LATERAL SWELLING PRESSURE RELATIONSHIPS
FOR TWO OKLAHOMA CLAYS

By

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To my wife, Cheryl, for her
devotion, understanding and
encouragement during this
study.

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CHAPTER I

INTRODUCTION

General

Structural damage resulting from swelling pressures developed in compacted clay soils has been studied and documented by numerous authors (Means, 1959; Kassiff and Zeitlen, 1961; Parcher and Means, 1968; and many others). Until the early 1960's the standard one-dimensional (vertical) swell test was used to predict the amount of swell that was likely to occur. During this period these authors began to publish material which indicated the lateral component (perpendicular to direction of compaction) was a primary cause of much of the damage to foundation walls and buried conduits. Lateral subgrade expansion has been reported (Haliburton, 1970) to produce tensile stresses in a pavement system of sufficient magnitude to result in longitudinal cracking of the pavement components. In most cases where this type of damage was initially observed the riding quality of the highway was not seriously affected. However, the longitudinal cracks opened the way for infiltration/evaporation through the pavement surface and permitted variations in the subgrade moisture conditions to occur. Any change of moisture conditions in the expansive subgrade would then be reflected as further damage to the pavement system. As a result, several investigations were initiated to measure and correlate the lateral swell and swelling pressure characteristics of compacted clay soils with respect to physical properties.

Initially, research at Oklahoma State University involved the measurement of free swell in the lateral and vertical directions (Liu, 1964; Ozkol, 1965; Srinivasan, 1970). These types of data are valuable in determining the general behavior of expansive soils, however, the situation in the field is somewhat different. Generally, the structure in question applies a certain degree of confinement to the expansive soil, which leads to the development of swelling pressures that result in damage to the structure. The more confinement applied, the greater the swelling pressure developed for a given set of initial conditions. Thus the need for a device to measure both lateral and vertical swelling pressure became more evident. Measurement of maximum swelling pressure requires that displacement resulting from particle re-orientation during the swelling process be minimized.

In addition to amount of confinement, the swelling pressure behavior of compacted clay soils is influenced by the amount and type of clay mineral present, initial moisture content, dry density, soil structure, availability and properties of water, curing period, time allowed for swelling, and temperature. The amount and type of clay mineral present determines whether the soil possesses a potential for volume change. The remaining factors determine the extent to which the swelling potential is realized, i.e., the amount of swell or swelling pressure. If the soil has a volume change potential, compacted soil structure as determined by initial moisture content, dry density, and compaction mode and energy are all major interrelated factors which influence the final magnitude of swell and swelling pressure. For a given soil, a working knowledge of the influences of initial moisture content, dry density, and compaction mode and energy is more significant to the soils engineer than any other combination of factors.

Purpose and Scope of Study

The purpose of this investigation was twofold: 1) develop a device for the measurement of lateral swelling pressure of compacted clay soils, and 2) measure the relative magnitudes of lateral swelling pressure for two Oklahoma soils as influenced by initial moisture content, dry density, compaction mode and energy, and lateral swell. In addition, vertical swelling pressure data were collected and correlated with lateral swelling pressure data.

CHAPTER II

FACTORS AFFECTING THE SWELLING AND SWELLING PRESSURE CHARACTERISTICS OF COMPACTED CLAY SOILS

A considerable amount of knowledge has been accumulated concerning the characteristics and behavior of expansive clay soils. A substantial portion of this knowledge describes the factors affecting the swelling and swelling pressure characteristics of compacted clay soils. To thoroughly understand swelling and swelling pressure phenomena in compacted clay soils one must study compaction and structure of clay minerals, physico-chemical aspects of soil behavior, current theories of swelling, and mechanical (or physical) factors affecting the swelling phenomena.

Composition and Structure of Clay Minerals

Natural soils nearly always occur as some combination of sand, silt, and clay. The sand and silt fractions contribute essentially nothing to the expansive characteristics of the soil. Almost all of the problems encountered with expansive soils are caused by the clay fraction, from both the physico-chemical and mechanical standpoint.

The major elements which make up clay minerals are silicon, aluminum, and oxygen. Frequently iron, alkali metals (Li, Na, K), and alkaline earth metals (Mg, Ca) are present.

All clay minerals are built from two fundamental building blocks. One is the silica tetrahedron (Figure 2.1a) in which four oxygens or hydroxyls having the configuration of a tetrahedron, enclose a silicon atom. The tetrahedra are combined in a sheet structure so that the oxygens of the bases of all the tetrahedra are in a common plane, and each oxygen is shared by two tetrahedra (Figure 2.1b). The silica sheet may be viewed as a layer of silicon atoms between a layer of oxygens and a layer of hydroxyls (tips of the tetrahedra).

The second building block is the alumina octahedron (Figure 2.2a) in which an aluminum, iron, or magnesium atom is usually enclosed equidistantly by six oxygens or hydroxyls having the configuration of an octahedron. The octahedral units compose a sheet structure (Figure 2.2b) which may be viewed as two layers of oxygens or hydroxyls with the cation between the sheets in octahedral coordination.

Grim (1953) describes nine major groups of clay minerals that are present in most natural soils. Of these nine, the three most commonly occurring clay mineral groups are kaolinite, montmorillonite, and illite.

The kaolinite unit cell consists of one layer of silica tetrahedra and one layer of alumina octahedra attached in such a way that the tips of the silica sheet and one of the layers of the octahedral sheet form a common surface (Figure 2.3a). The unit cell is denoted as having a "one to one" layer configuration. The unit cell is approximately 7.1 Å thick and extends indefinitely in the other two directions. The kaolinite mineral is a stacking of the unit cells with a structure similar to that of a book with each leaf 7.1 Å thick. The successive unit cells are held together by hydroxyl type hydrogen bonds, which are much weaker than ionic or covalent bonds. As a result of the weak hydrogen bonds, the

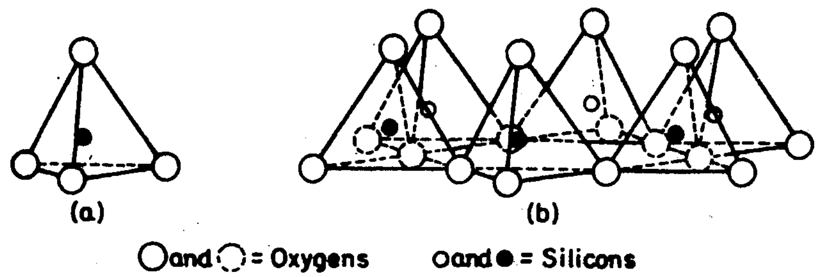


Figure 2.1. Diagrammatic Sketch Showing (a) a Single Silica Tetrahedron and (b) the Sheet Structure of the Silica Tetrahedrons (after Grim, 1968).

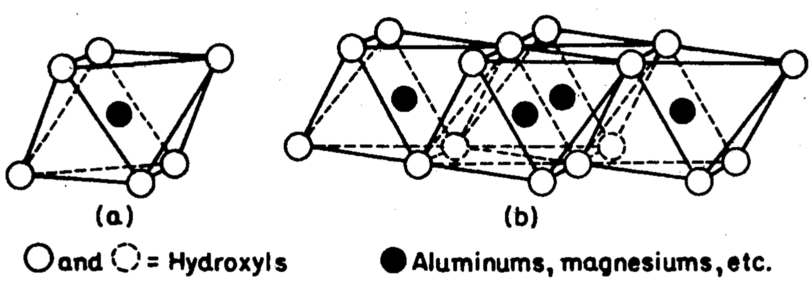


Figure 2.2. Diagrammatic Sketch Showing (a) a Single Aluminum Octahedron and (b) the Sheet Structure of the Aluminum Octahedrons (after Grim, 1968).

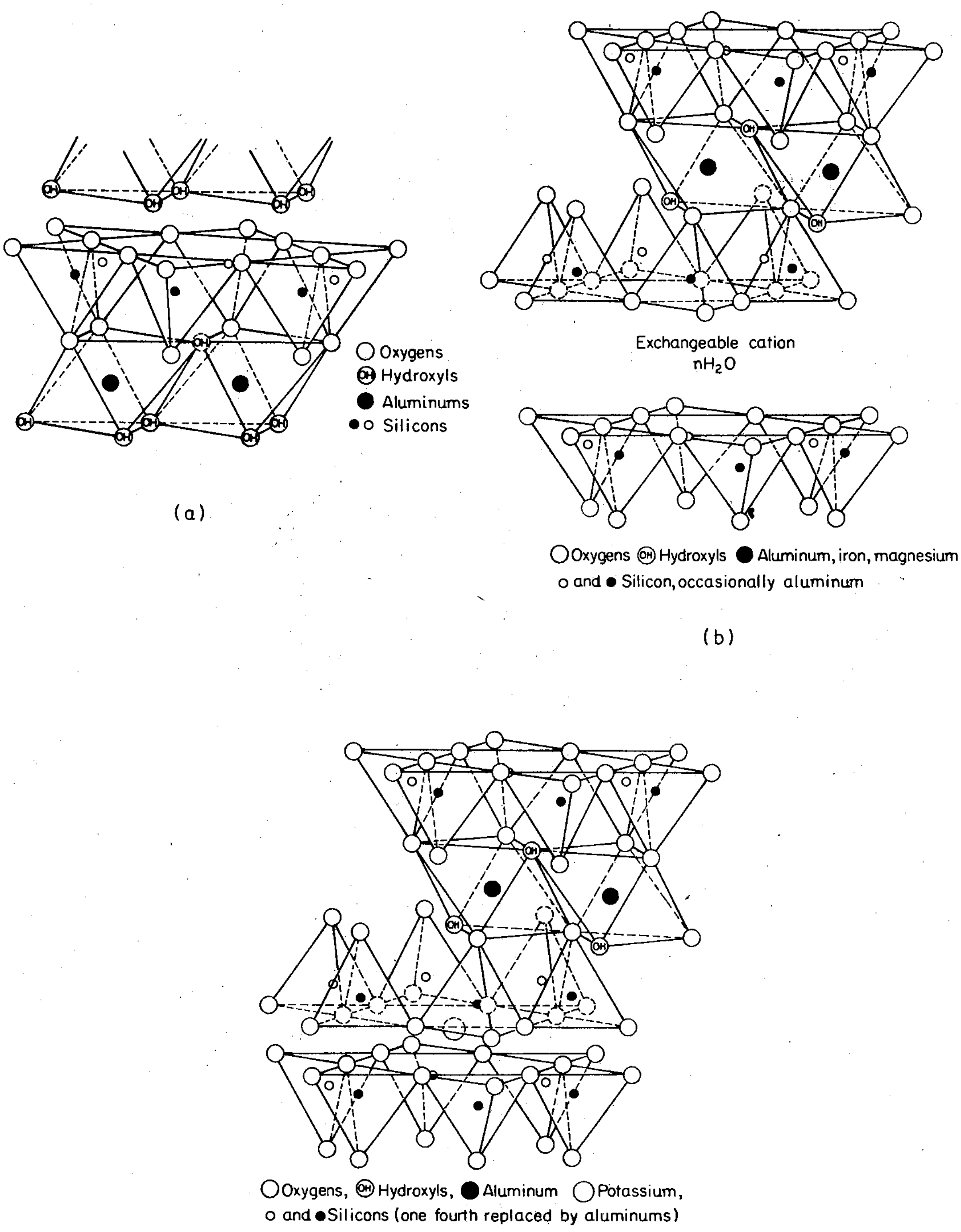


Figure 2.3. Structure of the Major Clay Mineral Groups: (a) Kaolinite; (b) Montmorillonite; and (c) Illite (after Grim, 1968).

kaolinite mineral can be split into very thin sheets. Isomorphic substitution of cations into the kaolinite unit cell is essentially nil, and any net negative charge on the clay particle is a result of broken bonds along the edges.

The montmorillonite unit cell consists of repeating layers of an alumina octahedral sheet sandwiched between two silica tetrahedral sheets, with the tips of each tetrahedral sheet and the hydroxyl layer of the octahedral sheet forming a common surface (Figure 2.3b). The unit cell is denoted as having a "two to one" layer configuration. The unit cell is approximately 9.5 Å thick and extends indefinitely in the other two directions. The 9.5 Å thickness occurs when no polar molecules are present between the individual unit layers. Polar molecules consist of dipole molecules in which constituent atoms are unsymmetrically arranged so that centers of positive and negative electrical charges are not located at the same point in the molecule. Such molecules act as if they carried both centers of positive charges and centers of negative charges. Water is a polar molecule and clay minerals assume polar characteristics when in contact with polar substances such as water. The normal thickness of the unit cell is approximately 14.0 Å due to the presence of polar molecules. If polar molecules are in excessive abundance, the unit cell thickness may increase to near separation of the individual units. The montmorillonite mineral is a stacking of the 9.5 Å unit cells like the pages of a book, held together by secondary valence bonds and exchangeable ion linkage. The resulting bonding force is very weak and water may enter between the unit cells and cause the mineral to expand. Isomorphic substitution of magnesium or iron for aluminum in the alumina sheet is a frequent occurrence. Also, substitution of aluminum for silicon in the silica sheet may occur. As a result of these substitutions nearly all montmorillonite minerals possess some net negative charge which can be neutralized by adsorbed cations. These adsorbed cations are readily exchangeable.

The illite unit cell is very similar to montmorillonite except that some of the silicons are always replaced by aluminum atoms (approximately 20% ±). Consequently, a net negative charge exists on the individual units which is balanced by potassium ions (Figure 2.3c). The potassium ions are the bonding force between unit layers and are usually not exchangeable. The potassium bonding force is weaker than the hydrogen bond of kaolinite, but is stronger than the bonds existing in montmorillonite. Consequently, there is normally no expanding lattice structure in illite as is present in montmorillonite. The thickness of the illite unit cell is approximately 10.0 Å, with the other two dimensions extending indefinitely. As previously noted, isomorphic substitution of aluminum for silicon in the silica sheet does occur. In addition, substitution of magnesium or iron for aluminum in the alumina sheet often occurs and results in a net negative charge on the illite particle.

In summary, kaolinite minerals, which have fixed crystal lattices, have very small hydration and cation 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 are the main cause of considerable hydration and cation adsorption. Dipolar water molecules and available cations are adsorbed both on the exterior and interior surfaces of the montmorillonite unit cell. The water adsorbed on the interior surfaces introduces relatively high volume changes. Illite minerals lie somewhere between kaolinite and montmorillonite in their behavior.

Physico-Chemical Aspects

As previously mentioned, most clay minerals possess a net negative charge which makes them capable of adsorbing cations. Since the ions present in nature have different chemical properties which can affect the swelling and swelling pressure characteristics of clay soils, it is necessary to understand some of these chemical properties before a suitable investigation may be carried out.

An important influence of ions on swell characteristics is the amount and rate of hydration of the ions. Baver (1956) reported that the lithium ion has the greatest amount of hydration, with sodium hydrating to nearly the same amount. His work led him to conclude that ions with smaller ionic radii have greater amounts of hydration.

The valence of free cations has an important influence on the cation exchange capacity, which directly affects the swelling characteristics of expansive clays. The higher the valence of a cation the greater is its replacing power and generally the harder it is to replace. Baver (1956) reported that swelling decreases with an increase in the valence of exchangeable cations. Grim (1968) stated that for ions of the same valence, replacing power tends to increase as the size of the ion increases, i.e., the smaller ions are less tightly held than the larger ones. Another factor influencing the replacing power of ions is their geometric fit in the clay mineral structure. In general the replacing power of cations is in the following sequence:

$$Li^{+} < Na^{+} < H^{+} < K^{+} < NH_4^{+} << Mg^{++} < Ca^{++} << Al^{++}$$

For example, potassium will more easily replace sodium and calcium will more easily replace potassium, etc.

The cation exchange capacity (C.E.C.) is a measure of the adsorption characteristics of clay minerals and is an indicator of the influence of the type and amount of free cations, that are adsorbed, on the swelling behavior of expansive clays. The C.E.C. is usually defined as the total amount of exchangeable cations a soil is capable of adsorbing, expressed in milliequivalents per 100 grams of soil. Researchers have found that all clay soils possess a C.E.C. value. Grim (1968) summarizes several factors which result in variations of C.E.C. of a given soil: particle size, temperature, availability and concentration of ions in solution, clay mineral structure, and isomorphic substitution. He suggests that there are three causes for cation exchange of clay minerals: 1) broken bonds around the edges of the clay mineral, 2) substitution within the lattice structure of the clay mineral, and 3) replacement of the hydrogen of exposed hydroxyls by cations which may be exchangeable. Some representative values of C.E.C. for various clay minerals are presented in Table 1. In general, the expansive properties of clay minerals increase with increasing C.E.C.

Theories of Swelling and Swelling Pressure Development

As a result of extensive research into the behavior of expansive clay soils, three major theories of soil swelling have been developed: 1) the double-layer theory, 2) the suction-potential theory, and 3) the elastic theory.

The double-layer theory attributes swelling of clay soils to osmotic pressure differentials between the middle plane of adjoining

TABLE I

CATION EXCHANGE CAPACITY OF CLAY MINERALS,
IN MILLIEQUIVALENTS PER 100 GM. (AFTER GRIM, 1968)

Clay Mineral	C.E.C.
Kaolinite	3 - 15
Halloysite $2H_2O$	5 - 10
Montmorillonite	80 - 150
Illite	10 - 40
Vermiculite	100 - 150
Chlorite	10 - 40

clay particles and the external pore water solution. The electric field of clay particles hinders ion movement and causes the ions to accumulate in the interparticle spaces, so that their concentration in the double-layer exceeds that in the external pore water solution. This concentration differential causes diffusion of the water in the same direction, forcing clay particles apart and thus inducing swell. According to this theory a suitable increase in electrolyte concentration of the external solution should result in zero osmotic pressure, thus eliminating swelling altogether. Gupta, Gupta, and Shukla (1967) have shown that swelling is actually suppressed as electrolyte concentration increases, but complete elimination is not achieved.

The suction-potential theory is based on the hypothesis that soil at a certain moisture content has a high capillary potential and loses its potential energy as more water is adsorbed. Many authors associate soil suction with unbalanced forces which result in moisture uptake by the soil causing it to swell. According to this theory swelling should cease when the soil suction (pF) reaches zero. However, Gupta, Gupta, and Shukla (1967) have shown that residual swell exists even at zero soil suction since moisture uptake continues beyond that point, as long as hydration of ions and soil particles is incomplete, and until soil particles have been reoriented relative to confining pressures and attractive forces present in the system.

The elastic theory, according to Terzaghi (1931), attributes swelling of clay soils to the elastic expansion resulting from a lowering of capillary pressure. It was his belief that the purely physical properties such as porosity, elasticity, capillary force, permeability, and hydrostatic pressure had the greatest influence on soil swell. He concluded that physico-chemical aspects influence the swelling process by altering the elastic properties of the soil.

It is evident from the previous discussion that the three conventional theories advanced for the swelling process are not adequate when used alone. This is evident from the existence of residual swell at high electrolyte concentration, from the existence of continued hydration of ions with soil suction reduced to zero, and from the impossibility of expelling interparticle and interlayer water by external force only. In addition, the double-layer and suction-potential theories do not consider the elasticity effect in relation to external load. To explain the swelling phenomena more fully, a combination of the three theories would be more nearly satisfactory.

Mechanical or Physical Factors

To complete the discussion of swelling and swelling pressure phenomena of compacted clay soils, it is necessary to consider the mechanical or physical factors affecting the soil-water system. As a result of considerable research on the subject, several factors influencing soil swell have been identified:

1) Amount and type of clay mineral,
2) Soil structure, as determined by initial moisture content and dry density,
3) Availability and properties of water,
4) Confinement during swell,
5) Curing period,
6) Time allowed for swelling, and
7) Temperature of soil-water system.

Amount and Type of Clay Mineral

As previously mentioned, natural soils consist of some combination of sand, silt, and clay particles, with the clay fraction being the contributing factor to soil swelling. The composition and structure of the various clay minerals have been discussed by numerous authors, for example Grim (1968). A brief summary of the composition and structure of kaolinite, illite, and montmorillonite was presented earlier, as they are the major groups of clay minerals in most natural soils.

Seed, Woodward, and Lundgren (1962) indicated that the type and amount of clay minerals present determines the swelling potential of the soil, i.e., these factors determine whether the soil would have the capacity to swell under any conditions. They contend that the remaining factors affecting swell determine the extent to which the swelling potential is realized, i.e., the amount of swell. Their research on artificial soils, consisting of commercial grade clay minerals, substantiates the fact that soil swell increases with increasing amount of expansive clay minerals present (Figure 2.4).

Srinivasan (1970) stated that differences in crystal lattice, hydration, and ion exchange characteristics of the clay minerals result in variations of the swelling behavior of soils containing these minerals. In general, soils containing sodium montmorillonite exhibit high volume change.

Gupta, Gupta, and Shukla (1967) reported that swelling increases with increasing montmorillonite content, base exchange capacity, and specific surface area (Figure 2.5).

Soil Structure

Compacted soil structure, as determined by initial moisture content, dry density, and compaction mode, plays a very important role in swelling and swelling pressure phenomena. Soil swelling and swelling pressure will vary with moisture content for a constant dry density and with dry density for a constant moisture content. In addition, varying the soil structure due to different modes of compaction will influence soil swelling.

The effects of initial moisture content on dry density and particle orientation for impact compaction of Boston Blue Clay were reported by Lambe (1958) as indicated in Figure 2.6. At low initial moisture contents a random or flocculent particle orientation exists, but with increasing moisture content the soil particles move into a more parallel or dispersed orientation.

Seed and Chan (1961) indicated similar findings from their investigation of compacted kaolinite (Figure 2.7). They reported that

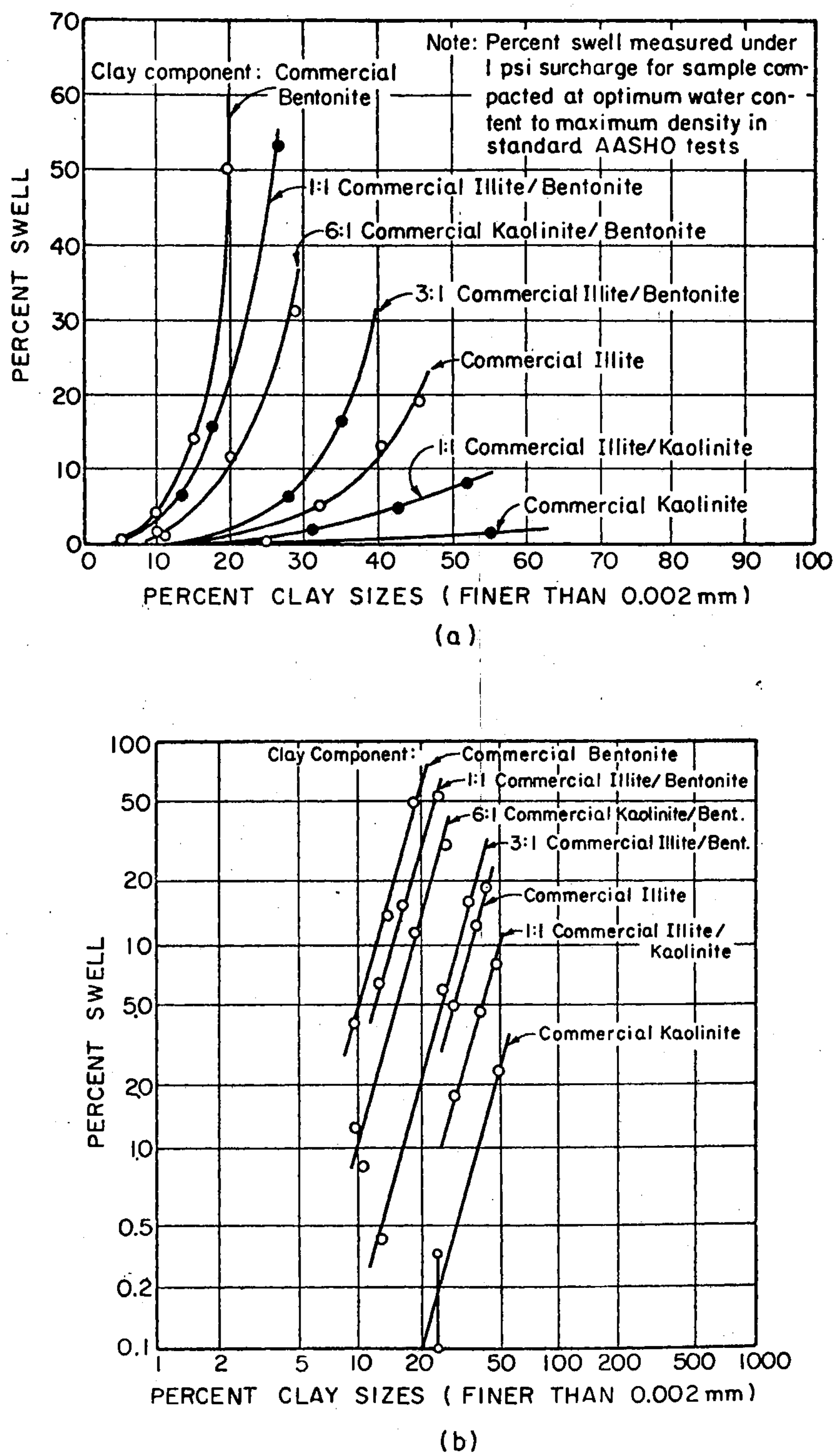


Figure 2.4. Relationship Between Percentage of Swell and Percentage of Clay Sizes for Experimental Soils: (a) Arithmetic Scale and (b) Logarithmic Scale (after Seed, Woodward, and Lundgren, 1962).

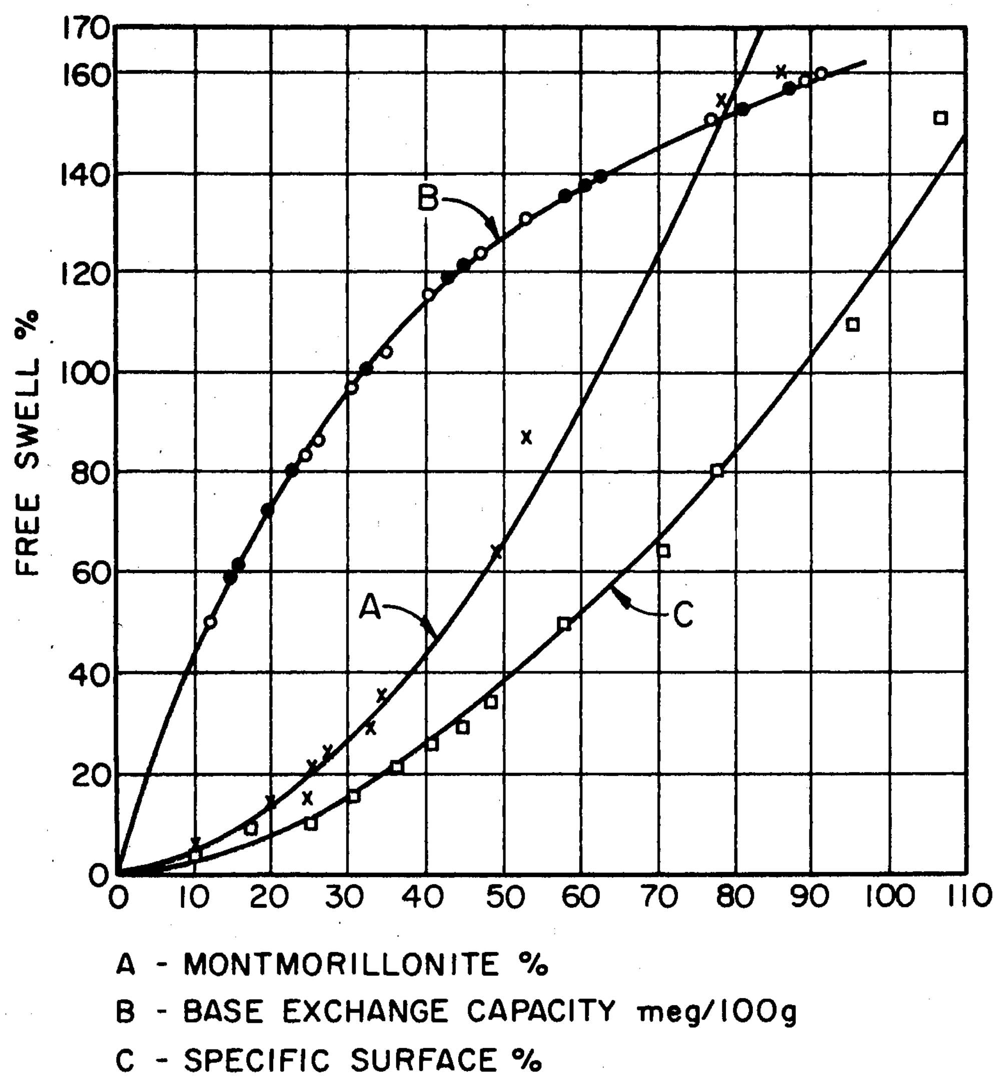


Figure 2.5. Free Swell versus Montmorillonite Content, Base Exchange Capacity and Specific Surface (after Gupta, Gupta, and Shukla, 1967).

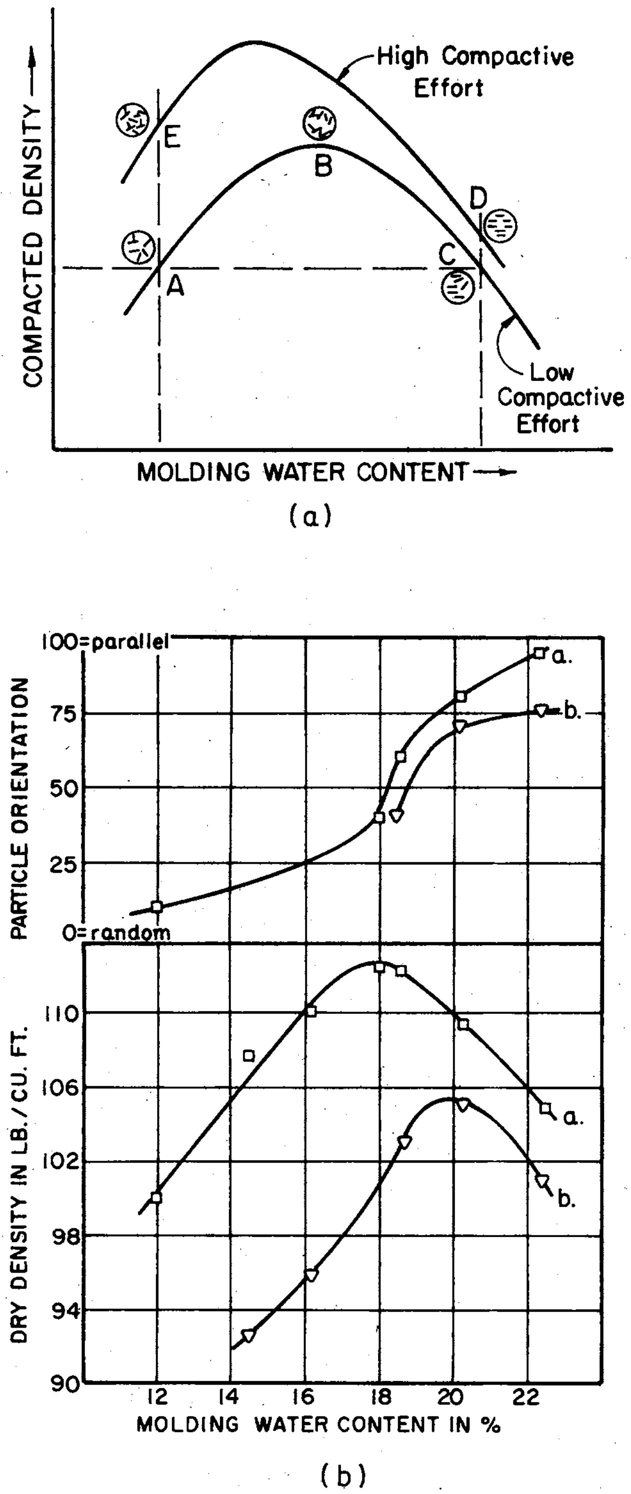


Figure 2.6. (a) Effects of Compaction on Soil Structure and (b) Particle Orientation versus Water Content for Boston Blue Clay (after Lambe, 1960).

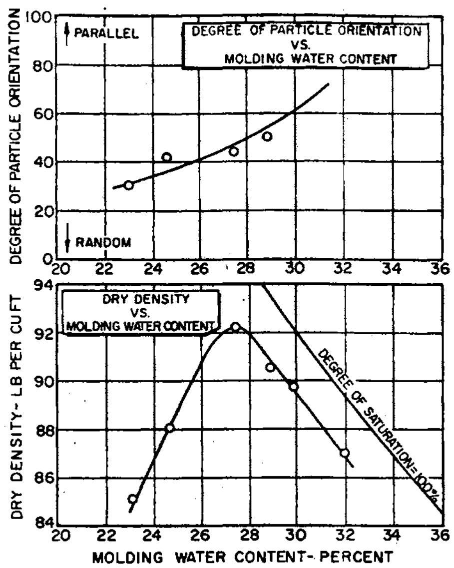


Figure 2.7. Influence of Molding Water Content on Particle Orientation for Compacted Samples of Kaolinite (after Seed and Chan, 1961).

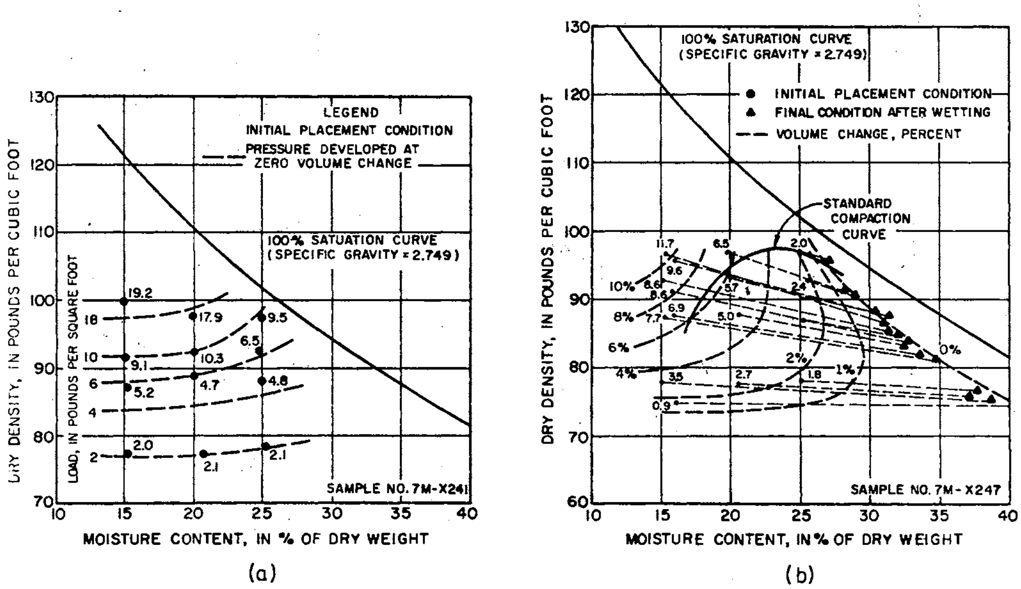


Figure 2.8. (a) Total Uplift Pressure for Various Placement Conditions and (b) Percent Expansion for Various Placement Conditions for Soil Under 1 psi Load (after Holtz and Gibbs, 1956).

increased swelling and swelling pressure at lower initial moisture contents could be interpreted as a manifestation of the greater swelling tendency of flocculent soil structures.

Holtz and Gibbs (1956) investigated the effects of placement conditions on swell and swelling pressure development for several natural soils (Figure 2.8).

Ladd's study (1959) of the mechanisms of swell of compacted clay revealed that the thickness of the double-layer water is roughly proportional to the initial moisture content. Hence, the lower the initial moisture content (other factors being equal) the greater is the water uptake required to satisfy the double layer deficiency, thus increasing the swelling tendency. He also indicated that, for a constant initial moisture content, an increase in dry density would lead to an increase in the amount of swelling. Ladd's conclusions generally summarized the influence of initial moisture content on swelling and swelling pressure behavior:

a) For samples compacted wet of optimum water content, swell can be explained by osmotic repulsive pressures arising from the difference in ion concentration in the double-layer water between interacting clay particles and that in the free pore water.

b) For samples compacted dry of optimum water content, swelling is influenced by factors in addition to osmotic pressure. The other factors may include the effect of negative electric and van der Waals force fields on water, cation hydration and the attraction of the particle surface for water, elastic rebound of particles, a flocculated particle orientation, and the presence of air.

Availability and Properties of Water

The electrical charge characteristics of clay minerals result in a layer of water adsorbed around the particle. The attractive forces holding the water decrease with distance from the particle. At degrees of saturation less than 100% the diffuse double layer of water is not completely developed. If water is made available to clay minerals, they will adsorb the water into the diffuse double layer as a result of the polar behavior of soil and water in contact. As a result, osmotic repulsive forces will develop and swelling will occur. Therefore, a readily available source of water is necessary for swell or swelling pressure development.

The attractive force resulting from the electrical charge properties of clay minerals is influenced by the nature of exchangeable cations initially present and by the kinds of ions dissolved in the added water.

Ladd (1959) reported that soaking of compacted samples in salt solutions produced a marked decrease in the amount of fluid pickup and heaving. As a result he concluded that the replacement of low valence exchangeable cations by higher valence cations, e.g., calcium for sodium, can reduce swelling since the number of exchangeable cations in the double-layer is reduced. In addition, the mixing of salt with a compacted clay can reduce swelling, since the ion concentration in the pore water is increased. Indications of the influence of calcium salt on heave and water uptake according to Ladd are evident in Figure 2.9.

Seed, Mitchell, and Chan (1961) reported similar results using calcium acetate solution for soaking their samples. They suggested that the electrolyte-sensitive factors influencing swell are relatively insensitive to structure (Figure 2.10).

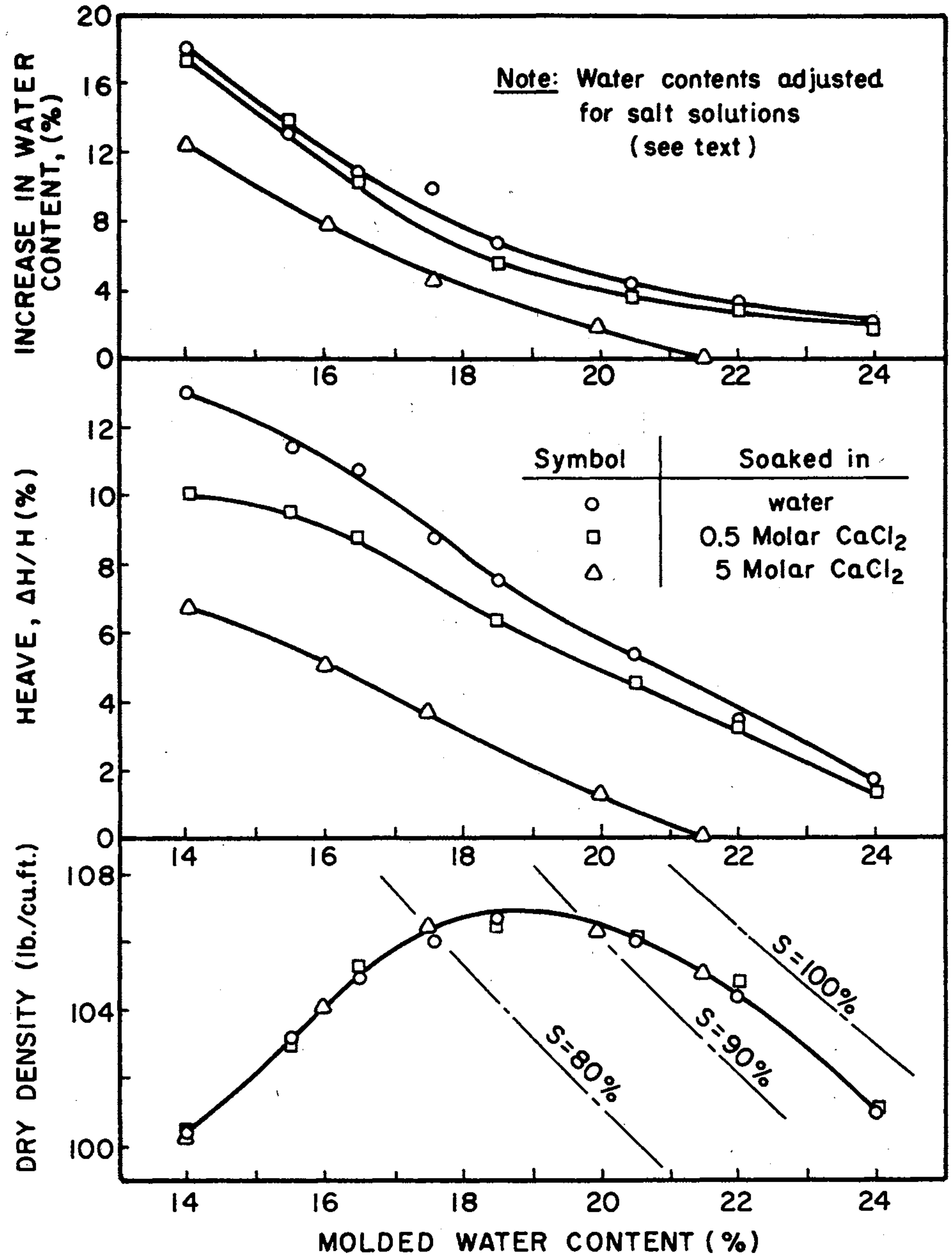


Figure 2.9. Effect of Salt Concentration on Swelling Behavior (after Ladd, 1959).

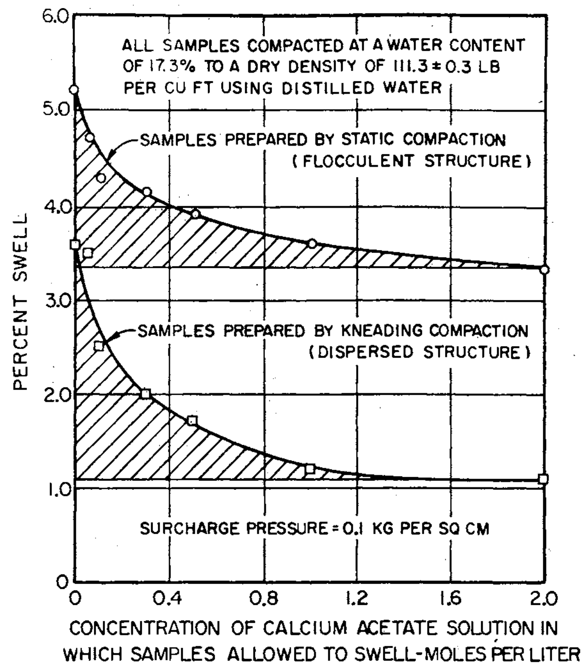


Figure 2.10. Effect of Structure and Electrolyte Concentration of Absorbed Solution on Swell of Compacted Sandy Clay (after Seed, Mitchell, and Chan, 1961).

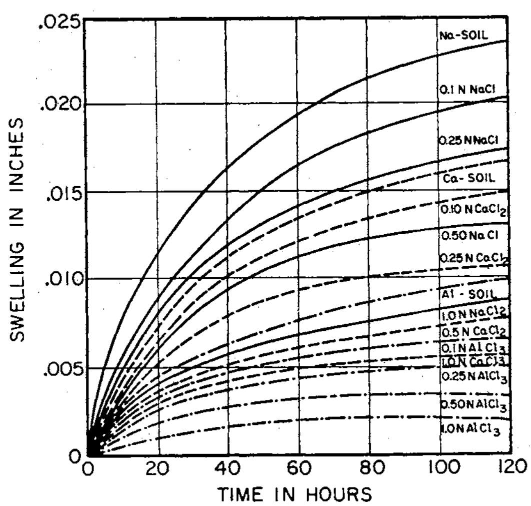


Figure 2.11. Swell versus Time for Various Electrolyte Concentrations (after Gupta, Gupta, and Shukla, 1967).

Gupta, Gupta, and Shukla (1967) reported that swelling is actually suppressed as the electrolyte concentration increases (Figure 2.11).

Confinement During Swelling

Maximum swelling pressure will develop only when maximum confinement occurs. Any volume change resulting from free swell has the tendancy to reduce the swelling pressure. Several authors have investigated the influence of confinement on swell pressure (Barber (1956), Dawson (1956), DuBose (1956), Seed, Mitchell and Chan (1961), and many others.)

Seed, Mitchell, and Chan (1961) reported that volume expansions as small as 0.10 percent during swelling pressure measurement may cause an error of large magnitude in the observed values. Some of their results are presented in Figure 2.12.

Ho (1967) concluded that the effect of volume change on vertical swelling pressure was related to the initial moisture content of soil samples and the surcharge pressure exerted on them. Similar results were obtained by DeGraft-Johnson, Bhatia, and Gidigasu (1967).

Curing Period

The curing period is defined as the time interval between compaction of the sample and measurement of swell or swelling pressure data. According to Barber (1956), the magnitude of the swelling pressure (and, presumably, the amount of free swell) of compacted samples decreases with increasing curing period. He noted a substantial difference in swelling pressure when the curing period was increased from 5 minutes to 24 hours.

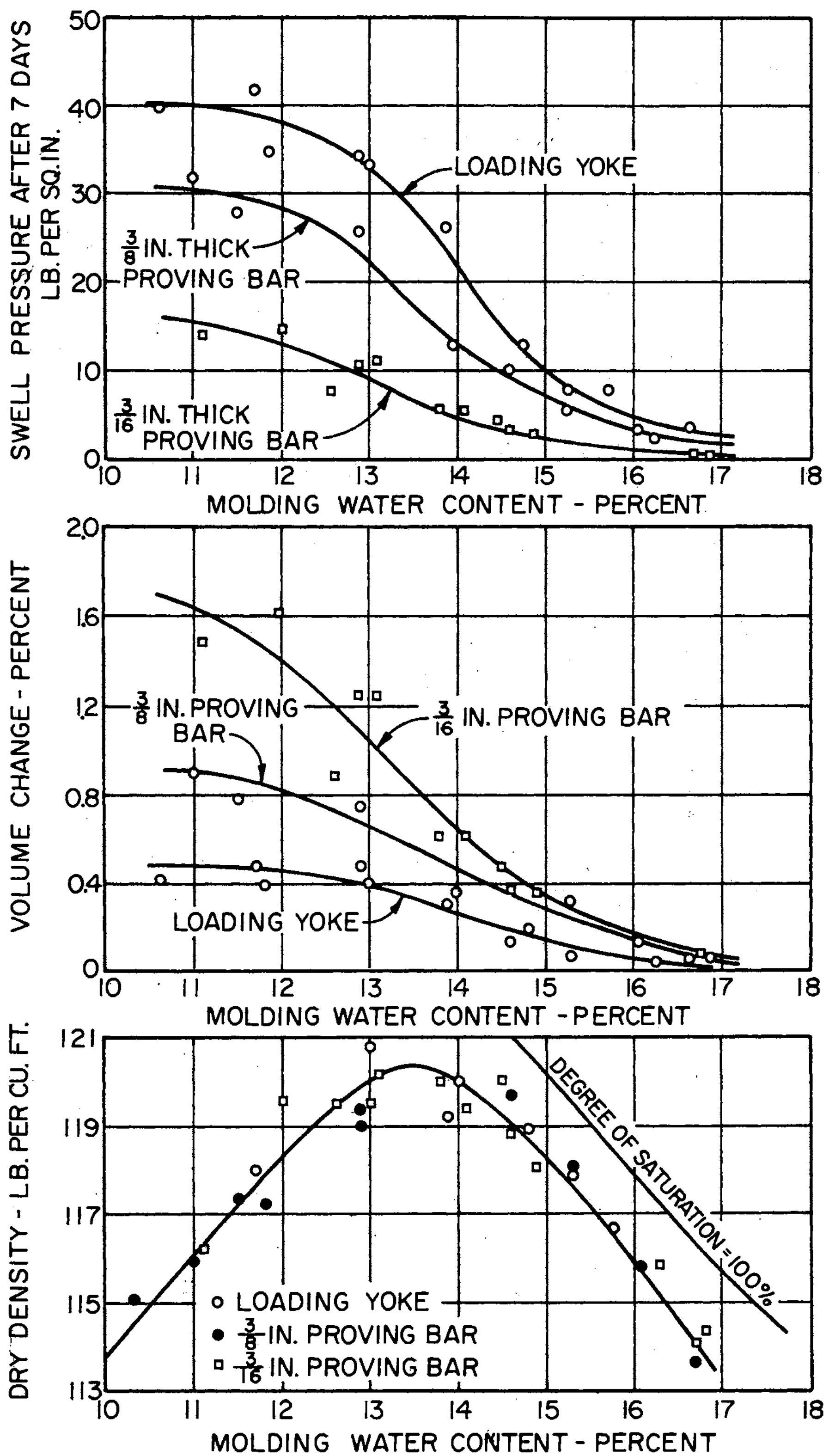


Figure 2.12. Effect of Volume Change on Swelling Pressure Compacted Sandy Clay (after Seed, Mitchell, and Chan, 1961).

Kassif and Baker (1971) investigated the aging effects on the swelling potential of compacted clays and concluded:

1) The swelling pressure of a compacted clay, particularly at high initial densities, tends to increase with aging and then gradually decrease to approximately the final value after about 20 days. This behavior is attributed to the opposite effects of suction and bonding on swelling potential (Figure 2.13a).

2) The amount of swell under relatively light loads is not markedly affected by aging, although there is a slight tendency for swell to behave similarly to the swelling pressure. This phenomenon is explained by changes occuring in the structure of the clay following volume change (Figure 2.13b).

3) The peak values of swelling pressure and percent swell of an aged compacted clay may amount to two of three times the initial value and depend on initial conditions of moisture and density.

Srinivasan and Parcher (1971), in a discussion of Kassif and Baker's work, believe that the curing period significantly affects unit swelling values parallel and perpendicular to the direction of compaction.

<u>Time Allowed for Swelling</u>

Since soil will continue to swell until some equilibrium is reached between internal and external forces, the amount of swelling at any instant depends on the quantity of water entering the soil. The rate with which water enters the soil is a function of its permeability. In addition, the hydraulic gradient of the pore water affects the rate of water entry.

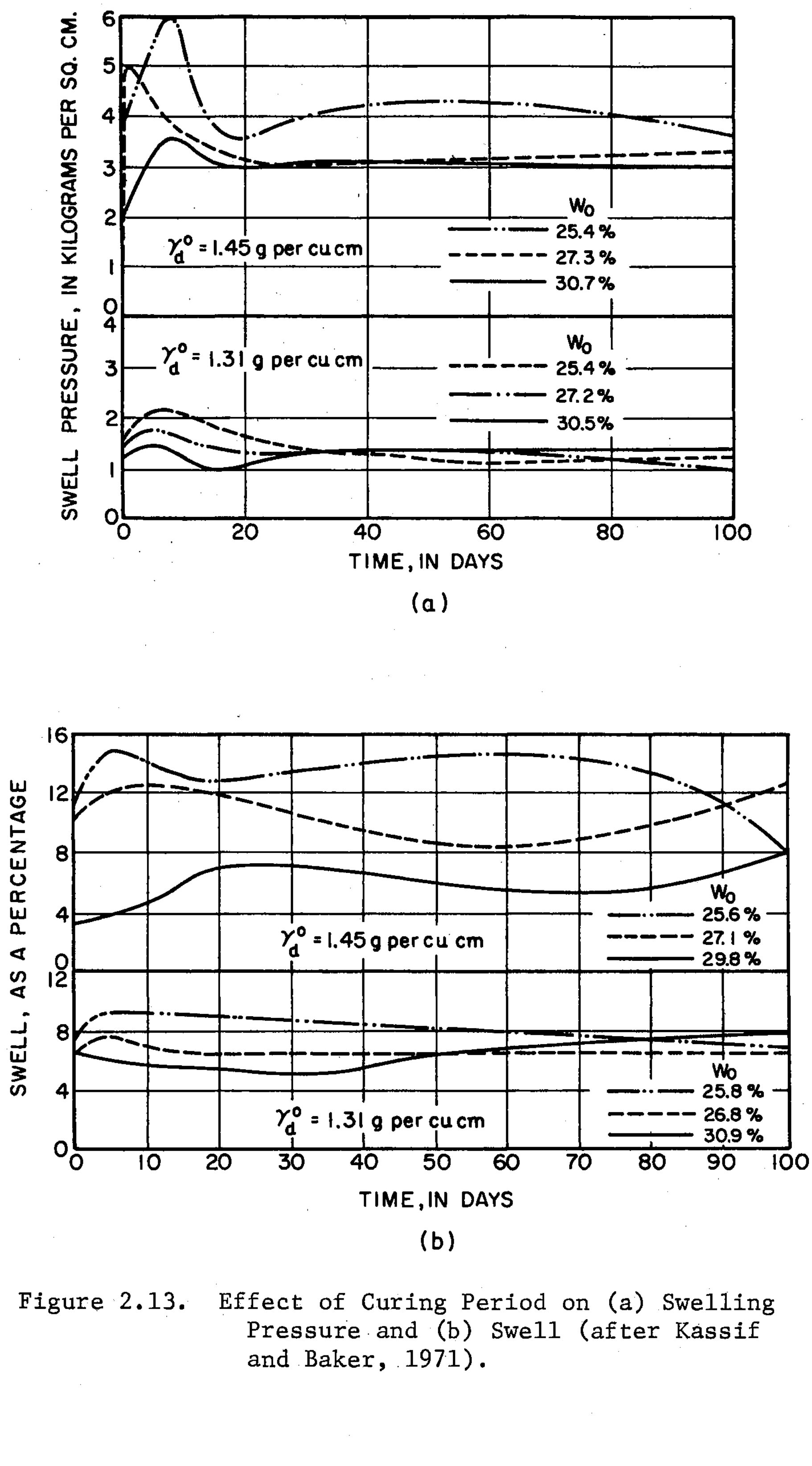


Figure 2.13. Effect of Curing Period on (a) Swelling Pressure and (b) Swell (after Kassif and Baker, 1971).

It is a generally accepted fact that clays compacted to the same density on the dry side of optimum moisture content have higher permeabilities than those samples compacted on the wet side of optimum. This is because compaction on the dry side results in a more random or flocculent structure.

Lambe (1960) studied the time period required for swelling and found that the minimum permeability exists at approximately optimum moisture content (Figure 2.14).

Temperature

The effect of temperature on swell and swelling pressure is obvious when its influence on the thickness of the double-layer water is considered. Increases in temperature tend to depress the double-layer, while temperature decreases result in double-layer expansion and soil swelling.

Previous Research on Lateral Swell and Swelling Pressure

Until the early 1960's the primary concern of researchers in the area of compacted expansive clays was measurement of vertical swell and swelling pressure. The vertical direction usually represented a direction parallel to compaction. Realizing the anistropic characteristics of expansive soils and noting damage to buried conduits, highway pavements, and foundation walls, researchers began to investigate lateral swell and swelling pressure behavior of compacted soil. In this context, lateral indicates a direction perpendicular to compaction.

One of the major problems hindering research in the area of lateral swell and swelling pressure has been the development of instrumentation to measure these values while allowing measurement of vertical

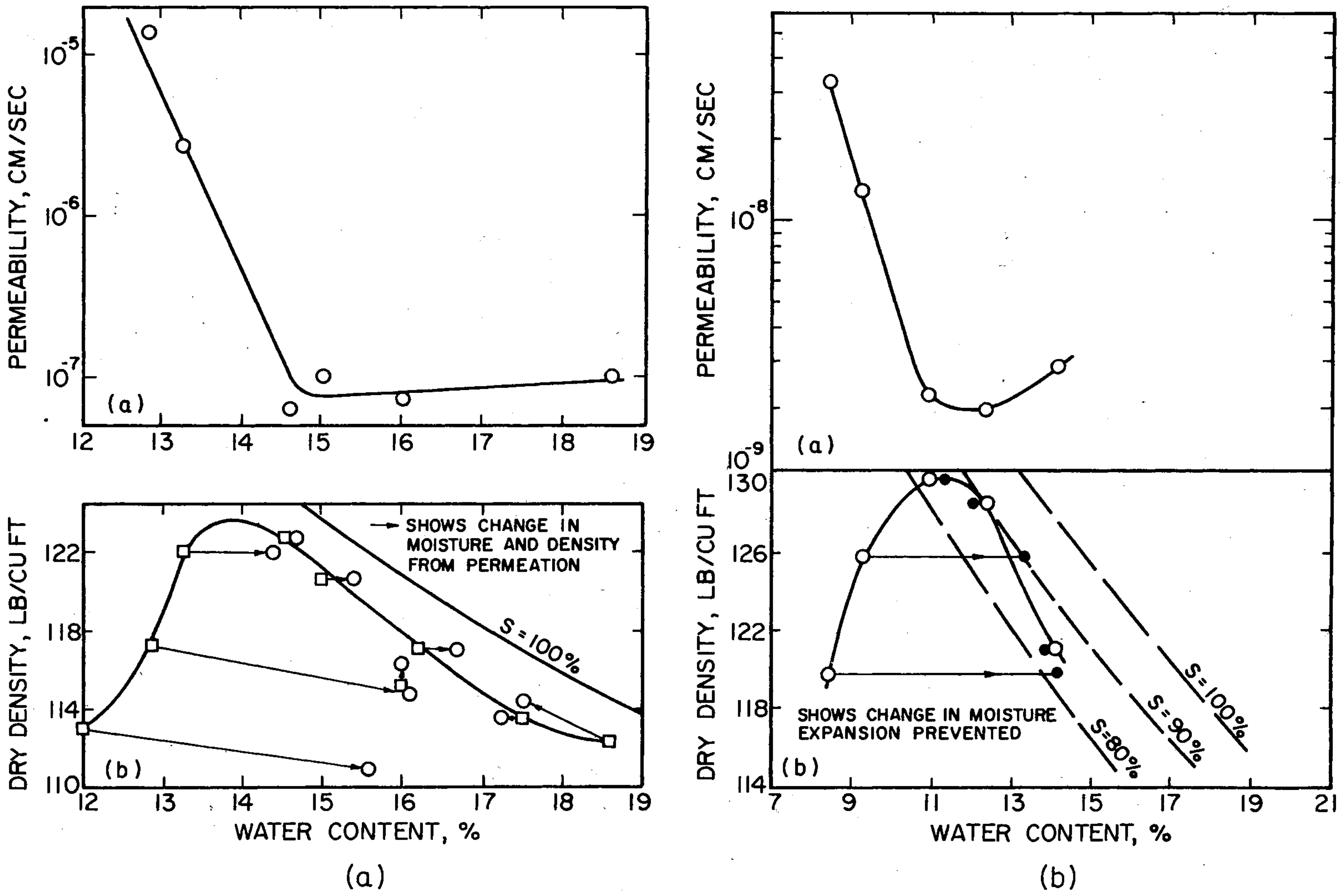


Figure 2.14. Compaction - Permeability Tests on (a) Jamaca Sandy Clay and (b) Siburua Clay (after Lambe, 1960).

swelling data. Initially, apparatus for measuring vertical swelling data were used with horizontally oriented samples trimmed from larger masses (i.e., Standard Proctor sample). This procedure gave relatively consistent results, but was time consuming.

As a result of the need for more rapid measuring procedures and a means to measure both lateral and vertical swelling data simultaneously, various devices were developed. Komornik and Zeitlen (1965) developed a special device which allowed the concurrent measurement of lateral and vertical swelling pressure. The apparatus consisted of a stainless steel ring, with its central portion turned down to a wall thickness of 0.3 mm over a height slightly less than that of the specimen under test, so that the wall action was that of a thin membrane. Three thin electrical wire conductors (of the type used in electrical-resistance wire strain gages) were stretched around the outside of the membrane at its center and quarter-height levels (Figure 2.15). The ring was calibrated by means of a piston applying pressure to a heavy oil within the ring. During testing the ring was placed in a fixed type consolidometer, which allowed the measurement of vertical swell and swelling pressure data.

Komornik and Zeitlen (1970) used the previously described apparatus to investigate the influence of various factors on lateral and vertical swelling pressures. The testing program utilized statically compacted samples of an expansive clay typical of Israel. Three initial moisture contents with three dry densities at each moisture content were used for initial placement conditions. In addition, the effects of time allowed for swell, curing period, and varying vertical confinement and load were investigated.

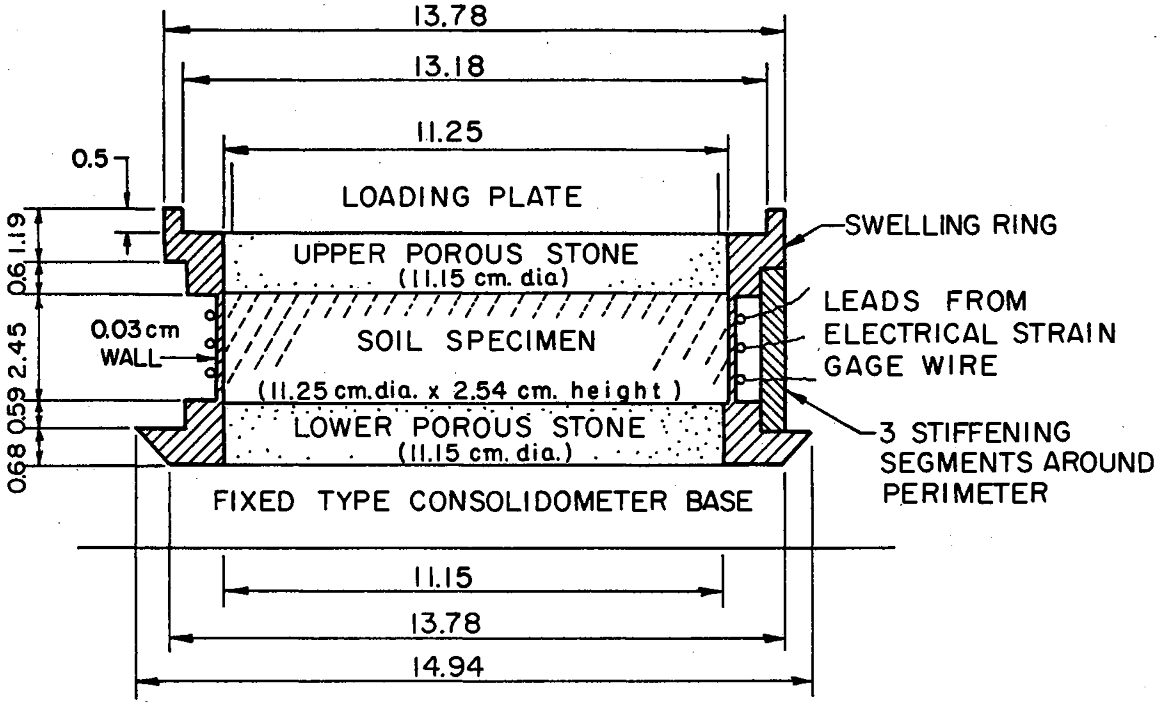


Figure 2.15. Swelling Pressure Ring for Lateral Swelling Pressure Measurements (after, Komornik and Zeitlen, 1970).

The effects of time allowed for swelling and curing period are presented in Figure 2.16a. Komornik and Zeitlen believe that the variations are the result of the specimen being in a state of prestress, resulting from compaction. Their normal procedure was to allow these stresses to dissipate prior to testing. Figure 2.16b shows the time allowed for swelling using their normal testing procedure.

The influence of initial moisture content, dry density, and vertical swell on lateral swelling pressure is presented in Figures 2.17 and 2.18. The relationship between lateral and vertical swelling pressure for the various moisture contents and dry densities is shown in Figure 2.19.

Komornik and Zeitlen's statements concerning the overall swelling characteristics of their particular soil and testing procedure were:

1) For the same density, the amount of vertical swell was larger for those specimens which were compacted at a lower moisture content.
2) For the same moisture content, the amount of vertical swell was larger for those specimens which were compacted to a higher density.
3) The swelling pressures associated with no vertical movement did not show large differences with changes in moisture content for specimens compacted to the same density.
4) The higher the density, the higher were the vertical swelling pressures, regardless of the moisture content of the sample.
5) The higher the density, the lower the compressibility.

Statements 1, 2, and 5 are generally accepted trends in the area of expansive soils and substantiate the work of many previous researchers.

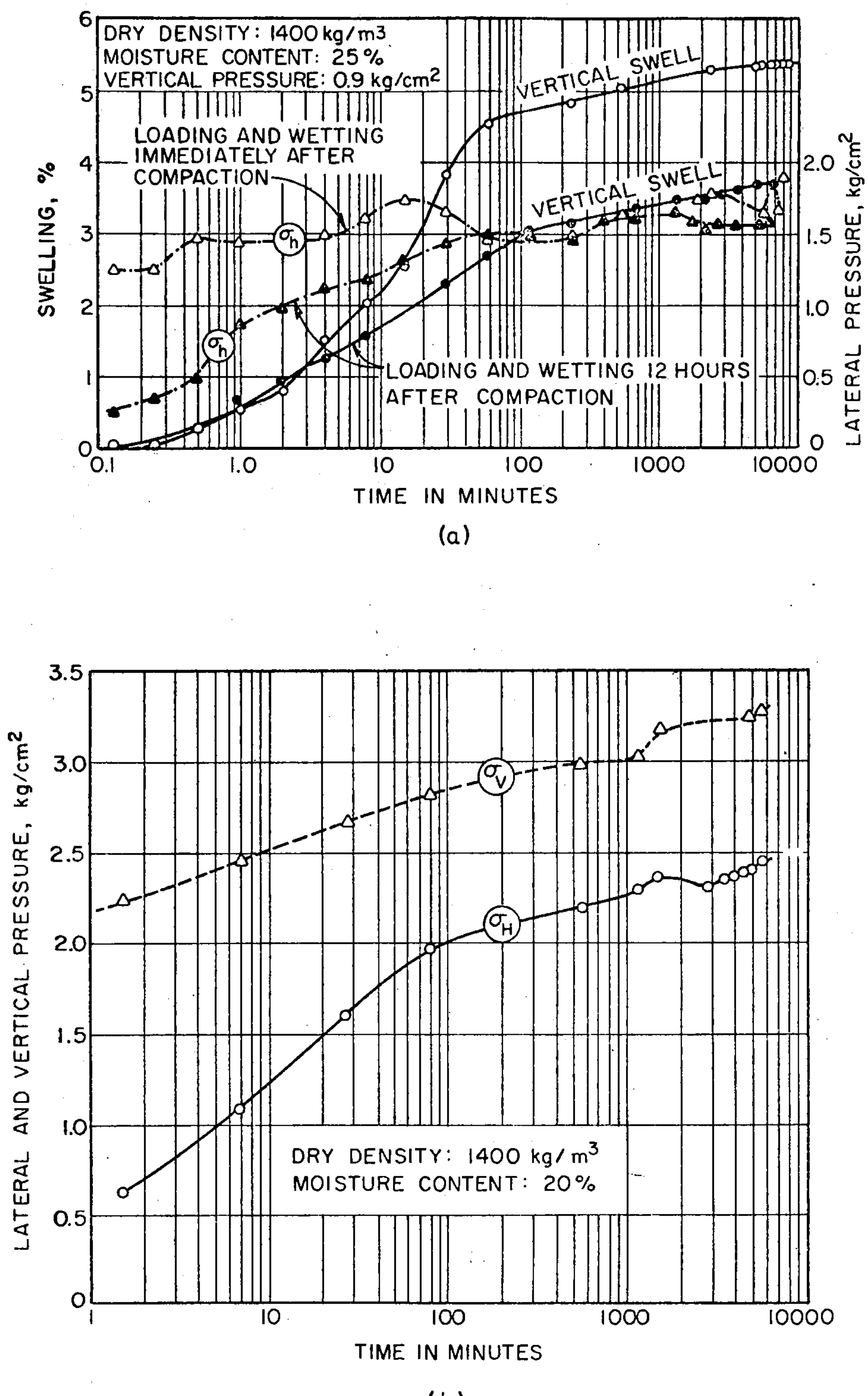


Figure 2.16. Vertical Swell and Lateral Swelling Pressure as Influenced by (a) Curing Period and (b) Time Allowed for Swelling (after Komornik and Zeitlen, 1970).

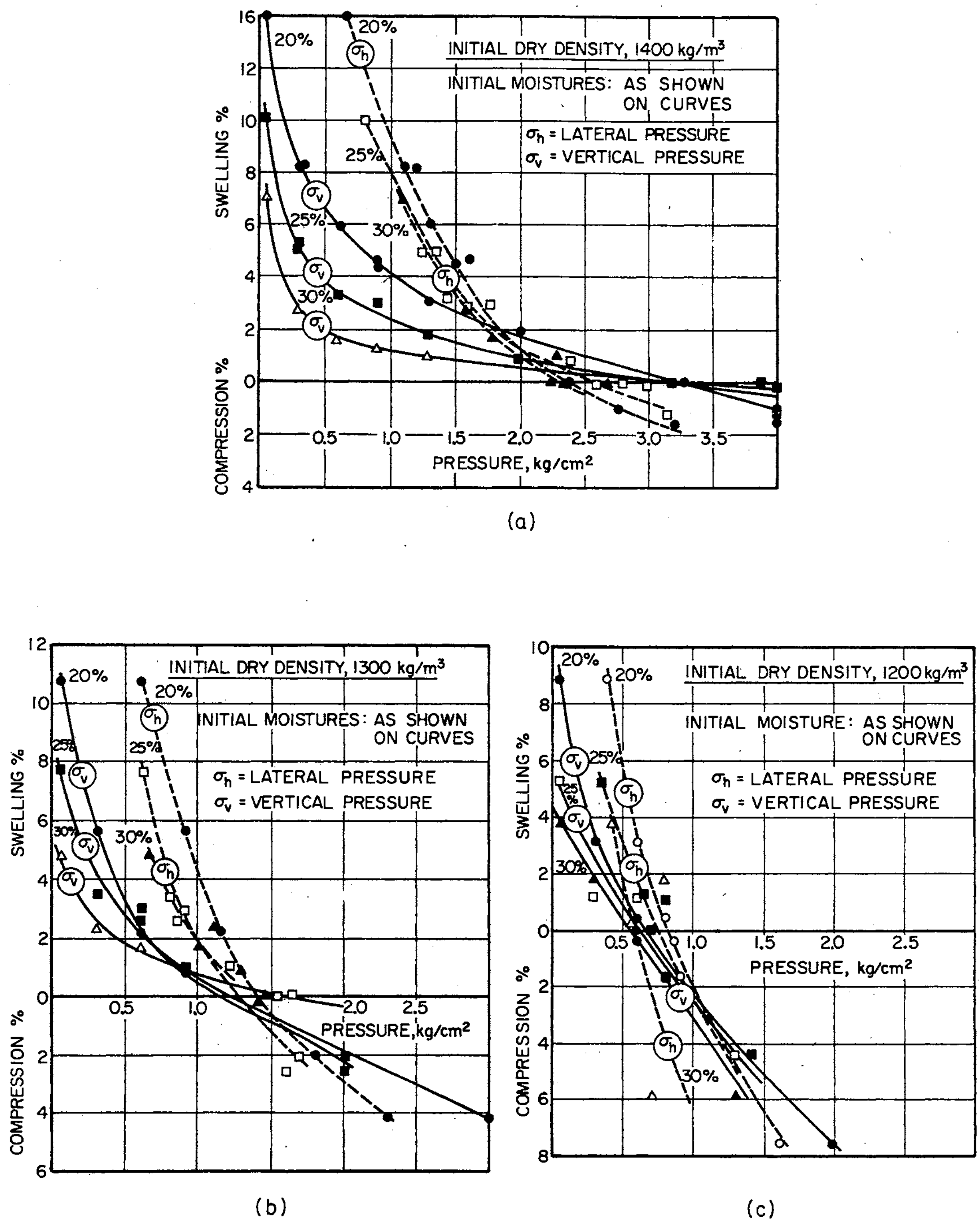


Figure 2.17. Amount of Vertical Swell versus Vertical and Lateral Swelling Pressure for Various Dry Densities: (a) 1400 Kg/m^3; (b) 1300 Kg/m^3; and (c) 1200 Kg/m^3 (after Komornik and Zeitlen, 1970).

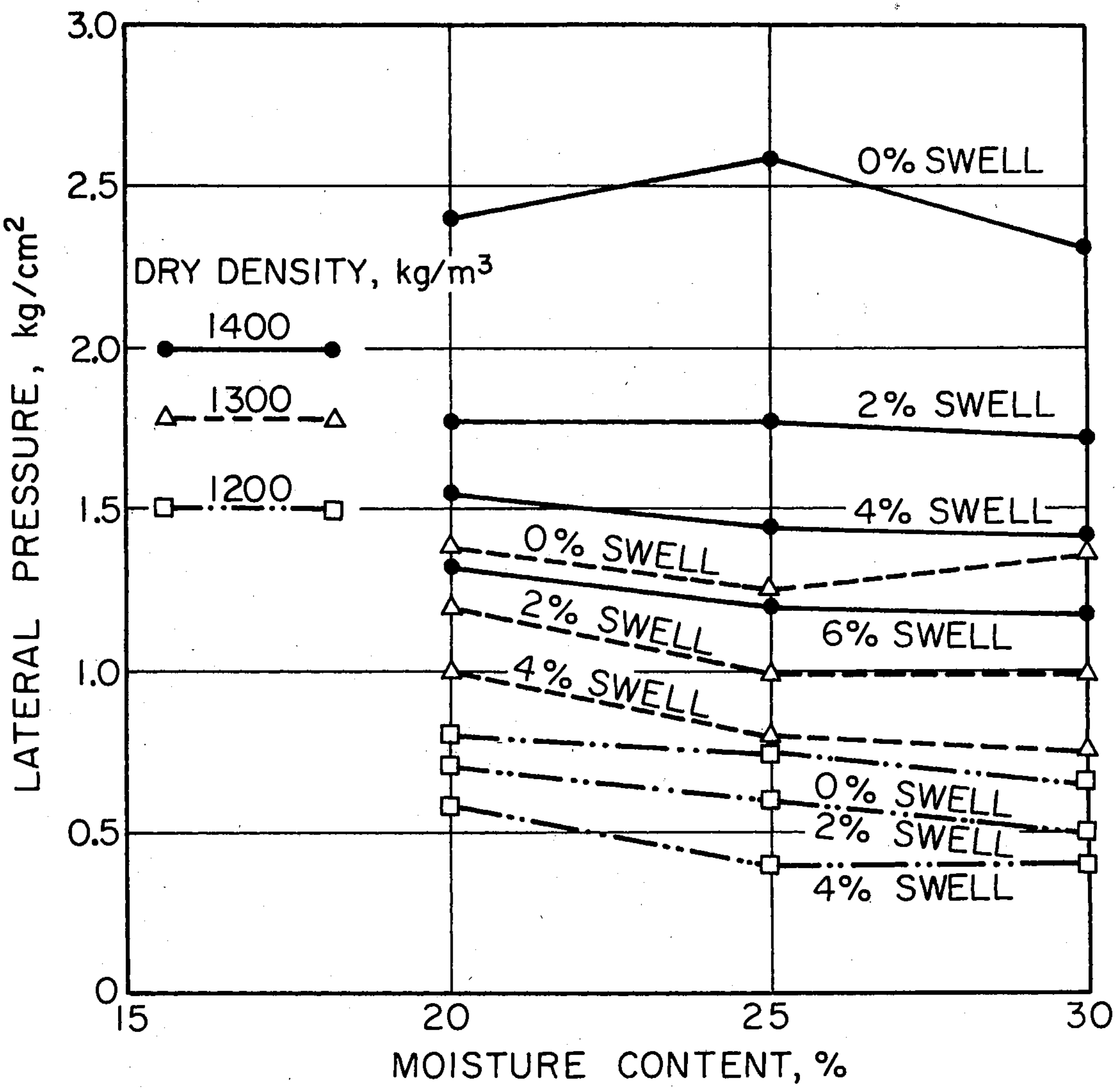


Figure 2.18. Lateral Swelling Pressure versus Initial Moisture Content at Various Percentages of Vertical Swell (after Komornik and Zeitlen, 1970).

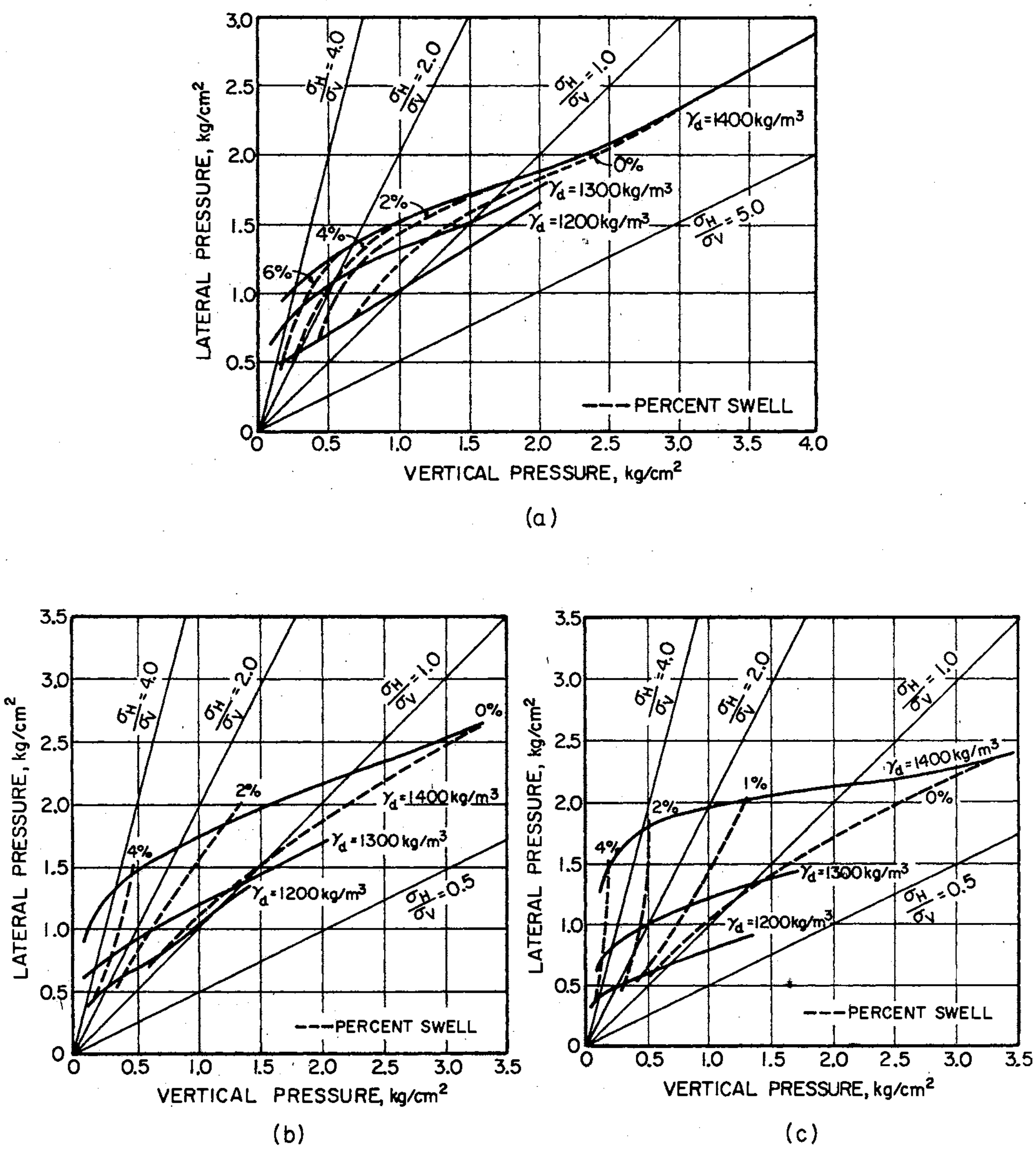


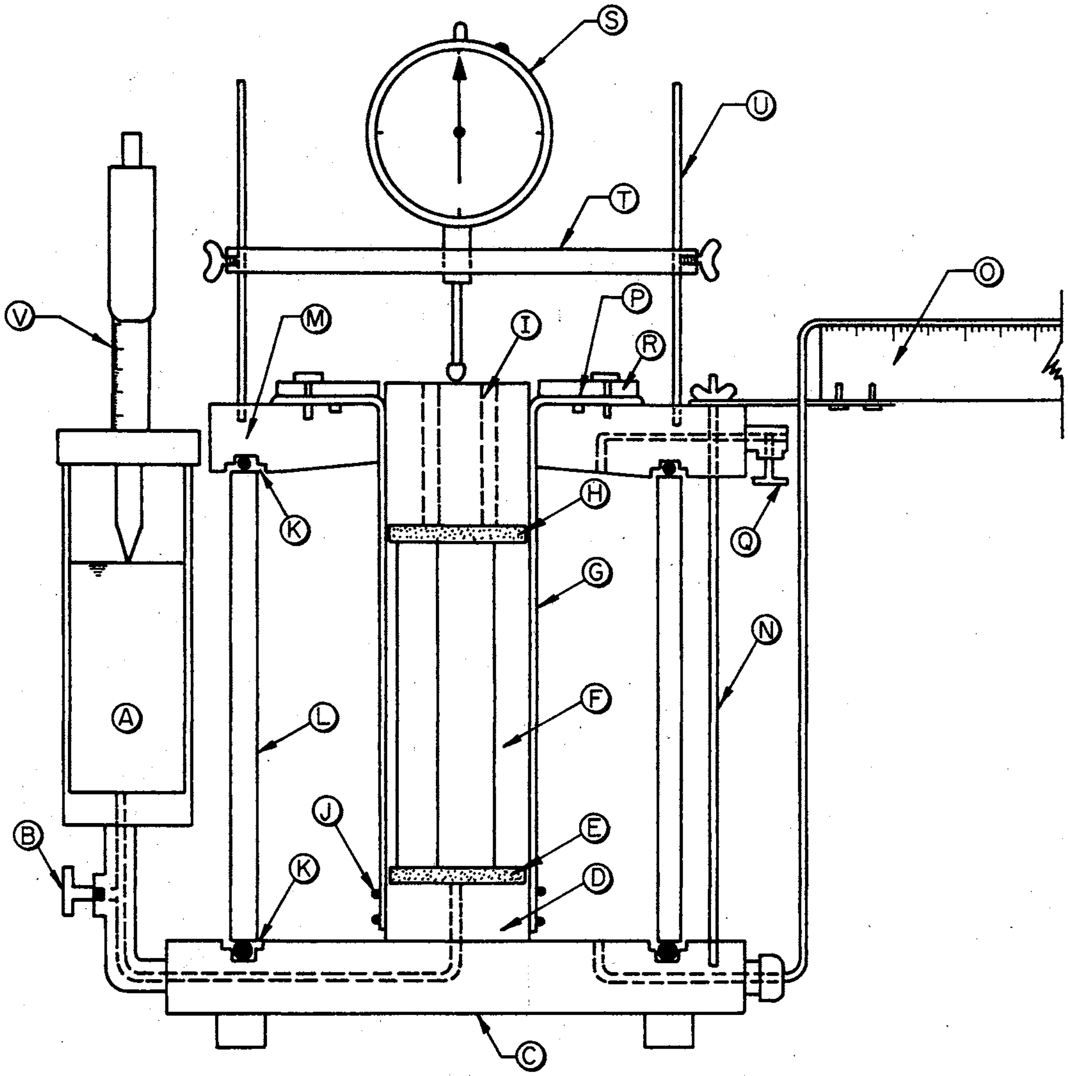
Figure 2.19. Relationship Between Lateral and Vertical Swelling Pressure for Various Initial Moisture Contents: (a) w = 20%; (b) w = 25%; and (c) w = 30% (after Komornik and Zeitlen, 1970).

However, statements 3 and 4 tend to contradict the generally accepted behavior. One possible explanation for the data which lead to these statements lies in the fact that static compaction nearly always results in a flocculent structure, and increasing the dry density would result in a similar structure, only more dense. Thus, the variation of structure with moisture content which is evident from compaction theory and the influence of this variation on swelling behavior is minimized.

Concerning lateral swelling pressure the authors stated:

1) The higher the density, the higher the lateral swelling pressure.
2) Although, for the same dry densities, the effects of molding moisture content on lateral swelling pressure is small, lateral swelling pressure tends to be higher at lower moisture contents.
3) When the influence of molding moisture content is examined for specimens showing equal percentages of swell, it may be seen that the lateral pressure developed is not particularly dependent on the moisture content, but mainly on the densities.
4) The larger the vertical load, the higher the lateral swelling pressure.

Fost (1962) describes an apparatus developed under the supervision of Dr. J. V. Parcher at Oklahoma State University, which allows the concurrent measurement of lateral and vertical swell of compacted soils. The apparatus (Figure 2.20) consists of a plexiglass cell in which a sample enclosed by a rubber membrane is placed. The cell is then filled with water and the average lateral swell is determined by measuring the amount of water displaced by the swelling soil. The vertical swell was measured by means of a dial gage.



Ⓐ - WATER RESERVOIR
Ⓑ - LOWER VALVE
Ⓒ - BASE PLATE
Ⓓ - PEDESTAL
Ⓔ - POROUS STONE 1
Ⓕ - SPECIMEN
Ⓖ - FLANGED MEMBRANE
Ⓗ - POROUS STONE 2
Ⓘ - CAP
Ⓙ - LOWER O-RING MEMBRANE SEAL
Ⓚ - O-RING CHAMBER SEAL (TOP AND BOTTOM)
Ⓛ - CHAMBER
Ⓜ - TOP PLATE
Ⓝ - VERTICAL TIE RODS
Ⓞ - METER STICK
Ⓟ - O-RING FLANGE SEAL
Ⓠ - UPPER VALVE
Ⓡ - COVER PLATE
Ⓢ - DIAL GAGE
Ⓣ - GAGE HOLDER
Ⓤ - GAGE HOLDER RODS
Ⓥ - NEEDLE POINT MICROMETER WATER LEVEL GAGE

Figure 2.20. Details of Triaxial Swelling Apparatus (after Parcher and Liu, 1965).

Liu (1964) utilized the previously described apparatus to investigate the swelling behavior of the Permian Red Clays of West Central Oklahoma. As well as substantiating the generally accepted trends concerning the influence of initial moisture content, dry density, and time, his data indicate some interesting facts about different compaction modes and energies and their effects on lateral and vertical swell. He concluded that for samples having the same initial moisture content and dry density, those prepared using static compaction swell more than those molded by kneading compaction or impact compaction. The amount of swelling of statically compacted samples is larger compared to that of samples compacted by kneading; but there is little difference in the volume of swelling of statically and dynamically compacted samples (Figure 2.21).

It may also be noted from Figure 2.21 that the horizontal swell exceeds the vertical swell in most cases.

In other investigations on the Permian Clays by Ozkol (1965) and Srinivasan (1970) similar results were obtained.

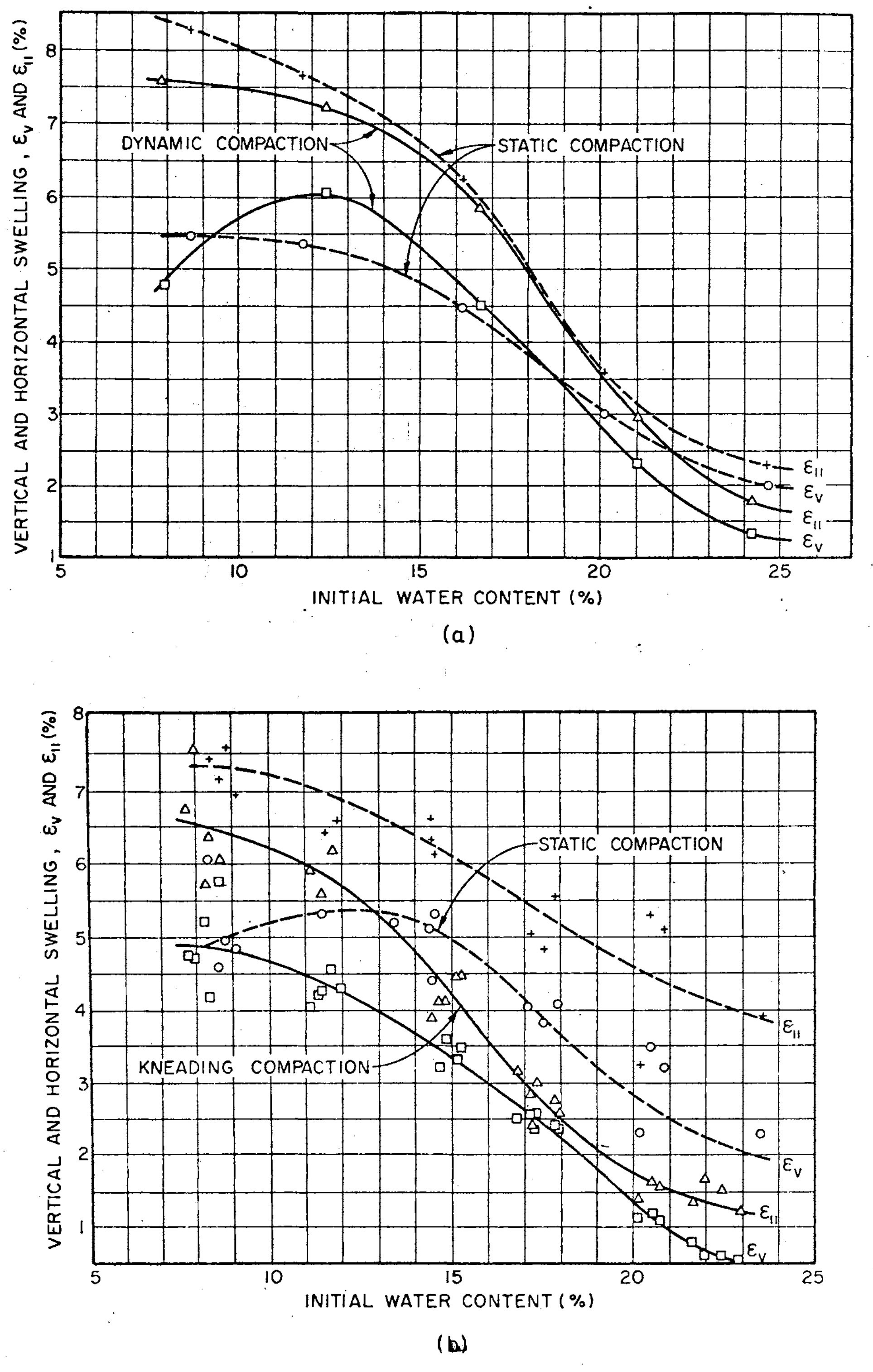


Figure 2.21. Effect of Initial Moisture Content on Swelling (a) Comparison of Dynamic and Static Compaction (b) Comparison of Kneading and Static Compaction (after Liu, 1964).

CHAPTER III

MATERIALS, LABORATORY EQUIPMENT, AND PROCEDURES

Introduction

This Chapter describes the soils, equipment, and procedures used to carry out the research on lateral swelling pressure. The physical and geological properties of the two soils are presented. The section on equipment describes the modification of a previously developed apparatus so that lateral swelling pressure could be measured. In addition, a brief description of other apparatus that were tried and found unsuitable for lateral swelling pressure measurement is included. Sample preparation and testing procedures are also described.

Materials

The entire research program was carried out on two native Oklahoma soils, with different index properties and geologic histories.

One soil is a low to medium plasticity red clay, abundant in the central portion of Oklahoma. This area of Oklahoma is characterized by sedimentary deposits which were laid down during the Permian Period. Later deposits during the Mesozoic Era covered the Permian Red Beds to a depth of 400 to 600 feet. As a result of uplifts in later geologic history the general slope of the area was altered and erosion of the Mesozoic deposits began. Through the ages nearly all of the Mesozoic material has been removed. The resulting exposed Permian deposits are heavily overconsolidated with preconsolidation pressures in the range of 20 to 30 tsf. In addition, the surface clays have been subjected to many cycles of saturation and drying, resulting in apparent preconsolidation or swelling pressures from desiccation in the range of 3 to 5 tsf. The inherent red color of the Permian Red Clay (PRC) is indicative of the presence of iron oxide. PRC possesses a moderately high tendency to shrink and swell with changes in moisture content. The PRC used to carry out the research program was obtained from the excavation for a new fine arts building being constructed on the campus of the Oklahoma State University at Stillwater. The clay was obtained from a depth of approximately ten feet below the existing surface in the southeast corner of the excavation.

The second soil is a high plasticity gray clay from Roger Mills County in western Oklahoma. In this area the deposit is approximately 60 feet thick and underlain by the Permian Red Beds. The material is thought to be the result of outwash plains extending from the Rocky Mountain uplift. It is somewhat less overconsolidated than the Permian deposits. The gray color indicates an absence of high percentages of iron oxides. The Roger Mills Gray Clay (RMGC) used throughout the study was obtained from a depth of approximately three feet below the surface on private land seven miles west of Roll, Oklahoma (Section 11, R25W, TWP15N).

Index properties of PRC and RMGC are presented in Table II. As indicated, the two soils have different physical properties. Grain size distribution curves for both PRC and RMGC are presented in Figure 3.1. The PRC contains lower percentages of the coarse clay fraction, while the RMGC contains lower percentages of the fine clay fractions. The compaction characteristics for PRC and RMGC are shown in Figure 3.2. Compaction tests were carried out using Standard Proctor procedures (3 layers, 25 blows per layer) with the Harvard Miniature mold and O.S.U. impact hammar. As indicated, the particular PRC tested has an optimum moisture content of 19.4% and 102.1 pcf maximum dry density. The optimum moisture content and maximum dry density for RMGC are 22.7% and 92.8 pcf, respectively.

TABLE II

PHYSICAL PROPERTIES OF PRC AND RMGC

Properties	PRC	RMGC
Specific Gravity	2.79	2.72
Liquid Limit	47.4	61.6
Plastic Limit	20.4	25.5
Plasticity Index	27.0	36.1
Flow Index	6.7	14.9
Toughness Index	4.0	2.4
Activity Number	0.59	1.03
Linear Shrinkage *	16.7%	16.7%
Free Swell **	22.0%	26.0%

*THD Bar Method

**Lambe (1960)

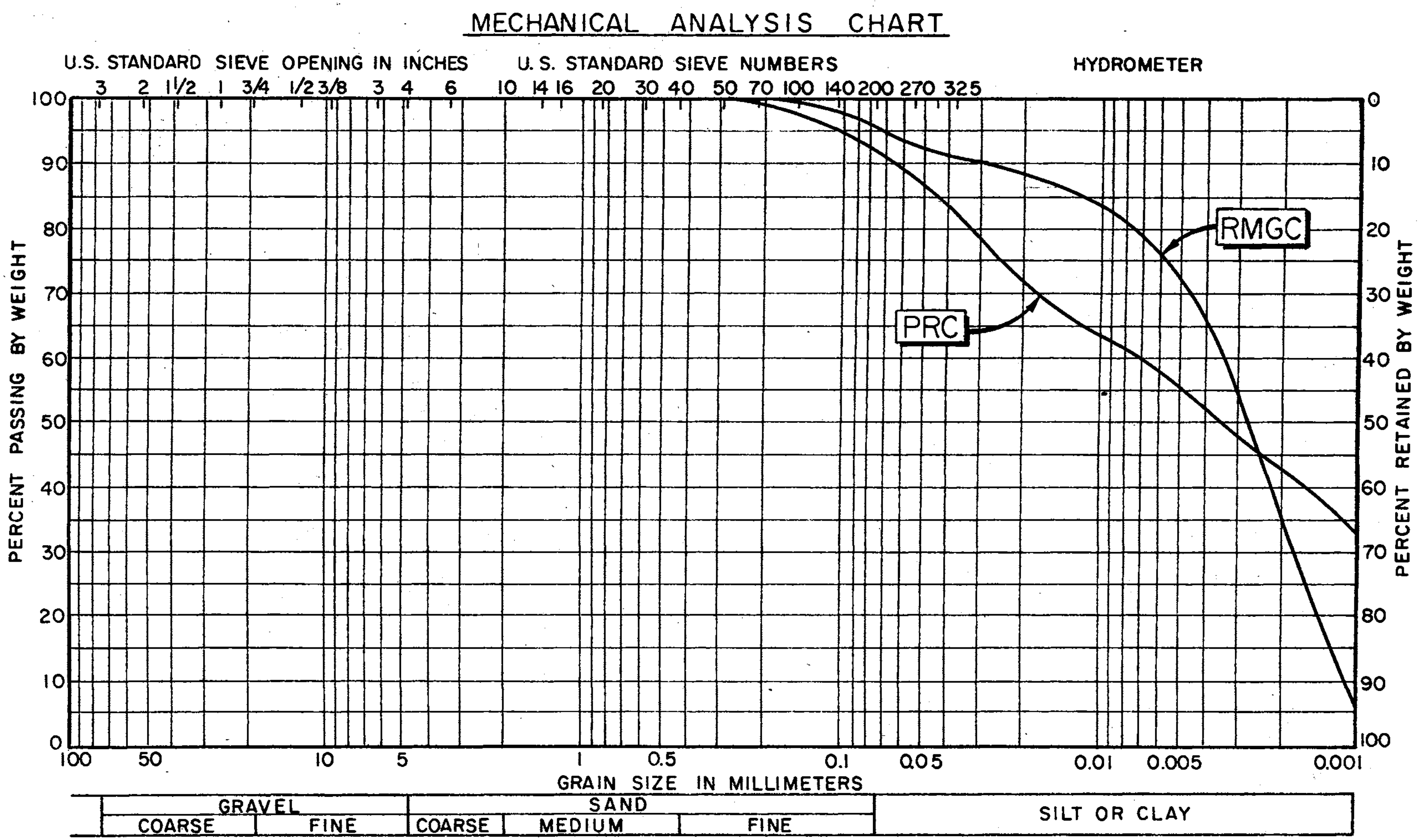


Figure 3.1. Grain Size Distribution Curves for PRC and RMGC.

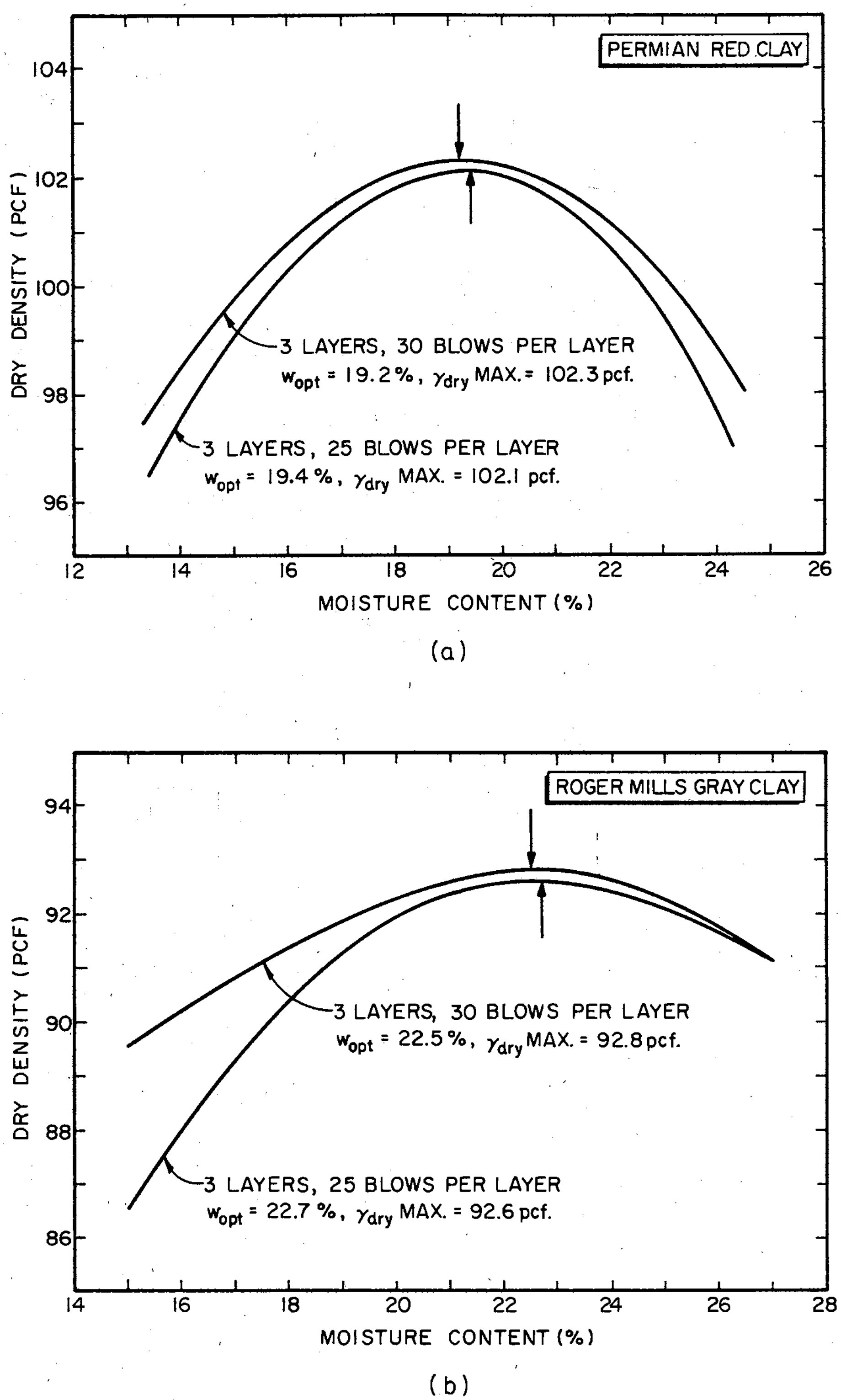


Figure 3.2. Moisture - Density Curves for (a) PRC and (b) RMGC.

Equipment

As previously discussed in Chapter II, one of the major problems hindering research in the area of lateral swell and swelling pressure was the development of instrumentation which would allow concurrent measurement of lateral and vertical swelling data. A portion of this research program was to develop a device which would allow simultaneous measurement of lateral and vertical swelling data. Several devices were tried and evaluated. Before describing the actual apparatus used for data collection, a brief discussion will be presented concerning the problems encountered with devices which did not work.

The first apparatus investigated consisted of a stainless steel ring (1.000 in. high, 2.500 in. ID, and 0.050 in. wall thickness), instrumented with two semiconductor strain gages, placed at center height and on opposite sides of the ring. A soil sample was to be placed in the ring and allowed free access to water. The ring stress would reflect the lateral component of soil swelling pressure, while the vertical component would be measured by a 0.50 in. stainless steel rod instrumented with the same type of strain gages. The major problem with this device was semiconductor strain gage output variation resulting from minute changes in temperature and humidity. The magnitude of the expected strains was in the range of five to ten microinches, therefore, very slight variations in temperature and humidity caused considerable discrepancies in the output. Problems also developed in calibration, since it was virtually impossible to apply a uniform calibration pressure to the interior surface of the ring. All attempts to calibrate the ring resulted in different nonlinear curves relating pressure to strain indicator reading. It could also be argued that measuring strain at two points on the circumference of the ring does not consider the possibility of strain variation over the height of the ring. The stainless steel rod proved to be much easier to calibrate, but was still sensitive to changes in ambient environmental conditions.

A second device consisted of a piezoelectric ceramic ring (1.00 in. high, 2.50 in. ID, and 0.25 in. wall thickness), instrumented with a thin coating of silver on the inside and outside diameters which acted as electrodes. Piezoelectricity is the generation of electrical charge in a material by a mechanical stress that changes its shape or a proportional change in the shape of a material when voltage is applied. In other words, it is a means of converting mechanical energy into electrical energy and vice versa. A sample of compacted clay placed in the ring and allowed to imbibe water would swell and cause the mechanical deformation needed to produce a change in voltage across the interior and exterior surfaces. One problem with the piezoelectric ring involved insulating the interior and exterior surfaces so the system would not ground itself when placed in water. A light spray coating of Teflon seemed to alleviate this problem. The major problem involved the time-dependent charge "drain-off", which is an inherent characteristic of piezoelectric materials. A major use of these materials is in the area of electroacoustics, where measurements are made instantaneously. Swelling pressure does not develop immediately, therefore the device was very susceptible to charge reduction with time, causing serious discrepancies in the collected data.

A third device consisted of two concentric rings, a thin inner ring (1.000 in. high, 2.500 in. ID, and 0.025 in. wall thickness) and a heavy exterior ring (2.000 in. high, 2.650 in. ID, and 0.250 in. wall thickness). With the interior ring in place an annular distance of 0.050 in. existed between the two rings. The basis of measurement for this device relied on the change of capacitance across the annular distance. As the soil expanded in the interior ring, causing it to deform and result in a decrease of the annular distance, the change in capacitance could be measured. Calibration of the ring with respect to applied pressure and capacitance change was accomplished easily, however, the sensitivity was restricted by available output instrumentation. The dielectric material used (in the annular space) for this device was air, which caused problems with output variation, resulting from changes in air temperature and humidity between the rings. This problem evolved as a result of poor or incomplete sealing of the annular space. The vertical stress, in this case, was to be measured by a 1000 lb BLH strain gage load cell.

Comparing the relative merits of the previously described devices, the capacitance ring would probably be best suited to meet the requirements for measuring lateral swelling pressure. However, the device needs some refinements, such as: precise machining of rings to provide a completely smooth and uniform annular spacing; a special holding plate to maintain uniform annular spacing; and possibly some type of soft, deformable, dielectric material in the annular space to reduce temperature and humidity effects.

As a result of the problems encountered in trying to develop a device which would allow concurrent measurement of lateral and vertical swelling pressures, an apparatus which measured only the lateral swelling pressure was used. The vertical swelling pressure was then measured by a load cell-type device, utilizing samples compacted by the same mode of compaction and to the same moisture content and dry density as the lateral swelling pressure samples.

The lateral swelling pressure was measured using a modified version of a device described by Fost (1962). The apparatus, shown in Figure 3.3, is made entirely of plexiglas. Modifications made to Fost's version were: a top plate to inhibit vertical movement, a procedure by which water could be applied to both ends of the sample under back pressure, and the use of a pressure transducer and strip chart recorder to measure and record the lateral swelling pressure.

A compacted sample surrounded by filter paper and a rubber membrane was placed in the cell and the cell filled with de-aired distilled water. Water from the reservoir was introduced to the sample under back pressure, causing the swelling pressure to develop. Since the system was sealed, the water surrounding the sample would maintain (for all practical purposes) zero deformation and transmit the developed swelling pressure to the pressure transducer, which translated the mechanical force to an electric signal for the strip chart recorder.

The pressure transducers used in the research program were manufactured by Consolidated Engineering Corporation and had a range of 0 to 100 psia. Each transducer was placed in a specially machine plexiglas container equipped with a reservoir, toggle valve and two quick-connect fittings (Figure 3.4). One fitting allowed connection to the swelling pressure cell and the other allowed removal of small amounts of water from the system so that the effect of lateral swell on lateral swelling pressure could be investigated.

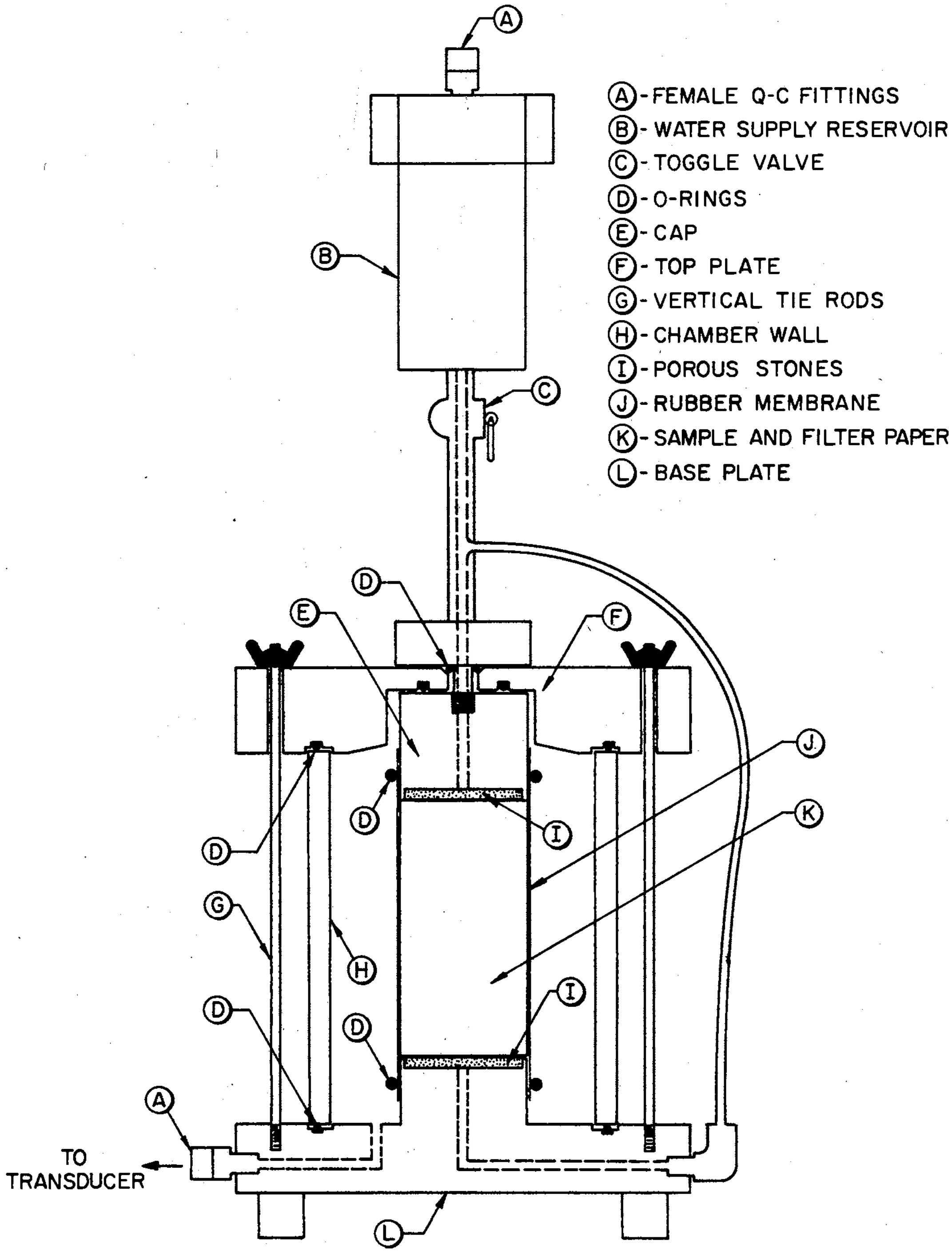
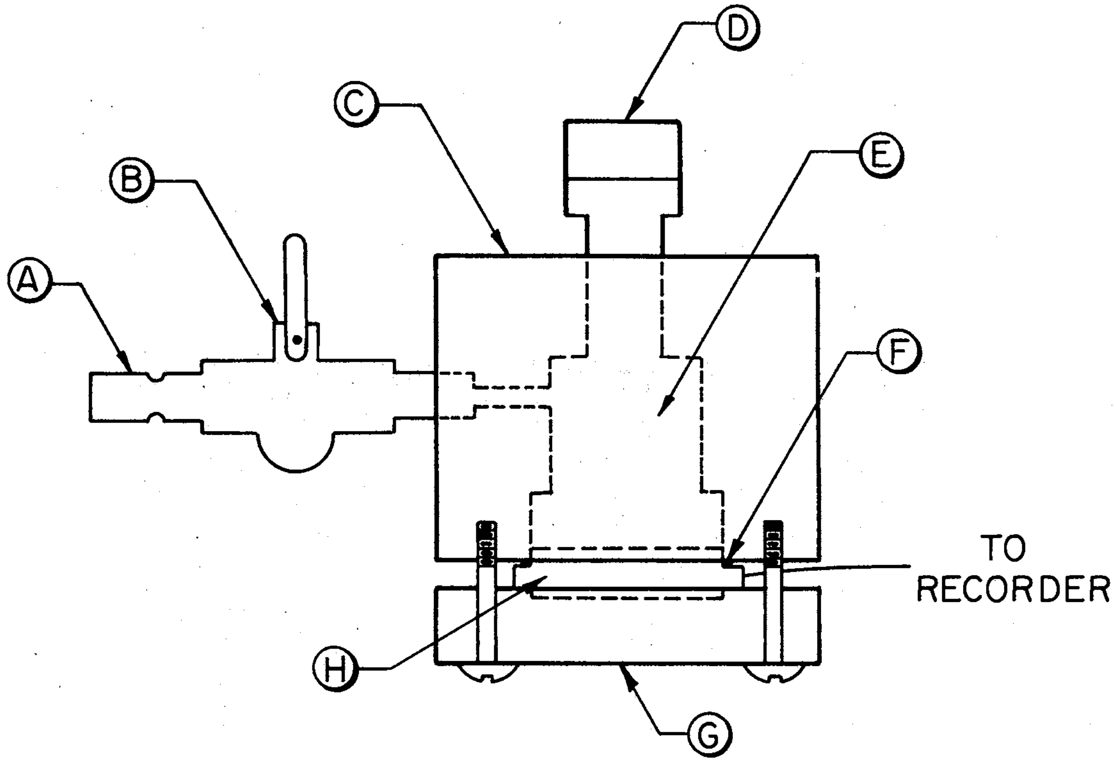


Figure 3.3. Diagram of Lateral Swelling Pressure Cell.



Ⓐ - MALE Q-C FITTING
Ⓑ - TOGGLE VALVE
Ⓒ - PLEXIGLASS CYLINDER
Ⓓ - FEMALE Q-C FITTING
Ⓔ - RESERVOIR
Ⓕ - O-RING
Ⓖ - HOLDING PLATE
Ⓗ - PRESSURE TRANSDUCER

Figure 3.4. Diagram of Pressure Transducer Assembly.

During early stages of testing, a major problem developed which seemed to affect final swell pressure data considerably. The lateral swelling pressure would develop and then drop off to approximately zero in a relatively short time (approximately 2 to 3 hours). It was thought the problem evolved from back pressure application of water to both ends of the sample and the use of small strips of filter paper along the sides of the sample. As a result, the water did not penetrate the sample uniformly and the end portions would swell and consolidate the drier center portion. Enough particle reorientation appeared to occur such that the sample was useless for any further data collection. To alleviate the problem, a 1/8 in. hole was drilled through the long axis of the sample while it was still in the mold and a 0.125 in. OD by 0.031 in. wall thickness nylon tube (same length as the sample) with numerous small slits cut along its length was placed in the hole. The nylon tube had enough stiffness that negligible distortion of the hole could occur from swelling. This tube allowed water to reach the interior portion of the sample more rapidly. In addition, the sample was completely surrounded by a single piece of filter paper equal in size to the circumferential area of the sample. Use of the nylon tube and a solid sheet of filter paper allowed water to enter the sample more uniformly and let the swelling pressure reach its maximum value.

A typical set-up, showing swelling pressure cell, pressure transducer device, and recorder is pictured in Figure 3.5.

Vertical swelling pressure was measured using the apparatus pictured in Figure 3.6, consisting of a small fixed frame which held the BLH-U1 1000 lb. strain gage load cell and a plexiglas bowl into which the sample was placed for immersion. The influence of vertical swell on vertical

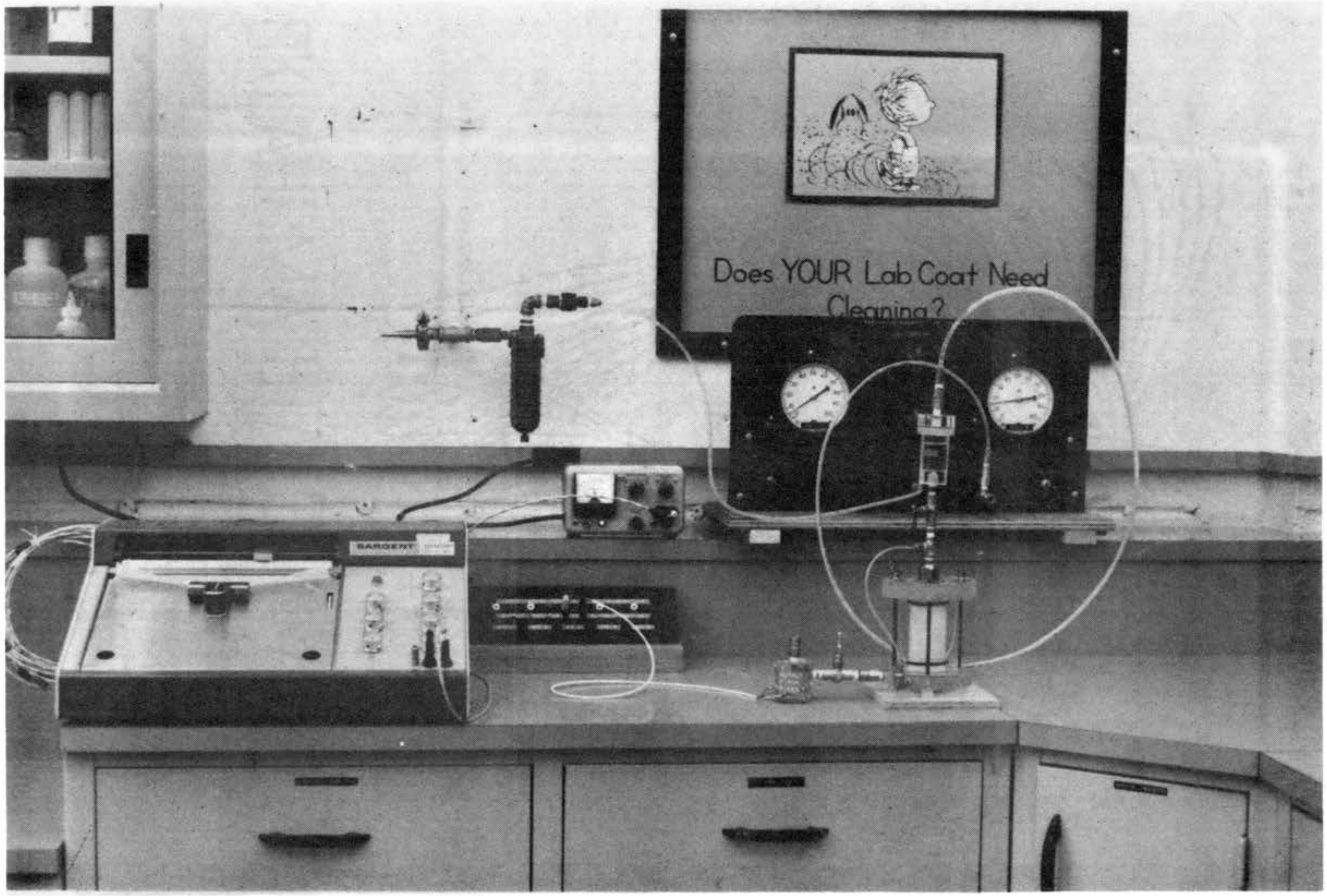


Figure 3.5. Test Assembly for Lateral Swelling Pressure Measurement.

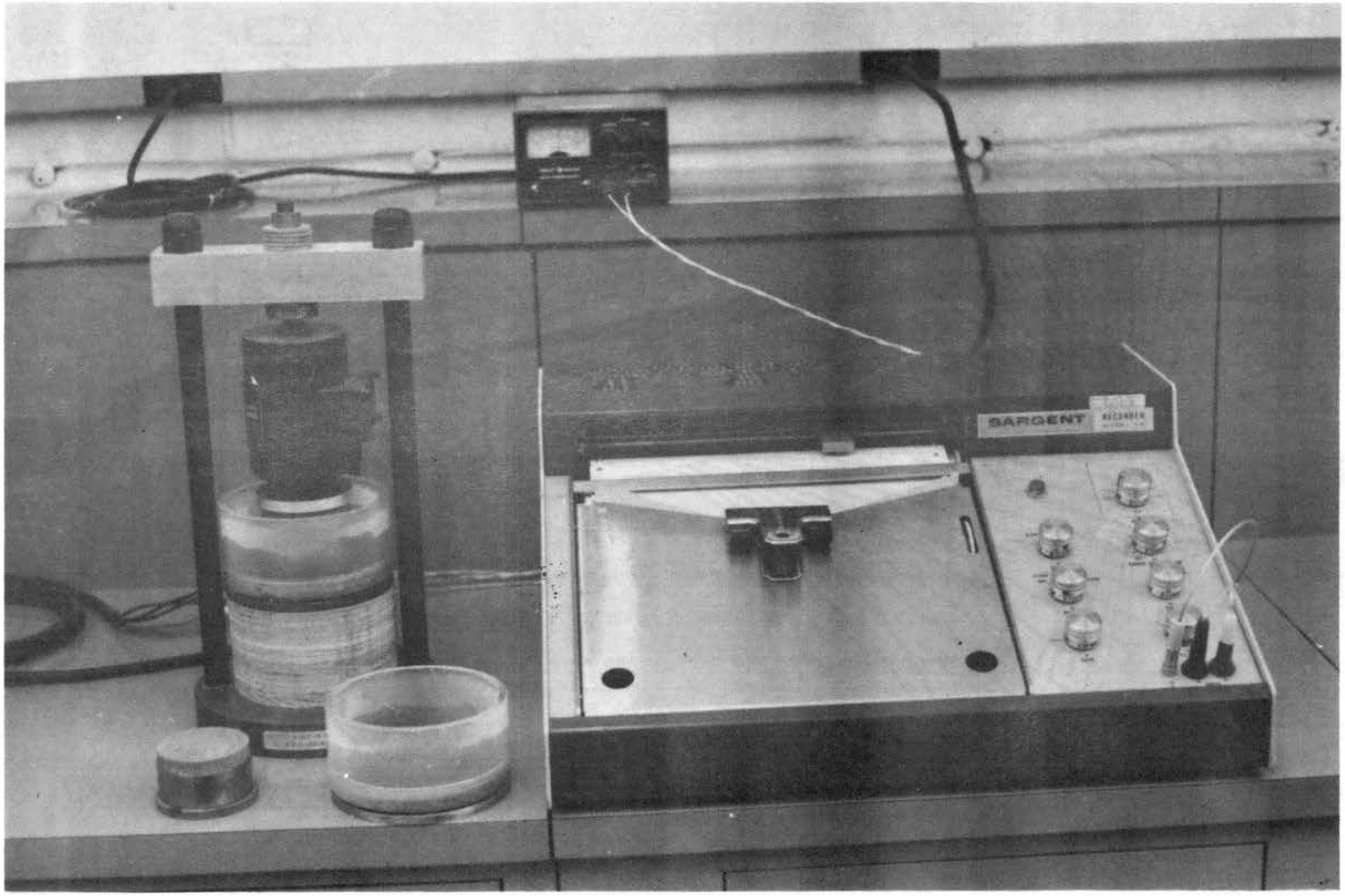


Figure 3.6. Test Assembly for Vertical Swelling Pressure Measurement.

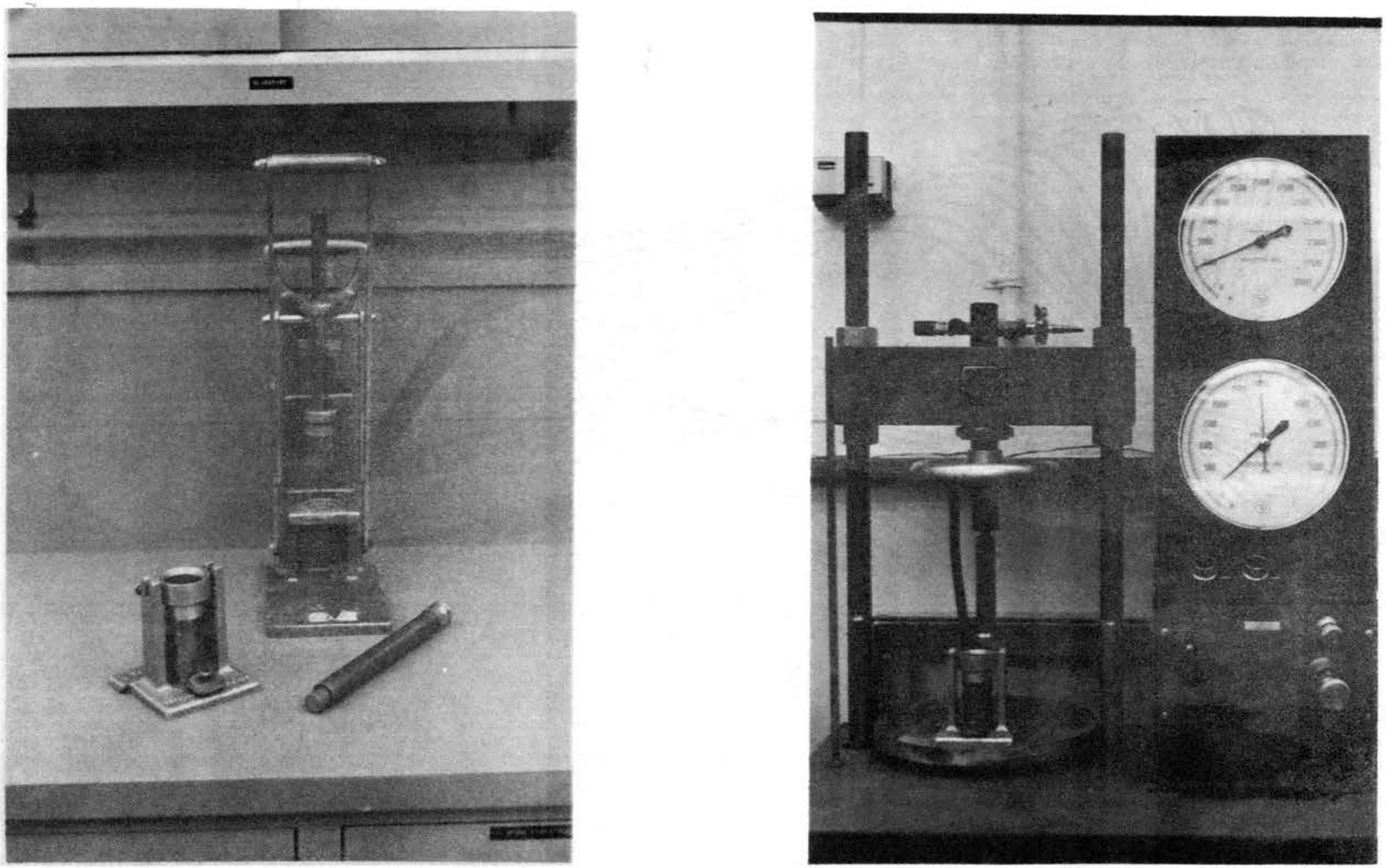


Figure 3.7. Compaction Equipment for Lateral Swelling Pressure Samples.

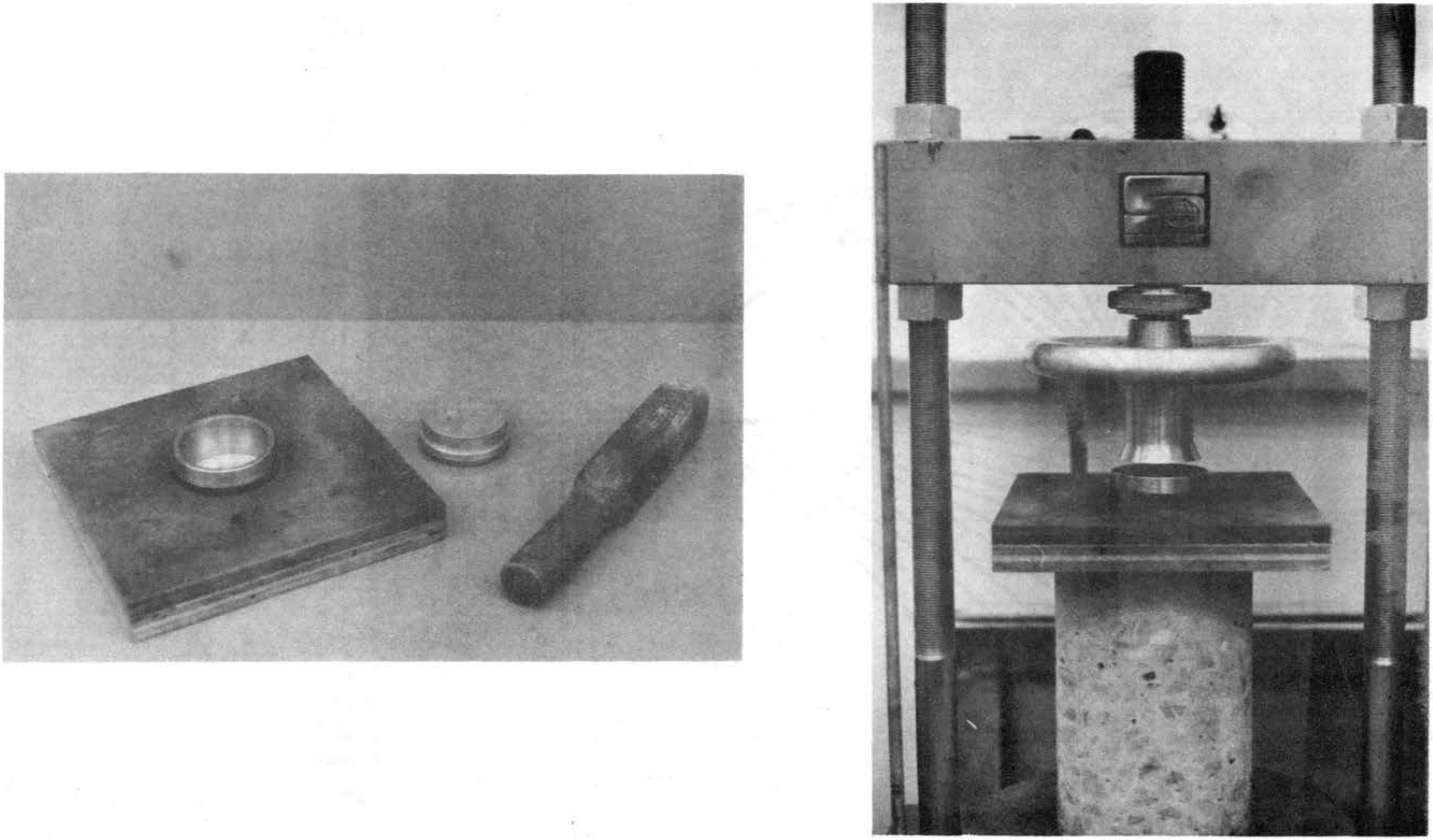


Figure 3.8. Compaction Equipment for Vertical Swelling Pressure Samples.

swelling pressure was investigated by rotating the platen on the load cell (1/8 revolution equals 0.00625 in. deformation) after constant swelling pressure conditions were established.

Procedures

The discussion of procedures used during the research program will be broken into two major catagories; sample preparation and testing procedure.

Sample Preparation

For the lateral swelling pressure measurements, all samples were compacted in Harvard Miniature molds using the O.S.U. impact hammer (Figure 3.7a). Prior to compaction, large amounts of PRC and RMGC, which had been ground to minus U.S. No. 40 sieve size, were oven-dried and stored in desiccators until needed. Enough dry soil for one sample and a moisture content test was weighed out and water added until the design moisture content was reached. The soil and water were allowed to sit for approximately 24 hours, then mixed and compacted. As previously mentioned, a 1/8 in. hole was drilled through the sample and a slotted plastic tube placed in the hole while the sample was still in the mold. The sample was extruded and placed in a sealed plastic bag for approximately 24 hours prior to testing. As a check on the influence of structure (as determined by compaction method) on lateral swelling pressure, several samples were compacted statically in Harvard Miniature molds using a hydraulic testing machine and static compaction foot (Figure 3.7b).

Vertical swelling pressure samples were compacted by impact and static methods. The procedure for sample preparation prior to actual compaction was the same as that used for lateral pressure samples. Equipment used for the compaction of these samples is shown in Figure 3.8. The procedure consisted of mixing the samples uniformly and placing 1/3 of the required amount of soil for the design dry density in the stainless steel ring (1.250 in. high by 2.500 in. ID) and applying an impact force to the compaction block with a wooden mallet. A small rib on the compaction block restricted penetration into the ring beyond a pre-measured distance, so that the final compacted sample was 1.00 in. high and consisted of three uniform layers. Statically compacted samples were prepared in the same manner, except that hydraulic testing machine was used to apply the force at a relatively low loading rate. After compaction the samples were extruded from the ring and allowed to sit for approximately 24 hours in sealed plastic bags prior to testing.

Testing Procedures

Lateral swelling pressure samples were placed in the swelling cell by the procedure used in triaxial testing, and the cell completely filled with de-aired distilled water and sealed. Back pressure was applied to the reservoir and recorder pen set to zero positive. The toggle valves below the reservoir and between the cell and transducer were opened simultaneously, so that the back pressure could be checked by the recorder. Samples were allowed to take in water and develop swelling pressure until the latter stabilized at its maximum value. At that time, both toggle valves were closed and a burette placed in the quickconnect above the transducer. Using the same amount of back pressure applied through the burette as to the sample, the lower toggle valve was opened and enough water removed to allow the swelling pressure to decrease to zero, with resulting lateral expansion of the sample. The burette was removed and the swelling pressure allowed to develop again. This process was repeated until the incremental lateral swell was so small that essentially no water could be removed, then a final swelling pressure was developed and recorded. Following the test, the sample was removed and its moisture content determined.

Vertical swelling pressure samples were placed in a stainless steel ring (1.000 in. high, 2.500 in. ID) and then positioned under the platen of the load cell. The platen was lowered until contact was made with the porous stone covering the sample and the recorder pen was slightly deflected. The bowl holding the sample was filled with water and the sample allowed to develop its maximum swelling pressure. For samples on which the influence of vertical swell on swelling pressure was to be investigated, the platen was rotated (causing upward advance) until the swelling pressure decreased to zero. One revolution corresponded to 0.05 in. vertical deformation. Vertical swelling pressure was again allowed to develop. This process was repeated until sufficient data to establish the relationship were collected.

CHAPTER IV

PRESENTATION AND DISCUSSION OF RESULTS

Using the testing procedures outlined in the previous Chapter, the influences of initial moisture content, dry density, compaction mode and energy, and lateral swell on lateral swelling pressure were investigated. Several interesting trends were established, as well as the substantiation of some existing relationships. Although an apparatus for the concurrent measurement of lateral and vertical swelling data was not successfully developed, the lateral swelling pressure cell described in Chapter II performed very well and yielded results which were easily correlated to vertical swelling pressure data.

Effect of Compaction Variables on Lateral Swelling Pressure

Initial moisture content directly influences the dry density, double layer water thickness, and particle orientation of compacted soils. All of these factors combine with the other factors described in Chapter II and determine the expansive behavior of compacted clay soils. To understand the swell and swelling pressure characteristics of compacted clays, these individual factors and their interrelationships must be carefully considered. The effect of initial moisture content on dry density for any given soil is easily established through the use of compaction tests and needs little discussion. Its effect on the thickness of the double layer is less evident at first notice, but is quite important when considering the swelling phenomena. The importance lies in the fact that a large portion of the swell and swelling pressure developed in a compacted soil is the result of osmotic repulsive forces between particles, which are developed in and transmitted through the double layer. Ladd (1959) indicated that the thickness of the double layer is roughly proportional to initial moisture content. In most compacted soils, the thickness of the double layer is less than the individual particles would like it to be, if given free access to water. Therefore, the lower the initial moisture content the greater the water uptake required to satisfy this double layer deficiency. For a constant initial moisture content, an increase in the dry density results in increased osmotic repulsive forces and thus increased swell or swelling pressure. The effect of initial moisture content on particle orientation was previously discussed and may be summarized: compaction on the dry side of optimum results in a more nearly random or flocculent structure and compaction on the wet side of optimum results in a more nearly parallel or dispersed structure, with varied amounts of orientation achieved at moisture contents between these two extremes. It is a generally accepted fact that cohesive soils with flocculent structures tend to swell more and develop larger swelling pressures than those with dispersed structures, if both are compacted at the same initial moisture content and dry density.

The fact that lower initial moisture contents require a greater water uptake for lateral swelling pressure samples to establish equilibrium status is shown in Figure 4.1. Both soils tested reflect the same type of relationship, however, RMGC requires a greater volume of water at any given moisture content as compared to PRC. This is probably the result of different mineralogical composition of the two soils. It is

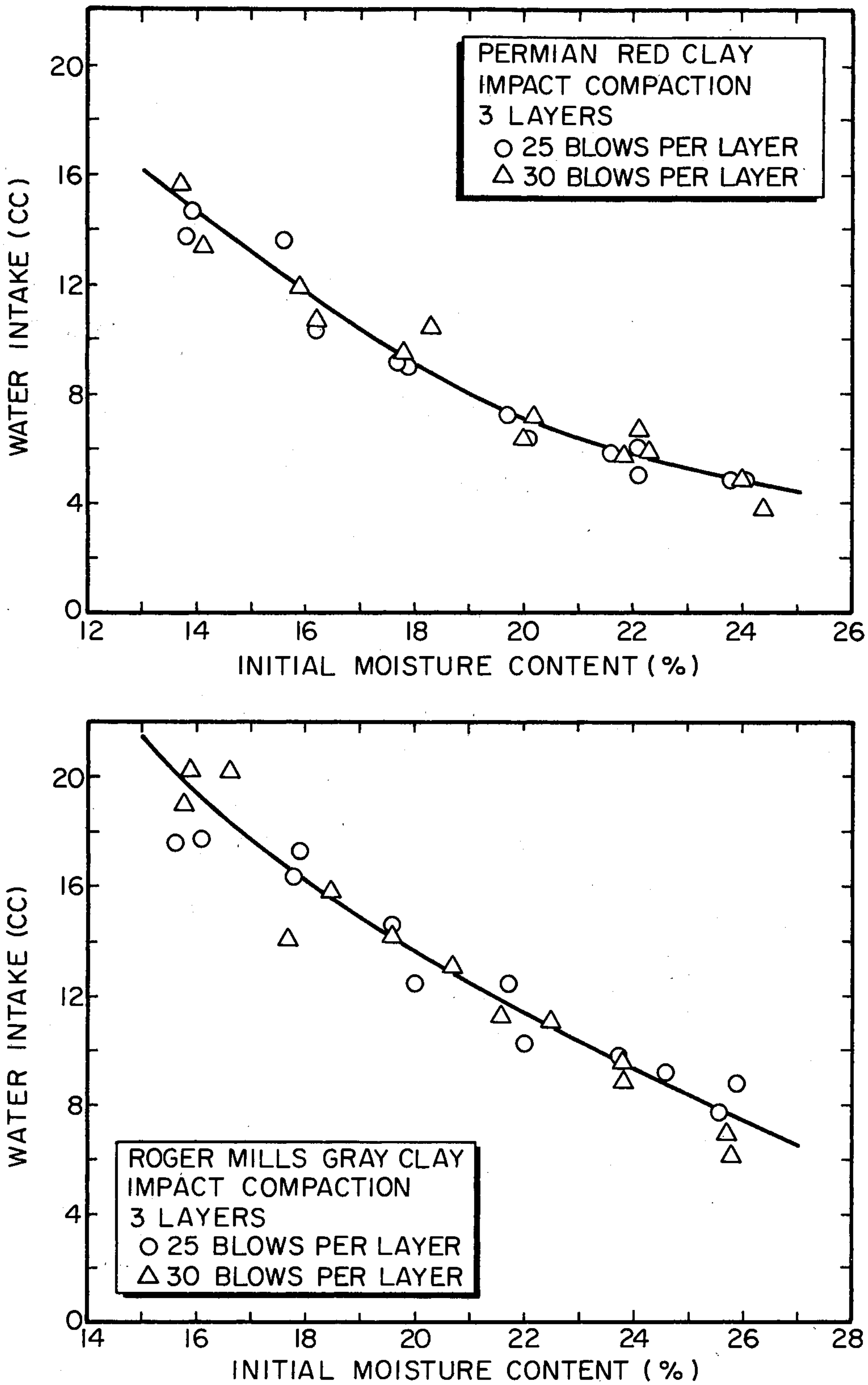
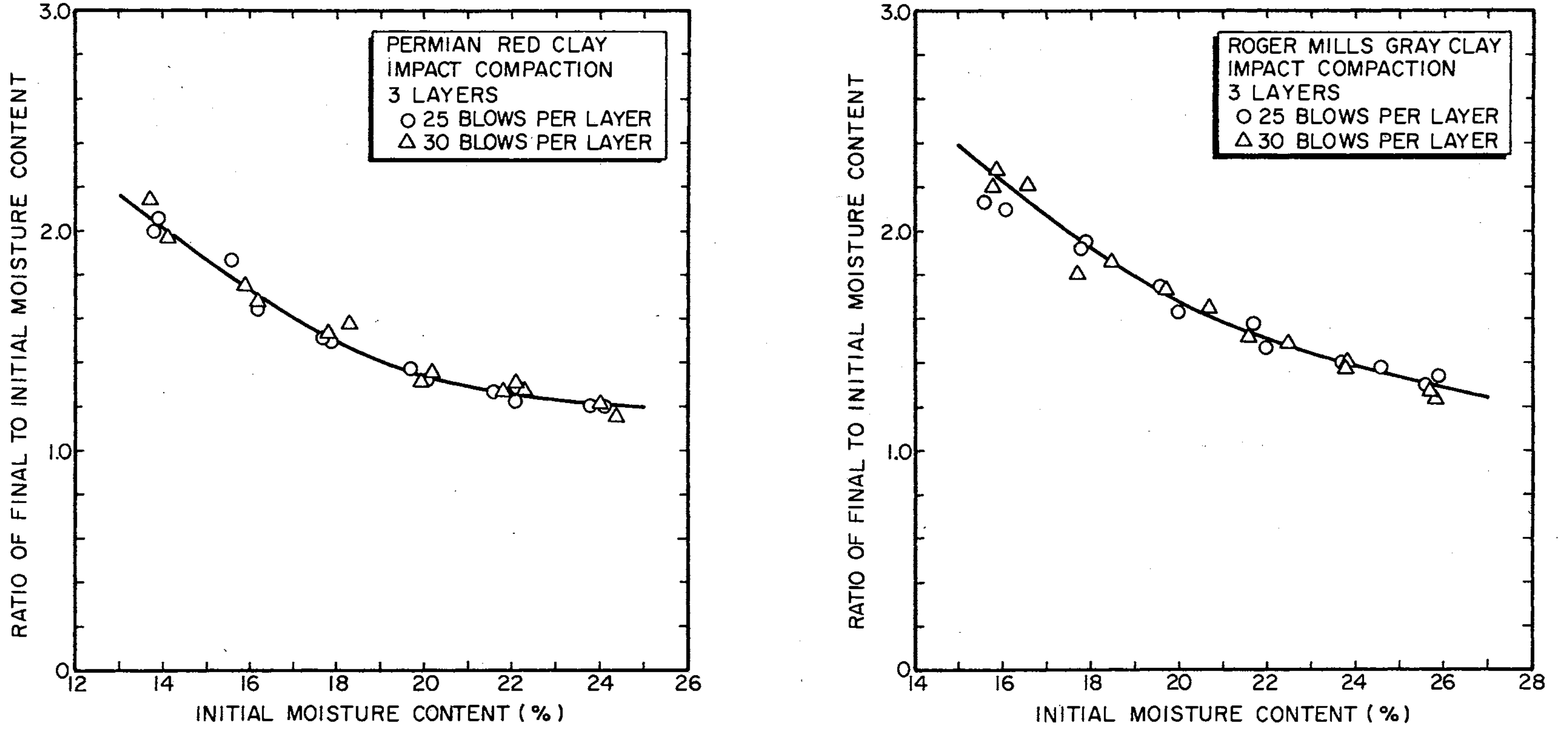


Figure 4.1. Water Intake versus Initial Moisture Content for PRC (upper) and RMGC (lower).

also evident from Figure 4.1 that, for both soils, an increase in compactive energy has little effect on the water uptake--moisture content relationship. An alternate procedure for presenting the data is shown in Figure 4.2. This type of presentation is more practical in view of the parameters presented, that is, ratio of final to initial moisture content versus initial moisture content. For both PRC and RMGC at low initial moisture content, the final moisture content is approximately two times the initial value. At the higher initial moisture contents tested the final to initial ratio appears to be leveling off at approximately 1.2. Presumably, there is some higher initial moisture content at which no swelling pressure (or swell) will occur because the soil-water system is in complete equilibrium, thus the final to initial ratio should actually stabilize at a value equal to 1.0. This much higher moisture content is definitely out of the range of normal compaction procedures. For all PRC samples tested the resulting final moisture contents were in the range of 26.0% to 29% and for RMGC samples the final moisture content range was from 32.0% to 36.0%. Both PRC and RMGC, over the range of initial moisture contents tested, exhibited ratios of final moisture content to plastic limit in the range of 1.30 to 1.45.

The influence of initial moisture content on lateral swelling pressure for PRC and RMGC is shown in Figures 4.3 and 4.4, respectively. This data substantiates the generally accepted trend that swelling pressure decreases with increasing initial moisture content.

The influence of dry density on lateral swelling pressure for PRC and RMGC is shown in Figures 4.5 and 4.6. Comparing Figures 4.5 and 4.6 with the Standard Proctor compaction curves in Figure 3.2, it may



(a) (b)

Figure 4.2. Ratio of Final to Initial Moisture Content versus Initial Moisture Content for (a) PRC and (b) RMGC.

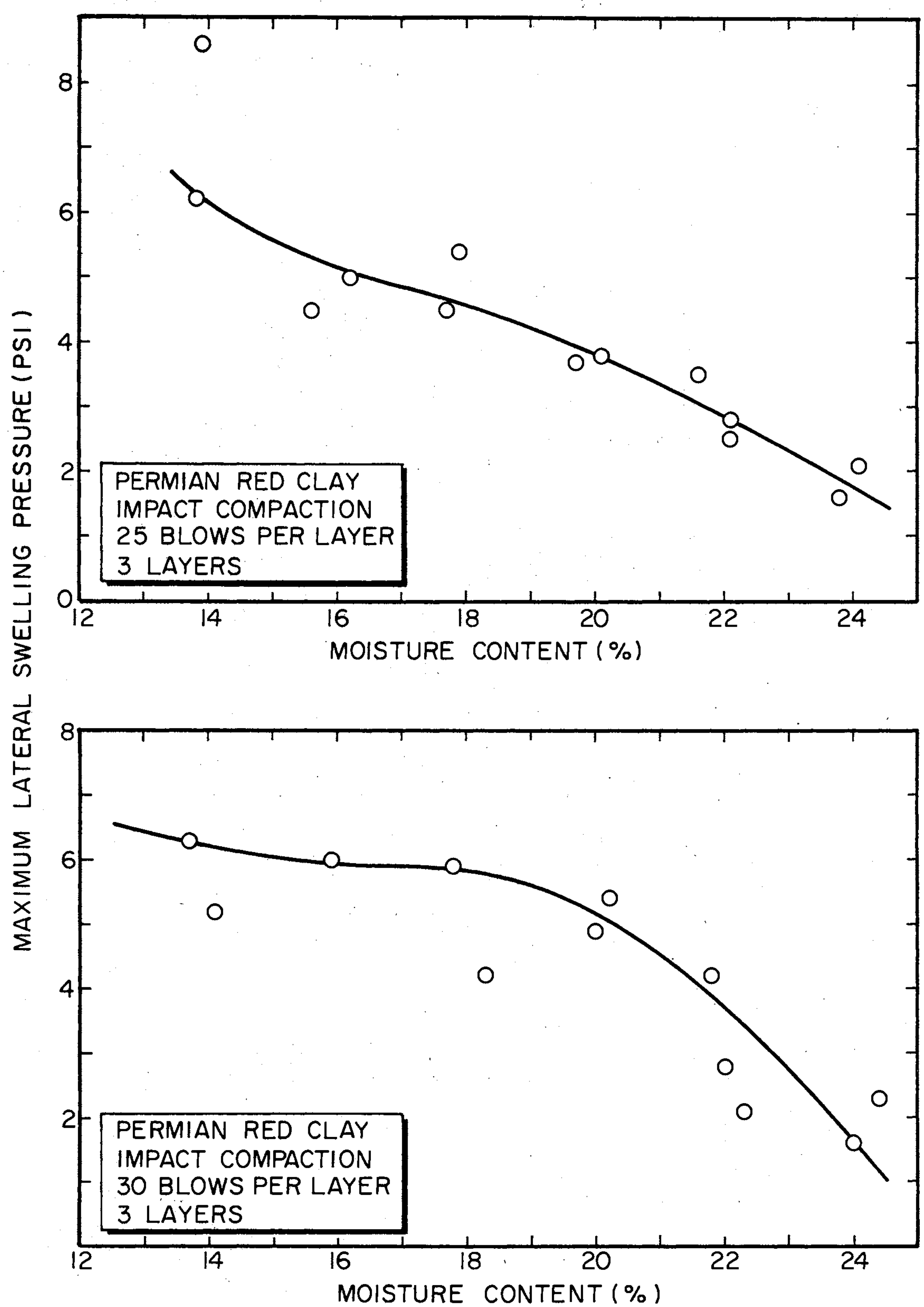


Figure 4.3. Effect of Initial Moisture Content on Lateral Swelling Pressure for PRC.

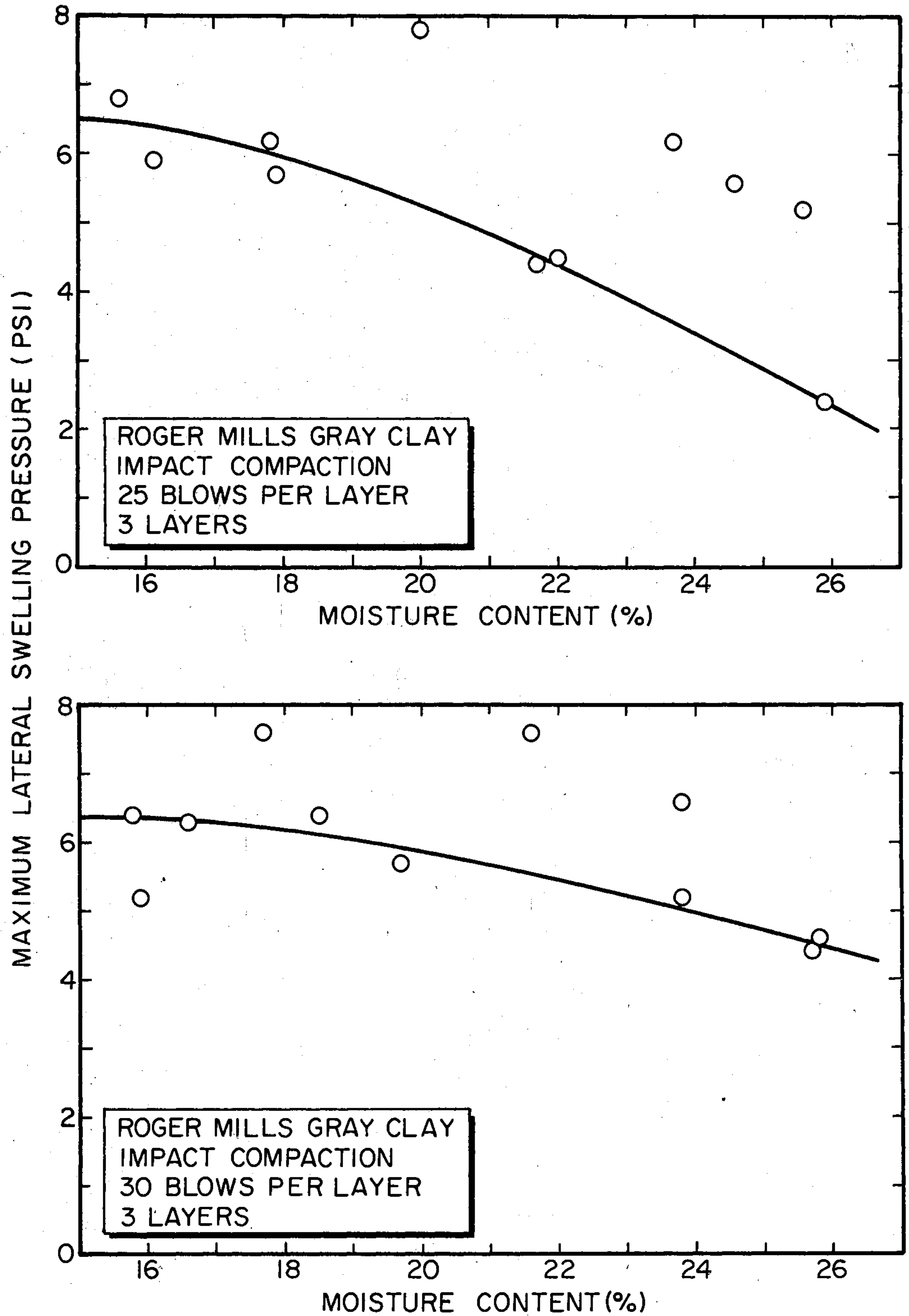


Figure 4.4. Effect of Initial Moisture Content on Lateral Swelling Pressure for RMGC.

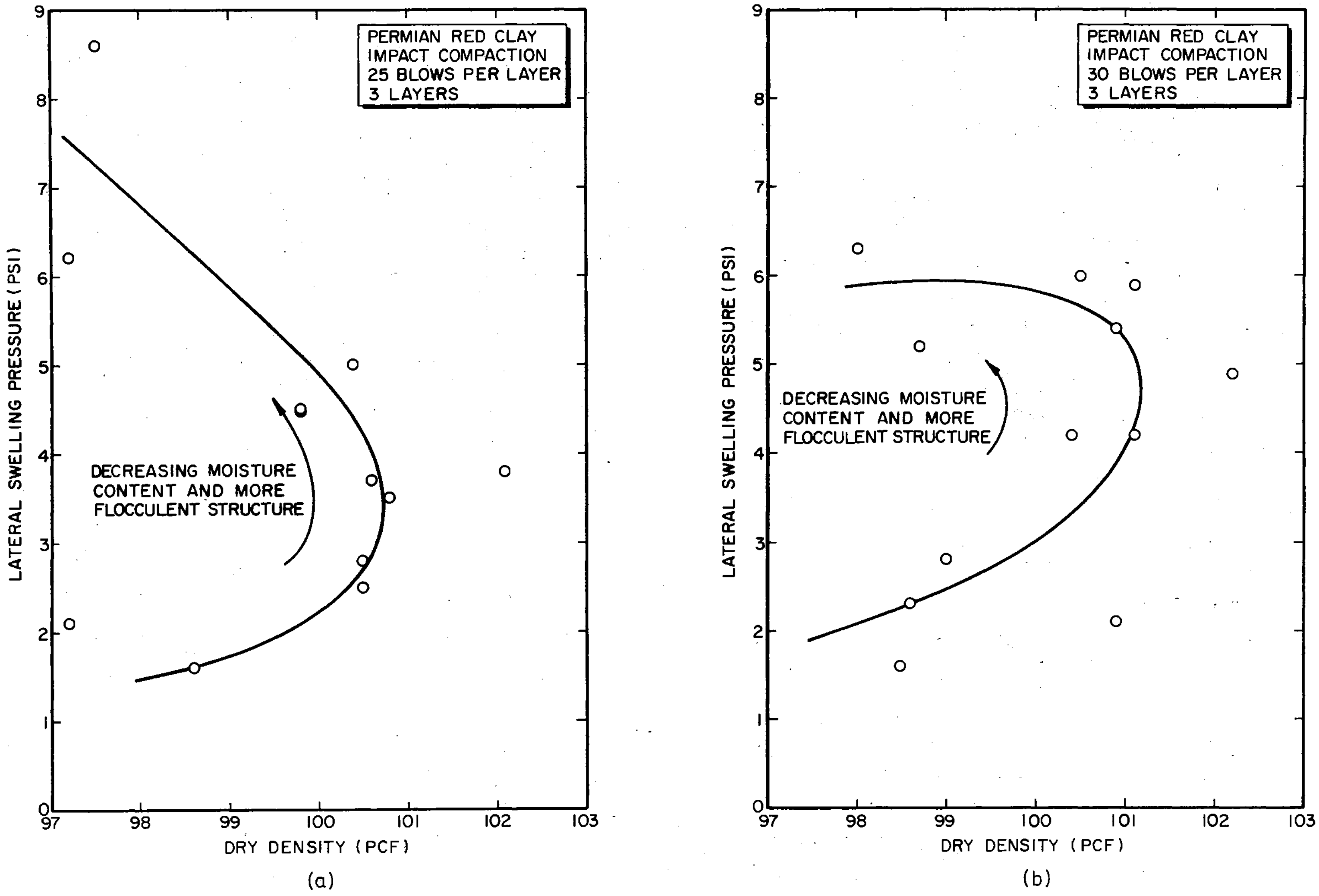


Figure 4.5. Effect of Dry Density on Lateral Swelling Pressure for PRC: (a) 25 blows per layer and (b) 30 blows per layer.

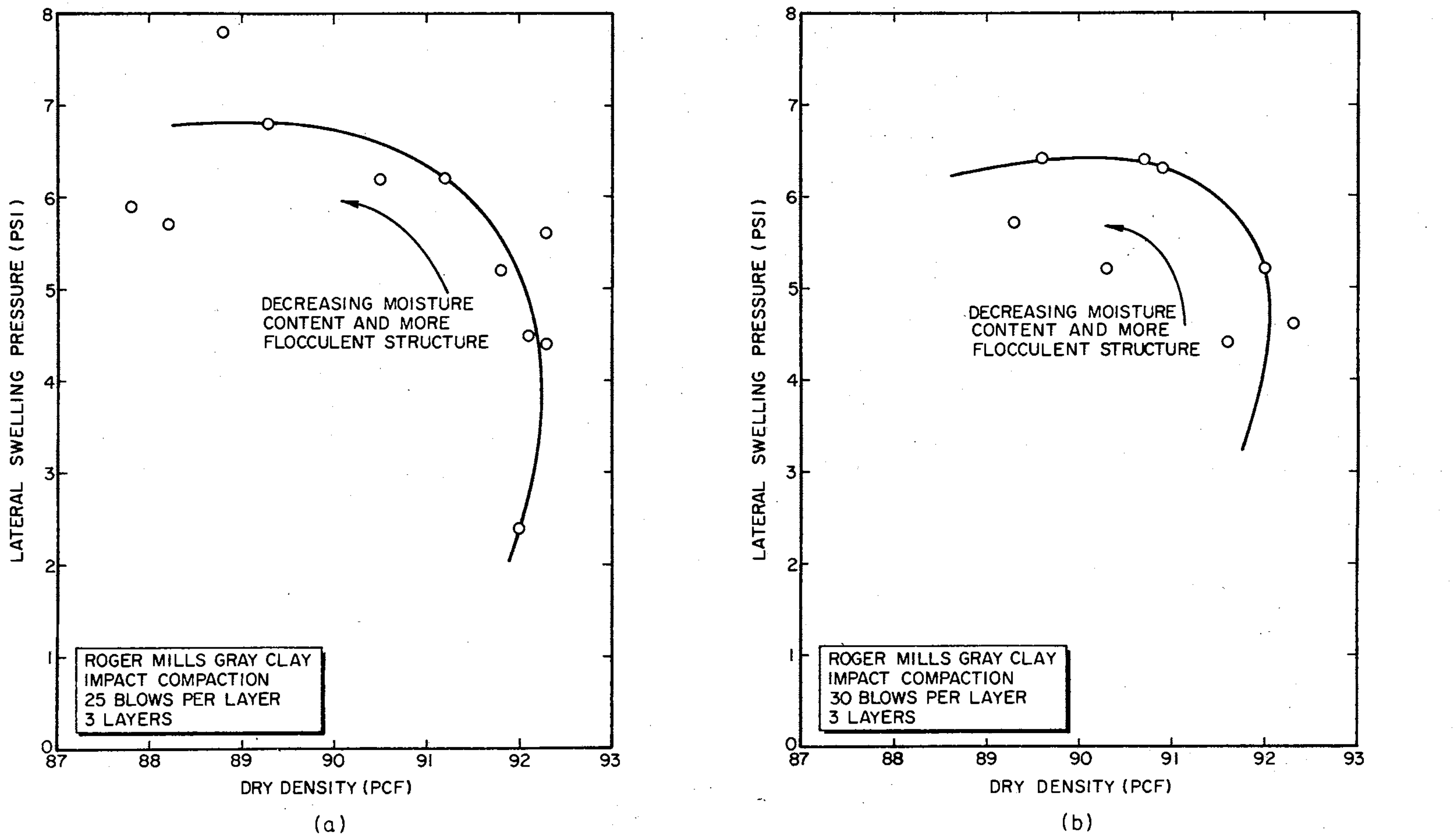


Figure 4.6. Effect of Dry Density on Lateral Swelling Pressure for RMGC: (a) 25 blows per layer and (b) 30 blows per layer.

be noted that the general shape of all curves is quite similar. PRC has a uniformly peaked curve, indicating a relatively sensitive variation of dry density with moisture content at both compactive energies. The shape of the lateral swelling pressure versus dry density curve for PRC is of similar configuration. On the other hand, RMGC has relatively flat compaction curves, showing it to be somewhat insensitive to changes in dry density with respect to changes in moisture content. Here again the general shape of the compaction curve is reflected in the lateral swelling pressure versus dry density curve, although the relative rates of change of the various parameters are different, as a result of the orientation of the two curves with respect to the abscissa or dry density axis.

For PRC samples compacted in three layers at 25 blows per layer, the lateral swelling pressure slowly decreases with increasing moisture content and dry density until the maximum dry density is approximately reached, then rapidly drops off. Slightly above optimum moisture content and maximum dry density, the lateral pressure begins decreasing slowly. At 30 blows per layer, PRC exhibits the same general trend; however, the lateral swelling pressure for samples compacted at dry densities below the maximum value for this compactive effort is relatively insensitive to increasing density. Above optimum moisture content and maximum dry density.

RMGC samples, compacted in three layers, at both 25 and 30 blows per layer, exhibit a relatively constant lateral swelling pressure behavior below optimum moisture content and maximum dry density. However, above optimum moisture content and maximum dry density, the lateral pressure decreases rapidly, with only slight decreases in dry density.

An overall comparison of Figures 4.3 through 4.6 indicates that, at initial moisture contents below optimum, lateral swelling pressure is relatively insensitive to changes in moisture content. In this range the tendency for decreasing swelling pressure with increasing initial moisture content is offset by increasing dry density with increasing moisture content, which has an overall tendency to increase the swelling pressure. Also, in this range the particle orientation resulting from impact compaction is nearly always flocculent. At initial moisture contents near optimum, the dry density is not changing rapidly and the effects of moisture content and particle orientation determine the swelling behavior. This is evident in Figures 4.3 and 4.4, where the slope of the curves begin to increase due to the soil particles imbibing water to satisfy their double layer deficiency. Also, soil particles in the compacted structure are more nearly parallel in this range. Figures 4.5 and 4.6 show a rapid decrease in the lateral swelling pressure with little change in dry density, for samples compacted slightly below and above optimum. At initial moisture contents above optimum the compacted soil structure is of a more nearly dispersed nature, and the double layer deficiency is gradually becoming satisfied, since the tendency for soil particles to take on water decreases with increasing moisture content. In this range, dry density appears to have the greatest influence on lateral swelling pressure. As the dry density decreases, so does the lateral swelling pressure.

Further indication of the influence of compacted soil structure on lateral swelling pressure is shown in Figures 4.7 and 4.8. The data

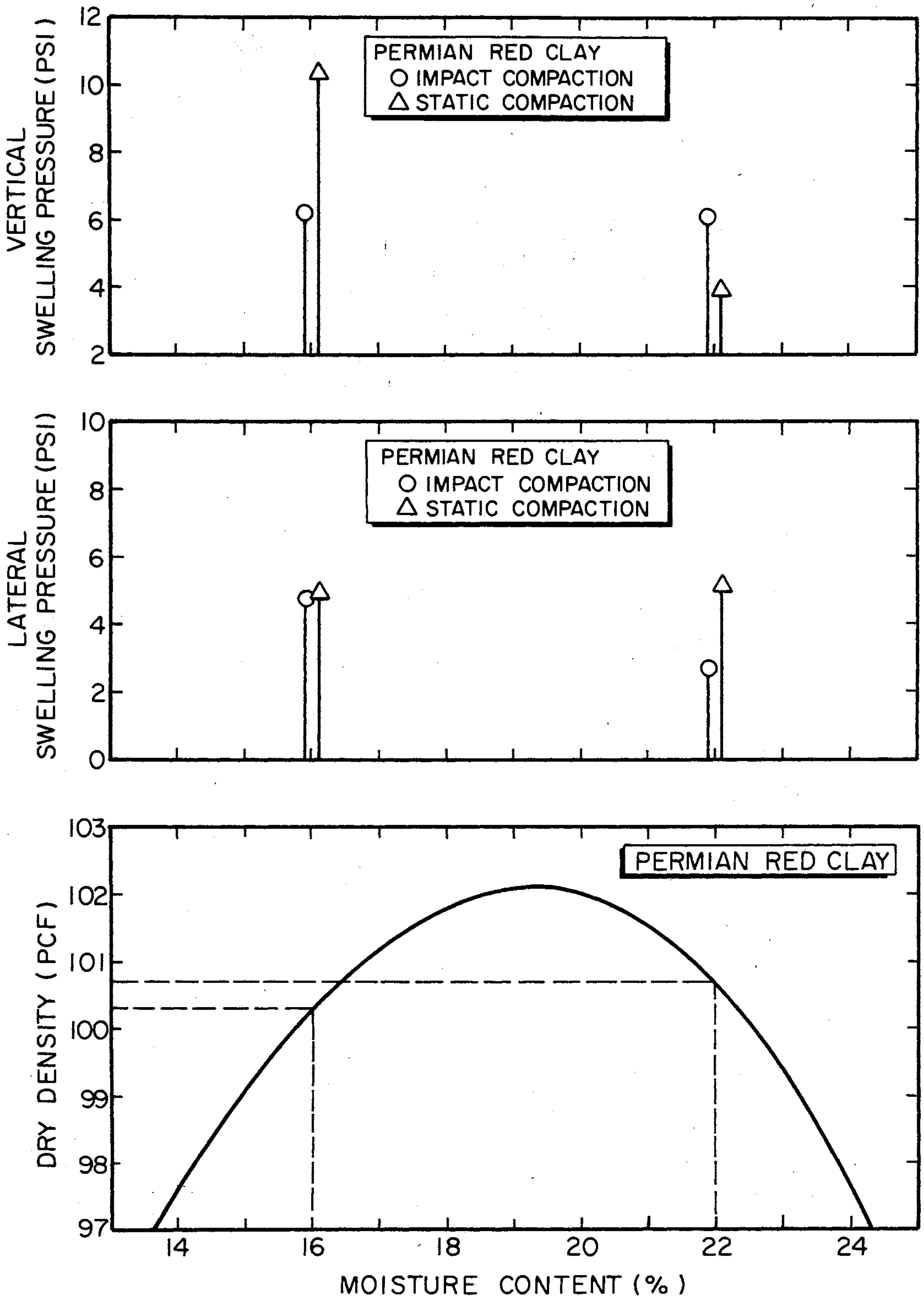


Figure 4.7. Effect of Compaction Method on Lateral and Vertical Swelling Pressure for PRC.

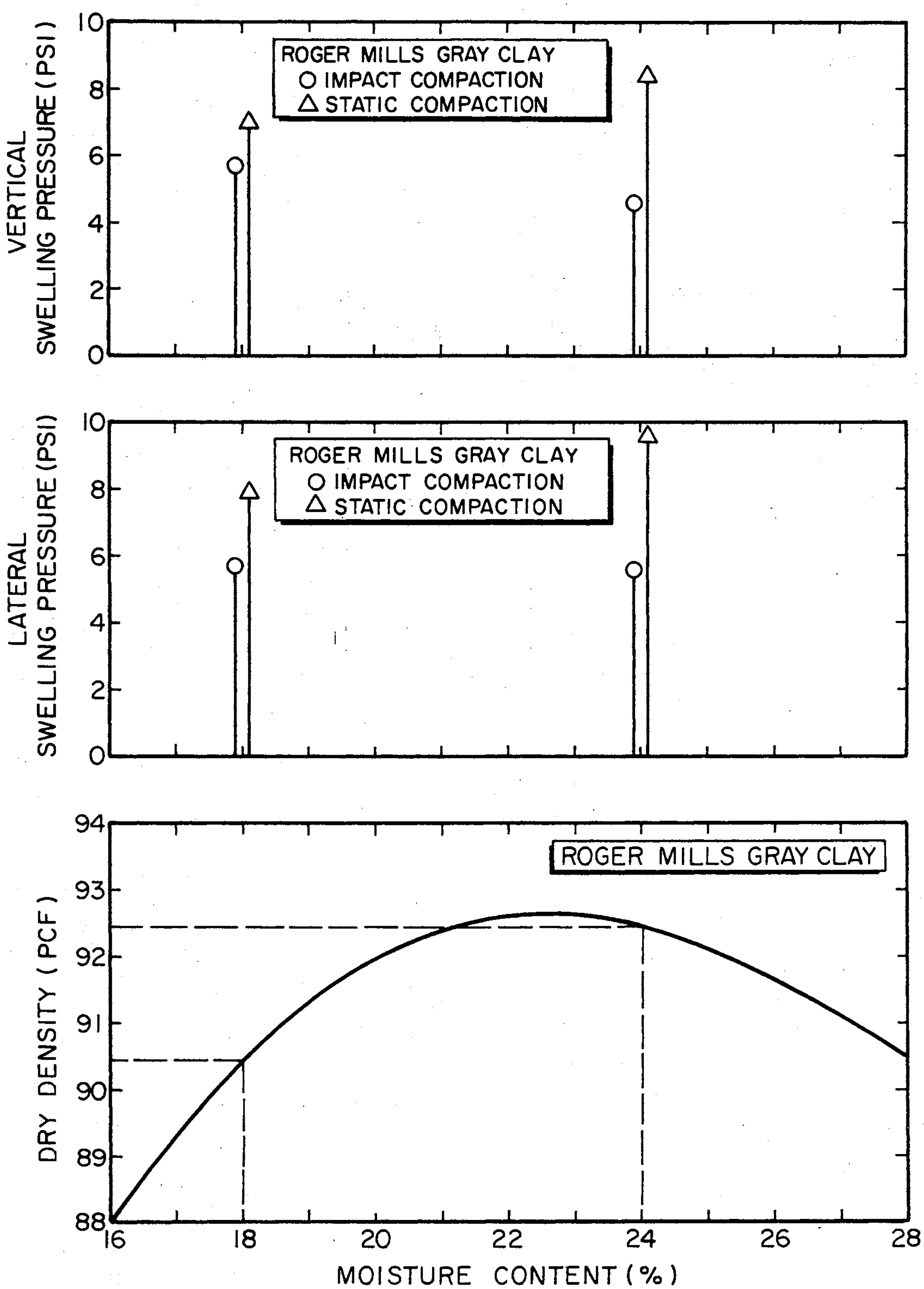


Figure 4.8. Effect of Compaction Method on Lateral and Vertical Swelling Pressure for RMGC.

shown in each Figure are for samples compacted on both sides of optimum moisture content by two different compaction modes (impact and static). PRC samples compacted by impact and static methods show very slight differences in the magnitude of lateral swelling pressure below optimum, while above optimum considerable difference in lateral pressure exists for the two methods. Similar behavior is exhibited by RMGC, as indicated in Figure 4.8, except that the relative magnitudes of the differences in lateral swelling pressure are slightly larger. This substantiates the inference that flocculent soil structures swell more and develop larger swelling pressures than dispersed soil structures for similar placement conditions.

Effects of Lateral Swell on Lateral Swelling Pressure

The procedure used for investigating the effect of lateral swell on lateral swelling pressure was described in detail in the previous Chapter. Briefly, the procedure consisted of allowing the swelling pressure to develop, removing a measured amount of water from the swelling cell, and allowing the swelling pressure to develop once again.

The data collected for PRC and RMGC are shown in Figures 4.9 and 4.10. For both soils, the lateral swelling pressure decreases with increasing lateral swell. The lateral swelling pressure relationship for PRC is curvilinear in that the lateral swelling pressure decreases gradually at low percentages of lateral swell, then decreases rapidly with further increases in lateral swell. Extrapolated portions of the relationships indicate that the lateral swelling pressure for samples compacted at optimum moisture content or below would decrease to zero at lateral swell values between 1.2% and 1.4%. The lateral swelling

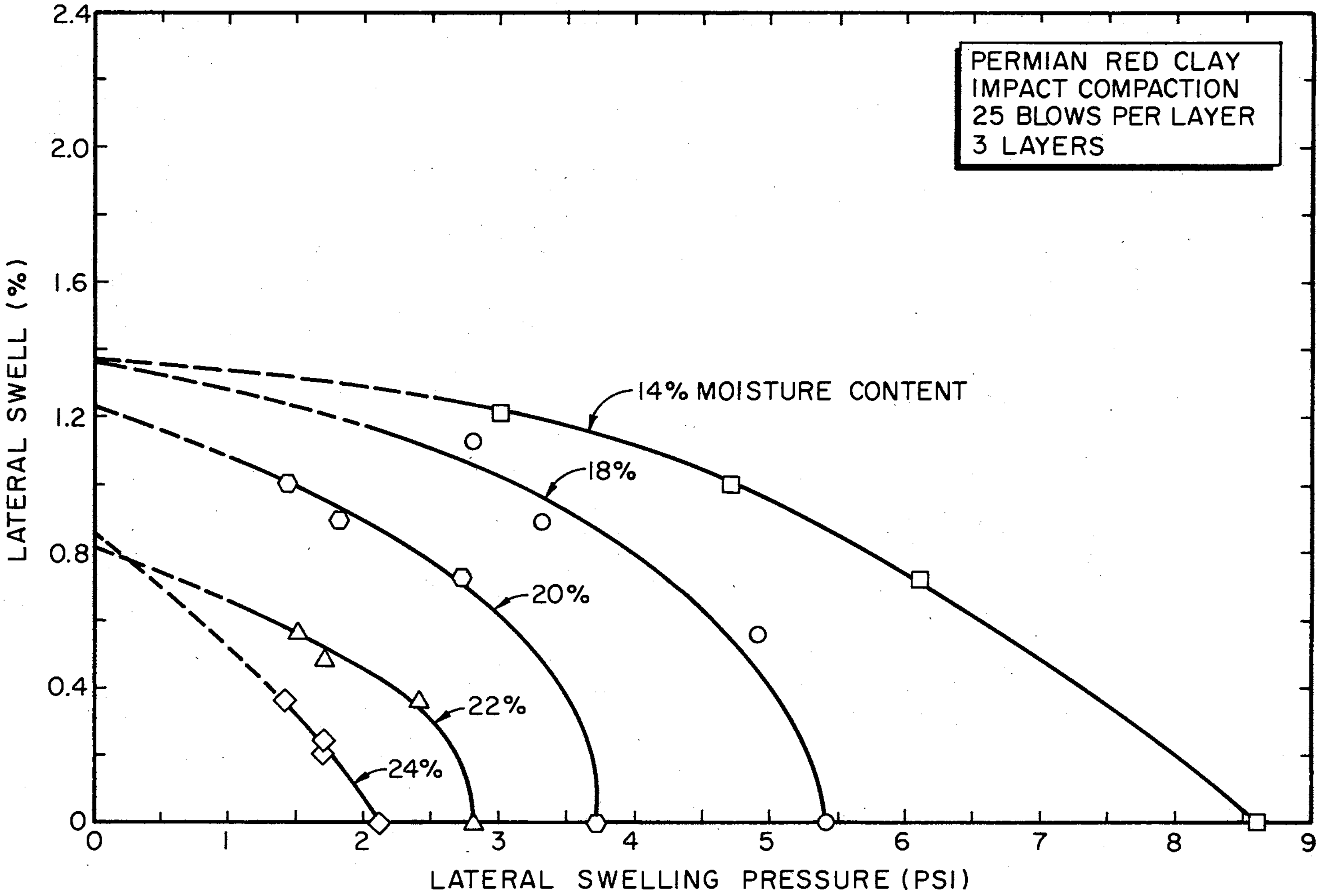


Figure 4.9. Effect of Lateral Swell on Lateral Swelling Pressure for PRC.

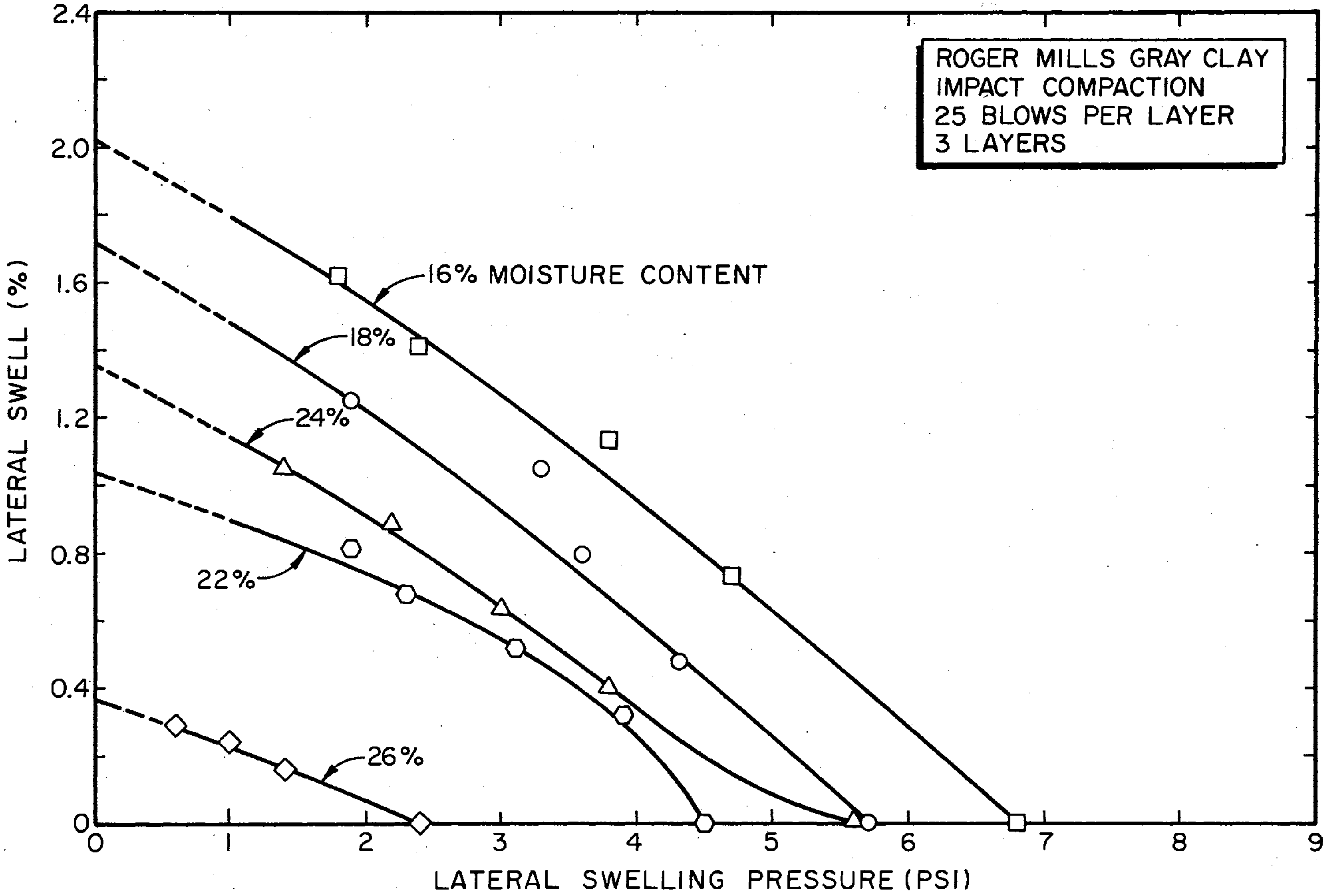


Figure 4.10. Effect of Lateral Swell on Lateral Swelling Pressure for RMGC.

pressure for samples compacted at moisture contents above optimum would decrease to zero at a lateral swell value of approximately 0.8%.

The lateral swell-swelling pressure relationship for RMGC is nearly a linear function for all initial moisture contents. As a result, distinct values of lateral swell which would result in zero lateral swelling pressure exist for each initial placement condition. The range of values include 0.4% to 2.0% lateral swell for initial moisture contents from 26% to 16%, respectively.

Using the data of Figures 4.9 and 4.10, Figures 4.11 and 4.12 were drawn, showing the change in lateral swelling pressure with respect to increasing initial moisture content for equal percentages of lateral swell. Also shown are the particular dry densities for the samples used to obtain these data. It should be noted that lateral swelling pressure is a continually decreasing function with respect to increasing initial moisture content, for all percentages of lateral swell and for both PRC and RMGC.

PRC exhibits a relatively high rate of decrease, while RMGC exhibits a somewhat slower rate. Figure 4.11 indicates that, for PRC, the lateral swelling pressure is more sensitive to lateral swell at lower initial moisture contents at or above optimum, as evidenced by the relative spacing between lateral swell contour lines. The lateral swelling pressure for RMGC appears to be less sensitive at lower initial moisture contents, than at moisture contents in the optimum range.

Relationships Between Lateral and Vertical Swelling Pressures

Comparing the lateral and vertical swelling pressures for the two soils and testing procedures used, the vertical component was greater

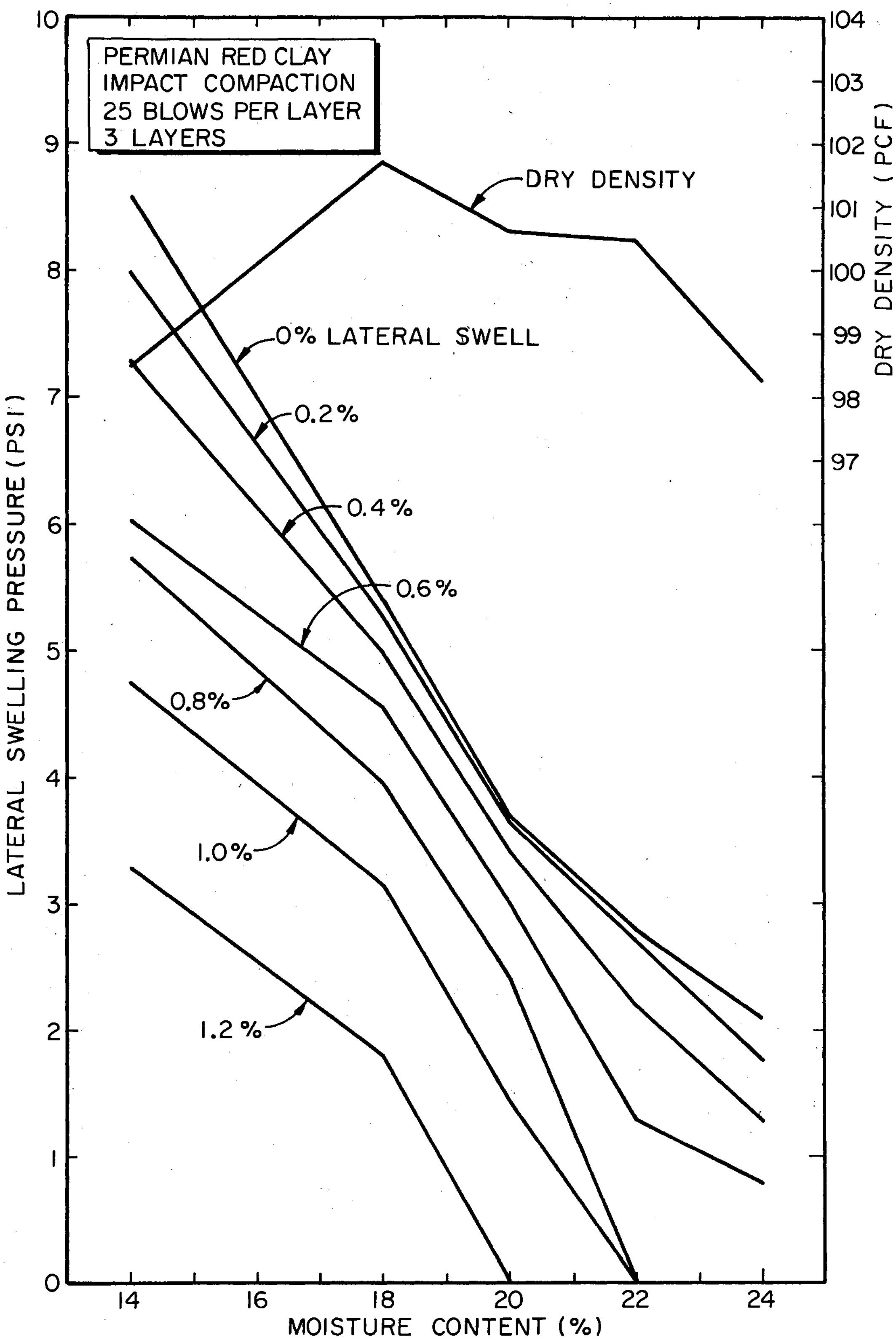


Figure 4.11. Effect of Initial Moisture Content on Lateral Swelling Pressure at Equal Percentages of Lateral Swell for PRC.

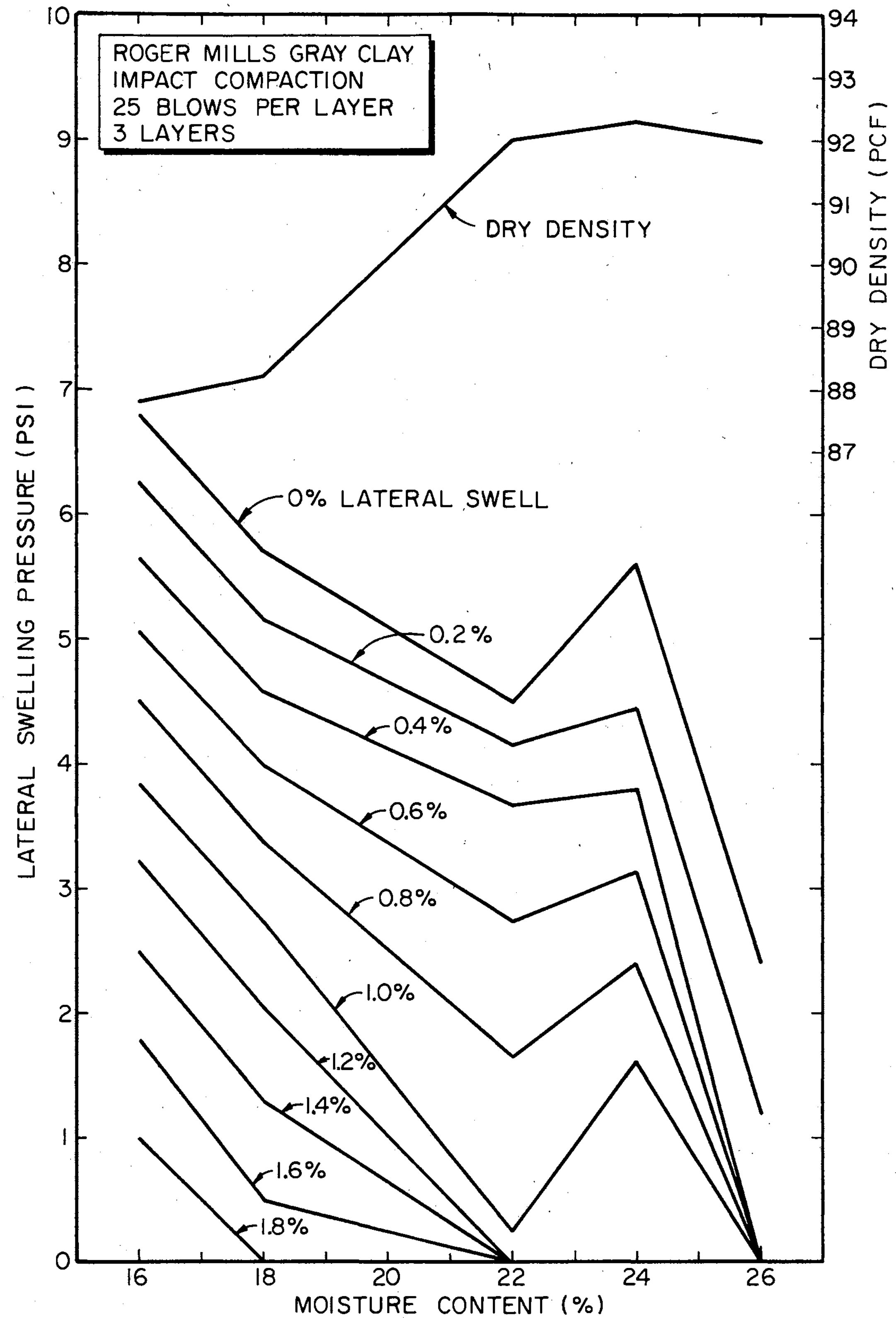


Figure 4.12. Effect of Initial Moisture Content on Lateral Swelling Pressure at Equal Percentages of Lateral Swell for RMGC.

for nearly every initial placement condition used. Figures 4.13 and 4.14 show the lateral and vertical swelling pressure versus initial moisture content relationship for PRC and RMGC, respectively. The lateral swelling pressure curve represents data from all dynamically compacted samples tested, i.e., both 25 and 30 blows per layer compactive energy. The general trends exhibited by both soils are similar. The low vertical swelling pressures at low initial moisture contents are probably the result of testing procedure, because allowing water entry from the ends of the sample only resulted in immediate swelling in these regions, which allowed some consolidation of the center portion of the sample. Since the sample was relatively thin (1.00 in. high) and possessed large end areas, this phenomenon was only evident at lower initial moisture contents, where the rate of swelling pressure development was greatest. The possibility of drilling a small hole through the sample, as used in the lateral swelling pressure samples, was not practical because of sample geometry and the fact that it occurred at only very low initial moisture contents.

A more practical representation of the relationship between lateral and vertical swelling pressures is shown in Figure 4.15, where the ratio of lateral to vertical swelling pressure (swelling ratio) is plotted as a function of initial moisture content. Both soils exhibit similar swelling ratio-moisture content relationships. PRC has a maximum swelling ratio of 0.98, occurring at an initial moisture content of 14%. Above 14% the swelling ratio decreases with increasing moisture content to a value of approximately 0.5, which occurs at optimum moisture content. Above optimum the swelling ratio is essentially constant. RMGC has a maximum swelling ratio of 1.05 and a minimum of 0.66, occurring at

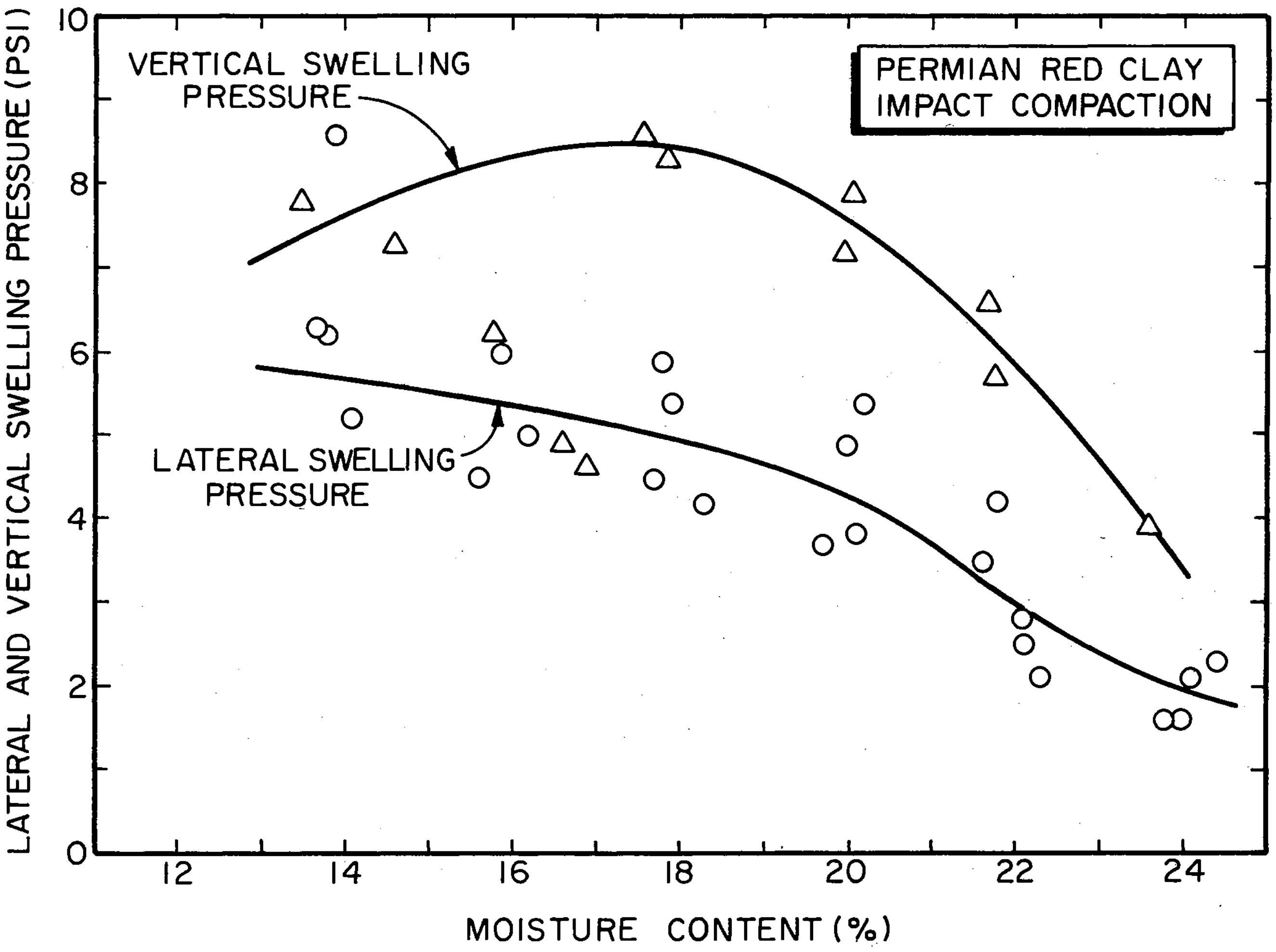


Figure 4.13. Lateral and Vertical Swelling Pressure versus Initial Moisture Content for PRC.

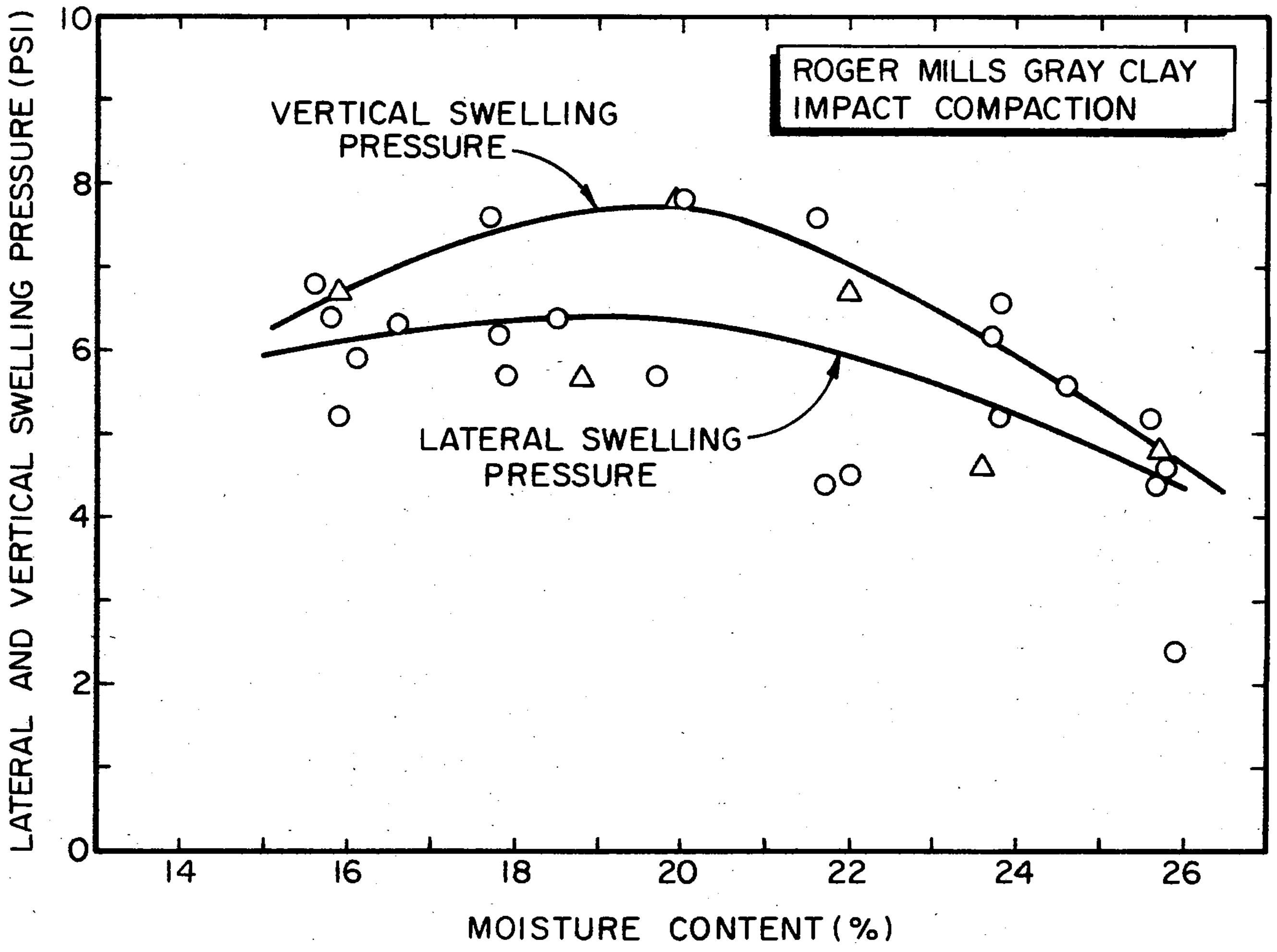


Figure 4.14. Lateral and Vertical Swelling Pressure versus Initial Moisture Content for RMGC.

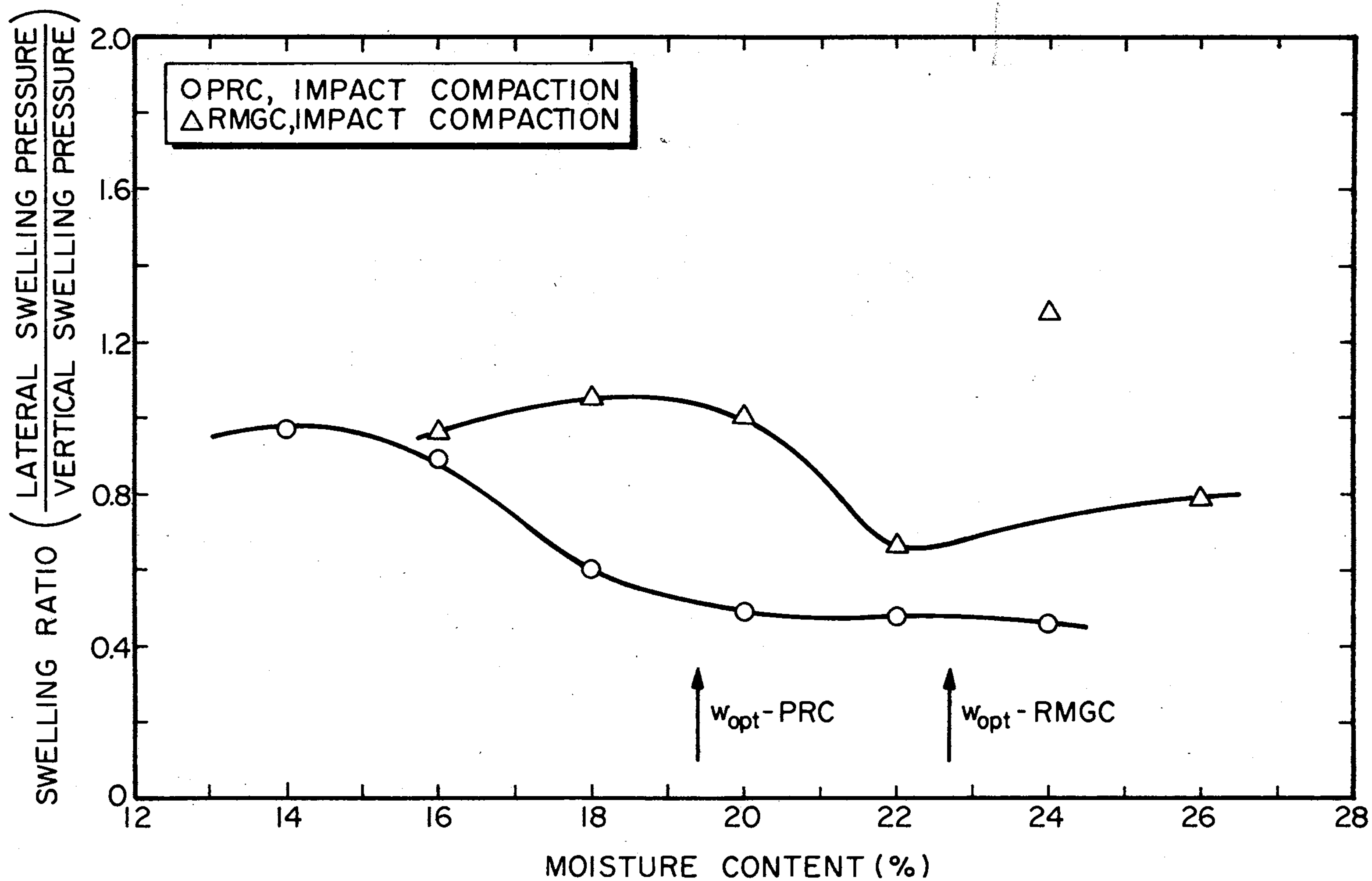


Figure 4.15. Effect of Initial Moisture Content on Swelling Ratio for PRC and RMGC.

optimum moisture content. Above optimum there is a slight increase in the swelling ratio, but a relatively constant trend is still present. The practical significance of this relationship is evident when compacted clays are used to build or support engineering structures. Most field compaction is carried out at moisture contents below optimum, depending on the type of compaction equipment used. If moisture is made available and the compacted soils swells, the lateral swelling pressure could be approximately equal to or greater than the vertical swelling pressure.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The influences of initial moisture content, dry density, compaction mode and energy, and lateral swell on lateral swelling pressure were investigated for two cohesive Oklahoma soils. The major portion of the research was carried out using a modified version of the triaxial swelling cell described by Fost (1962). Vertical swelling pressure data were also collected for correlation with lateral swelling pressure data. Based on the experimental data and discussions presented in previous chapters, it may be concluded that:

1) For both PRC and RMGC, the vertical swelling pressure exceeded the lateral swelling pressure for nearly all initial conditions. Data confirmed the well-known fact that samples compacted by the same compaction mode and energy develop greater swelling pressures when compacted at low initial moisture contents than when compacted at higher initial moisture contents.

2) The influences of initial moisture content, dry density, and compacted soil structure on lateral swelling pressure are highly interrelated for samples compacted with a given compactive effort. However, some general observations may be made:

a) At initial moisture contents below optimum, the resulting soil structure is presumably of a more nearly flocculent nature. The trend toward decreasing lateral swelling pressure with increasing initial moisture content in this lower range is offset by the tendency towards increased lateral pressure with increasing dry density. The result is a relatively constant magnitude of lateral swelling pressure.

b) At initial moisture contents slightly below and above optimum the dry density is not changing rapidly, so the effects of moisture content and compacted soil structure determine the swelling behavior. In this range of initial moisture contents the double layer deficiency is more nearly satisfied than before, and the tendency for soil particles to imbibe water is reduced.

c) At initial moisture contents above optimum the compacted soil structure is presumably of a more nearly dispersed nature and the further influence of increasing moisture content and decreasing dry density combine to reduce the lateral swelling pressure.

d) The ratio of final to initial moisture content versus initial moisture content relationship indicates that the final moisture content for both PRC and RMGC is a function of initial moisture content and is relatively insensitive to dry density. For PRC and RMGC this ratio was approximately 2.0 for low initial moisture contents, decreased with increasing initial moisture content and stabilized at a value of approximately 1.2 for the higher initial moisture contents tested.

3) The range of lateral swelling pressures measured for PRC varied from a maximum of approximately 6.5 psi at an initial moisture content of 14% to a minimum of approximately 1.5 psi at 24%. For RMGC the range varied from approximately 6.5 psi at 16% to approximately 2.5 psi at 26%. Increased compactive energy (30 blows per layer) resulted in slightly greater magnitudes of lateral swelling pressure in the higher initial moisture content range, i.e., for PRC the lateral pressure was approximately 2.0 psi at 24% and for RMGC it was approximately 4.5 psi at 26%.

4) Impact or dynamic compaction is a better compaction mode than static compaction for the study of lateral swelling pressure with respect to the influence of compacted soil structure. It results in a wider variety of particle orientation; flocculent, semi-oriented, and dispersed. For the two soils tested, static compaction nearly always appeared to produce the behavior commonly ascribed to a flocculent structure, regardless of the initial moisture content or dry density. Statically compacted samples developed higher lateral swelling pressures as compared to dynamically compacted samples for both PRC and RMGC when tested at the same initial moisture content and dry density, both above and below optimum.

5) The obvious effect of lateral swell on lateral swelling pressure, is the reduction of lateral pressure with increased lateral swell. In this study, lateral expansion of 1.0% or less resulted in a 50.0% or greater reduction of lateral swelling pressure, with zero lateral swelling pressure obtained at a maximum of 1.4% lateral swell for PRC samples compacted at moisture contents above optimum the amount of lateral swell required to reduce the lateral pressure to zero was approximately 0.8%. RMGC samples required lateral swell values between 0.4% and 2.0% to

reduce the lateral pressure to zero for initial moisture contents between 24% and 16%, respectively. Similar effects of vertical swell on vertical swelling pressure were observed with the relative magnitudes being approximately the same.

6) Samples on the dry side of optimum moisture content exhibited higher swelling ratios, (lateral swelling pressure/vertical swelling pressure) approximately equal to 1.0 for both PRC and RMGC. For both soils, the swelling ration decreased with increasing initial moisture content to a minimum value occurring at or near optimum moisture content. Above optimum the swelling ratio is essentially constant at 0.50 and 0.65 for PRC and RMGC, respectively.

7) The modified triaxial swelling apparatus performed exceedingly well for the study of lateral swelling pressure of compacted clay soils. The apparatus is dependable and relatively simple to use for quantitive measurements.

Recommendations

In order to develop a better understanding of lateral and vertical swelling pressures and the influences of physical and physcio-chemical properties on the swelling process, the following recommendations for further research may prove useful:

1) Continue the development of an apparatus for the concurrent measurement of lateral and vertical swelling pressure data. A suggested device, shown in Figure 5.1, uses a strain gage load cell to measure the vertical component and a pressure transducer to measure the lateral component. A small semi-circular cell filled with de-aired distilled water surrounds the sample and allows the lateral swelling pressure to be

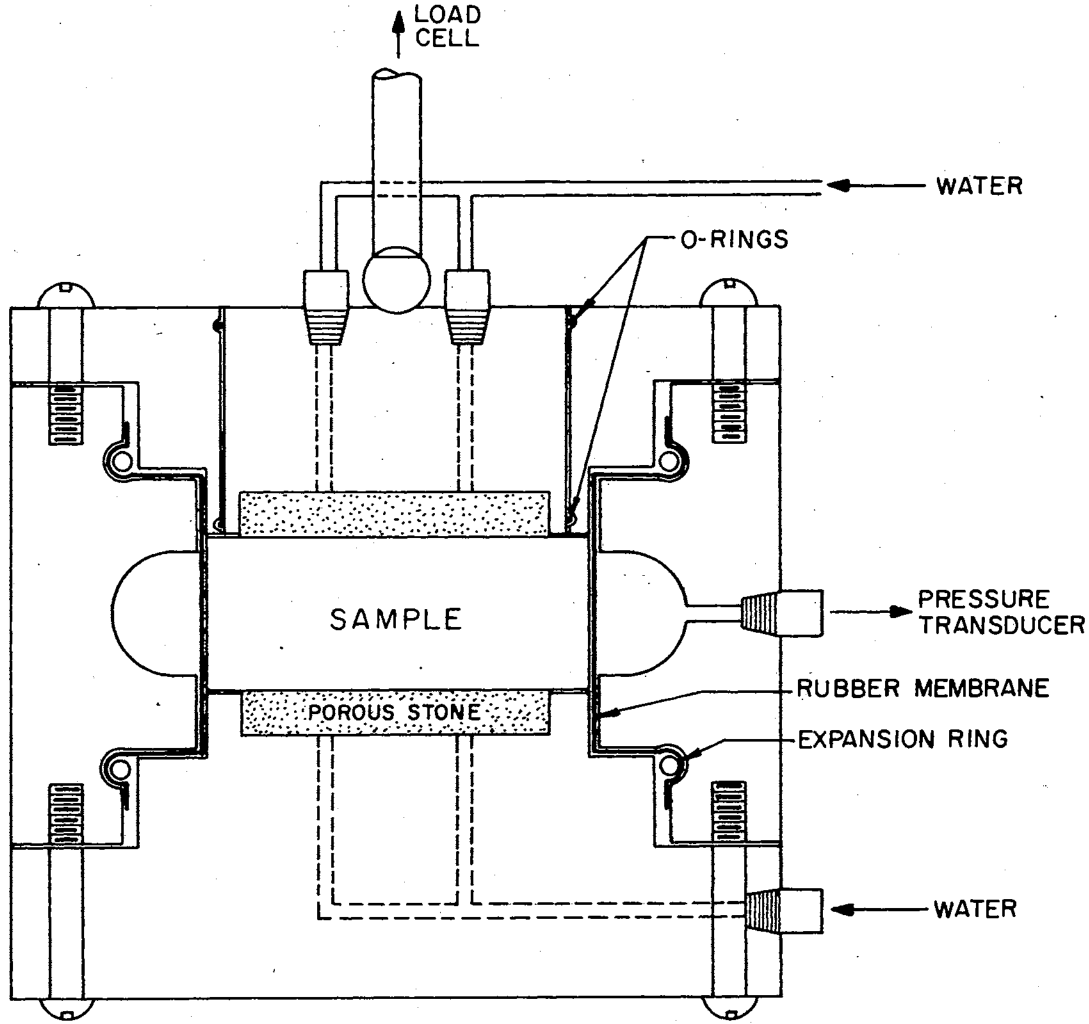


Figure 5.1. Suggested Device for Concurrent Measurement of Lateral and Vertical Swelling Pressure.

transmitted to the pressure transducer. This device would also allow study of the rate of swelling pressure development, as it could be used without back pressure saturation.

2) Use the procedures outline in Chapter III to determine the influences of initial moisture content, dry density, compaction mode and energy, and lateral swell on lateral swelling pressure for other natural soils and combinations of pure clay minerals.

3) Determine the type of clay minerals present in the natural soils and some of the physcio-chemical properties of the soils (i.e., cation exchange capacity and exchangeable cations) so that this knowledge is available to aid in explaining the swelling pressure phenomena.

4) Use the device in Figure 5.1 to investigate the effects of curing period and time allowed for swelling on lateral and vertical swelling pressures for natural soils, as well as the effects of controlled wetting of swelling pressure samples. In other words, apply water to the sample in stages, to simulate the gradual accumulation of moisture under structures.

5) Investigate the influence of different ions in the solution used to saturate the soil sample. This could be helpful in the area of chemical stabilization of soils.

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