WATER RETENTION IN CLAY SOILS
BY CAPILLARY AND SWELLING FORCES

A thesis

by

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I. INTRODUCTION.

Water in clay soils is considered to be held by capillary and swelling forces. Both forces are operative but the importance of each force depends upon the water content. This relationship was assessed from water retention, swelling pressure, and volume change studies using samples of different aggregate sizes compacted to different porosities. The effects of texture and particle orientation on water retention in kaolinite-glass bead mixtures and in marine-deposited Leda clay were also studied.

Clay soil aggregates used in these investigations differ from pure clays, clay blocks, or a clay soil with a stable structure. An attempt was made by a macro approach, to discuss the variables affecting soil water in clay soil aggregates.

Methods for preparing samples, methods for measuring volume changes, and design of apparatus for swelling pressure studies were involved in the investigation.

In addition, an apparatus for volumetric measurement of water retention is discussed in an appendix.

II. LITERATURE REVIEW

1. Aggregate Formation and Properties of Aggregates.

Soil structure is defined by Baver (1956) as the arrangement of primary particles -sand, silt, and clay fractions- and the secondary particles -aggregates- into a certain structural pattern. It is generally accepted that aggregate size is one of the criteria by which soil structure may be evaluated (Tiulin, 1928, Low, 1954, etc.). Swanson and Peterson (1942) emphasized pore size, total pore space, and shape of pore as the factors to describe natural soil structure, but these properties are determined by aggregate sizes, shape of aggregates, and degree of compactness. Sieving methods, either dry or wet-sieving, were used for separating the aggregates.

Colloids, clay, organic matter, and sesquioxides were considered to play the most important role in aggregation, as they act as cementing agents (Lutz, 1936, Sideri, 1936, Peterson 1944, and 1947). Russell (1934) was among the first to propose that aggregate formation was due to a linking system consisting of: particle - orientated wetting molecule - cation - orientated wetting molecule - particle. The forces responsible for aggregation result from London - van der Waals forces, Madelung forces, Coulombic forces, hydrogen bonding, orientation of water dipoles or osmotic forces, depending upon the interacting distance.

Chepil (1950) and Tamboli (1961) found that apparent density decreases with increase in aggregate size. However, the calculation of apparent density from measurement of bulk density probably leads to this conclusion. The difference in apparent density among the different aggregate sizes could be the difference of inter-aggregate porosities, which is a function of aggregate size at the same packing level.

Antipov-Karataev and Kellerman (1962) found practically no difference in particle size distribution among the different aggregate sizes, except the clay content of the <0.25 mm fraction was slightly higher. There was no trend in organic matter or sesquioxide content for different sizes.

2. Clay Particle Arrangement.

Clay particles carry negative charges at the neutral point (pH 7), and the amount of negative charge usually increases as pH of the clay suspension increases. These additional charges are considered to be due to ionization of -OH groups from broken bonds at the edges of silicon-oxygen sheets. At low pH, extra H^+, or H_3O^+ is attracted from the broken bond of unbalanced

$\left\{+\frac{1}{2}-(OH^{-1})\right\}^{-\frac{1}{2}}$ charge; the clay particle can therefore have positive charges at these sites (Schofield, 1939). The nature of the charge determines the repulsion or attraction between edge and face of clay plates. Particle orientation is thus controlled by controlling pH in the clay suspension. A clay suspension disperses when the force of repulsion is predominant; each clay particle settles independently from this suspension. A clay suspension flocculates when attractive forces prevail; the clay particles clump together and settle as large units (Yong and Warkentin, 1966).

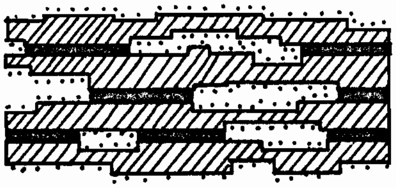
Kaolinite usually occurs in the form of large crystals with 70 to 100 layers, which are held together by hydrogen bonding between hydroxyls from the alumina sheet on one face to oxygens from the silica sheet on the adjacent layer. The hydrogen bonding is relatively strong, and can prevent any hydration between the layers (Yong and Warkentin, 1966). This property accounts for the low water retention. The clay platelets are bonded together in an irregular manner. These irregularly shaped crystals are stacked together into units known as the clay matrix (e.g. Kemper, 1958), or domain (Quirk and Aylmore, 1960) or polyplates (Koenigs, 1963). The clay particle orientation in these units differs (Kemper, 1958). Slurrying (Croney and Coleman, 1954) or compressing (de Jong, 1963) a moist soil probably changes the particle orientation. The remoulded clay is more parallel than the undisturbed Leda clay (Warkentin, 1962a). Application of mechanical forces probably breaks the edge to face and organic matter bonds. Particle orientations for kaolinite can be represented as in A and C in Fig. II-1 for parallel and random orientations respectively. Application of mechanical forces, e.g. mixing or compression will change the flocculated kaolinite to a more parallel orientation as illustrated in B, Fig. II-1.

Orientation of clay particles can also be varied by the conditions of sedimentation and by remoulding. The slurried samples of Croney and Coleman (1954) retained much more water than the undisturbed samples. Koenigs (1963) stated that this was due to the development of shear planes. Increased tangential movement between the clay plates resulted in more parallel particle orientation due to slurrying.

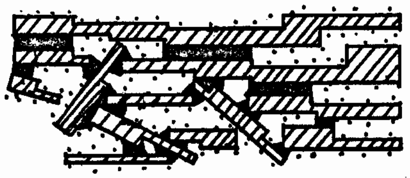
3. Volume Changes.

3-1. General Considerations.

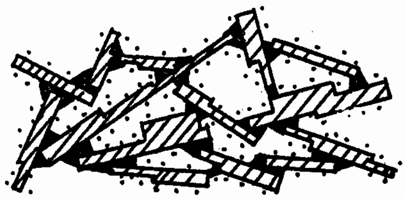
The shrinkage occurring on progressive and slow reduction of water content of a soil sample can be distinguished into four stages: structural, normal, residual, and no shrinkage. In addition, some soils may increase in volume after the stage of no shrinkage.



A, DISPERSED KAOLINITE.



B, FLOCCULATED KAOLINITE,
AFTER APPLICATION OF
MECHANICAL FORCES.



C, FLOCCULATED KAOLINITE.

LEGEND:

CROSSED HATCHED AREA = CLAY CRYSTAL.

SHADED AREA = WATER RETAINED ABOVE GIVEN pF.

POINTS = HYDRATED ADSORBED CATIONS.

FIG. II-1, <u>KAOLINITE POLYPLATE CONFIGURATION.</u>

Haines (1923) measured the shrinkage of a black clay loam, and found that one-third of the amount of water originally present was lost before the shrinkage became measurable. Lauritzen (1948) found that his natural clay soil showed a stage in the wetter part of the moisture range where the change in soil volume was less than the volume of water removed. The aggregates apparently moved somewhat closer together but pores emptied and allowed the entry of air. This report was supported by Stirk (1954), who termed this stage "structural shrinkage". This stage probably can only be observed for surface soils with well-developed structure.

Keen (1931) discussed the results of Haines (1923) and referred to the region where shrinkage was equal to water withdrawn as "normal shrinkage"; the percent saturation of the soil did not change in this region.

The succeeding region, in which the decrease in volume was less than the volume of water lost, was defined as "residual shrinkage" by Haines (1923). He explained this as due to colloidal coatings, but Lauritzen (1948) favoured an explanation of residual shrinkage based on the distinction between expanding and non-expanding lattice clay minerals. In the stage of residual shrinkage, water removed from the clay soil may be at the expense of both capillary or film water and water held in the expanding lattice of clay particles. Soil with no expanding lattice clay mineral should not show this stage.

Eventually, shrinking of the soil ceased when all particles were in contact, and the coarser fractions in the soil mass formed a rigid framework. In this region, soil volume remained constant even though water was still withdrawn (Lauritzen, 1948, Stirk, 1954). Stirk (1954) termed this region "no shrinkage".

The explanation for residual shrinkage proposed by Lauritzen (1948) apparently does not apply to kaolinite samples, which do not have an expanding lattice but which do show residual shrinkage (c.f. Haines, 1923). Stages of shrinkage probably relate to a balance of forces as implied in Koenigs' statement (1963):

> "The moisture content of clay soil is the result of an equilibrium between the swelling pressure on one hand and the soil suction plus Madelung attraction on the other hand. However, frictional forces, caused by organic matter bonds and by edge-face attraction, tend to fix any given arrangement. When the primary particles are moved in relation to each other, the true equilibrium between swelling pressure and suction is obtained, ...".

Clay soils swell on rewetting. The process of shrinking and swelling may be fully or partly reversible depending upon the type of clay minerals (Yong and Warkentin, 1966) and degree of drying. Both Haines (1923) and Holmes (1955) found that the volume on rewetting was equal to or larger than on drying at the same water content. They definitely concluded that the increase was due to the air locked in the pore space. It is essential that the soil was dried below the shrinkage limit, otherwise wetting and drying take place reversibly. de Jong (1963) allowed slurried samples of Leda clay to rewet before the shrinkage limit and found that volume increase on rewetting was only partly reversible. He explained this as due to an energy barrier, or to particle rearrangement, as suggested by Parry (1960). Closer examination of de Jong's results (1963) showed that there was no volume change with increase in water content in the wetter part of the reswelling curve.

Attention should be paid to the method used for changing the water content in investigating shrinking and swelling. Haines (1923) used spraying for rewetting the soil. Rapid watering from the top of the sample by this method probably causes air entrapment in the soil and uneven water distribution. This was probably the reason for Haines' result (1923) that volume in swelling was always larger than in shrinking at the same water content. If the soil is rewetted slowly from the bottom of the sample and the soil air allowed to escape, uneven rewetting would be eliminated.

3-2. Influence of Soil Properties on Volume Change.

Total shrinkage, stage of shrinkage, and characteristics of shrinkage are influenced by properties of the soil such as type of clay minerals, aggregates, texture, orientation of clay particles, exchangeable cations, pore space and organic matter.

Tempany (1917) and Haines (1923) found that total shrinkage increased with clay content. There are no systematic comparisons concerning total volume changes among the clay minerals, but it is generally observed that total shrinkage and residual shrinkage is linked with degree of expansion of lattice spacing in clay minerals. Kaolin has a non-expanding lattice whereas the lattice structure of montmorillonite is of the expanding type. Stirk (1954) found that total shrinkage and shrinkage limit of cracking soils were larger than for a non-cracking soil. He reasoned that the difference was probably due to clay content or type of clay minerals. Lauritzen (1948) observed that natural clods did not exhibit as much normal shrinkage as artificial blocks prepared from the soil. Lauritzen and Stewart (1941) found that with decreasing apparent specific volume of the soil, the characteristics of the shrinkage curve became similar to the curve exhibited by the blocks. Stirk (1954) found a large difference in shrinkage pattern between the soil aggregates and remoulded soil of the same material. The ratio of structural and residual shrinkage to total shrinkage increases with increase in aggregate sizes. A difference in shrinkage limit between the soil aggregates and remoulded soil was also observed by de Jong (1963). Using clay-glass bead mixtures, he found that total shrinkage and shrinkage limit were linearly related to texture in the range 50 - 100% clay content (de Jong and Warkentin, 1965).

According to the capacity for volume change, soils can be classified into three groups.

Croney & Coleman (1954)	Bolt & Miller (1958)	Babcock (1963)	Thermodynamic expression, present author.
Fully-compressible soil	Ideal clay-water system	Swelling soil	$(\frac{\partial V}{\partial \eta_w})_{P.T.} = \bar{V} = 1$
Partially-compressible soil	Non ideal clay-water system	Partially swelling soil (?)	$(\frac{\partial V}{\partial \eta_w})_{P.T.} = \bar{V} < 1$
Non-compressible soil	Coarse grain-water system	Non-swelling soil	$(\frac{\partial V}{\partial \eta_w})_{P.T.} = \bar{V} = 0$

where:

V = Specific pore volume.

$\bar{V}$ = Partial molar volume of water.

$\partial \eta_w$ = Amount of water change in the system.

4. Swelling Pressure.

4-1. Theoretical Considerations.

Clay plates bear negative charges on their surfaces due to isomorphous substitution in the clay lattice, dissociation of hydroxyl groups on the clay surface, and unbalanced charges from the broken bonds at the edges of the particles. Cations, probably hydrated, are attracted by these charges. From the Poisson equation, using the Boltzmann distribution of ions, it is possible to predict that these cation occur in a diffuse layer at some average distance from the charged surface. This was first worked out by Gouy and by Chapman. Interaction of the diffuse ion layers of parallel particles gives a concentration of cations at the mid-point which can be estimated from these equations (Yong and Warkentin, 1966).

$$C_c = \frac{\pi^2}{z^2 B(d - x_o)^2} \qquad \text{(II - 1).}$$

where:

C_c = Concentration of cations midway between particles.

z = Valence of adsorbed cations.

$$B = \frac{8\pi e^2}{\epsilon kT}$$

x_o = Correction factor varies from 1 to 4 Å depending on ion valance and charge density.

k = Boltzman constant.

T = Absolute temperature.

ϵ = Dielectric constant.

d = $\frac{100W}{S}$

S = Specific surface area.

W = Water content.

e = Electronic charge.

The difference in ion concentration half-way between the parallel clay plates and in soil solution is considered the cause for water to move into the soil. Therefore it is possible, by application of van't Hoff's equation, to calculate the swelling pressure. The equation is given as,

$$P = RT(C_c - C_o) \tag{II-2}$$

where:

P = Swelling pressure.

R = Gas constant.

T = Absolute temperature.

C_c = Calculated from equation (II-1).

C_o = Ion concentration in soil solution.

From the above equation, it is possible to estimate the relation between water content and swelling pressure of a certain soil in a given electrolyte solution.

The compression of a clay-water system has also been described by this osmotic theory of swelling (Bolt and Miller, 1955, Bolt, 1956, Warkentin et al, 1957, Greacen, 1959).

4-2. General Considerations.

Swelling pressure can be measured by a confining pressure at constant volume. Significant disagreement between calculated and measured swelling pressures appears in the literature. Calculated pressures higher than (Warkentin, 1962b, and Koenigs, 1963) or lower than measured (Warkentin, 1962b, de Jong, 1963, Kemper, 1958) have been found. The divergence is probably due to the soil material and method of sample preparation which affects the development of swelling pressure (Koenigs, 1963).

According to equation (II-2), a clay soil should swell infinitely at zero confining pressure, because the ion concentration between the clay plates is always higher than in the soil solution. Actually there is a limit to swelling for any soil. Usually swelling is very small for clay soils below pF 2. Norrish and Raussel-Colom (1962) called this constraint "internal load". Koenigs (1963) explained it as due to a frictional force caused by organic matter bonds and by edge to face attraction. This is probably true only for soils which have not been pre-consolidated or dried. According to results reported by Waidelich (1958), expansion for clay soils was very small when the samples experienced pre-consolidation at 8 tons/ft^2.

5. Water Retention

5-1. Analysis of Total Water Potential and the Thermodynamic Approach to Water Retention.

Energy status of soil water has been given much attention by a number of investigators since the energy concept was introduced by Buckingham (1907). The relation between soil suction or total potential and water content of soils can be measured without reference to the forces holding water, and is known as the water retention curve (Marshall, 1959), moisture characteristic curve (Childs, 1940), or pF curve (Schofield, 1935). More than one force is usually involved in holding water in soil, and it is necessary to distinguish such forces in order to understand the mechanisms of water retention. Such a breakdown of forces is also necessary before measuring the components contributing to total soil suction. As pointed out by Bolt and Frissel (1960), care must be taken in splitting the terms to prevent a term being hidden in other terms or being counted twice.

Day (1942) was among the first to use the chemical potential to describe soil moisture. He wrote,

$$d\Phi = du + d\psi \qquad \text{(II - 3).}$$

$$du = \left(\frac{\partial u}{\partial T}\right) dT + \left(\frac{\partial u}{\partial P}\right) dP + \sum_j \left(\frac{\partial u}{\partial N_j}\right) dN_j \qquad \text{(II - 4).}$$

where; Φ = Total potential.

u = Chemical potential.

ψ = Gravitational potential.

N_j = Mole fraction of solute species j.

P = Hydrostatic pressure.

T = Kelvin temperature.

He made his measurements with tensiometers, and implied that the pressure potential could be identified as Buckingham's capillary potential. Tschapek (1960) also emphasized capillary potential in water retention and suggested the following equation to express the total potential.

$$dG = \left(\frac{\partial G}{\partial T}\right)_{P.S.} dT + \left(\frac{\partial G}{\partial P}\right)_{T.S.} dP + \left(\frac{\partial G}{\partial S}\right)_{T.P.} \partial S \qquad \text{(II-5)}$$

where: G = Gibbs free energy.

S = Total surface of soil particles.

Tschapek (1960) concluded that the influence of surface tension on water retention $\left(\frac{\partial G}{\partial S}\right)_{T.P.}$ in equation (II - 5) shows the capillary force to be most important from saturation to the permanent wilting percentage. This is probably true for his sample, a kaolinite, but the equation (II-5) does not have general application.

Edlefsen and Anderson (1943) wrote the paper "Thermodynamics of Soil Moisture" in which all factors contributing to total potential were discussed in detail. Low (1951) and Low and Deming (1953) have added an electrostatic force and a van der Waals force field to the term $d\psi$ of Day's equation to account for positional potential. Babcock and Overstreet (1955) considered that water content should also be a variable in the chemical potential of soil water. Bolt and Frissel (1960) added another variable, the geometry factor, to Day's expression. Box and Taylor (1962) further demonstrated that bulk density affects the matric potential. Instead of a geometry factor, which is unmeasurable, bulk density is a measurable independent variable. The expression was revised as,

$$du = V_w dP_e - S_w dT + \left(\frac{\partial u}{\partial P_w}\right) dP_w + \left(\frac{\partial u}{\partial \rho_b}\right) d\rho_b + \sum_j \left(\frac{\partial u}{\partial N_j}\right) dN_j \qquad \text{(II - 6)}$$

where: P_e = External pressure.
P_w = Moisture variable.
ρ_b = Bulk Density.
S_w = Entropy of water.

The other notations are the same as in equation (II - 4).

Bolt and Frissel (1960) wrote two equations:

(a) Considering water as one phase of the three phase system soil-water-air, the appropriate equation is,

$$d\bar{G} = \bar{V}dP_e + \left(\frac{\partial \bar{G}}{\partial T}\right)dT + d\omega + Mgdh + \sigma d\bar{O} + d\alpha \qquad \text{(II - 7)}$$

(b) Considering the soil-water-air system as one homogeneous system, the corresponding equation would read,

$$d\bar{G} = \bar{V}dP_e + \left(\frac{\partial \bar{G}}{\partial T}\right)dT + \left(\frac{\partial \bar{G}}{\partial \theta}\right)d\theta + \left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi + d\omega + Mgdh \qquad \text{(II - 8)}$$

where: $\bar{G}$ = Partial molar free energy.

θ = Water content.

χ = Geometry factor

$\omega = \omega_o + \omega_a$, swelling forces included due to free salts and adsorbed cations respectively.

$\bar{O}$ = Surface area.

σ = Surface tension of liquid.

α = Adsorption forces.

P_e = External pressure.

Note: Chemical potential (u), Gibbs free energy (G), or partial molar free energy ($\bar{G}$) are used in thermodynamics of soil water by different authors. The same results are obtained, although their meanings from a purely thermodynamic stand point are somewhat different.

5-2. Factors Influencing Water Retention.

Soil moisture constants such as moisture equivalent, permanent wilting percentage (P.W.P.) and water retention at a given potential increase with increasing clay or colloid contents (Loughridge, 1894, Keen and Raczkowski, 1921, Lebedeff, 1927, Joseph, 1927). Wilcox and Spilsbury (1941) found that P.W.P. was related to colloid content. Lund (1959) found that this relationship was linear. Omstead (1937) and Wilcox and Spilsbury (1941) derived equations in which the water-holding capacity was expressed as the sum of coefficients for sand, silt, and clay. This may be valid only for some soils. de Jong (1963) conducted experiments with mixtures of glass beads and clays, and found that there was a linear relationship between water retention and texture for a clay content above 20% either on drying or on wetting.

Type of clay mineral influences water retention. Clays with expanding lattices retain more water than non-expanding lattice clays (Grim, 1953). Higher water retention is found for smaller particle size. Specific surface area, which is a direct function of particle size was considered the governing factor.

Adsorbed cations on the clay surface influence water retention. Sodium montmorillonite retains more water than the Ca^{++}, H^{+}, Al^{+++}, or K^{+} forms. These were considered to bond the particles together, suppressing swelling (Grim, 1958, Davidson and Page, 1958). Kemper (1958) explained that a Ca^{++}-saturated soil paste held more water than Ca^{++} - Na^{+}-saturated soil paste due to the effect of particle arrangement. Thomas and Moody (1962) found that the amount of water held at 1/3 atm was closely related to clay type and saturating cations, but there was little difference in water held at 15 atm among any of the clays regardless of cation saturation or clay type, except for Na^{+}-montmorillonite. On the basis of these findings, care must be taken in the application of diffuse ion layer equations to estimate water retention from swelling pressure.

The amount of water retained, especially in a sandy soil, depends upon the volume and size of pores present (Marshall, 1959). Tomboli (1961) found that an increase in bulk density increased water retention up to 5 bar. The opposite result was obtained by Wilcox (1939) who found a decrease in moisture holding capacity resulting from an increase in bulk density. Wilcox's result (1939) was supported by Taylor and Box (1961), and Box and Taylor (1962). The effects were quite marked with heavy soils but almost negligible with sandy soil

(Wilcox, 1939). Croney and Coleman (1954) prepared samples of plaster of Paris with different proportions of water. They found an increase in saturation moisture content, a decrease in the value of suction at which air first entered the structure, and a decrease in amount of water held at high suction as the water/plaster ratio increased. These results were explained on the basis of increase in pore size and pore volume.

The effect of aggregate size on water retention was investigated by Tomboli (1961). A silt loam sample was prepared at three different bulk density values, 1.36, 1.15, and 0.95 gm/cc from aggregates with diameters, 0.5, 1.0, 2.0, 3.0, and 5.0 mm. The results showed that the smaller the aggregate, the smaller is the water retention. The conclusion drawn by Tomboli (1961) was that at lower moisture tension, water retention is determined by size and shape of pores, whereas the moisture retained at higher tension values is determined by surface adsorption effects.

6. Hysteresis.

It has been generally observed that the adsorption isotherm in a porous solid is not retraced on desorption. Youngs (1960) stated that water content is a single-valued function for soil only in very special cases. The difference between adsorption and desorption is termed hysteresis. It is a general characteristic of water retention by soils. The same effect has also been found for volume changes (Haines, 1923, Holmes, 1955), and swelling pressure (Warkentin, 1956, Greacen, 1959). Hysteresis for water retention and swelling pressure can be generalized into two main types according to the loops shown in Fig. II-2.

TYPE - 1. The adsorption branch rejoins the desorption branch at a finite suction. Hysteresis of this type is usually reproducible (Holmes, 1955, Croney and Coleman, 1954). Scanning curves are always enveloped by the main branches.

TYPE - II. The wetting curve never rejoins the first drying curve (Haines, 1930, Holmes, 1955, de Jong, 1963), but succeeding cycles will have the same behaviour as that of type I (Poulovassilis, 1962, Collis-George, 1955). If drying were stopped at d and the sample allowed to rewet, the rewetting curve d-e will meet neither the first drying curve a-b nor the rewetting curve b-c but will lie between them (de Jong, 1963). The distance between a-c or a-e represents the amount of air

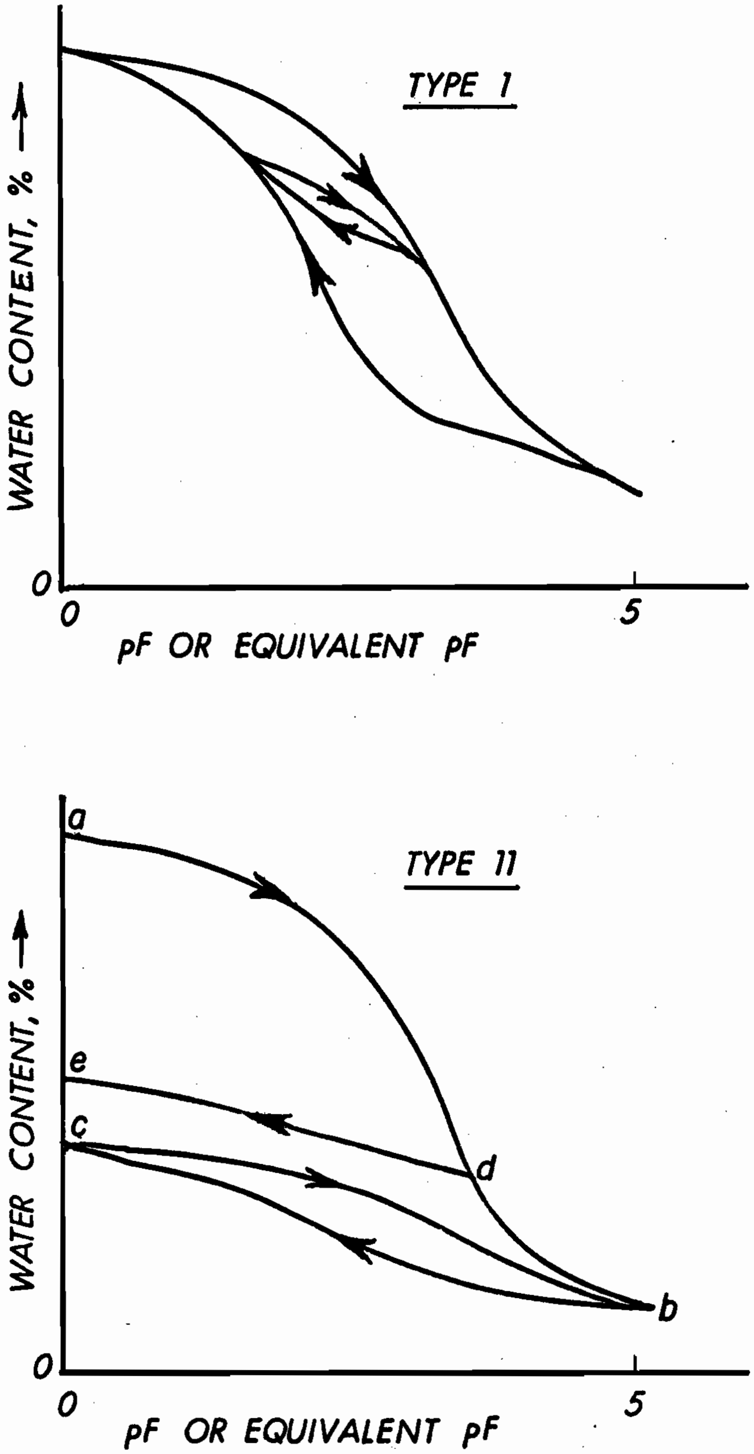


FIG.II-2, HYSTERESIS LOOPS WITH SCANNING CURVES FOR WATER RETENTION AND SWELLING PRESSURE, entrapped in the sample and the volume decrease.

A number of mechanisms have been postulated to explain the hysteresis effect; they fall into the category of fundamental theories of surface chemistry. Difference in contact angle, or effect of "ink bottle" pores that differe in filling or emptying account for the effect in soils with constant geometry. Haines (1930) considered V-shaped pores as contributing part of the effect in addition to "ink bottle" pores. Holmes (1955) considered that volume changes were the major cause of hysteresis in clay soils. Schofield (1935) explained hysteresis for fully compressible soil as plastic readjustment of position of clay particles. Warkentin (1956) explained differences in swelling pressure as due to particle rearrangement. Collis-George (1955) concluded that the independent domains described by Everett et al (1952) could describe hysteresis in both compressible and incompressible soils. Poulovassilis (1962) used the independent domain theory to calculate rewetting curves and found them to be close to the experimental result.

7. Development of Apparatus.

7-1. Water Retention.

Since porous plate apparatus was introduced by Richards and Fireman (1943) for investigation of soil-water relations, several workers have attempted to improve the apparatus in order to obtain reliable soil moisture data. The commercial pressure cooker based on Richard's design (1948) was found to have a persistent air leak that affected the soil moisture data (Johnston and Perrier, 1962). However, it is still considered a convenient apparatus for routine work, because the cooker can receive a number of samples at a time.

Tanner and Elrick (1958) tried to build a porous plate apparatus to study soil moisture volumetrically. Air which leaked through and accumulated under the porous plate had to be removed from time to time by a "milking" process. Reginato and van Bavel (1962) constructed a miniature pressure cell for soil cores. The air leak also could not be prevented.

The porous plate apparatus may be used from 0 to 15 bar pressure. However, simpler apparatus is preferred at the lower pressure range. Masonry brick covered with filter paper was used to measure water retention at saturation (Richards, 1954). Filter funnels (Richards, 1949) or sand tanks (Peerlkamp and Boekel, 1960) can be used between pF 0 to 2 simply by adjusting the water head. Pressure membrane apparatus designed by Richards (1947) can be used up to about 30 atmospheres. Air accumulated beneath the membrane can be driven off by circulating water under the porous plate.

7-2. Swelling Pressure.

Swelling pressure is measured by enclosing the soil sample in a cell with a definite volume, usually having a porous plate at one end and an impermeable membrane at the other. Water is admitted to the sample through the porous plate by a water head (Palit, 1953) or by suction (Kentze, 1961). The pressure developed is transferred through a proving ring or bar and indicated by a dial type of pressure gauge. The proving ring or bar has the disadvantage that deflection allows more or less soil volume change. The measured swelling pressure would be underestimated (Barber, 1956, Darson, 1956, and DuBase, 1956). Such apparatus is limited to one measurement. Seed et al (1962) reported a similar device in which the volume can be regulated by a piston operated by a screw.

Rengmark et al (1953) measured swelling pressure by enclosing the sample in a rubber cloth which was immersed in water. The applied mechanical force was transferred by the confined water. He claimed that it measured swelling pressure in several directions. Bolt and Miller (1955), and Warkentin et al (1957) placed the clay suspension between a porous plate and a sheet of flexible rubber in a miniature pressure cell. The salt concentration was maintained by circulating the desired solution under the porous plate. Confining pressure was regulated with nitrogen gas. Inter-particle spacing or water content changes were measured by the change in position of the nitrogen-water menicus above the rubber sheet.

7-3. Volume Change Measurements.

Volume of a given mass is usually measured from displacement of volume in a liquid. The soil is coated with wax or Dow "Saran" resin in advance. Haines (1923) used a mercury pycnometer to measure the soil volume. Tempany (1917) estimated shrinkage from measurements of the decrease in distance between two pins in the sample. Warkentin and Bozozuk (1961) inscribed two marks on the soil surface; the linear change was measured by a travelling microscope. The change in depth of a sample can be measured by a depth gauge (de Jong, 1963). Volume of a sample can also be measured from its image projected on a screen (Croney and Coleman, 1955).

III. COMPACTION - A METHOD FOR PREPARATION OF CLAY SOIL SAMPLES FROM AGGREGATES.

1. Introduction.

In a study to investigate the relationship of porosity and aggregate size to water retention, preparation of samples is very important. The method of preparation should be such that the samples have the following desirable properties:

(a) The aggregate must remain intact, otherwise it is not possible to determine the effect of aggregate size on water retention.

(b) Duplicate samples must be identical in all respects. This is necessary because separate samples are used for determination of water retention, swelling pressure and volume changes. Comparison of these would not be valid if samples were not identical.

(c) It must be possible to prepare samples with a desirable porosity.

When moist soils are compacted, soil structure is changed and the porosity cannot easily be controlled because it is a function not only of loading but also of water content of the soil.

The use of air-dry soil in the preparation of samples overcomes the difficulties encountered using moist soil and appears to give samples with the required properties. In addition, properties are a function of loading; thus providing a method of determining inter- and intra-aggregate porosities at any given loading pressure.

2. Compaction of Aggregates.

Two aggregate sizes, < 0.25 and 1.00-4.76 mm, were separated from four clay soils described in Table III-1. The aggregates were separated by sieving the air-dry soil on a vibrating shaker[★] for one hour.

Approximately 12 gms of the aggregates were poured into the compaction apparatus shown in Fig. III-1. The apparatus with plastic holders, as shown in Fig. III-1A was used for the lower loading pressures, 50 to 1,000 psi, while the stainless steel (Fig. III-1B) was used for loading pressures above 1,000 psi. Compaction was by one-dimensional, static loading, applied for five minutes. Levers were used for pressures below 1,000 psi and a hydraulic press[*] for the higher pressures. The soil air escaped through the clearance between the plunger and holder during loading. It was essential that the soil in the holder be levelled before application of loading pressure, otherwise the duplicates were not identical.

[★] Eberbach, Ann Arbor, Mich., USA.

[*] Black Hawk Mfg. Co., Milwaukee 1., USA.

TABLE III - 1

DESCRIPTION AND SOME PROPERTIES OF SOILS USED

Soils	Label Number	Location	Depth of Sampling	Minerals
Ste. Rosalie Clay	1	Morgan Arboretum, Macdonald College	Below 6 inches	Mica with chlorite feldspar and quartz.
Macamie	2	Near Palmorolle, Abitibi, Quebec	18" - 28"	--
Lamothe	3	Near Landrienne, Abitibi, Quebec	6" - 12"	--
Barbados 61-18 ✱	4	Claybury Plantation	0 - 6"	Kaolinite-halloysite with traces of illite and montmorillonite
Barbados 61-10 *	5	Mt. All beds of Scotland formation	--	Montmorillonite, 30% Illite, 40 % Kaolinite, 30%

✱ Used for compaction test only

* Not used in compaction test.

Continued

TABLE III - 1 (Continued)

DESCRIPTION AND SOME PROPERTIES OF SOILS USED

Soils	Label number	Loss on ignition (420-450° C), %	Hygroscopic moisture content, %	Mineral density gm/cc	Particle size distribution, %		
					>0.02 mm	0.02~ 0.002 mm	<0.002 mm
Ste. Rosalie Clay	1	5.6	3.10	2.70	32	16	52
Macamic	2	1.6	4.08	2.63	1	5	94
Lamothe	3	0.9	3.27	2.72	20	31	49
Barbados 61-18 ★	4	-	4.48	2.65	-	-	-
Barbados 61-10 ✱	5	3.3	2.26	2.70	26	20	54

★ Used for compaction test only

✱ Not used in compaction test.

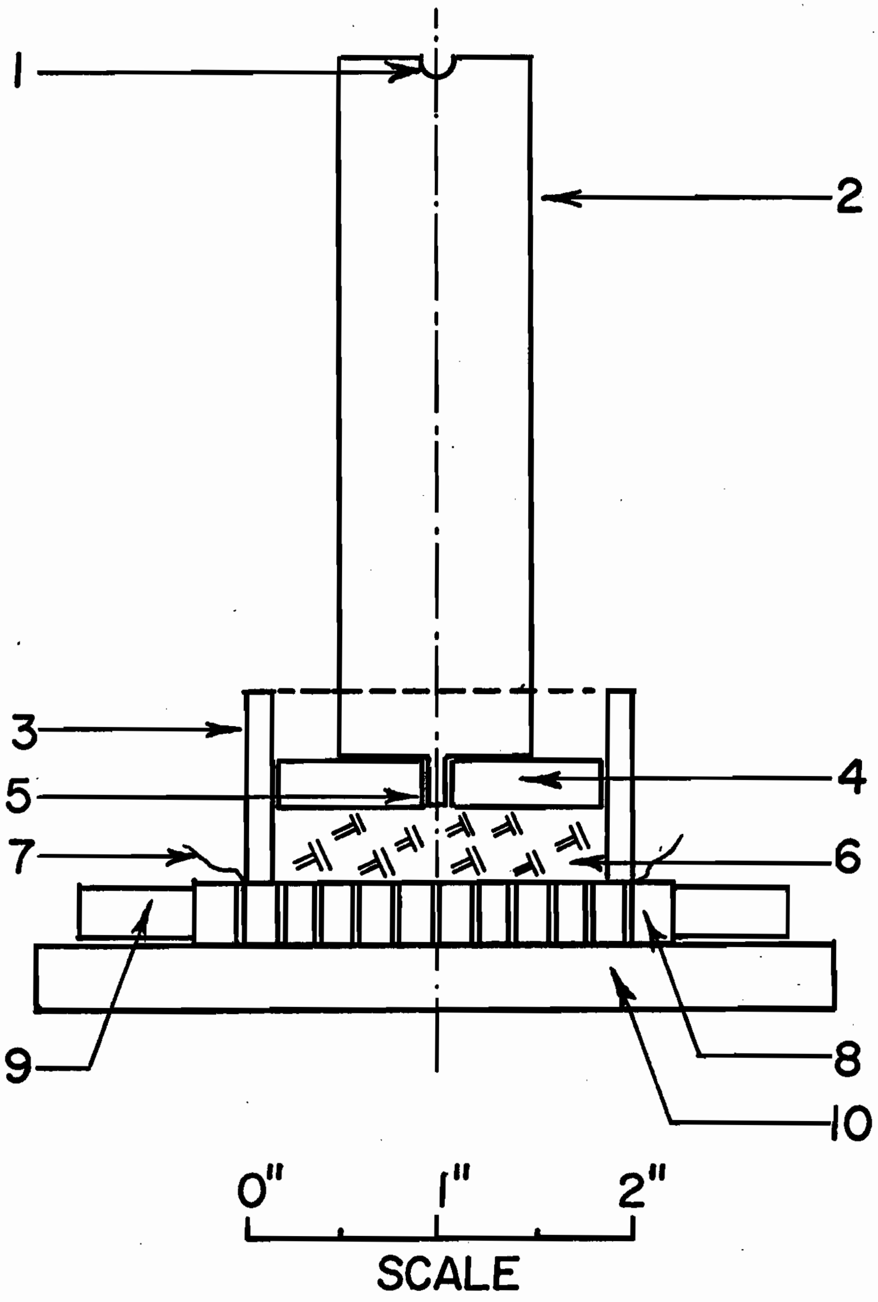
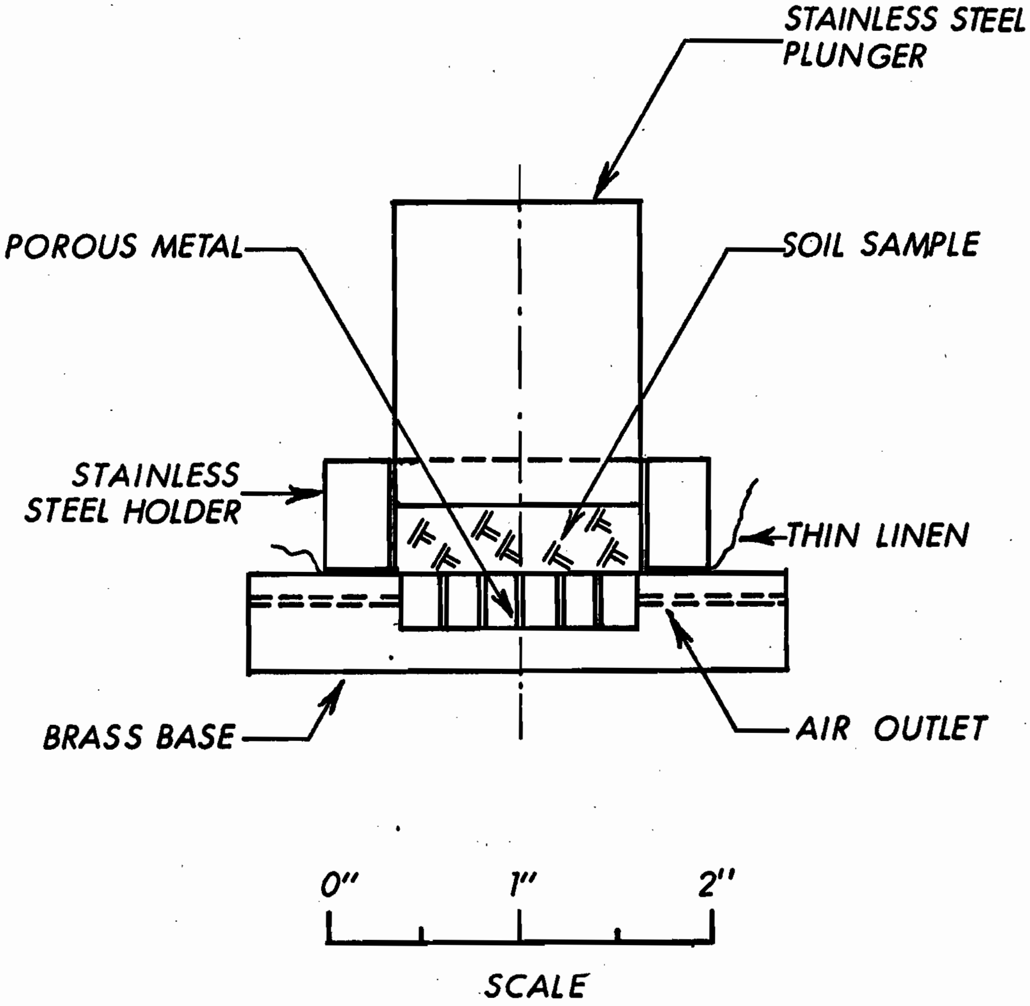


FIG. III-1A, COMPACTION APPARATUS FOR LOW LOADING PRESSURE,

LEGEND FOR FIGURE III-1A.

1. Curved recess for levelling load
2. Brass plunger (upper part), 2.08 cmϕx 7.00 cm H.
3. Plastic sample holder, 4.40 cmϕx 2.40 cm H.
4. Plastic plunger (lower part), 3.39 cmϕx 0.70 cm Th.
5. Locking pin.
6. Soil sample.
7. Thin linen.
8. Porous metal, 6.30 cm x 0.80 cm Th.
9. Plastic holder for porous metal, 6.30 cm I.D. x 11.00 cm O.D. x 0.60 cm Th.
10. Plastic base.



FIG, III-1B, COMPACTION APPARATUS FOR HIGH LOADING PRESSURE.

Bulk volume was determined after each application of loading pressure by measuring the thickness of the sample in the sample holder. The total porosity, sum of inter-aggregate and intra-aggregate porosities was calculated from the following formula:

$$\rho_T = 1 - \frac{m}{\pi r^2 \Delta hd} \quad x \quad 100\% \qquad \text{(III-1)}.$$

where: ρ_T = Total porosity, defined as the ratio of the volume of total pore space over bulk volume of the soil, %.

m = Weight of air-dry soil corrected to oven-dry weight, gms.

r = Radius of sample holder in the compaction apparatus, cm.

Δh = $h_1 - h_2$, h_1 is a constant which is an initial depth gauge reading without soil, cm. h_2 is a final depth gauge reading measured after each compaction, cm.

d = Real density of soil particles, gm/cm^3

and $$\rho_T = \rho\text{inter.} + \rho\text{intra.} \qquad \text{(III-2)}.$$

If one of the terms on the right hand side of equation (III-2) can be determined, the other term can be obtained since ρT is known. ρT of different aggregates vs logarithm of loading pressure is plotted on Fig. III-2. The point at which the two lines meet gives the intra-aggregate porosity. These values are compared with the Hg-pycnometer method in Table III-2. Selected large aggregates from the 1.00-4.76 mm sample were used in the latter method, based on the assumption that there was no significant difference in the apparent density of different sizes of aggregates. Larger aggregates were selected because use of smaller aggregates underestimated the apparent density. Mercury could not penetrate into the spaces between the smaller aggregates or between the wall of the pycnometer and the aggregates. This was observed in the transparent plastic pycnometer.

TABLE III-2

COMPARISON OF INTRA-AGGREGATE POROSITY BETWEEN COMPACTION METHOD AND Hg-PYCNOMETER METHOD, AND THE COMPACTIBILITY INDEX

Soils	Intra-aggregate porosity, % Compaction Method	Hg-pycnometer Method	Compactibility Index
1	40	39	0.55
2	40	38	0.60
3	35	35	1.00
4	38	38	0.46

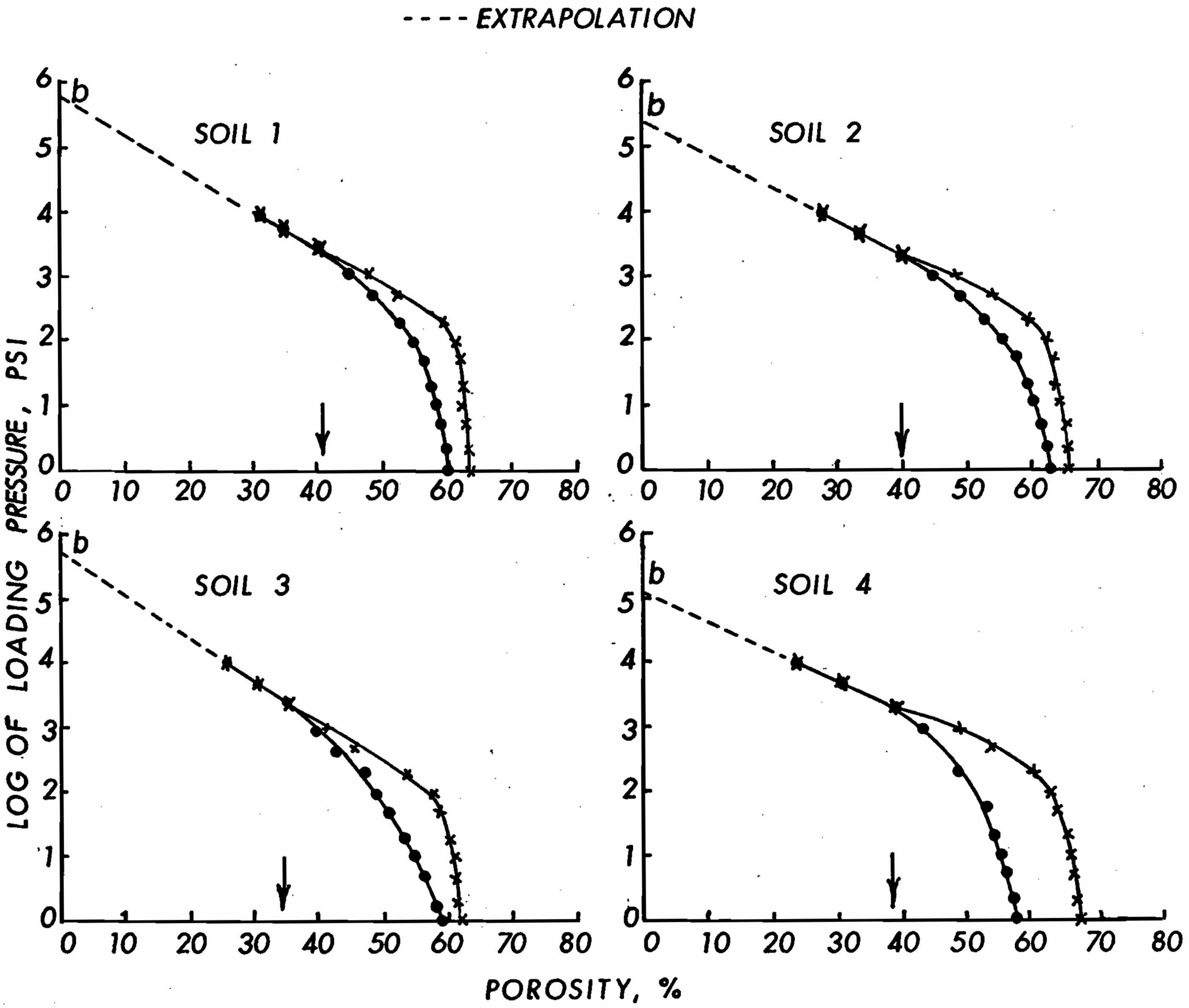


FIG. III-2, COMPACTION CURVES.

Duplicate samples were used for both methods and the duplicates were within 2%. error. The plots in Fig. III-2 and data in Table III-2 are averages from the duplicate samples. The compactibility index shown in Table III-2 was obtained from the slope of the compaction curve in the straight line region as shown in Fig. III-2.

3. DISUCSSION OF RESULTS.

Application of an external load causes aggregate rearrangement and closer approach. The applied stress is transmitted and carried by the soil skeleton. Physico-chemical properties are considered to be inactive in air-dry soil, therefore only universal attraction forces and frictional forces are operative during closer approach and increasing area and number of contacts between the aggregates as loading pressure is increased. The loading is assumed not to be high enough to change the water films around particles. At equilibrium, the applied stress is balanced by the frictional force at the point of inter-aggregate or/and inter-particle contacts. The mass force is considered to be negligible because the test sample is small. The loading pressure is the only factor governing the porosity of the sample because the frictional force is passive in nature and is a function of applied stress.

Fig. III-2 shows that two stages of compaction can be distinguished on the semi-log graph. The curvilinear section is termed inter-aggregate compaction; the straight line is named normal compaction.

A, Inter-aggregate compaction:

Initial inter-aggregate pore volume is larger for larger aggregates and the frictional force should be smaller for the larger aggregate due to fewer inter-aggregate contacts. Therefore the rate of decrease in porosity with increment of loading pressure, up to a critical value, should be larger for larger aggregates. As shown in Fig. III-2, it is only true above 100 psi. This indicates that there is a threshold pressure for aggregate rearrangement. An aggregate could not move between two others until the loading pressure was high enough to displace them. The amount of displacement required, and hence the loading pressure, increases with increasing size.

The intercept of the two lines is supposed to give the apparent density of the aggregate. It is the point at which intra-aggregate porosity begins to decrease. This is verified by the agreement with Hg-pycnometer results as shown in Table III-2.

B, Normal compaction:

The straight line portion may be represented by the empirical equation,

$$\log P = -k\rho_T + b \qquad \text{(III-3)}.$$

where:

P = External loading pressure.

ρ_T = Total porosity, %.

k = Compactibility index.

b = Zero porosity constant, psi. It is an intercept on y axis by extrapolation of the straight line.

Although a definite relationship between the intra-aggregate porosity and compactibility index has not been found, soil 3 indicates that a lower porosity will be accompanied by a higher index (Table III-2).

In this region there is no difference in interparticle distance between and within aggregates, but it does not mean that the soil sample has been united as a soil block. The surface properties of the aggregate probably remain. This was observed by separation of the aggregates, and verified by the difference in specific pore volume after saturation, (Column 5, Table V-1) between the samples prepared from different aggregate sizes even when the sample was compacted at pressures as high as 10,000 psi.

IV. MATERIALS AND METHODS.

1. General.

The investigations were carried out with different clays and with compacted clay soil aggregates. The former were used to study water retention only; the latter were used to study water retention, volume changes, and swelling pressure.

Water retention and volume changes were measured in a continuous manner so that one sample was used to complete the whole drying-wetting cycle, but they were measured on different samples because the material used for the bottoms of the sample holders had to be different. Choice of material for this purpose is critical. "Millipore" ultra filter paper, which is wrinkled when it is wetted but lasts long without rotting, was used for water retention studies. It was punched with several needle holes to facilitate movement of water. Thin linen cloth, of which the shape will not be affected by adsorption of water or change in water content, but which remains intact no more than forty-five days, was suitable for the bottoms of sample holders in volume change measurements. The same apparatus and process as in water retention was used for changing the water content in volume change measurements, except the period of the drying-wetting cycle was shorter at water contents below pF 3. These may not have been equilibrium values (except at pF 0) and volume is related to water content, not to suction. Apparatus, terminal pressures and direction of wetting-drying cycle for the respective studies are summarized in Table IV-1.

Every measurement was made on duplicate samples and the data presented are averages.

2. Preparation of Samples.

2-1. Compacted Samples of Aggregates from Clay Soils.

Six different samples for each of soil, 1, 2, 3, and 5 as described in Table III-1, were made by using two aggregate sizes, <0.25 and 1.00-4.76 mm, and three compaction levels, 50, 1,000, and 10,000 psi. The procedure of compaction is as described in section III-2. For the two lower compaction levels, samples were prepared directly in plastic holders. At the 10,000 psi compaction level, samples were prepared using the apparatus illustrated in Fig. III-1B. Then they were transferred into the sample holders. The samples were 0.5-0.7 cm in height with a diameter equal to the holder used.

TABLE IV - 1

APPARATUS, PRESSURE RANGE, AND DIRECTION OF WETTING-DRYING CYCLE FOR THE RESPECTIVE STUDIES.

Soil Samples	Pressure Range and Direction	Studies
Kaolinite and glass bead mixtures	Air-dry → pF 5 → 0 → 4.25	Water retention
Leda Clay	1. Air-dry → pF 0 → 4.25 → 0 2. Air-dry → pF 0 → 3.00 → 0	Water Retention
	1. Air-dry → pF 0 → 4.25 → 0 → 4.25 2. Air-day → pF 0 → 3.00 → 0 → 4.25	Water Retention
Clay Soil Aggregates	1. Air-dry → pF 0 → 4.25 → 0 → 4.25 2. Air-dry → pF 0 → 3.00 → 0 → 3.00	Swelling Pressure
	Air-dry → pF 0 → 4.25 → 0 → oven-dry	Volume Change

2-2. Undisturbed Clay Soil.

Undisturbed soil 1 (Ste Rosalie clay) was taken 6 inches below the surface with a copper tube having dimension 2.0-2.5 cm H. x 5.0 cm I.D. x 5.3 cm O.D.

2-3. Dispersed and Flocculated Kaolinite and Kaolinite-glass bead Mixture.

Dispersed kaolinite was prepared from 7% Peerless Kaolin* by adjusting the pH between 9.0-9.5 with 0.02N NaOH solution; it was allowed to settle ½ hour while the pH value remained above 9.0. The supernatant was siphoned into a ultrafilter apparatus, excess water removed by air pressure, and then air-dried. The kaolinite sample prepared in this way would have a more or less parallel particle orientation.

The flocculated kaolinite was prepared from the same supernatant as described above but adjusted to pH 3.5-4.0 with 0.02N HCl. The excess water in the flocs was forced out in the ultrafilter. The flocculated sample was supposed to have a random orientation with a mostly edge to face arrangement of the clay plates.

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* Distributed by R.T. Vanderbilt Co. Inc.,
New York 17, N.Y., USA.

Samples with 100%, 80%, 60%, 40%, 20% and 0% of dispersed or of flocculated kaolin were prepared from the respective prepared kaolin by an extensive mixing with No. 14[*] glass beads at liquid limit. After they were air-dried, they were ready for the water retention study. According to the specification of manufacturer, 95-100% of the beads has diameters smaller than 0.105 mm.

2-4. Sedimented and Slurried Leda Clay.

Sedimented Leda clay was prepared from 5 - 7% suspension of the 2 fraction by ultra filtering. The rapid settling should result in random orientation of the clay plates. This clay was slurried extensively at the liquid limit. The sample prepared in this way would be expected to have a more parallel particle orientation.

3. Methods.

3-1. Water Retention.

The time required to reach equilibrium at any pF value was approximately ten days. Apparatus used, specifications and operations are tables in Table IV-2. Between the duplicates the error was 3%.

3-2. Volume Change Measurement.

Samples with a cylindrical shape 0.5-0.7 cm H x 4.4 cm were prepared in a 2.0 cm H x 4.4 cm I.D. x 5.1 cm O.D. transparent plastic holder. The sample holder was marked at 120 degree intervals for three measurements which were then averaged. The early measurments were by the photographic method but

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[*] Potters Brothers Inc., Carlstadt, N.J., USA.

TABLE IV - 2

SPECIFICATION AND OPERATION OF THE APPARATUS FOR WATER RETENTION

Apparatus	pF Range	Specification and Operation
Saturation Tank	0	30 x 50 cm Masonery bricks covered with filter paper in a 35 x 60 x 15 cm plastic tank. Evaporation was prevented by covering the top of the tank with a sheet of plastic with small holes to maintain atmospheric pressure in the tank.
Sand Bath	1	<0.5 mm. fine sand was packed into a 4 gal. can to approximately 20 cm. in height. This was covered with a sheet of linen cloth. An outlet was connected from the bottom of the tank to a 500 ml. flask. The water surface in the flask was adjusted 10 cm below the surface of the sand in the tank. Evaporation was prevented with a cover.
Pressure Plate Extractor	2-3	Soil Moisture Equipment Co., Santa Barbara, Calif., USA. Flow diagram for connection of compressed air line was shown in Figure IV-1. Accumulated air beneath the plate was removed by application of suction every 6 hours.
Pressure Membrane Appratus	>4	Pressure plate built to withstand higher pressures (de Jong, 1963).

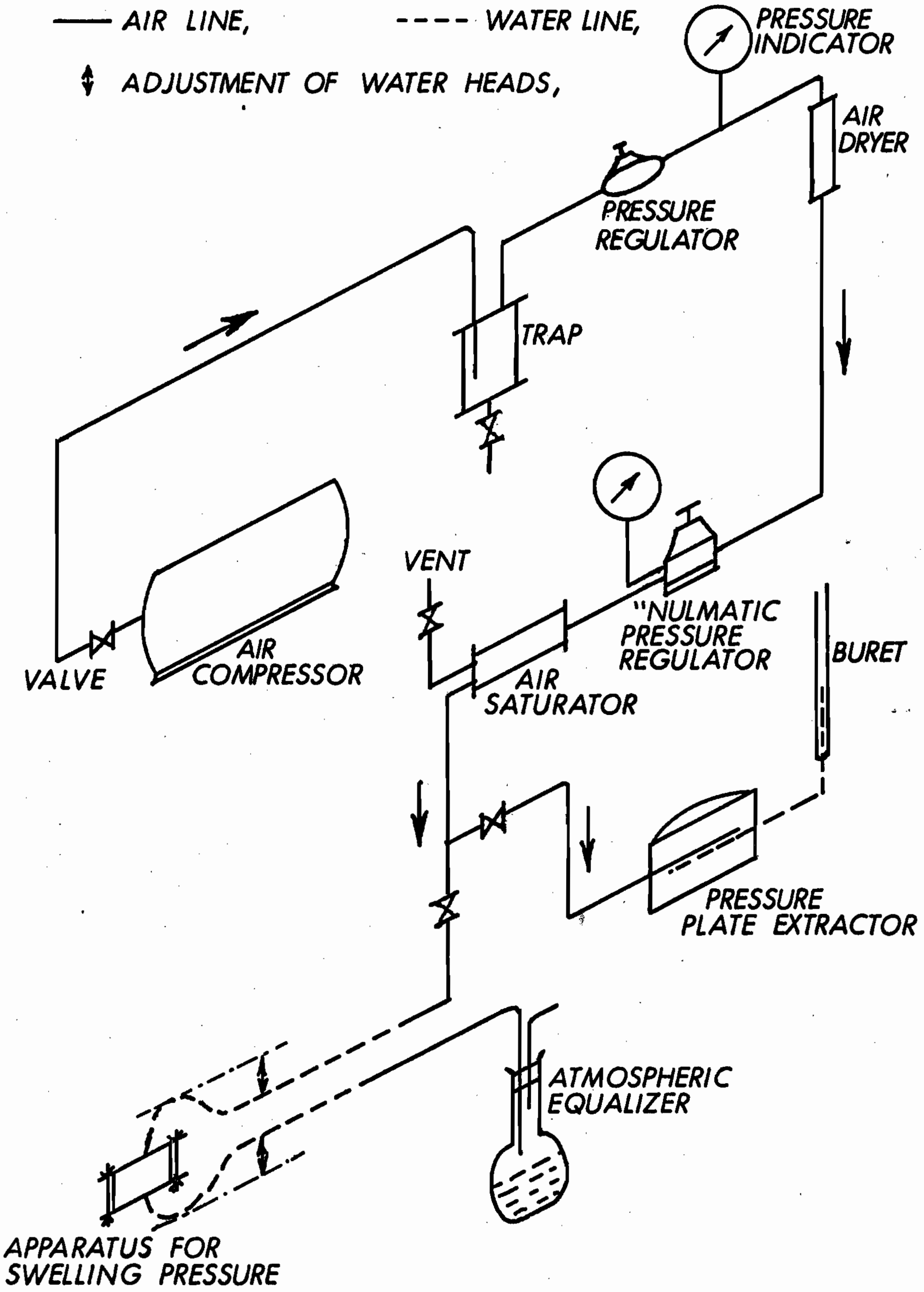

FIG. IV-1, FLOW DIAGRAM FOR AIR PRESSURE, most of the measurements were by the microscopic method. Both methods were found to have an error of 2% between duplicate samples and are described below.

A, Photographic Method.

The moist sample equilibrated at different pF values, was placed on a turntable with the same diameter as the sample holder. The sample was photographed by back lighting with three 60W bulbs, so that refraction from the curved plastic holder could be eliminated and evaporation from the sample under exposure minimized. An extension tube was attached to the camera.* After the film* was developed, the image was projected on a sheet of graph-paper. The specific bulk volume was measured from the image with reference to the image of the sample holder and calculated from the following equation.

$$V_B = \frac{d^2hk}{D^2Hw_s} \qquad (IV - 1)$$

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* Pentax HV-2, Asahi Pentax Co., Japan.

* Tri-X, ASA 400, Eastman Kodak Co., Toronto, Ont.

where: V_B = Specific bulk volume, cc/gm.

D = Measured O.D. or I.D. of the sample holder obtained from the image on graph paper.

d = Measured diameter of the sample obtained from the image on graph paper.

H = Measured height of sample holder obtained from the image on graph paper.

h = Measured height of the sample obtained from the image on graph paper.

k = Actual measurement for the volume of the given sample holder based on O.D. or I.D. which should be identical with D, cc.

w_s = Oven-dry weight of soil sample, gm.

If horizontal volume change was not observed, equation (IV-1) can be written as,

$$V_B = \frac{hk}{Hw_s} \qquad \text{(IV-2)}.$$

The method provided the advantage that the sample was exposed to open air for only a few seconds. Experimental errors in developing of film and in lens opening for the camera were sometimes present, but these errors can be greatly reduced by experience. This method is not suitable for shrinkage measurement on a sticky soil because soil adheres to the holder making the holder opaque, so that the pictures appeared indistinct.

B. Microscope Method.

A vernier microscope* was modified to suit the purposes of this investigation. The platform was changed to a transparent plastic plate for convenience of lighting. Both the ocular and objective lens were taken off. The barrel was turned up side down and was stoppered with a No. 3 rubber bung in which a small hole was drilled. To eliminate the sight error, an additional copper tube with dimensions 1" x 5/8" I.D. was fixed at the top of the rubber bung. A piece of thin wire was tightened in the middle at the bottom of the barrel. Measurement was performed by looking through the needled hole from the copper tube and adjusting until the wire was just tangent to the edge of the sample. Diameter was determined from the readings on the scale at two edges. Height of the sample was measured by a depth guage. To prevent the depth guage

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* Model No. P 1636, Griffin and George Ltd., Great Britain.

from protruding into the moist soil sample, the soil sample was covered at three places with pieces of cover glass. As in the photographic method, each measurement was averaged from measurements at three positions. The bulk volume was then calculated from the following equation.

$$V = \frac{\frac{1}{4} (D_1 - D_2)^2 (h_1 - h_2)}{w_s} \qquad (IV - 3).$$

Where V_B and w_s are the same notations and have the same dimensions as in equation (IV-1). D_1 and D_2 are the readings on the microscope scale; h_1 and h_2 are the readings on the depth guage and are the measure of the height without and with the soil sample respectively; their dimensions are all in cm.

The microscopic was more convenient than the photographic method. The errors encountered in the photographic method do not appear in the miscroscopic method.

3-3. Swelling Pressure.

Fig. IV-2 shows a cross section of the assembled apparatus. It was designed to study swelling pressure in the pressure range equivalent to pF 0 to 3. This

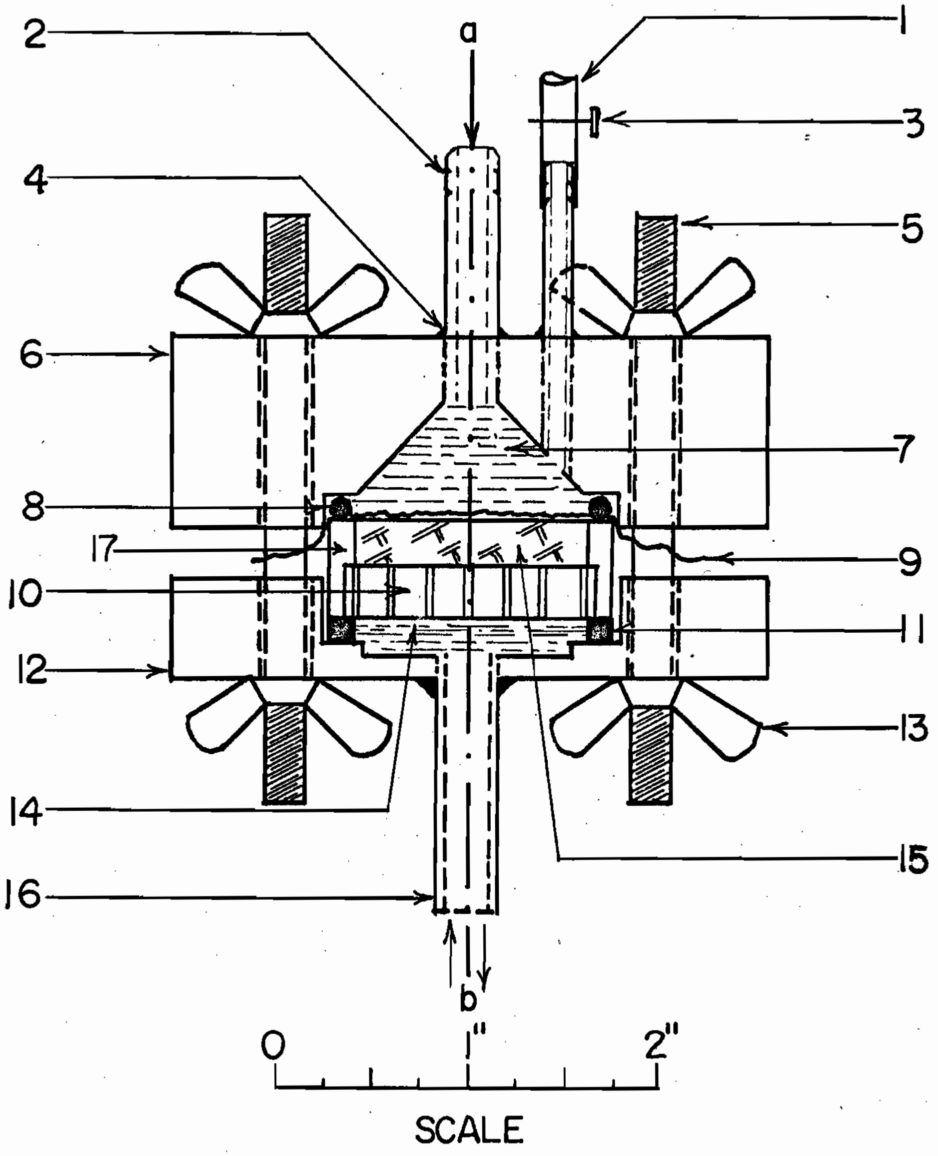

FIG. IV-2, DETAILS OF PRESSURE PLATE APPARATUS ASSEMBLED FOR SWELLING PRESSURE MEASUREMENT, LOW PRESSURE.

LEGEND FOR FIGURE IV-2

1. Plastic Tube Clamp.
2. Hose Connector (Plastic).
3. Clamp.
4. Plastic Soldering.
5. 4 Bolts.
6. Upper Base Plastic.
7. Conical Chamber,
8. Rubber O Ring.
9. Flexible Rubber Membrane.
10. Porous Stone.
11. Flat Rubber Seal.
12. Lower Base (Plastic).
13. Wing Nuts.
14. Clearance.
15. Soil Sample.
16. Brass Connector
17. Sample Holder

A. Connection to Capillary Tube.

B. Connection to Water in Measuring Tube.

apparatus made it possible to measure change in volume with change in water content during swelling pressure measurements.

The apparatus consists of an upper base, a lower base and a sample holder assembled with four bolts (14 N.S., 20). The upper and lower bases are machined from Lucite plastic plate. The sample holder is made from plastic tube with a porous stone* held in a recess which is machined into the tube to a height approximately equal to the thickness of the porous plate. The porous plate bottom is sanded off carefully with fine sand paper so that the bottom of the sample holder is perfectly level.

For operation of the apparatus, the cavity in the lower base and the calibrated capillary tube was filled with air-free water. The saturated soil sample in the sample holder covered with a sheet of flexible rubber membrane was slipped into the lower base on the flat rubber ring seal. The holder was held firmly, covered with the upper base, and the apparatus assembled with the bolts. Care had to be taken that no air bubbles were trapped between the rubber membrane and the soil sample, and beneath the porous stone. After the conical chamber and calibrated capillary tube were filled with water, the

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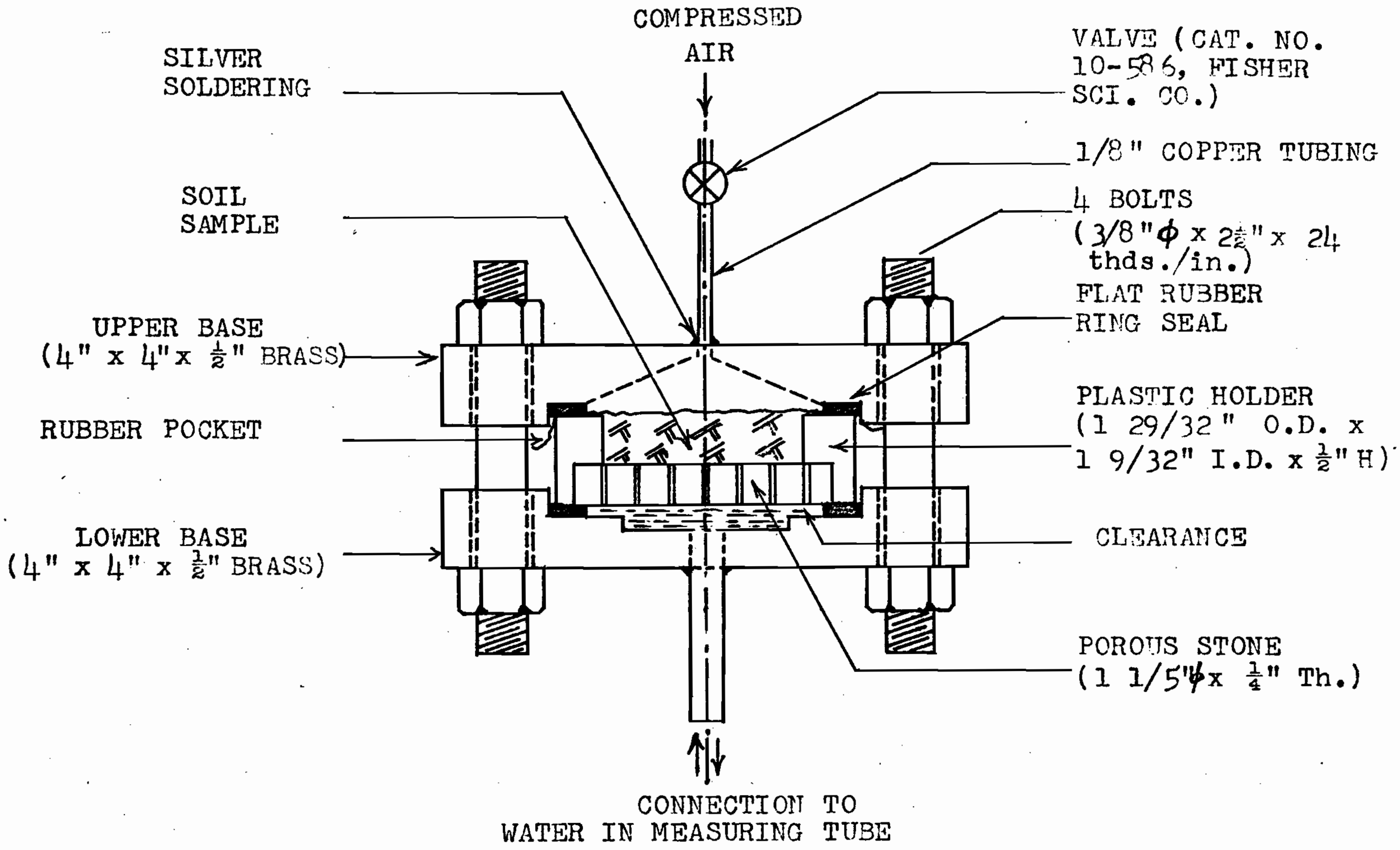
* 1 1/5" x ¼" Th. with air-entry value 2 bar, Soil Moisture Equipment Co., Calif., USA.

side opening for filling water was clamped. Air pressure equivalent to pF 0 was applied from the upper base. When equilibrium was established, the positions of the air-water meniscii in the capillary tubes were noted. The time required at each pressure step was approximately 24 hours. Change in positions of the meniscii with changes in applied pressure measured the volume change and the water taken up or forced out of the sample.

Each measurement of the volume change was corrected by the volume change in an empty apparatus which was operated in the same way as the apparatus containing soil samples, except that instead of a soil sample, a porous stone was placed in the sample holder.

The apparatus for high pressure, from equivalent pF 0 to 4.25, was the same in design and operation as the pressure plate apparatus for low pressure (c.f. Fig. IV-2) except the dimensions and materials used were as shown in Fig. IV-3. This apparatus differs from that for low pressure (c.f. Fig. IV-2) in not providing for measurment of volume change. The air pressure was applied directly to the rubber membrane. Air leaked through the rubber membrane at the highest pressure. This trouble was overcome



NO SCALE

FIG. IV-3, DETAILS OF PRESSURE PLATE APPARATUS ASSEMBLED FOR SWELLING PRESSURE MEASUREMENT, HIGH PRESSURE.

by using instead of a sheet of rubber membrane, a rubber pocket with a dimension 5 cm x 5 cm containing approximately 15 ml of glycerol. Glycerol was sealed in the rubber pocket with the exclusion of air.

Flow diagram for air pressure and adjustment of water heads in the capillary tubes is shown in Fig. IV-1. Six sets of apparatus were operated at one time, either in low pressure or in high pressure studies.

V. RESULTS AND DISCUSSION

1. Volume Changes for Clay Soil Aggregates

1-1. Definitions.

The most important terms used in this investigation, the terms used for the first time in this thesis (marked with an asterisk) and the methods for analysis of data will first be briefly described.

1. Specific Pore Volume *: Sum of pore space in inter- and intra-aggregate pores at any given water content based on 1 gm of over-dry soil. It was calculated from the measurement of bulk volume as obtained from equation (IV-1), (IV-2), or (IV-3) by the following equation.

$$e_{sp} = V_B - \frac{1}{d} \qquad (V\text{-}1).$$

where: e_{sp} = Specific pore volume, cc/gm.

V_B = Specific bulk volume, cc/gm.

d = Real density of soil particles, gm/cc.

2. Volume Changes: Change in specific pore volume either in shrinking or in swelling.

4. Degree of Saturation: Percent of water in specific pore volume. It is defined by taking the density of water equal to 1.

5. Degree of Unsaturation: Percent of air by volume in specific pore volume.

6. Average Equivalent Volume Change*: The average equivalent shrinkage* and average equivalent swell.*

   (a) Average equivalent shrinkage

$$= \frac{\text{Total shrinkage from pF 0 to pF 4.25}}{\text{Total water withdrawn from pF 0 to pF 4.25}}$$

   (b) Average equivalent swell

$$= \frac{\text{Total swell from pF 4.25 to pF 0}}{\text{Total water taken up from pF 4.25 to pF 0.}}$$

7. Structural Swelling*: Increase in specific pore volume is less than the increase in water content of the soil during wetting. It is obtained from the swelling curve.

8. Unsaturated Volume Change: Residual shrinkage and structural swell.

9. Normal Volume Change: Normal shrinkage and normal swelling*. Change in specific pore volume is equal to change in water content of the soil.

10. Volume Change Limits: The shrinkage limit and swelling limit* obtained from the volume

change curve and expressed as water content, %. These are the points of transition from $\Delta V/\Delta W = 1$ to $\Delta V/\Delta W \nless 1$ and from $\Delta V/\Delta W \nless 1$ to $\Delta V/\Delta W = 1$.

11. Free Swelling: The air-dry soil sample is allowed to swell at pF 0. The specific pore volume is considered to be maximum.

12. Net Swelling: Difference in specific pore volume between the soil after free swelling and the initial air-dry soil.

13. Apparent Equivalent Volume Change: Sum of equivalent volume changes for individual aggregates.

1-2. Volume Change Curves.

Since soil volume changes involve only the pore volume, it is best to express the results as specific pore volume rather than the whole soil volume, as has been commonly used. If specific pore volume is plotted against water content, the theoretical saturation line is drawn directly through the origin with a slope equal to 1. Moreover, from the ratio between Y-axis and X-axis values, any point on the curve represents degree of saturation. Normal volume change is parallel to or coincident with the theoretical line. Any deviation indicates a definite amount of air content of the soil.

Different aggregate sizes showed different volume change patterns, and the samples prepared by different compaction levels had different volume changes characteristics. Based on this graphing method, however, for constant aggregate size and compaction level, the different soils under investigation fell into the same pattern. One example is shown in Figure V-1.

1-3. Influence of Aggregate Size on Volume Change.

Both normal and unsaturated volume change were generally observed for the samples prepared from smaller aggregates, <0.25 mm (Fig. V-1A), but normal volume change was not important for the samples prepared from the larger aggregates, 1.00-4.76 mm (Fig. V-1B). Free swelling, shrinking and swelling will be discussed.

A. Free Swelling: The following conclusions are drawn from the results shown in Table V-1.

1. Specific pore volume after free swelling (at pF 0), was larger for the samples prepared from the larger aggregates (column 5).
2. Net swelling, ΔV, and equivalent swelling, $\Delta V/\Delta W$, was generally smaller for the samples prepared from smaller aggregates in soil 1 and 5, but larger for small aggregate samples in soil 2 and 3 (columns 8 and 9).

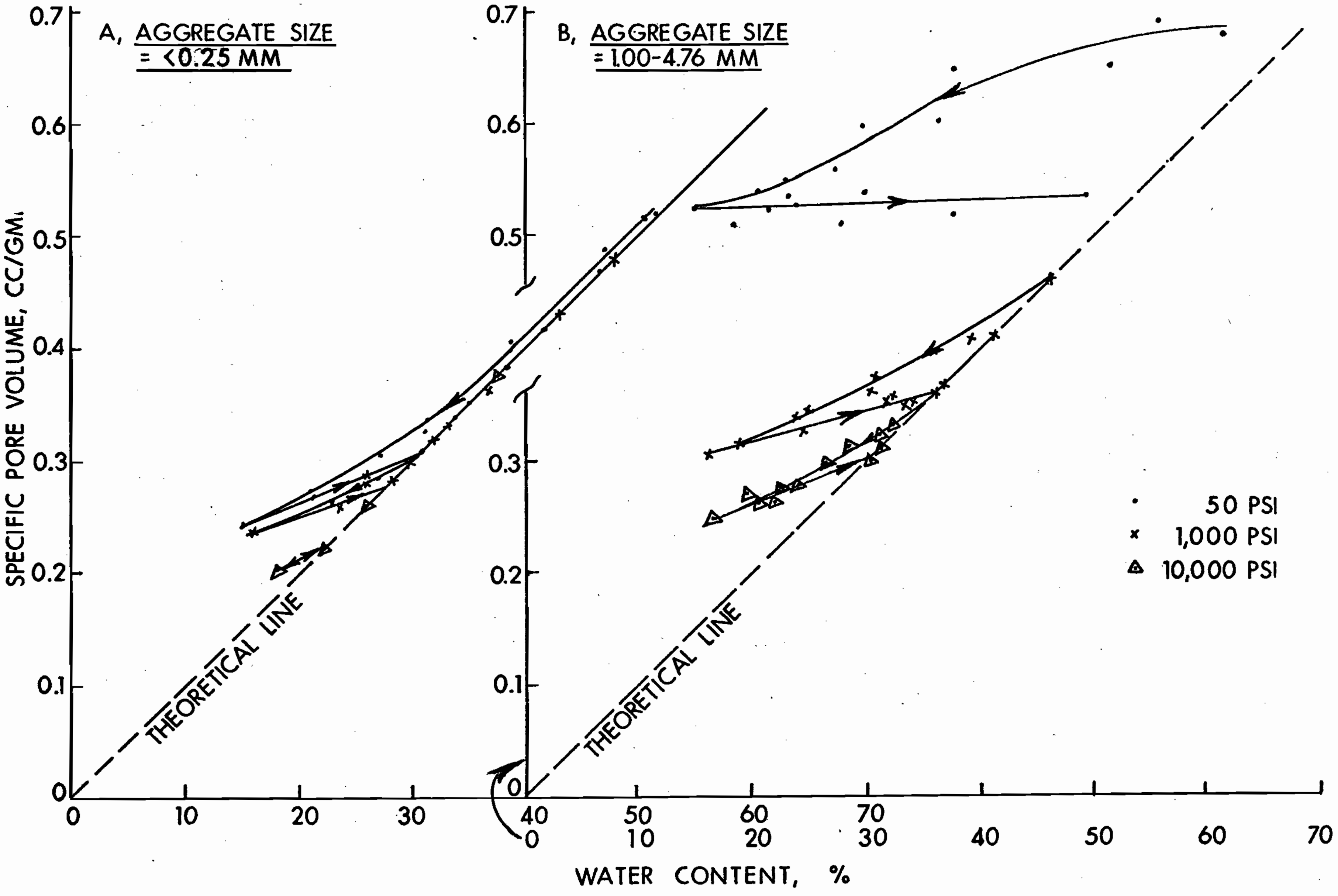


FIG. V-1, VOLUME CHANGE CURVES, SOIL 3.

TABLE V-1

VOLUME CHANGES UNDER FREE SWELLING (pF 0)

Soils	1 Soil No.	2 Size of aggregates, mm	3 Compaction level, psi	4 Sp. pore vol. of prepared samples, cc/gm	5 Sp. pore vol. at pF 0, V_f, cc/gm	6 Sp. pore vol. of oven-dry samples, cc/gm
Ste. Rosalie Clay	1	<0.25	50	0.475	0.690	0.265
			1,000	0.295	0.570	0.245
			10,000	0.210	0.480	0.220
		1.00 - 4.76	50	0.640	0.890	
			1,000	0.325	0.605	0.315
			10,000	0.195	0.475	0.230
Macamic	2	<0.25	50	0.550	0.800	0.240
			1,000	0.370	0.690	0.220
			10,000	0.235	0.600	0.220
		1.00 - 4.76	50	0.740	0.835	
			1,000	0.430	0.675	0.330
			10,000	0.240	0.600	0.270
Lamothe	3	<0.25	50	0.385	0.525	0.215
			1,000	0.300	0.480	0.213
			10,000	0.224	0.420	0.200
		1.00 - 4.76	50	0.560	0.680	0.330
			1,000	0.318	0.490	0.240
			10,000	0.224	0.440	0.213
Barbados 61-10	5	<0.25	50	0.464	0.655	0.170
			1,000	0.280	0.550	0.169
			10,000	0.175	0.485	0.152
		1.00 - 4.76	50	0.588	0.790	0.380
			1,000	0.300	0.560	0.235
			10,000	0.175	0.530	0.170
Undisturbed Soil					0.476	0.396

Continued

TABLE V - 1 (continued)

Soils	Soil No.	VOLUME CHANGES UNDER FREE SWELLING (pF 0) 7 Water content at pF 0, %	8 Net swelling (ΔV), cc/gm	9 Eq. swell (ΔV/ΔW) %	10 Degree of sat'n, %	11 Corr. Eq. swell (ΔV/ΔW), %	12 Corr. net swelling (ΔV), cc/gm
Ste. Rosalie Clay	1	68.5	0.215	32.9	99.3	32.7	0.213
		57.0	0.275	51.0	100.0	51.0	0.275
		48.0	0.270	60.1	100.0	60.1	0.270
		52.0	0.250	51.1	58.4	29.8	0.146
		50.5	0.280	59.1	83.5	49.3	0.234
		43.0	0.280	70.2	90.5	63.5	0.253
Macamic	2	80.0	0.250	32.9	100.0	32.9	0.250
		69.0	0.320	49.3	100.0	49.3	0.320
		60.0	0.365	65.3	100.0	65.3	0.365
		71.0	0.095	14.2	85,0	12.1	0.081
		65.0	0.245	40.2	96.3	38.7	0.236
		60.0	0.360	64.4	100.0	64.4	0.360
Lamothe	3	52.0	0.140	28.7	99.1	28.7	0.139
		48.0	0.180	40.2	100.0	40.2	0.180
		42.0	0.196	50.6	100.0	50.6	0.196
		64.0	0.120	19.0	94.1	18.6	0.113
		49.0	0.172	37.6	100.0	37.6	0.172
		44.0	0.216	53.0	100.0	53.0	0.216
Barbados 61-10	5	65.5	0.191	30.2	100.0	30.2	0.191
		55.0	0.270	51.2	100.0	51.2	0.270
		48.5	0.310	67.0	100.0	67.0	0.310
		53.0	0.202	39.8	67.1	26.7	0.136
		50.5	0.260	53.9	90.2	48.6	0.234
		48.5	0.355	76.8	90.7	69.7	0.322
Undisturbed soil		41.5					

3. After correction for degree of saturation, both ΔV and $\Delta V/\Delta W$ were larger for the sample prepared from small aggregates (column 12 and 11).
4. At the 10,000 psi, compaction level, there was practically no difference between the samples prepared from different size aggregates.

In the explanation of these results, it is assumed that (a) soil properties do not vary among aggregates of different sizes (c.f. II-1); (b) inter-aggregate pores are larger than the intra-aggregate pores; and (c) the water shell around the aggregate has the same thickness independent of size of aggregates or aggregate rearrangement. The thickness is a function only of applied suction.

The difference in V_f was the result of initial differences in the prepared samples. The larger aggregates had larger specific pore volumes (column 4). The influence of initial pore volume can be eliminated by considering ΔV. The reversal of the results for two soils is probably due to the shape of the aggregates, which affects inter-aggregate pore size distribution. The granular aggregates of soils 1 and 5 apparently have a greater proportion of large inter-aggregate pores at pF 0 that the platty aggregates of soils 2 and 3. This was supported by the finding that the degree of saturation of the former was less than that of the latter (column 10).

The corrected $\Delta V/\Delta W$ indicates that more water was retained in inter-aggregate pores in the samples prepared from larger aggregates than from the small aggregates. The relation between corrected ΔV and $\Delta V/\Delta W$ reveals the direct relationship between volume change and water retention.

Difference in repulsion between the aggregates caused by swelling of the aggregates can be explained by the greater number of inter-aggregate contacts for the smaller aggregate. If the thickness of water shell around the aggregate is the same for any size of aggregates, then the smaller the aggregate, the larger is the volume change.

Under certain conditions, particles at the surfaces of adjacent aggregates may be brought together in such intimate contact that the distance between them is not greater than the distance between the particles within the aggregate. However, the effect of organic matter and edge to face inter-particle attraction will not be present. The aggregate will remain discreet.

It reveals that swelling of aggregate enlarges inter-aggregate pores, of which the sizes and volume depend on shape, size and swelling capacity of the aggregates.

The differences discussed above were not marked for the samples prepared at the 10,000 psi compaction level. This does not mean that the aggregate had been destroyed or that the interaction between aggregates was not important. Probably the larger inter-aggregate repulsion for small aggregates was balanced by the larger volume of inter-aggregate pores for the large aggregates.

B. Shrinking: The characteristics of shrinkage observed from Table V-2 and Fig. V-1 can be summarized as follows:

1. Total shrinkage was larger for the samples prepared from smaller aggregates (column 5).
2. Water content at the shrinkage limit was lower for the samples prepared from smaller aggregates (column 8).
3. Average equivalent shrinkage, $\Delta V/\Delta W$ (pF $0 \rightarrow 4.25$), was generally larger for the sample prepared from smaller aggregates.
4. Normal shrinkage was more important than residual shrinkage for the samples prepared from the smaller aggregate but the ratio of residual shrinkage to total shrinkage was

TABLE V - 2

CHARACTERISTICS OF VOLUME CHANGES FOR CLAY SOIL AGGREGATES, SHRINKING FROM pF 0 TO 4.25

	1	2	3	4	5	6	7	8	9
		Size of	Compaction	Total water	Shrinkage, cc/gm			Water content	Ave. Eq.
Soil	Soil No.	aggregates, mm.	level, psi	withdrawn, gm/gm	Total	Normal	Residual	at shrinkage, limit, %	Shrinkage, $\Delta V/\Delta W$, %
Ste. Rosalie Clay	1	<0.25	50	0.435	0.320	0.275	0.045	40.0	73.6
			1,000	0.320	0.215	0.165	0.050	40.0	67.2
			10,000	0.230	0.150	0.105	0.045	37.5	65.2
		1.00-4.76	50	0.345	0.145	-	0.145	-	42.0
			1,000	0.300	0.165	-	0.165	-	55.0
			10,000	0.205	0.140	-	0.140	-	68.3
Macamic	2	<0.25	50	0.490	0.410	0.125	0.285	67.5	83.6
			1,000	0.380	0.320	0.215	0.105	47.5	84.2
			10,000	0.290	0.290	0.290	-	31.0	100.0
		1.00-4.76	50	0.450	0.135	-	0.135	-	30.0
			1,000	0.390	0.160	-	0.160	-	41.0
			10,000	0.340	0.215	0.085	0.130	51.5	63.2

Continued

TABLE V - 2 (Continued)

CHARACTERISTICS OF VOLUME CHANGES FOR CLAY SOIL AGGREGATES, SHRINKING FROM pF 0 to 4.25.

	1	2	3	4	5	6	7	8	9
					Shrinkage, cc/gm				
Soil	Soil No.	Size of aggregates, mm.	Compaction level, psi	Total Water with-drawn, gm/gm	Total	Normal	Residual	Water Content at shrinkage, limit, %	Ave. Eq. shrinkage, $\Delta V/\Delta W$, %
Lamothe	3	<0.25	50	0.370	0.280	0.170	0.110	35.0	75.7
			1,000	0.330	0.235	0.180	0.055	30.0	71.2
			10,000	0.270	0.230	0.195	0.035	22.0	85.0
		1.00-4.76	50	0.460	0.140	-	0.140	-	30.4
			1,000	0.380	0.185	0.025	0.160	46.5	48.7
			10,000	0.280	0.185	0.090	0.095	35.5	66.1
Barbados 61-10	5	<0.25	50	0.465	0.410	0.265	0.145	39.0	88.2
			1,000	0.350	0.300	0.220	0.080	33.0	85.7
			10,000	0.285	0.235	0.165	0.080	33.0	82.5
		1.00 - 4.76	50	0.395	0.165	-	0.165	-	41.7
			1,000	0.335	0.240	-	0.240	-	71.6
			10,000	0.290	0.240	-	0.240	-	82.6

larger for the samples prepared from larger aggregates (compare columns 7 and 5).

Shrinkage of the aggregates determines total shrinkage but number of inter-aggregate contacts and aggregate rearrangement during shrinking affect the measured shrinkage of the sample. The larger number of inter-aggregate contacts and the higher degree of aggregate rearrangement during shrinking for the samples prepared from smaller aggregates account for the observation that the measured total shrinkage and normal shrinkage were larger for these samples. The shrinkage limit depends upon air entry into the soil. Large pores prevail in the samples prepared from the larger aggregate, so the air-entry value occurs at low suction, where the water content of the aggregates is still high. Therefore the shrinkage of these samples occurred mostly as residual shrinkage. Similar results were also found by Stirk (1954) in his natural soil sample, with greater residual shrinkage for the larger aggregates.

C. Reswelling after Drying: The swelling measurements shown in Table V-3 and Fig. V-1 have the same trend as observed on shrinking (c.f. section B). The sample properties which depend upon aggregate size, infleunce both swelling and reswelling. Repulsion

TABLE V - 3

CHARACTERISTICS OF VOLUME CHANGES FOR CLAY SOIL AGGREGATES RESWELLING AFTER SHRINKING

	1	2	3	4	5	6	7	8	9
					Swelling, cc/gm				
Soils	Soil No.	Size of aggregates, mm	Compaction level, psi	Total water taken up, g/g	Total	Normal	Structural	Water content at swelling limit, %	Ave. eq. swell, %
Ste. Rosalie Clay	1	< 0.25	50	0.235	0.115	0.085	0.030	40.0	46.8
			1,000	0.200	0.100	0.075	0.025	37.5	50.0
			10,000	0.175	0.095	0.050	0.045	37.5	54.3
		1.00-4.76	50	0.265	0.040	-	0.040	-	15.1
			1,000	0.250	0.090	-	0.090	-	36.0
			10,000	0.200	0.080	-	0.080	-	40.0
Macamic	2	<0.25	50	0.220	0.140	0.045	0.095	48.5	63.6
			1,000	0.155	0.095	0.020	0.075	44.5	61.3
			10,000	0.155	0.155	0.155	0	31.0	10.0
		1.00-4.76	50	0.355	0.035	-	0.035	-	9.9
			1,000	0.290	0.040	-	0.040	55.0	13.8
			10,000	0.215	0.090	0.015	0.075	46.0	41.8

Continued.

TABLE V - 3 (Continued)

CHARACTERISTICS OF VOLUME CHANGES FOR CLAY SOIL AGGREGATES RESWELLING AFTER SHRINKING

1		2	3	4	5	6	7	8	9
					Swelling, cc/gm				
Soils	Soil No.	Size of aggregates, mm	Compaction level, psi	Total water taken up, g/g	Total	Normal	Structural	Water content at swelling limit, %	Ave. eq. swell %
Lamothe	3	<0.25	50	0.210	0.125	0.065	0.060	30.0	57.1
			1,000	0.180	0.095	0.050	0.045	28.5	52.8
			10,000	0.180	0.140	0.105	0.035	22.0	77.8
		1.00 - 4.76	50	0.355	0.010	0	0.010	-	2.8
			1,000	0.255	0.110	0.050	0.060	36.0	43.1
			10,000	0.215	0.125	0.060	0.065	31.0	58.1
Barbados 61-10	5	<0.25	50	0.210	0.155	0.070	0.085	33.5	73.8
			1,000	0.205	0.145	0.085	0.060	31.0	70.7
			10,000	0.140	0.090	0.050	0.040	29.0	64.3
		1.00 4.76	50	0.305	0.035	-	0.035	-	11.5
			1,000	0.255	0.125	-	0.125	-	49.0
			10,000	0.190	0.125	-	0.125	-	65.7

between the aggregates keeps the aggregate apart, and surface tension forces draw the aggregates closer together.

Two stages of swelling, saturated and unsaturated swelling which are termed "normal swell" and "structural swell", are generally observed for the samples prepared from smaller aggregates. A similar result had been observed by Haines (1923) in his kaolinitic samples, but his shrinking and swelling curves did not coincide in that region of normal swell. Air became trapped in his sample during rewetting. In the stage of structural swell, some of the larger inter-aggregate pores were not filled with water. At the swell limit, all pores are filled with water. The maximum radii of the inter-aggregate pores are just equivalent to the applied suction. On further decrease of applied suction, the increase in volume is equal to the water taken up by soil. For the samples prepared from larger aggregates, larger inter-aggregate pores are present, therefore the swell limit expressed as a water content is high (c.f. column 8, Table V-3). If pores larger than 3 mm are present (equivalent radius at pF 0), the stage of normal swell will never be obtained.

1-4. Influence of Compaction Levels for Preparing the Samples on Volume Changes.

A. Free Swelling (Table V-1). Specific pore volume at pF 0, V_f, was decreased with increasing compaction level (column 5). The differences result from the differences of specific pore volume of the prepared air-dry samples (c.f. column 4).

Net swelling, ΔV , increased with increasing compaction level (column 8). This is due to the decrease in average distance between aggregates and/or particles and to the increase in specific number of contacts in the prepared air-dry samples. The difference becomes more significant if ΔV is corrected for degree of saturation (column 10) as shown in column 12, because the degree of saturation was higher for higher compaction levels.

Equivalent swell, $\Delta V/\Delta W$ (column 9), and corrected $\Delta V/\Delta W$ (column 11) are higher for the higher compaction levels. This means that the volume change is different even though the same amount of water was taken up by the sample. The difference in $\Delta V/\Delta W$ or corrected $\Delta V/\Delta W$ is then due to the difference in specific number of contacts, and the original distance between the aggregates and/or particles.

B. Volume Changes (c.f. Tables V-2 and V-3): The results generally show that total volume changes increased with increase in compaction level for the larger aggregates (column 5). The opposite results were obtained for the samples prepared from the smaller aggregates; the total volume change decreased with increase in compaction level. This can be explained by aggregate rearrangement during drying or wetting. For samples prepared from the larger aggregates, the possibility of rearrangement is low because the radii of the inter-aggregate spaces required for rearrangement would be larger than 1.00 mm.

Total specific number of contacts and not rearrangement is the main factor in determining the total volume change for these samples. For the samples prepared from smaller aggregates, this rearrangement will take place when the radii of the inter-aggregate spaces are less than 0.25 mm. Therefore, the looser the original packing among aggregates, the greater is the rearrangement. Moreover, aggregate interference increases because of the larger number of inter-aggregate contacts for the samples prepared at higher compaction level. Volume change limits, expressed as water content (column 8), decrease with increase in compaction level. This is explained by a decrease in larger pores which determine the air-entry value

1-5. Influence of Soil Properties on Volume Changes.

As discussed in the last section, the total volume change decrease with increasing compaction level for smaller aggregates was due to aggregate rearrangement. From columns 5, 6 and 7, Tables V-2 and V-3, it is learned that the stage, structural or normal, at which aggregate rearrangement becomes important is different. This is probably related to soil properties such as shape of aggregate and to volume change of the aggregates at low pF. The shrinking results will be explained here; the trend for swelling is the same.

Soil 2 (Table III-1) has a high clay content, therefore water retention within the aggregate is high. At low pF , changes in water content and volume are very small. Water is removed only from inter-aggregate pores. This leads to air entry and the samples prepared at lower compaction levels have a shorter range of normal shrinkage. As soon as the aggregate shrinks, aggregate rearrangement is taking place. The same tendency occurred in soil 3, which has a high content of fine particles ($<$0.02 mm fractions) and small volume changes. These surface soils 1 and 5, have granular aggregates for which friction is smaller, and rearrangement can thus occur even in the saturation region.

1-6. Comparison of Shrinking and Swelling.

Comparison of shrinking (column 5, 6, and 7, Table V-2) and swelling (columns 5, 6, and 7, Table V-3), shows that total shrinkage, normal shrinkage and residual shrinkage are larger than total swell, normal swell, and structural swell respectively. This can be explained by aggregate rearrangement on drying. The aggregates will not go back to the same position on rewetting at the same water content. The same difference is shown between average equivalent shrinkage (column 9), (Table V-2), and average equivalent swell (column 9), (Table V-3). Particle rearrangement, which accounted for irreversible changes in structure (Parry, 1960) might also occur inside the aggregate, and add some degree of irreversible change in inter-aggregate rearrangement.

Volume changes show hysteresis in the unsaturated region (Fig. V-1). Shrinkage always lies above swelling, and they meet in the saturation region if the soil undergoes normal volume changes. This result is opposite to that found by Haines (1923), and was probably due to the different method of wetting (II-3-1 and IV-1).

1-7. Comparison Between Aggregates and Undisturbed Soil in Volume Changes.

Small volume changes 1.2 - 1.9% in specific pore volume between pF 0 - 4.25 were found either on shrinking or on wetting for the undisturbed surface soil (Soil 1). It is expected that a framework of inter-aggregates contacts was formed from the many cycles of drying and wetting in nature. Swelling by the clay fraction was probably inhibited in this rigid framework. Specific pore volume of undisturbed soil at pF 0 is found equivalent to the sample prepared from 10,000 psi but oven-dry pore volume is larger (Table V-1).

1-8. Mechanism for Volume Change of Clay Soil Aggregates.

Theories of shrinkage for soil particles as given by Schumacher (1864), for soil blocks as given by Haines (1923), and Lauritzen (1948) (c.f. II-3-1) are not satisfactory to explain shrinkage of aggregates with no rigid connections between the aggregates. As the results indicated, there was significant aggregate rearrangement taking place during swelling and shrinking of the aggregates. Based on the assumptions made in V-1-3A and the findings described above, the following mechanism is visualized to account for volume changes.

When suction is applied to the sample, water is first withdrawn from the inter-aggregate pores. The capillary force is increased and the aggregates are drawn closer together. On further increase in applied suction, shrinking of the aggregates takes place accompanied by aggregate rearrangement. During normal shrinkage, inter-aggregate pore size decreases due to aggregate rearrangement and closer approach. The smaller pores developed will not be emptied by the applied suction, and the pore volume decrease is equal to the water lost from the sample. At the shrinkage limit, aggregate rearrangement becomes restricted. As soon as the force of repulsion or the interference between aggregates exceeds the capillary force, the applied suction becomes larger than the equivalent radius of the inter-aggregate pores. On further drying, some water in the larger inter-aggregate pores are replaced by air, although modification of inter-aggregate pore size is still going on due to shrinking of the aggregates. Hence in the stage of residual shrinkage, decrease in volume, which is contributed by shrinking of the aggregates and by their rearrangement, is less than decrease in water in the sample.

During rewetting of the samples, water is first taken up within the aggregate. Reswelling of the aggregates will also cause rearrangement and modification of pores between the aggregates, but to a lesser degree than on shrinking. On further water increases, part of water will be taken up by the aggregate and part of it by the inter-aggregate pores. In the region of structural swell, increase in volume is less than increase in water in the sample. At the swell limit, all pores are filled. In the stage of normal swell, uptake of water results from swelling of the aggregate, repulsion between the aggregates, and development of inter-aggregate pores.

1-9. Conclusions.

Different aggregate sizes have different volume change patterns and the samples prepared at different compaction levels have a different volume change characteristics. Total volume change is larger for the sample prepared from smaller aggregates and lower compaction levels. Two stages of shrinkage, normal and residual shrinkage, are always observed for the samples prepared from smaller aggregates, but normal shrinkage is not an important mechanism for the samples prepared from larger aggregates. Swelling appears to have the same trend as the shrinkage. "Structural swell" takes place in the unsaturated region and "normal swell" in the saturated region. Volume change limits, expressed as water contents, are lower for samples with smaller inter-aggregate pores.

Total volume change is a function of aggregate rearrangement and of volume change within the aggregates. The change of size of inter-aggregate pores due to change in volume of the aggregates determines whether the soil is saturated during the volume changes.

The range of structural or normal volume change depends upon soil properties such as shape of aggregate and clay content, which determine the inter-aggregate pores.

Aggregate rearrangement is partly irreversible, causing hysteresis of volume changes. Hysteresis loops do not occur in saturated region.

Shrinkage and swelling of aggregates are different from undisturbed soil, because no aggregate rearrangement occurs and swelling or shrinking is inhibited by the rigid structure in the latter.

2. Swelling Pressure for Aggregate Samples.

2-1. General Considerations.

Kentze, (1961) has argued that air entrapped in the sample develops local pressure which probably decreases the swelling pressure. When water enters the pores, the air should be expelled to the larger pores which are beyond the extent of the inter-aggregate swelling. One might also consider that an increment of confining pressure causes the instantaneous development of pore pressure. Water is forced out of the pores until the pore pressure is equal to the atmospheric pressure. The time required for this process is short (c.f. Fig. App. 4), therefore this instantaneous air pore pressure does not affect swelling pressure, even though air is trapped in the sample. The capillary force required to release the entrapped air is considered to be very small.

2-2. Compaction and Compression.

Felt (1965) discussed methods and apparatus for compaction of cohesive and non-cohesive soils. Consolidation and expansion of soil under load can be determined in a consolidometer (Holtz, 1965). Triaxial and unconfined compression are standard tests for measuring soil strength in engineering (Sallberg, 1965). Warkentin (1957), Greacen (1959), etc., refer to the decrease in water content with increase in applied pressure in a confined cell as compression. However, the terms "compaction" and "compression" are adopted in this investigation. It is necessary to distinguish compression used in this section and compaction discussed in section III. The distinction will be based on whether soil air escapes from the soil body during decrease in soil volume.

In compaction, the soil in an open chamber is subjected to external loading. The soil-air pressure is always equal to that of the atmosphere.

In compression, the soil in a closed chamber is subjected to external loading. Instantaneous positive pressure will be developed. Equilibrium of internal pressure in soil to the external loading pressure results from removal of water from the soil body.

2-3. Apparatus.

Apparatus for low pressure (Fig. IV-2) or for high pressure (Fig. IV-3) was designed to apply the confining pressure uni-axially rather than tri-axially proposed by Kentze (1961). The glass beads or dry sands used in his experiment adsorbs some water and also becomes compacted with increments of the confining pressure. The former causes underestimation of the water content of the soil and the latter affects measurement of the volume changes. The effect on swelling pressure of the frictional force between the sample holder and soil particles was considered very small, especially for the thin samples used (c.f. IV-2-1).

The designed apparatus can be operated starting the measurement either with saturated samples (IV-3-3) or by filling water into the dry soil by suction as proposed by Kentze (1961) (c.f. App. II).

It is necessary to have a blank apparatus along with each measurement to correct for the volume change in the apparatus itself, and for the loss of water due to evaporation.

An example of measured volume changes ΔV, with change in water content, ΔW, due to change in swelling pressure is shown in Fig. V-2. The deviation from the theoretical line indicates that air is entrapped in the sample holder between the flexible rubber membrane and the saturated soil. The larger deviation is at the higher confining pressure. This small amount of entrapped air was considered to have a negligible effect on swelling pressure (V-2-1).

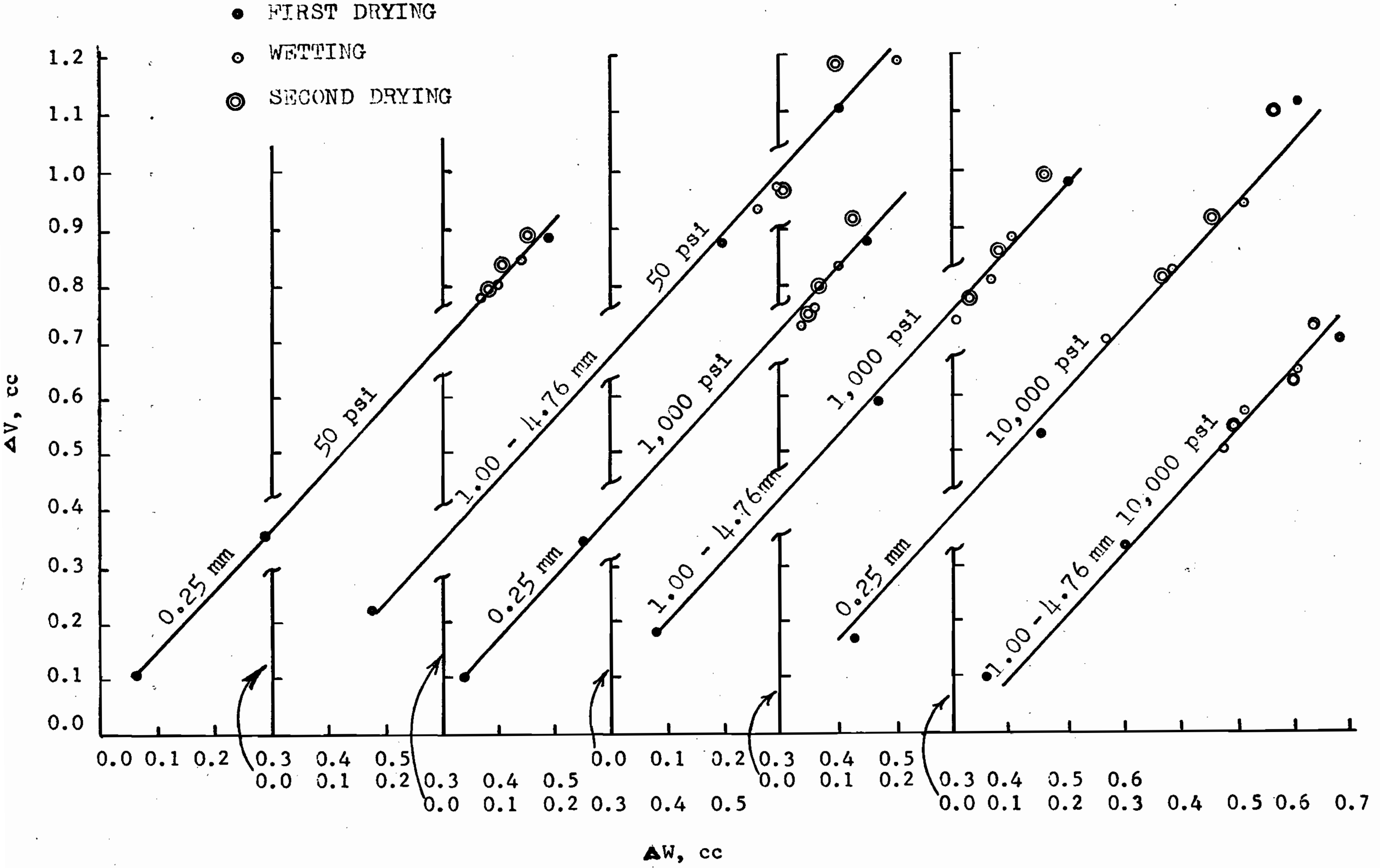


FIG. V-2, CHANGE OF VOLUME VS CHANGE OF WATER CONTENT IN SWELLING PRESSURE STUDIES, SOIL 3.

The time required to establish equilibrium was short (Fig. App 4). This suggests that the long period of time required in water retention studies (c.f. IV-3-1) is required to establish equilibrium between swelling pressure and the capillary force.

2-4. Compression and Swelling Pressure Curves.

Compression and swelling pressure curves for the four soils under investigation were found to have the same general shape, an example is shown in Fig. V-3. The characteristics of these curves are as follows:

(1) The large hysteresis between the first compression and swelling indicates irreversible changes. These changes are not only aggregate rearrangement and development of aggregate - aggregate bonds during compression but a change in pore volume in reswelling of the aggregate.

(2) The slopes of the swelling curves from pF 3.00 appear greater or are at least equal to the slopes of the curves for swelling from pF 4.25. This is the result of greater aggregate-aggregate bonding developed at higher pF.

(3) For the samples compressed to equivalent pF 4.25, the reswelling and second compression curves appeared nearly horizontal below equivalent pF 2. This is equivalent to "internal loading" (Norrish and Raussell-Colom, 1962, c.f. II-4-2). This behaviour was mostly

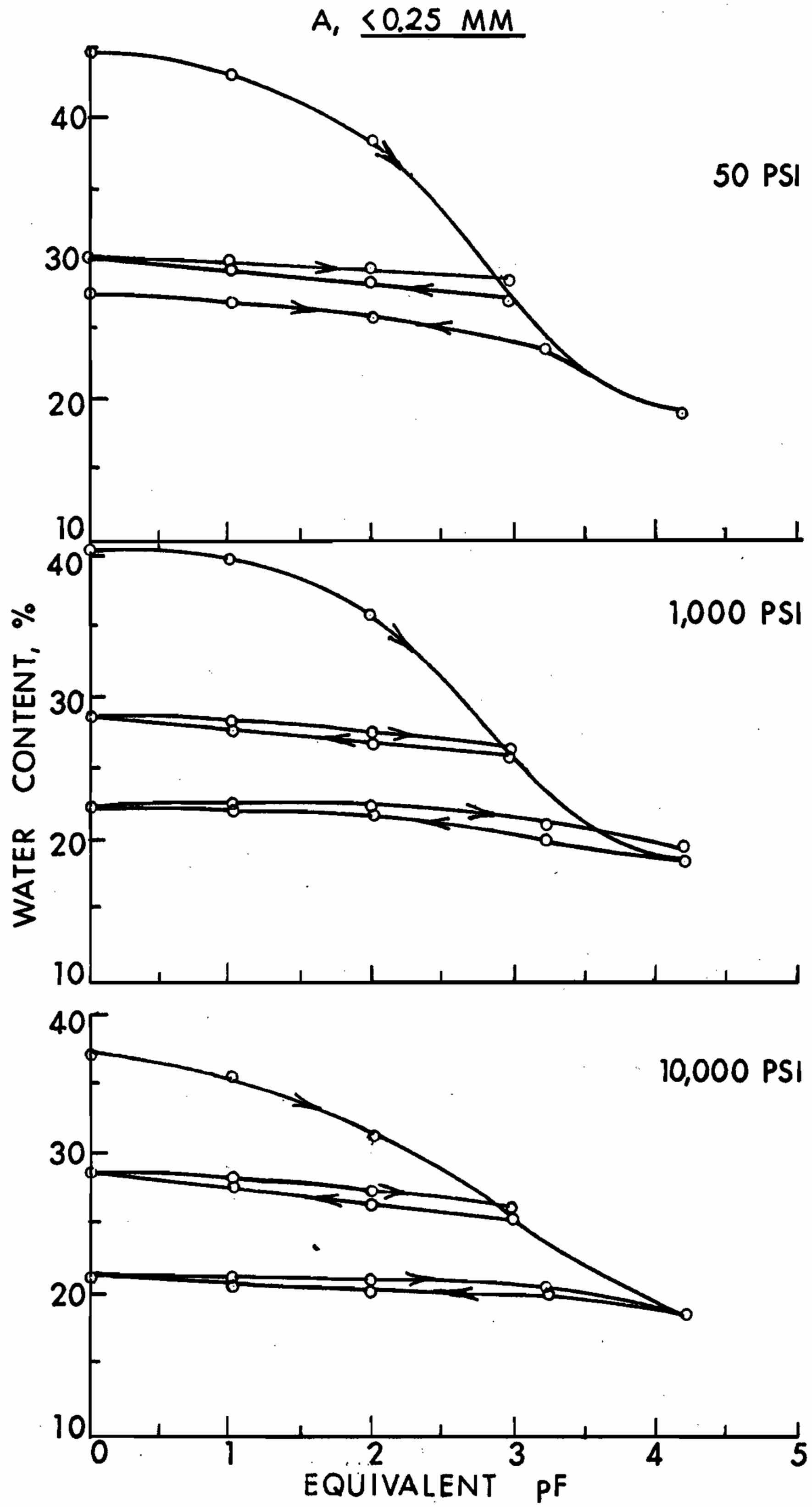


FIG. V-3, COMPRESSION AND SWELLING CURVES, SOIL 3,

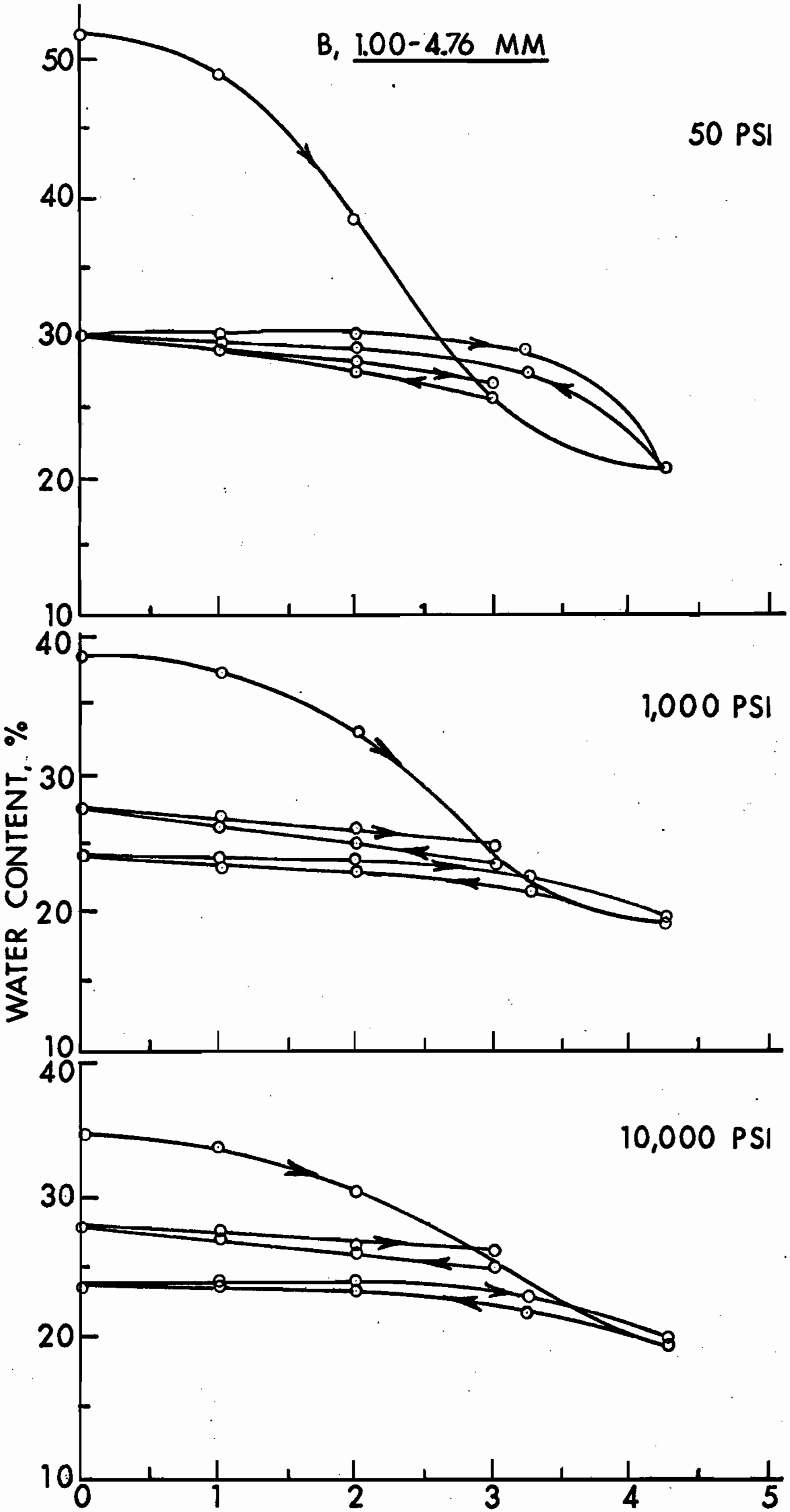


FIG. V-3 (CONTINUED).

not observed for the samples compressed to a terminal pressure of pF 3. These findings suggest that the "internal loading" depends upon the maximum compression. Many soils have experienced drying to equivalent pF 4.25.

The inter-particle or/and inter-aggregate bonding which limit reswelling are a function of the terminal pressure which the soil has experienced. This is supported by Waidelich's consolidation experiment (1958), in which he found that re-expansion of the soil was nearly constant in spite of clay minerals and immersing liquids used, after the soils had been consolidated at approximately 8 tons/ft^2.

(4) Water contents in reswelling and second compression are smaller than in the first compression, allowing 1% error. Exceptions were found for the samples prepared at 50 psi, from 1.00-4.76 mm aggregates for all soils under investigation and 1,000 psi, 1.00-4.76 mm size for soil 2, for which the water contents were higher for reswelling and second compression above pF 2 or 3 if the soil experienced a terminal pressure equivalent to pF 4.25. These anomalies indicate rearrangement of aggregates.

(5) Hysteresis loops for the small aggregates are larger for the samples prepared at lower compaction levels except 50 psi in soil 3 (Fig. V-3).

The explanation for these observations is given in the following sections (V-2-5, V-2-6).

2-5. Effect of Aggregate Size on Swelling Pressure.

Allowing 0.5% error, the water content at any confining pressure is usually higher for the samples prepared from smaller aggregates, except for the samples prepared from soil 3 (c.f. Tables V-4A and V-4B). The difference is much smaller on reswelling and second compression for the samples which have experienced a terminal pressure of pF 4.25. The result is explained by aggregate rearrangement, of which the degree is larger for the smaller aggregates. This also explains the larger amount of water lost in the first compression for these samples (column 1, Table V-4A). Development of aggregate-aggregate bonds, when the sample experienced a terminal pressure of pF 4.25, is the explanation for the small difference between reswelling and second compression for these samples. The anomaly for soil 3 is probably because its aggregates have the smallest swelling capacity of the soils under investigation (column 8 Table V-1). Therefore, most of the inter-aggregate pores developed during swelling of larger aggregates are filled with water. This is supported by the free swelling (c.f. column 10, Table V-1), where soil 3 has the highest degree of saturation.

The change in water content between any pF values is a better variable for comparison than the actual water content of any pF. Change in water content with change in confining pressure was generally larger for the samples

TABLE V - 4A

COMPRESSION AND SWELLING IN SWELLING PRESSURE STUDIES WITH THE TERMINAL PRESSURE pF 4.25, % WATER AT GIVEN pF

Soils	Soil No.	Size of aggregates, mm	Level of compaction, psi	pF 1st. compression 0 →	1 →	2 →	3* →	4.25 →	Swelling 3 →	2 →	1 →	0 →	2nd compression 1 →	2 →	3 →	4.25
Ste. Rosalie Clay	1	<0.25	50	57.5	55.5	49.0	37.0	26.0	32.0	33.0	33.5	34.0	34.0	34.0	33.5	25.5
			1,000	52.5	50.0	44.5	35.0	26.0	29.0	30.5	31.5	32.0	32.0	32.0	31.0	25.5
			10,000	42.5	41.5	39.0	33.0	24.0	26.5	27.5	28.5	28.5	28.5	28.5	27.5	24.0
		1.00-4.76	50	43.0	39.5	31.5	27.0	23.0	29.0	32.0	33.5	34.0	34.0	33.5	32.0	24.0
			1,000	47.5	44.5	40.0	32.0	24.0	27.0	29.5	30.5	31.0	31.0	30.5	30.0	24.5
			10,000	38.5	38.0	35.0	29.5	22.5	25.5	26.5	27.0	27.0	27.0	27.0	26.5	22.5
Macamic	2	<0.25	50	68.0	66.0	57.5	41.0	29.0	34.5	39.0	41.5	42.0	42.0	41.5	38.0	29.0
			1,000	48.0	47.0	45.5	38.0	29.5	32.5	35.0	36.0	36.5	36.5	35.5	34.0	29.5
			10,000	44.5	44.5	43.0	36.5	27.5	30.5	32.5	33.0	33.0	33.0	33.0	32.0	27.5
		1.00-4.76	50	47.5	45.5	38.0	30.0	27.5	35.0	37.5	38.5	38.5	38.5	38.5	37.0	27.5
			1,000	47.5	46.0	39.5	32.0	28.0	31.5	34.5	34.5	36.0	35.5	35.0	33.0	28.0
			10,000	45.0	44.5	40.0	33.5	27.5	31.0	32.5	33.5	33.5	33.5	33.0	32.5	27.5

* See Table III - 3

Continued.

TABLE V - 4A (Continued)

COMPRESSION AND SWELLING IN SWELLING PRESSURE STUDIES WITH THE TERMINAL PRESSURE pF 4.25, % WATER AT GIVEN pF

				pF												
				1st. Compression					Swelling				2nd Compression			
Soils	Soil No.	Size of Aggregates, mm	Level of Compaction, psi	0 →	1 →	2 →	3* →	4.25	→ 3 →	2 →	1 →	0 →	1 →	2 →	3 →	4.25
Lamothe	3	<0.25	50	44.5	43.0	38.0	27.0	19.0	24.0	25.5	26.5	27.0	26.5	25.5	24.0	19.0
			1,000	40.5	40.0	36.0	25.5	18.5	20.5	21.5	22.0	22.0	22.0	22.0	21.0	19.0
			10,000	37.0	35.5	31.0	25.0	18.0	19.5	20.5	20.5	21.0	21.0	20.5	20.0	18.0
		1.00-4.76	50	52.0	48.0	38.0	25.5	20.0	27.5	29.0	29.5	30.0	30.0	30.0	28.0	20.0
			1,000	38.5	37.0	33.0	24.0	19.5	22.0	23.0	23.5	24.0	23.5	23.5	23.0	19.5
			10,000	34.5	33.5	30.0	24.5	19.0	22.0	23.0	23.5	23.5	23.5	23.5	23.0	19.5
Barbados	5	<0.25	50	50.5	49.5	44.5	31.5	20.0	27.0	29.5	31.0	31.0	31.0	31.0	28.5	20.0
			1,000	44.0	43.0	39.0	29.0	20.0	25.0	27.0	28.0	28.0	28.0	27.0	26.0	20.0
			10,000	42.0	42.0	37.5	28.5	24.0	24.0	26.0	26.5	27.0	27.0	27.0	25.0	20.0
		1.00-4.76	50	44.0	43.0	36.0	24.5	18.5	25.0	27.0	28.5	29.0	29.0	28.0	26.0	18.5
			1,000	43.5	42.5	34.5	26.0	19.0	24.0	26.0	27.0	27.0	27.0	26.5	24.0	19.0
			10,000	40.0	39.0	35.0	26.0	19.0	24.0	26.0	27.0	27.0	27.0	26.5	25.0	19.0

* See Table III - 3

TABLE V - 4B

SWELLING AND RECOMPRESSION STUDIES WITH THE TERMINAL PRESSURE pF 3.0 , % WATER AT GIVEN pF.

Soils	Soil No.	Size of aggregates, mm	Level of compaction, psi	pF						
				Reswelling*				2nd Compression		
				3 →	2 →	1 →	0 →	1 →	2 →	3
Ste. Rosalie Clay	1	<0.25	50	37.0	38.5	40.0	42.0	41.5	40.0	37.5
			1,000	35.0	37.0	38.0	40.0	39.5	39.0	36.0
			10,000	33.0	34.0	35.5	37.0	36.5	35.5	33.0
		1.00 - 4.76	50	27.0	28.5	31.0	34.5	32.0	30.0	27.5
			1,000	32.0	34.0	35.0	36.0	36.0	35.5	32.0
			10,000	29.5	31.0	32.5	34.5	33.5	32.5	30.5
Macamic	2	<0.25	50	41.0	42.0	44.5	46.5	45.0	44.0	42.0
			1,000	38.0	39.0	41.0	42.5	42.0	40.5	39.0
			10,000	36.5	38.0	39.0	40.0	40.0	39.0	37.5
		1.00 - 4.76	50	30.0	32.0	34.0	38.0	35.0	32.5	31.0
			1,000	32.0	34.0	36.5	38.0	37.5	35.5	34.0
			10,000	33.5	35.0	37.5	39.5	38.0	36.5	34.5

* Continued fro, Table III - 1

TABLE V - 4B (Continued)

SWELLING AND RECOMPRESSION STUDIES WITH THE TERMINAL PRESSURE pF 3.0 , % WATER AT GIVEN pF.

Soils	Soil No.	Size of aggregates, mm	Level of compaction psi	pF						
				Reswelling *				2nd Compression		
				3 →	2 →	1 →	0 →	1 →	2 →	3
Lamothe	3	<0.25	50	27.0	28.0	29.0	30.0	29.5	29.0	28.0
			1,000	25.5	26.5	27.5	28.5	28.0	27.5	26.0
			10,000	25.0	26.0	27.5	29.5	28.0	27.0	25.5
		1.00- 4.76	50	25.5	27.0	29.0	30.0	29.0	28.0	26.5
			1,000	24.0	25.0	26.5	27.5	27.0	26.0	24.5
			10,000	24.5	26.0	27.0	28.0	27.0	26.0	25.5
Barbados	5	<0.25	50	31.5	33.5	35.0	35.5	35.5	35.0	32.0
			1,000	29.0	31.0	33.0	34.5	34.0	33.0	29.0
			10,000	28.5	30.5	33.0	34.5	34.0	33.0	29.0
		1.00 - 4.76	50	24.5	28.0	30.5	31.0	30.5	28.5	25.5
			1,000	26.0	28.0	30.5	31.5	31.5	29.5	26.0
			10,000	26.0	28.5	30.5	31.5	31.5	30.0	26.5

* Continued from Table III - 1

prepared from smaller aggregates in the first compression, but smaller in reswelling (column 5, Table V-5 and column 1, Table V-6) and second compression (column 9, Table V-5 and column 2, Table V-6). Most of the change in water content on swelling occurred in the higher pressure range. (columns 2, 3, 6, 7, 10 and 11, Table V-5).

The results show that the magnitude of the swelling ratio $\frac{\text{pF } 2 - 4.25}{\text{pF } 0 - 4.25}$, increased with increasing desorption - adsorption cycles which would strengthen aggregate-aggregate bonding. Swelling of the aggregates becomes more important than aggregate rearrangement.

2-6. Influence of Compaction Levels for Preparing the Samples on Swelling Pressure.

Water content at any confining pressure was higher for the samples prepared at lower compaction levels (Tables V-4A and V-4B). This is explained by larger inter-aggregate pores for these samples. This relation was only observed for the samples prepared from small aggregates. For the aggregate 1.00-4.76 mm, the non uniformity of the aggregate size probably resulted in inter-aggregate pores with a large size variation which would account for the un-uniform results for the samples prepared from the larger aggregates. Allowing a 3% error, the change in water content with change in swelling pressure appears larger or at least equal for the samples prepared at lower compaction levels. The results

TABLE V - 5

CHANGE IN WATER CONTENT WITH CHANGE IN SWELLING PRESSURE, % OF WATER.

Soils	Soil No.	Size of Aggregate, mm	Compaction level, psi	1st. Compression			
				pF 0 →4.25 (1)	pF 0 →2.0 (2)	pF 2 →4.25 (3)	$\frac{\text{pF } 2\rightarrow 4.25}{\text{pF } 0\rightarrow 4.25}$ (4)
Ste. Rosalie Clay	1	<0.25	50	31.5	8.5	23.0	73.0
			1,000	26.5	8.0	18.5	70.0
			10,000	18.5	3.5	15.0	81.0
		1.00-4.76	50	20.0	11.5	8.5	42.5
			1,000	23.5	7.5	16.0	68.0
			10,000	16.0	3.5	12.5	78.0
Macamic	2	<0.25	50	39.0	10.5	28.5	73.5
			1,000	18.5	2.5	16.0	86.5
			10,000	17.0	1.5	15.5	91.0
		1.00-4.76	50	20.0	9.5	10.5	52.5
			1,000	19.5	8.0	11.5	59.0
			10,000	17.5	5.0	12.5	71.5
Lamothe	3	<0.25	50	25.5	6.0	19.0	74.5
			1,000	22.0	4.5	17.5	79.5
			10,000	19.0	6.0	13.0	68.5
		1.00-4.76	50	32.0	18.5	18.5	56.0
			1,000	19.0	5.5	13.5	71.0
			10,000	15.5	4.5	11.0	71.0
Barbados	5	<0.25	50	30.5	6.0	24.5	80.0
			1,000	24.0	5.0	19.0	79.0
			10,000	22.0	4.5	17.5	79.5
		1.00-4.76	50	25.5	8.0	17.5	68.5
			1,000	22.5	7.0	15.5	69.0
			10,000	21.0	5.0	16.0	76.0

TABLE V - 5

CHANGE IN WATER CONTENT WITH CHANGE IN SWELLING PRESSURE, % OF WATER

Soil	Soil No.	Size of Aggregate, mm	Compaction level, psi	Swelling pF 4.25 → 0	 pF 4.25 → 2	 pF 2 → 0	 pF 4.25 → 2 / pF 4.25 → 0
				(5)	(6)	(7)	(8)
Ste. Rosalie Clay	1	<0.25	50	8.0	7.0	1.0	87.5
			1,000	6.0	4.5	1.5	75.0
			10,000	4.5	3.5	1.0	77.5
		1.00-4.76	50	11.0	9.0	2.0	82.0
			1,000	7.0	5.5	1.5	78.5
			10,000	4.5	4.0	0.5	88.5
Macamic	2	<0.25	50	13.0	10.0	3.0	77.0
			1,000	7.0	5.5	1.5	78.5
			10,000	5.5	5.0	0.5	91.0
		1.00-4.76	50	11.0	10.0	1.0	91.0
			1,000	8.0	6.5	1.5	81.3
			10,000	6.0	5.0	1.0	83.5
Lamothe	3	<0.25	50	8.0	6.5	1.5	81.5
			1,000	3.5	3.0	0.5	85.3
			10,000	3.0	2.5	0.5	83.3
		1.00-4.76	50	10.0	9.0	1.0	90.0
			1,000	4.5	3.5	1.0	78.0
			10,000	4.5	4.0	0.5	88.5
Barbados	5	<0.25	50	11.0	9.5	1.5	95.0
			1,000	8.0	7.0	1.0	87.5
			10,000	7.0	6.0	1.0	85.5
		1.00-4.76	50	10.5	9.5	2.0	90.5
			1,000	8.0	7.0	1.0	87.5
			10,000	8.0	7.0	1.0	87.5

TABLE V - 5

CHANGE IN WATER CONTENT WITH CHANGE IN SWELLING PRESSURE, % OF WATER.

Soil	Soil No.	Size of Aggregate, mm	Compaction level, psi	2nd Compression			
				pF 0 → 4.25	pF 0 → 2	pF 2 → 4.25	pF 2 → 4.25 / pF 0 → 4.25
				(9)	(10)	(11)	(12)
Ste. Rosalie Clay	1	<0.25	50	8.0	0	8.0	100.0
			1,000	6.5	0	6.5	100.0
			10,000	4.5	0	4.5	100.0
		1.00-4.76	50	10.0	0.5	9.5	95.0
			1,000	6.5	0.5	6.0	92.5
			10,000	4.5	0	4.5	100.0
Macamic	2	<0.25	50	13.0	0.5	12.5	96.0
			1,000	7.0	1.0	6.0	86.0
			10,000	5.5	0	5.5	100.0
		1.00-4.76	50	11.0	0	11.0	100.0
			1,000	12.0	1.0	11.0	91.5
			10,000	11.0	0.5	10.5	95.5
Lamothe	3	<0.25	50	8.0	1.5	6.5	81.0
			1,000	3.0	0	3.0	100.0
			10,000	3.0	0.5	2.5	83.5
		1.00-4.76	50	10.0	0	10.0	100.0
			1,000	4.5	0.5	4.0	89.0
			10,000	4.0	0	4.0	100.0
Barbados	5	<0.25	50	11.0	0	11.0	100.0
			1,000	8.0	1.0	7.0	87.5
			10,000	7.0	0	7.0	100.0
		1.00-4.76	50	10.5	1.0	9.5	90.5
			1,000	8.0	0.5	7.5	94.0
			10,000	8.0	0.5	7.5	94.0

TABLE V - 6

CHANGE IN WATER CONTENT WITH CHANGE IN SWELLING PRESSURE FOR THE CYCLE pF $0 \rightarrow 3 \rightarrow 0 \rightarrow 3$

Soils	Soil No.	Size of Aggregates, mm	Level of Compaction, psi	1 Reswelling	2nd 2 Compression
Ste. Rosalie Clay	1	<0.25	50	5.0	4.5
			1,000	5.0	4.0
			10,000	4.0	4.0
		1-4.76	50	7.5	7.0
			1,000	4.0	4.5
			10,000	5.0	4.0
Macamic	2	<0.25	50	5.5	4.5
			1,000	4.5	3.5
			10,000	3.5	3.0
		1-4-76	50	8.0	6.5
			1,000	6.0	4.0
			10,000	6.0	5.0
Lamothe	3	<0.25	50	3.0	2.0
			1,000	2.5	2.5
			10,000	3.5	3.5
		1-4.76	50	4.5	3.5
			1,000	3.5	3.0
			10,000	3.5	3.0
Barbados	4	<0.25	50	4.0	3.5
			1,000	5.5	5.0
			10,000	6.0	5.5
		1-4.76	50	6.5	5.5
			1,000	5.5	5.5
			10,000	5.5	5.0

further suggest the importance of inter-aggregate pores resulted from shrinking and swelling of aggregates contributing to water retention.

2-7. Conclusions.

It is necessary to have a blank apparatus to correct measured soil volume change. The small amount of entrapped air which existed between the membrane and soil sample was considered not to affect the measurement of swelling pressure. The time required for equilibrium of swelling pressure is short.

Large hysteresis in first compression and swelling is due to aggregate rearrangement. When the samples were compressed to pF 4.25, swelling pressure below pF 2 approached a constant which is the "internal pressure" described by Norrish and Raussell-Colom (1962). The samples with a terminal pressure of pF 3 did not have this property because there was less aggregate-aggregate bonding. The aggregate-aggregate bonding also increased with increasing desorption-adsorption cycles.

Aggregate rearrangement, which affects inter-aggregate pores, determines the change in water content with change in swelling pressure. Development of aggregate-aggregate bonding restricts aggregate rearrangement, so that change in volume of the inter-aggregate pores will be a direct function of aggregate size.

3. Water Retention.

3-1. Effect of Particle Orientation.

A large difference in water retention between dispersed and flocculated kaolinite was expected. The small difference found (Table V-7) was probably due to the change in original structure caused by extensive mixing during sample preparation (IV-2-3). This can be illustrated as A and B in Fig. II-1. Water retention by samples of dispersed kaolinite was generally slightly higher than by the flocculated samples. This effect of orientation was confirmed by the results for Leda clay in which water held by the parallel particle orientation was always higher than by random particle orientation (Fig. V-4).

Examination of the results for 100% kaolinite (Table V-7) for the wetting run shows that water retention for dispersed kaolinite was higher than for flocculated kaolinite above pF 3, but they became nearly equal between pF 3 and 2. Below pF 2, water retention between these two samples became different again. On redrying the samples, water retention became equal again above pF 2. The same trend was also observed for clay-glass beads mixtures. Based on observations, the mechanism for water retention in kaolinite, starting from air-dry can be postulated as follows.

TABLE V - 7

WATER CONTENT FOR DIFFERENT PARTICLE ORIENTATIONS AND DIFFERENT KAOLINITE-GLASS BEAD MIXTURES

Particle orientation	Clay/glass beads proportions	5	4	3	2	1	0	1	2	3	4.2
Dispersed	100/0	4.0	24.0	32.5	34.5	43.0	50.5	47.5	36.5	35.0	29.0
Flocculated		2.5	19.0	32.5	34.5	41.5	46.5	46.0	36.5	35.0	29.0
Dispersed	80/20	3.5	19.0	29.0	32.5	36.0	40.0	38.5	34.0	33.0	24.0
Flocculated		2.5	16.5	28.5	30.0	34.0	38.5	37.5	32.0	29.5	24.0
Dispersed	60/40	2.0	14.5	22.5	24.0	26.0	30.5	28.5	24.5	22.5	17.5
Flocculated		2.0	14.5	22.5	24.0	26.0	27.5	27.0	24.5	24.0	20.0
Dispersed	40/60	1.5	11.0	17.5	20.0	23.5	28.0	26.5	20.0	19.5	14.5
Flocculated		1.5	11.0	17.5	20.0	21.0	22.5	22.5	20.0	19.5	14.5
Dispersed	20/80	1.0	9.5	15.0	17.0	18.0	21.5	21.5	17.0	13.0	12.0
Flocculated		1.0	9.5	15.0	17.0	17.0	17.5	17.5	15.0	13.0	10.0
	No. 14 glass beads	0	0	0.5	1.0	21.5	26.0	26.0	2.0	1.5	0.8

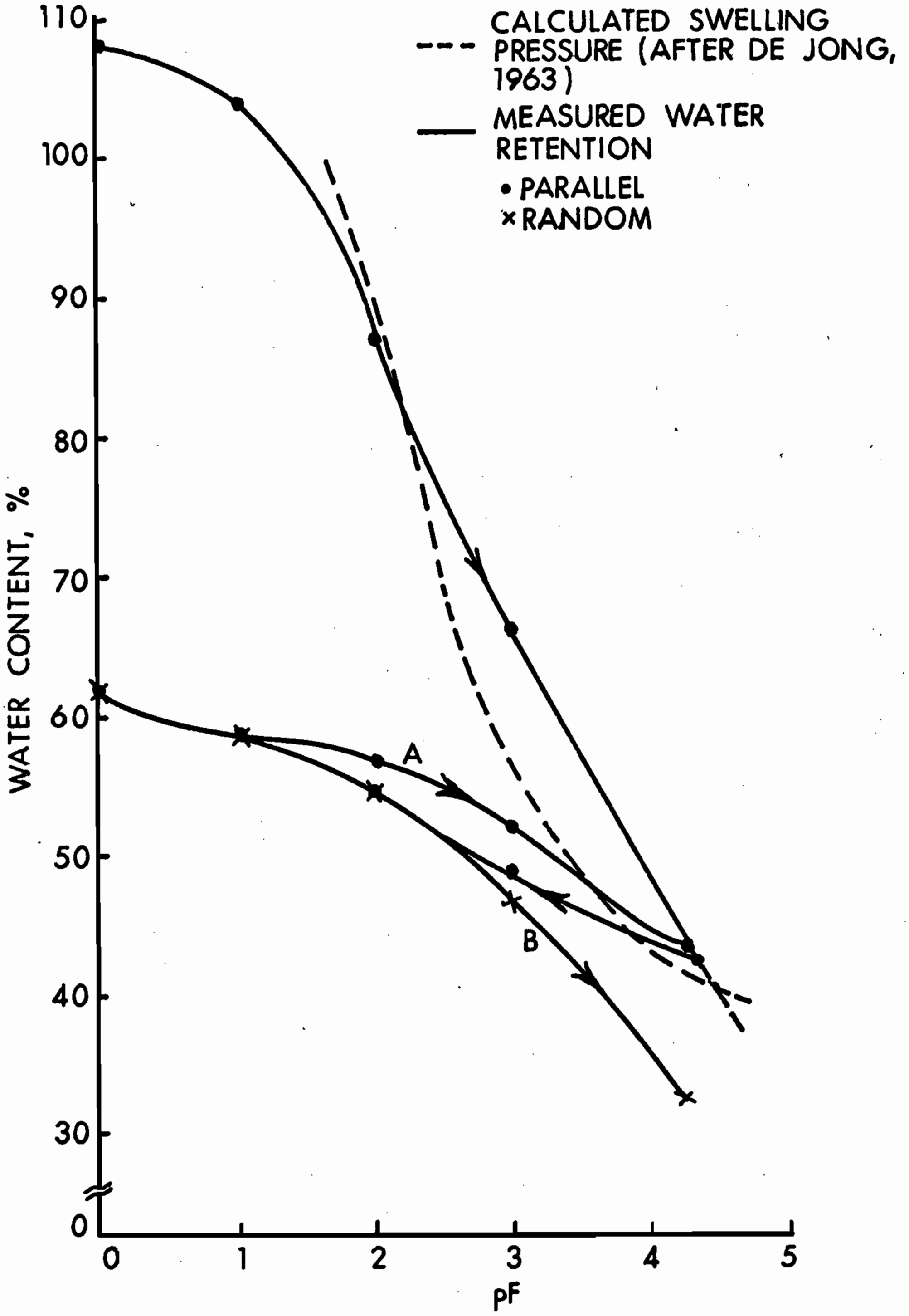


FIG. V-4, WATER RETENTION FOR PARALLEL & RANDOM PARTICLE ORIENTATION AND COMPARISON BETWEEN MEASURED WATER RETENTION & CALCULATED SWELLING PRESSURE, LEDA CLAY.

(1) Above pF 3, water is retained mainly by capillary forces in small pores. As shown in A & B in Fig. II-1, dispersed kaolinite has a greater volume of small pores than flocculated kaolinite. Therefore, dispersed kaolinite retained more water.

(2) Between pF 3 and 2, water was retained resulting from an equilibrium between the swelling pressure on one hand and capillary force plus Madelung attraction on the other hand. Swelling pressure would be expected to be larger for the dispersed kaolinite, but specific total pore volume with a Kelvin pore radius smaller than 10^4 Å was probably larger for flocculated kaolinite. The sum of water held by swelling pressure and capillary pores was the same for dispersed and flocculated kaolinite in this suction range.

(3) Below pF 2, water was retained by swelling forces. It is probable that the samples were saturated below pF 2. Further water moved in due to repulsion between the clay plates. The repulsive force is larger for parallel particle orientation than for random particle orientation, as already mentioned. This explanation is different from that given by de Jong (1963), but his experiments seem to support this explanation. His result showed that a surface active liquid decreased water retention between pF 3 and 1 but had practically no influence below pF 1. This implies that capillary force was the mechanism, or at least operative with swelling pressure, in the range of pF 3 and 1, and at the

lower range the swelling force was the only source retaining water in his Ca-kaolinite samples. Tschapek (1960) also concluded that capillary force is the important mechanism of water retention in kaolinite.

The proposed mechanism also explains water retention for kaolinite on drying. The difference in water retention between the samples below pF 2 was due to the difference in swelling potential. Above pF 2, further water was removed against capillary and swelling forces. The curves for the two samples during drying above pF 2 remained similar implying that irreversible changes in pore size distribution took place after the wetting-drying cycle.

A large difference was found in water retention between sedimented and slurried samples of Leda clay on the first drying (Fig. V-4). This shows the importance of sample preparation. Curves A & B, which start from the same water content, show that, water retention was higher for parallel than for random particle orientation. The difference increased with increasing pF value. Swelling pressure is the main mechanism for water retention in parallel particle orientation but capillary forces are dominant for random orientation. Water would be removed more easily from the open matrix in the random particle orientation, where edge to face bonding prevents contraction of the clay plates. Alternatively, it can be explained by the difference in effective pore size distribution.

Small pores prevail in the parallel particle orientation where the clay plates come closer together when water is removed.

Agreement between calculated swelling pressure (after de Jong, 1963) and measured water retention was found for slurried Leda clay for the first drying curve. (Fig. V-4). This supports Koenigs (1963) statement that the theoretical calculation is only applicable for a soil which is completely dispersed. Below pF 2.2, measured water retention was lower than calculated swelling pressure. Increased degree of dispersion and decreased edge to face bonding could cause this small difference. Between pF 2.2 and 4.4, water trapped in polyplates caused the measured water retention to be higher than calculated swelling pressure. At pF 4.4, unsaturation probably began, therefore, the swelling force will be underestimated. The calculated swelling pressure was thus higher than measured water retention above pF 4.4.

Water retention for the kaolinite-glass bead mixtures was calculated from the measured values for 100% clay and 100% glass beads, by assuming additivity based on proportion present, with no interaction. Calculated water retention was lower above pF 2 and higher below pF 1.5 than the measured water retention either on wetting or on drying, (Fig. V-5). The deviations were larger for the samples prepared from lower clay contents. Above pF 2,

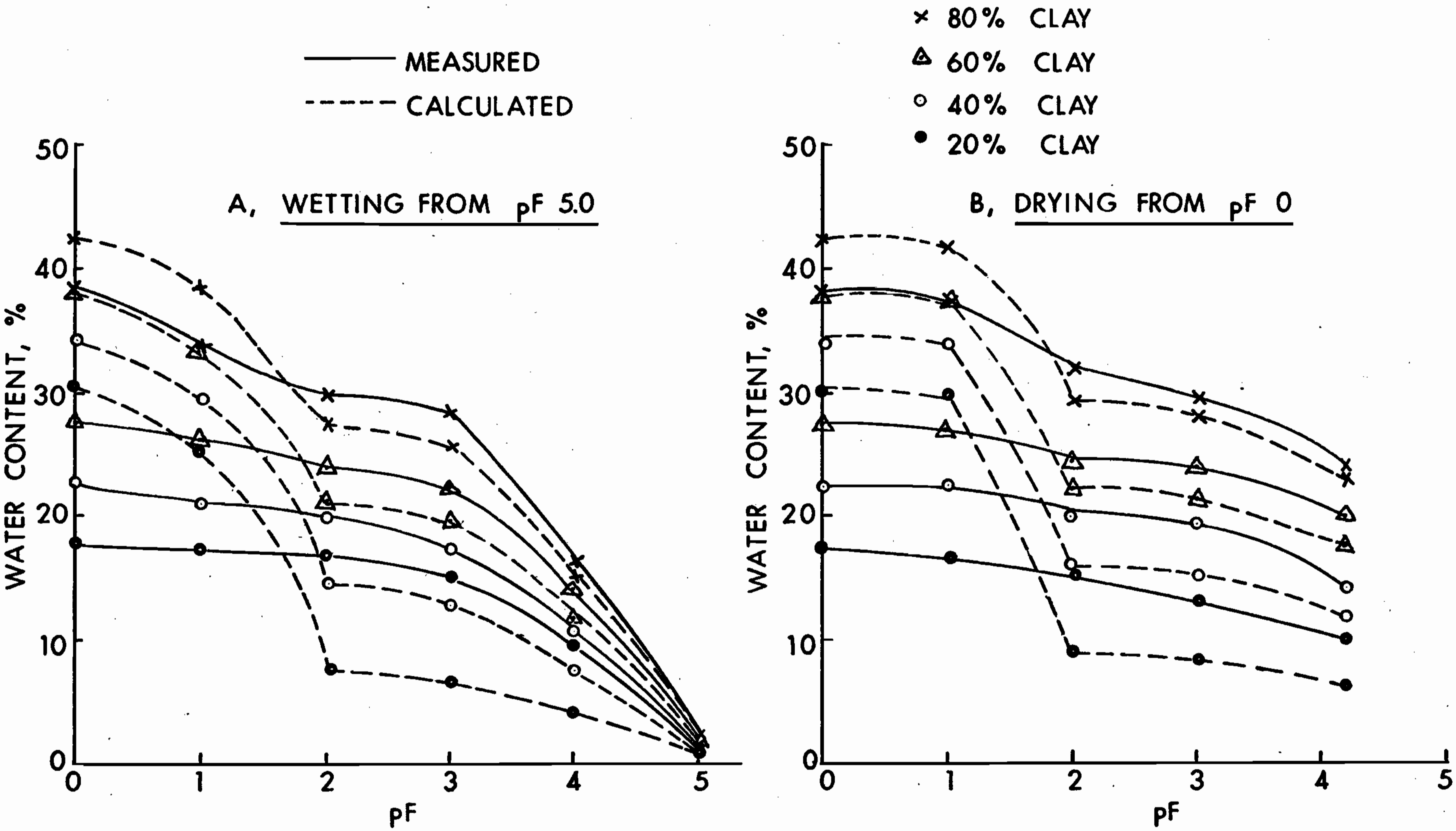


FIG. V-5, CALCULATED AND MEASURED WATER RETENTION, FLOCCULATED KAOLINITE-GLASS BEAD MIXTURES, CALCULATION BASED ON 100 % CLAY & 100 % GLASS BEADS.

the difference can be explained by modification of the size of capillary pores by the clay retained in the pores between glass beads. This was more obvious for higher glass bead contents in the mixture. If water retention was due to swelling pressure above pF 2 the measured water retention should be lower than the calculated because dilution should be more extensive for higher glass beads content.

At low pF (<1.5), calculated water retention exceeded the measured values. This can be explained partly by the clay filling up the pores between the beads; originally these pores were filled with water. Water taken up by swelling should be greater for the higher clay content. The slopes of the curves increase with decreasing clay content, indicating that water was taken up due to swelling force.

The same results are shown by comparison between measured and calculated water retention based on clay only (Fig. V-6). The change between measured and calculated values occurs mostly above pF 2. It further indicates that the capillary force is important for water retention in kaolinite above pF 2.

3-2. Water Retention by Clay Soil Aggregates.

The water retention curves for aggregates from the four soils under investigation were found to have the same slope. An example is shown in Fig. V-7, in which the first drying and the rewetting curves from the terminal

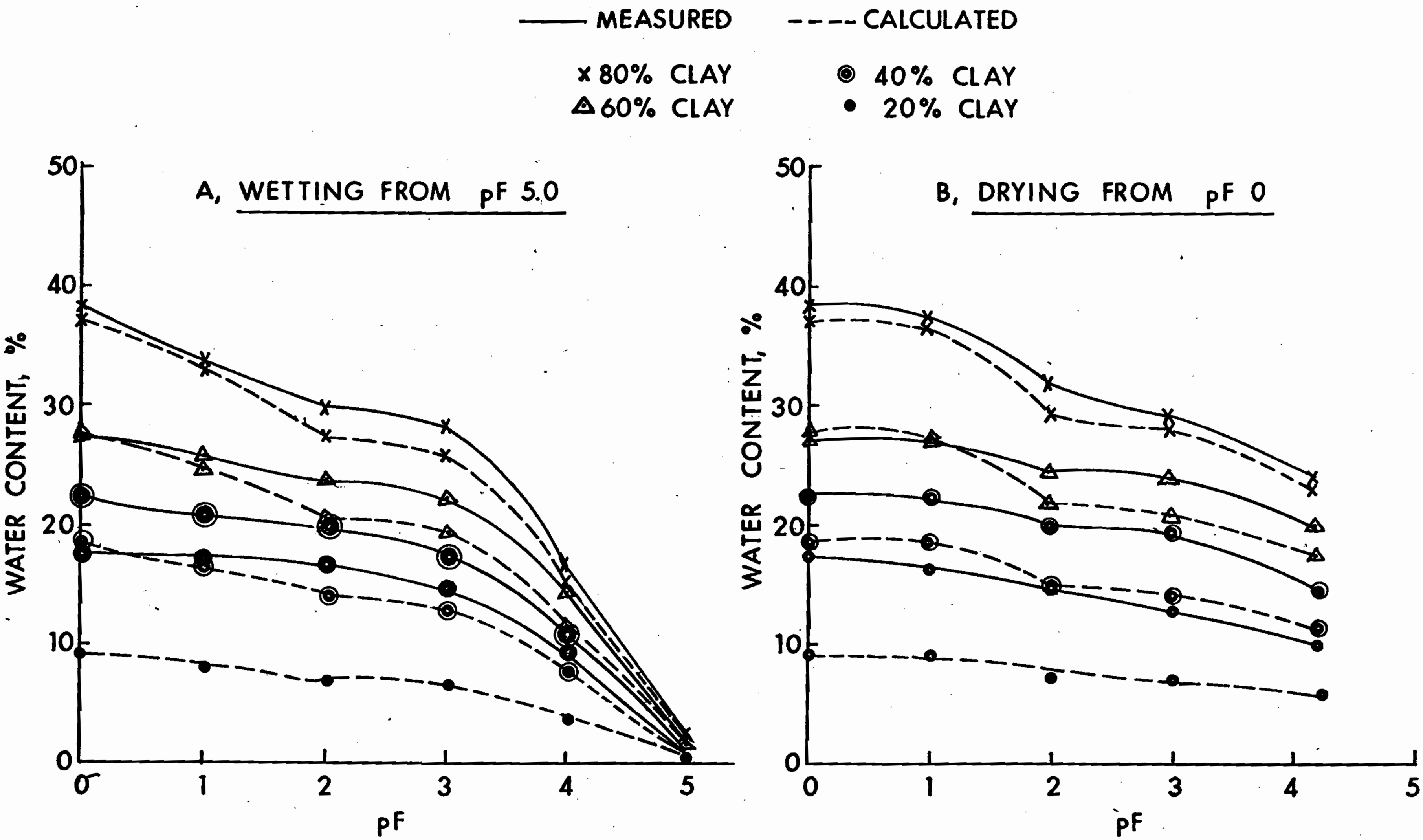


FIG. V-6, CALCULATED AND MEASURED WATER RETENTION, FLOCCULATED KAOLINITE - GLASS BEADS MIXTURES, CALCULATION BASED ON CLAY ONLY.

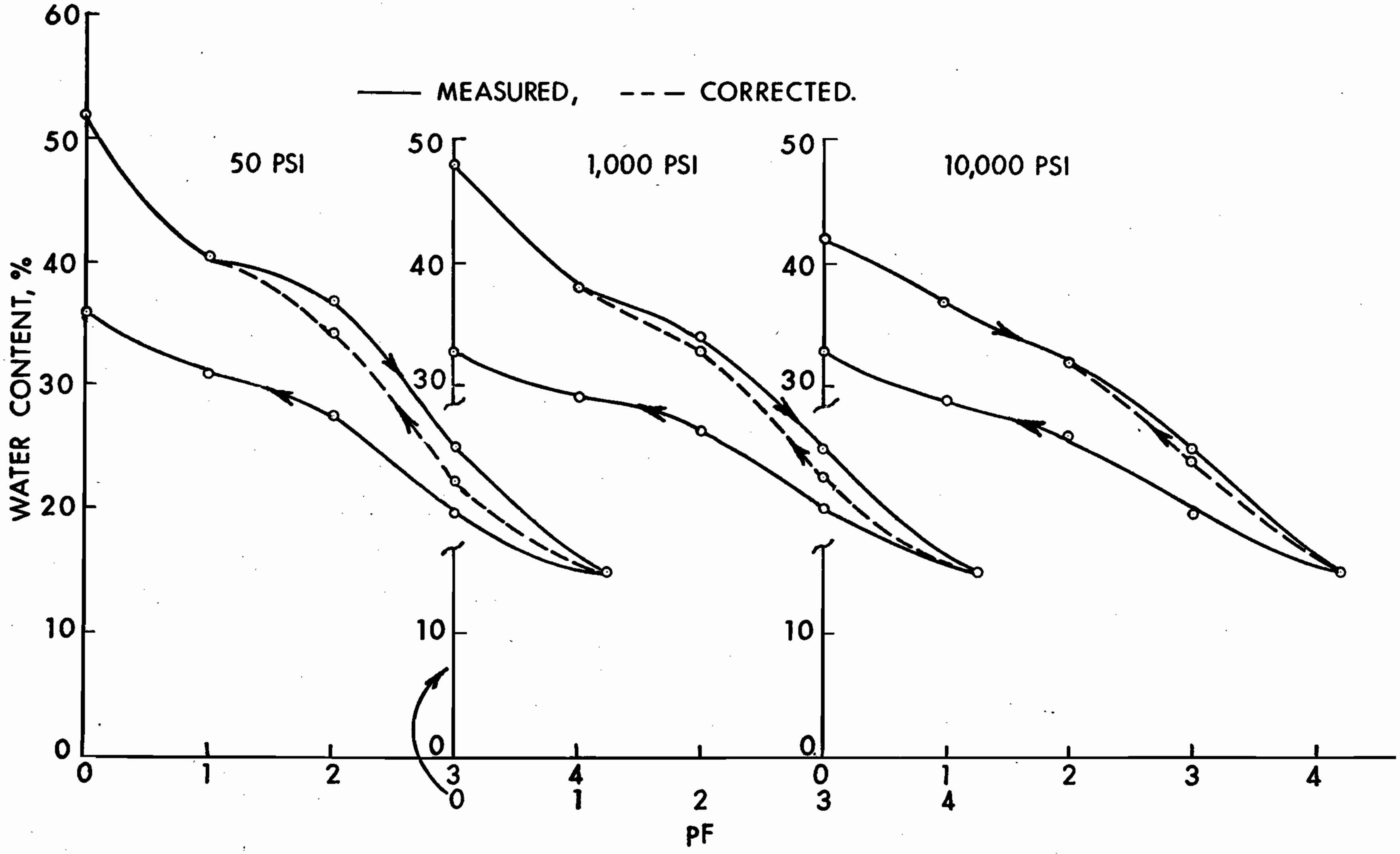


FIG. V-7, WATER RETENTION CURVES & WETTING CURVE CORRECTED FOR HYSTERESIS, <0.25 MM, (SOIL 3)

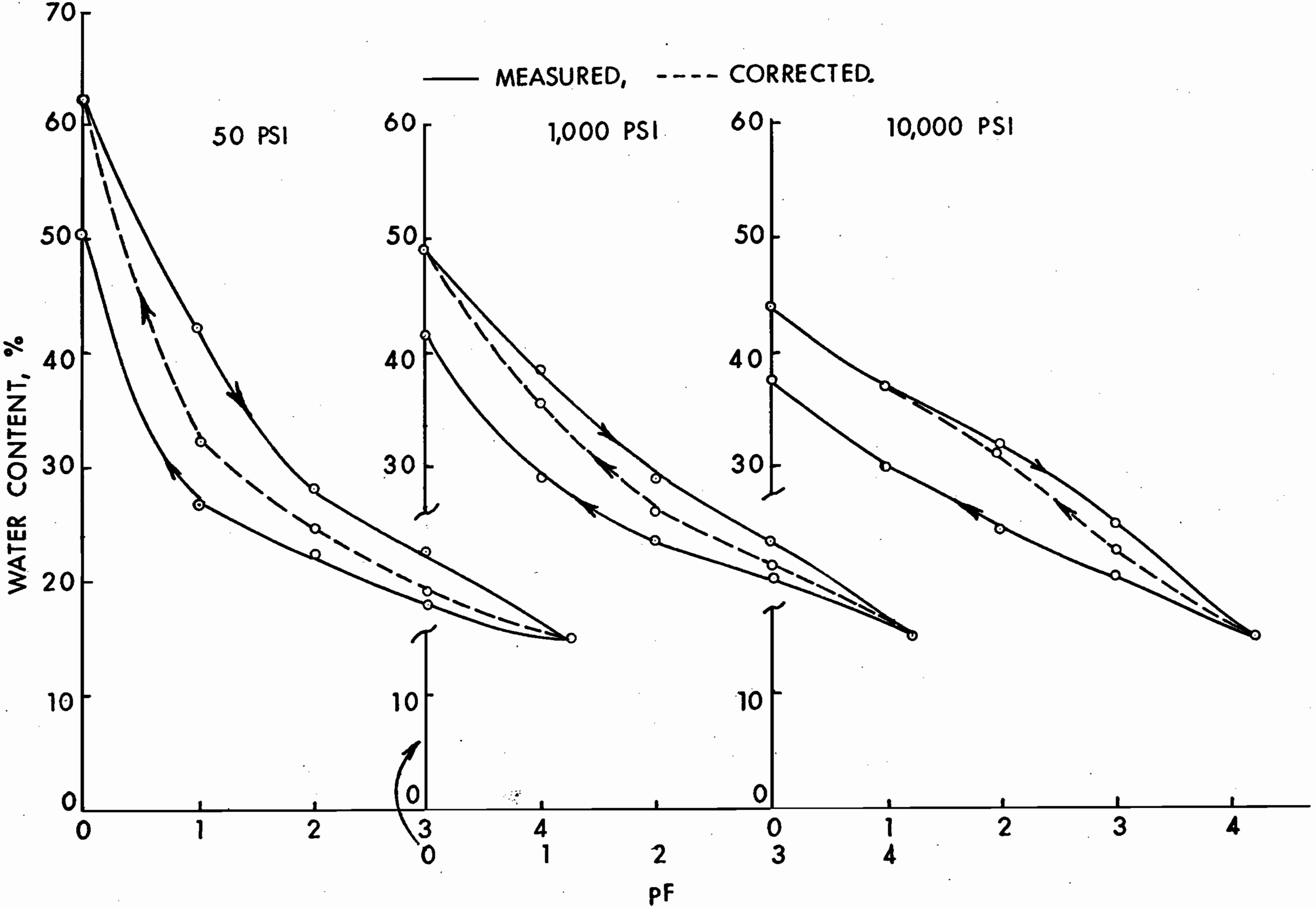


FIG. V-7, (CONT'D), 1.00-4.76 MM,

pressure of pF 4.25 are shown. More details are given in Tables V-8 and V-9. The following observations were made:

1. All samples showed a large hysteresis effect; the rewetting curves never rejoined the first drying curve. This kind of hysteresis loop had been observed by de Jong (1963, c.f. II-6). This was probably due to the volume changes resulting from aggregate rearrangement (c.f. V-1-9).
2. The two rewetting curves from pF 3 and 4.25, might or might not meet at pF 0. The wetting curve from pF 3 was a scanning curve (Fig. V-8) because of the higher rate of water taken up for the samples being dried from pF 4.25. This can be explained by pore volume-size distribution and capillary attraction between the aggregates, determined by degree of aggregate rearrangement, smaller pore size and larger attraction between the aggregates. Difference in degree of aggregate interference during rewetting and probably the difference in degree of development of inter-aggregate bonding explains the observation that the curves may or may not meet at pF 0. Soil 1 is a surface soil with granular aggregates. Aggregate interference will be smallest and aggregate rearrangement will be easier. As shown in Table III-1, this

TABLE V - 8

WATER RETENTION FOR DRYING AND WETTING CYCLES WITH TERMINAL PRESSURE pF 4.25. WATER CONTENT, % .

				pF												
				1st. Drying run					Wetting run				2nd Drying run			
Soils	Soil No.	Size of aggregate, mm	Compaction psi	0	→ 1	→ 2	→ 3*	→ 4.25	→ 3	→ 2	→ 1	→ 0	→ 1	→ 2	→ 3	→ 4.25
Ste. Rosalie Clay	1	<0.25	50	68.5	60.0	52.5	37.0	25.0	29.5	34.0	39.5	48.5	44.5	40.5	34.0	27.0
			1,000	56.5	50.0	45.0	35.0	25.0	29.5	33.0	37.5	45.0	41.5	38.5	33.0	25.5
			10,000	48.0	42.0	39.0	32.0	25.0	29.0	31.0	36.0	42.5	40.0	36.5	32.5	27.0
		1.00-4.76	50	52.0	32.5	28.0	26.0	17.5	22.5	25.0	31.0	44.0	35.5	29.5	26.0	19.0
			1,000	50.5	39.0	29.5	27.0	20.5	23.0	27.0	35.5	46.0	41.5	35.0	27.5	22.0
			10,000	43.0	37.5	34.0	28.0	22.0	26.0	29.0	34.5	42.0	39.0	34.5	29.0	22.0
Macamic	2	<0.25	50	80.0	70.0	60.0	47.5	31.0	34.0	40.5	47.0	53.0	51.0	46.0	36.5	29.5
			1,000	69.0	60.0	52.0	44.5	31.0	34.0	39.0	42.5	46.5	45.5	43.0	36.5	29.5
			10,000	60.0	50.0	44.5	39.0	31.0	35.5	37.0	40.5	46.5	44.5	41.5	36.5	29.5
		1.00-4.76	50	71.0	42.0	38.0	36.0	26.0	29.0	31.5	36.5	60.5	38.0	33.0	30.5	27.5
			1,000	66.0	46.5	40.0	36.0	26.0	31.5	34.0	41.0	55.0	44.5	36.5	32.5	28.0
			10,000	60.0	48.5	43.5	36.0	26.0	31.5	34.0	40.0	47.5	44.0	37.5	32.5	28.0

* Continue to Table VI - 9.

Continued.

TABLE V - 8 (Continued)

WATER RETENTION FOR DRYING AND WETTING CYCLES WITH TERMINAL PRESSURE pF 4.25 WATER CONTENT, %.

Soils	Soils No.	Size of aggregate mm	Compaction psi	pF												
				1st. drying run					wetting run				2nd drying run			
				0	→ 1	→ 2	→ 3★	→ 4.25	→ 3	→ 2	→ 1	→ 0	→ 1	→ 2	→ 3	→ 4.25
Lamothe	3	<0.25	50	52.0	40.5	37.0	25.0	15.0	19.5	27.5	31.0	36.0	32.5	30.5	26.5	15.0
			1,000	48.0	38.0	34.0	25.0	15.0	20.0	26.5	29.0	33.0	30.0	29.0	26.0	15.0
			10,000	42.0	37.0	32.0	25.0	15.0	19.5	26.5	29.0	33.0	30.0	29.0	26.0	15.0
		1.00 - 4.76	50	62.0	42.0	28.0	22.5	15.0	18.0	22.5	26.5	50.5	30.5	27.5	23.0	15.0
			1,000	49.0	38.5	29.0	23.5	15.0	20.5	23.5	29.0	41.5	33.0	28.5	23.5	16.0
			10,000	44.0	37.5	30.5	25.0	15.0	20.5	24.5	30.0	37.5	31.5	29.0	24.5	16.0
Barbados	5	<0.25	50	65.5	56.0	46.0	30.0	19.0	22.5	28.0	33.0	40.0	37.5	35.0	29.5	19.0
			1,000	55.0	50.5	42.0	29.5	20.0	23.5	30.0	34.0	39.5	36.5	35.0	29.5	20.0
			10,000	48.5	44.0	38.5	28.0	20.5	22.0	27.0	31.0	34.0	32.0	30.0	26.0	19.0
		1.00 - 4.76	50	53.0	37.0	30.0	22.0	13.5	17.0	22.5	26.5	44.0	32.0	28.5	24.0	14.5
			1,000	50.5	42.0	32.0	24.0	17.0	19.0	25.0	31.5	42.5	35.0	30.0	25.0	17.0
			10,000	48.5	44.0	36.0	25.5	19.5	21.0	27.0	32.0	38.0	34.5	29.5	25.0	19.5

★ Continue to Table VI - 9

TABLE V - 9

WATER RETENTION FOR DRYING AND WETTING CYCLES WITH TERMINAL PRESSURE OF pF 3.0, WATER CONTENT, %.

Soils	Soil No.	Size of aggregate mm	Compaction level psi	pF Rewetting run 3[*] →	2 →	1 →	0	2nd Drying run → 1	→ 2	→ 3	→ 4.25
Ste. Rosalie Clay	1	<0.25	50	37.0	39.0	41.5	48.5	46.0	42.5	36.0	27.5
			1,000	35.0	37.0	39.0	45.0	43.0	40.0	34.5	26.0
			10,000	32.0	33.5	36.5	42.5	40.0	36.5	32.5	27.0
		1.00 - 4.76	50	26.0	27.0	32.0	44.0	36.5	32.0	27.0	20.5
			1,000	27.0	29.0	35.5	46.0	42.5	35.5	29.0	22.0
			10,000	28.0	30.0	34.5	42.0	40.5	35.0	30.0	23.5
Macamic	2	<0.25	50	47.5	50.0	52.0	58.5	55.5	52.0	41.5	34.0
			1,000	44.5	46.0	48.0	55.5	51.0	48.0	44.5	32.5
			10,000	39.0	40.0	42.0	51.5	46.0	43.0	39.0	30.0
		1.00 - 4.76	50	36.0	38.0	40.0	61.5	42.5	39.0	36.5	29.0
			1,000	36.0	38.0	41.5	58.0	44.0	39.5	36.5	29.0
			10,000	36.0	38.0	41.5	53.0	47.5	40.5	36.5	29.0

[*] Continue from Table VI - 8

Continued

TABLE V - 9 (Continued)

WATER RETENTION FOR DRYING AND WETTING CYCLES WITH TERMINAL PRESSURE OF pF 3.0, WATER CONTENT, %.

Soil	Soil No.	Size of aggregate mm	Compaction level, psi	pF							
				Rewetting run				2nd drying run			
				3* →	2 →	1 →	0 →	1 →	2 →	3 →	4.25
Lamothe	3	<0.25	50	25.0	28.0	31.5	36.0	32.5	30.5	26.5	19.0
			1,000	25.0	28.0	30.5	35.5	32.0	30.0	26.5	20.0
			10,000	25.0	27.5	30.0	34.5	31.5	30.0	26.5	20.0
		1.00-4.76	50	22.5	26.0	34.5	50.5	38.0	31.5	24.5	17.0
			1,000	23.5	26.0	33.5	41.5	38.5	32.0	27.0	18.5
			10,000	25.0	27.0	32.5	38.0	36.0	32.5	27.5	20.0
Barbados	5	<0.25	50	30.0	33.0	38.5	43.5	41.0	37.5	31.0	22.0
			1,000	29.5	32.0	36.5	40.5	40.5	36.5	31.0	22.0
			10,000	28.0	31.5	36.0	40.5	40.5	36.0	30.0	22.0
		1.00-4.76	50	22.0	25.5	30.5	45.5	34.5	30.0	24.5	15.0
			1,000	24.0	26.5	34.5	46.0	40.5	33.5	28.0	20.0
			10,000	25.5	29.5	36.0	45.5	40.0	33.5	28.0	25.0

* Continued from Table VI - 8.

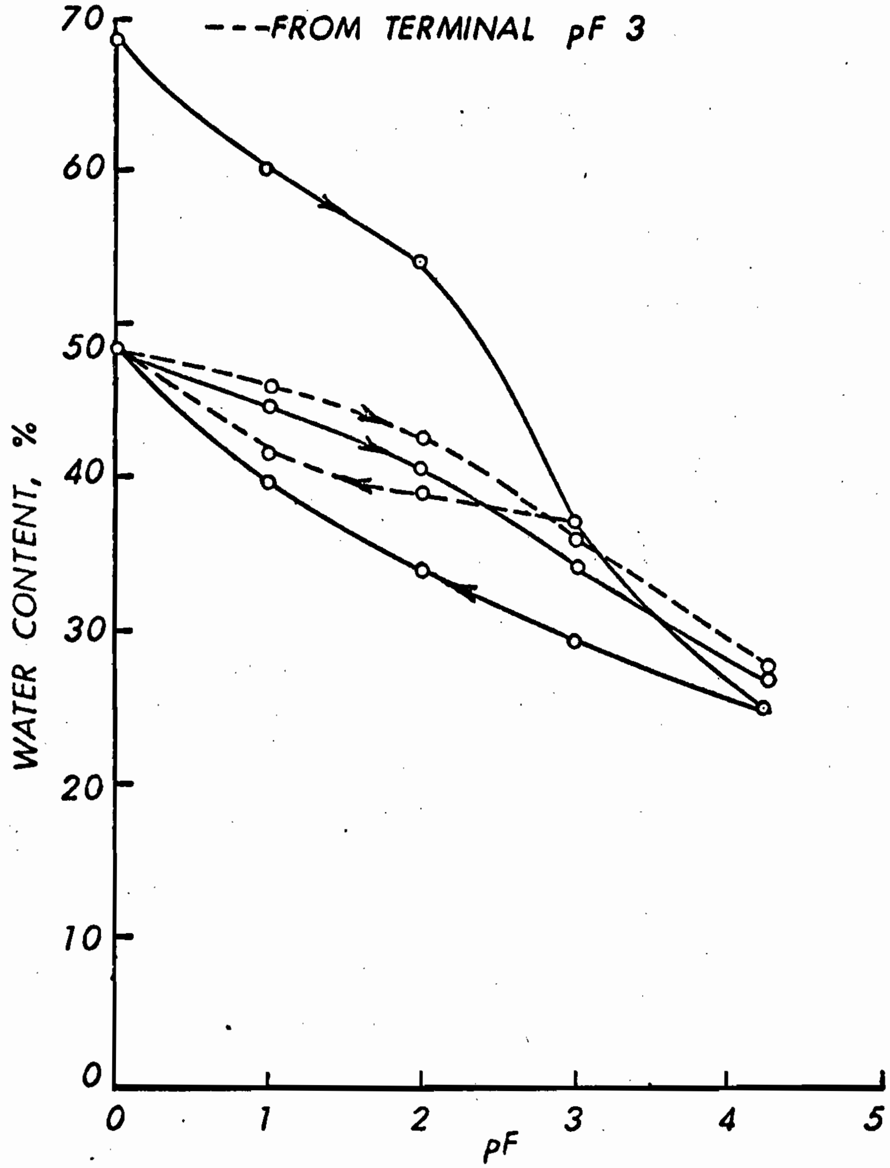


FIG. V-8, WATER RETENTION CURVE, <0.25 MM, 50 PSI, SOIL 1.

soil contained the largest proportion of sand-size particles so that development of inter-aggregate bonding should be the smallest among the four soils under investigation. These two reasons were considered to account for the observation that the two rewetting curves for soil 1 met at pF 0. It should be realized that if aggregate bonding does exist when the samples were dried to pF 4.25, it should be very small.

3. The hysteresis loops were larger for smaller aggregates prepared at lower compaction level. The effect was attributed mainly to the first drying. As explained in section V-1-4, these samples undergo more aggregate rearrangement and larger change in water content on drying. Although rearrangement is also found in rewetting, it is of smaller magnitude and hence the net result is a large hysteresis. A similar result was obtained by Croney and Coleman (1954), for soft and hard chalk, where a decrease in bulk density increased the hysteresis loop. This is solely due to larger pore size in soft chalk.

The results for the samples prepared from larger aggregates were not as regular as for the samples prepared from smaller aggregates (Tables V-8 and 9). This irregularily occurred mostly in samples prepared at the lower compaction level. Although the water content change on drying was large for this sample, the hysteresis loop was narrowed because of the large pore volume developed on swelling.

4. In the second drying run, the samples previously at a terminal pressure of pF 3 retained more water than for pF 4.25 (Fig. V-8, Tables V-8 and V-9). Even though the total pore volume was the same, the distribution of pore size was different due to different drying history.

3-3. Effect of Aggregate Size.

Samples prepared from smaller aggregates generally retained more water than the samples prepared from larger aggregates in the first drying run (Table V-8). Soil 3 was anomolous in that the sample prepared from larger aggregate retained more water between pF 0 and 1 (Fig. V-9A).

On rewetting from pF 3 or pF 4.25 and on the second drying, the samples prepared from smaller aggregates retained more or at least an equal amount of water above pF 1-2, but less below pF 1-2, than the samples prepared from larger aggregates (Tables V-8 and V-9, Fig. V-9 B, C, D, E). Aggregate rearrangement was greater for smaller aggregates, and inter-aggregate pore volume was decreased more. This is evidence that inter-aggregate pore volume became important at low pF. An exception was found for the samples prepared from soil 1, at 50 psi. The explanation lies in the low degree of saturation for this sample with larger aggregates (column 10, Table V-1).

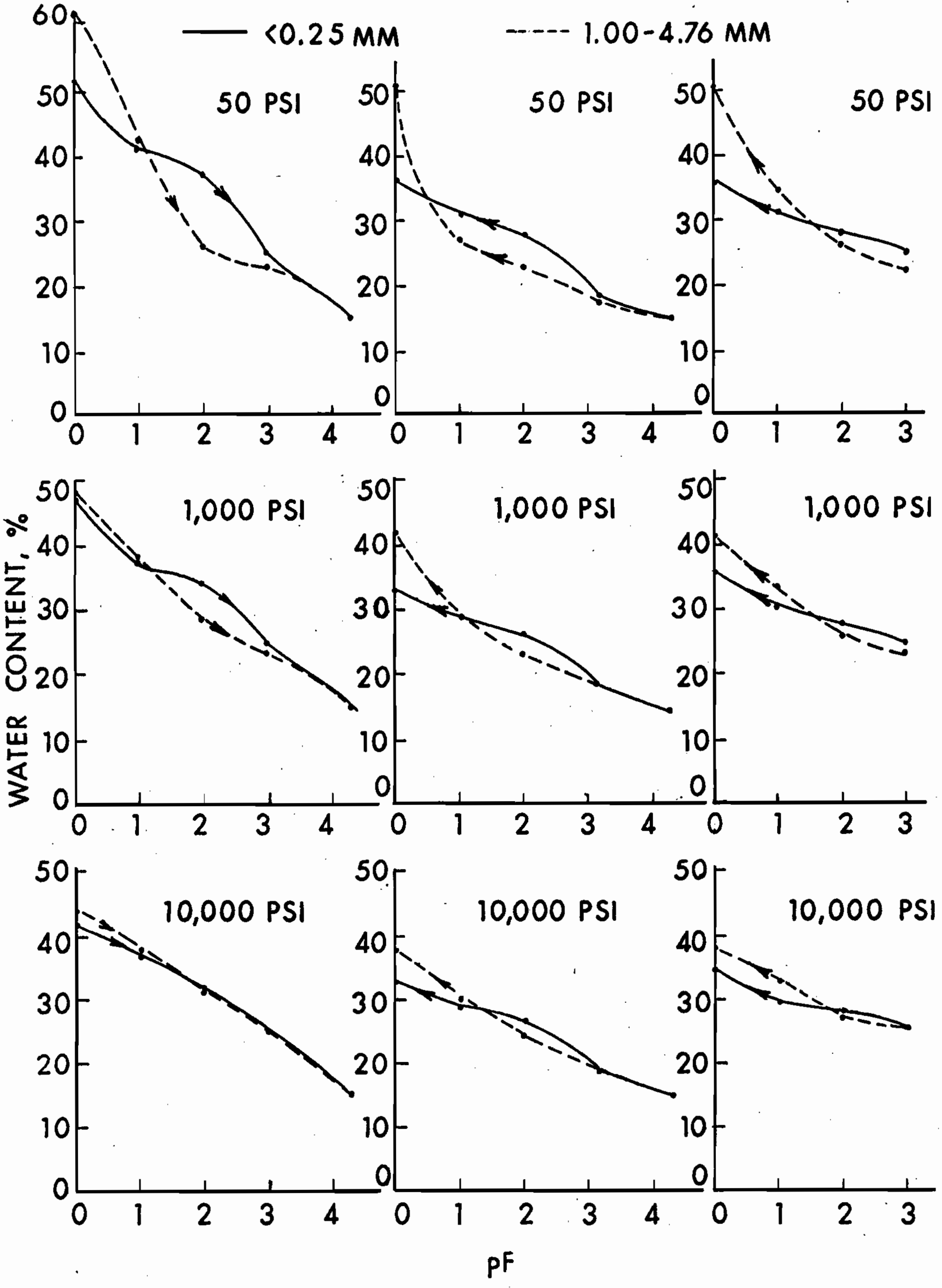
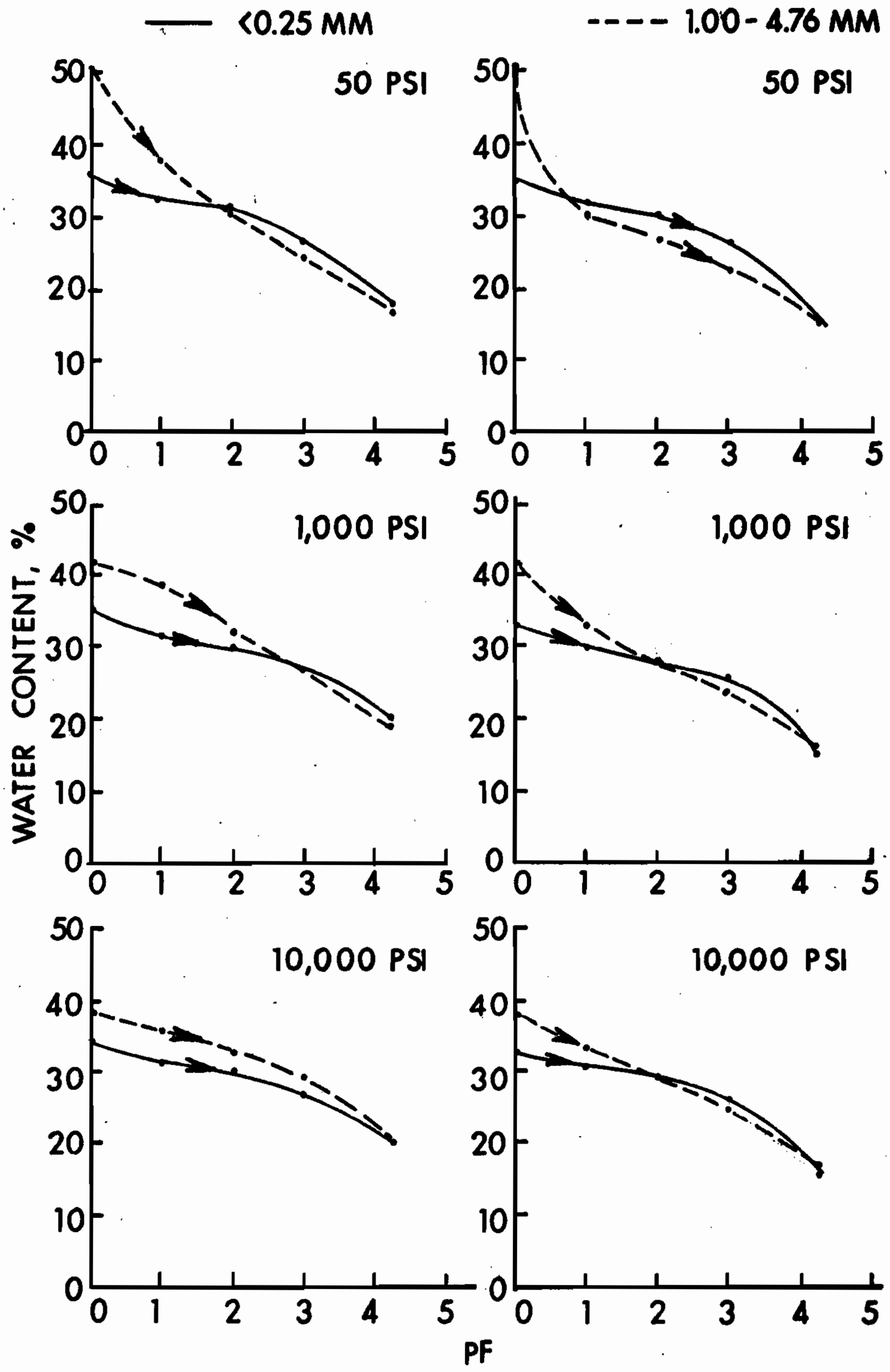


FIG. V-9, COMPARISON OF WATER RETENTION BETWEEN THE SAMPLES PREPARED FROM DIFFERENT AGGREGATE SIZES, SOIL 3.



D, 2ND. DRYING FROM pF 3.0   E, 2ND. DRYING FROM pF 4.25

FIG. V-9 (CONTINUED).

The capillary force drawing the aggregates into closer approach on drying should be small, therefore the chance of developing the right size of inter-aggregate pores for retaining water was also small.

3-4. Effect of Compaction Levels in Preparing the Samples.

The effects of compaction level on water retention for the samples prepared from larger aggregates (Fig. V-10B, D, F, Tables V-8 and V-9) are as follows:

1. Water retention above pF 2 is larger for the samples prepared at higher compaction level.
2. Water retention at pF 0 is larger for the samples prepared at lower compaction level.

These results were also found by Croney and Coleman (1954), although the sample used and explanation of the results were different (II-5-2). Total pore volume is important in water retention in the low pF range. In the higher pF range, pore volume-size distribution or volume of small pores is important. Aggregate rearrangement and modification of inter-aggregate pore volume-size distribution due to swelling or shrinking of the aggregate contributes a significant effect.

For the samples prepared from smaller aggregates either in drying or in wetting (Tables V-8 and V-9), Fig. V-10A, C, E), the results show that the lower compaction level results in the higher water retention.

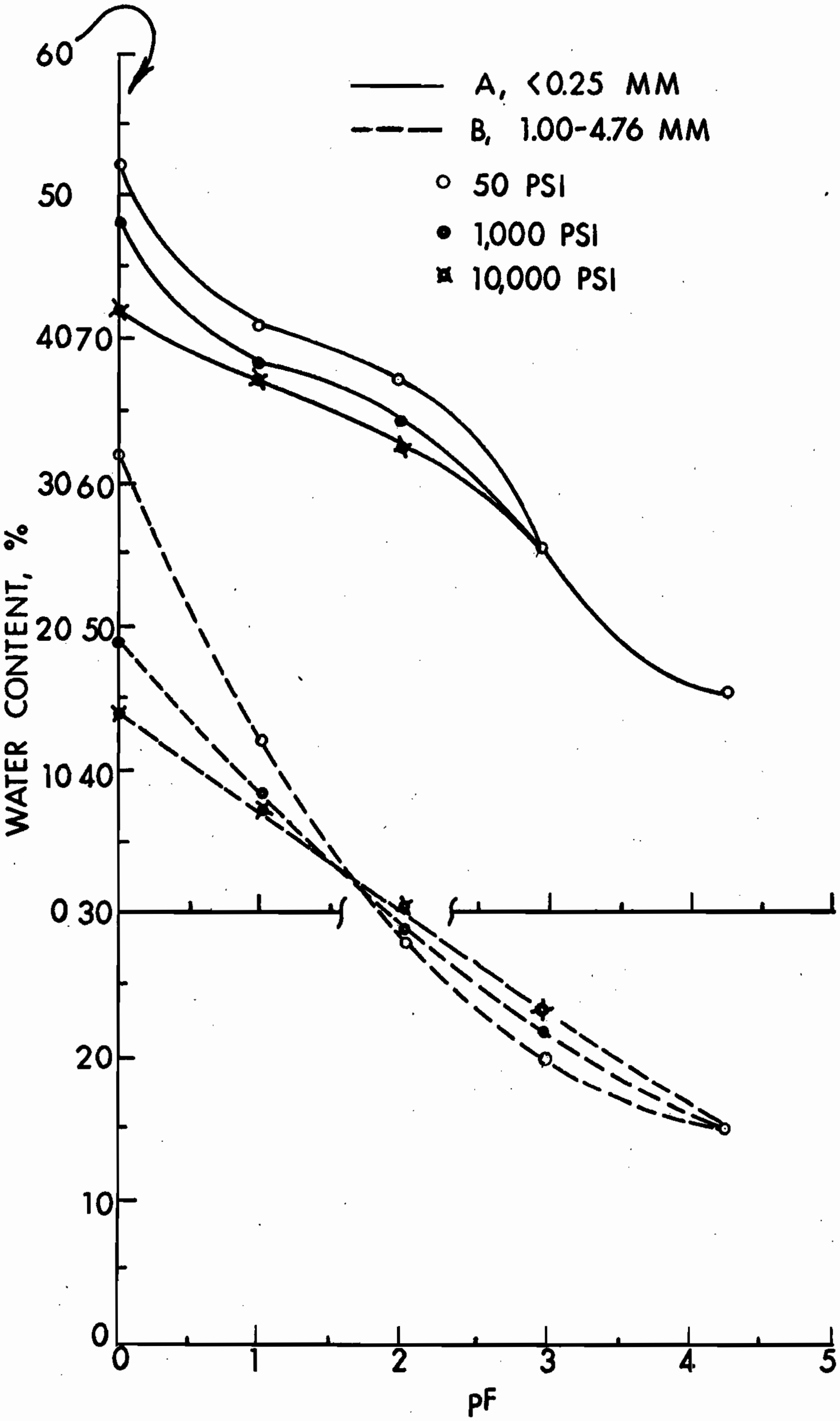


FIG. V-10. COMPARISON OF WATER RETENTION FOR SAMPLES PREPARED AT DIFFERENT COMPACTION LEVELS, 1ST. DRYING CURVES, SOIL 3.

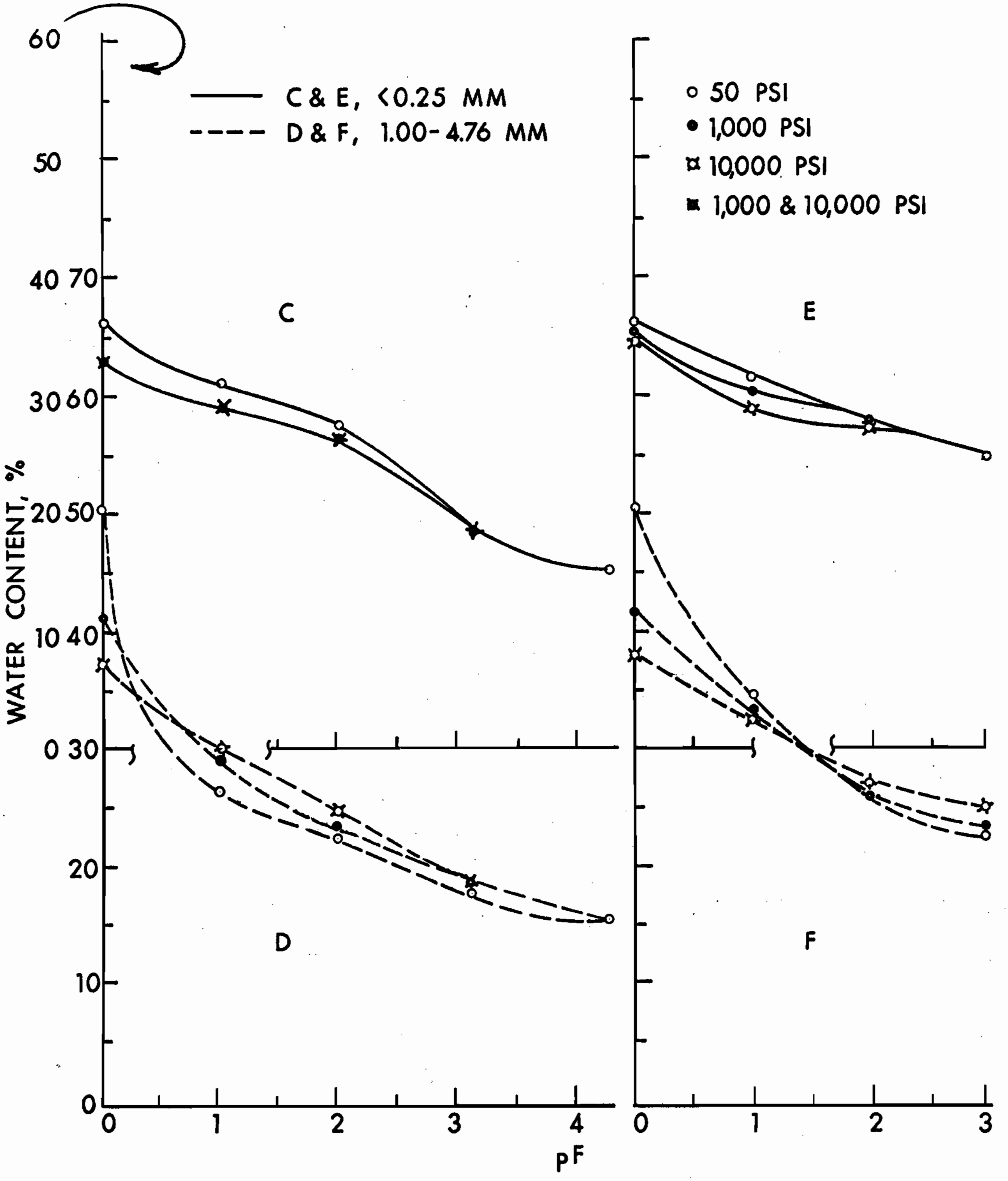


FIG. V-10 (CONTINUED), WETTING CURVES.

The difference generally increases with decrease in pF value. These results are supported by Box and Taylor (1962) but are opposite to those of Tamboli (1961).

Box and Taylor (1962) prepared a loam soil sample at different water contents, and found an increase in bulk density at any temperature (10°, 25° and 40°C). This was explained by the changing curvature of air water interfaces for the water held in the capillaries of the moist soil. There were no aggregate units in their samples. Tamboli (1961), for silt loam samples, found that the moisture retained at any given tension (up to 5.0 bars) and by any given aggregate size were in the following order $0.95 < 1.15 < 1.36$ g/cc. Closer approach of the aggregates and smaller pores between the aggregates on increasing the compaction level, and the significance of the interaction between the aggregate size and bulk density, were his explanations.

At high pF value, the samples prepared at higher compaction levels would be expected to retain more water. This did not occur up to pF 4.25, probably because the pore volume developed due to aggregate rearrangement was larger for the samples prepared at the lower compaction level.

3-5. Conclusions.

1. Parallel particle orientation retains more, or at least equal amounts of water, compared with random particle orientation.

2. Water retention by kaolin was mainly due to capillary forces, especially at higher pF values. Swelling forces are operative at low pF. This agrees with Tschapek's report (1960).

3. Calculated swelling pressure estimates the measured water retention in the first drying run in slurried Leda clay. The theoretical calculation appears to be applicable only for a clay soil which is completely dispersed, which agrees with Koenigs' statement (1963).

4. Large Hysteresis effects were mainly due to aggregate rearrangement. The hysteresis loop was decreased with increasing compaction level for smaller aggregate samples.

5. Inter-aggregate pore volume-size distribution is important for water retention but development of inter-aggregate pore volume due to aggregate rearrangement became important at low pF range.

6. Different aggregate sizes have different water retention patterns for different bulk densities. It is concluded that the geometry factor proposed by Bolt and Frissel (1960) is a proper component contributing to total water potential. Bulk density as proposed by Box and Taylor (1962) can be used

instead of the geometry factor, for the sample prepared from smaller aggregates but not for samples from larger aggregates.

4. Relationship Between Swelling Pressure and Water Retention for Clay Soil Aggregates.

4-1. Theoretical Considerations.

A conclusion drawn in section V-3-5 is that the geometry factor rather than bulk density is a proper factor contributing to water retention in soil aggregates. As pointed out by Babcock (1963), the equations given by Bolt and Frissel (1960) are somewhat bewildering because of the large number of equations and the inconsistency of their nomenclature. Actually, it is not possible to make a clear cut distinction between water as one phase of a three phase system and soil-water-air as one homogeneous system, especially for a clay soil with well developed structure or for aggregate samples as used in this investigation, because water is not homogeneously distributed or equally withdrawn from within the aggregate and between the aggregate. It is not a homogeneous system; however, change in volume with change in water content is equal if the sample is saturated. Based on the "parent equation" on a macro-approach as suggested by Bolt and Frissel (1960) in equations (II-7) and (II-8), a "working equation" at constant temperature and soil solution without free salt can be written as:

$$d\bar{G} = \bar{V}dp_e + d\omega_a + Mg\,dh + \sigma d\bar{o} + \left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi \qquad \text{(V-1)}$$

The notations are the same as in equations (II-7) and (II-8). The terms, $d\alpha$ and $\left(\frac{\partial \bar{G}}{\partial \theta}\right)d\theta$ which appear in equations (II-7) and (II-8) are covered by $d\omega a$ and $\sigma d\bar{o}$. However $d\alpha$ is very small compared to the total potential and can be neglected. With the proper limitations, equation (V-1) can be used to study water retention and swelling pressure for aggregates. In the laboratory studies the terms $\bar{V}dP_e$ and Mgdh can be defined. The former might be considered a factor contributing to total water potential by confining pressure, and the latter is the application of suction or pressure on a pressure plate as a multiple of the gravitational force. Application of the "working equation" to water retention and swelling pressure can be made as follows:

1. Coarse grain - water system: For water retention by fritted glass with a constant geometry, $\bar{V}dP_e$, $d\omega a$, and $\left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi$ are equal to zero. At equilibrium, dG= o, equation (V-1) becomes,

$$-Mg\int dh = \sigma\int d\bar{o} \qquad \text{(V-2)}$$

$$\because \bar{o} = \frac{\bar{V}}{r}$$

$$\because -\int dh = \frac{\bar{V}}{Mg}\int d\,\frac{2}{r} \qquad \text{(V-3)}$$

which results on integration,

$$\Delta h = \frac{2\sigma}{\rho g r} \qquad (V\text{-}4).$$

Equation (V-4) is Laplace's capillary rise equation. It can be written as,

$$\Delta h = \frac{3.0}{d} \qquad (V\text{-}5).$$

where d is the diameter of the capillary pore, mm, and Δh is applied suction, cm of water head.

In studying swelling pressure, a confining pressure is applied to the fritted glass. Mgdh is equal to 0. The term $\sigma d\bar{O}$ is eliminated if the fritted glass is saturated with water since no air-water interface exists, $(\frac{\partial \bar{G}}{\partial \chi})d\chi = 0$ as already stated. Therefore, equation (V-1) becomes

$$\bar{V}dP_e = d\omega_a \qquad (V\text{-}6).$$

$\bar{V} = (\frac{\partial V}{\partial \theta}) = 0$, since volume of the system is constant with change in water content. Therefore, equation (V-6) is not defined. No swelling pressure is developed by the fritted glass.

2. Clay-water system: It is assumed that the clay suspension is completely dispersed with parallel particle orientation. The geometry factor will be

covered by $d\omega_a$, because a change in clay plate spacing occurs only ~~and~~ with a change in water content. Therefore, $(\frac{\partial \bar{G}}{\partial \chi})d\chi = 0$ either in water retention or in swelling pressure studies. If the clay remains saturated to high pF values $\sigma d\bar{O}$ will not be involved, since there are no air-water interfaces. At equilibrium, $d\bar{G} = 0$, equation (V-1) becomes,

$$-Mgdh = d\omega_a \quad \text{(V-7), for water retention.}$$

$$-VdP_e = d\omega_a \quad \text{(V-8), for swelling pressure.}$$

Therefore,

$$-Mgdh = \bar{V}dP_e = d\omega_a = -\bar{V}d\pi = \bar{V}RTd(C_c - C_o) \quad \text{(V-9)}$$

Equation (V-9) shows that water retention or measured swelling pressure would be equal to calculated swelling pressure.

3. Clay soil aggregate-water system: With the approach as used above, except that the geometry factor should be included, equation (V-1) becomes,

$$-Mgdh = d\omega_a + \sigma d\bar{O} + (\frac{\partial G}{\partial \chi})d\chi \quad \text{(V-10).}$$

for water retention, and

$$-\bar{V}dP_e = d\omega_a + (\frac{\partial \bar{G}}{\partial \chi})d\chi \quad \text{(V-11).}$$

for swelling pressure.

The need to take into account the geometry factor in equations (V-10) and (V-11) was verified for water retention (c.f. V-3) and for swelling pressure (c.f. V-2).

If equation (V-11) is transformed into,

$$-dP_e = RTd(C_c - C_o) + \frac{1}{\bar{V}}\left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi \qquad (V\text{-}12)$$

it shows that measured swelling pressure would not be equal to calculated swelling pressure because of the geometry factor, which will be positive or negative depending on the sample used.

Probably it has a positive effect for the clay soil aggregates because the inter-aggregate pores will hold water which is beyond the influence of the double layer as shown in the shaded area in Fig. V-11. Although the measurement is unambiguous, care must be taken in the explanation of the results for the aggregate sample. As shown in Fig. V-11, two types of aggregate arrangement, close packing and open packing, are possible. If they were subjected to the same confining pressure, water content vs swelling pressure curves would not be the same for these two samples although the aggregate sizes are the same. Open packing as illustrated in A, Fig. V-11, will retain more water than close packing (illustration B) although the number of inter-aggregate contacts is higher for the latter.

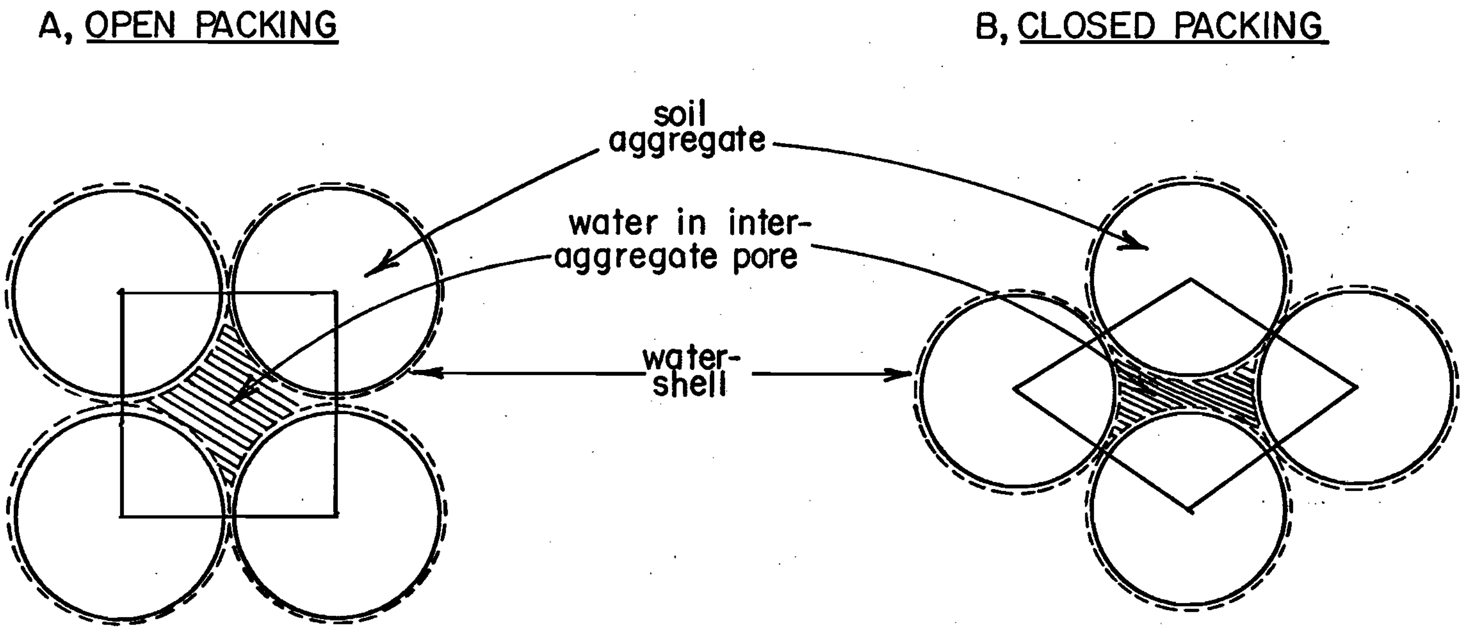


FIG. V-11, CROSS SECTION FOR ARRANGEMENT OF AGGREGATES.

As stated by Box and Taylor (1962), hysteresis in soil water retention is associated at least in part with shrinking and swelling. These effects are probably covered by $(\frac{\partial \bar{G}}{\partial \chi})d\chi$ in equations (V-10) and (V-11). Attention must be paid to $(\frac{\partial \bar{G}}{\partial \chi})d\chi$ which is probably not the same for water retention as for swelling pressure at the same equivalent pF.

As discussed above and in Fig. V-11, aggregate geometry is a function of swelling and shrinking of the aggregates as well as repulsion and attraction between the aggregates in swelling pressure studies, but the geometry depends on both swelling pressure and capillary force in water retention studies.

4-2. Comparison between Swelling Pressure and Water Retention.

A comparison of measured swelling pressure and water retention is illustrated in Fig. V-12, for the rewetting curves for soil 3. More details and values for the other soils are shown in Tables V-4A, V-4B, V-8 and V-9. Either on drying or on rewetting the curves fall into the same pattern showing water content from water retention measurements is higher than from swelling pressure in the low pF range. The difference increases with a decrease in pF value. Based on equations (V-10) and (V-11), the difference would be due to the difference of capillary potential, $d\bar{O}$. According to

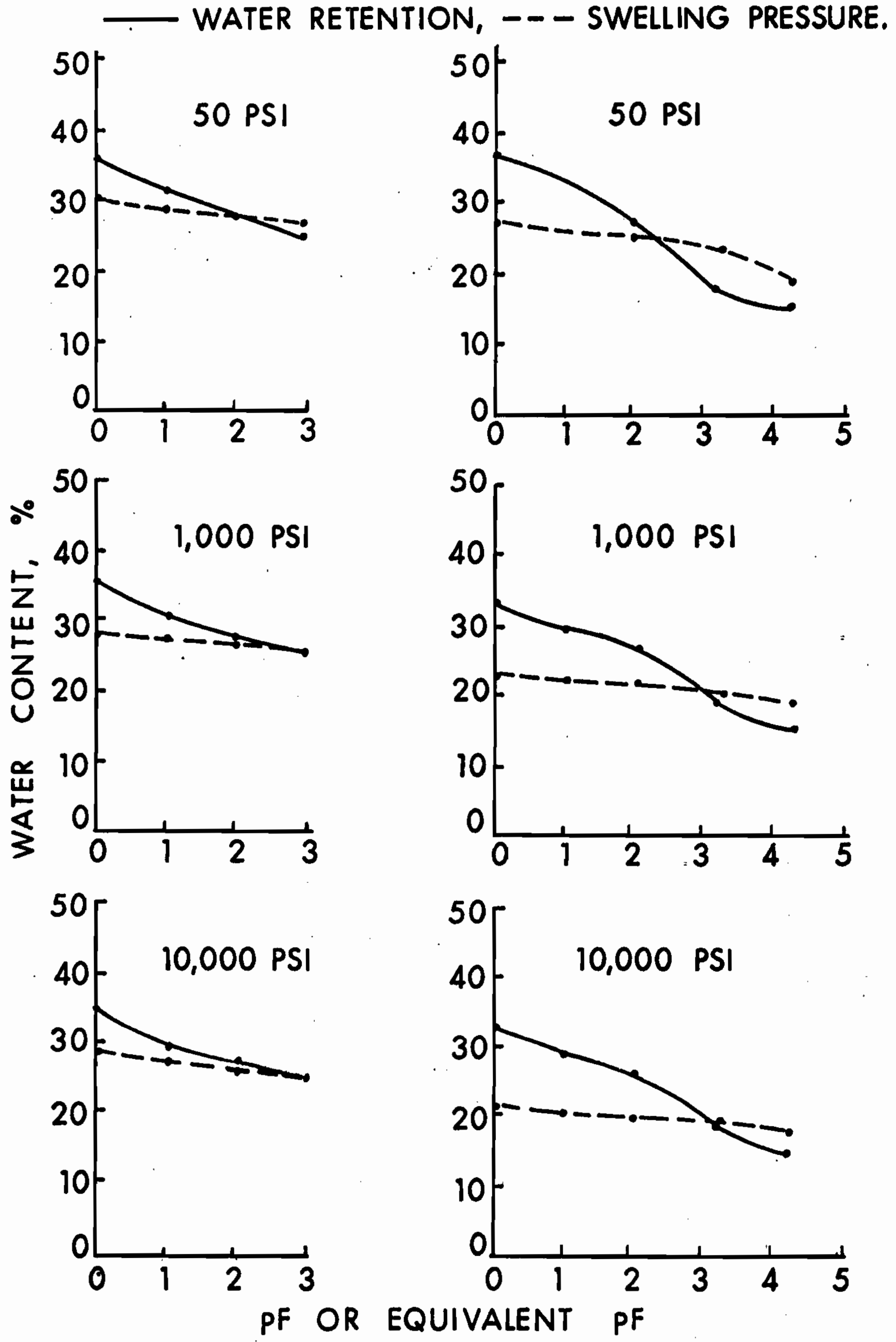


FIG. V-12, COMPARISON BETWEEN WATER RETENTION AND SWELLING PRESSURE, WETTING CURVES, SOIL 3. <0.25 MM

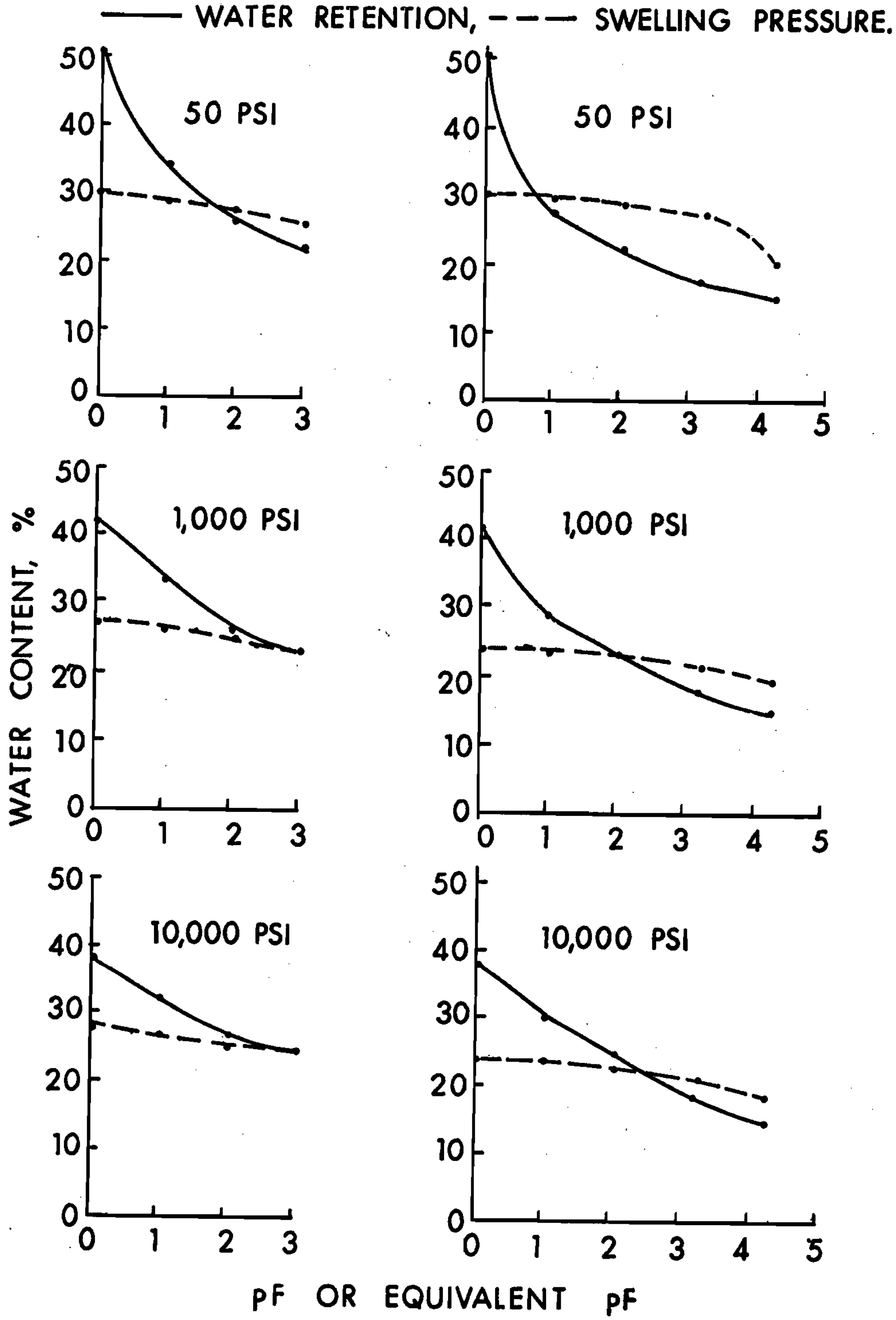


FIG. V-12 (CONTINUED), 1.00-4.76 MM

measurements of volume changes (c.f. Fig. V-1), however, this explanation of the results is erroneous because the soils were saturated in the low pF range, especially the samples prepared from smaller aggregate or/and at higher compaction levels. This means that $6 d\bar{O}$ should be equal to zero or at least negligible. Therefore, equation (V-10) should become,

$$-Mgdh = d\omega_a + \left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi \qquad \text{(V-13)}$$

for water retention at saturation. Comparison of equations (V-11) and (V-13), and the measured water retention and swelling pressure as shown in Fig. V-12, now indicates that the difference in water content at the same equivalent pF is actually due to the difference in the geometry factor. This further indicates the importance of inter-aggregate pore volume in retaining water at the low pF range. This pore volume is determined by aggregate arrangement or geometry.

The difference in geometry factor, $\left(\frac{\partial \bar{G}}{\partial \chi}\right)d\chi$ in equations (V-11) and (V-13), is due to the difference in degree of aggregate rearrangement. This differs for shrinkage under no load and for shrinkage on compression or consolidation. Aggregate rearrangement will be restricted to some degree by the formation of aggregate-aggregate bonds during the first compression (c.f. V-2-7).

This affects water holding capacity in rewetting and on successive drying. This bonding is greater for the samples having undergone compression than for those that were drying. This accounted for the difference of water content between water retention and swelling pressure in reswelling and second drying.

Water content in swelling pressure was higher than in water retention at higher pF values (Fig. V-12). This is explained by unsaturation of inter-aggregate pores in water retention measurements, but these pores always remained saturated in swelling pressure studies. This is also shown by the lower pF at the point of intersection for the samples prepared at lower compaction levels, because larger pores for these samples are only filled at lower pF.

The effect of the geometry factor in comparing water retention and swelling pressure was further studied for an undisturbed soil with good structure (soil 1). The first drying curves (Fig. V-13) resemble the curves, in Fig. App. 3 and those given by Warkentin (1962b) who compared the results obtained for Leda clay by Penner (1958) and Bozozuk (1959) for water retention and swelling pressure respectively. The large difference at low pF occurred because the large inter-aggregate pores were filled with water in the swelling pressure measurement, but were emptied in water retention. This accounts for the higher water content in swelling pressure.

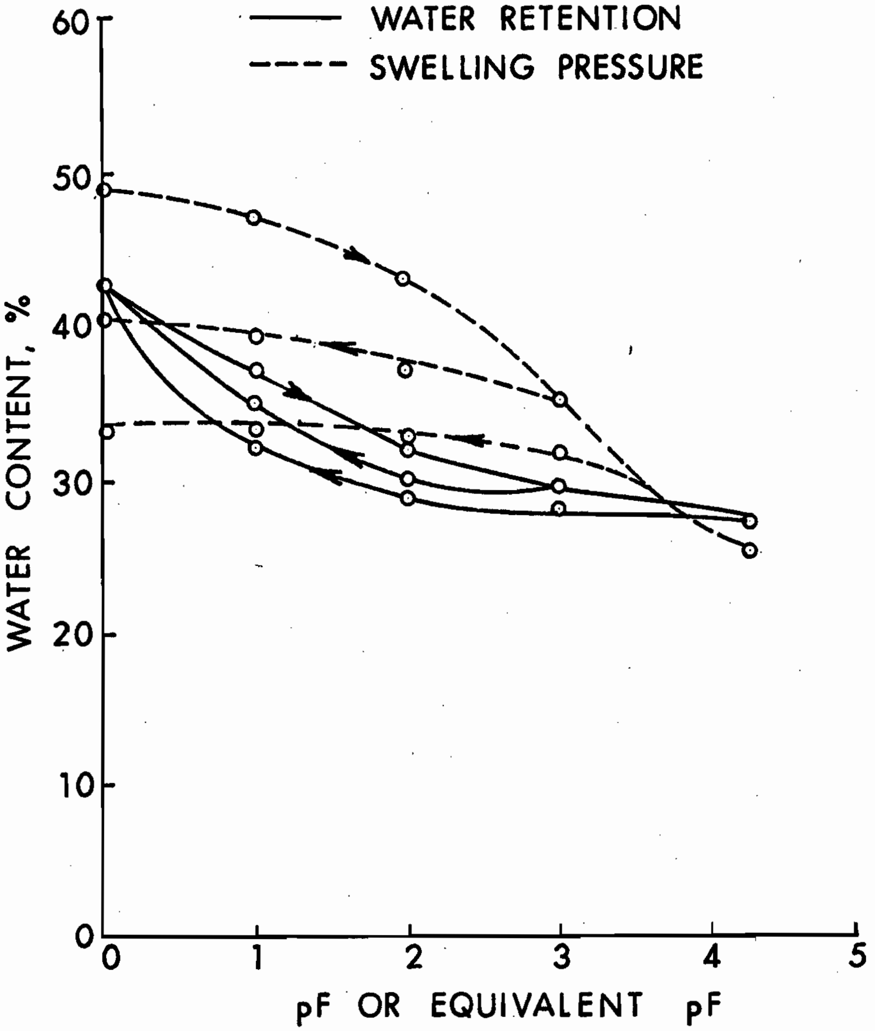


FIG. V-13, WATER RETENTION AND SWELLING PRESSURE FOR UNDISTURBED SOIL, SOIL 1.

The soil structure was probably changed under loading such that the total pore volume with radii smaller than that equivalent pF was decreased more than in water retention studies. This explains the water content being higher for the latter than for the former at higher pF values.

The increase in water content with decrease in pF value on rewetting from a terminal pressure of pF 3.0 or 4.25 is shown in Table V-10. The increase in water content due to decrease in total water potential was larger than due to decrease in confining pressure between the range pF 0 - 3.0. This is required since the total potential should be larger than a component potential. From pF 4.25 - 3.0 for the samples prepared at lower compaction levels and for all samples in soil 5, the increase in water content with a decrease in total water potentialwas smaller than with a decrease in swelling pressure. The same samples also showed the largest difference in water content increases between pF 2 and 0. These results suggest aggregate rearrangement and formation of aggregate-aggregate bonds which determine the geometry factor which influences the total water potential and swelling pressure. Probably aggregate rearrangement is different for shrinking of the aggregates in water retention and for compression in swelling pressure studies. Formation of aggregate-aggretate bonds

TABLE V - 10

COMPARISON OF INCREASE IN WATER CONTENT ON SWELLING FOR WATER RETENTION AND FOR SWELLING PRESSURE MEASUREMENTS

Soils	Soil No.	Size of aggregate, mm	Compaction level, psi	Method	Sample with terminal pressure 4.25			Sample with terminal pressure 3.	
					pF			pF	
					4.25 → 3	3 → 2	2 → 0	3 → 2	2 → 0
					(1)	(2)	(3)	(4)	(5)
Ste. Rosalie Clay	1	< 0.25	50	T	4.5	4.5	13.5	2.0	9.5
				S	6.0	1.0	1.0	0.5	3.5
			1,000	T	4.5	3.5	12.0	2.0	8.0
				S	3.0	1.5	1.5	2.0	3.0
			10,000	T	4.0	2.0	11.0	1.5	9.0
				S	2.5	1.0	1.0	1.0	3.0
		1.00-4.76	50	T	5.0	2.5	19.0	1.0	17.0
				S	6.0	3.0	2.0	0.5	6.0
			1,000	T	2.5	4.0	19.0	2.0	15.0
				S	3.0	2.5	1.5	2.0	2.0
			10,000	T	4.0	3.0	13.0	2.0	12.0
				S	3.0	1.0	0.5	1.5	3.0

T = Total water potential from water retention

S = Swelling pressure

Continued

TABLE V - 10 (Continued)

COMPARISON OF INCREASE IN WATER CONTENT ON SWELLING FOR WATER RETENTION AND FOR SWELLING PRESSURE MEASUREMENTS

Soils	Soil No.	Size of aggregate mm	Compaction level, psi	Method	Sample with terminal pressure 4.25 pF			Sample with terminal pressure 3. pF	
					4.25 → 3 (1)	3 → 2 (2)	2 → 0 (3)	3 → 2 (4)	2 → 0 (5)
Macamic	2	< 0.25	50	T	3.0	6.5	12.5	2.5	8.5
				S	5.5	4.5	3.0	1.0	4.5
			1,000	T	3.0	5.0	7.5	1.5	9.5
				S	3.0	2.5	1.5	1.0	3.5
			10,000	T	4.5	1.5	9.5	1.0	11.5
				S	3.0	2.0	0.5	1.5	2.0
		1.00-4.76	50	T	3.0	2.5	29.5	2.0	23.5
			1,000	S	7.5	2.5	1.0	2.0	6.0
			1,000	T	5.5	2.5	21.0	2.0	20.0
				S	3.5	3.0	1.5	2.0	4.0
			10,000	T	5.5	2.5	13.5	2.0	15.0
				S	3.5	1.5	1.0	1.5	4.5

TABLE V - 10 (Continued)

COMPARISON OF INCREASE IN WATER CONTENT ON SWELLING FOR WATER RETENTION AND FOR SWELLING PRESSURE MEASUREMENTS

					Sample with terminal pressure 4.25 pF			Sample with terminal pressure 3. pF	
Soil	Soil No.	Size of aggregate, mm	Compaction level, psi	Method	4.25 → 3 (1)	3 → 2 (2)	2 → 0 (3)	3 → 2 (4)	2 → 0 (5)
Lamothe	3	< 0.25	50	T	4.5	8.0	8.5	3.0	8.0
				S	5.0	1.5	1.5	1.0	2.0
			1,000	T	5.0	6.5	6.5	3.0	7.5
				S	2.0	1.0	0.5	1.0	1.5
			10,000	T	4.5	7.0	6.5	2.5	7.0
				S	1.5	1.0	0.5	1.0	3.5
		1.00-4.76	50	T	3.0	4.5	28.0	3.5	24.5
				S	7.5	1.5	1.0	1.5	3.0
			1,000	T	5.5	3.0	18.0	2.5	15.5
				S	2.5	1.0	1.0	1.0	2.5
			10,000	T	5.5	4.0	13.0	2.0	11.0
				S	3.0	1.0	0.5	1.5	2.0

T = Total water potential from water retention

S = Swelling pressure.

Continued

TABLE V - 10 (Continued)

COMPARISON OF INCREASE IN WATER CONTENT ON SWELLING FOR WATER RETENTION AND FOR SWELLING PRESSURE MEASUREMENTS

Soil	Soil No.	Size of aggregate, mm	Compaction level, psi	Method	Sample with terminal pressure 4.25 pF			Sample with terminal pressure 3 pF	
					4.25 → 3 (1)	3 → 2 (2)	2 → 0 (3)	3 → 2 (4)	2 → 0 (5)
Barbados	5	<0.25	50	T	3.5	5.5	12.0	3.0	10.5
				S	7.0	2.5	1.5	2.0	2.0
			1,000	T	3.5	6.5	9.5	2.5	8.5
				S	5.0	2.0	1.0	2.0	3.0
			10,000	T	1.5	5.0	7.0	3.5	9.0
				S	4.0	2.0	1.0	2.0	4.0
		1.00-4.76	50	T	3.5	5.5	21.5	3.5	20.0
				S	6.5	2.0	2.0	3.5	3.0
			1,000	T	2.0	6.0	17.5	2.5	19.5
				S	5.0	2.0	1.0	2.0	3.5
			10,000	T	1.5	6.0	11.0	4.0	16.0
				S	5.0	2.0	1.0	2.5	3.0

T = Total water potential from water retention

S = Swelling pressure

is probably also different for these two conditions. Bond formation is apparently small in water retention studies, as shown by the large amount of water taken up in the lower pF range (Table V-10), but in swelling pressure, water taken up in that range was very small.

Amount of water taken up increases with decrease in pF for both change in total water potential and change in swelling pressure for the sample rewetted from pF 3.0, but not for reswelling from pF 4.25. This difference in swelling from pF 3 and pF 4.25 has already been pointed out in section V-2, and is due to the degree of formation of aggregate-aggregate bonding. Higher rate of water taken up on decrease in total water potential for the sample rewetted for pF 4.25 was explained by more swelling of the aggregates for these samples. This further indicates the absence of aggregate-aggregate bonding during drying under no load.

The anomaly of change in water content due to change in total water potential being smaller than in swelling pressure results from the larger inter-aggregate pores which are filled with water in swelling pressure measurements but are emptied in water retention measurements. This is verified by the observation that these anomalies occur for samples with larger inter-aggregate pores.

4-3. Conclusions.

Inter-aggregate pore volume determines the geometry factor, which was different between loading and drying at the same equivalent pF value. Aggregate rearrangement was greater under the loading, as long as aggregate-aggregate bonds were not formed. Water content was higher in swelling pressure than in water retention measurements in higher pF range. This was due to emptying of inter-aggregate pores in the latter. The geometry factor was also different for water retention and swelling pressure of the undisturbed soil.

The difference of the change in water content with change in pF value increased with decrease in pF value, with decrease in compaction levels used in preparing the samples, and with increase in aggregate size. This was more obvious at the low pF range, pF 0.-2.0. Anomolies in higher pF range were due to water in large inter-aggregate pores.

The water content increased with decrease in pF for total water potential and for swelling pressure, except for the swelling from a terminal pressure of pF 4.25. It was thus definitely concluded that formation of aggregate-aggregate bonds was not important in drying to pF 4.25 under no load.

Aggregate arrangement contributes to retention of water in low pF range, but swelling pressure is dominant in the higher pressure range, pF 3.0 - 4.25, in which usually more than 50% of the swelling occurs. The importance of swelling pressure above pF 3.0 was supported by Quirk and Panabokke (1962).

5. Relationship Between Volume Change and Water Retention for Clay Soil Aggregates.

5-1. Theoretical Considerations.

Warkentin (1962b) considered that if clay soil is fully saturated, there are no air-water interfaces within the soil sample, and any water uptake is by swelling forces. In section V-1, it was shown that measured volume change in the low pF range was largely normal volume change. Only at higher pF values, where the soil is unsaturated, can a change in water content be caused by a change in area of the air-water interface. This would lead to the conclusion that swelling pressure prevails at the low pF range and capillary force is predominant in the higher pressure range.

The measurements of swelling pressure, on swelling from a terminal pressure pF 4.25 (c.f. Table 4A), however, show that most swelling takes place above pF 2.0. The contradiction between these two approaches shows that one must consider swelling and shrinking due to interaction of diffuse ions layers and also due to aggregate and/or particle rearrangement originating from this interaction. Interaction of ion layers results in swelling pressure but aggregate rearrangement changes the capillary force. Therefore, measurement of volume changes with changes in water content, $\Delta V/\Delta W$, includes both of these forces.

Relation Between Volume Change and Water Content Change.

Volume change as a percent of water content change is usually higher between pF 0 and 2 than between 2 and 4.25 (Table V-11). This is true for drying or for wetting. This indicates that aggregate rearrangement to allow volume change takes place more easily under saturated conditions.

Soil prepared at 50 psi showed the opposite result, probably due to an error made in volume measurement at pF 0. Even a slight pressure by the depth guage would cause an underestimation of the depth. Samples prepared

TABLE V - 11

VOLUME CHANGE AS PERCENT OF WATER CONTENT CHANGE OVER DIFFERENT pF RANGES.

Soils	Soils No.	Aggregate sizes, mm	Compaction level, psi	First drying, △V/△W		Wetting, △V/△W	
				pF 0 - 2	pF 2-4.25	pF 4.25 - 2	pF 2 - 0
Ste. Rosalie Clay	1	<0.25	50	97	61	19	76
			1,000	100	49	13	74
			10,000	100	42	33	65
		1.00-4.76	50	33	62	23	13
			1,000	41	71	62	24
			10,000	67	65	15	54
Macamic	2	<0.25	50	78	90	79	52
			1,000	100	72	53	67
			10,000	100	100	100	100
		1.00-4.76	50	18	67	23	9
			1,000	42	39	40	2
			10,000	63	62	69	26

Continued.

TABLE V - 11 (Continued)

VOLUME CHANGE AS PERCENT OF WATER CONTENT CHANGE OVER DIFFERENT pF RANGES.

Soils	Soil No.	Aggregate sizes, mm	Compaction level, psi	First drying, $\Delta V/\Delta W$		Wetting, $\Delta V/\Delta W$	
				pF 0-2	pF 2-4.25	pF 4.25-2	pF 2-0
Lamothe	3	<0.25	50	100	59	52	59
			1,000	100	83	80	91
			10,000	100	79	70	100
		1.00-4.76	50	31	38	7	4
			1,000	65	39	29	47
			10,000	89	48	37	73
Barbados	5	<0.25	50	100	78	56	83
			1,000	100	80	60	89
			10,000	100	73	43	82
		1.00-476	50	49	36	14	11
			1,000	56	90	74	34
			10,000	90	79	67	67

from larger aggregates at the lowest compaction level also showed higher values of $\Delta V/\Delta W$ in the higher pressure range, pF 2.0 - 4.25. Swelling or shrinking of aggregates takes place in this pressure range. This sample has larger inter-aggregate pores, and is unsaturated even at low pF value. The small value of $\Delta V/\Delta W$ between pF 0-2.0 results from the limited aggregate rearrangement because the sample was unsaturated.

The value of $\Delta V/\Delta W$ is generally higher on drying than on wetting. During drying, aggregate rearrangement occurs and develops small inter-aggregate pores, which are then filled during wetting grom 4.25 to 2.0. Although the swell limit is lower than the shrinkage limit (c.f. V-2) but water content change is small, causing $\Delta V/\Delta W$ to be smaller in lower pF region.

5.3. Hysteresis.

The hysteresis in water retention was examined further by correcting the wetting curve for the amount of volume change. The correction was made by considering the soil in wetting as having the same volume as in first drying, as shown in equation

$$W' = W + \Delta V \times s \qquad (V-14)$$

where: W' = Corrected water content in wetting, %

W = Measured water content in wetting, %

ΔV = Difference in volume between drying and wetting.

s = Degree of saturation based on wetting, %.

These corrected curves approach the first drying curve closely (Fig. V-7). A similar result was reported by Holmes (1955). The corrected curves in Fig. V-7, reveal that aggregate rearrangement is a major, but not the lone factor, contributing to hysteresis for clay soil aggregates. Ink-bottle pores are also involved. This was confirmed by the observation that corrected hysteresis was only occurred in the dryer region. The ink-bottle effect would not appear when the pores were fully saturated.

The corrected hysteresis showed the same trend as the uncorrected values; larger values were for the samples prepared at the lower compaction level. This further indicates an ink-bottle effect in addition to volume change causing hysteresis. The difference in the corrected hysteresis loops was due to the difference in the interior radii of the inter-aggregate pores. The radius at the neck of the ink-bottle was assumed constant, because the thickness of the water-shell around the aggregate was assumed to be the same for a given suction, independent of the compaction level for preparing the samples and of aggregate size (c.f. V-1-2). According to Laplace's equation and the principle of filling ink-bottle pores (Adamson, 1960), the larger the interior radius, the lower is the suction at which these pores fill, and the larger is the hysteresis loop.

This also accounted for the observation that at higher compaction levels, the loop was closed at higher pF values. It also explains the differences between the samples prepared from different aggregate sizes.

The importance of volume changes due to aggregate rearrangement contributing to hysteresis is further supported by the study of the undisturbed soil. As shown in Fig. V-13, the small closed hysteresis loop resembled the corrected hysteresis for the sample prepared from larger aggregates. This hysteresis was attributed to the ink-bottle effect because aggregate rearrangement for this undisturbed soil was very small.

5-4. Conclusion.

The hysteresis effect if mainly due to volume changes and partly to the ink-bottle effect in water retention.

Swelling or shrinking of aggregates is predominant in determining water retention from pF 2.0 to 4.25, but aggregate rearrangment becomes important at lower pF ranges, from 0 to 2.0. Volume change as a percent of water content change is generally much higher in drying than in wetting. This is a hysteresis effect.

CONTRIBUTION TO KNOWLEDGE

1. The compaction method devised provides reproducible soil samples in which the aggregates remain intact, and which have the desirable porosity. It also provides a method for determining average apparent bulk density of the aggregate, and for determining the two stages of compaction, inter-aggregate and normal.
2. Two stages of swelling, structural and normal are described. Total volume change, either shrinkage or swelling, is greater for samples from smaller aggregates. Two stages of volume change, normal and residual shrinkage and structural and normal swell, were always observed for the samples from smaller aggregate but normal volume change is not an important mechanism for the larger aggregate samples. Volume change limits, expressed as water contents, are lower for samples prepared at higher compaction levels.
3. Forces of water retention were found to vary with the clay minerals. Leda clay retained most of the water by swelling forces but kaolin retains water mostly by capillary forces
4. Inter-aggregate pore-size distribution or volume of small pores was found to be important for water retention at higher pF but development of inter-aggregate pore volume due to aggregate rearrangement was more important at low pF.

5. Swelling pressure, as a component of the total water potential, has been measured and evaluated for the aggregate samples.

6. Water retention by swelling for the range pF 0 to 4.25 was found to be dominant in the pressure range from pF 3.0 to 4.25, where more than 50% of the swelling occurred. The pressure range in which swelling prevailed depended upon the terminal compression which the soil had experienced.

7. The geometry factor, which is different for mechanical loading than for drying to the same equivalent pF value, is a proper variable contributing to total water potential.

8. Irreversible aggregate rearrangment causes hysteresis in volume change. Hysteresis in water retention is partly due to volume changes and partly to the ink-bottle effect.

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APPENDIX I.

Volumetric Measurement of Water Retention in a Temperature-Controlled System.

A miniature pressure plate apparatus was constructed to study soil water retention volumetrically. The design and operation were essentially the same as those for the apparatus for swelling pressure (c.f. IV-3-3, Fig. IV-2) except that the upper base of the latter had an extra outlet. The cross section of the apparatus after assembling is shown in Fig. App-1.

Changes in room temperature resulted in the condensate on the wall of the sample holder and interior of the upper base. This error in water retention measurements was overcome by a sensitive temperature control system shown in Fig. App. 2. The water in the water bath was circulated by a water pump. The temperature was controlled with a thermostat.

The apparatus and temperature control system were tested with Barbados 61-19 sample which was remoulded at the liquid limit and compressed at 12.5 psi. It was then air-dried and smoothed to a flat surface with a sharp knife. The air-dry sample had a density of 1.79 gm/cc. This sample was put in the sample holder and brought to saturation (pF 0) before it was assembled in

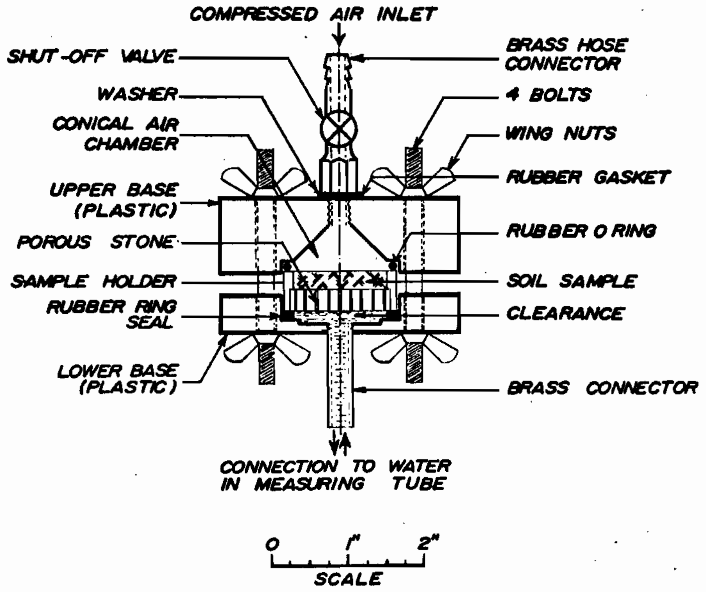

FIG. APP. 1, DETAILS OF PRESSURE PLATE APPARATUS ASSEMBLED FOR WATER RETENTION MEASUREMENT

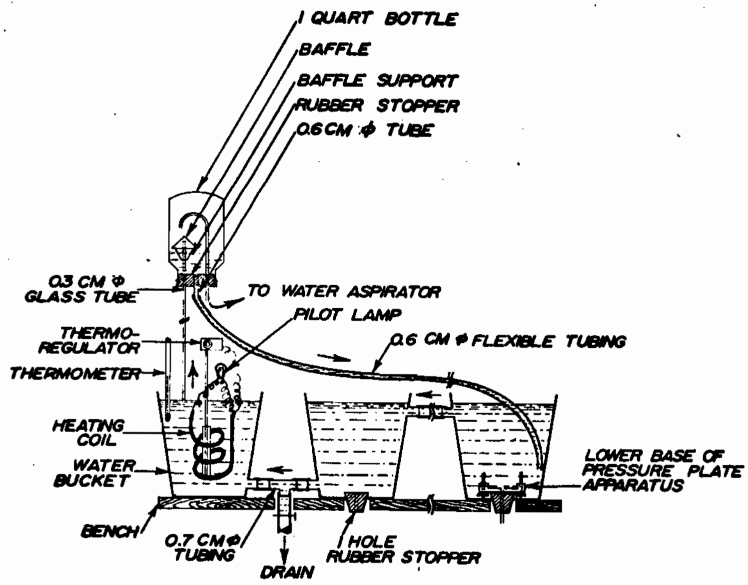

FIG. APP. 2, TEMPERATURE CONTROL BATH FOR SWELLING PRESSURE AND WATER RETENTION STUDIES the apparatus. The temperature was controlled at $29^{\circ} + 0.2^{\circ}$ C. Results are shown in Fig. App. 3 (solid line).

No leakage was found. It was, therefore, possible to study the water content changes volumetrically without the cumbersome "milking" process (c.f. II-7-1). The most important aspect of the design of this apparatus was that the sample holder rested on a flat rubber seal which effectively stopped air leaks through the contact between the porous plate and plastic holder. This apparatus is easily set up in the water bath which was observed to maintain constant temperature.

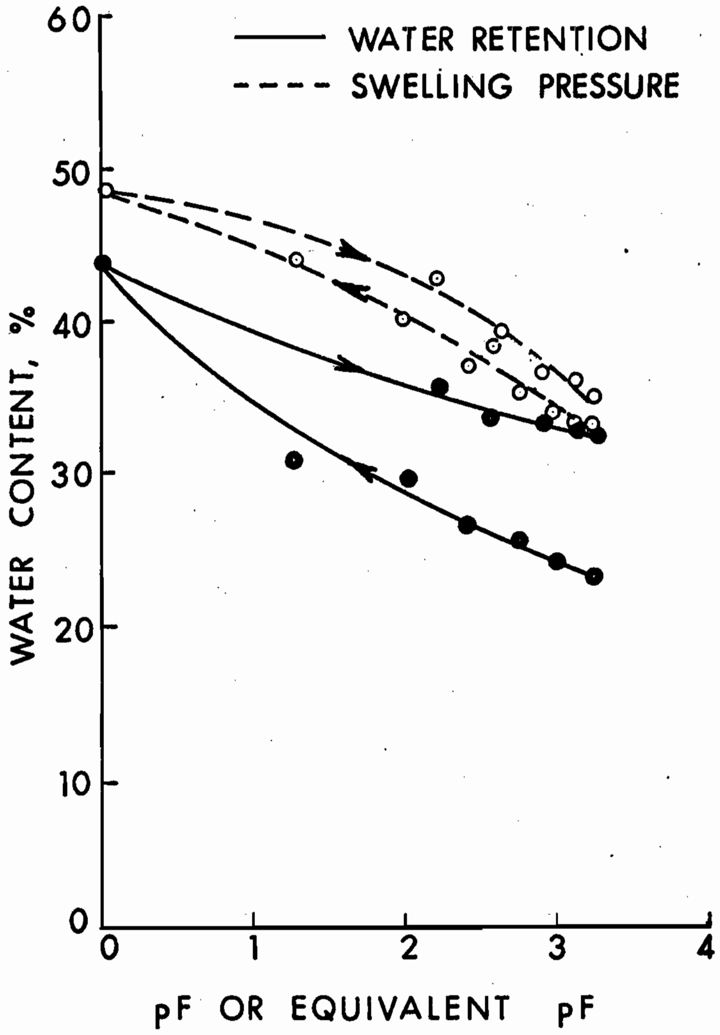

FIG. APP. 3, WATER RETENTION AND SWELLING PRESSURE, BARBADOS 61-10.

APPENDIX II

Methods for Swelling Pressure Studies.

The apparatus for measuring swelling pressure, shown in Fig. IV-2, was originally designed so that the sample could be saturated by filling water into the soil under vacuum. It was also designed to measure volume changes and swelling pressure at the same time.

The sample holder with a dry porous plate, on which air-dry soil was placed, was covered with a sheet of flexible rubber and assembled between the bases. The procedure for filling water in the conical space and capillary tube is described in section IV-3-3. Air was removed from the soil through a capillary tube attached to the opening in the lower base, and air pressure equivalent to pF 3.25 was applied at the top. After the air-water meniscus in the upper capillary tube was stationary, the position was marked on the tube, and water was allowed to fill into the soil under vacuum. The procedure for measurement of volume and water content change with change in swelling pressure are the same as described in section IV-3-3. The water content corresponding to each confining pressure was determined from the final water content of the sample on completion of the measurements.

The test sample was the same as used in Appendix 1. The time required to establish equilibrium at each surcharge pressure is shown in Fig. App. 4. Soil volume decrease after it reached a maximum on swelling in the first two stages, indicates particle rearrangement. The results are shown in Fig. App. 3 (dotted line). The differences between water retention and swelling pressure showed that the following factors must be considered in measuring swelling pressure and in comparing water retention and swelling pressure.

1. Hysteresis Effect: Part of the difference between the two measurements probably was due to a different hysteresis effect in the two methods even though preparation of the samples was exactly the same.
2. Saturation Effect: Some of the pores, with a diameter larger than 0.3 cm, were not filled at pF 0 in water retention studies, but all pores of the soil were filled in swelling studies.

The degree of saturation at pF 0 is dependent on the vacuum from which the sample is saturated. This was further investigated with a sample of No. 10 glass* beads by application of different levels of vacuum for filling in the water and also by using a sample which was saturated before being placed in the apparatus.

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* 95-100% of the beads with diameters 0.25 - 0.42 mm (manufacturer's specification),
Potters Brothers Inc., Carlstadt, N.J., USA.

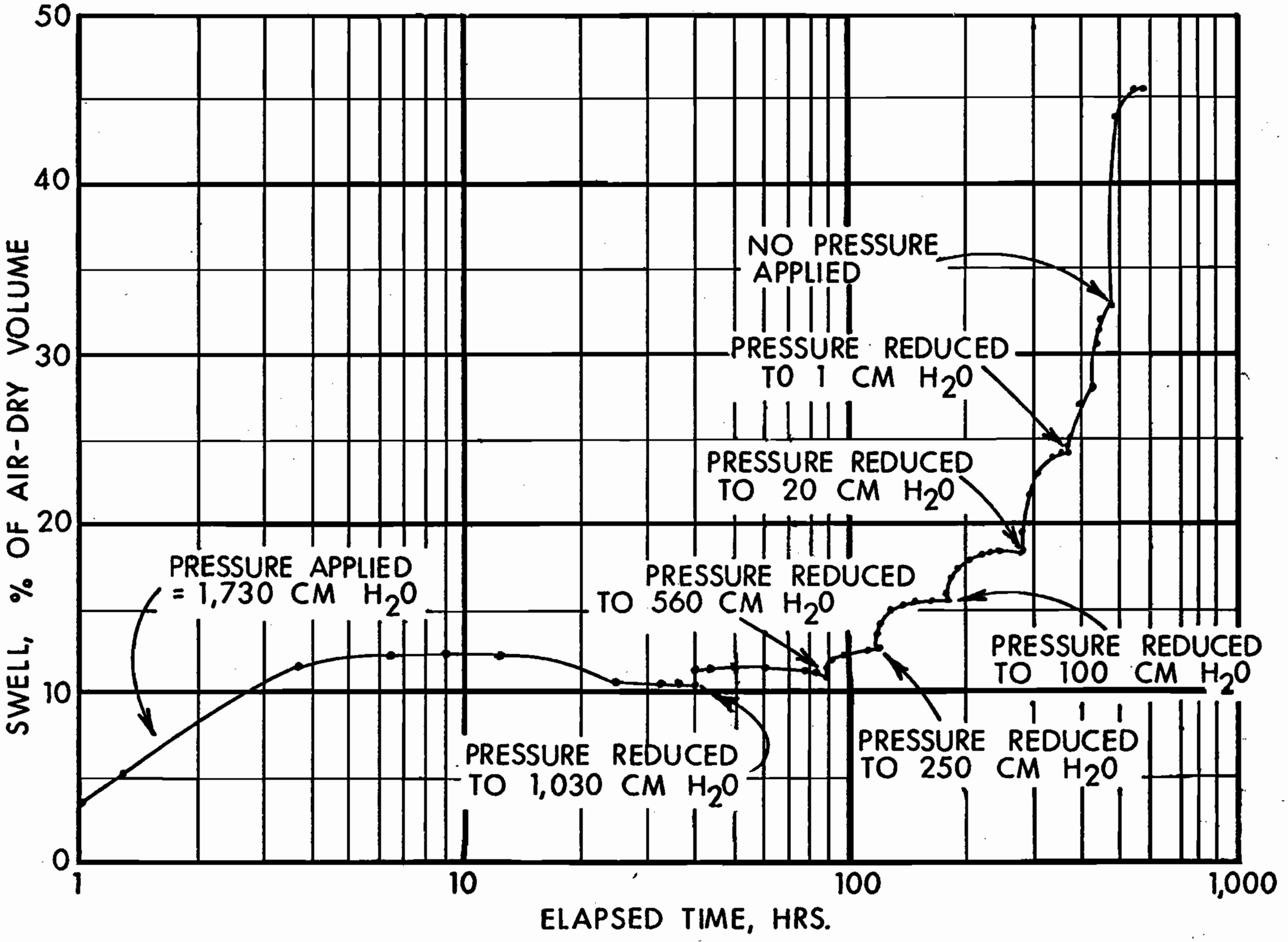

FIG. APP.4, TIME DEPENDENCE OF SWELLING, BARBADOS 61-10

TABLE APP. 1.

COMPARISON OF WATER CONTENT UNDER DIFFERENT VACUUM FOR FILLING WATER IN SWELLING PRESSURE STUDIES. SURCHARGE PRESSURE: 1 ATM.

Method of filling water	Water content at 1 atm., %
74 cm Hg suction	25.7
69 cm Hg suction	22.7
49 cm Hg suction	0.4
From saturation	23.1

The results (Table App. 1) suggest that other methods should be devised instead of the suction method. (c.f. section IV-3-3 and V-2-1).

APPENDIX III.

CONSTRUCTION OF AIR SATURATOR

Fig. App. 5 shows a cross section of the air saturator. This air saturator also detects air leakage in the apparatus for swelling pressure and water retention measurements (c.f. Fig. IV-1) by the presence of air bubbles coming out of the water column.

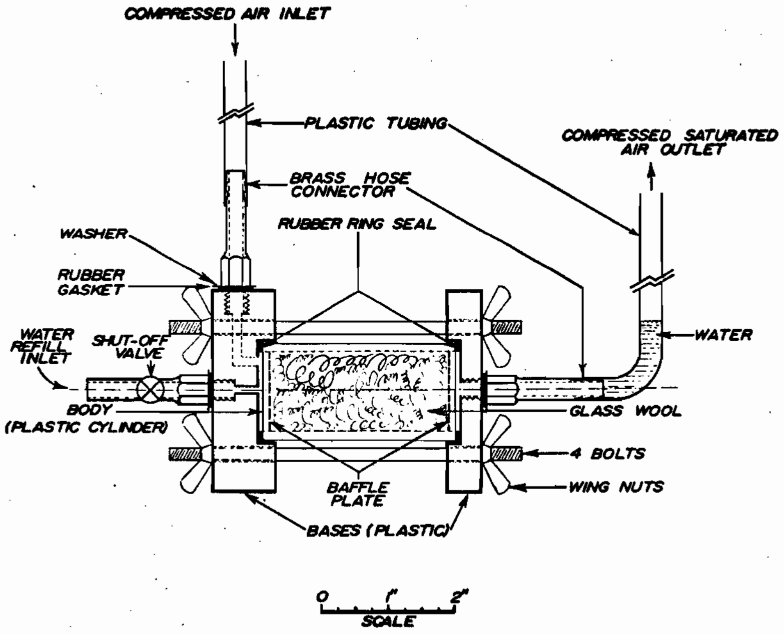

FIG. APP.5, DETAILS OF AIR SATURATOR WHICH SERVES AS LEAK INDICATOR