VOLUME CHANGES IN CLAY SOILS - SHRINKING AND SWELLING

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PREFACE

The problem of volume change in clay soils arising as a result of shrinking and swelling has been studied extensively by Dr. B.P. Warkentin of the Department of Agricultural Physics. Because of the need for a clearer understanding by soil engineers and research workers of this behaviour characteristic of clay soils, this report on Volume Changes in Clay Soils - Shrinking and Swelling is being presented as a Soil Mechanics Series.

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by

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Volume Changes in Clay Soils - Shrinking and Swelling

Clay soils typically undergo changes in volume with changes in water content; shrinking and cracking on drying and swelling on rewetting. This change will be seasonal in a climate with a dry summer, while smaller changes will result from alternate precipitation and drying periods. If the volume change is uniform it is not easily observed, and considerable vertical soil movements may occur without being recognized. Problems associated with volume changes usually arise from uneven shrinking or swelling, especially in the engineering use of soils to support loads. The cracking associated with shrinking is of concern for plant growth on agricultural soils. This may be beneficial in promoting aeration, or harmful in breaking roots and allowing extreme drying. Smaller cracks promote formation of soil structure units.

A large amount of shrinkage occurs when water-deposited clays are first dried. The amount of reswelling depends primarily upon the clay minerals. High-swelling clays containing montmorillonite show an almost reversible swelling and shrinking on rewetting and redrying, whereas the marine-deposited clays, especially those containing illite and chlorite, show an initial large volume decrease on drying with only a limited swelling on rewetting. The net decrease in volume after each drying and wetting cycle for the latter clays becomes smaller until an equilibrium is reached where swelling and shrinking occurs between constant limits. This reversible volume change between fixed limits is also found for surface horizons of agricultural soils which have undergone numerous wetting and drying cycles.

In the following sections the mechanisms of volume change and the soil properties determining the magnitude will be discussed.

Shrinking

If the volume of a saturated clay sample is measured as it is slowly dried, a relationship of the type shown in figure 1 is obtained between volume and water content. At high water content the slope of the line is 45°; for each unit of water lost the volume decreases by one unit and the soil remains saturated. This was termed normal shrinkage by Haines (1923). A soil sample need not be fully water-saturated to show normal shrinkage. Undisturbed samples taken from below the water table are usually less than 100 per cent saturated but the amount of the gas phase remains constant on drying, resulting in normal shrinkage. Figure 1 illustrates such a case; the theoretical line for complete saturation is shown below the shrinkage line for the sample. On further drying, the slope changes and air enters the voids at the shrinkage limit. A small amount of shrinkage, termed residual shrinkage, takes place on further drying. The shrinkage limit has been defined in several ways as shown by points A, B and C in figure 1. The water content at the shrinkage limit which has a physical significance is at the point of unsaturation, point A. The other two are plotting conveniences, although point C gives total shrinkage.

The force causing shrinking arises from the pressure difference across the curved air-water interfaces of the voids at the boundaries of the sample. As water evaporates from the surface a curved interface is formed in the voids at the surface with a lower pressure on the convex inner side, and water is drawn from inside the sample due to this pressure difference. As long as this force exceeds the resistance of the clay particles to closer approach, i.e. to shrinkage, the sample remains saturated with a volume decrease equal to the water content loss. This is the range of normal shrinkage. Eventually a condition is reached where particle interaction restricts shrinkage and further increments of water removed are partly replaced by air. Some additional, residual, shrinkage occurs due to further rearrangement and in some cases bending of particle

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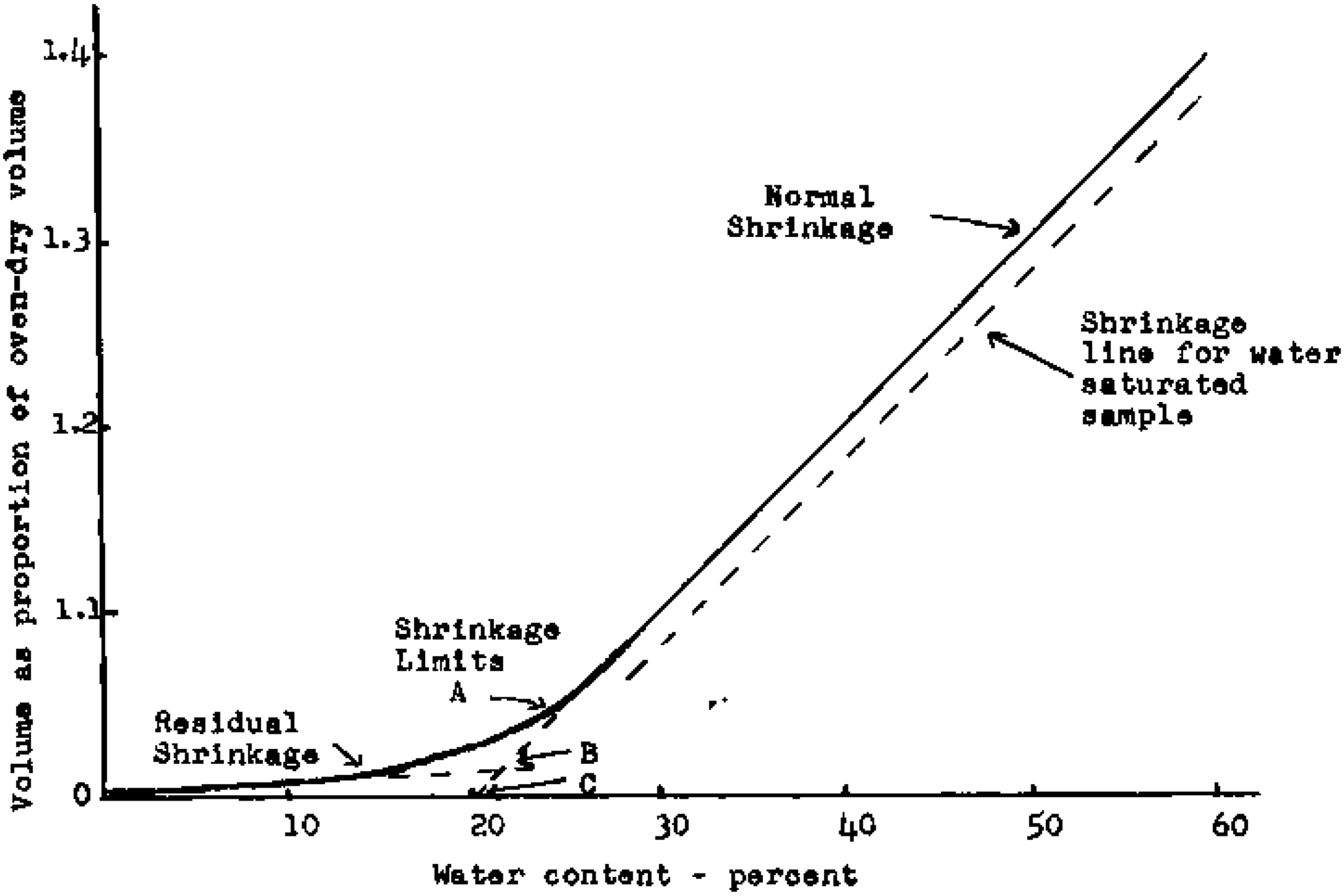

Figure 1 Generalized shrinkage curve for a clay soil

This particle interaction resisting closer approach may be direct contact of particles or of hydration layers, or it may be interparticle repulsion due to forces causing swelling. This interaction is discussed in more detail in the chapter on clay minerals.

Soil characteristics affecting shrinkage:

Characteristics of the shrinkage curve vary with the nature of the soil. Total shrinkage increases with increasing initial water content, which is in turn a function of clay minerals, mode of geological deposition, the depositional environment which determines both particle arrangement and overburden pressure, and degree of weathering. High-swelling clays containing the mineral montmorillonite have high initial water contents. Sediments deposited in salt water have a random or edge-to-face association of particles with large volumes of trapped water. Under these conditions high initial water contents are found in the absence of high-swelling clays. Overburden pressure consolidates sediments and decreases the water content. Repeated cycles of wetting and drying have overcome the influence of depositional environment for surface soils, and total shrinkage depends primarily upon the clay minerals.

Total shrinkage is less for random particle arrangement as shown by shrinkage measurements for two clays in figures 2 and 3. When shrinkage for the kaolinite samples in figure 3 is compared at the same water content, the dispersed sample with more parallel particle arrangement shows a much larger change than the flocculated sample with random particle arrangement. The final dry densities must then also be different. The lower densities for random particle arrangement are shown in table 1 for the kaolinite and for the marine-deposited Leda clay which contains some chlorite and illite.

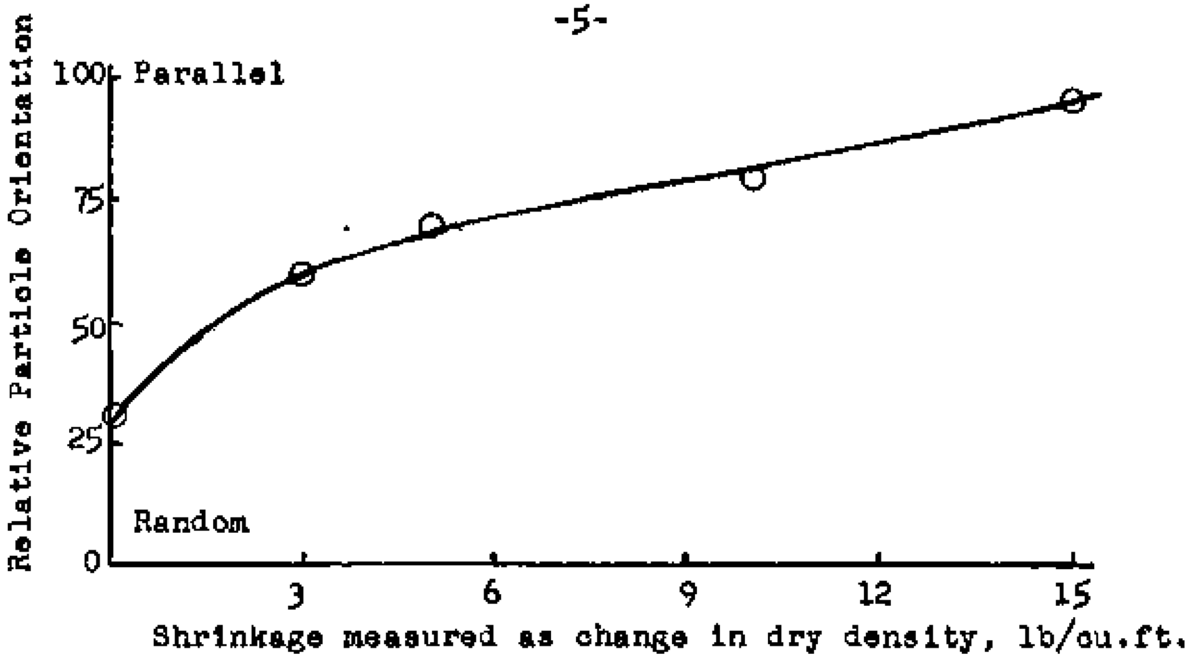

Figure 2 Measured shrinkage of compacted Boston clay as a function of particle orientation. Parallel arrangement is 100% orientation and random arrangement is 0% (from Lambe, 1960)

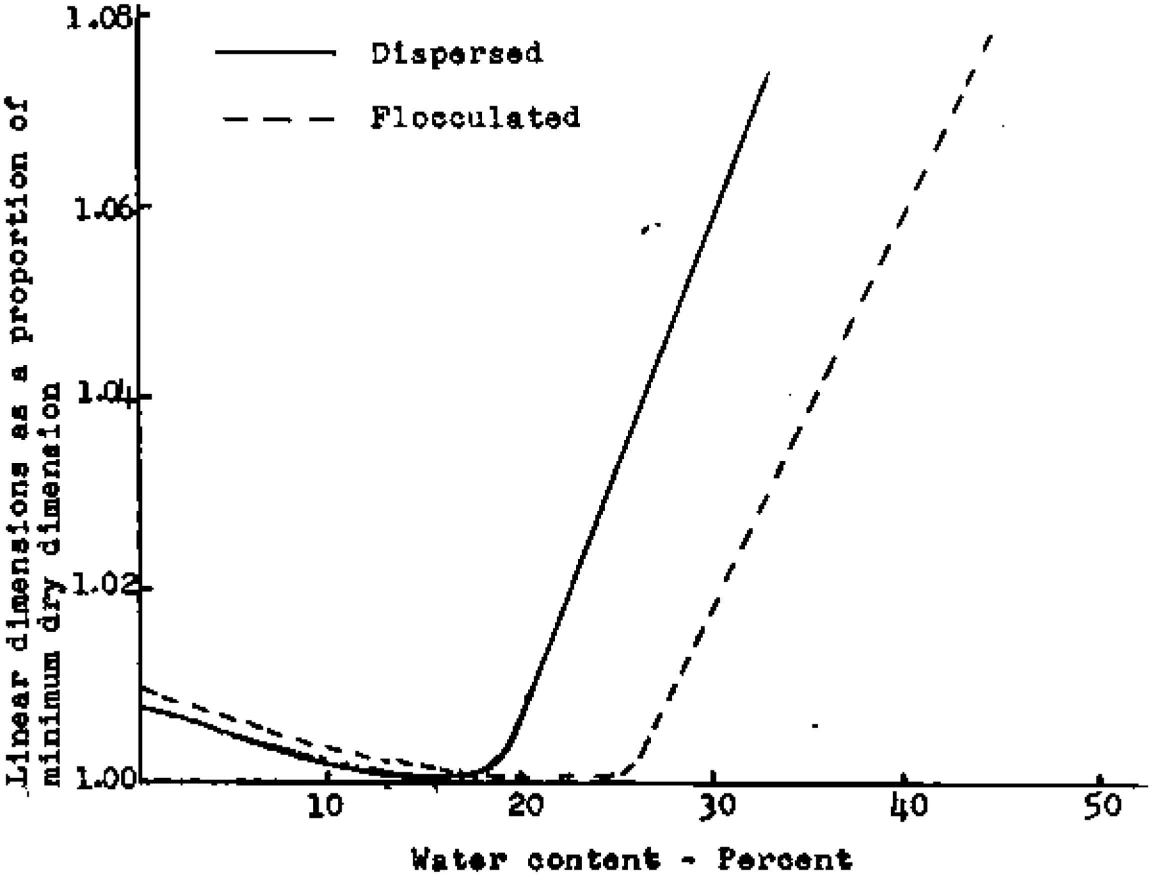

Figure 3 Measured shrinkage curves for kaolinite with flocculated (random) and dispersed (parallel) particle arrangement. (Warkentin, 1961)

Table 1. Shrinkage limit and oven-dry volume weight as influenced by particle orientation.

Clay	Qualitative Orientation	Water Content at Shrinkage limit(%)	Oven-dry Vol Weight,(gm/
Dispersed Kaolin (pH10)	parallel	19	1.70
Flocculated Kaolin (pH4)	random	26	1.52
Remoulded Leda	partly parallel	20	1.77
Undisturbed Leda	random	30	1.64

The water content at which unsaturation occurs, the shrinkage limit, also depends upon the arrangement of particles in the clay soil and upon the clay minerals. (Table 1 and Figure 3) A more random arrangement increases the shrinkage limit, a more parallel arrangement decreases it. Particle interaction leads to unsaturation at a higher water content for the random edge-to-face arrangement of particles than for the more parallel arrangement. This additional volume is trapped between particles in the random arrangement. The particle arrangement in flocculated and in dispersed clays is discussed in chapters 3 [illegible]

Kaolinite usually shows a residual swelling rather than shrinking. (Figure 3) This is probably due to elastic rebound of particles after the connecting water films are broken.

Sand and silt-size particles decrease total shrinkage because they decrease the water content at saturation. The influence of texture on the water content at the shrinkage limit depends upon the clay mineral. Figure 4 shows the decrease in total shrinkage and the change in shrinkage limit as 100μ average diameter glass beads are mixed with < 2μ montmorillonite and Leda clay. These measurements are for a simplified system where the coarse particles are of one size. Total shrinkage expressed per weight of clay should be independent of the proportion of clay to sand-size material until the volume of clay is less than the volume of

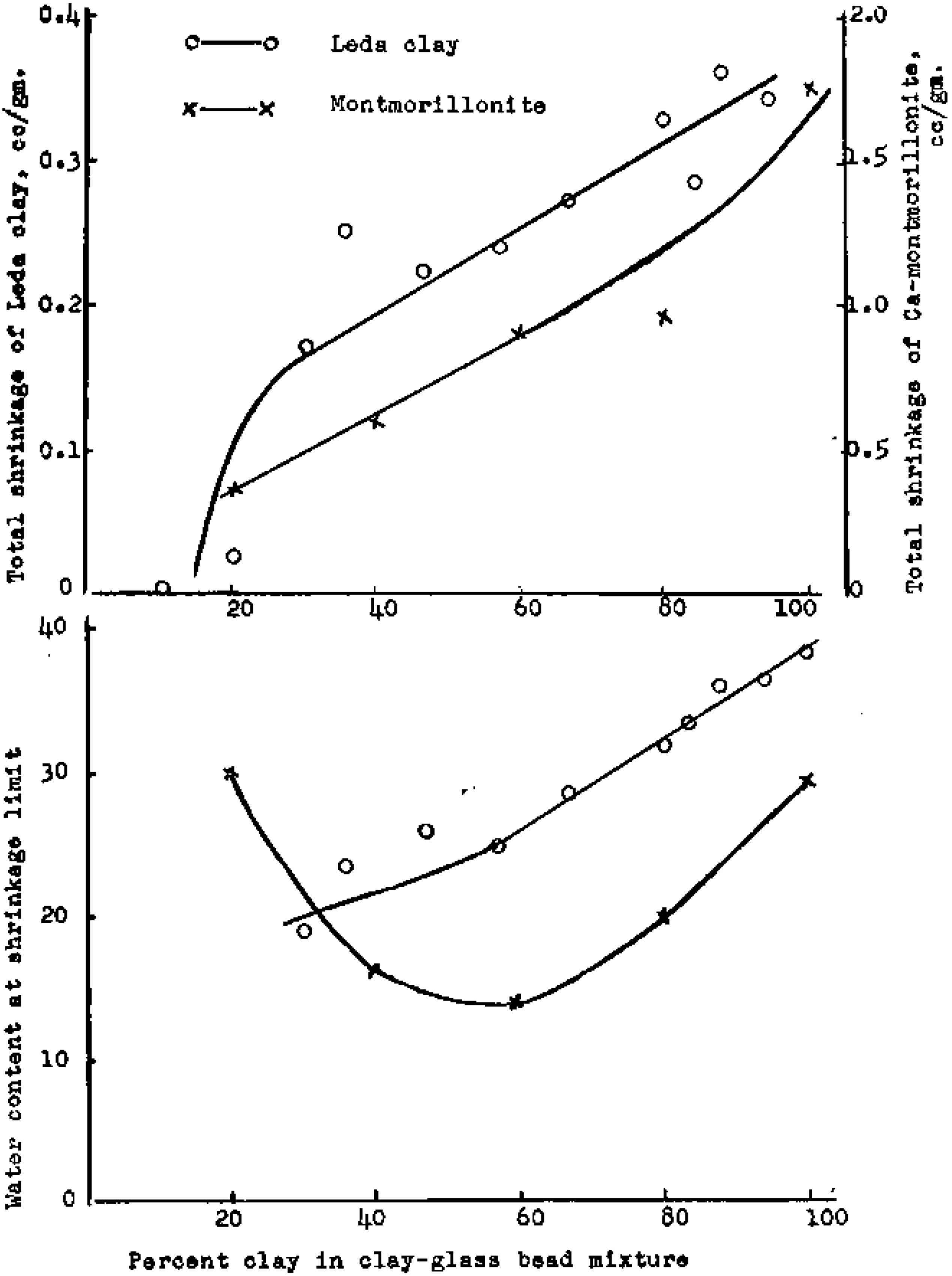

Figure 4 Influence of sand-size particles on total shrinkage and shrinkage limit of two clays. (de Jong, 1962)

pore space between the coarse particles when they are touching. At this proportion of clay to sand, shrinkage should cease. Figure 4 shows this effect semi-quantitatively. The slope of the shrinkage line is approximately one; total shrinkage for 50% clay is about one-half that for 100% clay. At about 25% Leda clay, shrinkage drops sharply to almost zero. This is in line with the calculated value of 28% (de Jong, 1962). For montmorillonite, shrinkage is expected to stop below 15% clay. Even for the spherical glass beads it is difficult to check this quantitatively. because the packing of the spheres and the orientation of clay particles in relation to the spheres and to each other are known only within limits (de Jong, 1962). The clay fills the voids between the larger particles but also forms oriented layers around them.

The water content at the shrinkage limit also decreases nearly in proportion to the amount of the larger particles down to 50% clay. Below this clay percentage, the larger particles interfere to allow unsaturation. The increase in water content at the shrinkage limit for calcium montmorillonite with more than 50% glass beads has not been satisfactorily explained.

Shrinkage will be anisotropic if the tabular clay particles have a preferred orientation in the sample. This occurs in sediments deposited under lacustrine conditions, or where overburden pressure has oriented the particles during consolidation. Vertical shrinkage exceeds horizontal shrinkage and the dimensional shrinkage is not linear with decreasing water content. This is shown in figure 5 for an undisturbed sample of a glacial lacustrine clay containing montmorillonite and illite. For a clay plate with a longer horizontal than vertical dimension, shrinkage will be greater in the vertical dimension even if a water film of uniform average thickness surrounds the particle, because the proportion of water to solid is greater along a line in the vertical direction. In addition interparticle repulsion is greater

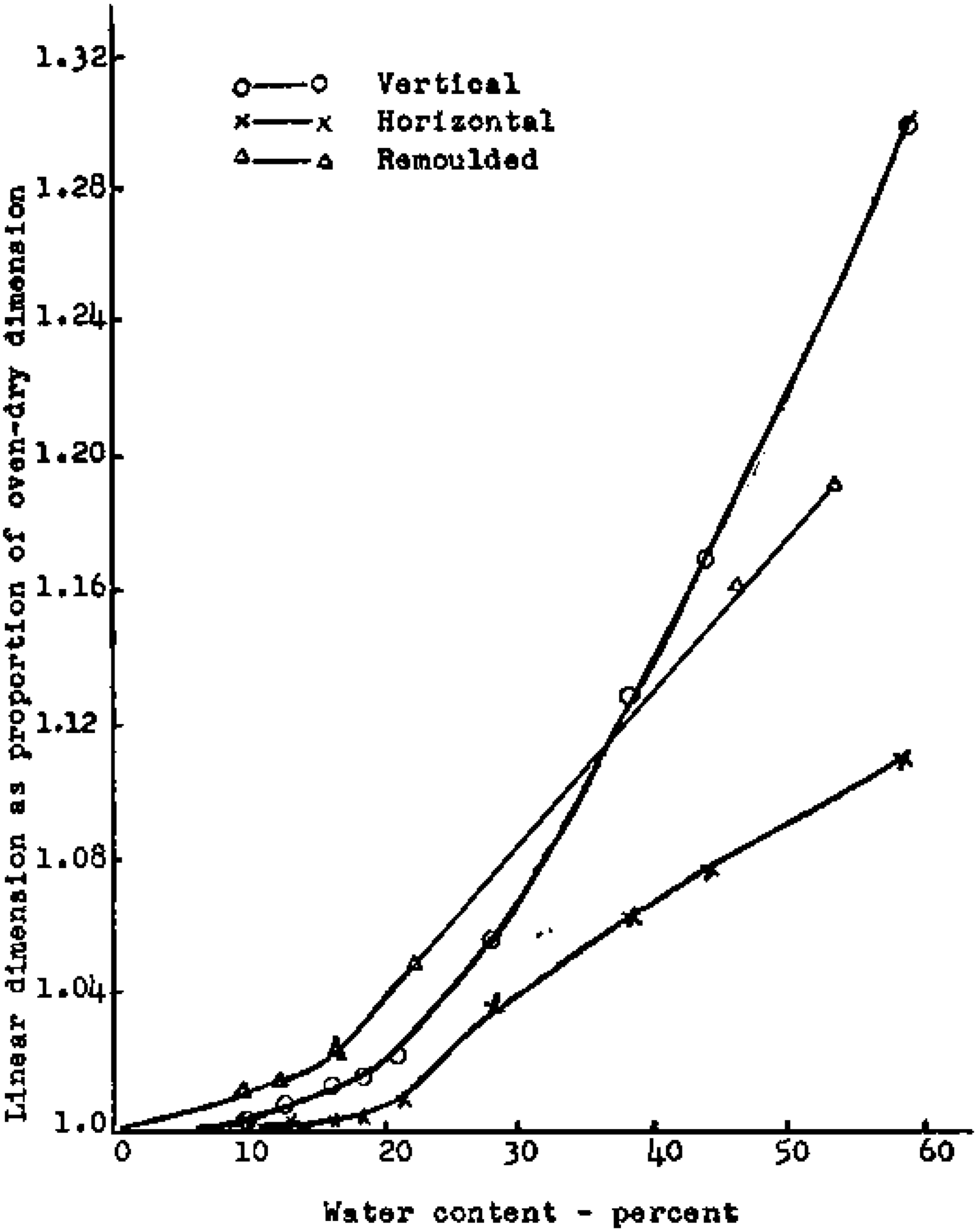

Figure 5 Shrinkage curves for a lacustrine clay with partial orientation of particles. (Warkentin and Bozozuk, 1961)

between flat surfaces, resulting in a larger average distance between fla surfaces than between edges. As seen from the slopes of the dimensional shrinkage curves, the rate of vertical shrinkage gradually decreases while the rate of horizontal shrinkage increases until the shrinkage limit is reached. If the volume is calculated from the dimensional shrinkage it can be shown that normal shrinkage occurs. Shrinkage for the remoulded sample is isotropic. Shrinkage of weathered surface soils and soils with random particle arrangement will be isotropic. Orientation of particles can be induced in samples by one-dimensional consolidation or by drying from suspensions. Such samples will also show anisotropic shrinkage.

Surface soils with a low clay content or with a well developed crumb structure may show no range of normal shrinkage as the water conten is decreased. The degree of unsaturation increases with decreasing water content and hence the total shrinkage is lower than it would be for normal shrinkage. This is typical for soils with a wide range of void sizes where water, especially in the largest voids, is held by capillary forces. In a clay soil with a well developed crumb structure these large voids are between crumbs and they become unsaturated at low soil suction values. The voids within the crumbs, where water is held by the forces associated with swelling, remain saturated up to high values of suct In these soils the first increments of water loss are accompanied by a volume decrease less than the volume of water lost. This has been termed *structural* shrinkage (Stirk, 1954). As drying proceeds, normal shrinkage may occur when the water within the crumbs is lost.

Since the shrinkage curve shape depends upon particle arrangement, which is the most important factor in soil sturcture, it has been suggested that the change in this curve on remoulding or puddling a sample be used as a measure of soil structure (Lauritzen, 1948). When a surface soil with well-developed structure is remoulded, the larger voids disappear. The range of normal shrinkage increases while the water content at the shrinkage limit decreases. For clay subsoils which do not contain large voids the change on remoulding may be very small. The change in the shrinkage curve will depend upon the original and the remoulded particle arrangements.

Measurement of shrinkage for samples:

Shrinkage curves have been experimentally determined by measuring either linear dimensions or volume as a wet sample loses water. The average water content can be easily obtained by weighing the sample. There is the problem of ensuring that the sample has a uniform water content, since drying proceeds at the surface and water must move from inside the sample. This can be accomplished by slow drying of small samples or by allowing the samples to equilibrate in a saturated atmosphere after a short drying period. Accurate measurement of the volume is more difficult.

Haines (1923), in his classical work defining the characteristics of the shrinkage curve, measured volume by displacement of mercury in a special pycnometer bottle. If the samples are plastic, the required handling will deform the sample; dry samples may break under the pressure. Also the mercury becomes contaminated with soil, and there is the general undesirability of handling mercury extensively. However, this remains the most accurate method of measuring volumes unless very regular sample shapes can be obtained. Volume can be determined by displacement in water if the sample is coated to prevent water entry. Paraffin and films of plastic, obtained by evaporating off the solvent, are used. The disadvantage is that the sample can be used for only one measurement. Several samples must be used to define the shrinkage curve, and variability of soil samples must be taken into account. Volume can also be measured if the voids are filled with a liquid such as kerosene (Stirk, 1954).

Linear dimensions of the sample, from which volume shrinkage co be calculated, were measured in early studies of shrinking, (see Keen, 19 More recently, the magnified image of a cube sample projected on a screen has been measured (Croney, Coleman and Black, 1958). Linear dimension changes have also been determined from the changing distance between two marks on a sample face, either pins or marks scratched into the sample. The distance between points on the surfaces of small samples can be measured with a travelling microscope. If the sample has a thin wafer shape, the water distribution within the clay on drying is more easily kept uniform (Warkentin and Bozozuk, 1961).

The shrinkage limit defined as point C in figure 1 is the water content which would be required to fill the voids present in the dry sample. This can be obtained from the volume weight if the density of the mineral particles is known or measured. Volume weight can be determined by measuring the volume, or the weight, of mercury displaced by the sample in some form of pycnometer bottle or constant volume vessel in which the dry sample is immersed in mercury. Alternatively, the sample can be coated with a water resistant material and a measurement made of the amount of water displaced (Russell, 1949). This shrinkage limit may also be estimated by measuring the linear shrinkage of bars of soil made to different water contents and dried. An extrapolation to zero shrinkage gives the water content at the shrinkage limit, C.

Soil characteristics affecting swelling:

Volume increase due to swelling is distinguished from water content regain on rewetting. An unsaturated soil can take up water, replacing air in the pore space with water, without a consequent increase in volume. This occurs typically for sandy and silty soils. Swelling requires a force of repulsion separating clay particles as the water content increases.

The amount of swelling depends upon the clay minerals and their arrangement or orientation in the clay soil as well as upon physical-chemical properties such as valence of exchangeable cations, pore-water salt concentration and cementing bonds between clay particles. Swelling increases with increasing surface area of the clay and with decreasing valence of the exchangeable cation. Specific differences between clays within a mineralogical group give rise to smaller differences in swelling.

Surface area of a clay depends more upon thickness of the tabular particles than upon the other dimensions. It decreases from the thin particles of montmorillonite to the much thicker kaolinite particles as shown in table 2. Monovalent exchangeable ions, such as sodium, cause greater swelling than divalent calcium ions. Highly acidic clays have polyvalent aluminum as exchangeable ions, with a consequent low swelling. An increase in pore-water salt concentration decreases swelling of the high-swelling clays, especially if monovalent ions are present. Where much exchangeable sodium is present in soils, swelling and dispersion are reduced at higher salt concentrations. Usually swelling is undesirable but for purposes such as lining irrigation canals montmorillonite with exchangeable sodium is used.

Table 2 Size and swelling properties of clay mineral groups

Mineral	Approximate Thickness (A)	Surface Area m²/gm	Observed Volume Change
Montmorillonite	20	800	high
Illite	200	80	medium
Kaolinite	1000	15	low

Cementation between particles is usually considered a major factor in limiting volume regain of clays on swelling. Iron hydroxides, carbonates and various organic molecules are the cementing materials.

It is not clear in many cases whether these materials bond between particles to form a restraint to swelling or whether they affect the physical-chemical properties of the surface in such a way as to reduce the swelling force. Iron salts dried into a clay can markedly reduce swelling; this occurs in some "non-swelling" montmorillonites. In many studies showing increased swelling after removal of iron oxides, the soil was left with sodium as exchangeable ion, and this may have been the caus of the increased swelling (Prebble and Stirk, 1959). Particle arrangement, which influences swelling, is also altered in the chemical removal of the cementing materials.

The decrease in swelling caused by cementing materials will be greater for weathered clays which have undergone cycles of wetting and drying. Most of the mechanisms for cementation depend upon dehydratio of colloidal material to form bonds between particles. Baver (1956) has summarized the studies of cementation and aggregate stability in surface soils. Measurements of volume regain for two unweathered clays in figure 6 show that removal of iron oxides and carbonates resulted in only a small increase in swelling of the high-swelling clay and decreased the volume regain of the low-swelling clay. This decrease was likely due to the more thorough remoulding during chemical removal of cementing materials. The change in particle arrangement caused by remoulding had the largest influence on swelling.

The difference in the water retention curves of disturbed and undisturbed clays discussed in chapter —— show the influence of particle arrangement on water content and swelling. The direction of the change in swelling with changing particle arrangement seems to depend upon the type of clay. For high-swelling clays such as sodium montmorillonite, swelling against restraint is greatest for parallel particle orientation (Warkentin, 1961). The swelling volume and swelling

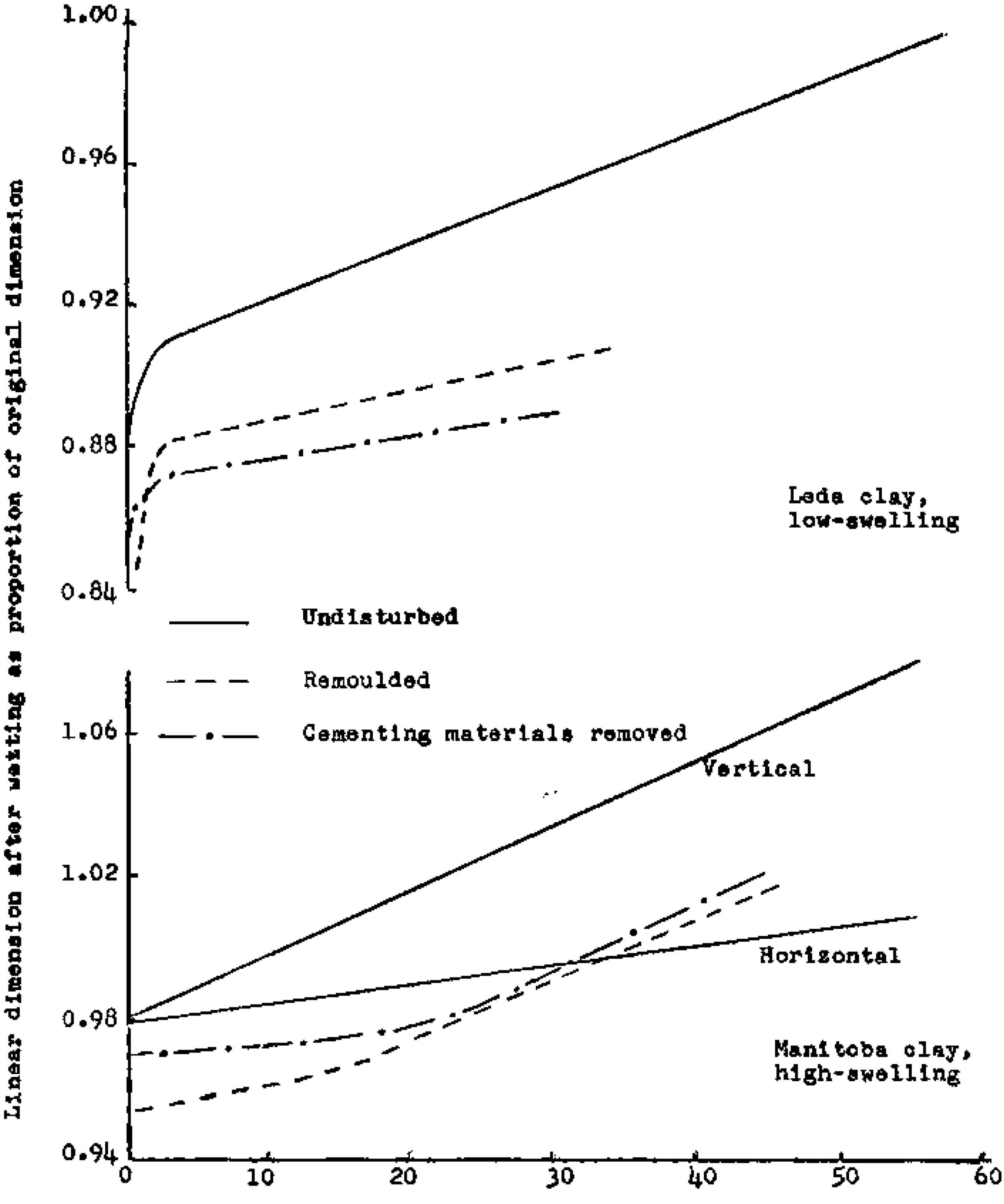

Figure 6   Measured swelling of two clays as influenced by remoulding and removal of cementing materials. (Warkentin, 1961, Warkentin anc (Bozozuk, 1961)

pressure for most natural soils is greatest for random or flocculated particle arrangement (Seed and Chan, 1959). Figure 6 shows the effect of remoulding on volume regain for the low-swelling Leda clay and for a high-swelling Manitoba clay. The Leda clay has a flocculated random particle arrangement; remoulding results in more parallel particle arrangement over short distances and volume or water content regain is decreased. The high-swelling clay is partially oriented in the natural state; remoulding changes the orientation but it is not known whether the remoulded orientation is more or less parallel from particle to particle. An explanation for the influence of particle arrangement on swelling is discussed in the section on mechanism of swelling.

Swelling occurs primarily in the plane perpendicular to the flat surface of the clay particle, so swelling and shrinking are anisotrop for clays with an overall orientation of particles. Samples of high-swelling montmorillonite orientated by pressure or by drying from dilute suspension show horizontal swelling which is only a few per cent of the vertical swelling. Anisotropic swelling of a sample of the Manitoba clay is shown in figure 6. Swelling in the horizontal direction does not reach the original dimension, but vertical swelling exceeds the original vertical dimension. This difference will be discussed further in the section on mechanism of swelling.

Swelling pressure of soils:

Swelling clays exert pressure against a confining load when water is available for a volume increase. This pressure exceeds usual loading, so that volume change is decreased but not prevented by the structures which the soil supports. The magnitude of these pressures can be seen in table 3 where some measured pressures reported in the literature for soils are listed. Except for high-swelling clays, the swelling pressure

Table 3. Some values of swelling pressure of soils reported in the literature.

Soil	Swelling Pressure Tons/sq.ft.	Reference
Black Cotton Soil	3	Palit, 1953
Sandy clay		
Random	3	Seed & Chan, 1959
Oriented	0.1	
Houston, 2 μ clay	0.2	Davidson & Page, 1956.

decreases rapidly with small volume increases and the amount of swelling under load is usually small.

The dependence of swelling pressure on volume change makes a precise measurement of swelling pressure difficult, and unless special precautions are taken in the measurement to prevent volume change, measured pressures will underestimate the swelling pressure. A pressure measuring device is required which is actuated by the lowest volume changes, an ordinary oedometer allows too much volume expansion. The normal rebound curve, therefore, underestimates the swelling pressure at any void ratio.

A number of devices for measuring swelling pressure have been described in the literature (e.g. Palit, 1953). Typically they consist of a rigid cell confining the sample, with access to water through a porous stone or water-permeable membrane at one end and a solid or fluid piston at the other which allows a pressure measurement. Swelling pressure is measured as the restraint which has to be applied to the piston to prevent movement. Swelling pressure in several directions can be measured if the confining cell is fluid rather than a rigid wall.

The swelling pressure measured in these devices is not developed instantaneously. The results given by Palit (1953) show that the pressure increases approximately exponentially for a number of weeks.

Two factors contribute to this increase. If an initially air-dry sample is being tested, the complete hydration of clay mineral surfaces on wetting will require time. Emerson (1955) has shown that a clod of soil containing illite continues to take up water for many weeks. The full swelling pressure will not be manifested until hydration is complete. Secondly, most pressure measuring devices depend upon some volume change for actuation. This expansion of the sample requires that water move into the clay. Since the permeability of swelling clays is low the necessary distribution of water under small pressure differences will require considerable time.

Measured swelling pressures for pure clays in figure 7 show the influence of surface area and valence of exchangeable ion. The sodium-montmorillonite shows much higher swelling pressures than the other clays. The illite has a lower surface area, and the divalent calcium ion also decreases swelling.

Mechanism of swelling:

Swelling, or a volume increase on wetting, requires an attraction of water to the clay to provide an effective repulsion between clay particles. From thermodynamic considerations, as long as the free energy of the water in the soil is less than that of free water, water will move into the soil. Water fills the voids of a sand without a significant increase in volume, but for clays this wetting usually results in a volume increase and the reason is sought in the surface properties of clays.

Different mechanisms have been suggested for water sorption causing swelling. There is evidence from many experiments that water at the clay mineral surface has a structure, giving it properties different from free water. This has been generally termed "bound water". Forces at the surface cause an ordering of water molecules which may extend some distance from the surface and provide the inter-particle repulsion required for swelling (Low, 1958). Another explanation is that the repulsion arises from the osmotic pressure due to the concentration of exchangeable ions. These concepts are discussed in more detail in the chapter on properties of clay minerals. When two clay particles are sufficiently close for their diffuse ion-layers to overlap, the ion concentration in the plane midway between particles is greater than that in free water, and water moves between the particles. As the particles are separated, the difference in ion concentration is lowered and the repulsion or swelling pressure decreases. A third mechanism to account for small amounts of swelling measured on release of pressure is elastic recovery, both unbending and rearrangement of particles. Evidence exists to support all three of these mechanisms.

It is of interest to calculate the amount of swelling predicted by the proposed mechanisms and to compare the values with measured swelling. The swelling volume is difficult to calculate because it depends upon the balance between forces of attraction and repulsion. The driving force decreases as swelling increases and the final volume is sensitive to outside influences. Swelling pressures at volumes less than completely swollen are more easily handled because they depend upon the larger net forces of repulsion.

The properties of bound water cannot be calculated with the present knowledge, so the influence of various clay properties on swelling cannot be predicted in this way. Osmotic swelling can be calculated with certain simplifying assumptions discussed in chapter ——. These assumptions severely restrict its application in predicting swelling of clay soils, but it will be seen that where the theoretical model is valid, the calculations can predict observed swelling pressures.

The following discussion will be from the standpoint that bound water accounts for the first few water layers taken up on swelling and that extended swelling, especially with monovalent ions, is osmotic in nature.

The swelling pressure is calculated as the osmotic pressure due to the difference in concentration of ions between clay particles and in the outside pore water. This gives only the force of repulsion, and will be in error in predicting swelling by the amount of any forces o attraction. The model assumed is that of charged, tabular particles in parallel arrangement with diffuse layers of exchangeable ions which overlap, resulting in an ion concentration between particles higher than that away from their influence. The properties of the system which must be known to make this calculation are: specific surface area of the clay, nature of the exchangeable ions, concentration of ions in the pore water, and exchange capacity or surface density of charge of the clay.

For water contents below 60 per cent on a weight basis, and pore water salt concentrations below 0.001 M, the concentration of anions between the clay particles can be neglected, and the calculation is simplified. The concentration of cations at the midpoint between two interacting plates cannot be measured. It can be calculated from the model (Langmuir, 1938) and is given by:

$$C_c = \frac{\pi^2}{z^2 B (d + x_o)^2}$$

where: C_c = concentration of cations midway between two clay plates
z = valence of exchangeable ions
d = half distance between two clay plates
x_o = correction factor of 1 - 4Å depending upon ion valence and charge density of clay
B = 10^{15} cm/m mole. This constant depends upon temperature and dielectric constant.

The swelling pressure can then be calculated from the van't Hoff equation, which for monovalent ions is:

$$P = RT\,(C_c - 2C_o)$$

where: P = calculated swelling pressure
R = gas constant
T = absolute temperature
C_o = concentration of salt in the pore water in moles/litre

The relationship between water content and interparticle spacing is given by:

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

where: W = water content in weight per cent
S = surface area of clay in m^2/gm. for, d, in A

These calculations adequately predict measured swelling pressures for the high-swelling sodium-montmorillonite at low salt concentrations (Figure 8). The samples were oriented by drying dilute suspensions to achieve the parallel particle arrangement required in the theory. At higher salt concentrations the measured pressures of sodium montmorillonite exceed calculated values. This is not due to flocculation, and probably results from the errors in using concentrations rather than activities of the exchangeable ions (Warkentin and Schofield, 1962).

Calculations of swelling pressure from diffuse ion-layer theory for divalent ions are not well substantiated experimentally. For montmorillonite there is an uncertainty about the relevant surface area because the particles are arranged in packets with extended swelling only between the packets. When the surface area is reduced to take this into account theoretical and measured swelling pressures are in better agreement (Blackmore and Miller). Increasing salt concentration appears to have little effect in decreasing swelling pressure, although this may be the result of low swelling in water combined with the error in concentrations which was measured for the sodium clay. Free swelling of natural clays which are largely calcium-saturated is less in salt

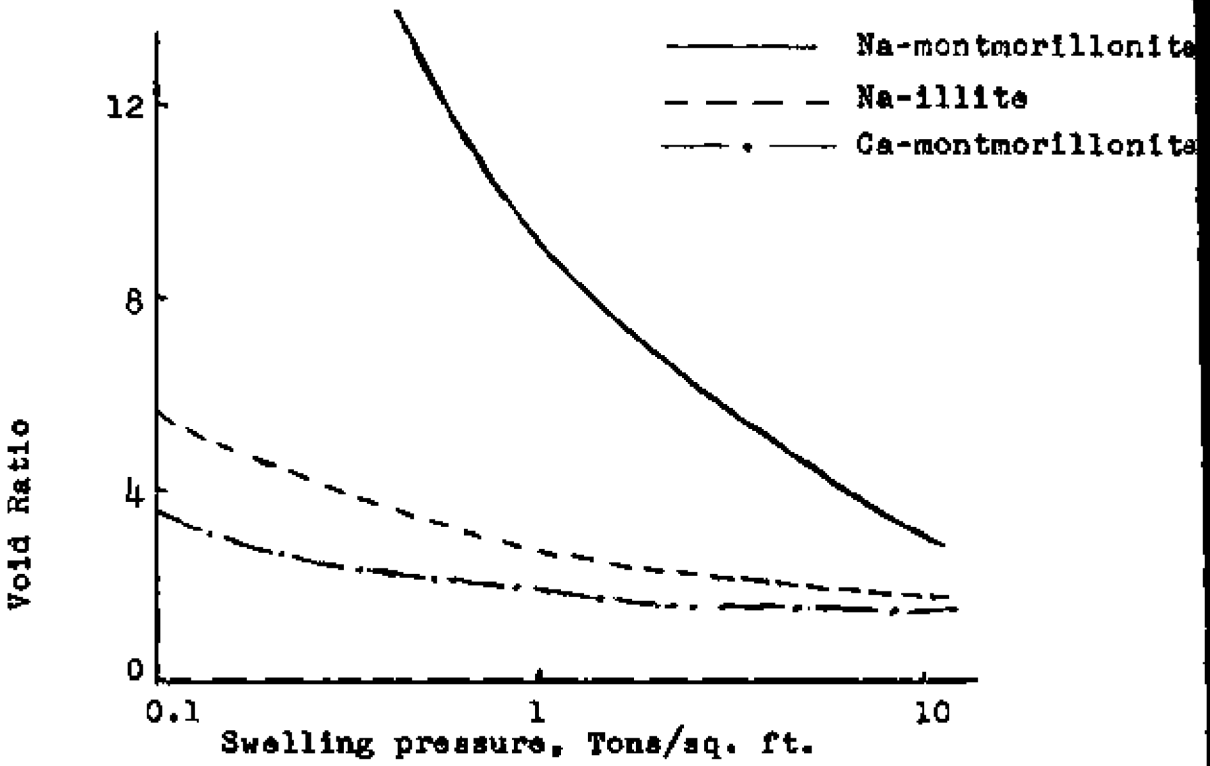

Figure 7

Measured swelling pressures of three clays (Bolt, 1956; Blackmore and Miller, 1961)

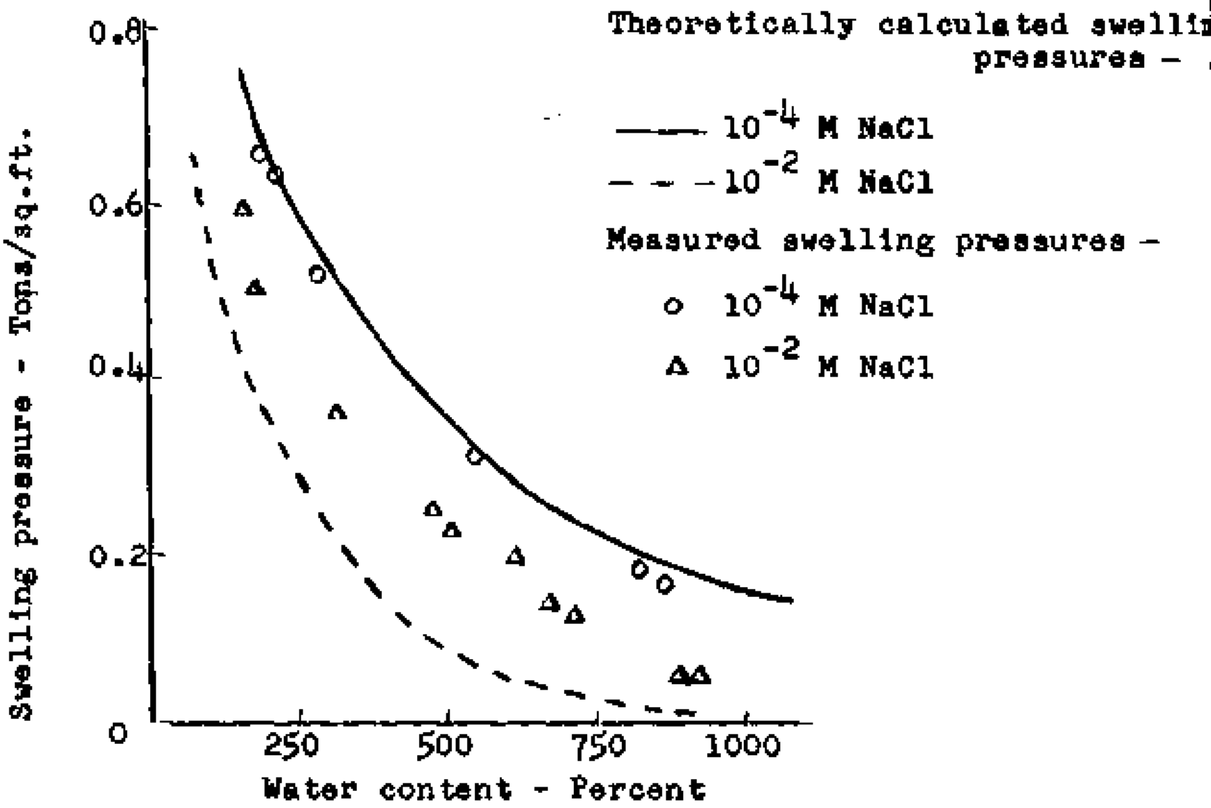

Figure 8

Comparison of calculated with measured swelling pressure for sodium montmorillonite at two salt concentrations (Warkentin and Schofield, 1962).

arrangement if osmotic swelling is small. The amount of osmotic swelling and the swelling pressure are, however, dependent upon the amount of surface which is interacting, so for high swelling clays the parallel particle orientation results in greatest swelling. This difference is illustrated in figure 6 by the volume increase of a high-swelling and a low-swelling clay with different particle arrangement.

A swelling clay deposited from fresh water has an oriented particle arrangement with the flat faces lying horizontally. The particles sediment individually and settle in this minimum energy configuration. Repulsion between faces sustains the overburden. A sample prepared by one dimensional consolidation will have the same characteristics, and will have a large average distance between edges in the direction perpendicular to consolidation. On drying, this sample will show considerable shrinkage in the horizontal direction as particle edges approach. Swelling, however, will occur predominantly in the vertical direction from repulsion between faces.

A sample allowed to swell without being loaded will increase in volume until forces of attraction balance the forces of repulsion. These forces of attraction are not quantitatively understood but probably include van derWaals forces, Coulomb forces between unlike charges, and organic and inorganic molecules which bond between particles These forces are discussed in chapter ——. Some sodium-saturated clays will swell until they disperse; repulsion exceeds attraction even at large distances between particles.

Net Volume Change

A sample allowed to swell in water after being dried will attain a final volume which is usually different from the original volume of the sample. This difference will depend upon the factors which control swelling. If there is a net decrease in volume after one cycle of drying and wetting the second cycle usually shows a further volume decrease. Eventually equilibrium is reached where the volume changes are reversible.

The volume during swelling is also different from the volume the sample had at the same water content on shrinking. Usually the volume is higher on swelling, indicating entrapped air. It is possible also that the sample will contain less air after swelling.

Some change in particle arrangement occurs during shrinking and swelling, as shown by the hysteresis loop when suction is plotted against water content, and by the fact that the final water content after reswelling is often lower than the initial water content. For unsaturated materials this hysteresis may result from capillary effects, but in saturated clays where water uptake results in swelling it is likely due to plastic readjustment of the clay particles. The area of the hysteresis loop represents the energy lost in this readjustment per cycle of wetting and drying (Holmes, 1955).

Shrinking and Soil Suction

In most studies on shrinking, the volume has been measured as a function of water content. It is of interest to determine the soil suction values associated with different stages of shrinkage. Suction as a function of water content is usually measured on separate samples and then compared with the shrinkage curves.

The soil suction value at which unsaturation occurs depends upon the characteristics of the shrinkage curve, i.e. upon the factors such as particle orientation, clay minerals etc. mentioned above. For clay soils with appreciable volume change the suction at the shrinkage limit is usually between pF 4 and 5. Smith (1959) shows that at pF 4.2 the shrinkage is still normal for the swelling Texas Blackland soils. Holmes (1955) reported values of pF 5.1 and 5.5 at the shrinkage limit, and pF 5.7 and > 6.0 where shrinkage ceased for two clay soils in Australia. Croney, Coleman and Black (1958) show pF values from 4 to over 5 at the shrinkage limit. Stirk (1954) found values between pF 4.2 and 4.9 at commencement of residual shrinkage for soils which cracked on drying. For surface soils in which the larger pores predominate, the pF at the shrinkage limit should decrease until eventually a material is obtained which shows no region of normal shrinkage. This is indicated in the values reported by Stirk (1954) for non-cracking soils; the pF at commencement of residual shrinkage varies from < 2.0 to 4.2.

Crack Formation during Shrinking

Cracks will form in clay soils on drying unless the shrinkage is one dimensional and vertical. This might occur in a plastic soil at depth where the overburden consolidates the clay, but the usual case is approximately three dimensional shrinkage. Cracks form where the cohesion of the soil is lowest. Where drying is not uniform, cracks will form in the moister soil. A change in particle orientation occurs at the crack surface, and on redrying after wetting, the cracks will appear in the same place if the soil has not been otherwise disturbed.

The number of cracks per unit area depends upon the clay and particle arrangement. A large number of cracks will form in flocculated clays, while in dispersed clays with higher cohesion a few relatively large cracks result. The cracks in a surface soil with a well-developed crumb structure may be unnoticed because each small unit becomes separated by a small distance from the adjoining one.

When a crack has been formed, water loss proceeds from the crack faces, so that a larger surface is available for evaporation. Water loss per unit area of crack face may be as high as one-half the loss per unit area of surface soil. This increases the size of a crack once formed.

Volume Changes in the Field

The soil characteristics affecting shrinking and swelling which have been discussed in this chapter have been studied on small samples in the laboratory. Volume changes of soils in situ may differ in degree. The only unconfined boundary occurs at the surface so that aspects such as cracking must necessarily be studied in the field. In general, the volume changes occuring in situ will be lower than those measured for small samples.

Climate, in determining soil water content changes, determines the degree to which the potential volume change of a clay will be expressed. The amount of shrinking and swelling can be predicted if the clay properties and the climate are known. This is the application to be made of laboratory studies of volume change.

Structures placed upon clay soils can change the water relationships of the soil beneath them by decreasing water loss by evaporation, or preventing water content increases from rainfall. Differential volume changes will then occur between exposed and unexposed soil. Deep rooting plants decrease the water content of soils at depth. The increased shrinking around trees is well documented and readily observed on clay soils where reswelling is only a fraction of initial shrinkage. The volume changes may occur to a depth of 10 to 15 feet. Recent more numerous studies of naturally occuring volume changes, based upon a knowledge of shrinking and swelling mechanisms, are defining the important practical aspects of these volume changes.

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