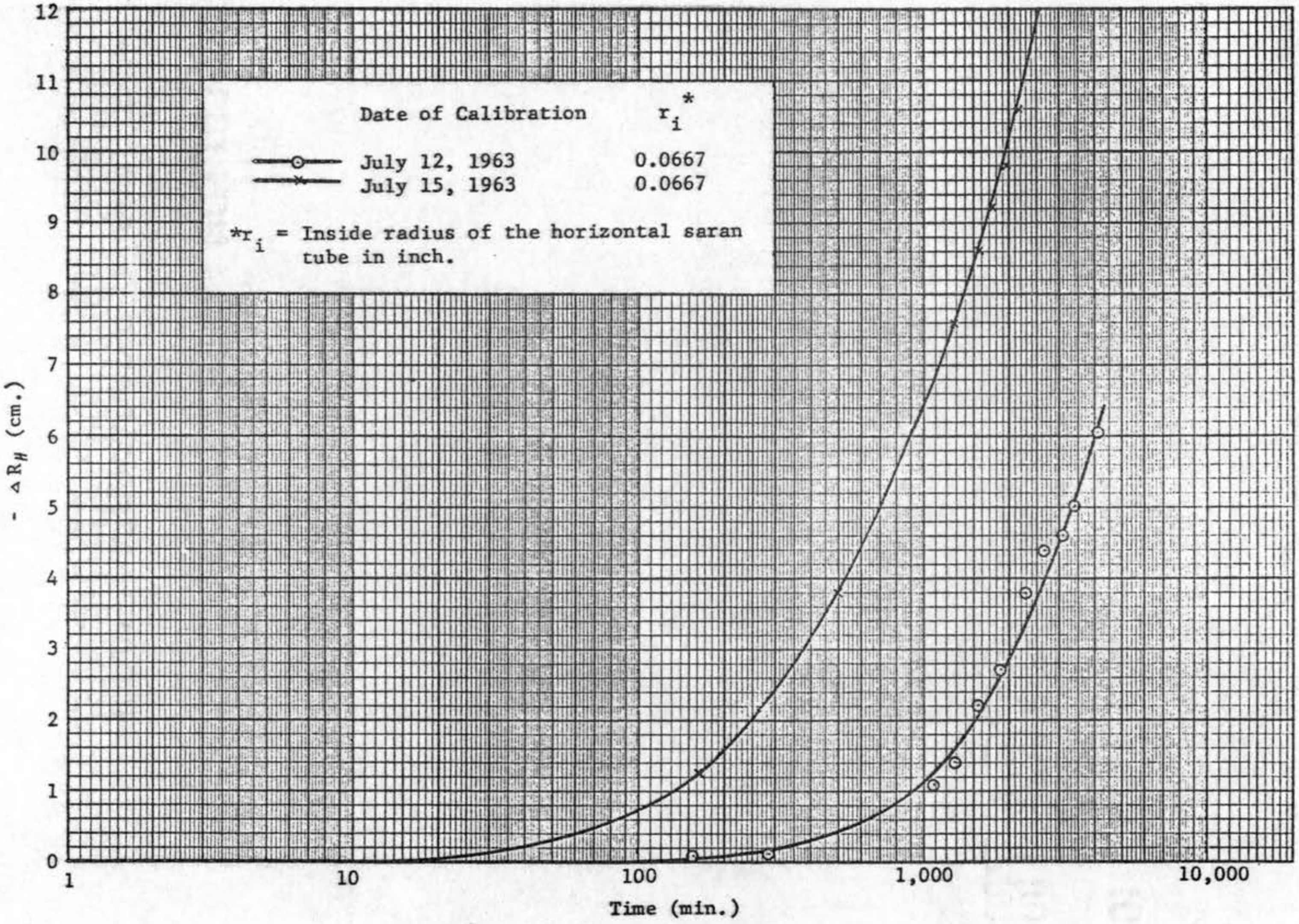


FIGURE 32. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 5.

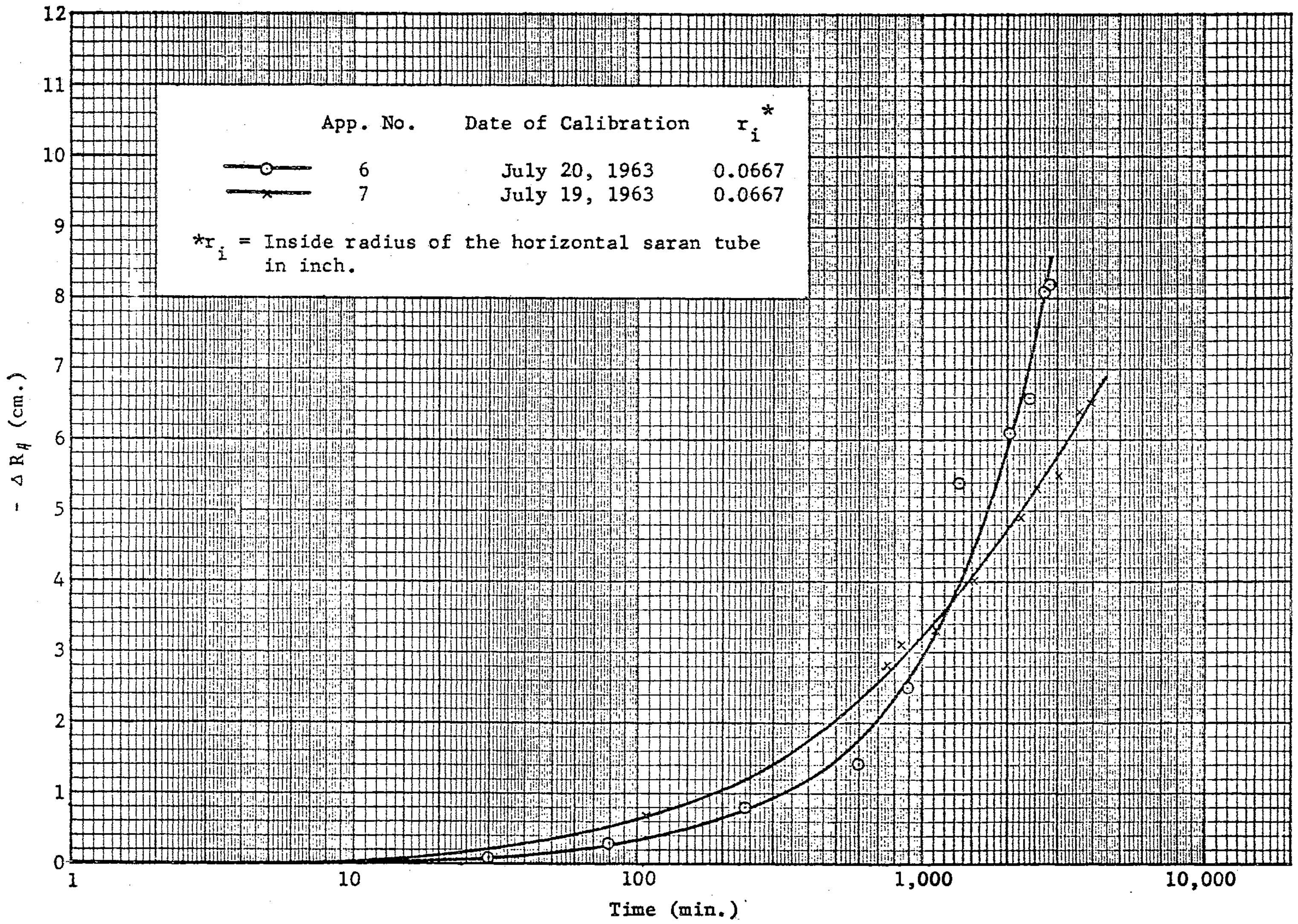
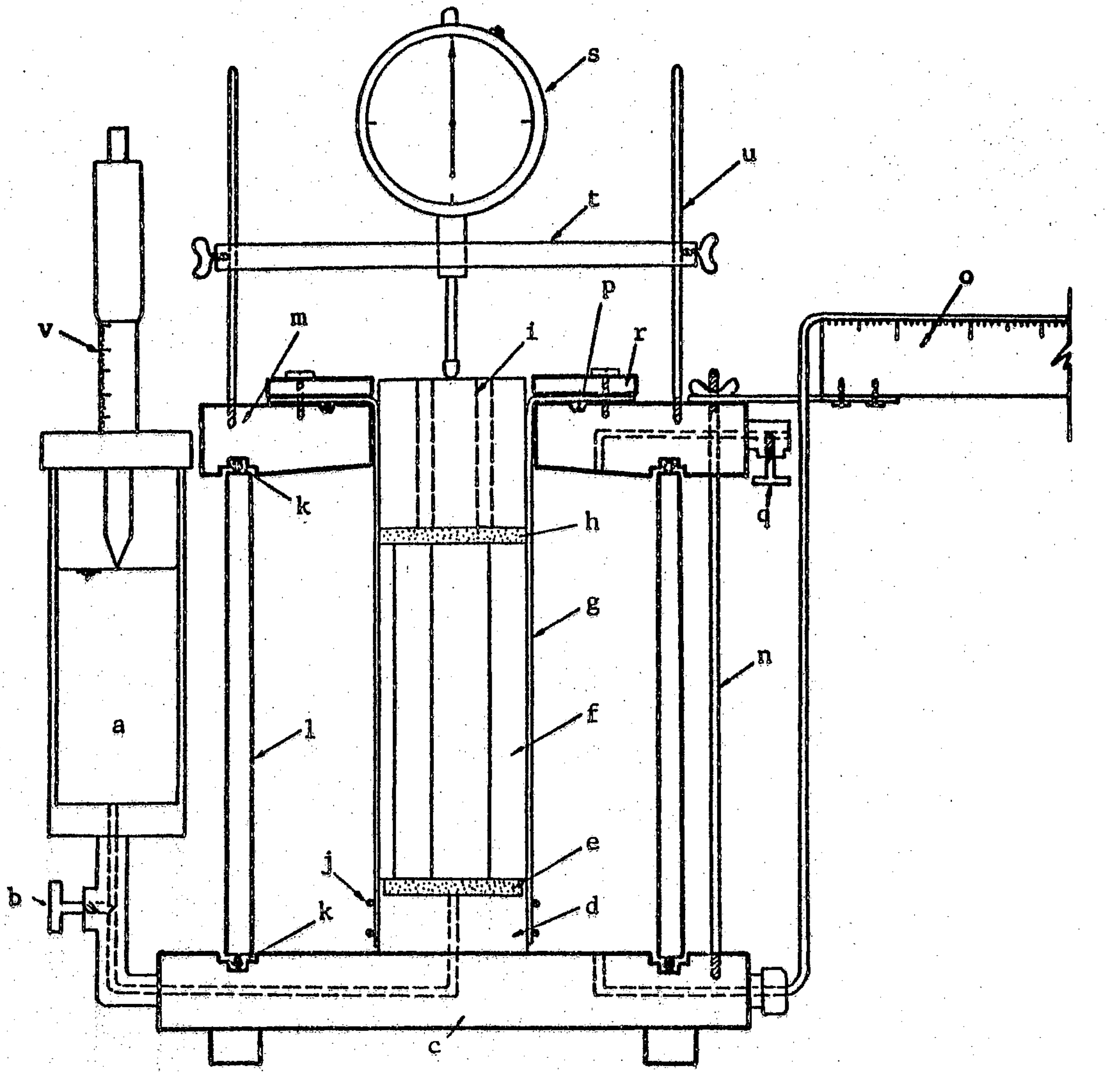


FIGURE 33. CALIBRATION CURVES FOR HORIZONTAL SWELLING OF APPARATUS NO. 6 AND NO. 7.



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 34. APPARATUS ASSEMBLED FOR TRIAXIAL SWELLING TEST.

previously de-aired, 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 on 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 overlaps 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 plate passes down around the cap. The flange of the membrane should be lying on top of the top plate when this step is completed.

8. Insert the three vertical tie rods through the top plate and screw them into the base plate until finger tight. Next, after placing 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 affected. 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 eight hours swelling is less than one per cent of the magnitude of total swelling.

17. Drain the chamber fluid and 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

One of the main purposes of this study is to find a relationship between certain initial conditions and the swelling ratio, S, which is defined as the ratio of vertical swelling to horizontal swelling. The magnitudes of vertical and horizontal swellings are determined as follows:

1. Vertical Swelling: Vertical swelling as a percentage of compacted sample height can be given by the simple formula

$$\mathcal{E}_v = \frac{\Delta H}{H} \times 100 \qquad (1)$$

in which $\mathcal{E}_v$ = vertical strain (%), H = initial sample height, and ΔH = incremental vertical dial reading.

2. Horizontal Swelling: In the apparatus used in this research, the volume change due to horizontal swelling, ΔV_1, should be equal to the volume of water, ΔV_2, that has been forced from the Plexiglas chamber because of the swelling. Using the notation in Figure 35 the following relationships

can be developed:

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

$$\Delta V_2 = C\,\Delta R_H$$

in which ΔV_1 = volume change due to horizontal swelling

ΔV_2 = volume of water that has been forced from the Plexiglas chamber

r = initial radius of specimen = 0.7 in. = 1.788 cm.

Δr = incremental increase in the radius due to horizontal swelling (cm.)

H' = total height of specimen after completion of swelling (cm.)

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

C = capacity of saran tube (c.c./cm.)

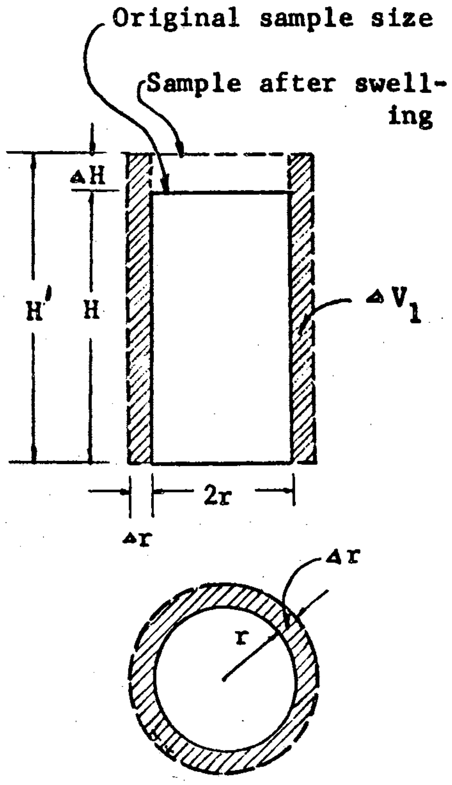


FIGURE 35. CROSS SECTIONS OF A SAMPLE.

Since,

$$2\pi(r + \frac{\Delta r}{2})\Delta r H' = C \cdot \Delta R_H$$

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

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

Neglecting the second term of this relation which is a second order differential

$$2\pi r\ \Delta r H' = C\ \Delta R_H$$

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

The average horizontal strain in per cent can be expressed as,

$$\mathcal{E}_H = \frac{\Delta r}{r} \times 100 \qquad (2)$$

and the total height of the specimen after swelling will be

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

then,

$$\Delta r = \frac{C\Delta R_H}{2\pi r\ H'} = \frac{C\Delta R_H}{2\pi r\ H\ (1 + 0.01\mathcal{E}_V)}$$

substituting this value of Δr in equation (2) produces,

$$\mathcal{E}_H = \frac{\Delta r}{r} \times 100 = \frac{C \cdot \Delta R_H}{2\pi r^2 H\ (1 + 0.01\mathcal{E}_V)} \times 100 \qquad (3)$$

In laboratory tests three different sizes of saran tubes were used whose properties are given below:

TABLE III

CHARACTERISTICS OF SARAN TUBES

Saran Tube Type	Inside Radius (inches)	Capacity (cc./cm.)
1	0.0313	0.018
2	0.0400	0.049
3	0.0667	0.091

Using these quantities, the values of unit horizontal strains corresponding to the different sizes of saran tubes were determined, and are given in Table IV.

3. Volumetric Swelling: The volumetric swelling can be determined from vertical and horizontal swellings. If the unit volumetric swelling is designed as Υ then Υ is equal to the summation of the vertical and horizontal volume changes which are designated as ΔV_V and ΔV_H, then referring to Figure 36,

TABLE IV

HORIZONTAL STRAIN WITH RESPECT TO SARAN TUBE TYPE

Saran Tube Type	Inside Radius (inches)	Horizontal Strain, $\mathcal{E}_H$ (%)
1	0.0313	$0.0128\ \Delta R_H$
2	0.0400	$0.0338\ \Delta R_H$
3	0.0667	$0.0645\ \Delta R_H$

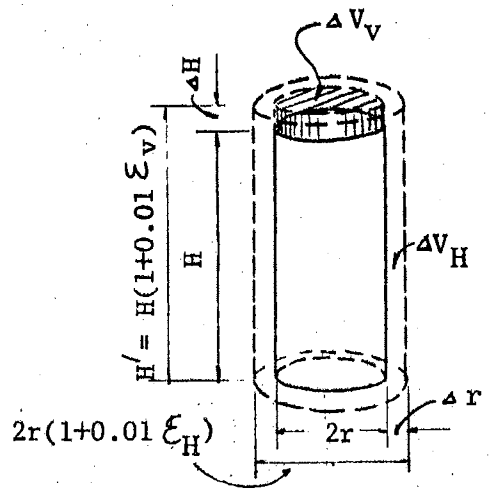


FIGURE 36. SKETCH OF SAMPLE SWELLING

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

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

therefore, the total volumetric swelling will be,

$$\Delta V = \Delta V_V + \Delta V_H = \pi r^2 \Delta H + 2\pi(r + \frac{\Delta r}{2})\Delta r H'$$

then,

$$\Upsilon = \frac{\Delta V}{V} \times 100\ (\%) \tag{4}$$

where V = volume of the original specimen.

Substituting ΔV in equation (4) gives

$$\Upsilon = \frac{100}{V}\left[\pi r^2 \Delta H + 2\pi(r + \frac{\Delta r}{2})(H + \Delta H)\Delta r\right] \tag{5}$$

Finally substituting $V = \pi r^2\ H$ and

$$\Delta H = H\ (0.01\ \mathcal{E}_v)$$

$$\Delta r = r\ (0.01\ \mathcal{E}_H)$$

into equation (5) gives:

$$\Upsilon = \mathcal{E}_v + 2\ (1 + 0.01\mathcal{E}_v)(1 + 0.005\mathcal{E}_H)\mathcal{E}_H \qquad (6)$$

Water Absorption

The elevation of the water in the reservoir is measured at definite intervals to find the rate of water absorption. The difference between the initial and final measurements gives the reservoir discharge. The amount of water absorbed by a specimen in swelling can also be determined from the initial and final moisture contents of the specimen. This absorbed amount of water should be equal to the amount of water imbibed from the reservoir. The relation can be given as $V_w = 20.95\ \Delta R_R$

in which V_w = volume of absorbed water (c.c.)

R_R = the magnitude of change of water elevation in inches in the cylindrical reservoir whose inside radius is 1.62 cm. (0.6375 cm.)

First Phase of Investigation

Clay Specimens without Additives or Inorganic Chemicals

In the first phase of the investigation the effects of type and magnitude of compactive efforts on the swelling of clay specimens were studied. The relation between kneading, static and dynamic compaction and the swelling rate and magnitudes constituted the subject of the Master's Thesis of P. C. Liu, who worked with the author in this phase of the study. Certain results developed by Liu (38) were mentioned earlier in this dissertation.

The author's main interest in the first phase of the study was to investigate the effects of different magnitudes of kneading compaction on the horizontal and vertical swelling. The same method of compaction was also used in the second and third phases of the study. Kneading compaction is done by using the Harvard miniature compaction equipment. (Refer to Plate II.) The specimens were compacted in a cylindrical mold whose diameter is 1.4 inches and whose height is 2.8 inches. Distilled water was used to produce the desired moisture content before compaction. For given constant compactive effort at least three different initial water contents were used, one approximately equal to optimum water content, another about three per cent lower and another about three per cent higher than the optimum. In all series, specimens were compacted in three layers, using 25 tamps of a spring loaded tamper, except for one series in which five layers were used. The tamping forces employed were 20, 40 and 60 pounds. In order to have approximately the same dry density and initial water content, and presumably, approximately the same structure, all the samples of a given series were compacted at the same time. After the completion of compaction, specimens were extruded from the cylindrical mold and wrapped successively in saran wrap and aluminum foil and finally were inserted in molten microcrystalline wax to form a wax coating approximately 1/16 inch thick. All these meas-

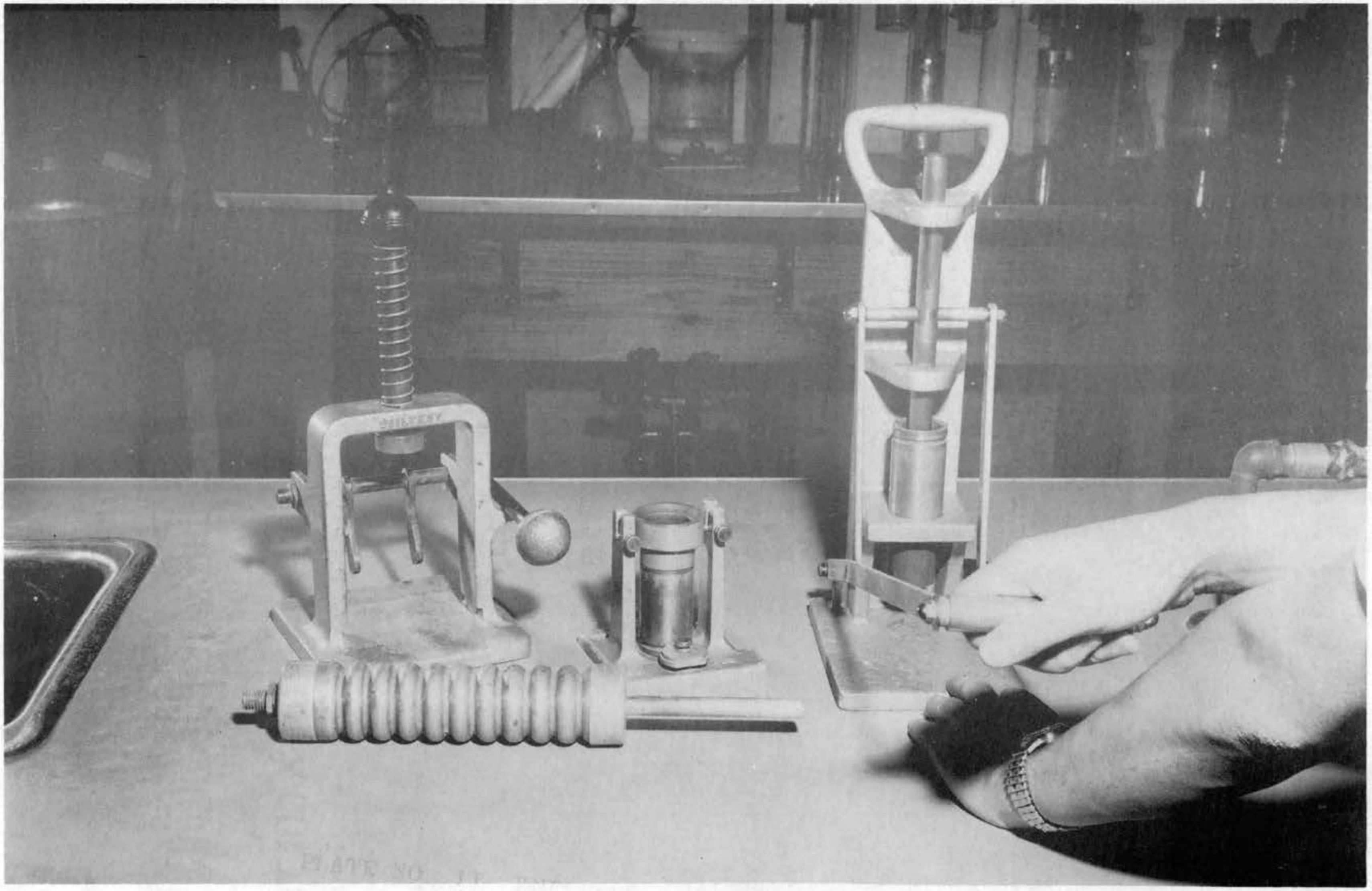


PLATE NO. II KNEADING COMPACTION APPARATUS
Harvard Miniature Compaction Equipment

ures were taken to retain the initial water content of compacted specimens.

In order to identify the specimens, labels were attached and specimens were stored in a room of high humidity. As the effect of the curing period is not considered in this part of the study, the tests were conducted as soon as possible to reduce the unknown effects of prolonged curing.

Second Phase of the Investigation
Clay Specimens with Gypsum

In the second phase of the investigation the effect of gypsum on the horizontal and vertical swelling of clay specimens was studied. The purpose of the study was to investigate whether gypsum addition would reduce the magnitudes of horizontal and vertical swelling. For these tests various combinations of gypsum and clay were dry-mixed, and specimens were prepared at different water contents by kneading compaction. The gypsum was obtained from the U. S. Gypsum Co. Plant at Southard, Oklahoma. The grain size distribution for the material is given in Figure 37. Gypsum has a hardness of two on Moh's Scale and its specific gravity ranges between 2.3 and 2.4.

The gypsum contents used were 5%, 10%, 20% and 30% based on the dry weight of the soil. For a given gypsum content three different initial water contents were used, one approximately equal to optimum water content, another about three per cent lower and another about three per cent higher

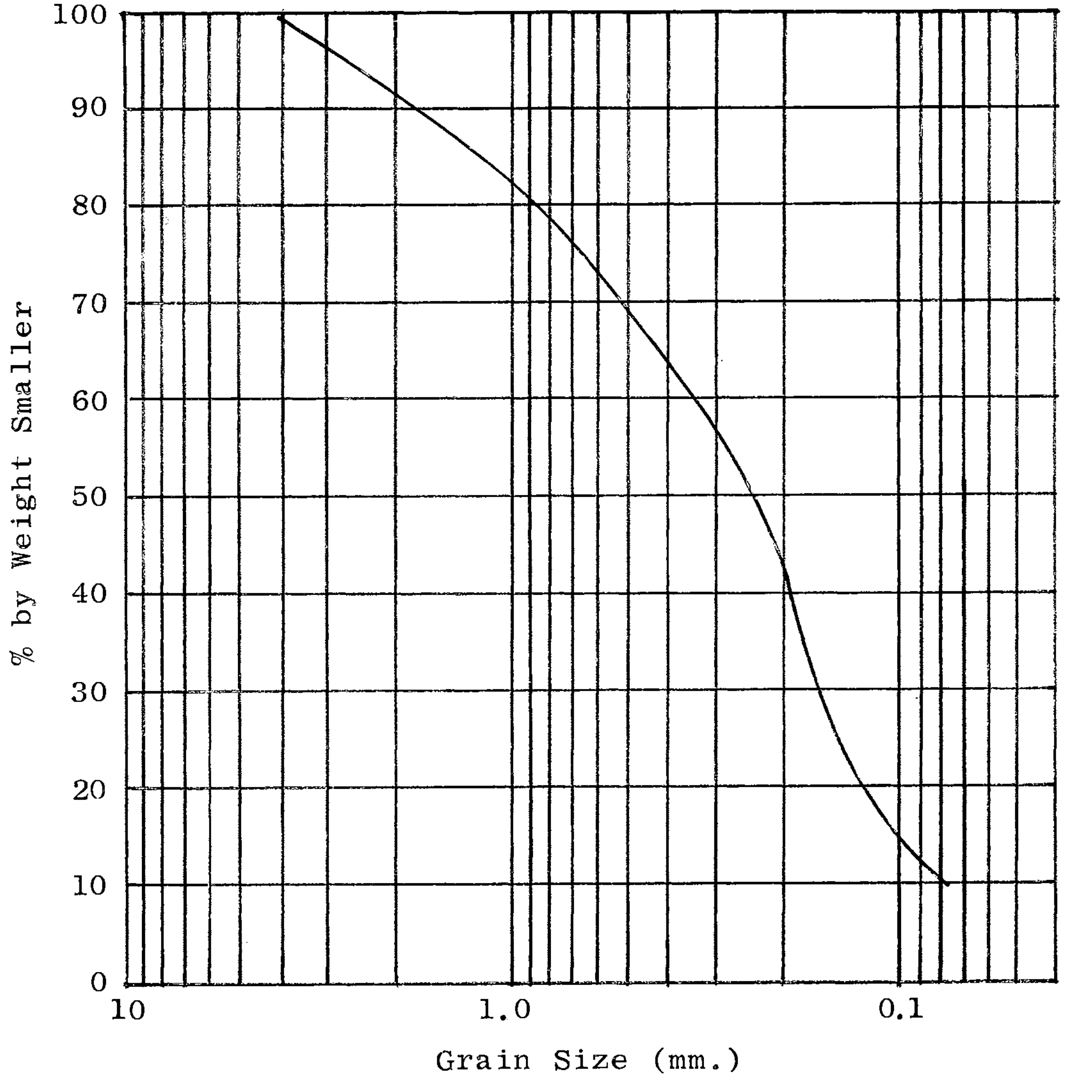


FIGURE 37. GRAIN SIZE DISTRIBUTION CURVE FOR GYPSUM.

than the optimum. In all series, the effect of curing was taken into consideration in order to establish whether a significant cation exchange would take place in longer periods of time. Therefore, in a given series of compacted specimens, half of them were tested one day after compaction and half of them were stored in the humid room for 28 days and then tested.

Third Phase of the Study

Clay Specimens with Inorganic Chemicals

In the third phase of the investigation, the effects of NaCl and $Ca(Cl)_2$ on the horizontal and vertical swelling of compacted clay specimens were studied. In the first part of this phase, 1 per cent and 2 per cent of NaCl and $Ca(Cl)_2$ by dry weight of clay soil were mixed with soils before specimens were compacted by kneading. The chemicals were dissolved in the mix water added to the soil. The effect of curing was taken into consideration in order to establish whether a significant cation exchange would take place in a longer period of time. Therefore, in a given series of compacted specimens, half of them were tested one day after compaction and the other half were stored in the humid room for seven days and then tested.

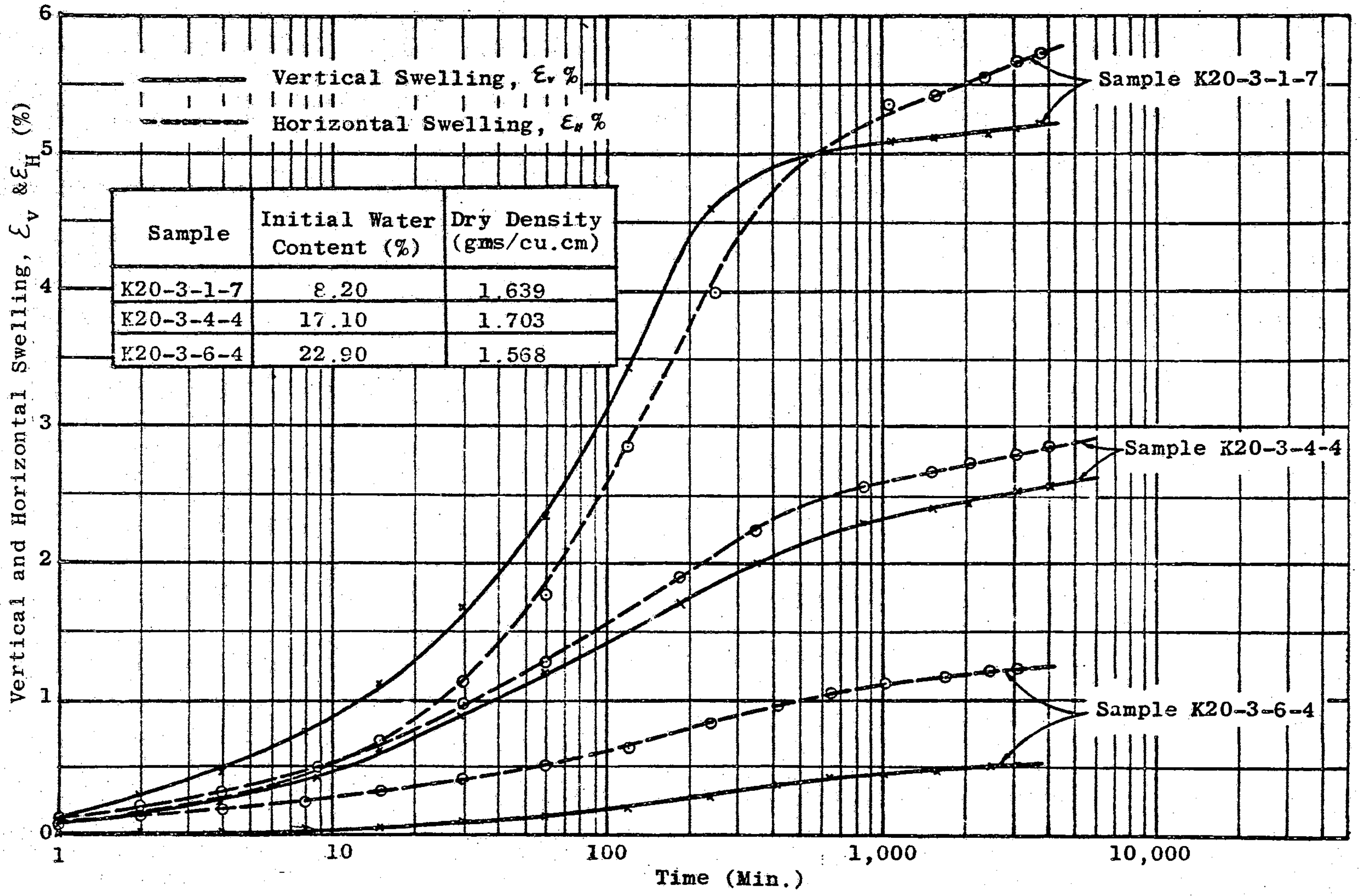
In the second part of this phase three per cent of NaCl and $Ca(Cl)_2$ by weight of reservoir water was added to the reservoir water and triaxial swelling of clay specimens compacted without any additives or inorganic chemicals was investigated. Here the effect of curing was not taken into consideration because of the nature of the study, and compacted clay samples were tested one day after compaction.

CHAPTER IV

DISCUSSION OF LABORATORY TEST RESULTS

Clay Samples without Additives or Inorganic Chemicals

1. Time Period Required for Swelling: If water is available for compacted clay samples, the time period required for unit swelling is inversely proportional to the permeability of a specimen. Samples compacted on the dry side of optimum are more permeable than the samples compacted to the same dry density on the wet side of optimum. Therefore, the time period required for unit swelling must be different for different initial water contents. However, the magnitude of swelling is greater in specimens compacted on the dry side of optimum. Therefore, the time required for total swelling in the two cases is about the same. Swelling time curves are given in Figure 38. In the beginning of the study, the water flow to the specimen was not accelerated by any means. However, later on, filter strips were applied on the surfaces of the specimens which accelerated water flow during swelling. In Figure 39 this effect is demonstrated. Filter strips reduced the time period required for swelling for two equivalent samples to not more than one-fourth of its original duration. Most of the swelling of compacted clay specimens is finished in three days when filter strips are employed.



Sample	Initial Water Content (%)	Dry Density (gms/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 38. SWELLING TIME CURVES - KNEADING COMPACTION SAMPLES WITH VARIOUS INITIAL WATER CONTENTS

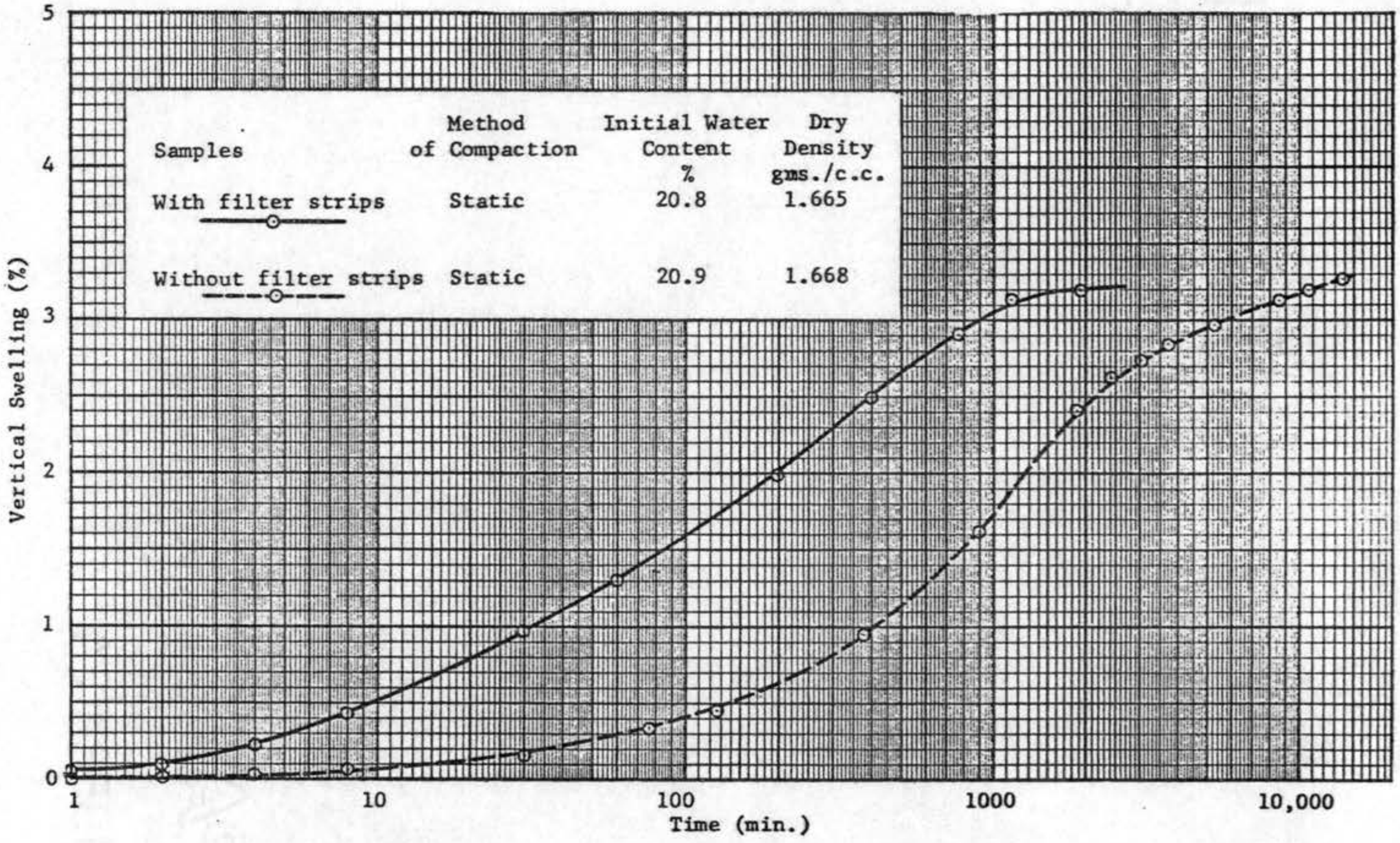


FIGURE 39. TIME PERIOD REQUIRED FOR SWELLING

Reduction of the time period for swelling makes tests more practicable and also reduces most of the prospective effects of environmental factors such as humidity, apparatus' water absorption and temperature which might be significant if test periods were considerably longer.

2. Effects of Initial Water Content on Swelling: In this study clay specimens were compacted at various initial water contents employing a specific type of compaction method and energy. The results show that samples compacted on the dry side of optimum swell more than samples compacted on the wet side of optimum, and that the horizontal swelling is usually greater than the vertical swelling. (See Tables V, VI, VII, VIII, IX and X.)

For a given compactive method and energy, vertical and horizontal swellings were correlated statistically with initial water contents. The results are given on Table XI. In a series of tests if dependent observations are designated as Y_i and independent variable as X_i, then for a sample size, n , r_c, the correlation coefficient for simple linear regression is

$$r_c = \frac{\Sigma x_i y_i}{\sqrt{\Sigma x_i^2 \; \Sigma y_i^2}}$$

in which $x_i = X_i - \overline{X}_i$

$y_i = Y_i - \overline{Y}_i$

$\overline{X}_i = \frac{\Sigma X_i}{n}$

$\overline{Y}_i = \frac{\Sigma Y_i}{n}$

$i = 1, 2, 3 \ldots n$

Table XI shows that there is a strong negative correlation between swelling and initial water content. In other words, the higher the initial water content, the smaller the swelling is. It can be observed in Table XI that for horizontal strains, the r values decrease with increasing compactive efforts. This can be explained in terms of structure created by different compactive efforts. For a given water content, increased compactive efforts tend to create a more dispersed structure and due to this fact, the correlation between horizontal strain and initial water content is not as pronounced as in the case of relatively smaller compactive energies. Figures 40 to 47 show the graphical relationship between swelling and initial water contents for given compactive method and energies. On these graphs, the relationship between swelling and initial water content are shown by least squares lines, which are valid only for the range of experimental values.

The soil that was used has a maximum dry density of 1.740 gm/cc. (or 108.7 lbs./cu. ft.) at an optimum water content of 17.5 per cent, utilizing the kneading compaction method with three layers of soil and a 20 pound spring tamper exerting 25 tamps on each layer. Figure 38 shows the effects of initial water content on the vertical and horizontal swelling rates. As both horizontal and vertical swelling rates are affected by approximately the same degree, then the rate of volumetric swelling is also affected by the initial water content. Figure 48 shows the relationship among time, swelling ratio and initial water content. Clay samples compacted on the dry side of optimum start to swell

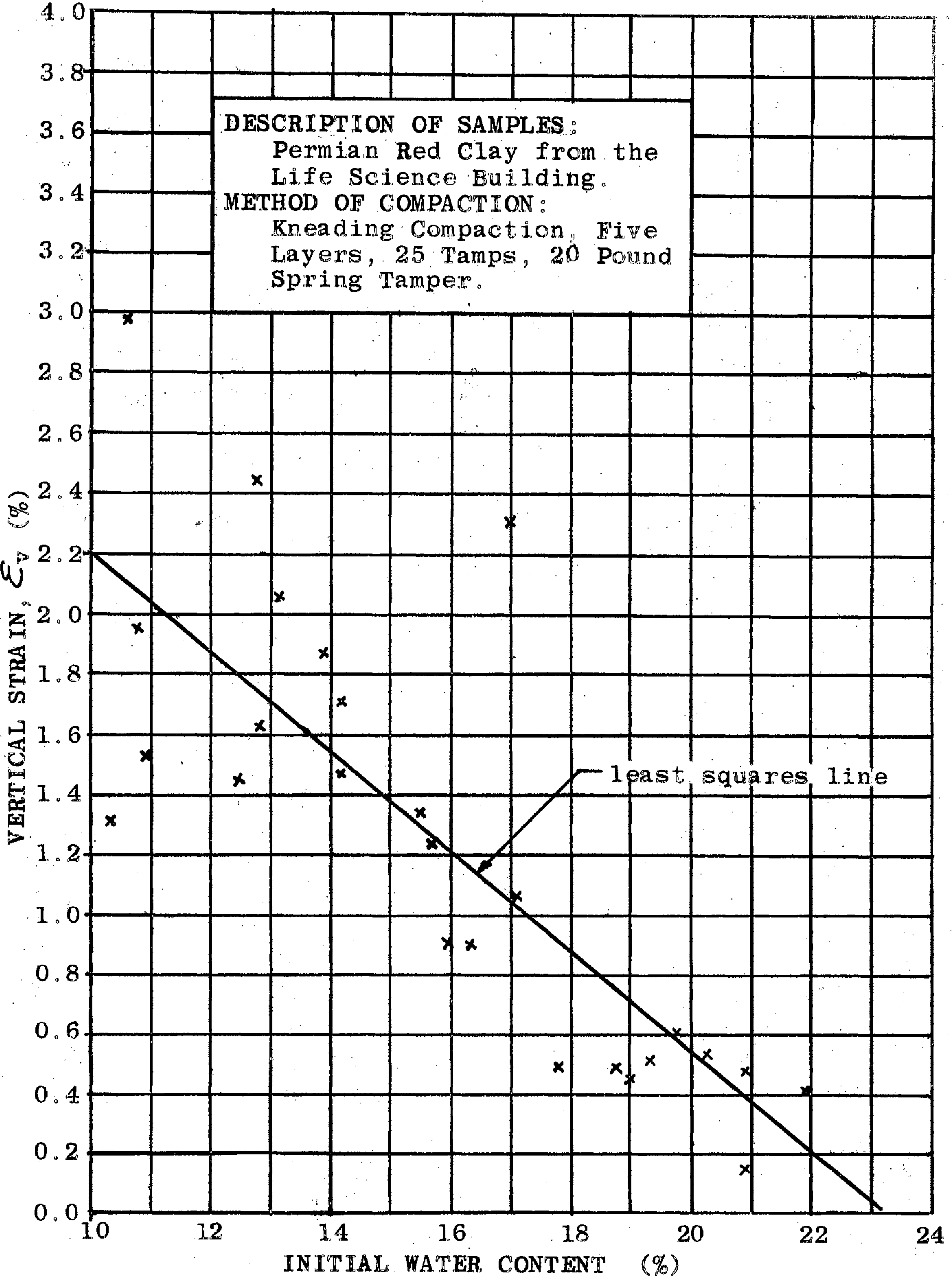


FIGURE 40. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_V$ (%) AND INITIAL WATER CONTENT (%).

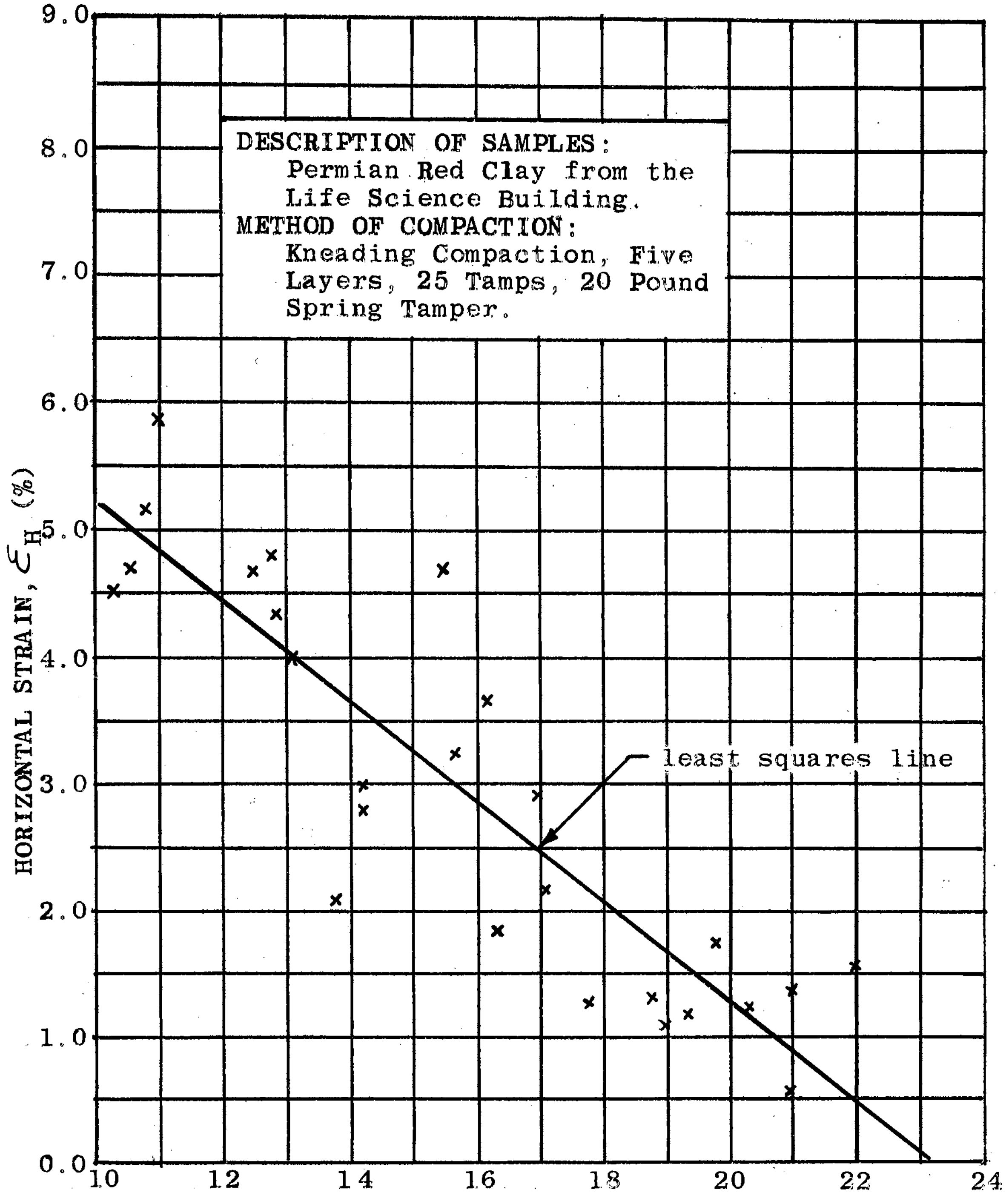


FIGURE 41. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$(%) AND INITIAL WATER CONTENT (%).

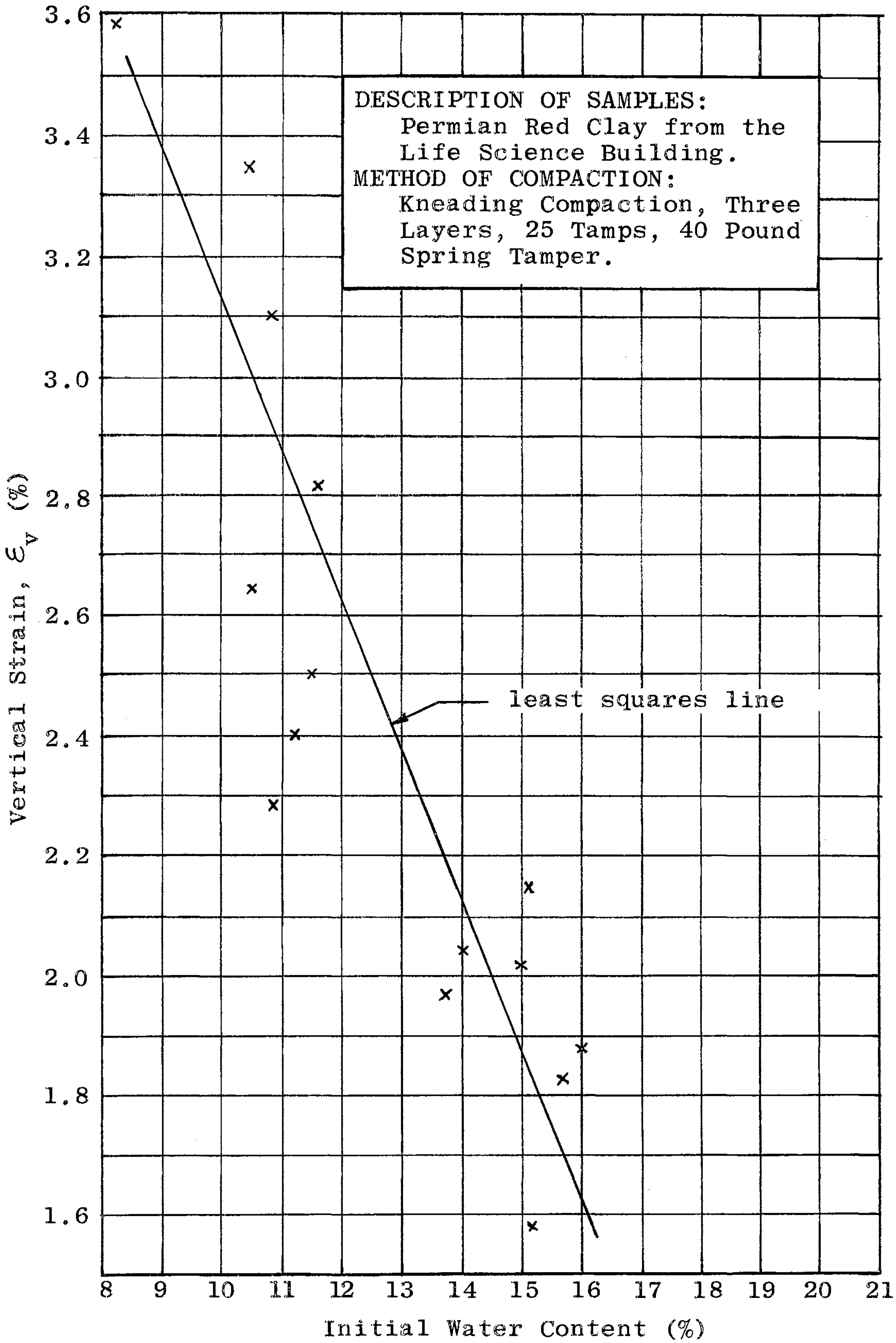


FIGURE 42. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, ε_v(%), AND INITIAL WATER CONTENT (%).

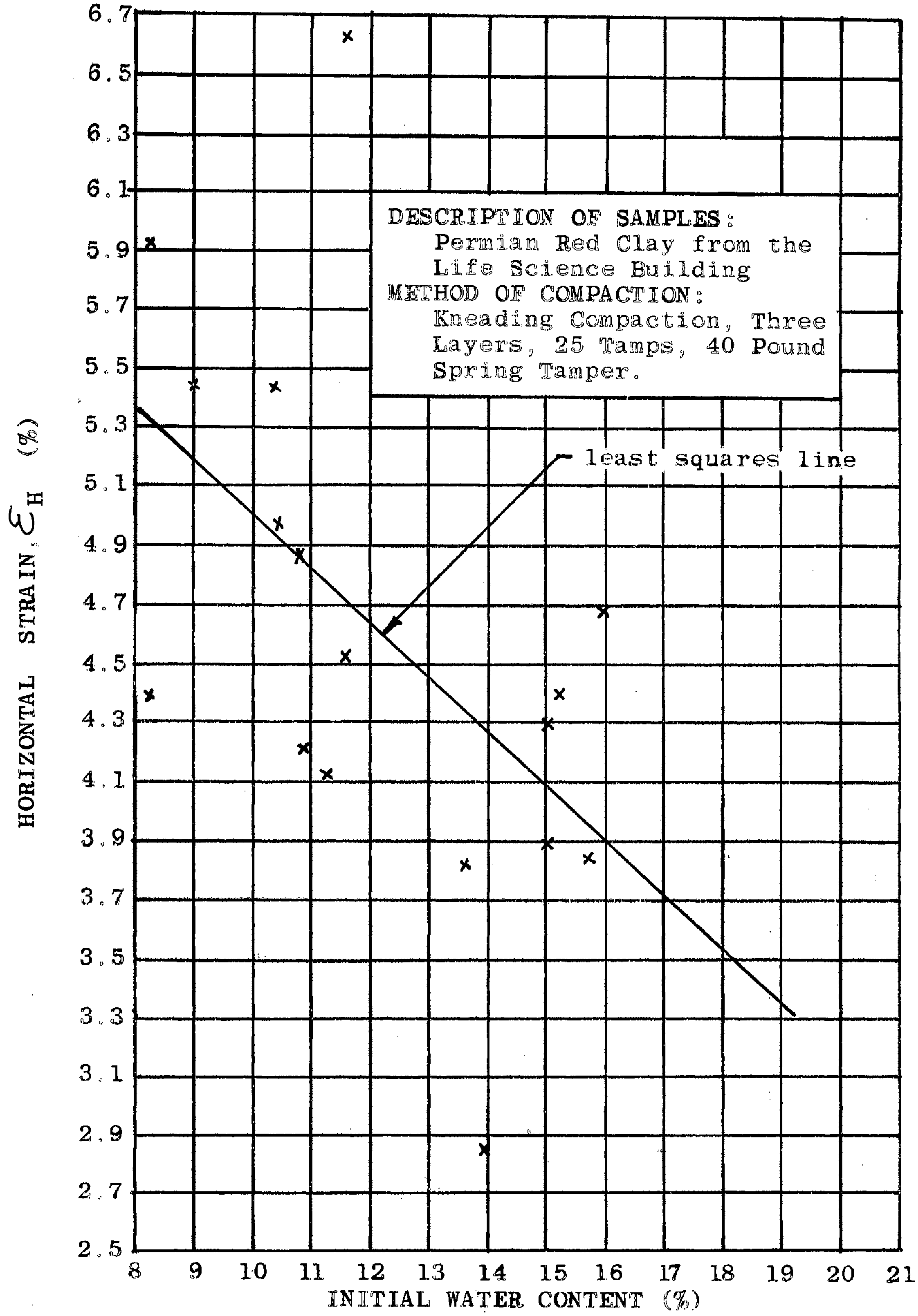


FIGURE 43. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$ (%) AND INITIAL WATER CONTENT.

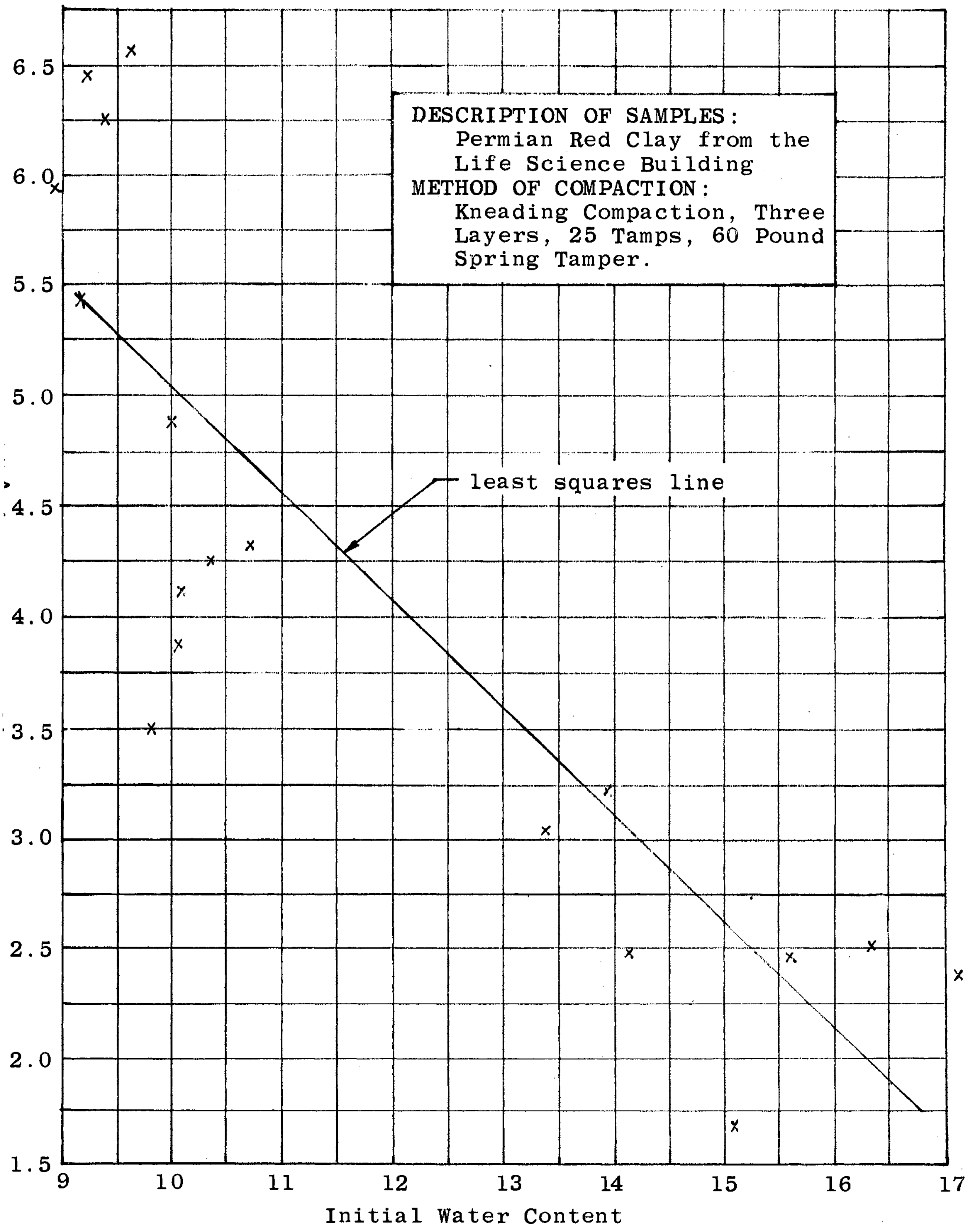


FIGURE 44. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$, (%) AND INITIAL WATER CONTENT.

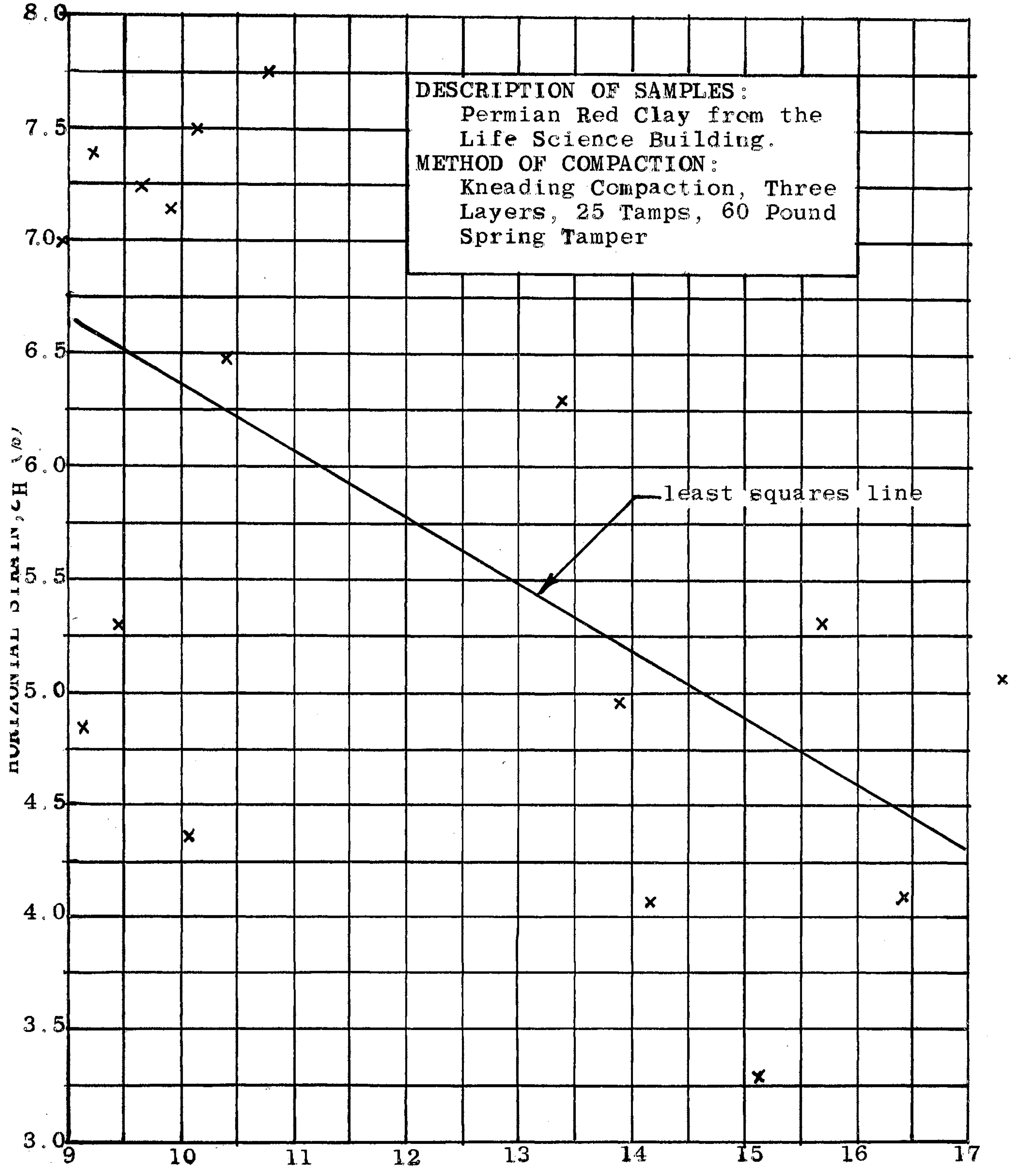


FIGURE 45. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H, (%) AND INITIAL WATER CONTENT (%).

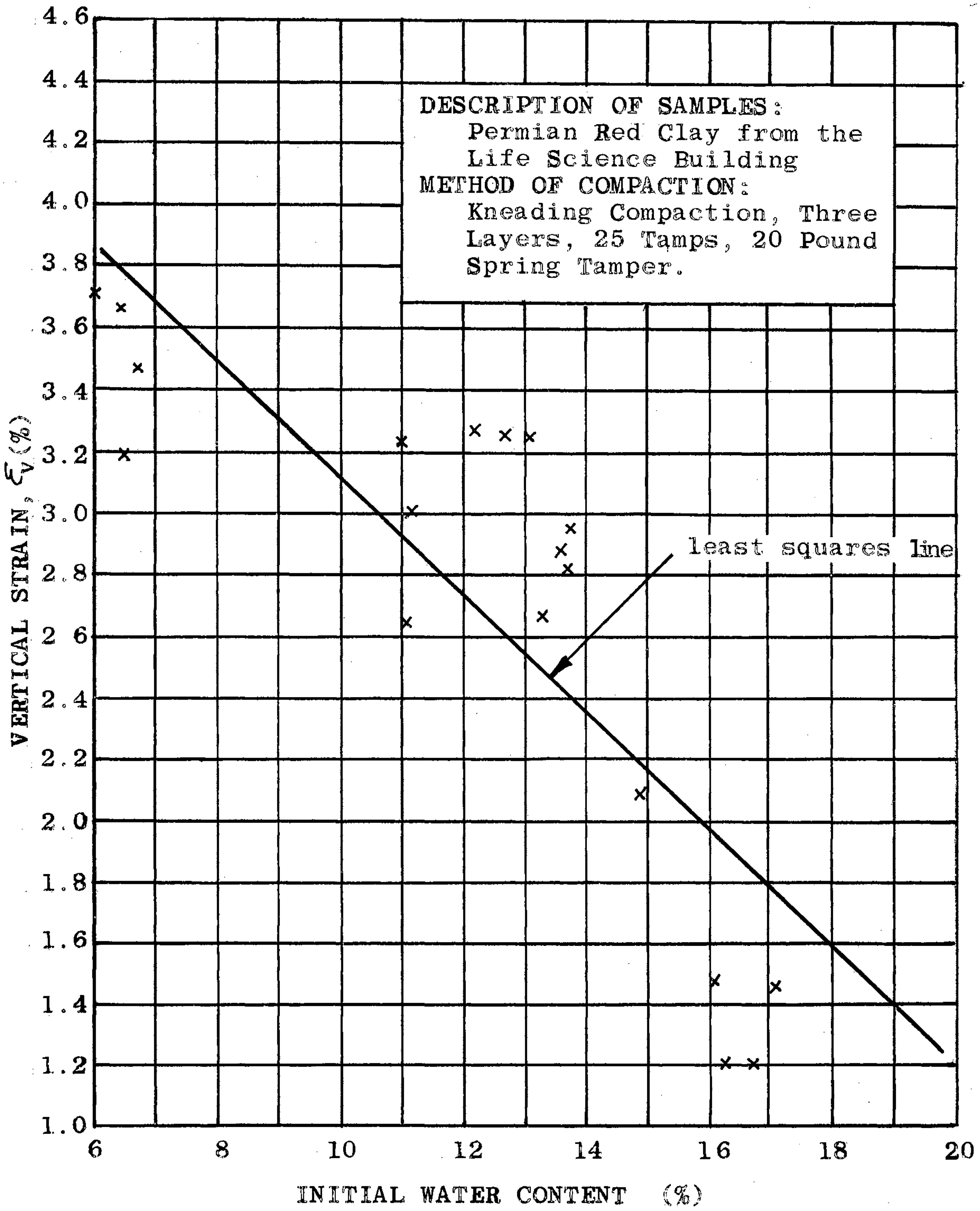


FIGURE 46. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$ (%) AND INITIAL WATER CONTENT.

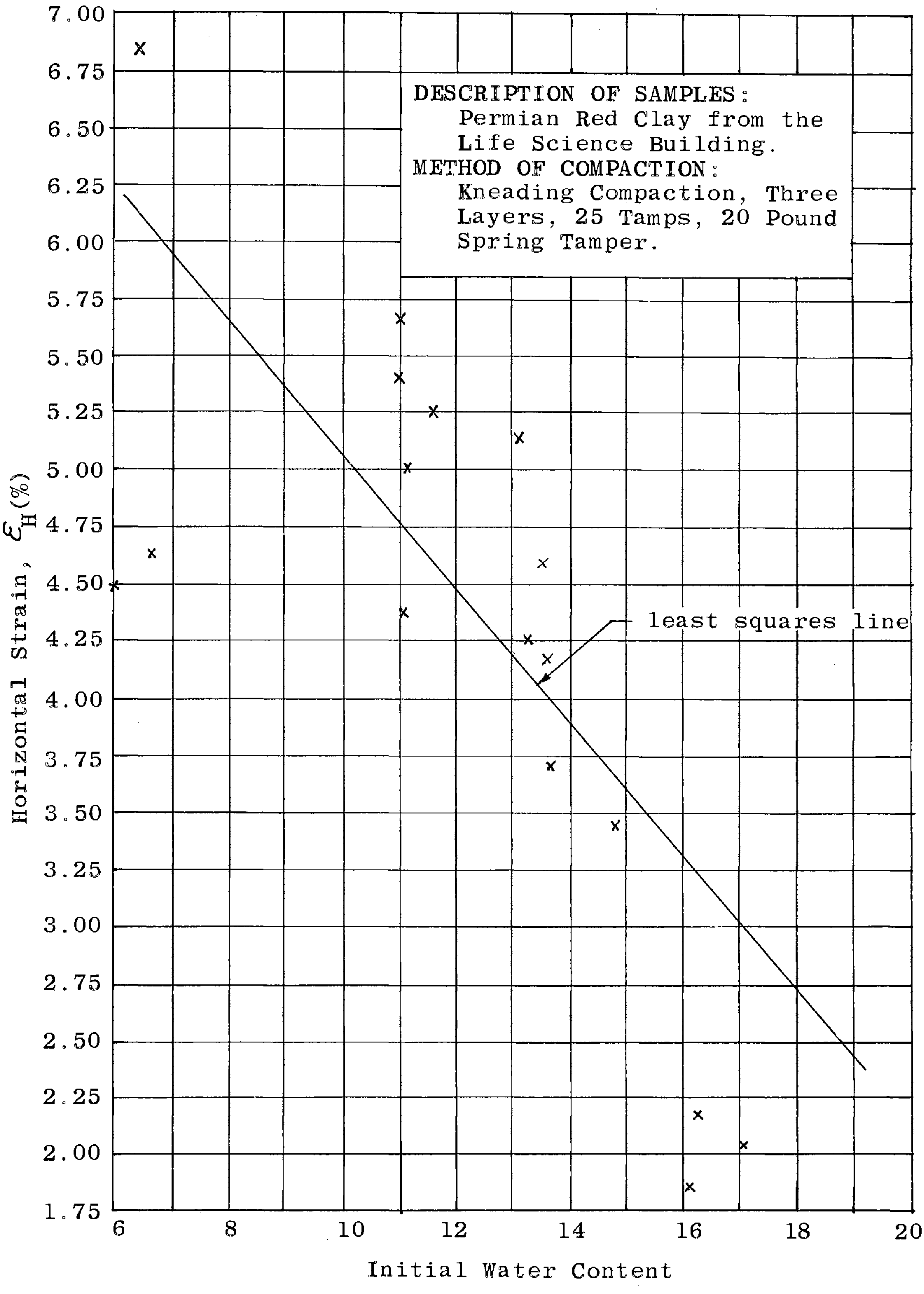
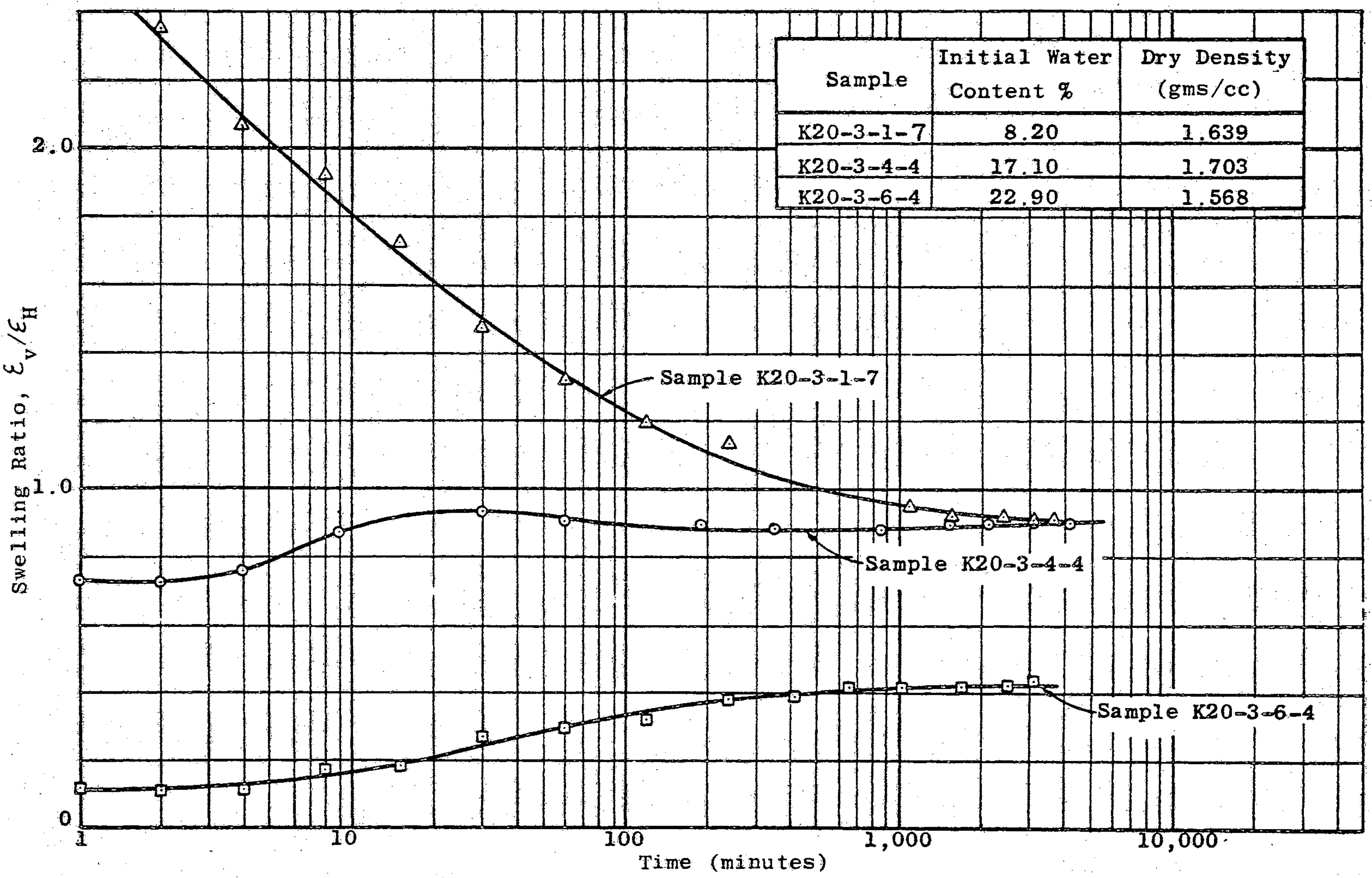


FIGURE 47. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H(%) AND INITIAL WATER CONTENT (%).



Sample	Initial Water Content %	Dry Density (gms/cc)
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 48. SWELLING RATIO - TIME CURVES - KNEADING COMPACTION SAMPLES WITH VARIOUS INITIAL WATER CONTENTS.

with higher swelling ratios ($\varepsilon_V/\varepsilon_H > 1$) that decrease rapidly. Samples compacted approximately at optimum water content or on the wet side of optimum start with a lower swelling ratio ($\varepsilon_V/\varepsilon_H < 1$) and the effect of time on this ratio is not very significant. Figure 49 gives a comparison of vertical and horizontal swellings for different initial water contents, and demonstrates that horizontal swelling is generally larger than the vertical swelling. At optimum water content, however, the difference between the magnitudes of horizontal and vertical swellings becomes minimum. Therefore, the swelling ratio reaches its maximum value, in the case of kneading compaction, in samples compacted at about optimum water content.

Figure 50 shows the relationship between the water pick-up and total volumetric swelling, and demonstrates that for all samples the volumetric swelling is less than the volume of imbibed water. However, the difference between the volume of swelling and the volume of the imbibed water gets smaller with increasing initial water contents.

The effect of the initial water content on the initial degree of saturation and the final degree of saturation is shown in Figure 51. Compacted clay specimens with different initial degrees of saturation attain almost the same degree of saturation after the swelling process is over.

3. Effects of Compaction Energy on Swelling: The effects of compaction energy on both vertical and horizontal swelling are studied by comparing clay specimens of equal

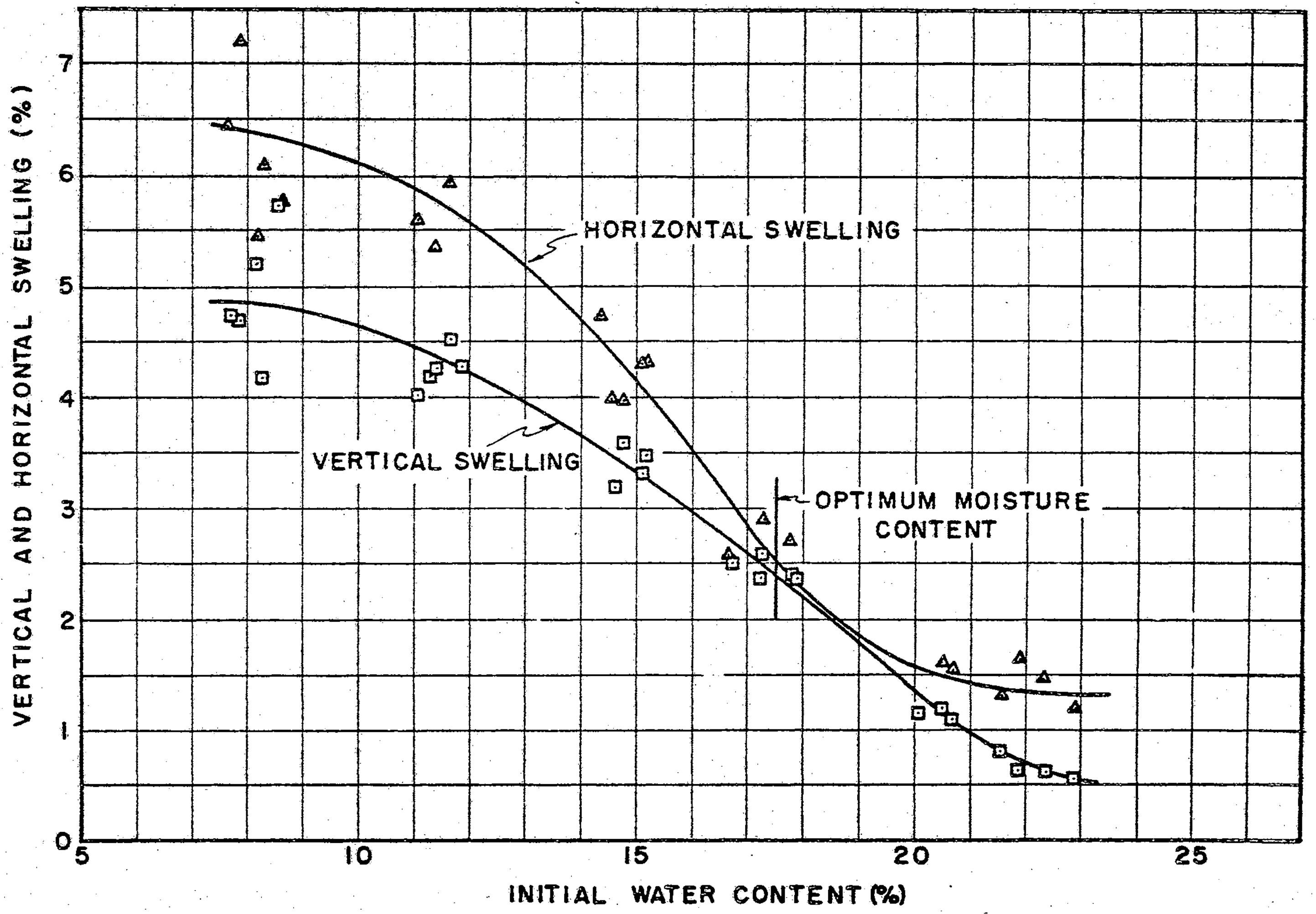
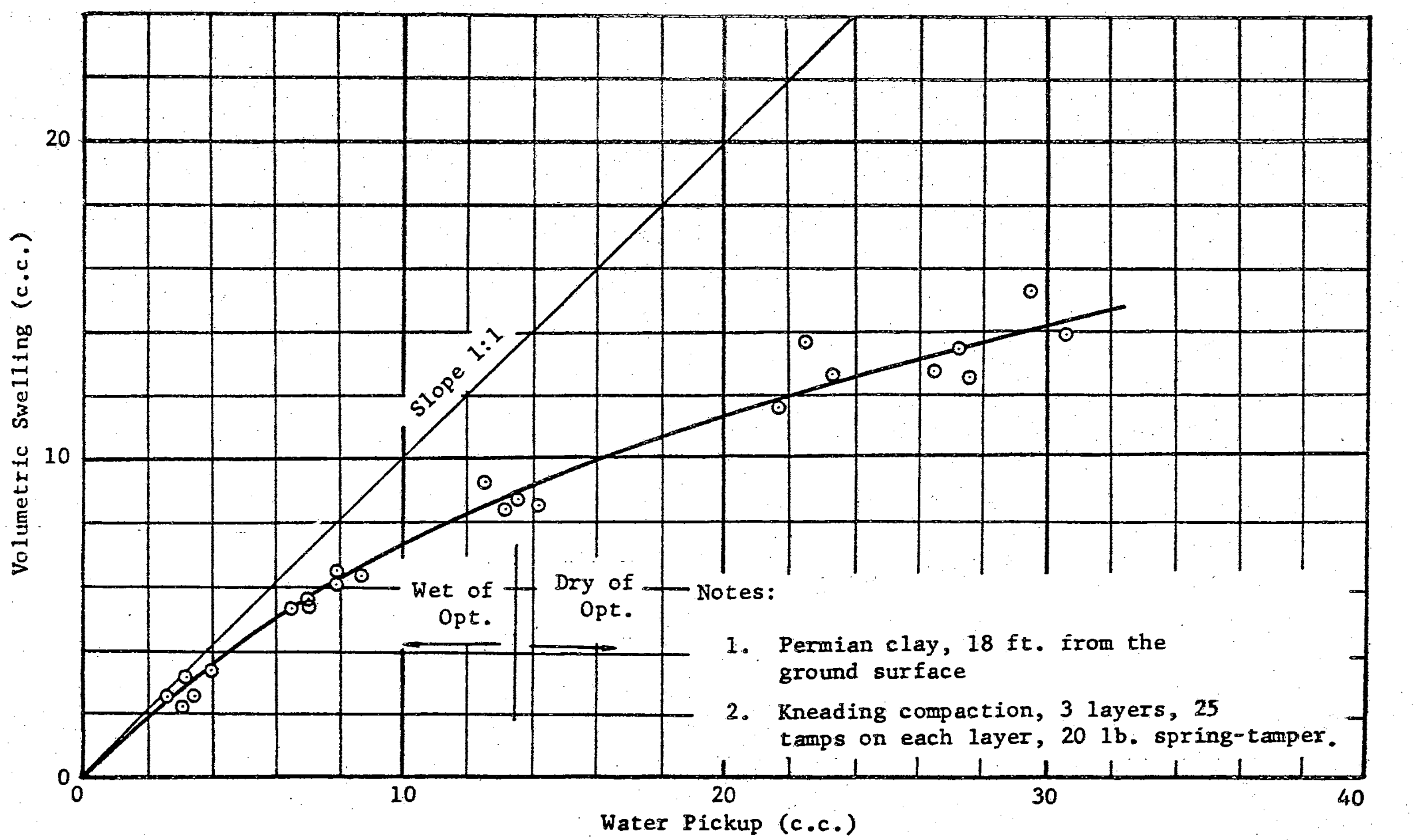


FIGURE 49. EFFECT OF INITIAL WATER CONTENT ON SWELLING



Notes:

1. Permian clay, 18 ft. from the ground surface
2. Kneading compaction, 3 layers, 25 tamps on each layer, 20 lb. spring-tamper.

FIGURE 50. RELATIONSHIP BETWEEN VOLUMETRIC SWELLING AND WATER PICKUP OF COMPACTED CLAY

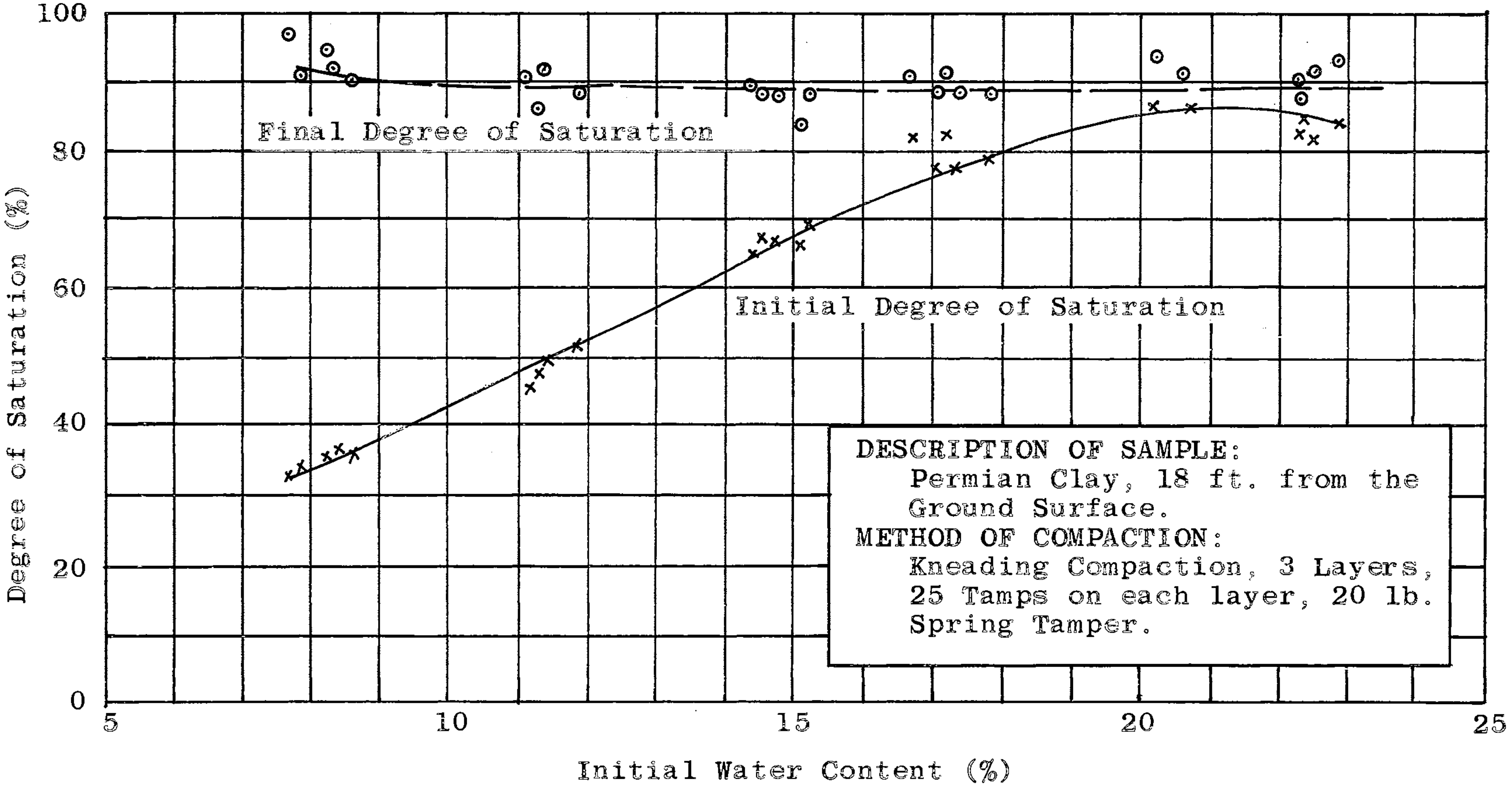


FIGURE 51. INITIAL AND FINAL DEGREES OF SATURATION

dry densities, compacted by different compactive efforts at various initial water contents. It is found that if for a given density, either horizontal or vertical swellings are plotted versus the applied force in kneading compaction, on log-log paper, the points approximate a straight line. Therefore, an exponential relationship may exist between the magnitude of swelling and compactive energy which can be formulated as,

$$SL = K' (F)^{\lambda}$$

in which SL = the magnitude of swelling

K' = a parameter depending on the amount of compactive energy

F = force applied by spring tamper in kneading compaction

λ = a parameter depending upon the amount of compactive energy.

If this relationship holds true, then

$$\log SL = \log K' + \lambda \log F$$

Therefore, when log SL values are plotted against log F values, the points should approximate a straight line. The parameter, λ, is determined by the slope of the straight line and the parameter, K', by the value of SL when F = 1, or in other words, by the intercept of the straight line.

Figure 52 shows the experimental relationship between vertical and horizontal swelling and different compactive energies on the log-log scale. As mentioned before, points on this figure approximate a straight line. Furthermore, the correlations between the log SL values and log F values are

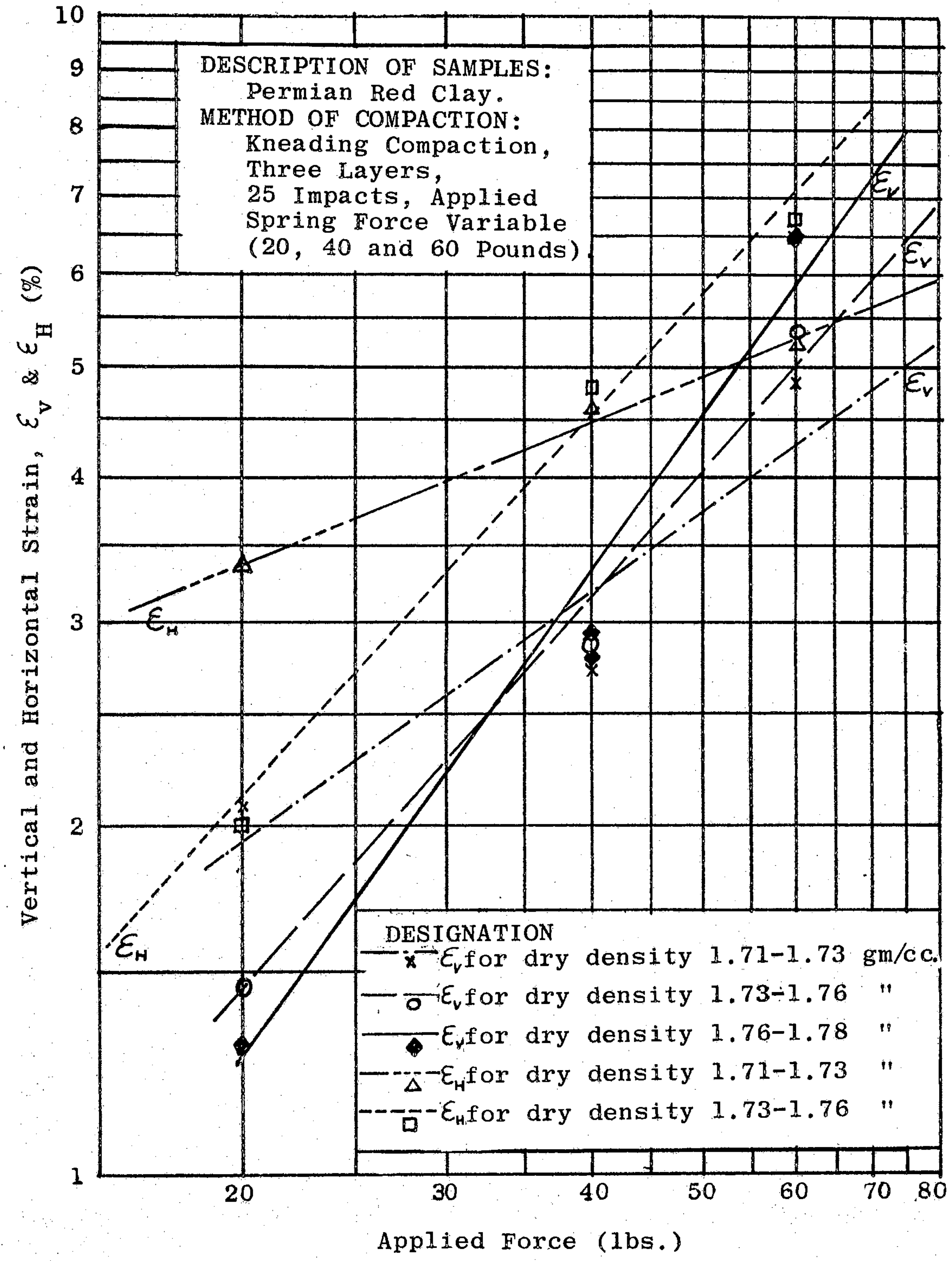
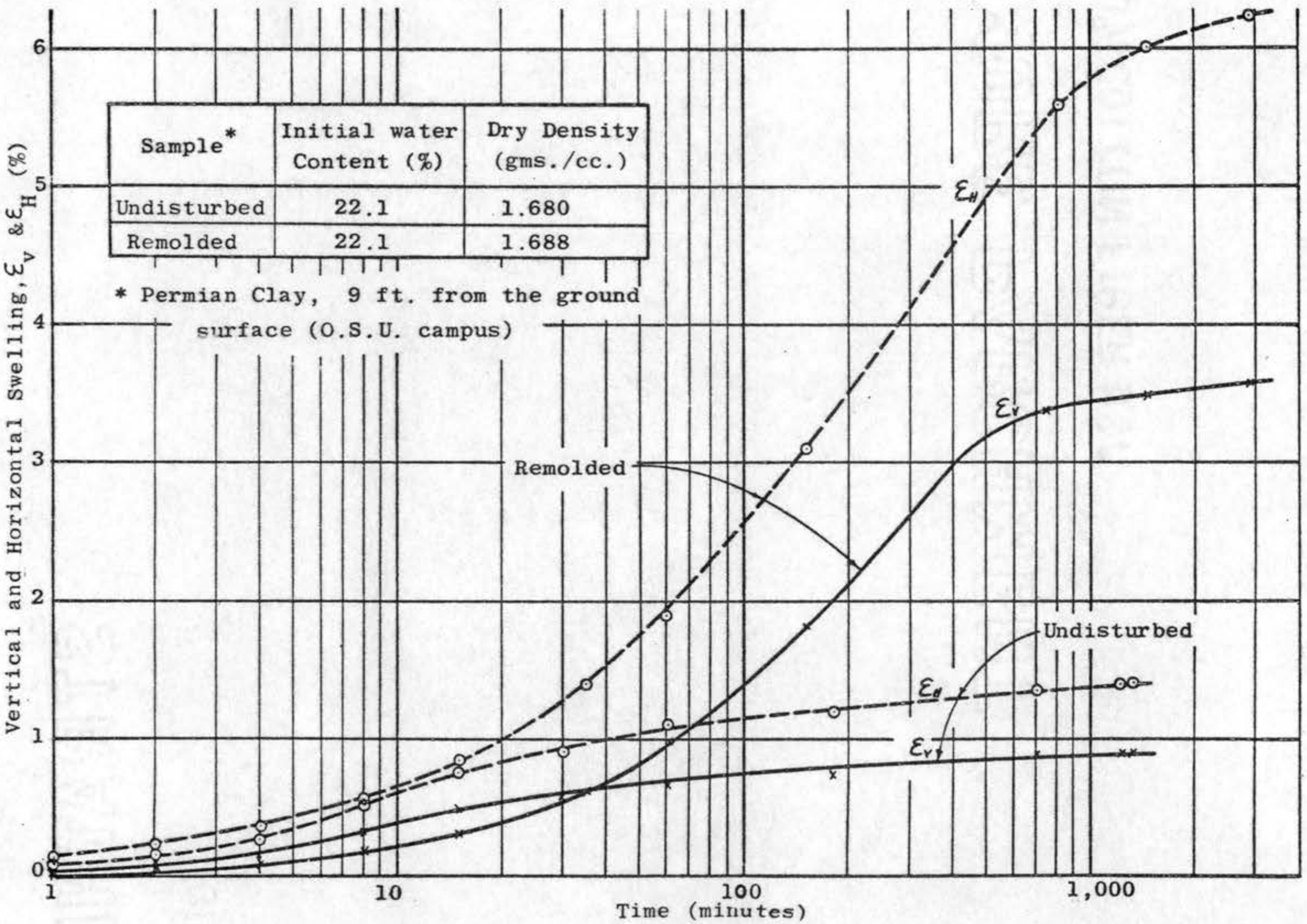


FIGURE 52. THE RELATIONSHIP BETWEEN VERTICAL AND HORIZONTAL STRAIN AND APPLIED SPRING FORCE.

very strong. Table XII gives these correlation factors (assuming single linear regression). However, as only three different compactive energies are employed, it is difficult to extrapolate these results. Even though the existence of an exponential relationship cannot be proved explicitly with the data available, it is obvious that the higher the compactive energy, the larger are the horizontal and vertical swelling.

4. Swelling Characteristics of Clay in the Undisturbed and Remolded States: To compare vertical and horizontal swelling of undisturbed and remolded clay specimens, undisturbed samples were taken from depths of approximately 9 and 18 feet near the northeast corner of the excavation for the New Engineering Building. Table XIII gives the swelling test results of 13 undisturbed samples. The average initial water contents and dry densities for samples taken at the two different levels were found to be different. For samples taken at the nine foot depth, the average dry density was 1.680 gms./cc. (105 lbs./cu. ft.) and the average initial water content was 21.92 per cent. Yet for samples taken at 18 feet, these values were 2.009 gms./cc. (125 lbs./cu. ft.) and 13.66 per cent, respectively. The magnitudes of vertical and horizontal swelling for undisturbed samples were compared with the respective swellings of compacted equivalent samples. Figures 53 and 54 show the significant difference between the magnitude of swelling for the undisturbed and remolded states, and demonstrate that remolded samples swell approximately four times more than the undisturbed sample in both the



Sample*	Initial water Content (%)	Dry Density (gms./cc.)
Undisturbed	22.1	1.680
Remolded	22.1	1.688

* Permian Clay, 9 ft. from the ground surface (O.S.U. campus)

FIGURE 53. SWELLING TIME CURVES --- Comparison of Undisturbed and Remolded State

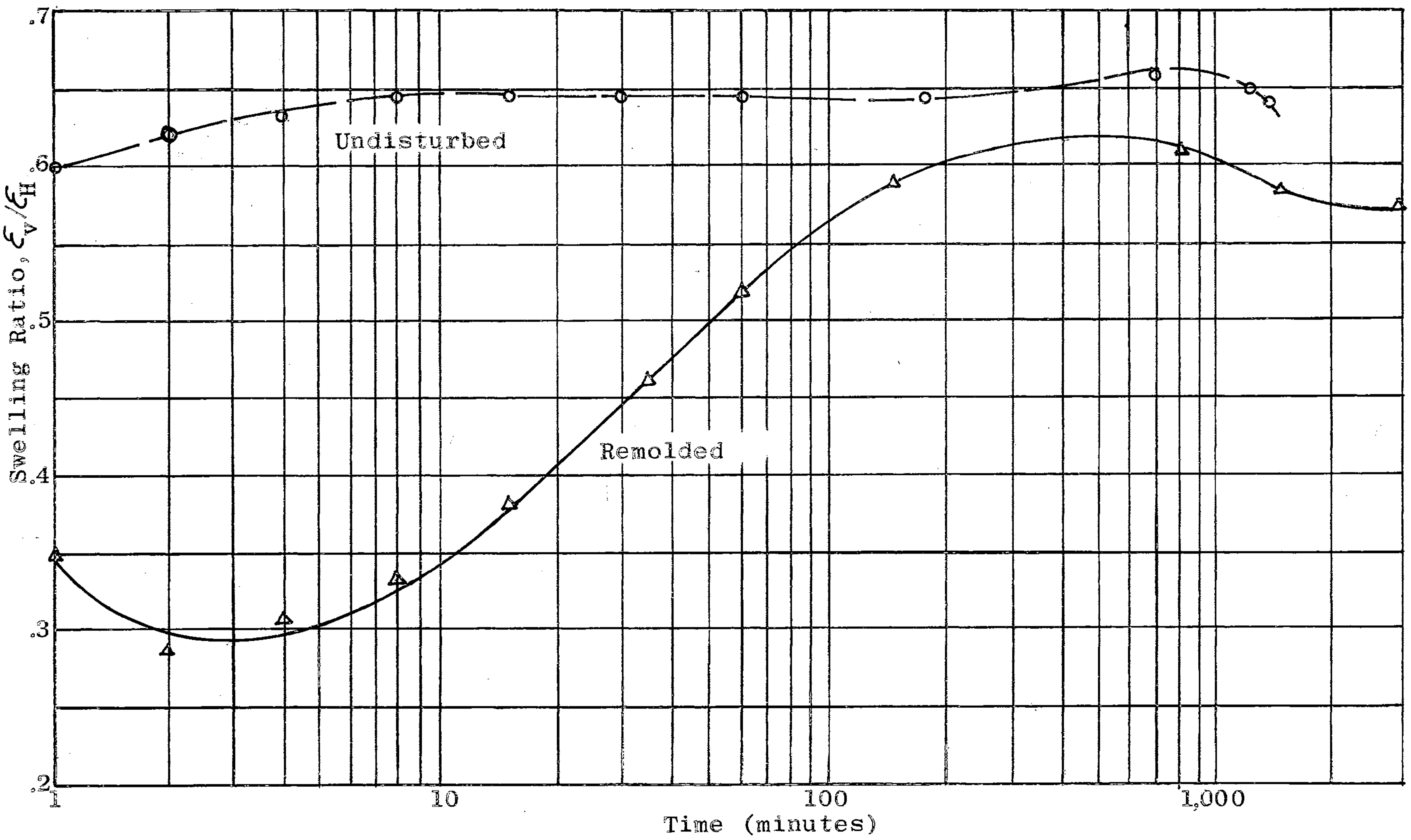


FIGURE 54. SWELLING RATIO - TIME CURVES
Comparison of Undisturbed and Remolded State

horizontal and vertical directions. This is an expected outcome, due to the fact that remolding an undisturbed sample destroys its original structure by eliminating or reducing certain bond stresses between clay particles. Therefore, an individual clay particle which has been released from most of these stresses has more freedom for swelling.

Figure 54 shows that final swelling ratios for undisturbed and remolded states are not very different. Yet differences in the time variations of the swelling ratio for two states are quite pronounced. The swelling ratio of the undisturbed sample is almost constant during the swelling process, whereas for remolded samples it varies significantly. As the clay particles are attracted to each other by strong bonding stresses, it may be possible for an undisturbed clay sample to behave as a single structural unit which, consequently, yields an almost constant swelling ratio. On the other hand, remolding destroys this unique property of the undisturbed clay sample, causing variation of the swelling ratio during the swelling process.

Figure 55 shows the relationship between the volumetric swelling and water pick-up for undisturbed clay samples. As in the case of the compacted samples, it was found that the swelling volume is always less than the volume of imbibed water.

Clay Samples with Gypsum

1. <u>Time Period for Swelling</u>: In the second phase of the study, as mentioned previously, 5, 10, 20 and 30 per

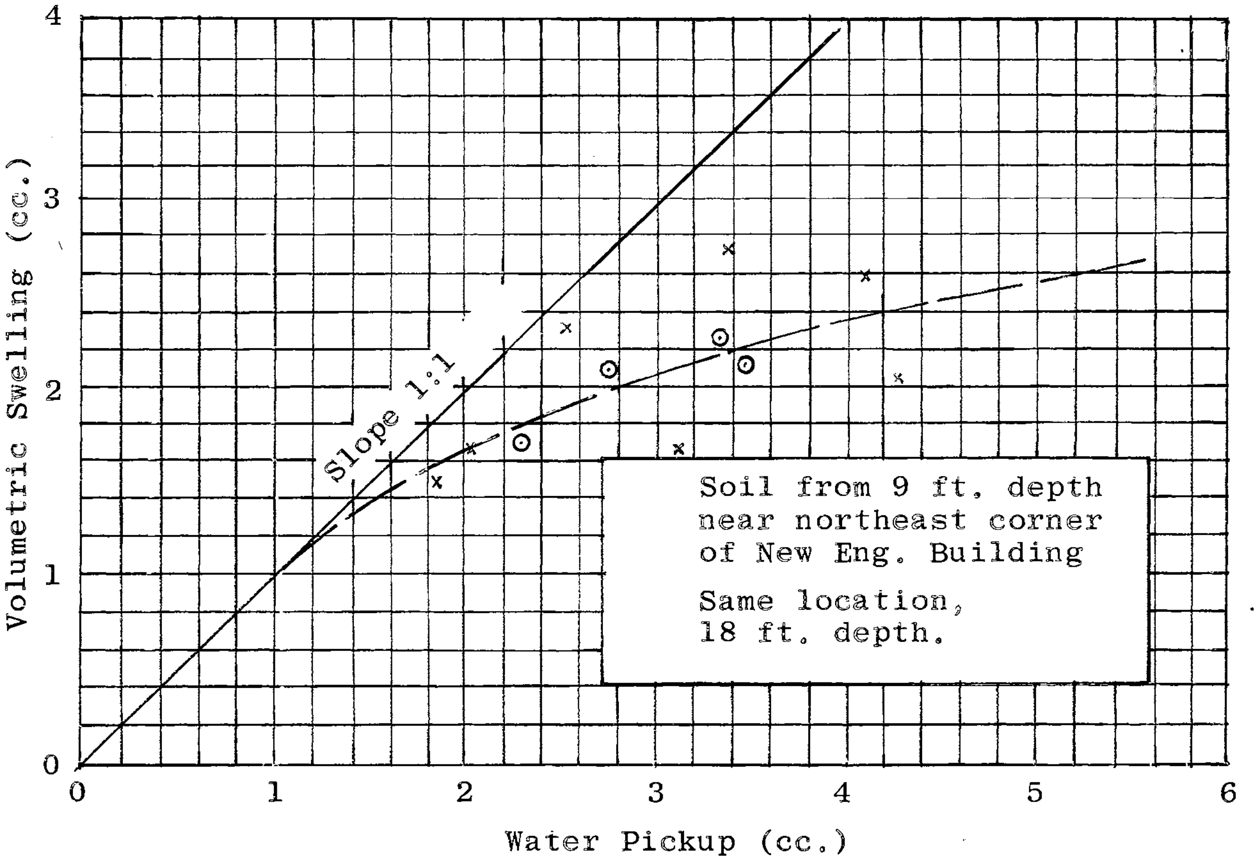
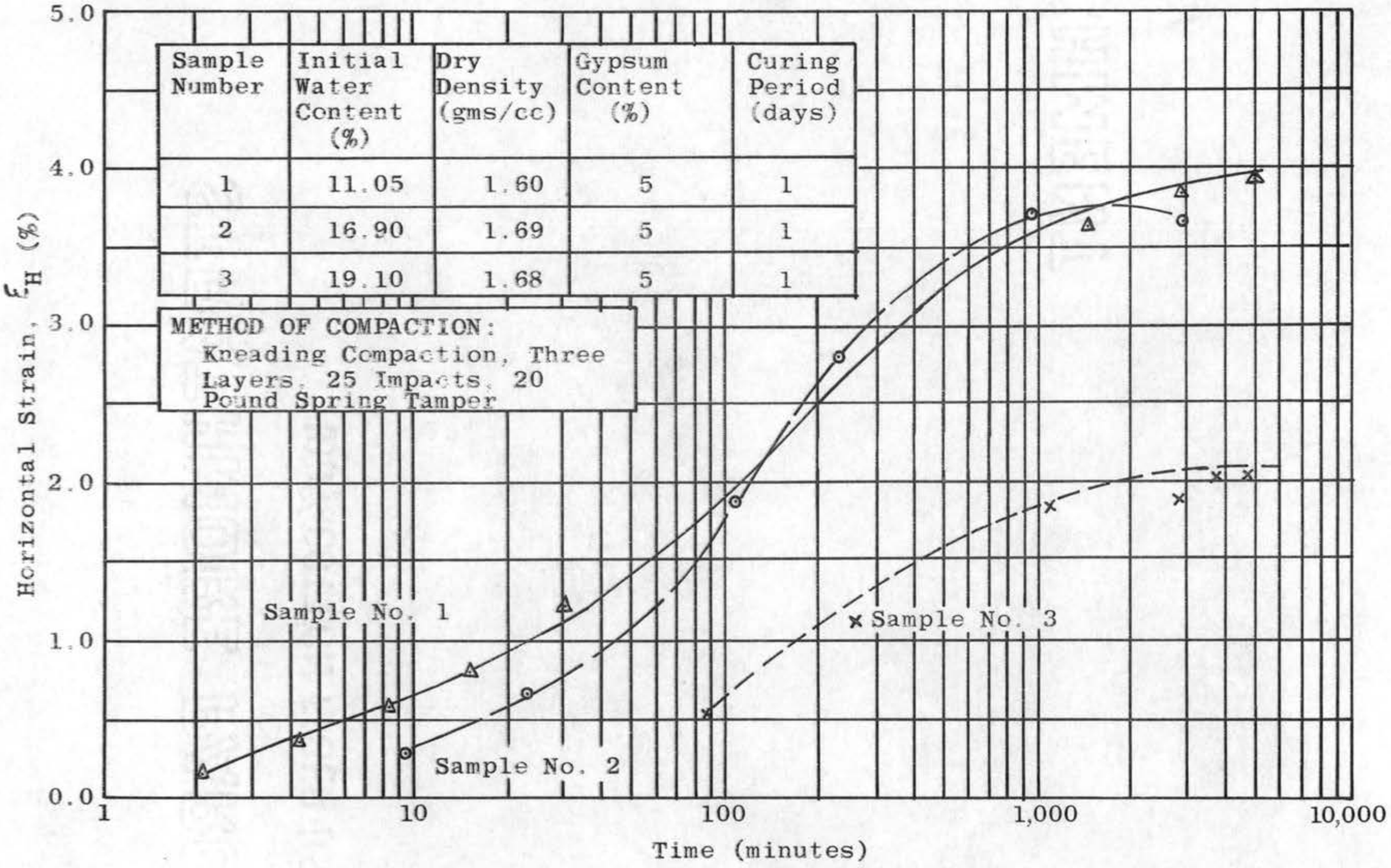


FIGURE 55. RELATIONSHIP BETWEEN VOLUMETRIC SWELLING AND WATER PICKUP OF UNDISTURBED CLAY.

cent of gypsum by dry weight of soil were mixed with clay soil. The samples were compacted by kneading compaction, in which a 20 pound spring tamper was applied 25 times on each of the three consecutive layers in the compaction cylinder. To accelerate the swelling filter strips were applied on the surfaces of the specimen. The complete results are given in Table XIV. Figures 56 to 61 show the relationship between time and vertical and horizontal swelling for samples compacted at various initial water and gypsum contents. These figures show that the time period required for total swelling varies between 1,030 and 5,870 minutes. Samples compacted on the dry side of optimum water content generally require more time for total swelling than those compacted at optimum or on the wet side of optimum water content.

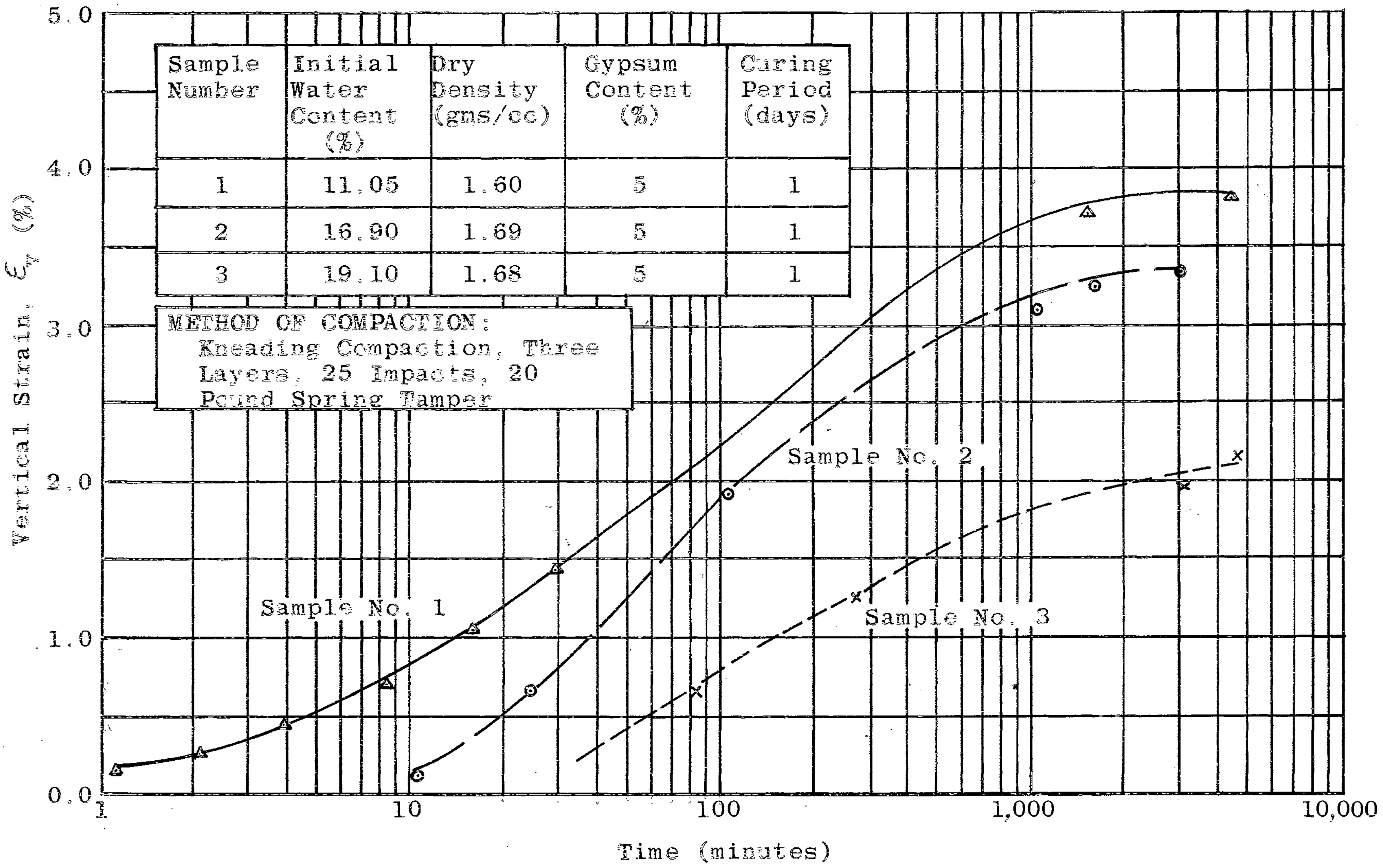
2. Effects of Initial Water Content on Swelling: In order to investigate the relationships between horizontal and vertical swelling and initial water content, samples with a given gypsum content (5, 10, 20 and 30 per cent) were compacted at various initial water contents. Figures 62 to 73 show these relations in graphical form. On these graphs least squares lines were drawn for given data to indicate the aforementioned relations in a quantitative manner. Futhermore, assuming that gypsum content and initial water content are experimental variables that are absolutely independent of each other; correlation factors between the magnitude of swelling and initial water contents were calculated. These factors which are given in Table XV and the



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
1	11.05	1.60	5	1
2	16.90	1.69	5	1
3	19.10	1.68	5	1

METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

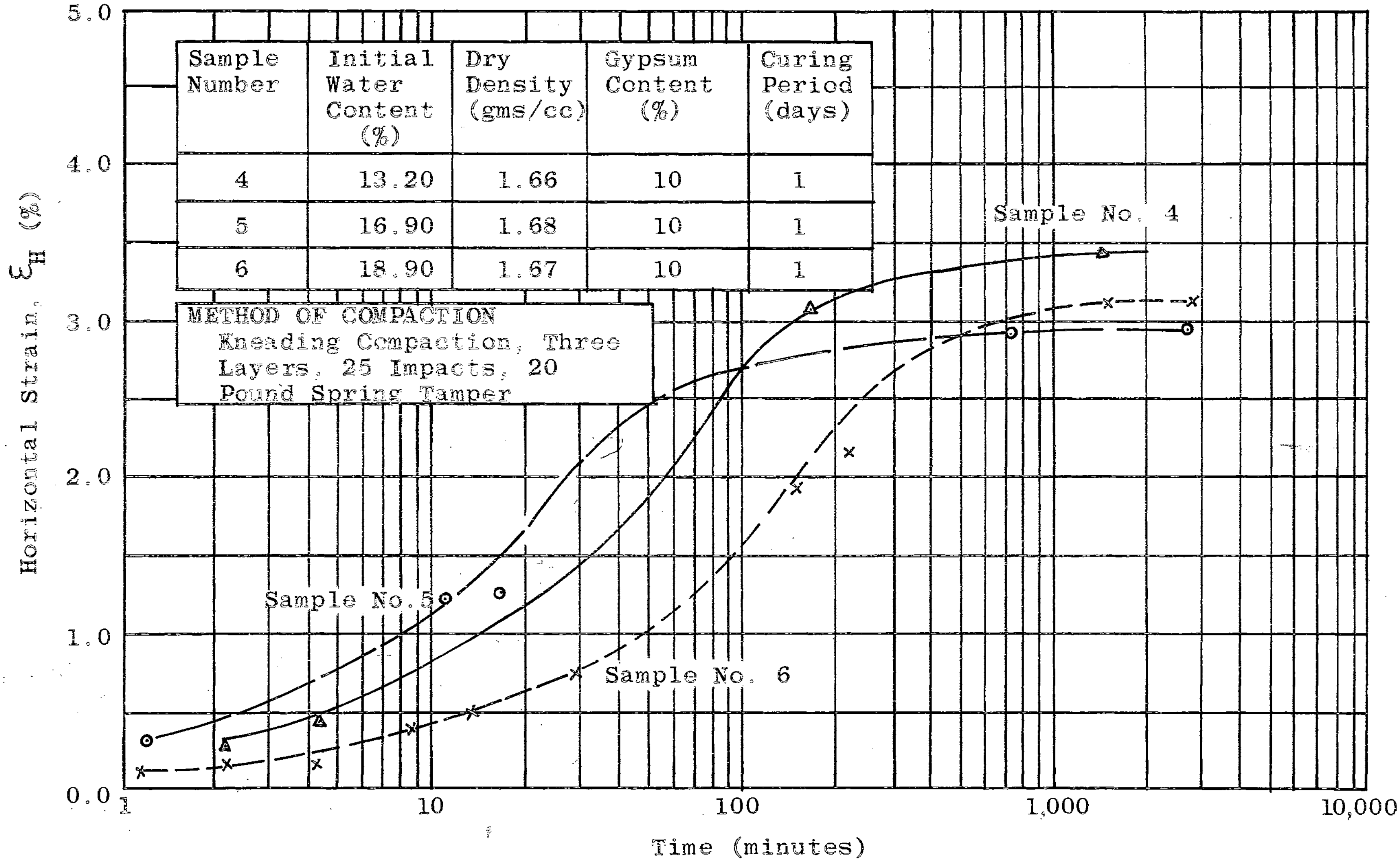
FIGURE 56. SWELLING TIME CURVES



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
1	11.05	1.60	5	1
2	16.90	1.69	5	1
3	19.10	1.68	5	1

METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

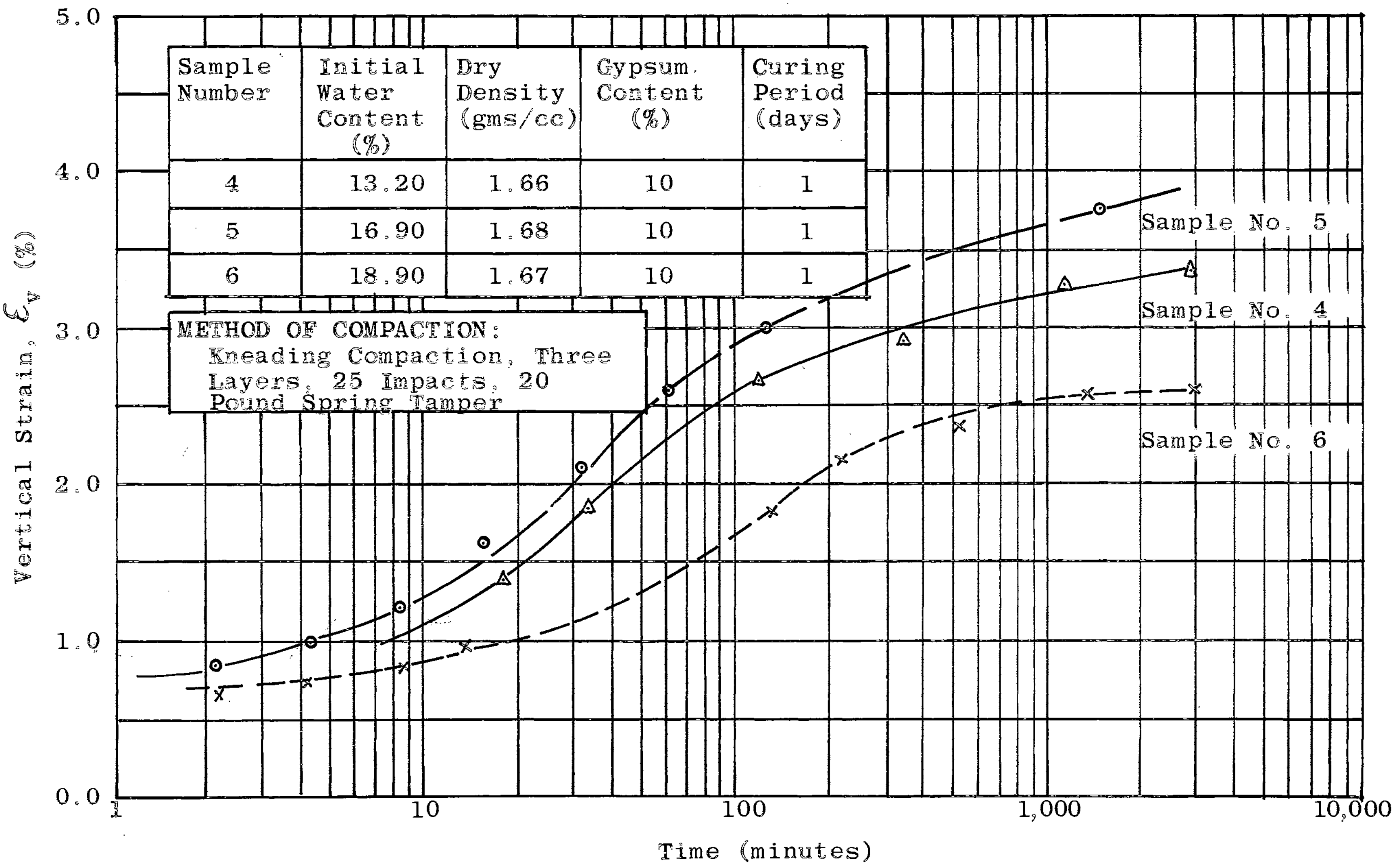
FIGURE 57. SWELLING TIME CURVES



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
4	13.20	1.66	10	1
5	16.90	1.68	10	1
6	18.90	1.67	10	1

METHOD OF COMPACTION
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

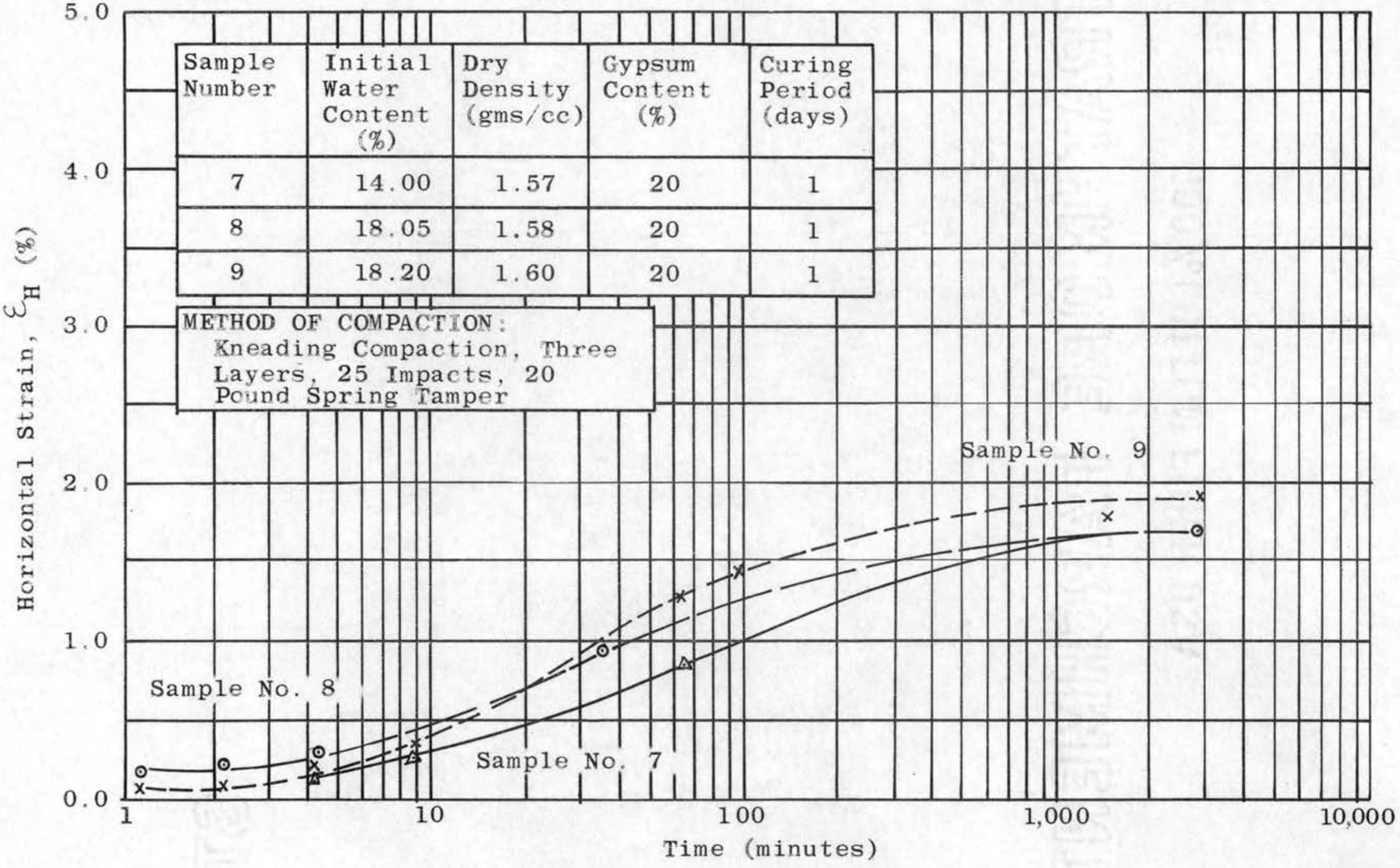
FIGURE 58. SWELLING TIME CURVES



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
4	13.20	1.66	10	1
5	16.90	1.68	10	1
6	18.90	1.67	10	1

METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

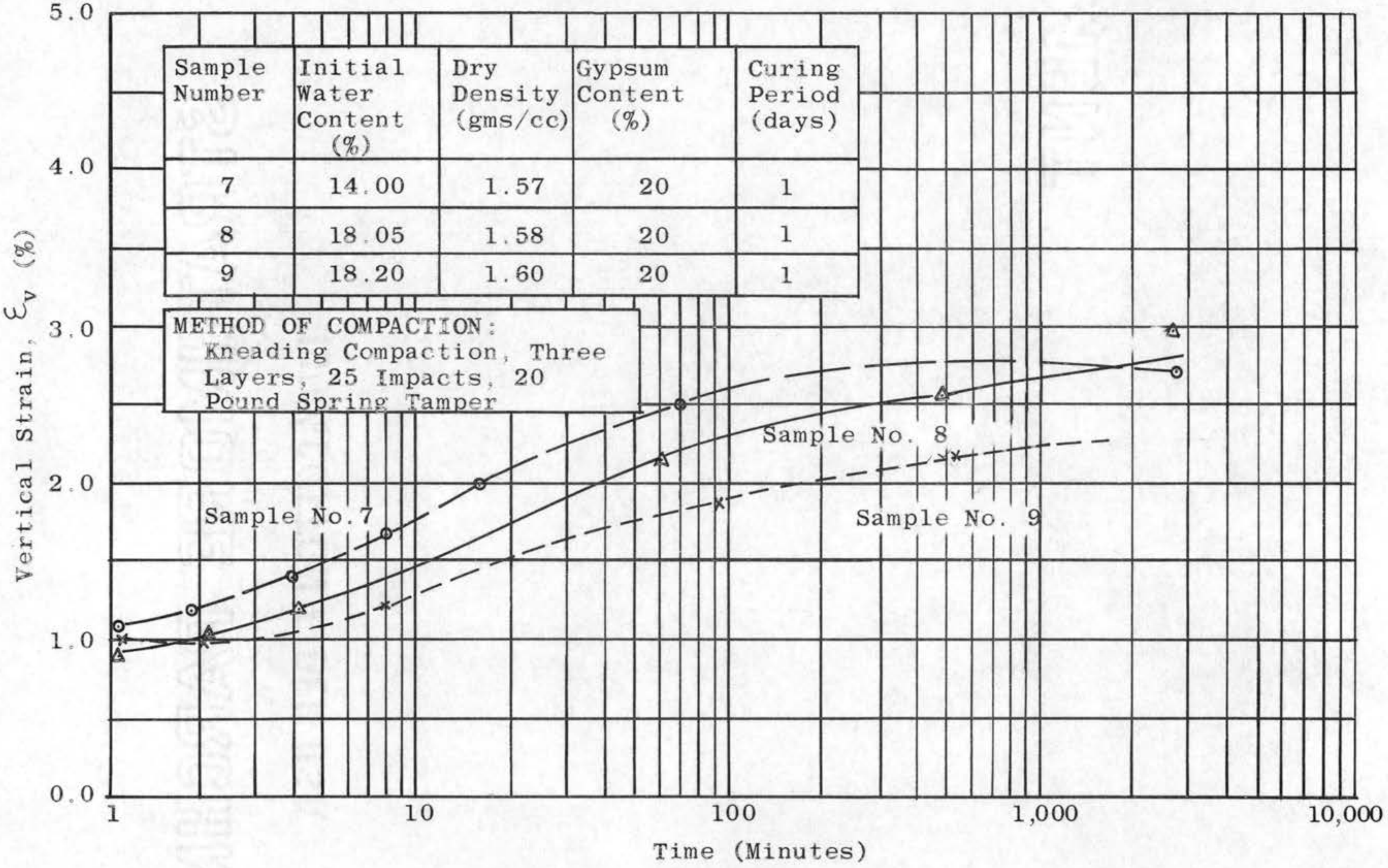
FIGURE 59. SWELLING TIME CURVES



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
7	14.00	1.57	20	1
8	18.05	1.58	20	1
9	18.20	1.60	20	1

METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

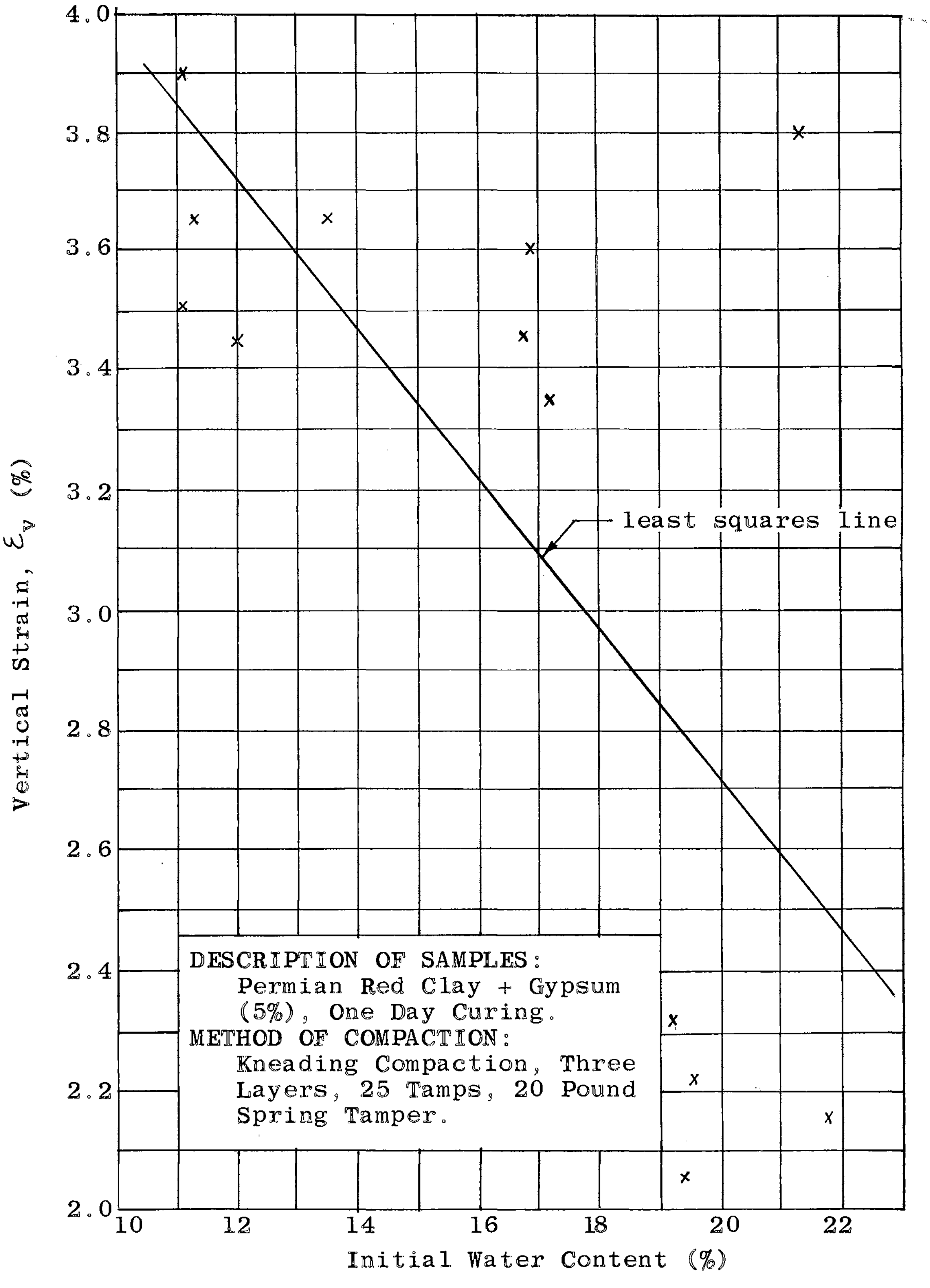
FIGURE 60. SWELLING TIME CURVES



Sample Number	Initial Water Content (%)	Dry Density (gms/cc)	Gypsum Content (%)	Curing Period (days)
7	14.00	1.57	20	1
8	18.05	1.58	20	1
9	18.20	1.60	20	1

METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Impacts, 20 Pound Spring Tamper

FIGURE 61. SWELLING TIME CURVES



DESCRIPTION OF SAMPLES:
Permian Red Clay + Gypsum (5%), One Day Curing.
METHOD OF COMPACTION:
Kneading Compaction, Three Layers, 25 Tamps, 20 Pound Spring Tamper.

FIGURE 62. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$ (%), AND INITIAL WATER CONTENT (%).

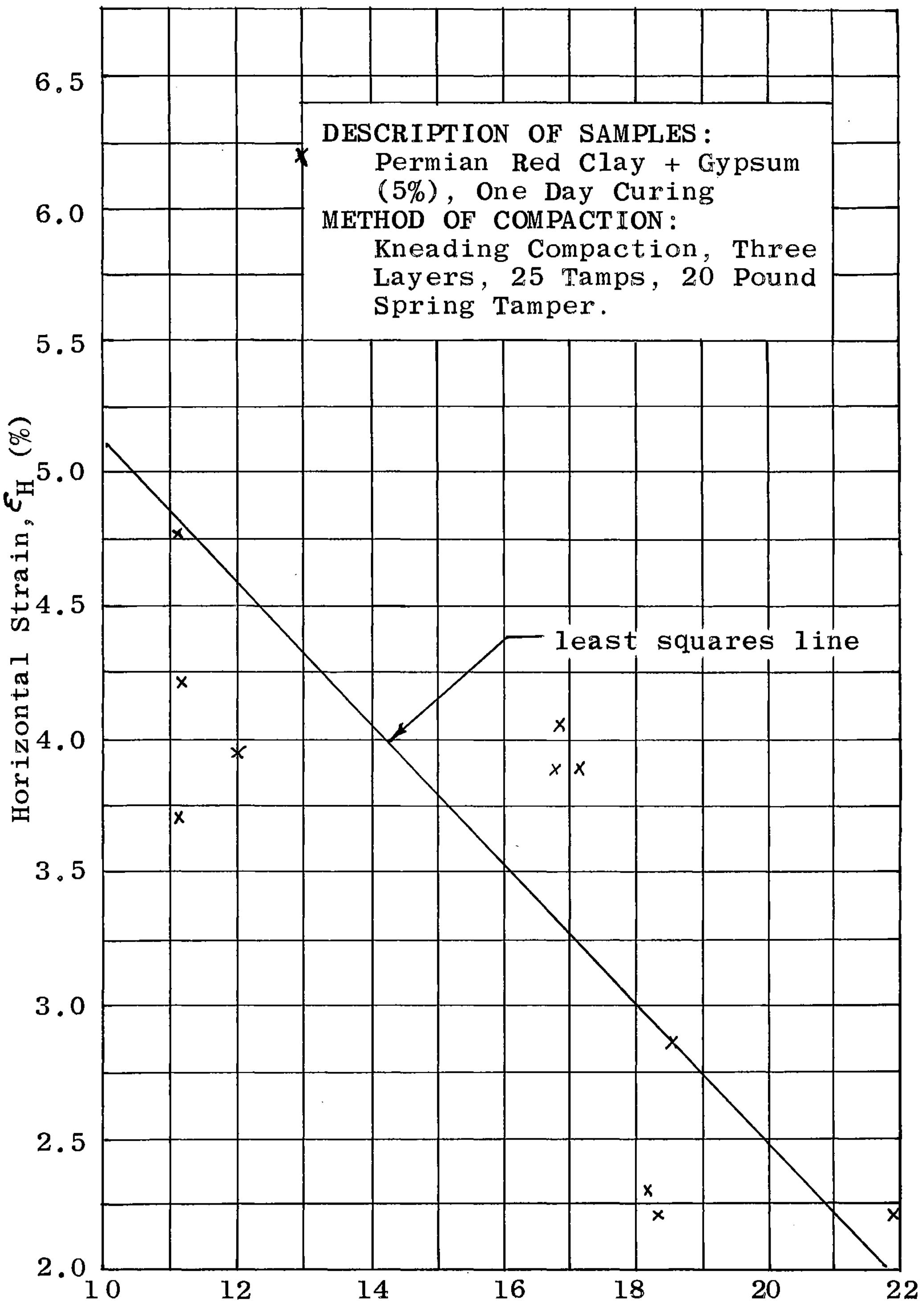


FIGURE 63. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H (%) AND INITIAL WATER CONTENT (%).

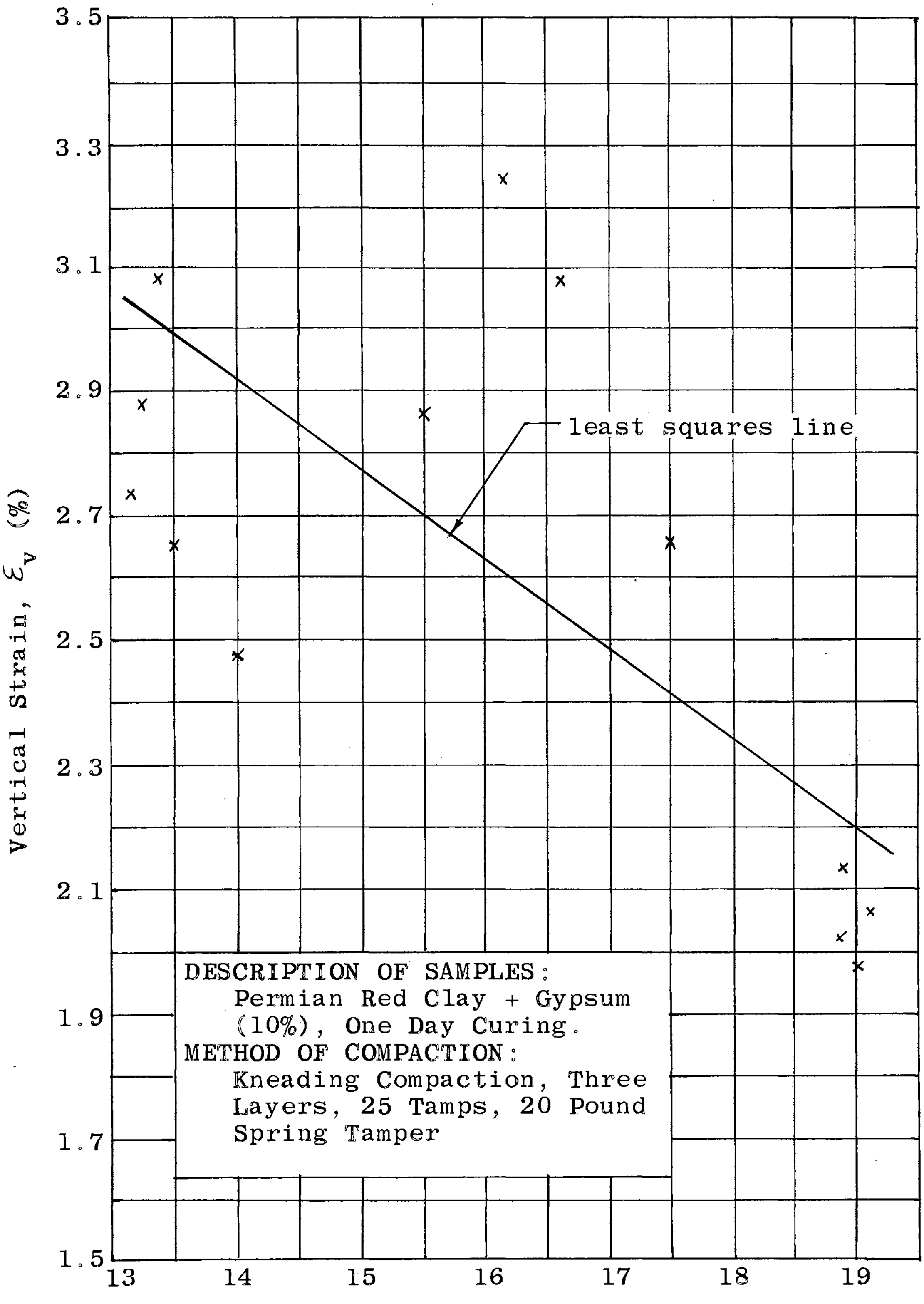


FIGURE 64. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, ε_v(%), AND INITIAL WATER CONTENT (%).

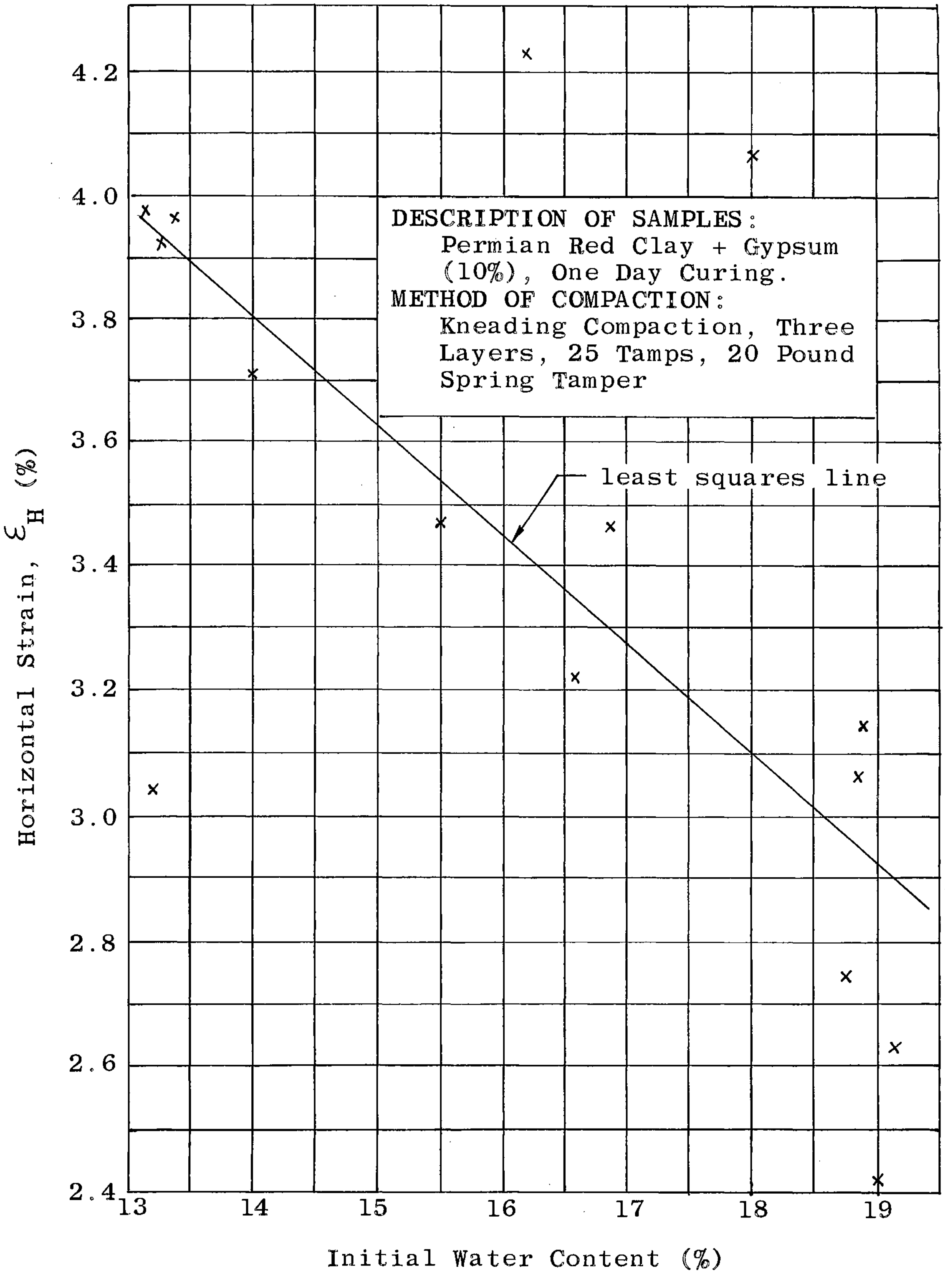


FIGURE 65. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H (%) AND INITIAL WATER CONTENT (%).

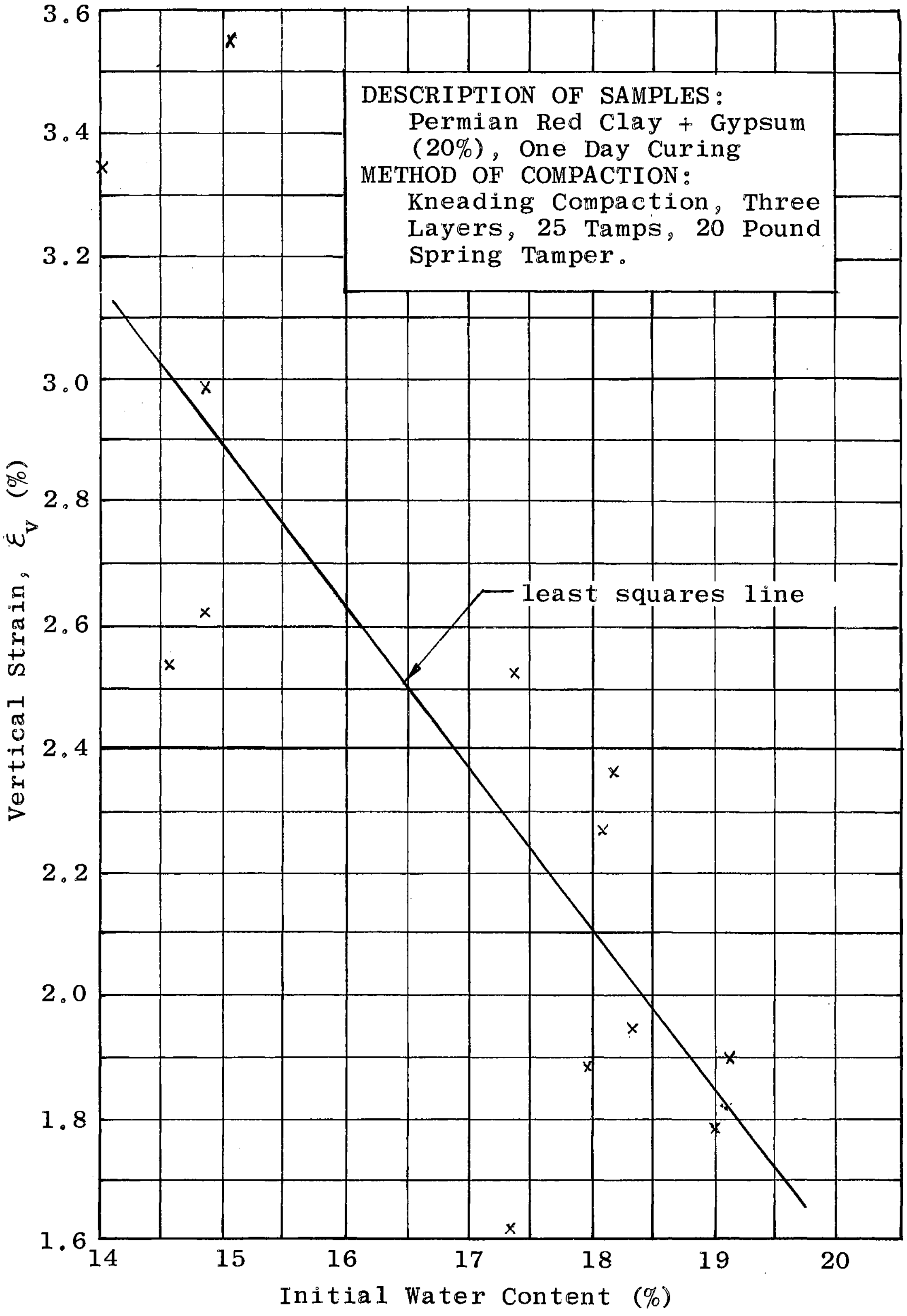


FIGURE 66. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, ε_v(%) AND INITIAL WATER CONTENT (%).

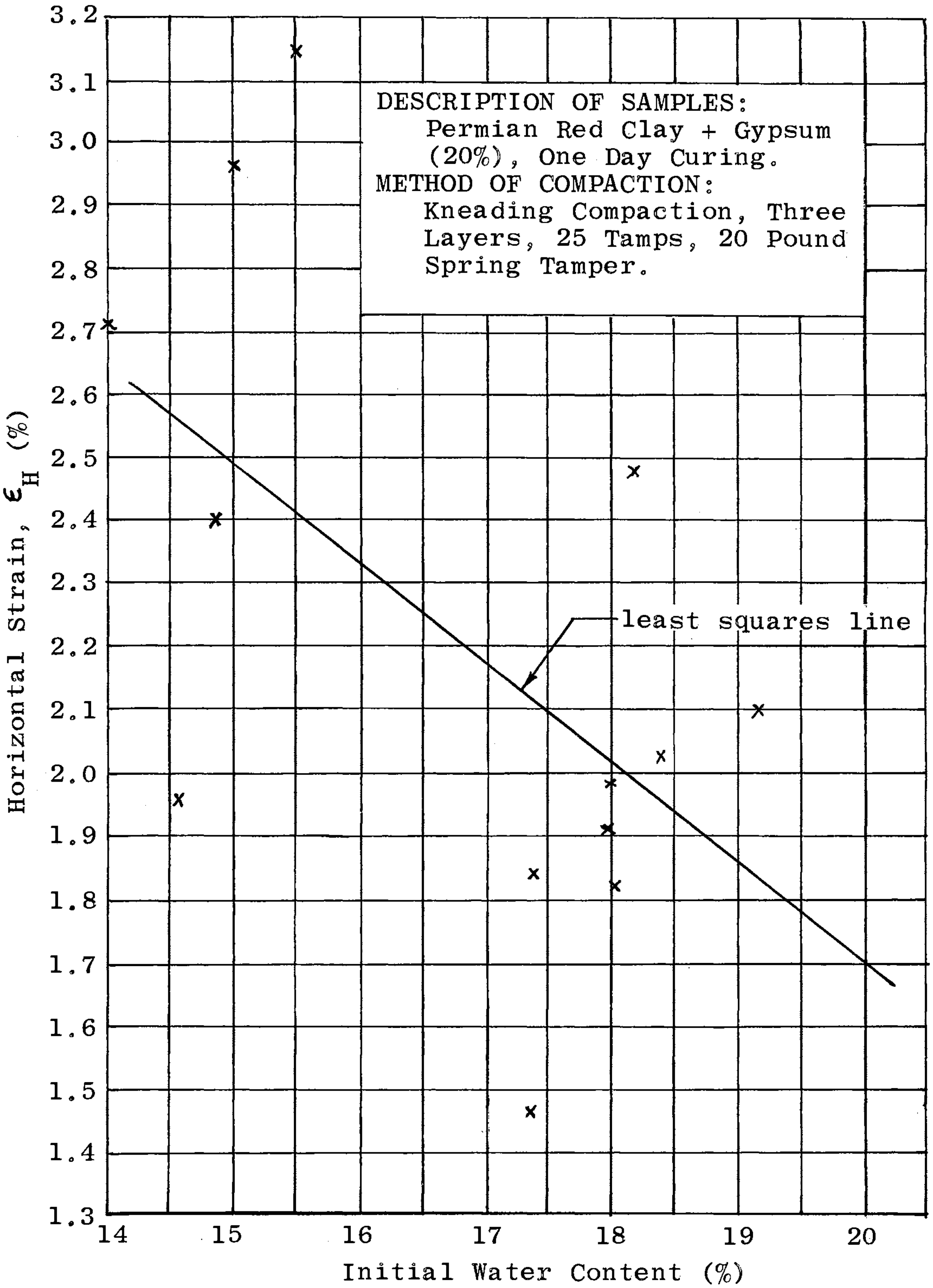


FIGURE 67. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H (%) AND INITIAL WATER CONTENT (%).

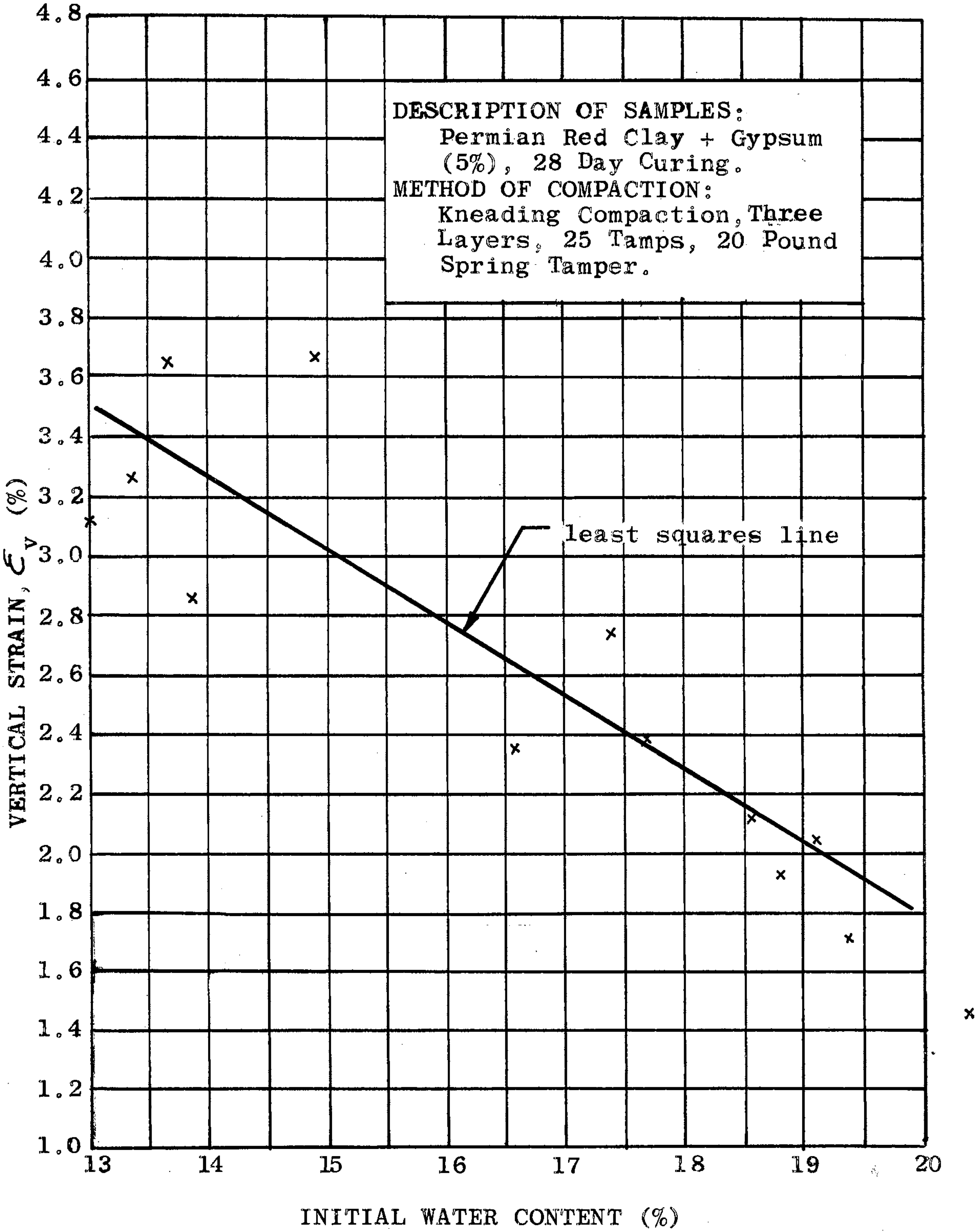


FIGURE 68. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$, (%) AND INITIAL WATER CONTENT (%).

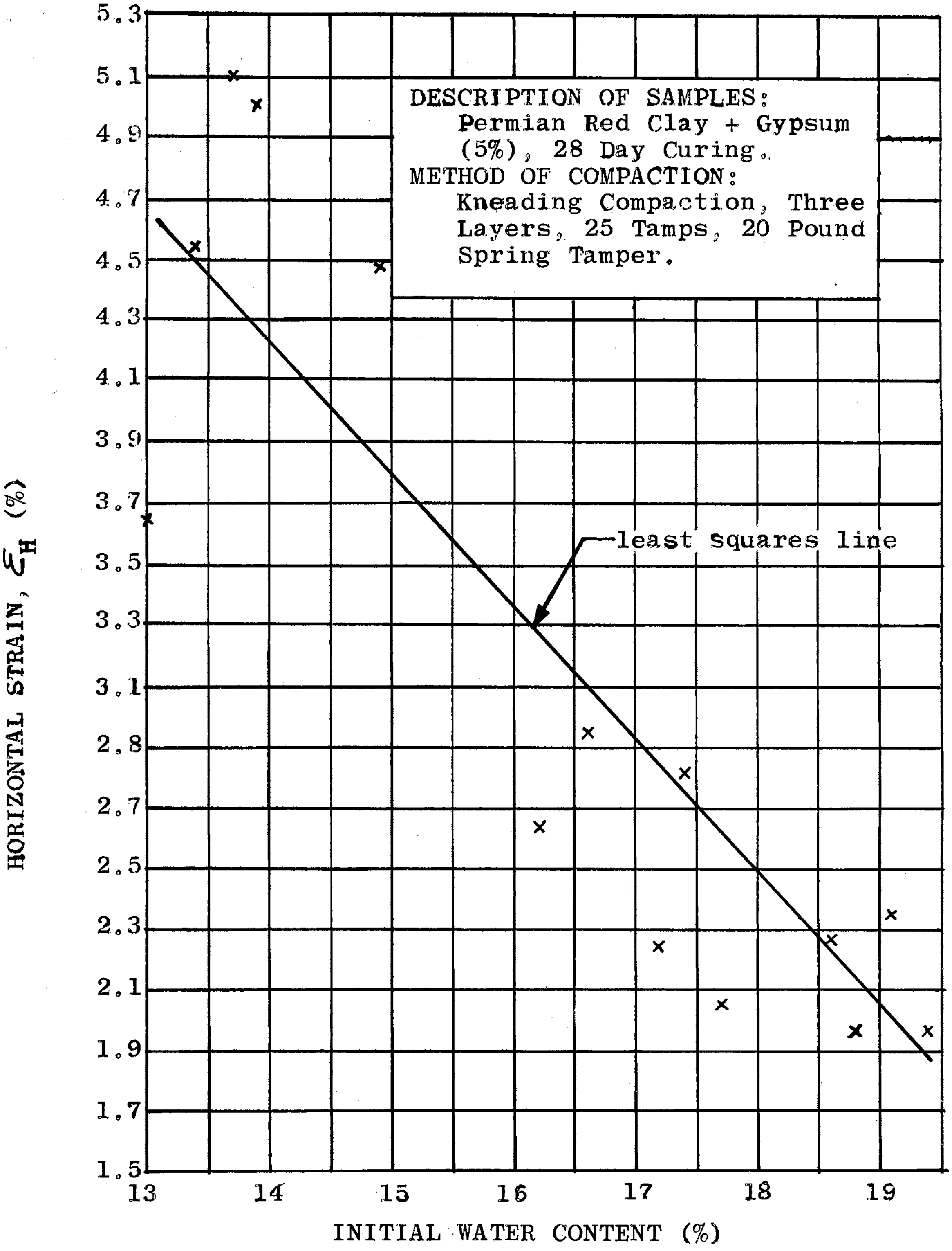


FIGURE 69. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$ (%) AND INITIAL WATER CONTENT (%).

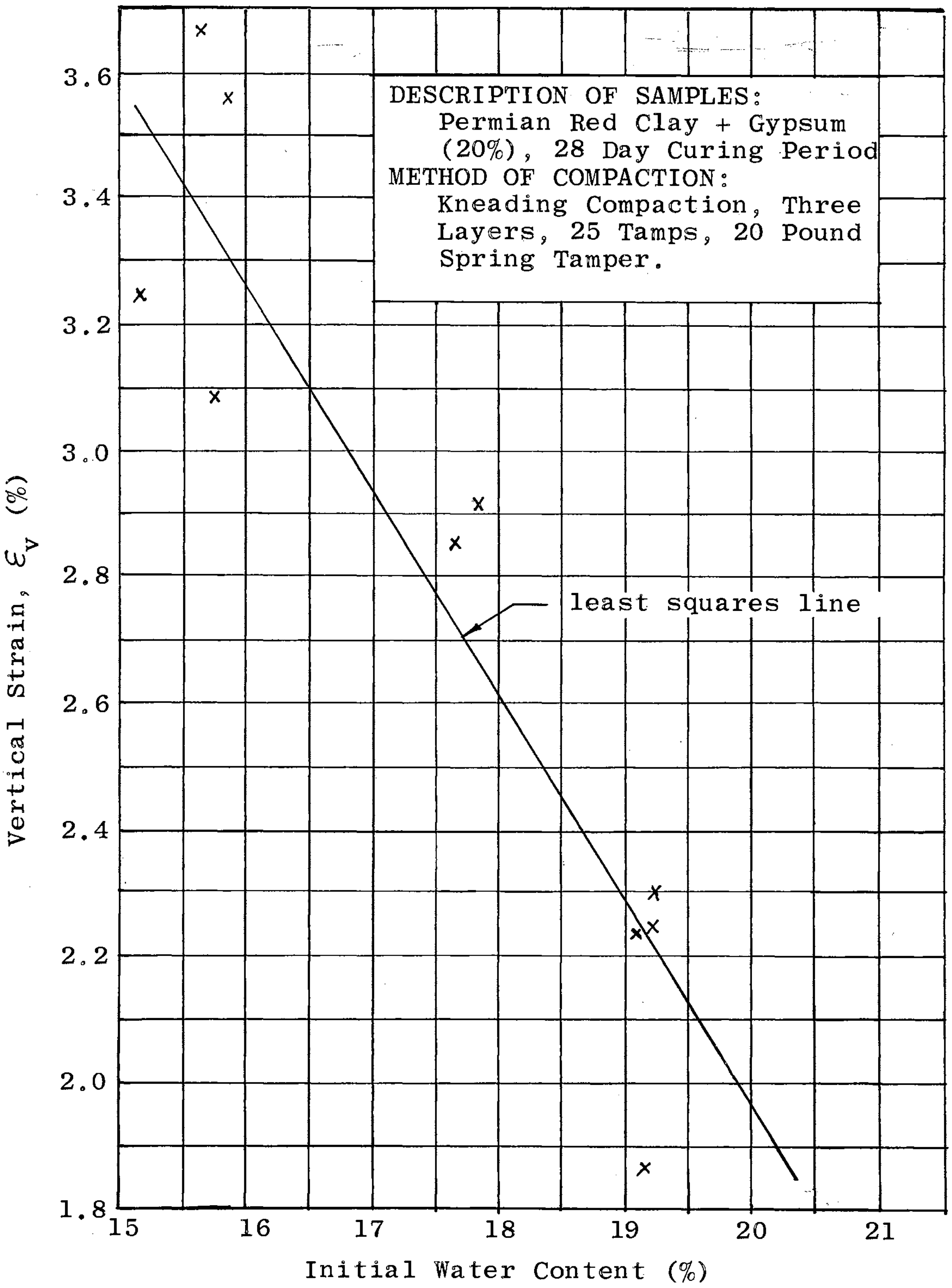


FIGURE 70. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, ε_v (%), AND INITIAL WATER CONTENT (%).

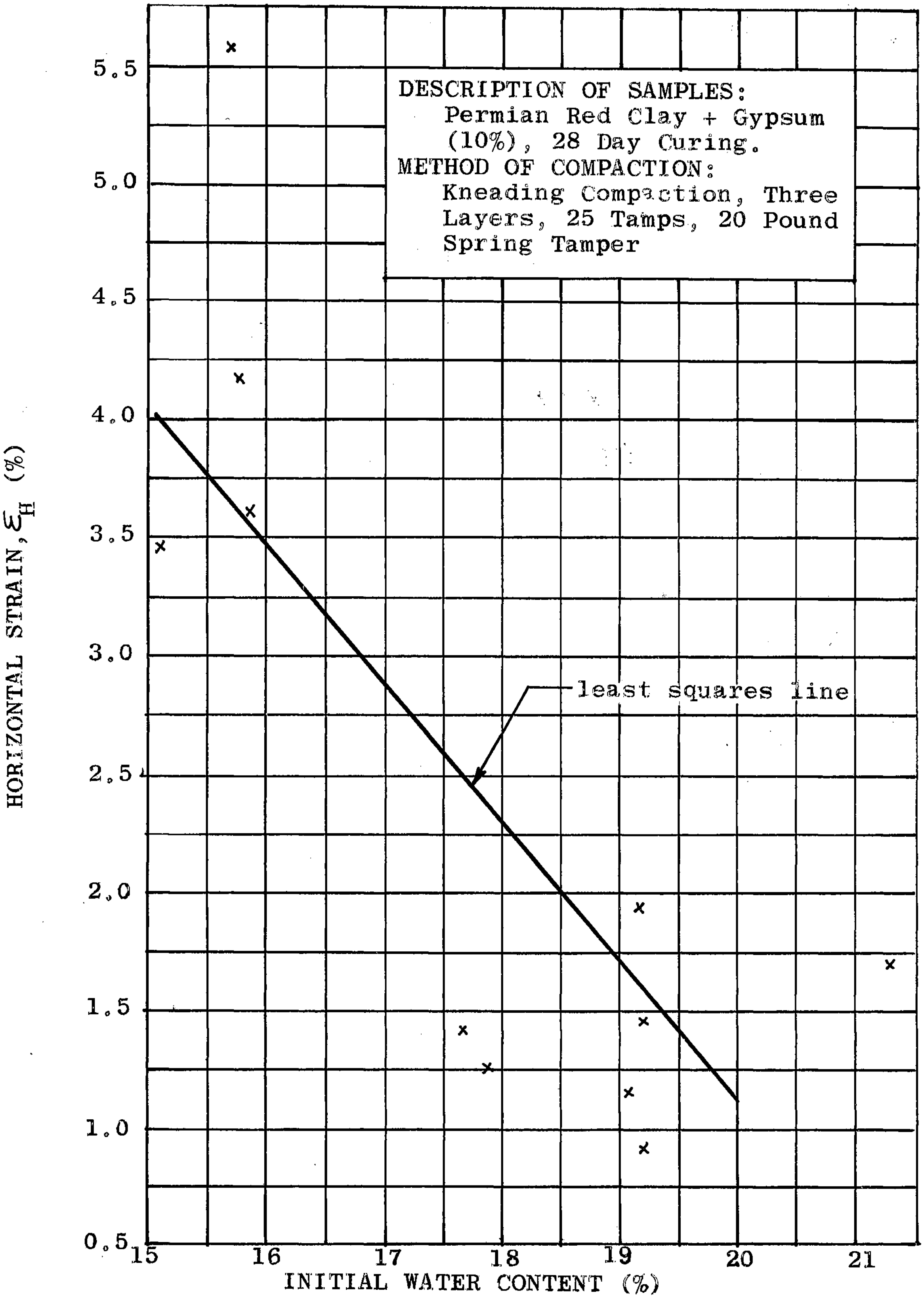


FIGURE 71. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$(%) AND INITIAL WATER CONTENT (%).

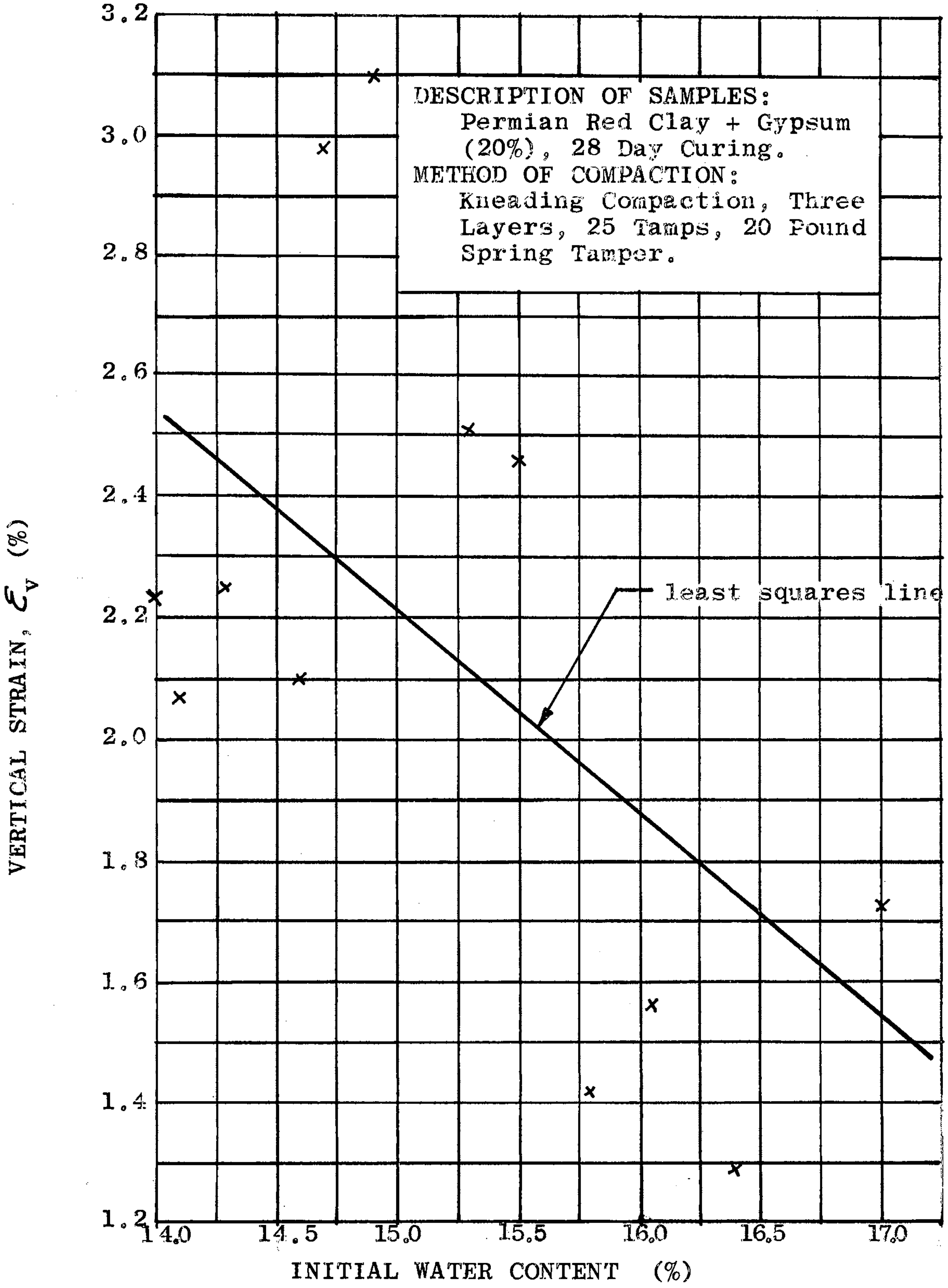


FIGURE 72. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_V$, (%) AND INITIAL WATER CONTENT (%).

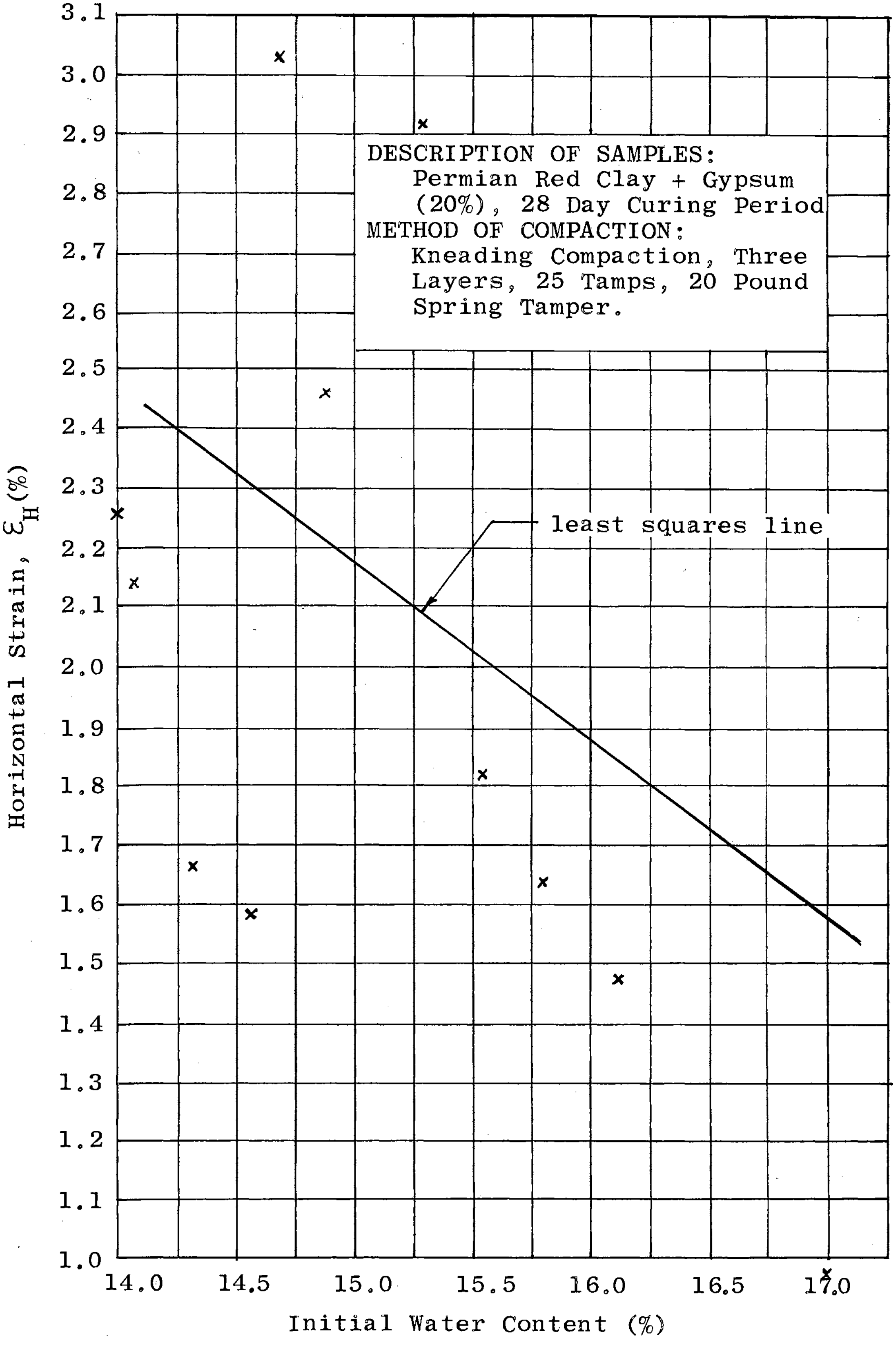


FIGURE 73. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H(%) AND INITIAL WATER CONTENT (%).

least squares lines clearly show that for a given gypsum content the higher the initial water content, the smaller are the magnitudes of horizontal and vertical swellings. The initial water content has the same type of effect here as in the case of samples compacted without gypsum.

3. Effects of Gypsum Content on Swelling: In order to investigate the effects of gypsum content on swelling, samples for a given initial water content were compacted with different gypsum contents (5, 10, 20 and 30 per cent). The results of swelling tests show that horizontal and vertical swellings decrease with increasing amounts of gypsum contents. In other words, it appears that there is a negative correlation between gypsum content and swelling. The correlation factors assuming linear regression were calculated and are given in Table XVI. These values are very close to -1, which indicates that there is a very strong inverse relationship between swelling and gypsum content. Figures 74 to 83 show this relationship in graphical form. Here once again, least square lines were drawn which are valid in the range of the experimental data.

Table XVII gives a direct comparison of the experimental results for different gypsum contents. This table, futhermore, demonstrates that for a given water content and dry density, samples compacted with gypsum generally swell less, both horizontally and vertically than samples compacted without gypsum. The reduction was as high as 62.2 per cent in the horizontal direction and 39.1 per cent in the vertical direction. All these experimental results indicate that

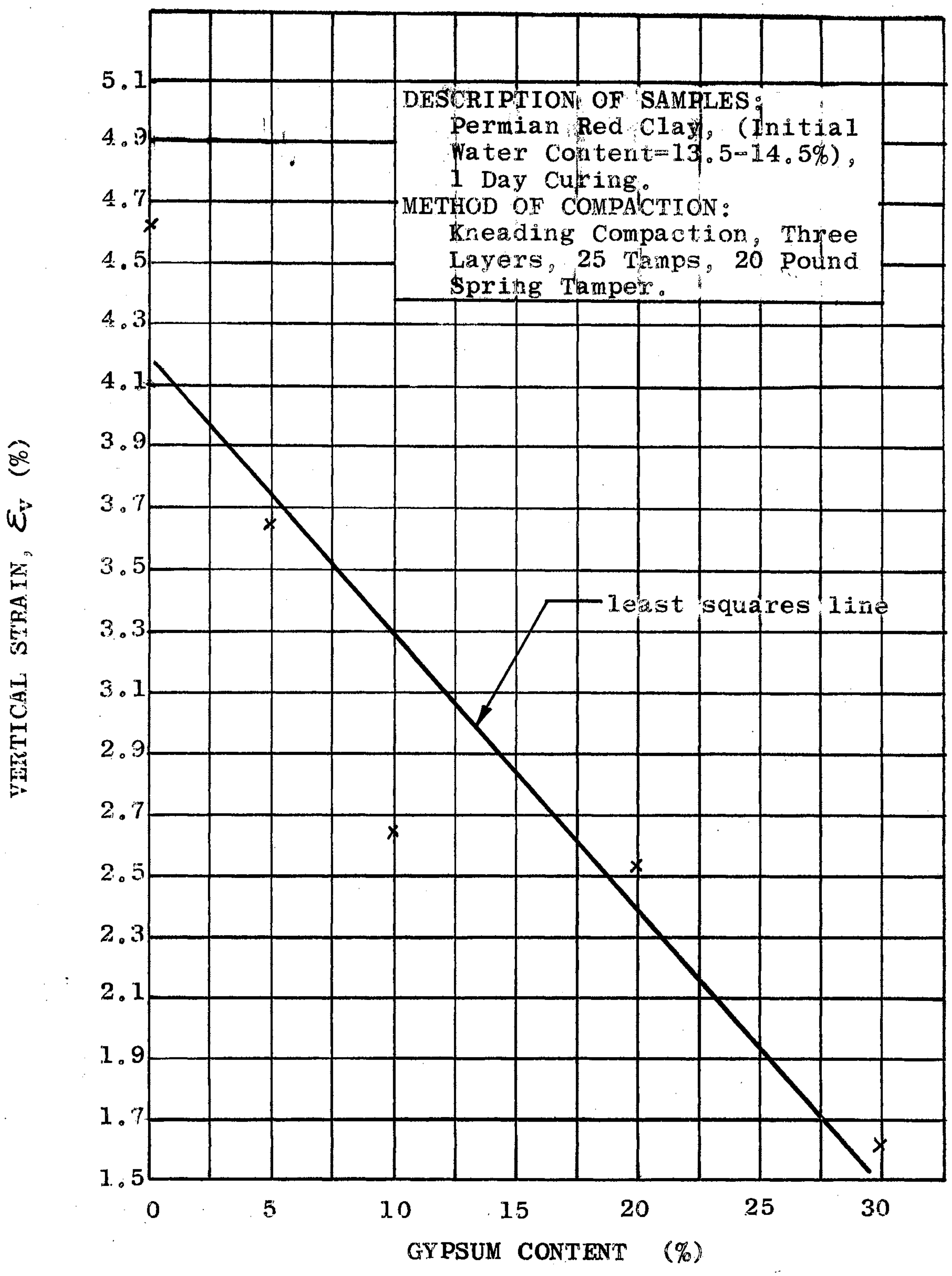


FIGURE 74. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$ (%) AND GYPSUM CONTENT (%).

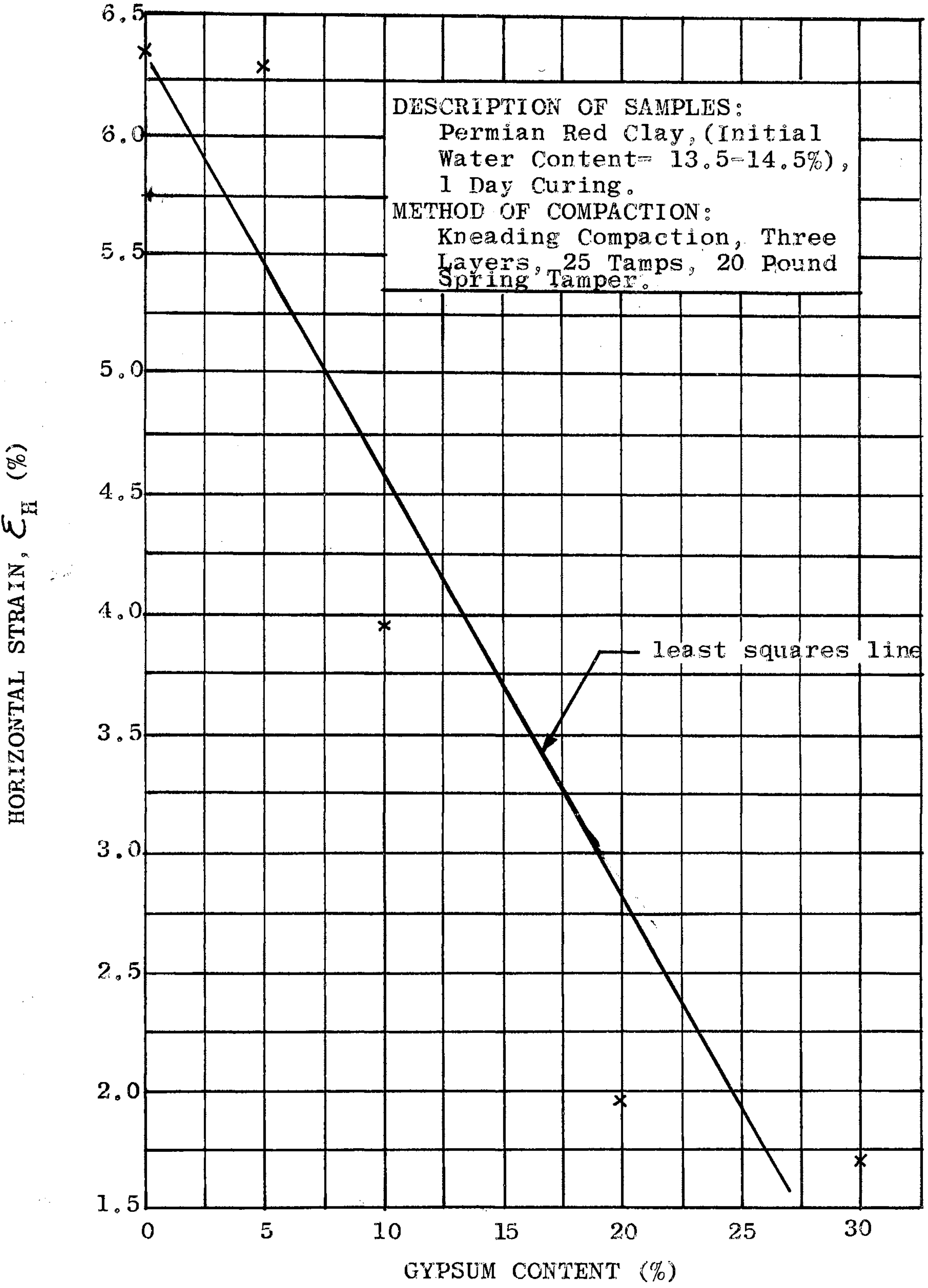


FIGURE 75. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$(%) AND GYPSUM CONTENT (%).

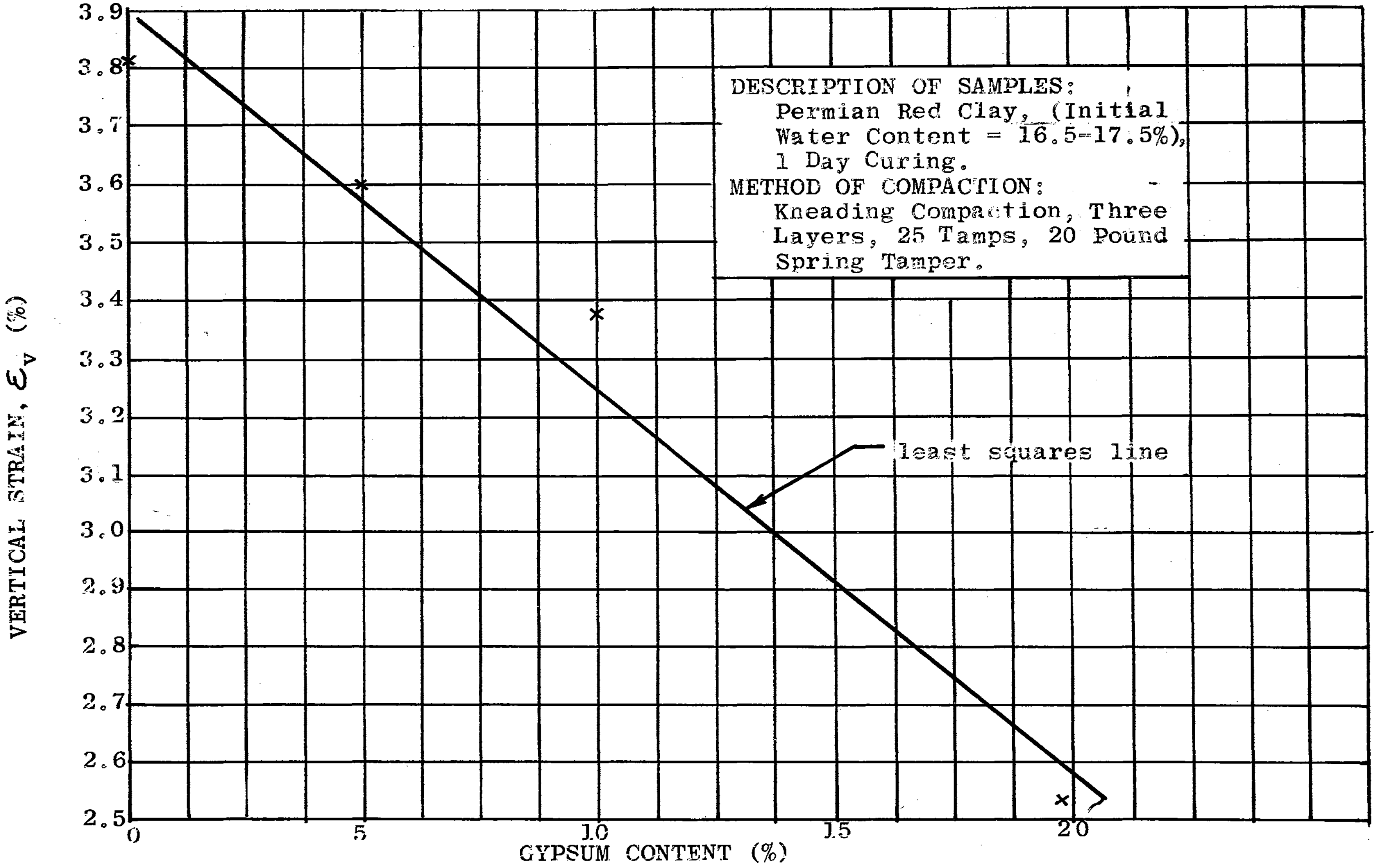


FIGURE 76. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$(%) AND GYPSUM CONTENT(%)

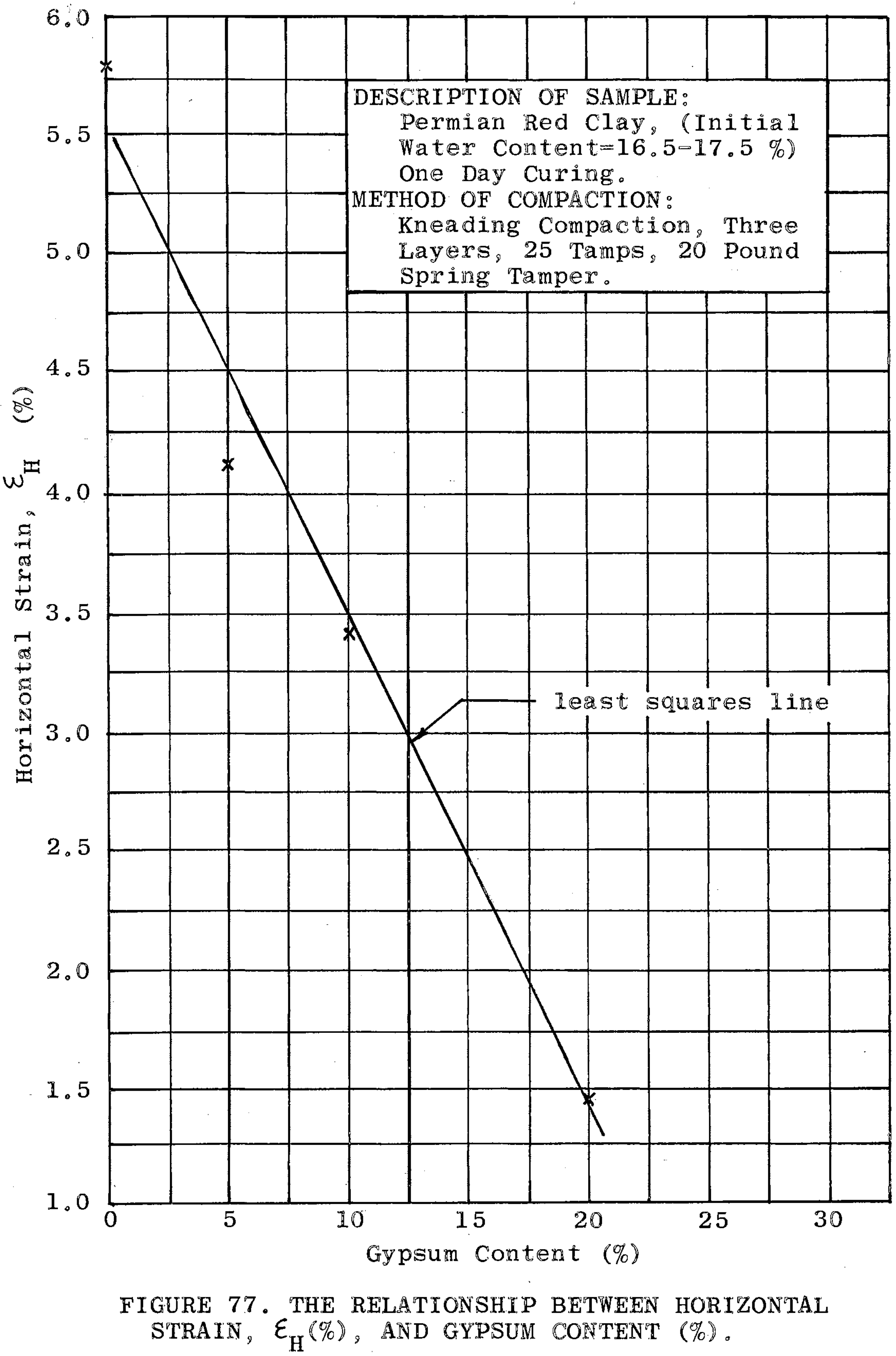


FIGURE 77. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H(%), AND GYPSUM CONTENT (%).

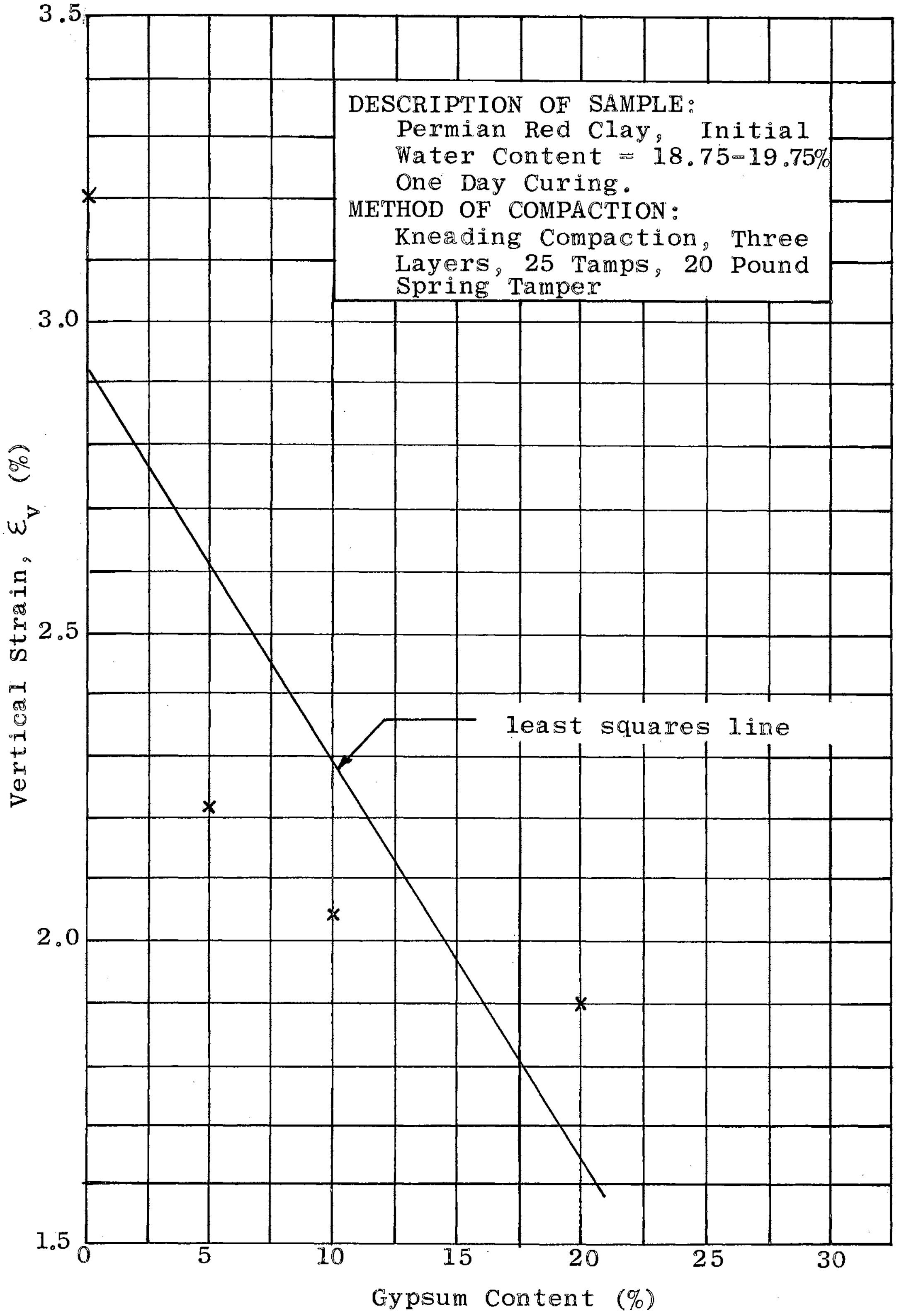


FIGURE 78. THE RELATIONSHIP BETWEEN THE VERTICAL STRAIN, $\mathcal{E}_v$(%) AND GYPSUM CONTENT (%).

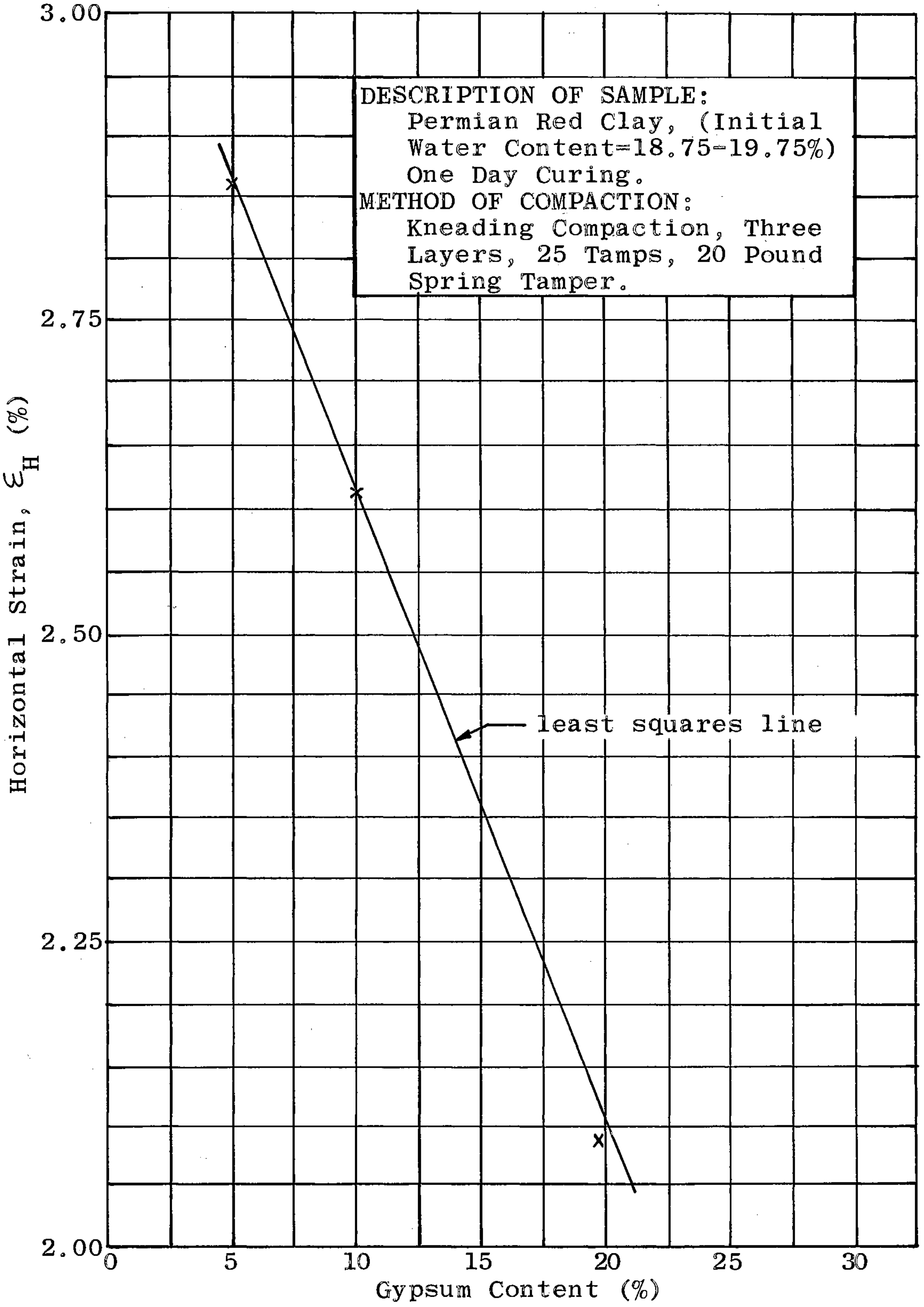


FIGURE 79. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H (%), AND GYPSUM CONTENT (%).

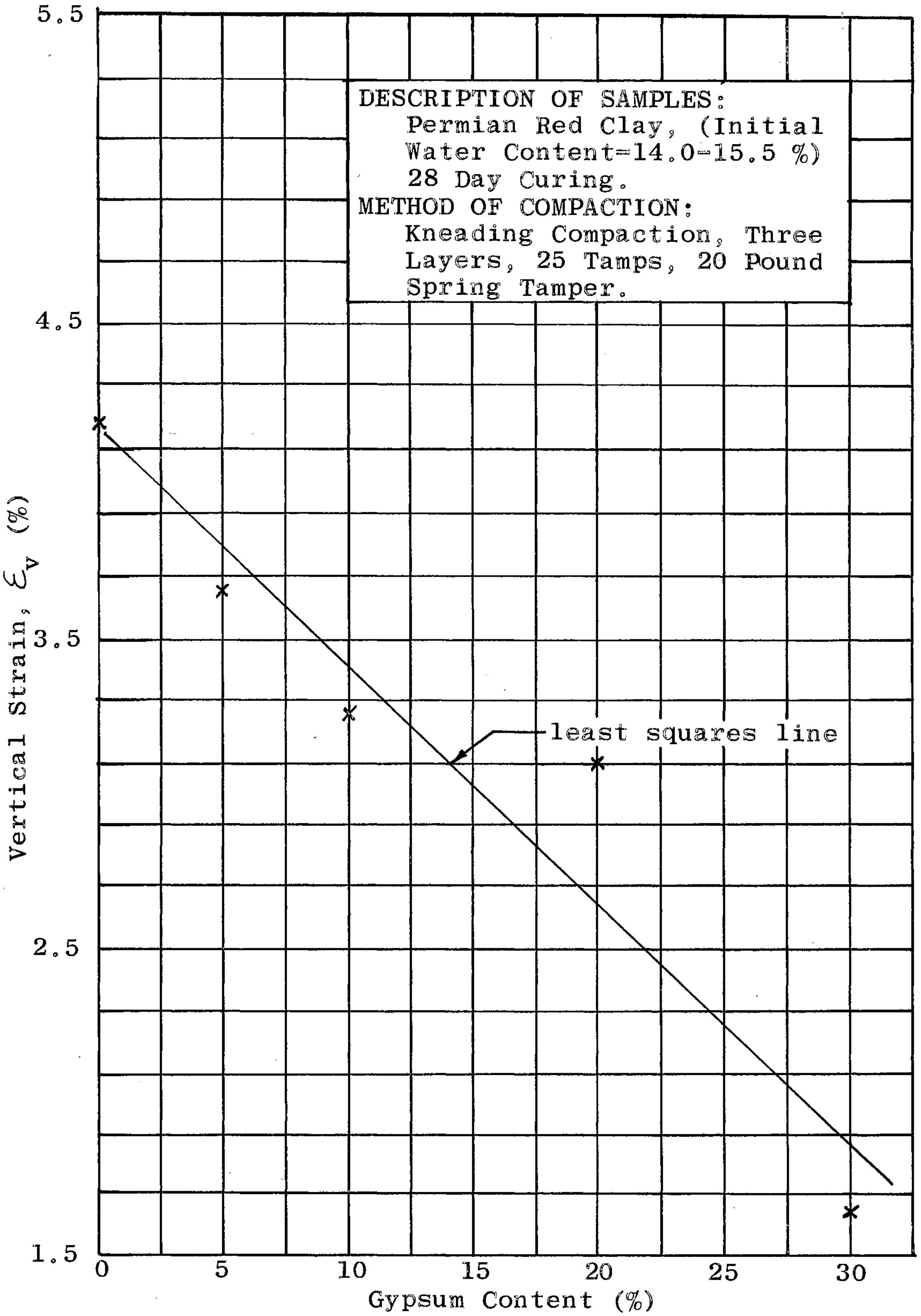


FIGURE 80. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, $\mathcal{E}_v$(%) AND GYPSUM CONTENT (%)

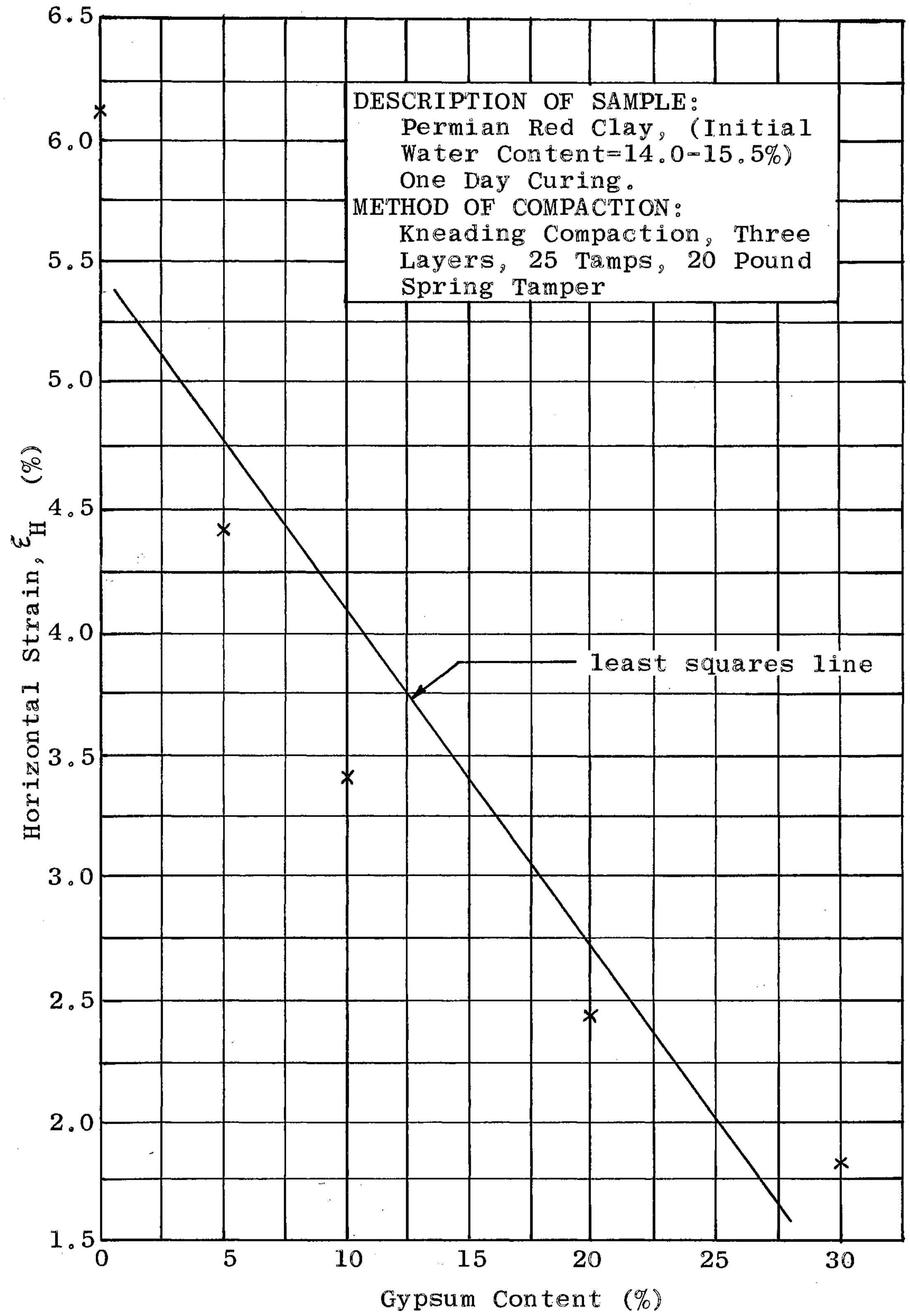


FIGURE 81. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, ε_H (%), AND GYPSUM CONTENT (%).

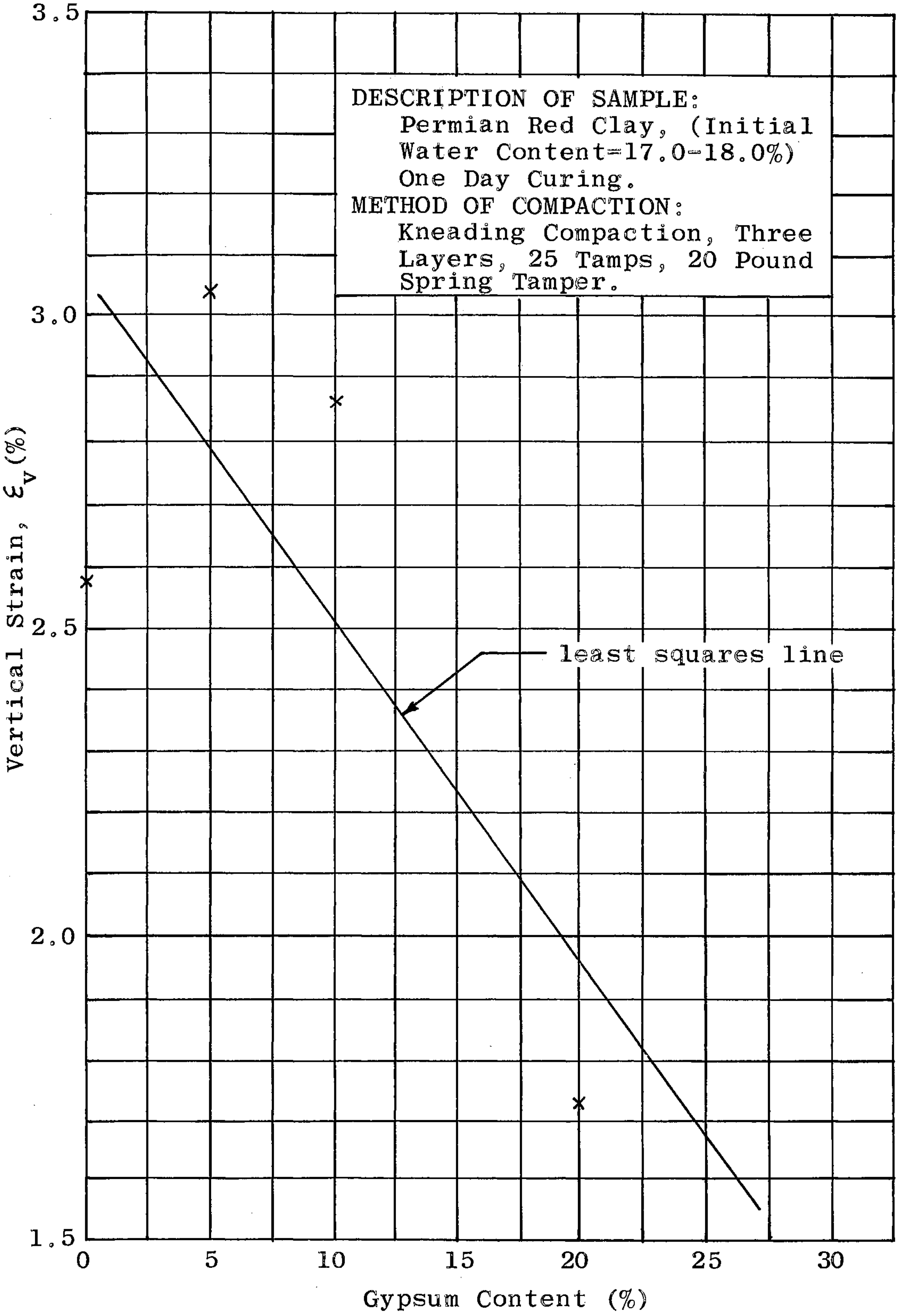


FIGURE 82. THE RELATIONSHIP BETWEEN VERTICAL STRAIN, ε_v(%), AND GYPSUM CONTENT (%).

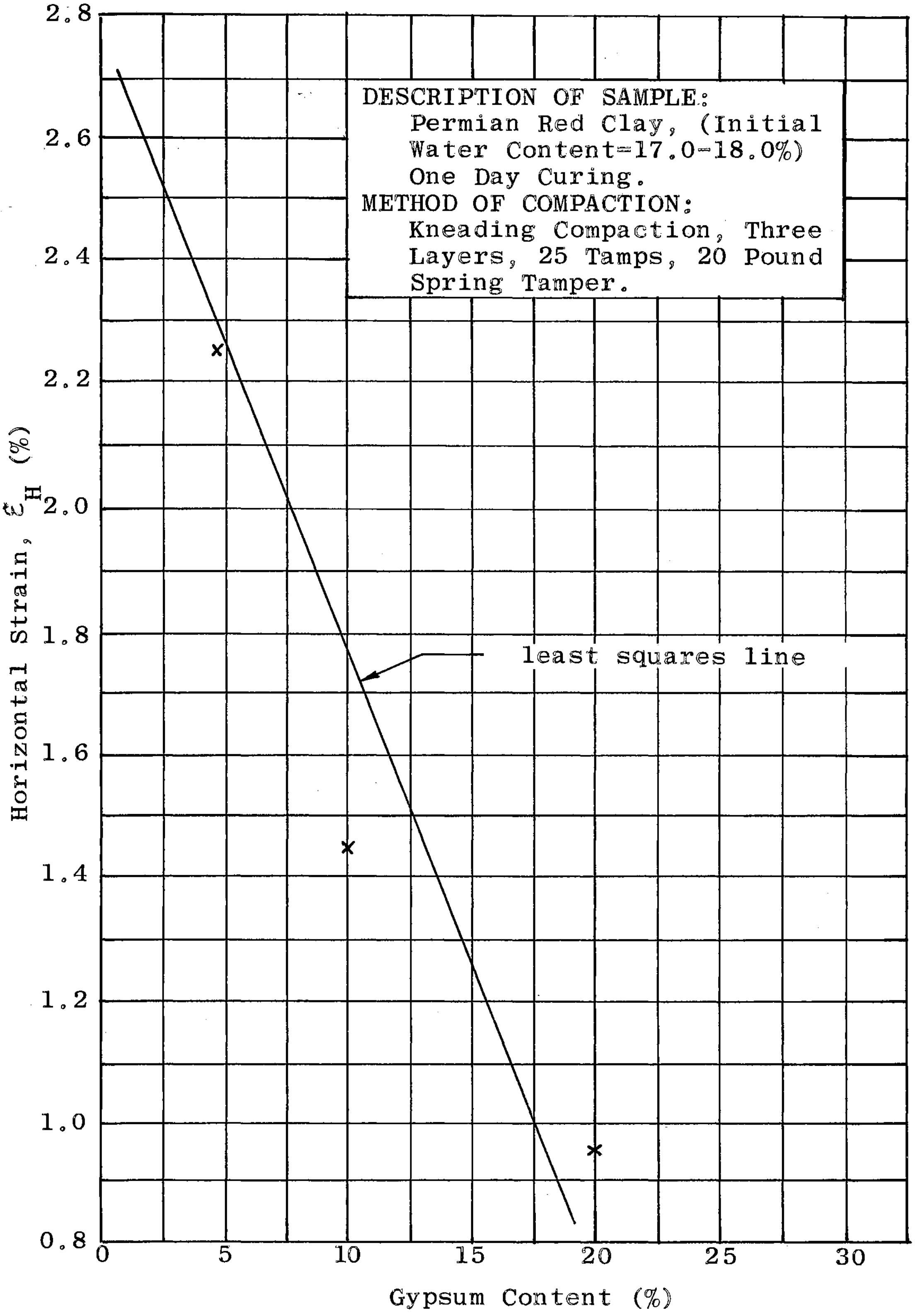


FIGURE 83. THE RELATIONSHIP BETWEEN HORIZONTAL STRAIN, $\mathcal{E}_H$ (%), AND GYPSUM CONTENT (%).

gypsum appears to be an effective additive for reducing the magnitudes of horizontal and vertical swellings.

4. Effects of Curing: In order to investigate the effect of longer curing periods, half of the compacted samples were tested after one day of curing, and the other half after 28 days of curing, as mentioned previously. The results of swelling tests show that samples that have been tested after 28 days of curing period generally swell less both in the horizontal and vertical directions than samples tested after one day of curing period. The direct comparison can be made by referring to the figures given in Table XVII. As gypsum has a very low solubility, a process of ion exchange on a greater scale is not expected with longer curing periods. Therefore, the reduction in swelling can not be explained in terms of cation and anion exchanges that may have satisfied some unbalanced charges on the surface and around the edges of clay particles. However, as Barber's data (40) indicate the swelling pressures and, consequently, the amount of swelling decrease with longer curing periods. When compaction is finished (in a longer curing period) the deformation caused by elastic flexibility of soil particles is recovered as elastic rebound. This may explain why longer curing periods reduce the amount of swelling.

Clay Samples with Inorganic Chemicals (NaCl, $CaCl_2$)

Part I. Inorganic Chemicals in Soil Mix

(A) General Effects of Inorganic Chemicals on Swelling: In order to investigate the effects of inorganic chemicals on swelling, NaCl and $CaCl_2$ were used. The results of swelling tests clearly show that these chemicals when mixed with clay soils, reduce the magnitude of vertical swelling, yet the reduction in the horizontal direction is very slight. Table XVIII gives the experimental results. Direct comparisons between the swelling magnitudes of clay samples with and without NaCl and $CaCl_2$ can be made by referring to the figures in this table. For a given initial water content, clay specimens with these chemicals always swell less in the vertical direction than specimens without the chemicals. The fact that NaCl and $CaCl_2$ reduce the vertical swelling yet have very slight effect on the horizontal swelling is attributed to the differences between the cation and anion exchange processes of clay minerals. It is generally accepted that there are three factors contributing to the cation exchange capacity of the clay minerals. According to Grim (26) they are:

1. Broken Bonds around the edges of the silica-alumina units which would create unbalanced charges that can be satisfied by adsorbed cations. In Kaolinite minerals broken bonds are the major cause of cation exchange capacity. In illites part of the cation exchange capacity is caused by broken bonds and the remaining part by substitutions within the lattice structure. In montmorillonites broken bonds constitute approximately 20 per cent of cation exchange capacity.

2. Substitions within the lattice which generally take place on the basal cleavage surfaces of the layer clay minerals is the second cause. In Montmorillonites substitution within the lattice constitutes approximately 80% of the total cation exchange capacity.

3. The hydrogen replacement of exposed hydroxyls by a cation that is exchangeable is the third cause. Around the broken edges some hydroxyl groups may be exposed and available cations may replace the hydrogens of exposed hydroxyls. In kaolinites this cause of cation exchange capacity can be significant. The cation exchange capacities of clay minerals are given in Table XIX.

TABLE XIX

CATION EXCHANGE CAPACITY OF CLAY MINERALS

(in Milliequivalents per 100 grams)

(After Grim, 26.)

Kaolinite	3 - 15
Halloysite $2H_2O$	5 - 10
Halloysite $4H_2O$	40 - 50
Montmorillonite	80 -150
Illite	10 - 40
Vermiculite	100 -150
Chlorite	10 - 40
Sepiolite-Attapulgite-Palygorskite	20 - 30

Anion Exchange Process

The anion exchange process is very difficult to investigate as there is a possibility that decomposition of the clay minerals may take place during this process. Hendricks (9) has suggested that the geometry of the anion in relation to the geometry of the clay mineral structure units may be a significant factor in the anion exchange process. Anions that have approximately the same size and geometry as the silica tetrahedral sheets will be adsorbed on the edges of the silica tetrahedral sheets and will grow as extensions. Among these types of anions are phosphate, arsenate and borate anions. However, anions such as sulfate, nitrate and chloride cannot be easily adsorbed, as their geometry does not fit that of the silica tetrahedral sheet. This type of anion exchange will take place only around the edges of the clay minerals. Therefore, there will be no anion exchange on the basal planes of clay minerals. In montmorillonites anion exchange capacity is only a small fraction of the cation exchange capacity. In illites anion-exchange capacity is slightly less than cation exchange capacity. The anion exchange capacity of clay minerals is given in Table XX.

The fact that the inorganic chemicals NaCl and $CaCl_2$ reduce the vertical swelling and yet have only slight effect on horizontal swelling can now be explained in terms of aforementioned cation and anion exchange processes. When clay specimens are compacted by kneading compaction, the structure of the compacted clay is not completely flocculent.

TABLE XX

ANION EXCHANGE CAPACITIES

(in Milliequivalents per 100 grams)

(After Grim, 26.)

Montmorillonite, Geisenheim	31.0
Montmorillonite, Wyoming	23.0
Beidellite, Unterrupsroth	21.0
Notronite, Untergriesbach	20.0
Notronite, Pfreimdtal	12.0
Saponite, Groschlattengrun	21.0
Vermiculite, South Africa	4.0
Kaolinite (Collodial)	20.2
Kaolinite, Melos	13.3
Kaolinite, Schnaittenbach	6.6

In other words, some degree of dispersity is created by this compactive effort. Due to the structural characteristics of clay minerals there will exist unbalanced negative charges on the basal cleavage surfaces of the clay minerals. When inorganic chemicals NaCl or $CaCl_2$ are mixed with clay soils Na or Ca (depending on which inorganic chemical is used) cations are attracted to these surfaces and consequently some of the unbalanced negative charges are satisfied. Swelling, however, is explained in terms of attraction of water molecules to basal cleavage surfaces due to the unbalanced negative charges. As most of these unbalanced negative charges are satisfied by the cation exchange process, the clay particles will not be able to attract the same quantity of water molecules. Consequently, the vertical swelling will be reduced.

However, the anion exchange capacity is always less than the cation exchange capacity of clay minerals and, furthermore, chloride anions are not geometrically suited for adsorption to the silica tetrahedral sheet. Even though broken bonds result in unbalanced positive charges on the edges of clay particles, these charges remain relatively unaffected when inorganic chemicals are added to clay soils, as the anion exchange is extremely difficult. As almost no anion exchange takes place which could satisfy some of the unbalanced positive charges on the edges of clay particles, the capacity of attracting water molecules to the edges of the clay particles remains relatively unaffected. Consequently, the effect of the inorganic chemicals NaCl and $CaCl_2$ on horizontal swelling is very slight.

(B) <u>Effects of the Amount of Inorganic Chemicals on Swelling</u>: As mentioned previously, 1 per cent and 2 per cent of NaCl and $CaCl_2$ by dry weight of clay soil were used to investigate the effects (on swelling) of increasing the amount of inorganic chemicals. The experimental results in Table XVII show that increasing the amount of inorganic chemicals from one to two per cent decreases the magnitudes of vertical and horizontal swelling only slightly. It appears that most of the cation and anion exchange take place when one per cent NaCl or $CaCl_2$ is utilized, and additional amounts introduce only small additional cation and anion exchange. Consequently, the reduction in both vertical and horizontal swelling is slight.

(C) Effect of Curing Period on Swelling: Table XVII gives the magnitudes of vertical and horizontal swelling for approximately identical samples that were tested after one and seven day curing periods. The results show that samples tested after a seven day curing period swell slightly less than samples tested after a one day curing period, both in the vertical and the horizontal directions. However, it appears that most of the cation and anion exchange take place in the first 24 hours and that only small additional cation and anion exchange occur thereafter. Consequently, increasing the curing period beyond 24 hours produces only a slight additional effect.

(D) Effects of the Type of Inorganic Chemical on Swelling: Table XVIII shows that in samples that have approximately the same initial water content, dry density, curing period and inorganic chemical, $CaCl_2$ appears to be slightly more effective than NaCl in reducing the magnitudes of vertical and horizontal swellings of the Permian clay.

It is known that the Ca cation will more easily replace the Na cation than that the Na cation will replace the Ca cation. Therefore, it may be concluded that the exchange process takes place on a more extensive scale when $CaCl_2$ is used as an inorganic chemical additive.

Part II. Inorganic Chemicals in Imbibed Water

(A) General Effects of Inorganic Chemicals on Swelling: The effects of inorganic chemicals on swelling were also investigated by adding three per cent NaCl or $CaCl_2$ by weight to the reservoir water. The results of swelling tests clearly show that this process reduces the vertical swelling considerably; however, the horizontal swelling remains relatively unaffected. Suggested reasons for this phenomenon are given in Part I, (A). A direct comparison between vertical and horizontal swelling of samples with and without inorganic chemicals can be made by referring to Table XXI.

(B) Effects of Type of Inorganic Chemical on Swelling: Table XXI shows that in samples that have approximately the same initial water content and dry density, $CaCl_2$ appears to be slightly more effective than NaCl in reducing the magnitudes of vertical and horizontal swellings. The reasons for this type of swelling behavior are given in Part I, (D).

TABLE V

SWELLING RATIO

Description of Samples: Permian Red Clay from Life Science Building

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

Initial Water Content %	Final Water Content %	Dry Density (gms./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
10.31	25.50	1.680	1.337	4.490	0.298
10.59	27.20	1.681	2.980	4.700	0.634

TABLE V (Continued)

Initial Water Content %	Final Water Content %	Dry Density (gms./c.c.)	ε_V %	ε_H %	$\varepsilon_V/\varepsilon_H$
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 VI

SWELLING RATIO

Description of Samples: Permian Red Clay from Life Science Building

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

Initial Water Content %	Final Water Content %	Dry Density (gms./c.c.)	ε_v %	ε_H %	$\varepsilon_v/\varepsilon_H$
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 VII

SWELLING RATIO

Description of Samples: Permian Red Clay from Life Science Building

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

Initial Water Content %	Final Water Content %	Dry Density (gms./c.c.)	ε_V %	ε_H %	$\varepsilon_V/\varepsilon_H$
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 VIII

SWELLING RATIO

Description of Samples: Permian Red Clay from Life Science Building (second time sampling)

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

Initial Water Content %	Final Water Content %	Dry Density (gms./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	3.10	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 IX

SWELLING RATIO

Description of Samples: Permian Red Clay from depth of 9 ft, at New Engineering Building

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

Initial Water Content %	Final Water Content %	Dry Density (gms./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 X

SWELLING RATIO

Description of Samples: Permian Red Clay from depth of 18 ft. at New Engineering Building

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

Initial Water Content %	Final Water Content %	Dry Density (gms./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 X (Continued)

Initial Water Content %	Final Water Content %	Dry Density (gms./c.c.)	ε_V %	ε_H %	$\varepsilon_V/\varepsilon_H$
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 XI

CORRELATION ANALYSIS

Swelling versus Initial Water Content

Compaction Method	Correlation Factor
Kneading Compaction, 5 Layers, 25 Tamps, 20 Pound Spring Tamper Life Science Building	$r(\varepsilon_V, I.W.C.) = -0.805$ $r(\varepsilon_H, I.W.C.) = -0.911$
Kneading Compaction, 3 Layers, 25 Tamps, 40 Pound Spring Tamper	$r(\varepsilon_V, I.W.C.) = -0.903$ $r(\varepsilon_H, I.W.C.) = -0.538$
Kneading Compaction, 3 Layers, 25 Tamps, 60 Pound Spring Tamper	$r(\varepsilon_V, I.W.C.) = -0.859$ $r(\varepsilon_H, I.W.C.) = -0.610$
Second Time Sampling, Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper, Life Science Building	$r(\varepsilon_V, I.W.C.) = -0.844$ $r(\varepsilon_H, I.W.C.) = -0.747$
Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper, New Engineering Building, 9 ft.	$r(\varepsilon_V, I.W.C.) = -0.741$ $r(\varepsilon_H, I.W.C.) = -0.895$
Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper, New Engineering Building, 18 ft.	$r(\varepsilon_V, I.W.C.) = -0.970$ $r(\varepsilon_H, I.W.C.) = -0.976$

ε_V = Vertical Strain (%)
ε_H = Horizontal Strain (%)
$r(\varepsilon_V, I.W.C.)$ = Correlation factor between Vertical Strain, ε_V and Initial Water Content.
$r(\varepsilon_H, I.W.C.)$ = Correlation factor between Horizontal Strain, ε_H and Initial Water Content.

TABLE XII

CORRELATION ANALYSIS BETWEEN LOGARITHM OF THE APPLIED FORCE AND LOGARITHM OF THE MAGNITUDE OF SWELLING

F = Applied Force (20, 40 and 60 lbs.)
$\log F$ = Logarithm of the Applied Force
ε_V = Vertical Strain (%)
$\log\varepsilon_V$ = Logarithm of the Vertical Strain
ε_H = Horizontal Strain (%)
$\log\varepsilon_H$ = Logarithm of the Horizontal Strain

Dry Density (gms./cc.)	Correlation Factor
1.71 - 1.73	$r_{(\log\varepsilon_V, \log F)} = 0.940$
1.71 - 1.73	$r_{(\log\varepsilon_H, \log F)} = 0.996$
1.73 - 1.76	$r_{(\log\varepsilon_V, \log F)} = 0.987$
1.73 - 1.76	$r_{(\log\varepsilon_H, \log F)} = 0.990$
1.76 - 1.79	$r_{(\log\varepsilon_V, \log F)} = 0.986$
1.76 - 1.79	$r_{(\log\varepsilon_H, \log F)} = 0.980$

$r_{(\log\varepsilon_V, \log F)}$ = Correlation factor between logarithm of the vertical strain, ε_V and the logarithm of the applied force.

$r_{(\log\varepsilon_H, \log F)}$ = Correlation factor between logarithm of the Horizontal strain, ε_H and the logarithm of the applied force.

TABLE XIII

SWELLING RATIO

Description of Samples: Undisturbed samples from New Engineering Building

Initial Water Content %	Final Water Content %	Dry Density (gms./c.c.)	ε_V %	ε_H %	$\varepsilon_V/\varepsilon_H$
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	0.435	1.110	0.391*
14.24	16.25	1.982	0.730	1.097	0.666*

TABLE XIV

EFFECT OF GYPSUM ON VERTICAL AND HORIZONTAL SWELLING

Description of Samples: Permian Red Clay from New Engineering Building

Method of Compaction: Kneading Compaction, 3 layers, 25 tamps using 20 pound spring tamper.

Gypsum Content (%)	Curing Period (days)	Initial Water Content (%)	Final Water Content (%)	Wet Density (gm/cc)	Dry Density (gm/cc)	Vertical Strain ε_v (%)	Horizontal Strain ε_H (%)	$\varepsilon_v/\varepsilon_H$
5	1	13.50	35.00	1.82	1.61	3.65	6.32	0.578
"	"	11.05	28.80	1.82	1.62	3.51	4.76	0.722
"	"	11.05	29.40	1.81	1.60	3.90	3.70	1.054
"	"	11.25	30.20	1.82	1.62	3.65	4.20	0.869
"	"	12.00	31.00	1.81	1.02	3.45	3.95	0.873
5	1	21.30	35.20	1.94	1.59	3.80	7.94	0.479
"	"	16.90	29.10	1.95	1.67	3.60	4.10	0.878
"	"	16.90	27.50	1.98	1.69	3.58	4.05	0.884
"	"	16.70	26.50	1.99	1.71	3.45	3.87	0.891
"	"	17.10	30.20	1.97	1.68	3.35	3.90	0.859
5	1	19.60	26.70	1.99	1.67	2.22	2.86	0.776
"	"	19.10	25.60	2.00	1.68	2.32	2.26	1.027
"	"	21.90	27.30	2.01	1.65	2.16	2.16	1.000
"	"	19.40	26.45	2.00	1.66	2.04	2.22	0.919
10	1	13.40	30.60	1.85	1.63	3.08	3.92	0.786
"	"	13.30	27.20	1.88	1.65	2.88	3.04	0.947
"	"	13.20	27.90	1.88	1.66	2.74	3.97	0.690
"	"	13.50	30.70	1.85	1.63	2.65	3.96	0.669
"	"	14.00	31.20	1.87	1.66	2.47	3.71	0.666

TABLE XIV (continued)

Gypsum Content (%)	Curing Period (days)	Initial Water Content	Final Water Content (%)	Wet Density (gm/cc)	Dry Density (gm/cc)	Vertical Strain $\mathcal{E}_v$ (%)	Horizontal Strain $\mathcal{E}_H$(%)	$\mathcal{E}_v/\mathcal{E}_H$
10	1	16.60	27.50	1.96	1.68	3.08	3.22	0.957
"	"	16.20	25.90	2.00	1.72	3.24	4.24	0.764
"	"	15.50	28.30	1.91	1.66	2.86	3.46	0.827
"	"	16.90	26.70	1.96	1.68	3.38	3.45	0.980
"	"	17.50	27.40	1.98	1.69	2.65	4.06	0.653
10	1	18.80	24.00	2.00	1.69	1.48	2.74	0.540
"	"	18.90	25.50	1.99	1.67	2.02	3.06	0.660
"	"	18.90	25.40	2.01	1.69	2.13	3.19	0.668
"	"	19.00	25.00	2.01	1.69	1.98	2.41	0.822
"	"	19.20	25.30	2.01	1.69	2.05	2.02	0.782
20	1	15.10	34.80	1.79	1.55	3.55	3.14	1.131
"	"	15.00	34.80	1.79	1.56	3.00	2.96	1.014
"	"	14.60	37.20	1.80	1.57	3.36	2.71	1.240
"	"	14.00	35.00	1.80	1.56	2.54	1.96	1.296
"	"	14.90	34.20	1.80	1.57	2.62	2.40	1.092
20	1	17.40	31.80	1.84	1.57	2.53	1.46	1.733
"	"	18.05	32.80	1.87	1.58	2.28	1.83	1.246
"	"	18.00	32.20	1.87	1.58	2.11	1.91	1.105
"	"	17.40	31.70	1.86	1.57	1.62	1.84	0.880
20	1	18.20	30.40	1.93	1.60	2.37	2.49	0.952
"	"	18.00	30.30	1.92	1.60	1.89	1.98	0.551
"	"	18.40	30.70	1.93	1.61	1.96	2.04	0.961
"	"	19.00	31.20	1.92	1.61	1.79	1.87	0.957
"		19.10	31.10	1.92	1.61	1.90	2.10	0.905
"	"	13.70	34.80	1.75	1.54	1.60	1.71	0.936
"	"	14.00	35.00	1.76	1.55	1.52	1.65	0.921

TABLE XIV (continued)

Gypsum Content (%)	Curing Period (days)	Initial Water (%)	Final Water Content (%)	Wet Density (gm/cc)	Dry Density (gm/cc)	Vertical Strain ε_v (%)	Horizontal Strain ε_H (%)	$\varepsilon_v/\varepsilon_H$
5	28	13.00	28.20	1.84	1.62	3.12	3.65	0.855
"	"	13.90	29.40	1.86	1.63	2.86	5.01	0.571
"	"	13.70	29.20	1.87	1.65	3.65	5.10	0.716
"	"	14.90	29.80	1.86	1.62	3.66	4.48	0.817
"	"	13.40	29.10	1.86	1.64	3.26	4.54	0.718
"	"	17.70	27.00	1.95	1.66	2.38	2.06	1.155
"	"	16.60	26.50	1.94	1.67	2.74	2.94	0.932
"	"	17.20	26.40	1.96	1.67	3.04	2.25	1.351
"	"	16.20	27.50	1.95	1.68	2.35	2.64	0.890
"	"	17.40	26.50	1.96	1.67	2.74	2.82	0.972
"	"	20.40	26.60	1.97	1.64	1.45	1.81	0.801
"	"	19.40	26.00	1.97	1.65	1.71	1.96	0.872
"	"	19.10	25.10	1.97	1.66	2.04	2.35	0.868
"	"	18.80	25.20	1.97	1.67	1.92	1.95	0.985
"	"	18.60	25.00	1.97	1.67	2.13	2.27	0.938
10	28	15.80	28.70	1.93	1.66	3.08	4.18	0.737
"	"	15.70	29.40	1.94	1.68	3.67	5.39	0.681
"	"	15.10	29.15	1.93	1.67	3.25	3.40	0.956
"	"	15.90	28.75	1.93	1.67	3.55	3.62	0.981
"	"	17.90	27.30	1.98	1.68	2.92	1.26	2.317
"	"	17.70	27.40	1.98	1.68	2.86	1.41	2.028
"	"	19.20	27.90	1.96	1.65	2.25	0.92	2.228
"	"	19.10	28.05	1.96	1.65	2.25	1.15	1.957
"	"	21.30	27.30	2.00	1.65	1.43	1.72	0.831
"	"	19.20	24.40	1.99	1.67	2.30	1.46	1.575
"	"	19.20	28.20	1.98	1.66	1.86	1.94	0.959

TABLE XIV (continued)

Gypsum Content (%)	Curing Period (days)	Initial Water Content (%)	Final Water Content (%)	Wet Density (gm/cc)	Dry Density (gm/cc)	Vertical Strain $\mathcal{E}_v$(%)	Horizontal Strain $\mathcal{E}_H$(%)	$\mathcal{E}_v/\mathcal{E}_H$
20	28	14.00	28.20	1.84	1.61	2.24	2.26	0.991
"	"	14.30	27.20	1.91	1.65	2.25	1.66	1.355
"	"	14.60	28.00	1.90	1.63	2.10	1.58	1.329
"	"	14.10	28.10	1.87	1.62	2.07	2.14	0.967
"	"	14.90	31.30	1.82	1.58	3.10	2.46	1.260
"	"	15.50	33.20	1.83	1.58	2.46	3.35	0.734
"	"	14.70	31.20	1.82	1.58	2.98	3.04	0.980
"	"	15.30	32.70	1.83	1.58	2.61	2.92	0.860
"	"	15.80	23.80	1.91	1.65	1.42	1.82	0.780
"	"	17.00	24.40	1.92	1.66	1.73	0.96	1.802
"	"	16.05	23.90	1.91	1.66	1.56	1.64	0.951
"	"	16.40	24.10	1.92	1.66	1.29	1.47	0.878
30	28	14.00	34.20	1.77	1.56	1.49	1.54	0.968
"	"	14.20	34.65	1.77	1.56	1.62	1.81	0.895

TABLE XV

CORRELATION ANALYSIS

Swelling Versus Initial Water Content

Description of Samples: Permian Red Clay from New Engineering Building

Method of Compaction: Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper

One Day Curing

Gypsum Content (%)	Correlation Factor
5%	$r_{(\varepsilon_v, I.W.C.)} = -0.72$
5%	$r_{(\varepsilon_H, I.W.C.)} = -0.68$
10%	$r_{(\varepsilon_v, I.W.C.)} = -0.63$
10%	$r_{(\varepsilon_H, I.W.C.)} = -0.73$
20%	$r_{(\varepsilon_v, I.W.C.)} = -0.82$
20%	$r_{(\varepsilon_H, I.W.C.)} = -0.60$

28 Day Curing

Gypsum Content (%)	Correlation Factor
5%	$r_{(\varepsilon_v, I.W.C.)} = -0.87$
5%	$r_{(\varepsilon_H, I.W.C.)} = -0.89$
10%	$r_{(\varepsilon_v, I.W.C.)} = -0.90$
10%	$r_{(\varepsilon_H, I.W.C.)} = -0.78$
20%	$r_{(\varepsilon_v, I.W.C.)} = -0.56$
20%	$r_{(\varepsilon_H, I.W.C.)} = -0.42$

ε_v = Vertical Strain (%)
ε_H = Horizontal Strain (%)
$r_{(\varepsilon_v, I.W.C.)}$ = Correlation factor between Vertical Strain, ε_v and Initial Water Content.
$r_{(\varepsilon_H, I.W.C.)}$ = Correlation factor between Horizontal Strain, ε_H, and Initial Water Content.

TABLE XVI

CORRELATION ANALYSIS

Swelling versus Gypsum Content

Description of Samples: Permian Red Clay from the New Engineering Building.

Method of Compaction: Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper.

One Day Curing

Initial Water Content (%)	Correlation Factor
13.50 - 14.50	$r_{(\varepsilon_v, \text{gypsum})} = -0.940$
13.50 - 14.50	$r_{(\varepsilon_H, \text{gypsum})} = -0.940$
16.50 - 17.50	$r_{(\varepsilon_v, \text{gypsum})} = -0.990$
16.50 - 17.50	$r_{(\varepsilon_H, \text{gypsum})} = -0.970$
18.75 - 19.75	$r_{(\varepsilon_v, \text{gypsum})} = -0.930$
18.75 - 19.75	$r_{(\varepsilon_H, \text{gypsum})} = -0.998$

28 Day Curing

Initial Water Content (%)	Correlation Factor
14.00 - 15.00	$r_{(\varepsilon_v, \text{gypsum})} = -0.960$
14.00 - 15.00	$r_{(\varepsilon_H, \text{gypsum})} = -0.940$
17.00 - 18.00	$r_{(\varepsilon_v, \text{gypsum})} = -0.790$
17.00 - 18.00	$r_{(\varepsilon_H, \text{gypsum})} = -0.900$

ε_v = Vertical Strain (%)
ε_H = Horizontal Strain (%)
$r_{(\varepsilon_v, \text{gypsum})}$ = Correlation Factor between Vertical Strain, ε_v, and Gypsum Content.
$r_{(\varepsilon_H, \text{gypsum})}$ = Correlation Factor between Horizontal Strain, ε_H, and Gypsum Content.

TABLE XVII

EFFECTS OF GYPSUM CONTENT AND CURING PERIOD UPON VERTICAL AND HORIZONTAL SWELLING

Description of Samples: Permian Red Clay from New Engineering Building

Method of Compaction: Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper

Gypsum Content (%)	Curing Period (days)	Initial Water Content (%)	Dry Density (gms/cc)	Average Vertical Strain $\mathcal{E}_V$(%)	Average Horizontal Strain $\mathcal{E}_H$(%)
0	1	13.50-14.50	1.48	4.63	6.37
5	1	"	1.61	3.65	6.32
10	1	"	1.63	2.65	3.96
20	1	"	1.56	2.54	1.96
30	1	"	1.54	1.60	1.71
0	1	16.50-17.50	1.45	3.81	5.91
5	1	"	1.67	3.60	4.10
10	1	"	1.68	3.38	3.45
20	1	"	1.57	2.53	1.46
0	1	18.75-19.75	1.46	3.21	-
5	1	"	1.67	2.22	2.86
10	1	"	1.69	2.05	2.62
20	1	"	1.61	1.90	2.10
0	1	14.00-15.50	1.44	4.16	6.18
5	28	"	1.62	3.66	4.48
10	28	"	1.67	3.25	3.40
20	28	"	1.58	3.10	2.46
30	28	"	1.56	1.62	1.81
0	1	17.00-18.00	1.69	2.58	3.00
5	28	"	1.67	3.04	2.25
10	28	"	1.68	2.86	1.41
20	28	"	1.66	1.73	0.96
0	1	18.75-19.50	1.46	3.21	-
5	28	"	1.65	1.71	1.96
10	28	"	1.65	2.25	0.92

TABLE XVIII

EFFECT OF INORGANIC CHEMICALS ADDED IN SOIL MIXTURE UPON VERTICAL AND HORIZONTAL SWELLING

Description of Samples: Permian Red Clay from the New Engineering Building

Method of Compaction: Kneading Compaction, 3 Layers, 25 Tamps, 30 Pound Spring Tamper

Chemical Added	Percentage By Dry Wt.	Curing Period (Days)	Initial Water Content (%)	Dry Density gm/cm.	Average Initial Water Content	Average Dry Density	Horiz. Strain ε_H(%)	Vertical Strain ε_v(%)	Average Horiz. Strain	Average Vertical Strain
None	None	None	8.6	1.61	8.25	1.63	6.06	5.77	6.42	4.97
None	None	None	8.3	1.64			6.35	4.16		
None	None	None	8.2	1.64			5.73	5.22		
None	None	None	7.9	1.63			7.55	4.73		
None	None	None	11.02	1.59	11.37	1.62	5.40	3.24	5.56	3.62
None	None	None	11.22	1.57			4.38	3.27		
None	None	None	11.72	1.59			5.25	3.25		
None	None	None	11.20	1.60			4.99	3.00		
None	None	None	11.10	1.61			5.70	2.64		
None	None	None	11.90	1.67			6.82	4.31		
None	None	None	11.40	1.68			5.57	4.28		
None	None	None	11.10	1.66			5.92	4.04		
None	None	None	11.70	1.64			6.17	4.58		
NaCl	1	1	12.08	1.59	12.04	1.59	6.82	2.49	6.63	2.48
NaCl	1	1	11.81	1.59			6.75	2.65		
NaCl	1	1	12.24	1.60			6.41	2.29		
NaCl	1	7	12.40	1.01			6.09	2.47		
NaCl	1	7	11.75	1.59	11.85	1.59	5.96	2.10	6.26	2.44
NaCl	1	7	11.40	1.57			6.74	2.74		
NaCl	2	1	10.45	1.60	10.05	1.59	6.42	1.70	7.03	2.24
NaCl	2	1	9.95	1.58			7.20	2.19		
NaCl	2	1	9.75	1.60			7.47	2.82		

TABLE XVIII (continued)

Chemical Added	Percentage By Dry Wt.	Curing Period (Days)	Initial Water Content (%)	Dry Density gm/cm	Average Initial Water Content	Average Dry Density	Horiz. Strain ε_H(%)	Vertical Strain ε_v(%)	Average Horiz. Strain	Average Vertical Strain
NaCl	2	7	9.90	1.59			5.96	2.65		
NaCl	2	7	9.30	1.61	9.55	1.61	6.66	2.68	6.79	2.54
NaCl	2	7	9.50	1.62			7.00	2.10		
NaCl	2	7	9.50	1.62			7.55	2.74		
$CaCl_2$	1	1	10.50	1.60			6.44	3.02		
$CaCl_2$	1	1	10.80	1.58	10.67	1.59	6.80	2.60	6.51	2.63
$CaCl_2$	1	1	10.72	1.60			6.29	2.26		
$CaCl_2$	1	7	8.80	1.64			6.93	1.68		
$CaCl_2$	1	7	8.95	1.61	8.93	1.62	6.46	2.55	6.76	2.13
$CaCl_2$	1	7	9.05	1.61			6.90	2.16		
$CaCl_2$	2	1	9.75	1.62			5.81	2.14		
$CaCl_2$	2	1	9.50	1.63	9.48	1.62	6.79	2.34	6.31	2.30
$CaCl_2$	2	1	9.20	1.62			6.33	2.42		
$CaCl_2$	2	7	9.00	1.63			6.68	2.25		
$CaCl_2$	2	7	9.10	1.63	9.17	1.63	6.73	2.46	6.64	2.36
$CaCl_2$	2	7	9.42	1.63			6.51	2.37		

TABLE XXI

EFFECT OF INORGANIC CHEMICALS ADDED TO THE RESERVOIR WATER UPON VERTICAL AND HORIZONTAL SWELLING

Description of Samples: Permian Red Clay from the New Engineering Building

Method of Compaction: Kneading Compaction, 3 Layers, 25 Tamps, 20 Pound Spring Tamper

Chemical Added	Initial Water Content (%)	Dry Density (gm/cc)	Average Initial Water Content	Average Dry Density (gm/cc)	Horizontal Strain ε_H(%)	Vertical Strain ε_v(%)	Average Horizontal Strain (%)	Average Vertical Strain (%)
none	8.6	1.61	8.25	1.63	6.06	5.77	6.42	4.97
"	8.3	1.64			6.35	4.16		
"	8.2	1.64			5.73	5.22		
"	7.9	1.63			7.55	4.73		
NaCl	8.90	1.61	8.87	1.61	5.99	2.56	6.57	2.45
"	8.50	1.63			7.04	2.33		
"	7.20	1.60			6.68	2.46		
$CaCl_2$	8.25	1.63	8.01	1.64	5.70	2.54	5.81	2.42
"	7.76	1.64			6.88	2.30		
"	8.01	1.64			6.04	2.41		

TABLE XXII

TOTAL VOLUME CHANGE IN TRIAXIAL SWELLING WITH INORGANIC CHEMICALS ADDED IN SOIL MIXTURES

Inorganic Chemical	Per cent by Dry Weight of Soil	Curing Period (days)	Total Volume Change (cc)		
			From Reservoir Reading	Final Water Content − Initial Water Content	Difference (%)
NaCl	1	1	26.33	23.75	+9.8
"	1	7	25.96	24.75	+4.7
"	1	7	26.38	26.25	+0.5
"	2	1	27.86	27.10	+2.7
"	2	7	31.38	28.30	+9.8
$CaCl_2$	1	1	29.31	26.85	+8.4
"	1	7	29.96	28.15	+6.0
"	1	7	29.46	26.20	+11.1
"	2	7	28.70	28.70	+0.0
"	2	7	27.65	25.60	+7.4

TABLE XXIII

TOTAL VOLUME CHANGE IN TRIAXIAL SWELLING WITH INORGANIC CHEMICALS ADDED TO THE RESERVOIR WATER

Inorganic Chemical	Total Volume Change (cc.)		
	from Reservior Reading	Final Moist. Content - Initial Moist. Content	Difference
NaCl	27.03	25.60	+5.3
NaCl	27.53	28.35	-3.0
$CaCl_2$	27.53	25.25	+8 3

CHAPTER V

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions

The principal purpose of this study was to investigate the swelling behavior of compacted and undisturbed clay specimens under different conditions, using a triaxial swelling apparatus that facilitates measurements of the magnitudes and rates of one-dimensional or three dimensional swelling. In three years of research, free triaxial swelling tests were performed on 306 samples with various initial water contents, and employing additives or inorganic chemicals which were compacted with various amounts of compactive energies. According to the assumptions, discussions and data presented in previous chapters, the following conclusions can be given:

1. For a given compactive method and compactive energy Permian clay specimens compacted at low initial water contents swell more than specimens compacted at relatively higher initial water contents, both in the vertical and horizontal directions.

2. For all samples compacted at various initial water contents, the horizontal swellings are generally larger than vertical swellings. It has been stated in past studies and

investigations that compaction on the wet side of optimum creates a more dispersed structure than that created by compaction on the dry side of optimum water content. However, this investigation indicates that clay samples compacted on either side of the optimum exhibit higher horizontal swelling characteristics. These results indicate that previous explanations of compacted clay structure may not be correct. It is also possible that the disparity may result from different adsorption characteristics of edge surfaces and basal planes of clay particles.

3. Clay specimens compacted on the dry side of optimum water content start to swell with higher swelling ratios $(\varepsilon_V/\varepsilon_H \quad 1)$ that decrease rapidly. Specimens compacted approximately at optimum water content or on the wet side of optimum start with lower swelling ratio and the effect of time on this ratio is not very significant. See Figure 48.

4. It appears that there is an exponential relationship between the magnitudes of swelling and applied compactive energy. This relationship may be expressed as

$$SL = K' (F)^{\lambda}$$

in which SL = the magnitude of swelling, K' and λ are parameters depending on the amount of the compactive energy, and F = force applied by spring tamper in kneading compaction.

5. For a given initial water content and dry density, remolded clay specimens swell more than undisturbed samples, both in the vertical and horizontal directions.

6. For undisturbed clay samples taken from depths of 9 and 18 feet, the average vertical strain, $\mathcal{E}_v$, is approximately one-half the horizontal strain.

7. Samples compacted with various gypsum contents exhibit the same general swelling characteristics as samples compacted without gypsum. Increased amounts of gypsum proportionately decrease both vertical and horizontal swellings. Samples tested after a 28 day curing period generally swell less than samples tested after one day of curing. This may be explained mostly by the thixotropic effects and elastic rebound and partly by a small scale cation exchange that is likely to occur during longer curing periods.

8. The principal effect of the inorganic chemicals, NaCl and $CaCl_2$, either in the molding water or in the imbibed water, is to reduce the swelling in the vertical direction. Their effect on horizontal swelling is very slight. The different effects that these chemicals have on the vertical and horizontal swelling can probably be attributed to differences in the cation and anion exchange processes of clay minerals, and to differences in the adsorption characteristics of edge surfaces and basal planes of clay particles. $CaCl_2$ appears to be slightly more effective than NaCl, and increasing the curing period from one to seven days reduces the swelling very slightly.

Finally, for all phases of the study it was established that the new triaxial swelling apparatus can be used as a dependable and practical apparatus in measuring the magnitudes and rates of both vertical and horizontal swellings of compacted and undisturbed clay specimens.

Recommendations for Future Research

In order to be able further to understand and predict the swelling characteristics of compacted and undisturbed clay specimens, additional research appears to be necessary. The following recommendations may be useful as guides for future research:

1. Clay samples from different locations should be taken and specimens should be tested in the triaxial swelling apparatus, in order to establish the differences in swelling behavior due to the depth of sampling, grain size distribution, and quantity and type of minerals.

2. The swelling pressures exerted by confined clay specimens (both remolded and undisturbed) should be investigated.

3. Increase the tamping force in kneading compaction from 60 pounds to 70 and 80 pounds in order to investigate whether the assumed exponential relationship between magnitude of swelling and applied tamping force holds in these regions.

4. Investigate the effects of stress history and curing period on swelling behavior.

5. Investigate the structure of the clay specimens before and after swelling in order to establish the nature of structural changes that take place during swelling.

6. Investigate the swelling characteristics of clay specimens compacted with various combinations of gypsum and inorganic chemicals.

7. Investigate the swelling properties of various pure clay minerals compacted with different inorganic chemicals in order to establish the basic means by which inorganic chemicals contribute to a reduction of the magnitude of swelling. The investigation would be especially facilitated by the use of inorganic chemicals that contain phosphate, arsenate or borate anions, which are assumed to be geometrically compatible with the silica-gibbsite sheet. This may affect a substantial reduction in horizontal swelling.

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APPENDIX A.

HORIZONTAL RESTRAINT DUE TO THE LATEX MEMBRANE

If a circular ring is subjected to uniformly distributed loading as shown in Figure 84, the diametral strain $\mathcal{E}_d$ will be,

$$\mathcal{E}_d = \frac{q\ r'}{A\ E} \qquad (1)$$

where q = uniformly distributed load (lbs./in.)

r′ = radius of the membrane (in.)

A = cross sectional area of the membrane (in.^{2})

E = modulus of elasticity of the membrane (lbs./in.^{2})

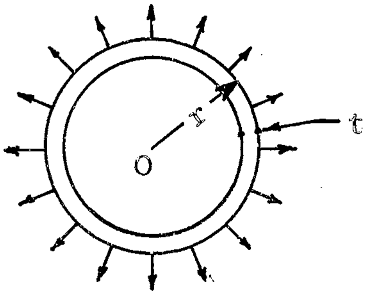

FIGURE 84. CIRCULAR RING SUBJECTED TO UNIFORMLY DISTRIBUTED LOAD.

Arranging equation (1), the result is

$$q = \frac{A\ E\ \mathcal{E}_d}{r'} \qquad (2)$$

For a section of membrane having a length of one inch, the cross sectional area, A, equals 1 x t, where t is the thickness of the membrane.

Furthermore, for a section of 1" length, the uniformly distributed load will be equal to the internal pressure, p.

Consequently,
$$p = q = \frac{A\ E\ \varepsilon_d}{r'} \tag{3}$$

Substituting $A = 1 \times t$ in equation (3), the result is

$$p = \frac{t\,\varepsilon_d E}{r'} \tag{4}$$

According to the notation used in this dissertation

$$\varepsilon_d = \varepsilon_H$$

where ε_H = horizontal strain (%).

Then, finally
$$p = \frac{t\varepsilon_H\ E}{r'} \tag{5}$$

Numerical Example

According to laboratory measurements:

The average thickness of the laytex membrane, $t = .0085$ inches.

The average radius of the laytex membrane, $r' = 0.7$ inches.

The modulus of elasticity of the laytex membrane, $E = \frac{2.00}{0.0085}$ lbs./in.^{2} In the case of maximum horizontal strain,

$$\varepsilon_{H_{max.}} = 7.75\ \%$$

Then,
$$p = \frac{t\varepsilon_H\ E}{r'} = \frac{.0085 \times 7.75 \times \frac{2.00}{.0085}}{0.7 \times 100}$$

$$p = 0.221 \text{ lbs./in.}^2 \rightarrow 15.537 \text{ gm/cm}^2$$

APPENDIX B.

THE EFFECT OF NEGLECTING THE SECOND DEGREE TERM ($\pi H'\Delta r^2$) IN HORIZONTAL SWELLING

It was found that $2\pi r\Delta r H' + \pi H'\Delta r^2 = C\Delta R_H$

in which r = initial radius of specimen = 0.7 in. = 1.788 cm.

Δr= incremental increase in the radius due to horizontal swelling (cm.)

H'= total height of specimen after completion of swelling (cm.)

ΔR_H= incremental increase in horizontal reading in the saran tube (cc./cm.)

C = capacity of saran tube (cc./cm.)

Numerical Example

In the case of maximum horizontal swelling,

$$\varepsilon_{H_{max.}} = 7.75\ (\%)$$

and corresponding, $\varepsilon_v = 4.32\ (\%)$

then,

$$\varepsilon_{H_{max.}} = \frac{\Delta r_{max.}}{r}$$

Therefore,

$$\Delta r_{max.} = \varepsilon_{H_{max.}} \times r = \frac{1.788 \times 7.75}{100}$$

$$\Delta r_{max.} = 0.139 \text{ cm.}$$

$$H' = H(1 + \varepsilon_v) = 7.11(1 + \frac{4.32}{100}) = 7.417 \text{ cm.}$$

$$\pi H'\Delta r^2 = 3.1416 \times 7.147 \times (0.139)^2 = 0.4502$$

$$2\pi\Delta r H' = 2 \times 3.1416 \times 1.788 \times 0.139 \times 7.417$$

$$2\pi \Delta r H' = 11.582$$

Neglecting the second degree term, $\pi H' \Delta r^2$ results in an error,

$$e_r = \frac{0.4502}{11.582 + 0.4502}$$

$$e_r = \frac{0.4502}{12.0322} = 3.74\ (\%)$$

Maximum error in neglecting the second degree term is 3.74(%)
The interpretation of data and consequent conclusions are not affected by this error.

VITA

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