SOIL WATER RELATIONSHIPS AND THEIR ENGINEERING APPLICATIONS

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R.N. Yong and R.D. Japp

Report to
Cornell Aeronautical Laboratory, Inc.
on Contract S-68-5

Sponsored by

Advanced Research Projects Agency
Project AGILE
Department of Defence
ARPA Order No. 841 dated 7 May 1966

SOIL MECHANICS LABORATORY

McGILL UNIVERSITY

DEPARTMENT OF CIVIL ENGINEERING AND APPLIED MECHANICS

MONTREAL, CANADA

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**COLOR ILLUSTRATIONS REPRODUCED
IN BLACK AND WHITE**

September 1968

PREFACE

The following is one of two closing out contract reports for work performed under Cornell Aeronautical Laboratories Contract No. S-68-5 and supports the Soil Mechanics Task of the Off-Road Mobility Research (ORMR) for which Cornell Aeronautical Laboratories is the prime contractor and is sponsored by the Advanced Research Projects Project AGILE, Department of Defense, and MONITORED [redacted] by the United States Army Research Office, Durham, under Contract No. DAHC04-67-C-0005.

These two reports are "Soil Bin Studies" and "Soil Water Relationships and Their Engineering Applications". The intent of the overall contract for Cornell Aeronautical Laboratories was to provide input information for application of the visioplasticity method of analysis for soil-vehicle interaction. In addition soil fabric studies were performed to assess the feasibility of applications of energy methods of analysis.

The study was performed during the period November 1967 to September 1968 under the guidance of Mr. George Bartlett, ORMR Program Manager and Mr. Paul Rosenthal and Dr. Patrick Miller, CAL ORMR Soil Mechanics Task Leaders. Mr. A.N. Tedesco was ARPA Technical Monitor.

This report also contains results obtained by Messrs. Sylvestri and How in the course of graduate studies that were not part of the ORMR Contract.

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CHAPTER I - SOIL WATER

INTRODUCTION

The energy relationship between soil and water is one of the most important characteristics of soils. From physical evidence we note that water is by far the most important variable in a clay-soil-water system influencing the various engineering properties such as stability, strength, consistency, compressibility, compactibility, permeability, etc. It is therefore important to understand how water is held in soils and how it can be measured. In this way we will better understand how it influences various soils properties.

We do not propose to enter into a long discussion of the nature of forces holding water to soils. Reference is made to the text "Introduction to Soil Behavior" [Yong and Warkentin (1966)] for a more complete understanding of the soil-water interaction phenomenon. For the present we recognize that water is held by clay particles by various mechanisms and forces and the degree to which water is held to the soil particle in general will depend upon the type of clay minerals present, the species and quantity of the dissolved solutes in the soil water, and particle spacing.

It is understood that to a very large degree, the fabric of a soil-water system is controlled by the clay-water forces present. For the purpose of this discussion the term clay-water forces refers to the interaction between the clay particles, the forces arising from within the particles themselves and the specific interaction between these forces and the dissolved solutes within the soil water. The sum total of interaction with clay-water forces when considered in conjunction with soil fabric will be refered to as soil structure. Thus it is very necessary to obtain an understanding of the parameters which control clay water forces and to recognize how these clay-water forces can be altered due to the application of external constraints. A very good example of this is the sets of external forces imposed by vehicle loading, whereby fabric alteration will occur as a result of changes in the stress regime in the sub-soil.

SOIL WATER POTENTIAL

The water holding capacity of soils can be expressed quantitatively in terms of the free energy difference of the soil water. This refers to the difference between free energy of the soil water in relation to the free energy of pure water. The movement of water within the soil mass is the result of the application of both external and internal gradients. It is therefore possible to express these quantitatively again in terms of free energy differences. The usual notation employed to describe these quantitative terms is the potential of the system. The total potential can be used as the sum of several components:

a) The matric potential ψ_m - which concerns itsel with the water holding capacity of the soil system due to forces originating from within the soil particles themselves, due to capillary effects in the case of partially saturated soils and due to adsorptive forces. In the case of high swelling soils the osmotic effect is included in the matric potential because of the forces which originate from within the soil particles themselves and their specific interactions with the solutes in the soil water.

b) The solute potential ψ_s - this concerns the activity of the solutes in the soil water itself. In particular we are interested in the polarizability factor of the ions and their activity in the soil water itself.

c) The gravitational potential ψ_h - this is due to the effect of gravity.

d) The potential arising from gas pressures ψ_g .

Thus

$$\psi_T = \psi_m + \psi_s + \psi_h + \psi_g$$

where ψ_T = total soil-moisture potential.

A granular soil may be approximated by a system of spherical particles thus permitting a fairly accurate value of the matric potential to be calculated. The solute potential is vanishingly small and can be ignored in most cases in granular soils. In laboratory controlled experiments ψ_h and ψ_g can be eliminated.

In clay soils the immensely complicated soil-water interaction generally makes any prediction of matric and solute potentials very difficult and experimental measurements must be relied upon to give us the total potential - which under these conditions will consist only of ψ_m and ψ_s .

In clay soils the particle surface attractive forces account for a major portion of the matric potential. In granular soils it is the surface tension forces giving rise to a capillary effect which are the major cause of the moisture potential.

The pressure in the soil water is regarded by some as being always less than or equal to atmospheric pressure and thus "in tension". However, this view is not shared by all workers in the field of soil mechanics. Others consider the water to have a pressure essentially the same as its surroundings but an activity which is reduced relative to free water. It is generally believed that the reduction in activity arises from the surface tension and adsorption forces by which water is retained in the soil structure (Taylor et al., 1961). In other words, a high matric potential indicates strong surface tension and/or adsorptive forces are present in the soil, leading to a lowered activity for the soil water.

MOISTURE POTENTIAL RELATED TO WATER CONTENT

In clays these forces are strongest near the particle surface and decrease as the inverse of a power of the distance from the particle (Verwey and Overbeek, 1948). Hence the activity of the water decreases with proximity to the particle. Extending this to the soil mass as a whole, it can be said that the lower the water content of a soil, the higher will be its soil moisture potential. (In granular soils, lower water contents introduce more menisci into the system with the same result.)

The moisture potential of a soil may thus vary from zero at saturation to many thousands of atmospheres when oven-dry. However a soil with zero potential need not necessarily be saturated (Boynton, 1939). There is therefore a relation between the amount of water in a soil and the potential energy (activity) of water in the moist films (surrounding the soil particles). In principle it should therefore be possible to infer one from the other so that a single moisture determination should be ample to describe the entire soil moisture system. In practice this cannot yet be done uniquely since the relations that are measured between amount of water and its energy of retention are multiple valued functions that depend upon the moisture content temperature, and history of the system. However, for conditions starting from say a set laboratory condition, if the test technique is standardized (including sample preparation), a single-valued condition is approximated. To achieve this, a soil suction test is generally performed.

Soil suction is a more revealing measure of the energy condition of the soil-water system than water content. However the true value of the soil suction is not easily obtained. The two most commonly used experimental techniques were first described by Haines (1930) and Richards (1949).

Discrepancies between the values thus obtained have been noted by many workers (Taylor, 1958; Taylor et al., 1961). In comparing the tensiometer to the pressure plate technique, Taylor, Evans and Kemper (1961) noted that "For most situations the pressure difference [for one] is the same as for [the other]. It may be different, however, if the soil inside the cell is in a different structural state because the matrix will then be different. In either case the pressure difference is the matric suction (tension) of the particular soil matrix that is in existance when the measurement is made."

This statement seems to imply that even though the method of measurement may change the original soil-water relationship, the value measured is an accurate one for the modified system. Their suggestion that discrepancies between the values determined by the two methods is due to a difference in soil structure may be misleading in the light of more recent work.

It appears that Chahal and Yong (1964, 1965) were the first to study these discrepancies in a systematic manner. They concluded from their studies on silt, that the discrepancies were related to the air content of the samples.

The amount of entrapped air in a soil is to a large degree influenced by its wetting characteristics. In a clay, these are strongly dependent on the interparticle forces and if these are varied (by using different pore fluids and several clays) the amount of entrapped air would be affected and hence it is possible to introduce measured discrepancies.

In summary, it would seem that for clay soils, because of the specific interactions, the effect of small amounts of entrapped air (say in the range of 90% saturation and over) is not as marked as in silts because the complexities of internal drainage are influenced more by clay-water forces. Thus it becomes important to take into account the degree of interaction occurring between particles.

CHAPTER 2 - SOIL-WATER RELATIONSHIPS

STATE OF SOIL WATER

There is considerable confusion concerning the physical state of the soil water, i.e., whether or not it is ever actually "in tension". Taylor (1958) states, "It is interesting to note that the water in the tensiometer is under suction or tension but that the water in the soil is at barometric pressure, its reduced activity having been caused by its thermodynamic state. It is quite unlikely that there is ever any true suction or tension on the soil water at equilibrium".

Chahal and Yong (1964) state, "It is assumed that after the sample is removed from the suction apparatus, the energy with which the water remaining in the sample is held is equal to the pressure under which it had been equilibrated. In other words, on release of air pressure that water remaining in the sample goes into an equivalent amount of tension".

The relation between the thermodynamic "activity" of the soil water and its physical state of "tension" or "pressure" is not fully understood. We may proceed however on the assumption that the soil water pressure at equilibrium is equal to the cell pressure. On this basis, physical interpretations of the experimental results may be made with a fair degree of success.

HYSTERESIS

The multiple valued nature of the relations between the amount of water in a soil-water system and its energy of retention are due to the hysteretic effects introduced by fluctuations in moisture and temperature.

Several of the mechanisms that have been proposed to explain the hysteretic effects and measurement discrepancies will be briefly reviewed below. The mechanisms considered by previous investigators studying hysteresis fall into these classes:

a) irregular pore configuration
b) relation between large and small pores
c) entrapped air
d) complex drainage
e) particle reorientation.

Irregular Pore Configuration

Because of irregularities in the pore configuration, sudden and hence irreversible changes in pressure deficiency are caused as moisture is extracted from the soil. Hence the case of falling moisture tends to be governed by a higher value of pressure deficiency as determined by the narrow sections of the pores while conditions of wetting or increasing moisture tend to be governed by a low value depending upon the wider sections of the pores. (A typical hysteresis loop is shown in Figure 1). This mechanism was probably first advanced by Haines (1930). It seems closely related to the mechanism later described by Croney and Coleman (1954).

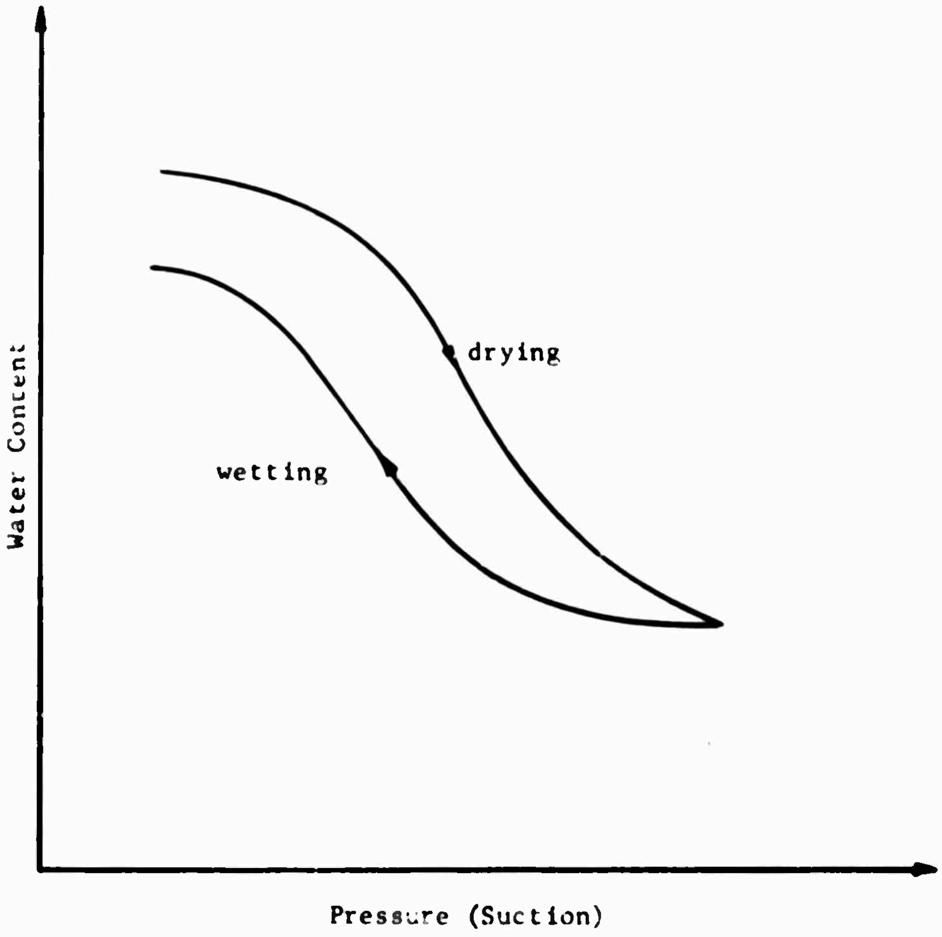


FIGURE 1 Typical hysteresis loop.

Relation Between Large and Small Pores

As described by Croney and Coleman (1954), hysteresis depends on the degree of control which the smaller pores exert on the suction at which the larger pores release their moisture as the suction is increased. Thus water is retained in large pores at suctions much greater than those at which the same pores will refill during the wetting process.

This concept appears to be widely accepted and is sometimes referred to as the "ink-bottle" effect (De Jong, 1964).

Croney and Coleman reported that increasing the density of one soil appeared to decrease the hysteretic effect, presumably because of the consequent increased uniformity in pore sizes.

Entrapped Air

Air trapped during adsorption following a desorption cycle in a saturated soil will cause a reduction in the soil moisture content at zero suction. Haines (1930) pointed this out but implied that it was a result only of "abnormally big" cells.

The practical importance of the effects of trapped air on soil behaviour is still considered negligible by some. There is evidence to show that in natural soils the major portion of the air phase is in direct contact with the atmosphere. During rapid increases in moisture content large volumes of air do become entrapped but in this state it is unstable and will dissolve or will break through into contact with the atmosphere again (Hilf, 1956; Burland, 1961).

However Chahal (1964, 1965) and Chahal and Yong (1965) consider entrapped air to be a feasible mechanism. Variation in the amount of air in the soil at any water content can significantly affect the measured matric suction, and may account for the observed discrepancies in the value of this quantity when measured by different techniques.

Complex Drainage

This is the proposed mechanism whereby air may become freshly trapped in even an initially saturated soil during drainage. It is described in detail by Chahal (1964).

Particle Reorientation

For clay soils, the lack of closure of the hysteresis loop obtained by alternate cycles of desorption and adsorption may be attributed to irreversible structural change caused by oven drying. After the first cycle, others over the range pF 1 - 7 follow the same loop - which may be considered unique for the soil (Croney and Coleman, 1954; Taylor et al., 1961).

In relating measured moisture tension to the state of disturbance of the soil, Croney and Coleman demonstrated that a unique characteristic curve may be obtained from disturbed soil samples, regardless of their method of preparation (i.e., wetted or dried to the desired water content).

TEMPERATURE CHANGES

It has been realized for some time, on the basis of theoretical considerations, that moisture tension is not independent of temperature. Many of the effects of temperature are indirect however, and it is difficult to differentiate between them either theoretically or experimentally.

Wadsworth (1944) concluded that temperature affected structural changes in soil samples although the mechanisms involved were not understood. Taylor et al (1961) reported a marked hysteresis effect in the soil moisture retention properties which depended on the direction of temperature change. The failure of the hysteresis curves to close suggested to them a possible change in structure in the soils. However, the nature of the change is not yet known.

Many workers have reported a general decrease in moisture retained at constant potential under a temperature increase: Richards and Weaver (1944), Gardner (1955), Taylor et al (1961), Taylor (1958), Lambe (1960). This data covers all types of soil, from sand to pure clay. However most of the soil used appears to have been obtained from field samples.

A few attempts have been made to predict the effects of a temperature change on the moisture retention properties of the soil. The operative mechanisms assumed in each case were quite different for granular and for clay soils. In granular soils two mechanisms proposed are surface tension and entrapped air; in clay soils, temperature effects on the interparticle forces must be considered.

Surface Tension

From the agreement obtained between calculated and experimental data, Wilkinson and Klute (1962) concluded that the principle force acting on the soil moisture in a coarse sand was due to pressure gradients associated with surface tension - radius of curvature effects. However they found that in fine sand and silt, the predicted effects were only about half the measured values.

Chahal (1965) reported data showing that predicted and observed temperature effects for a fine silt agreed very well. His calculated values were based on the classical surface tension temperature relationship. He suggested that the observed discrepancies reported by Wilkinson and Klute were a result of their method of experimentation.

Trapped Air

Peck (1960) developed a theoretical analysis which attempted to account for the change in moisture content with temperature for a granular soil by considering the effects of temperature on trapped air, surface tension and volume of water. Chahal (1964) modified this theory and, by a suitable (and arbitrary) choice of values for the parameters involved, showed that it gave very good agreement with the experimental results obtained by Wilkinson and Klute for fine silt and sand.

However, as already noted, he later attributed their results to their method of measurement rather than any intrinsic mechanism

(Chahal, 1965). In this same paper he reported that the effect of a temperature rise on soil moisture retention could be amplified if adsorption and desorption were performed at different temperatures. This result was attributed to the expansion of the air, trapped during adsorption, and subsequent increased expulsion of moisture during desorption.

Interparticle Forces

The Gouy-Chapman theory predicts an increase in temperature will cause an increase in the moisture retained by a pure, perfectly oriented clay at a constant potential. On the basis of this theory. the effect of a temperature change can be predicted. Yong, Taylor and Warkentin (1963) found the predictions to be in good agreement with experimental measurements obtained from a pure, oriented clay.

SUCTION-PRESSURE DIFFERENCES

Although it has been realized that the pressure membrane and tensiometer techniques may give slightly different values of soil suction (Taylor et al, 1961; Taylor, 1958), Chahal and Yong (1964, 1965) appear to have been the first to study these discrepancies in a systematic manner in an attempt to analyze them.

They concluded that the measured discrepancies between the two methods could be related qualitatively to the air content of the samples.

DEMONSTRATION OF SOIL-MOISTURE RELATIONSHIPS

To illustrate the existence of soil-water energy relationships, and to demonstrate the interdependencies discussed in the previous sections, some representative results from recent experiments conducted in the Soil Mechanics Laboratory of McGill University will be used. Since the relationships described are obvious in view of the previous discussions, we will not dwell at length on any of the graphs presented.

The points to be noted are:

1. The differences in the suction or pressure value at the same equilibrating water content. The differences in menici and drainage paths formed are to be noted here as major causes for the differences between ψ_T.
2. The influence of clay content on water holding capacity - and especially the kind of clay mineral involved, can be seen in the relationships described.
3. The effect of clay water forces is also obvious from clay content and salt concentration relationships.

We see therefore that ψ_T is sensitive to the various factors affecting the components of ψ as described previously. It becomes obvious that in remoulded soils where cementation bonds are absent, the integrity of the soil-water system should be related directly to ψ_T. This will be explored in the next chapter.

In natural bonded clays, the intensity of structural bonding will dictate ones approach to the problem of assessment of total energy content. It is obvious that remoulded clay-water relationships (e.g., clay-water force relationships) need not account for these cementation (and/or organic) bonds.

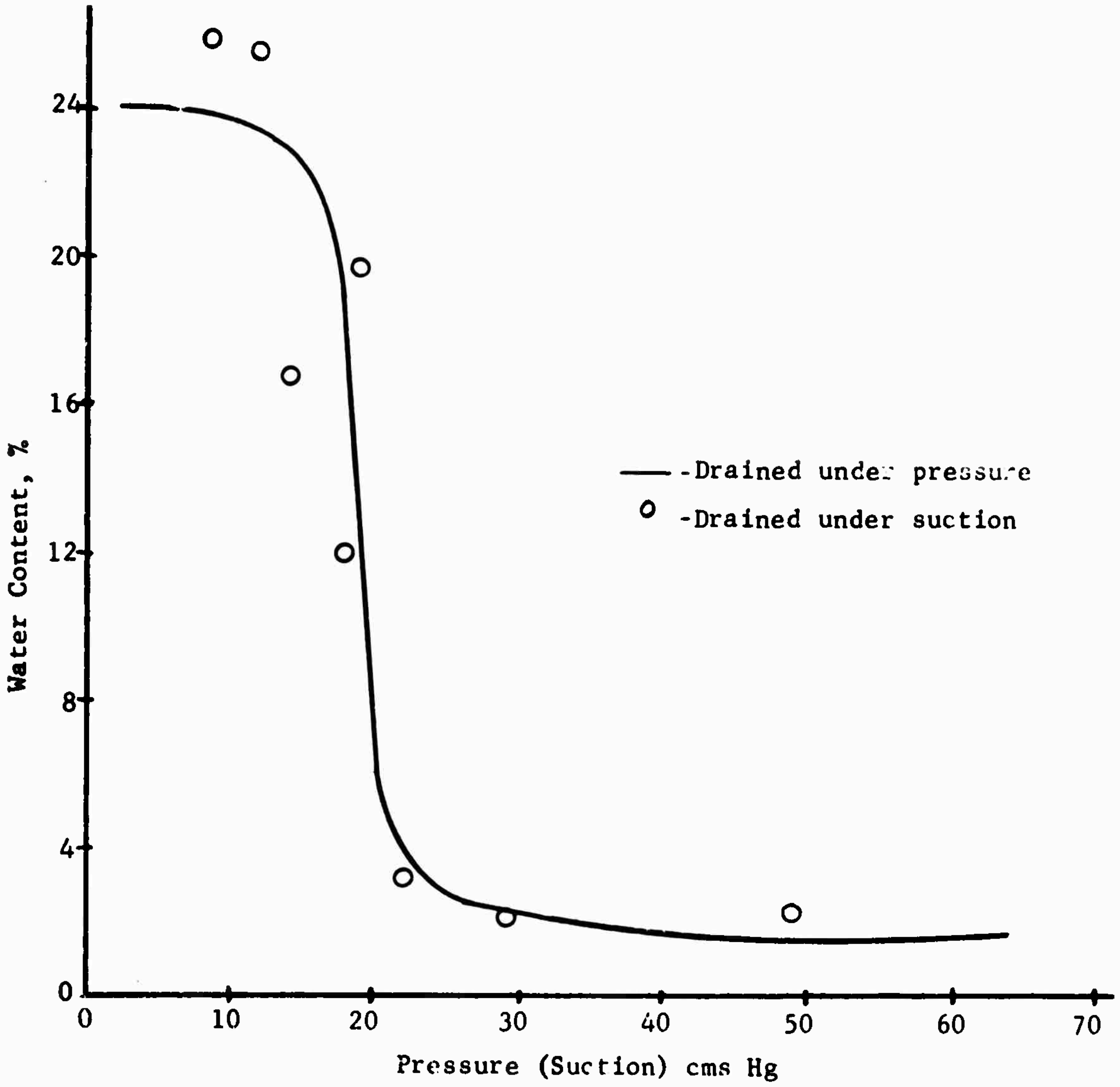


FIGURE 2-1 Suction drainage - Initially saturated glass beads.

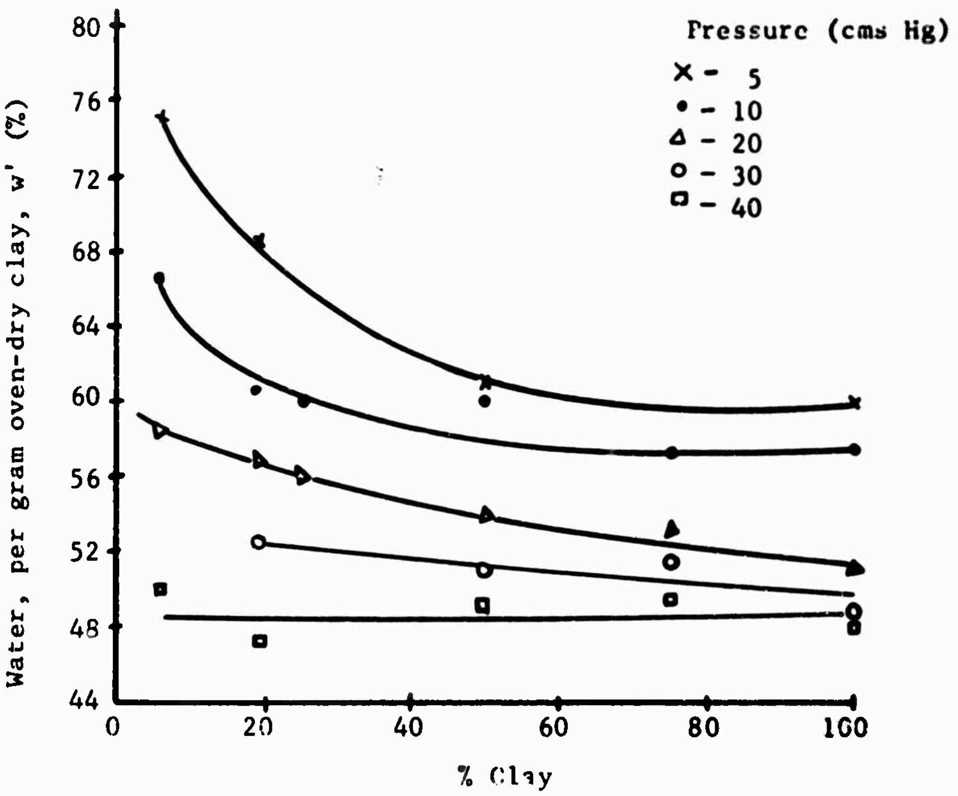


FIGURE 2-2 Moisture retention related to clay content - Initially unsaturated kaolinite.

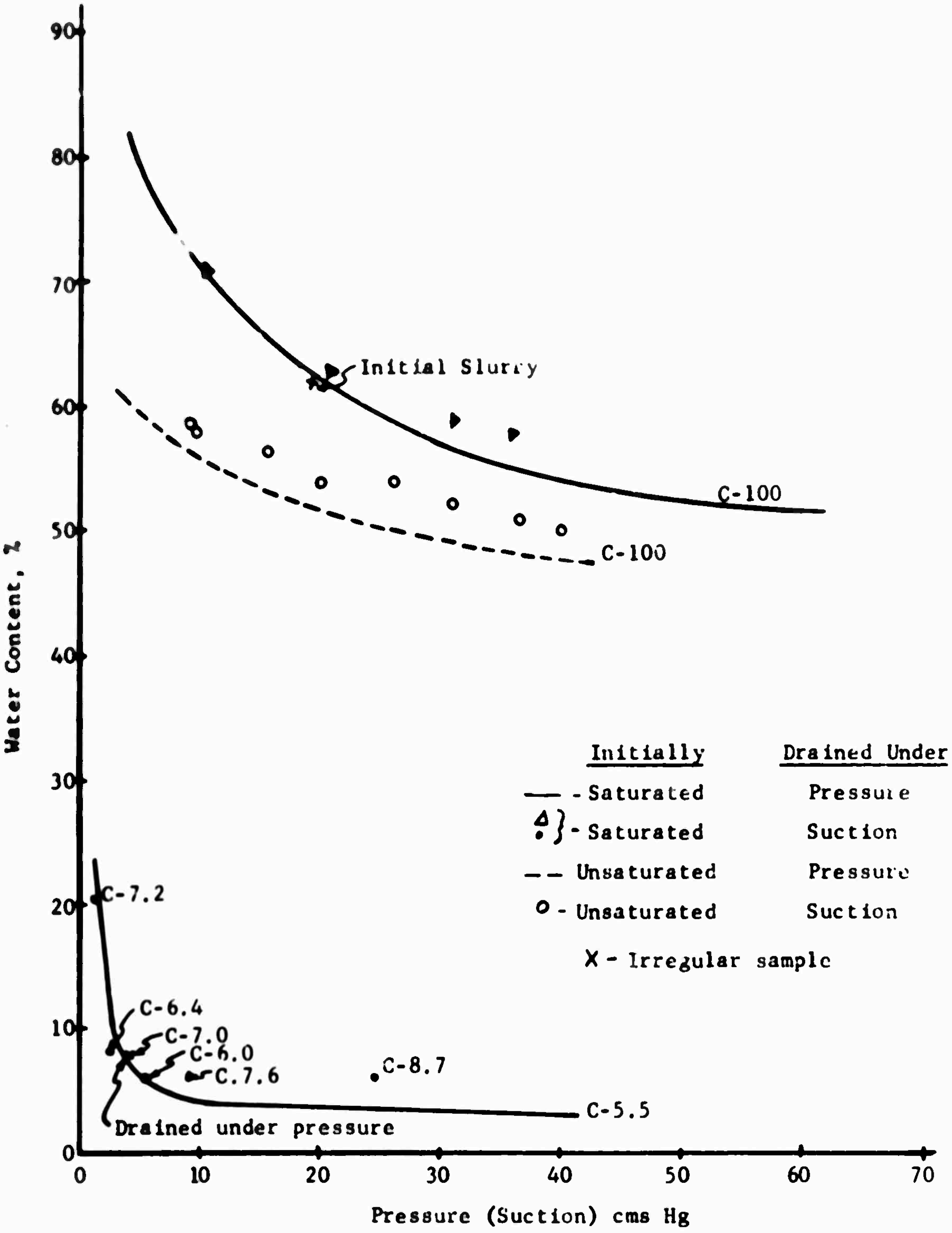


FIGURE 2-3 Suction Drainage - Kaolinite

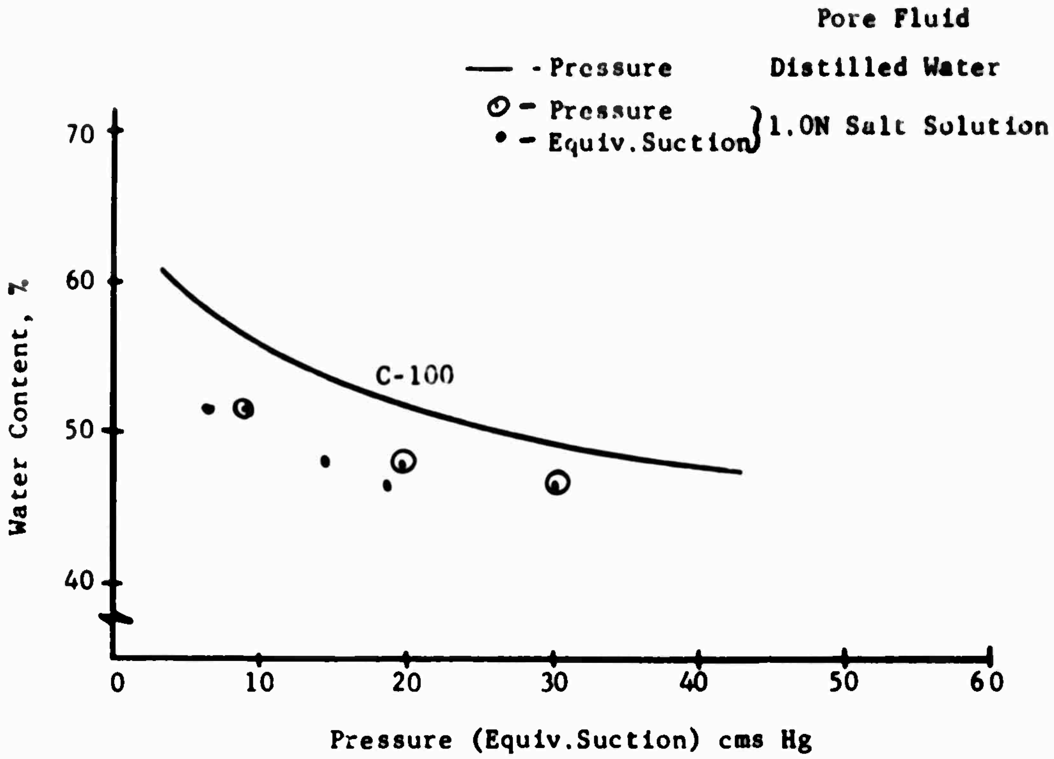


FIGURE 2-4 Effect of varying electrolytic concentration of pore fluid on moisture retention of initially unsaturated kaolinite.

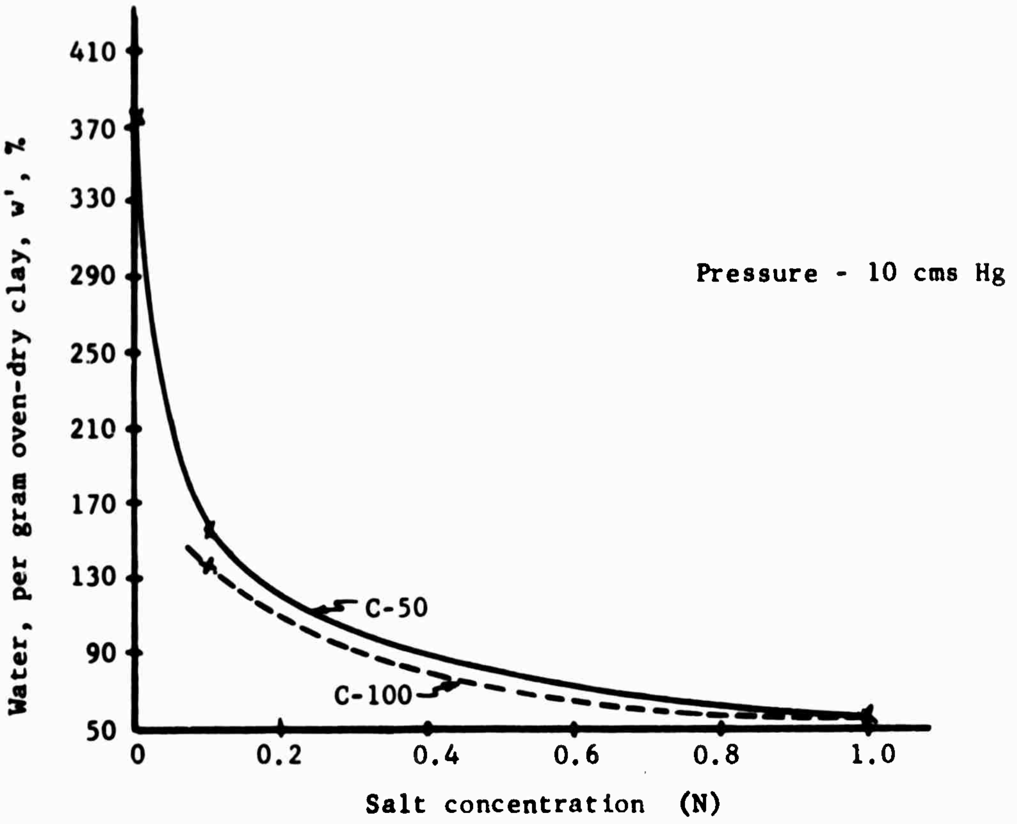


FIGURE 2-5 Moisture retention related to salt concentration of pore fluid - Initially unsaturated bentonite.

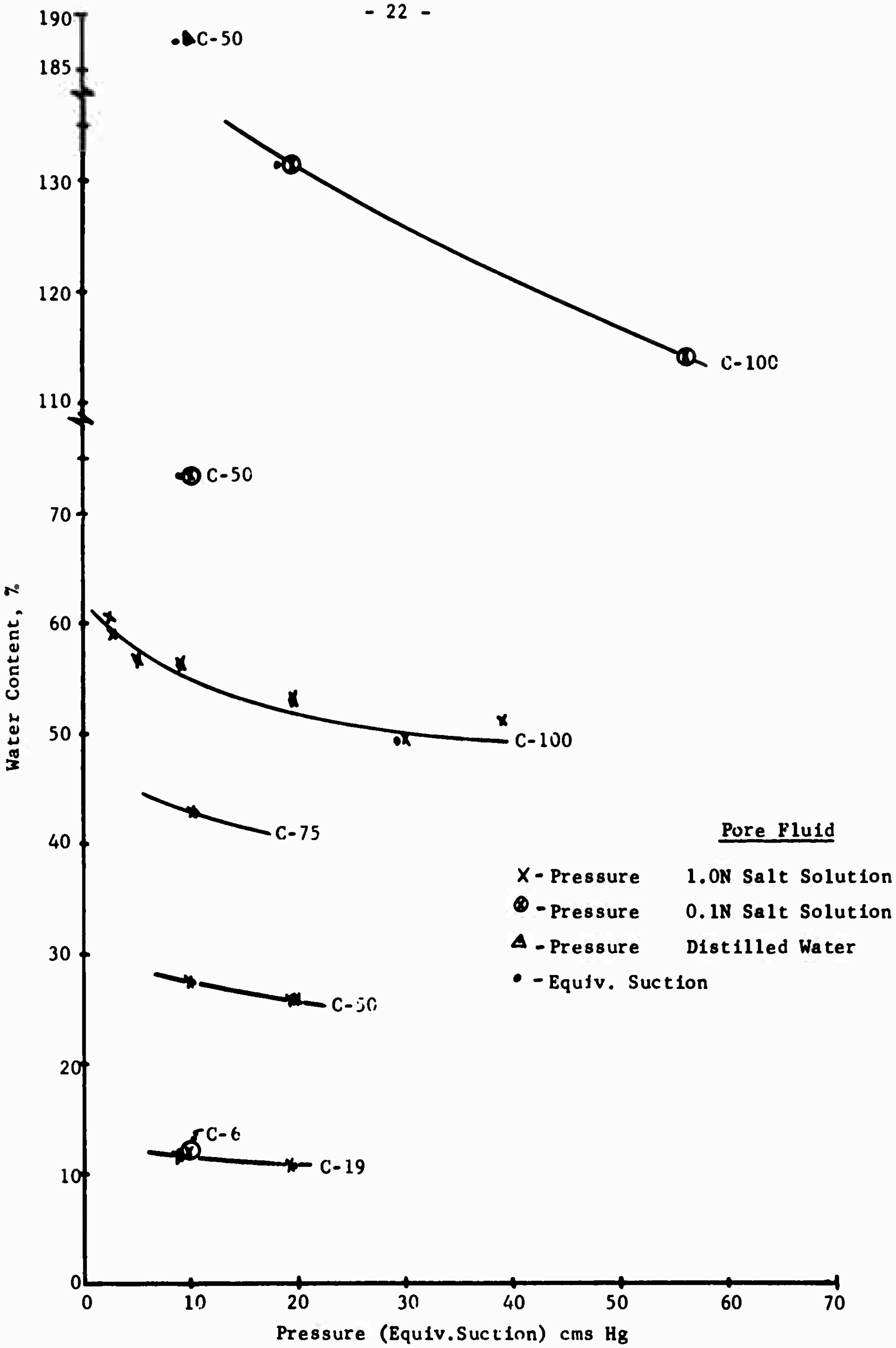


FIGURE 2-6 Suction-pressure differences - Initially unsaturated bentonite-bead mixtures.

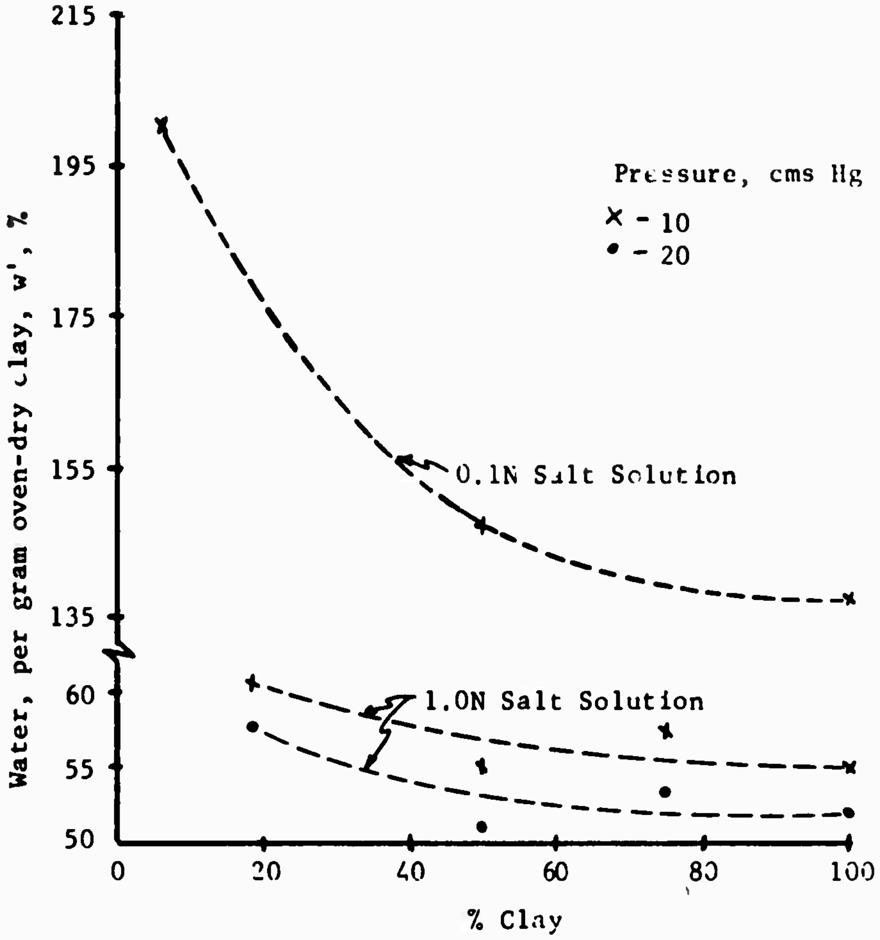


FIGURE 2-7 Moisture retention related to clay content - Initially unsaturated bentonite.

CHAPTER 3 - SOIL SUCTION AND CAL TEST SAMPLES

To obtain an appreciation of the feasibility for assessment of soil-wheel interaction, the soil suction approach was attempted in the CAL soil bin studies. The intent here was to obtain an idea of the scale involved - qualitatively.

Samples were taken at depth of 0" to 1", 2" to 3", 4" to 5", 6" to 7" and in the undisturbed zone. (Test CAL 18 and CAL 19.) The diameter of each sample was measured by means of a travelling microscope and the height of the sample by means of a depth gauge. The weight and volume of the kaolin samples, as obtained after the mobility test, were obtained. The samples were then put into the saturation tank and left to reach equilibrium. The weight and volume were again measured at equilibrium and the process was repeated at suctions corresponding to 10 cm, 100 cm, and 1,000 cm of water. Then samples were subsequently put into the oven at 110°C for 24 hours after having measured the weight and volume at a suction of 1,000 cm of water. The water content and dry density at the various suctions were thus obtained.

SUCTION MEASUREMENTS ON SAMPLES FROM TEST BIN

In the following graphs, the relationships between soil suction and test samples obtained from the soil bin are given. The samples as mentioned previously were obtained from various depths immediately after passage of the wheel for reference, to the original undisturbed sample soil moisture relationship is also shown. It will be seen that there is not one unique relationship between water content and soil suction (given in pF units). We recall here that pF refers to the log of the magnitude of tension in water given in terms of centimeters of water. Thus whilst it is possible and feasible to obtain a pF value for any one particular soil sample water content, it appears that a lot more work needs to be done to examine this relationship more closely. The reasons for the many individual curves shown describing this relationship can be ascribed in all probability to soil fabric influence. No fabric measurements have been made to date on these samples because it is doubtful if the fabric measurements at this time can be quantitized sufficiently well. Qualitative measurements of fabric (reported in the next Chapter) were performed as part of this investigation, and it will be seen that these tests can set the stage where sensible qualitative statements on fabric changes under external constraints can be made with a high degree of confidence. However, in order to quantitize this, some kind of scale needs to be established. This requires a long term work program which should cover a detailed assessment of bonds and forces in soil and their influence on fabric distortion.

What is desired at this stage is the establishment of some kind of relationship between fabric and soil moisture water content, such that one can with a knowledge of the fabric in a representative region, identify the curve for which this particular situation is applicable. It then follows that for the particular soil sample water content one could then associate or establish the internal energy correspondingly.

It will be seen for example that seemingly significant changes in pF values occur over a very small range in water contents, e.g., a 5% change in water content, say between 45 and 50 or between 40 and 45, could give rise to a pF change from 0 to 2. The order of magnitude of change in pF is 2, although when expressed in terms of soil moisture tension the order of magnitude of change is 100 (i.e., from 1 to 100 cm). Thus, if pF is expressed in terms of cm of water, it can be seen that the soil moisture suction change resulting over a small water content change is of a sufficiently large magnitude to make it feasible to pursue this kind of analysis further.

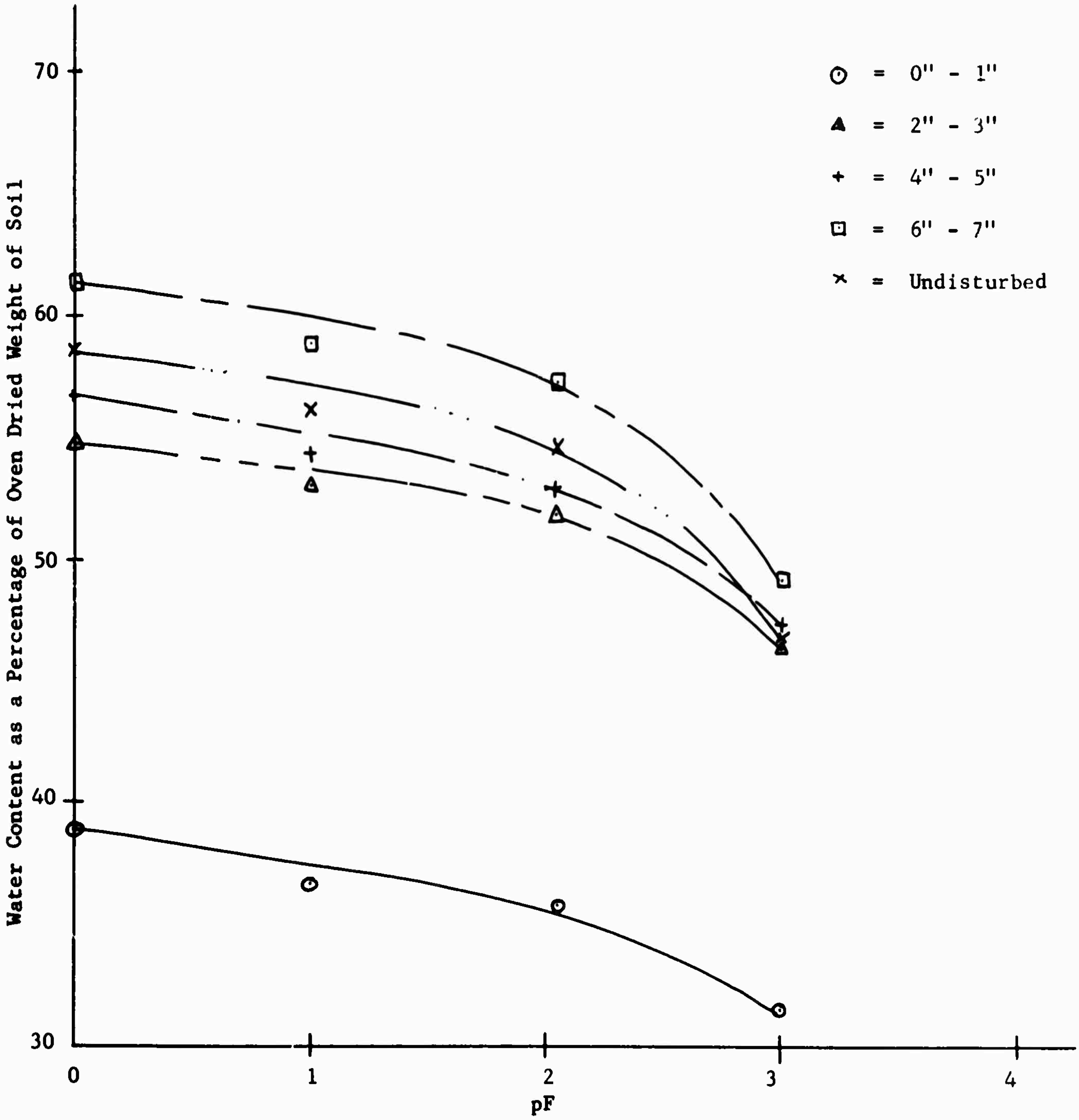


Figure 3.1 Water Content - pF Curve
Test CAL 18

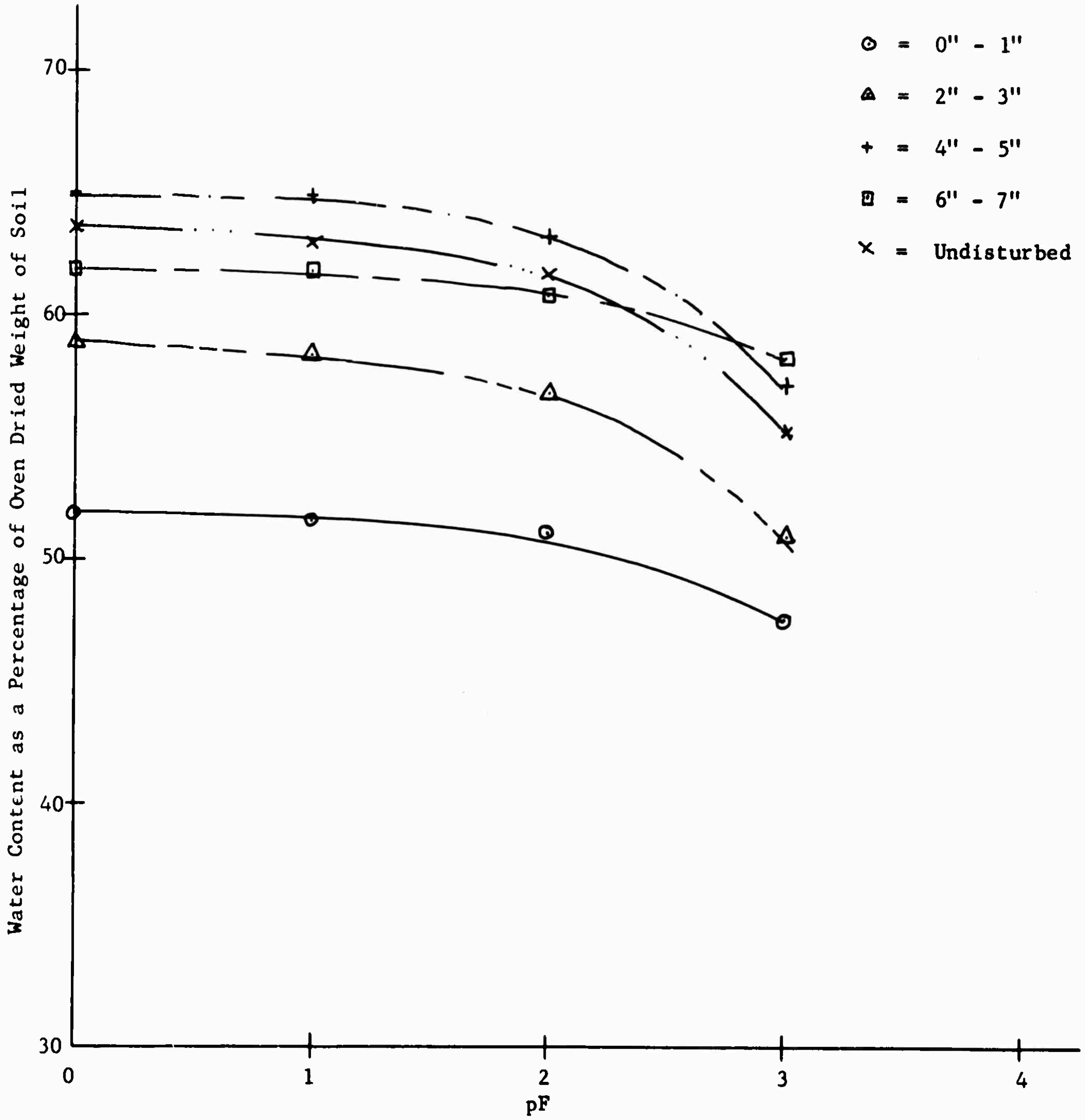


Figure 3.2 Water Content - pF Curve
Test CAL 19

APPLICABILITY OF RESULTS

One of the more serious problems at this stage is the establishment of representativeness of samples. It will be recalled that the samples are extracted from various locations in the soil bin. It is therefore inevitable that the fabric of any one sample would not be identical to that of another, no matter how close or how far apart these samples may be in their original location in the soil bin. Therefore, it is highly unlikely that the soil moisture relationships, which are to a very high degree dependent upon soil fabric, would be identical. What creates or magnifies this problem is that even in the original undisturbed state (unsaturated or even fully saturated and consolidated), because fabric is an important parameter in the determination of the soil moisture relationship, it is therefore a most difficult problem to resolve since one can obviously obtain varying soil moisture relationships for variable fabric samples from all over the soil bin itself. It would appear therefore that if one is to obtain a very rigorous and absolute measurement, one must:

a) obtain a sample from a specified location before wheel tests;

b) obtain a soil moisture characteristic;

c) relocate that sample in its original position in the soil bin;

d) restore it to its original fabric;

e) perform the wheel test;

f) remove the same sample and,

g) redetermine its soil moisture relationship.

This procedure is well nigh impractical and impossible.

It therefore remains for us to explore a more feasible method of obtaining the changes in soil energy relationships. The method which suggests itself is one which would require a large enough survey of samples from soil deformation tests. This can be extended to the wheel test system once sufficient information has been obtained.

From the qualitative standpoint, or even from a semi-quantitative standpoint, it is possible for example to establish an average water content and an average change in water content for a particular depth due to wheel loading. Because the soil suction curves for the various samples in the bin are nearly parallel, it becomes possible to establish the changes in soil energy relationships due to stress changes in fabric and soil water content. This method is advocated and it is obvious that from the available data this method can be made feasible. However a lot more tests need to be performed and fabric correlations need to be tied in at this stage. More time is therefore needed in order to explore this avenue which from indications at the present time appear to be most fruitful.

CHAPTER 4 - MICROSCOPIC ASSESSMENT OF FABRIC

BACKGROUND

The theories and technology associated with the use of a polarizing microscope for the study of orientation of minerals has been given in detail by Kerr. The reader will find this to be a very informative text book and it treats the subject for single crystals in sufficient length and detail. With regard to the application of the polarizing microscope technique for assessment of clay fabric, a detailed explanation and application may be found in Leitch and Yong (1967). Therefore, we will not attempt to repeat details concerned with the development of this theory. Rather, we will turn our attention to the use of colour patterns obtained in the polarizing microscope due to the addition of a Gypsum red interference. This in essence constitutes then the colour polarizing microscopy technique which performs the same function in regard to the illumination-extinction patterns one expects from a cross-nicols non interference technique. The advantage here is that it is possible to distinguish colours a little easier than light intensities without the aid of a photo-diode.

Thus, we are basically concerned with an easy technique for immediate visual appreciation of fabric. In the application of such a technique to visualization of clay fabric, it has been found that no recorded work is available and therefore it has necessitated a very slow and painstaking procedure in building up a complete bank of information. The portion of the study therefore is concerned with the beginning of the build-up of this supply of information, from which correlations may be made at a later time concerning fabric changes as identified by colour changes.

SPECIMENS STUDIED

The reference specimens made consisted of kaolin clay minerals where the polar positions of the spectrum were established by

a) obtaining fully oriented specimens using a very slow sedimentation technique (on specially dispersed samples) with a suction compression at the end of slow sedimentation, and

b) preparing fully random oriented sample using an exchange technique causing full dispersion of particles and solution into random orientation. The suction compression technique was also applied to the random sections to obtain a higher density.

Various suction compression values were used to try and obtain closer particle packing both for the oriented and the random samples. The attached sheets on colour key with side explanatory notes show the scale established for both particle orientation. Thin sections were obtained parallel to load application and normal to load application. Those that were obtained parallel to load application are called vertical sections and correspondingly those normal to load applications are identified as horizontal samples on the colour plates attached. The negatives for these are also attached.

In a complementary piece of work performed by Sylvestri and How, graduate students involved in studies on fabric and engineering properties (not part of CAL contract and hence not funded by CAL), the fabric changes as observed visually through the colour interference polarizing microscope technique show the typical change in orientation starting off from slurried samples to the compacted samples. As observed, one obtains fully random orientation with a slurry mixture of kaolinite, and if a pressure is applied to this system, a certain preferred orientation begins to occur which is then emphasized with higher suction compaction.

INTERPRETATION AND DISCUSSION

There is unfortunately little or no published information that one can use to really describe particle orientation from colour technique for an aggregate mineral mixture. In the following, we will postulate particle orientation based upon a knowledge of single crystal work and upon an examination of the available data.

The introduction of the gypsom red in between the cross-nicols produces the identifying brownish red colour when the gypsum red is oriented at 135^{o}counter-clockwise to the horizontal axis. The vibration of the light beam in the plane containing the lower index of refraction produces basically a fast ray and correspondingly at right angles to it we will obtain the slow ray component. These will constitute extraordinary and ordinary rays respectively. If we introduce a kaolin particle, and assume without too much error that the optical axis coincides with the C axis of the mineral, since the A and B axes and the corresponding refractive indices are almost identical (i.e., we will have axial symmetry) it will appear that so long as the polarized light transmitted is coincident with the optical axis, no retardation occurs and therefore a brownish red picture is obtained regardless of which way the turntable is rotated.

The explanations are better given in terms of the physical diagrams accompanying the report and the reader is advised to consult the diagrams in conjunction with the examination of the colour plates shown for the analysis of retardation of the kaolinite samples.

In the seven colour plates, these will show firstly the two ends of the spectrum as discussed previously (Plates 1 to 3), and then the work performed by How and Sylvestri showing the beginnings of orientation for the slurry samples as the pF value for consolidation is increased (Plates 4 to 7). In some of these slides (Plate 3 and Plate 4) the scaley effects for the horizontal pictures, indicate the effect of poor wax crystallization in replacement. Whilst they may look seemingly rather awkward, they do not in actual fact destroy the picture of particle orientation. What is interesting is the total colour scheme that is represented by these pictures.

In essence, the pictures showing the horizontal orientations, i.e., the thin section specimens mounted normal to the applied load show that close to brownish red for all horizontal angles of specimen rotation (if the particles are oriented flat, i.e., to the viewer). This is very evident for example in the oriented samples in Plate 1 where the specimen table can be rotated 360° without any change in the colour presented (horizontal). Looking at Plate 1, i.e., the oriented pF 1 samples, the vertical sections show green for zero degrees platform orientation indicating that the particles that provide the green spectrum are oriented left 45°, i.e., 135° counter-clockwise from the horizontal x-axis. The brown spectrum shows orientation of particles 45° counter-clockwise from the x-axis. In the zero degrees platform orientation, the red specks behind the overall green shows particles with edges obviously not inclined at 135° to the x-axis. It is suspected that these samples could have partial faces normal to the analyzer. This kind of reasoning can be extended all the way through, and the reader in consultation with the pictorial diagram, should obtain a better appreciation of the possible orientations of particles.

The most important point to be stressed here is that for vertical sections, i.e., for thin sections taken parallel to load orientation, the green or close to green colours indicate edge particles oriented 135° counter-clockwise to the horizontal x-axis, brown shows edge particles oriented 45° counter-clockwise to the x-axis. The brownish red colour that one sees indicates the flat face of particles. The degrees approaching brownish red from deep brownish to brownish red, etc., indicates whether or not the particles are becoming more face oriented to the eye, i.e., to the optical lens.

It is obvious that this method, up to the present time, of examination of fabric is totally qualitative and that more work needs to be done in order to obtain a more precise quantitive measure. It must be emphasized that up to the present time this present piece of work reporting the colour spectrums due to retardation and birefringent characteristics of the kaolinite clay is one of the most complete available.

Obviously more work needs to be done if this kind of study is to be pursued further. It would appear from the results available that this is a very feasible method of examination of fabric from the gross and overall point of view. The problem of obtaining a more precise assessment of the fabric is one which must take into account supplementary techniques such as electron microscopy and X-ray diffraction. If a sample is examined using all three different techniques, it is then possible to assess completely the position and role of fabric in the demonstration of the engineering properties of the material.

REFERENCES

Boynton, D. (1939) "Capillary Tension as a Measure of the Pore Space Unoccupied by Water in Some Dense Orchard Subsoils", Soil Science, Vol. 47, pp 347-352.

Burland, J.B. (1961) "The Concept of Effective Stress in Partly Saturated Soils", M.Sc. Thesis, Witwatersrand University, South Africa.

Chahal, R.S. (1964) "Effect of Temperature and Trapped Air on the Energy Status of Water in Porous Media", Soil Science, Vol. 98.

Chahal, R.S. (1965) "Effect of Temperature and Trapped Air on Matric Suction", Soil Science, Vol. 100, pp 262-266.

Chahal, R.S. and Yong, R.N. (1964) "Validity of the Energy Characteristics of Soil Water Determined With Pressurized Apparatus", Nature, Vol. 201.

Chahal, R.S. and Yong, R.N. (1965) "Validity of the Soil Water Characteristics Determined with the Pressurized Apparatus", Soil Science, Vol. 99.

Croney, D. and Coleman, J.D. (1954) "Soil Structure in Relation to Soil Suction (pF)", J. Soil Sci., Vol. 5.

De Jong, E. (1964) "Volume Change, Moisture Retention and Permeability", Ph.D. Thesis, McGill University.

Gardner, R. (1955) "Relation of Temperature to Moisture Tension of Soil", Soil Science, Vol. 79.

Haines, W.B. (1930) "Studies in the Physical Properties of Soils. V. The Hysteresis Effect in Capillary Properties and the Modes of Moisture Distribution Associated Therewith", J. Agric. Sci., Vol. 20, pp 97 - 116.

Hilf, J.W. (1956) "An Investigation of Pore Water Pressure in Compacted Cohesive Soils", U.S. Dept. Interior Bur. Reclamation Tech. Memorandum 654.

Kerr, P.F. (1959) "Optical Mineralogy", (pp 409 and 414ff), McGraw-Hill Book Co. (442pp).

Lambe, T.W. (1960) "Compacted Clay-Structure and Engineering Behaviour", Trans. ASCE, Vol. 125, pp 682 - 756.

Leitch, H.C. and Yong, R.N. (1967) "The Rate Dependent Mechanism of Shear Failure in Clay Soils", Soil Mechanics Series No. 21, Report to Defence Research Board of Canada, Report No. D. Phys.R.(G) Misc. 28.

Peck, A.J. (1960) "Change of Moisture Tension with Temperature and Air Pressure: Theoretical", Soil Science, Vol. 89.

Richards, L.A. (1949) "Methods of Measuring Soil Moisture Tension", Soil Science, Vol. 68, pp 95 - 112.

Richards, L.A. and Weaver, L.R. (1944) "Moisture Retention by Some Irrigated Soils as Related to Soil Moisture Tension", J. Agric. Research, Vol. 69.

Taylor, S.A. (1958) "The Activity of Water in Soils", Soil Science, Vol. 86, pp 83 - 90.

Taylor, S.A., Evans, D.D. and Kemper, W.D. (1961) "Evaluating Soil Water", Agric. Expt. Sta., Utah State University, Bull 426.

Verwey, E.J.W. and Overbeek, J.Th.G. (1948) "Theory of the Stability of Lyophobic Colloids", Elsevier Publishing Co., New York.

Wadsworth, H.A. (1944) "An Interpretation of the Moisture Content Surface Force Curve for Soil", Soil Science, Vol. 58.

Wilkinson, G.E. and Klute, A. (1962) "The Temperature Effect on the Equilibrium Status of Water Held by Porous Media", Soil Science Soc. America Proc., Vol. 26.

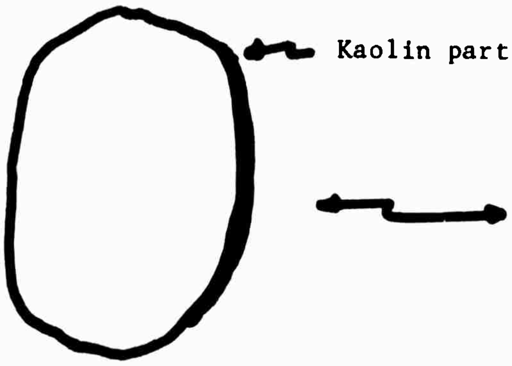
Yong, R.N., Taylor, L.O. and Warkentin, B.P. (1963) "Swelling Pressures of Sodium Montmorillonite at Depressed Temperatures", Clays and Clay Minerals, Vol. II, pp 268 - 280, Proc. 11th Nat. Conf. on Clays and Clay Minerals.

Yong, R.N. and Warkentin, B.P. (1966) "Introduction to Soil Behavior", Macmillan, New York.

COLOUR KEY FOR INFERRING PARTICLE ORIENTATION USING GYPSUM RED INTERFERENCE OPTICAL TECHNIQUE

The absence of past work using interference optical technique for aggregate crystal work makes it difficult for one to be completely precise at this stage without more supporting work. However, with a knowledge of single crystal theory, and using the data obtained from this present study, the following brief diagrams will describe the colour pattern. It will be emphasized that the theory underlying the single crystal work can be found in the classical text books, and this report will not repeat such theories.

We will presume that it is understood that the crossed-nicols technique is used and that the gypsum red interference plate is introduced between the thin section and the analyzer. Thus the brief diagrams will omit everything else and consider only the particle.

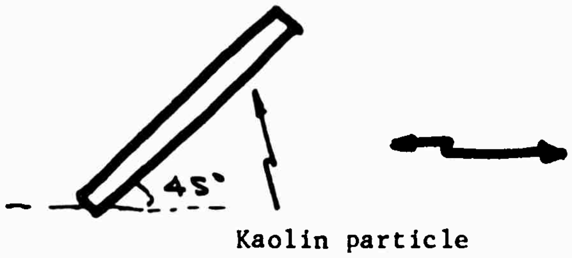


Polarized light coming out of paper. Viewer will see brownish red if particles are complete flat, i.e. polarized light completely normal to plate (clay plate). If clay plate is not completely flat with regard to viewing, rotation of specimen platform will result in greenish and more brownish shadings (as the case may be) in the observed red. The brownish red shown in

Plate 1 (horizontal) is not dependent on angular location of specimen platform. This shows complete flatness of particles with respect to viewer.

Polarized light coming out of paper. Polarized light going through edge of particles. Viewer will see green in this instance.

Red specks in Plate 1 (vertical 0°) indicate particles possibly in flat plane to viewer. Green indicates edge of particles oriented 135° counter clockwise to horizontal axis.

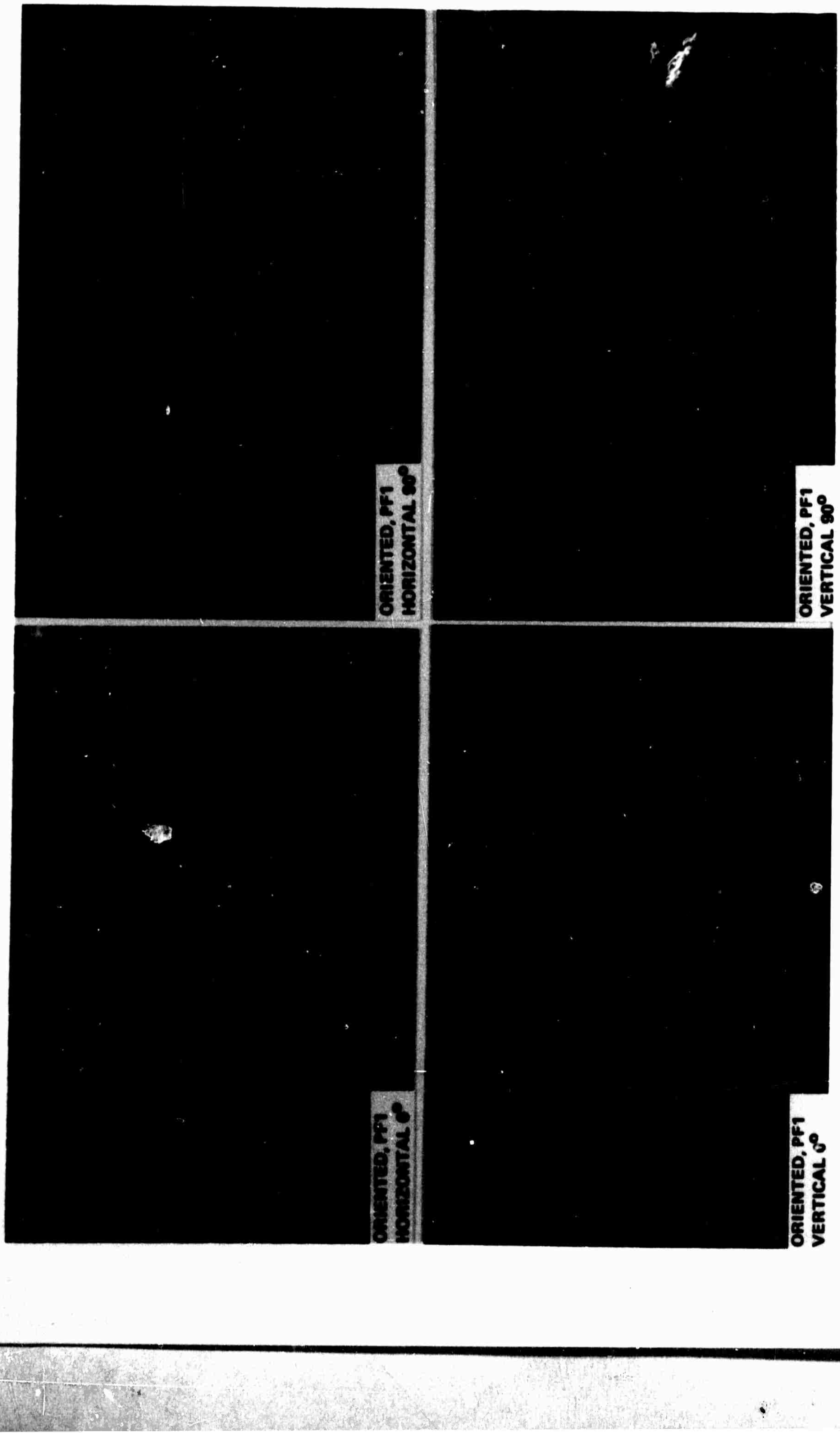


Polarized light coming out of paper. Polarized light going through edge of particles. Viewer will see brown in this instance.

Plate 1, vertical 90° shows this.

Angles of plates in between will show combinations going from green to brown for edges.

PLATE 1



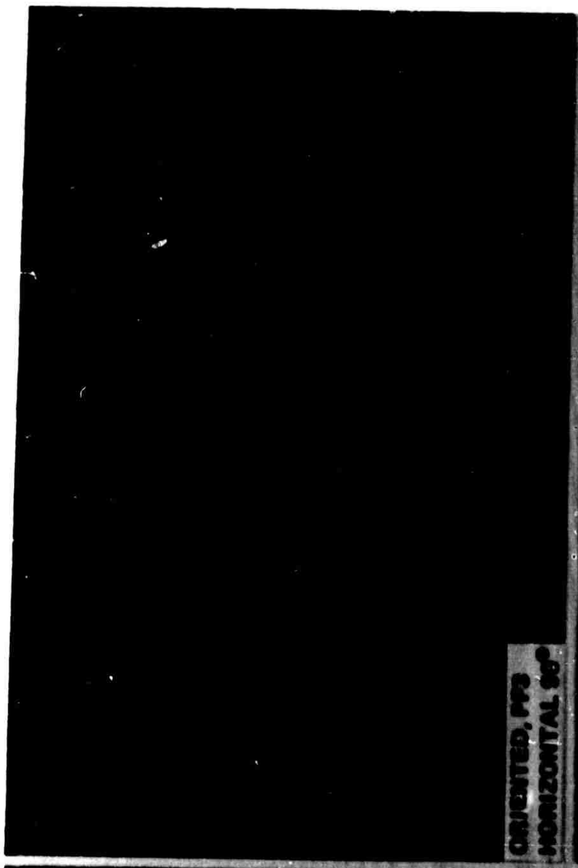
ORIENTED, PF1 HORIZONTAL 90°

ORIENTED, PF1 VERTICAL 90°

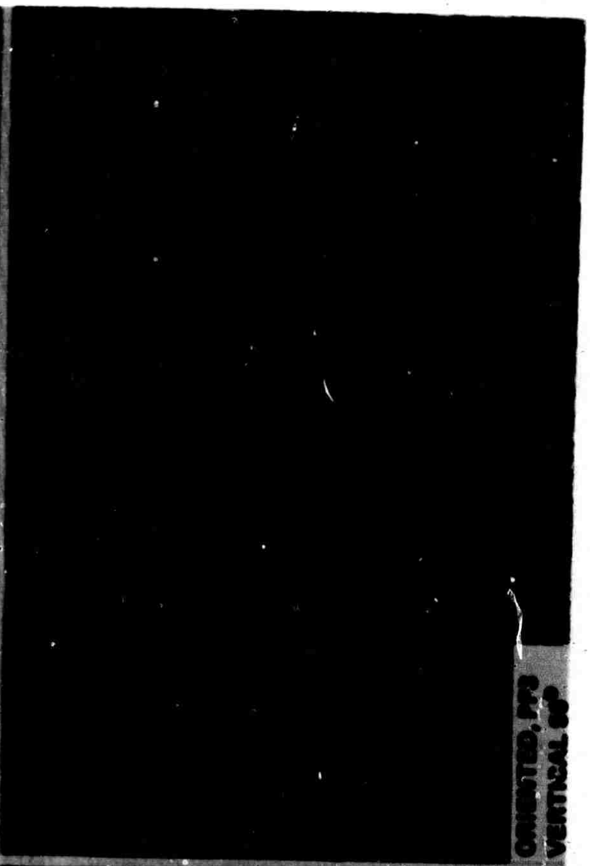
ORIENTED, PF1 HORIZONTAL 0°

ORIENTED, PF1 VERTICAL 0°

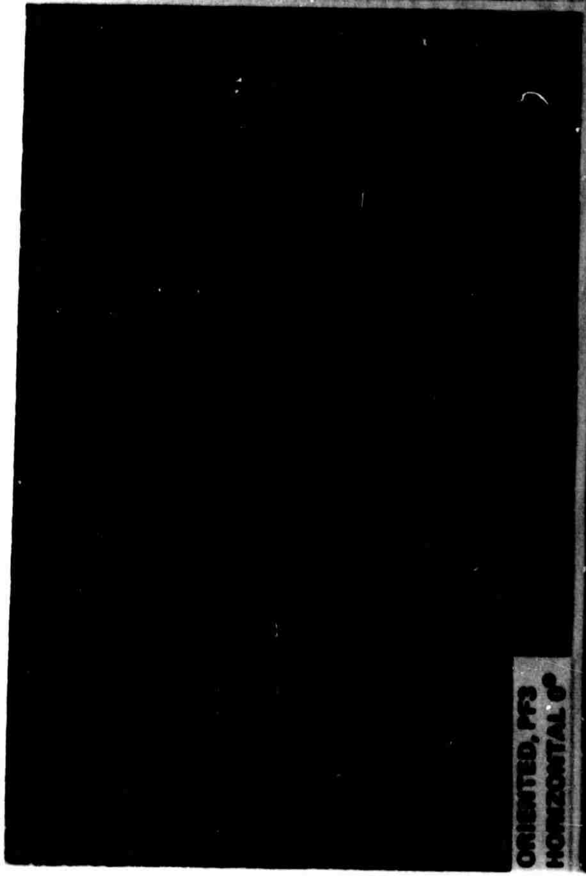
PLATE 2



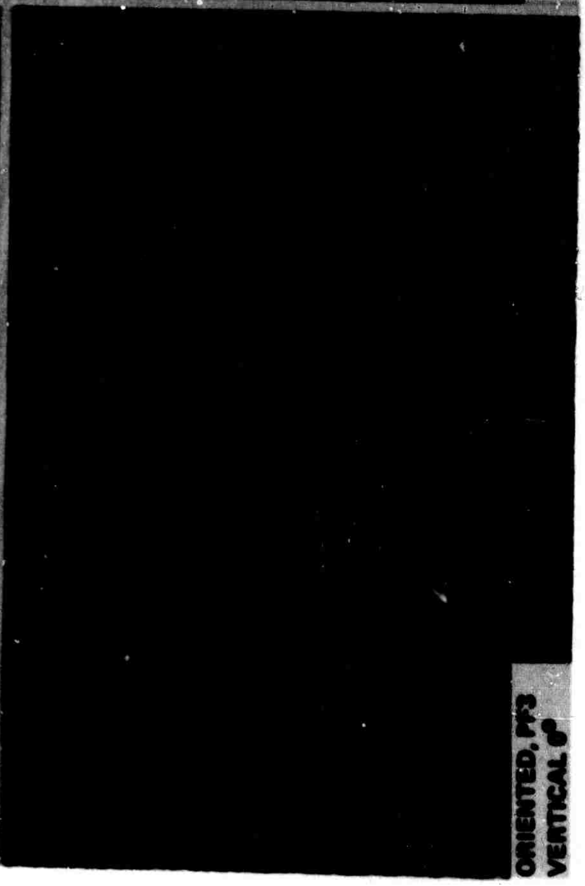
ORIENTED, PP3
HORIZONTAL 90°



ORIENTED, PP3
VERTICAL 90°

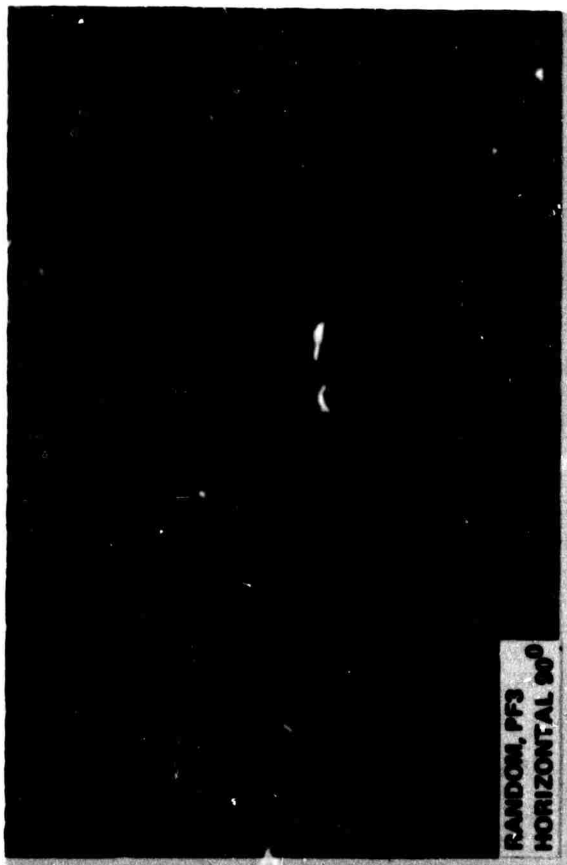


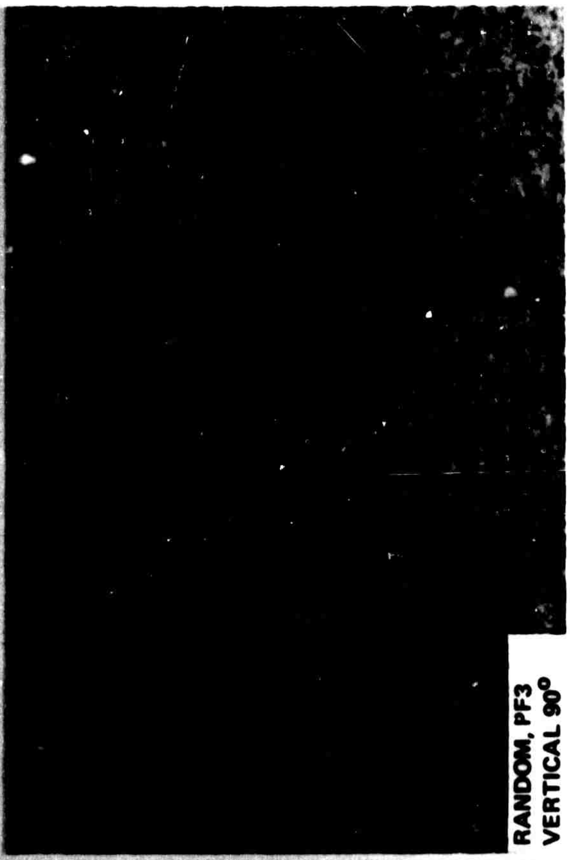
ORIENTED, PP3
HORIZONTAL 0°

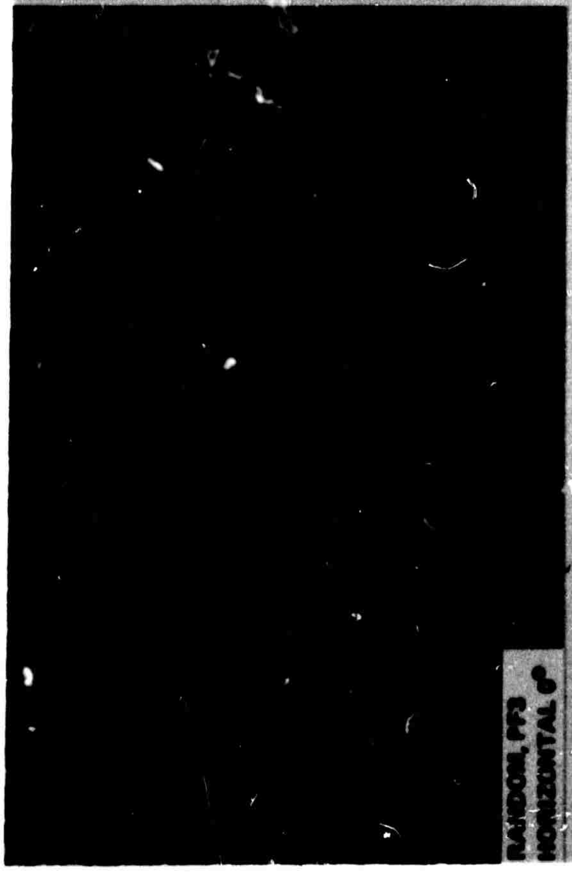


ORIENTED, PP3
VERTICAL 0°

PLATE 3


RANDOM, PF3 HORIZONTAL 90°


RANDOM, PF3 VERTICAL 90°


RANDOM, PF3 HORIZONTAL 0°

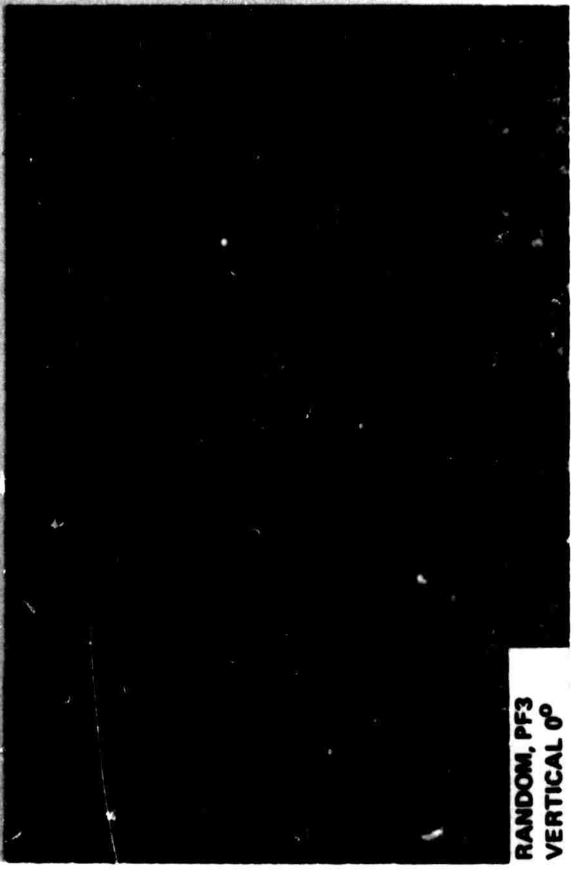

RANDOM, PF3 VERTICAL 0°

PLATE 4

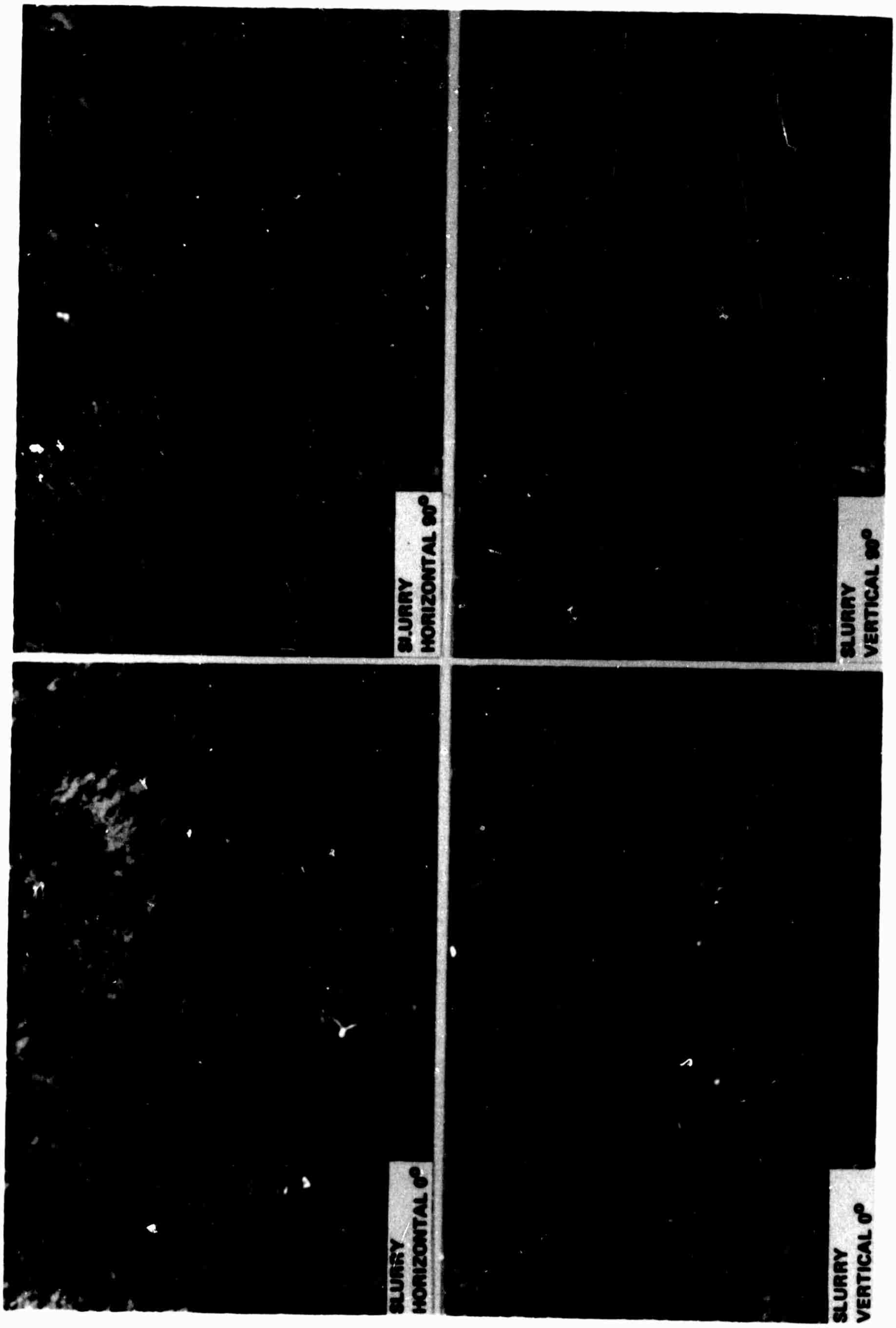
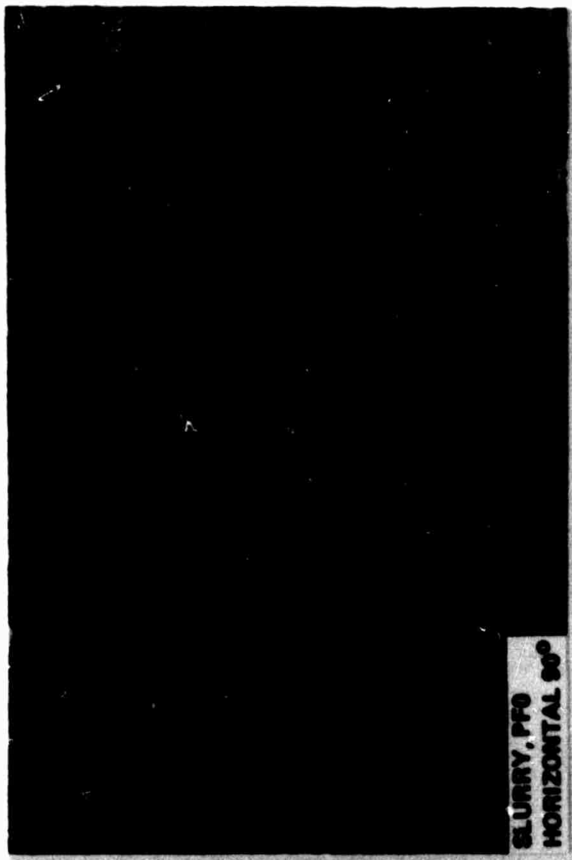
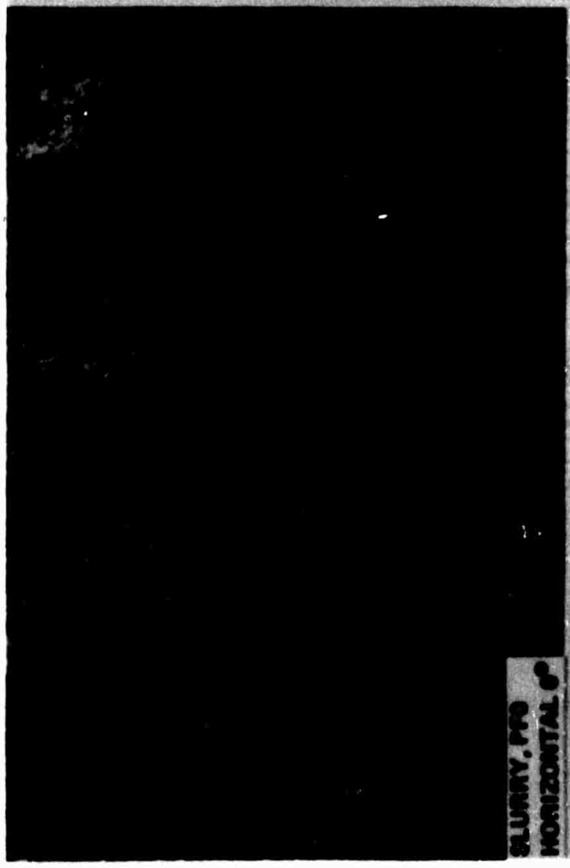

SLURRY HORIZONTAL 90°
SLURRY VERTICAL 90°
SLURRY HORIZONTAL 0°
SLURRY VERTICAL 0°

PLATE 5

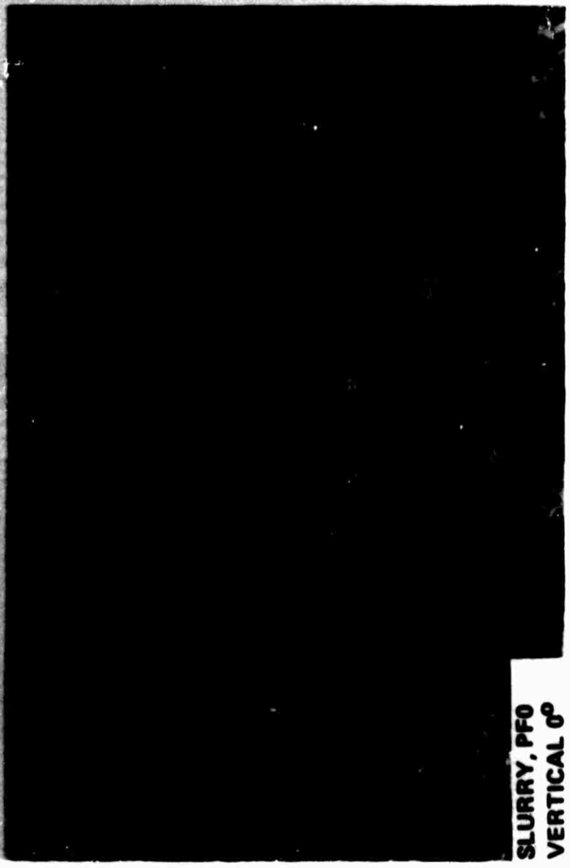


SLURRY, PF0
HORIZONTAL 90°

SLURRY, PF0
VERTICAL 90°

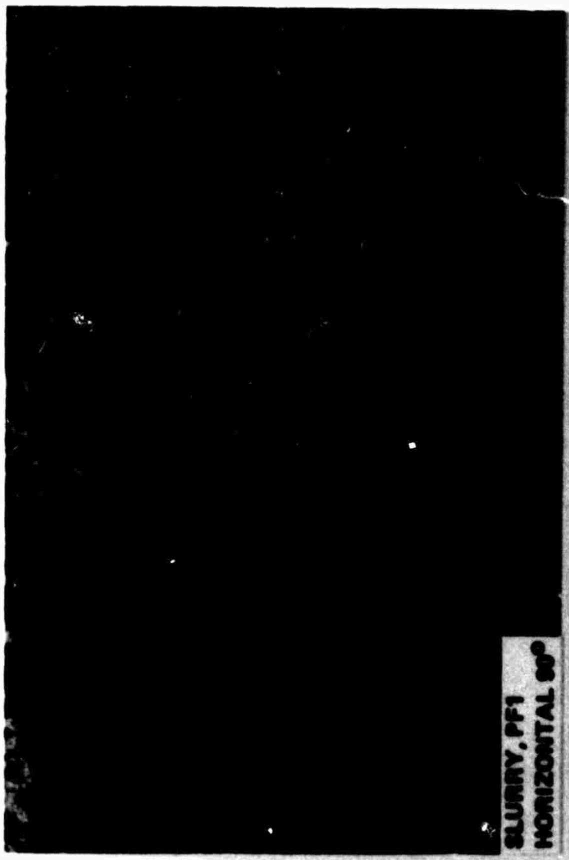


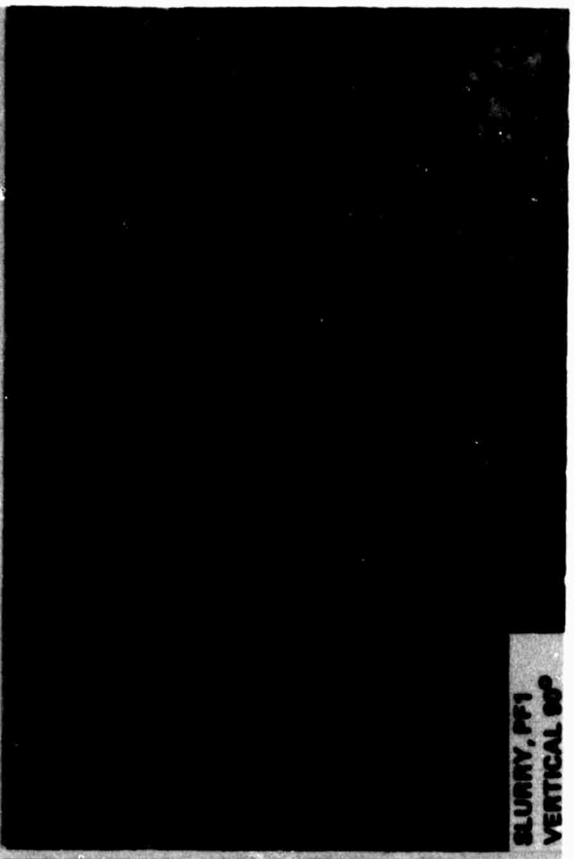
SLURRY, PF0
HORIZONTAL 0°

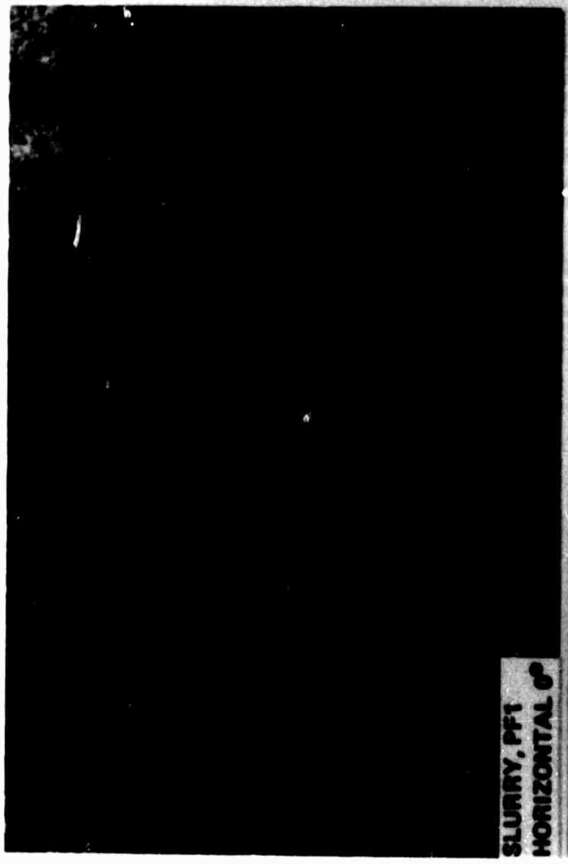


SLURRY, PF0
VERTICAL 0°

PLATE 6


SLURRY, PF1
HORIZONTAL 90°


SLURRY, PF1
VERTICAL 90°


SLURRY, PF1
HORIZONTAL 0°

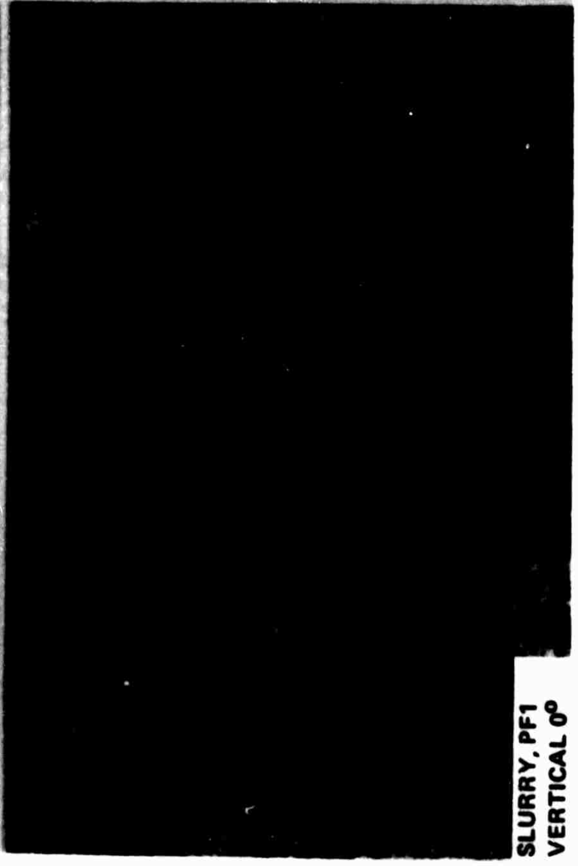
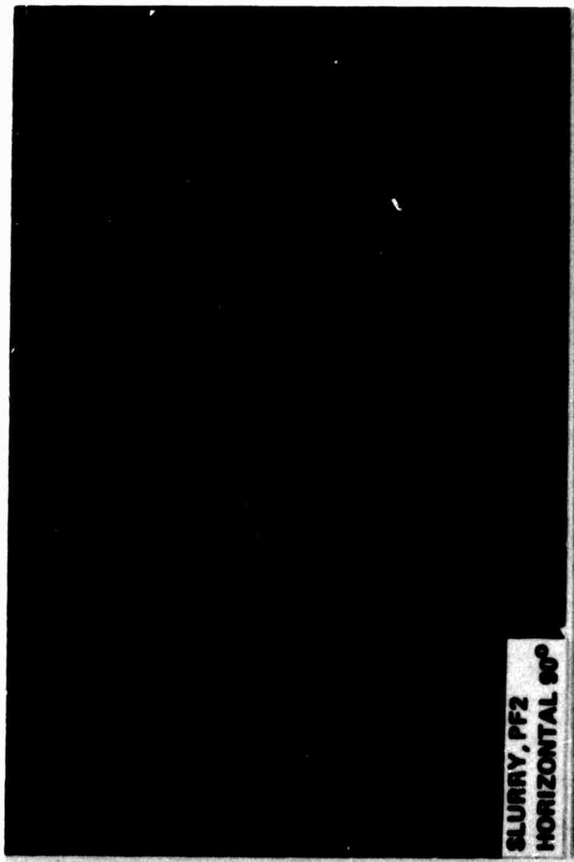
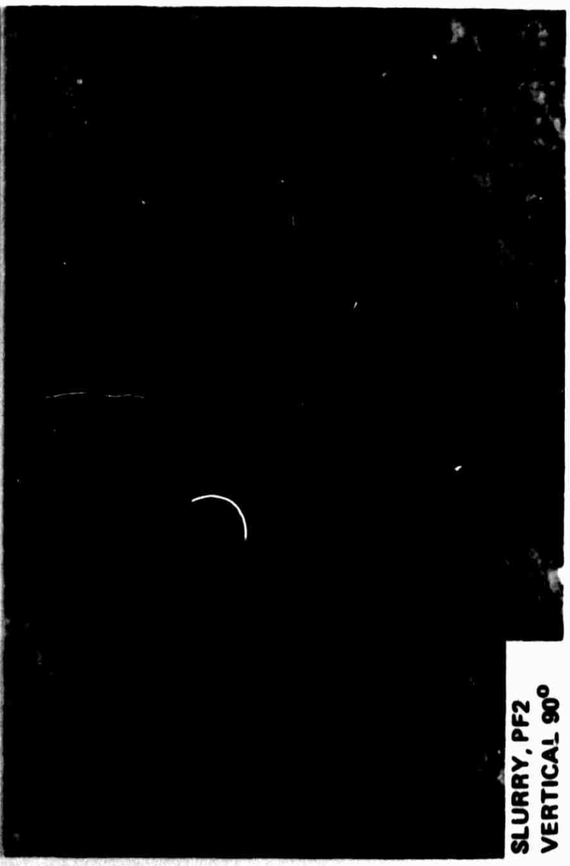

SLURRY, PF1
VERTICAL 0°

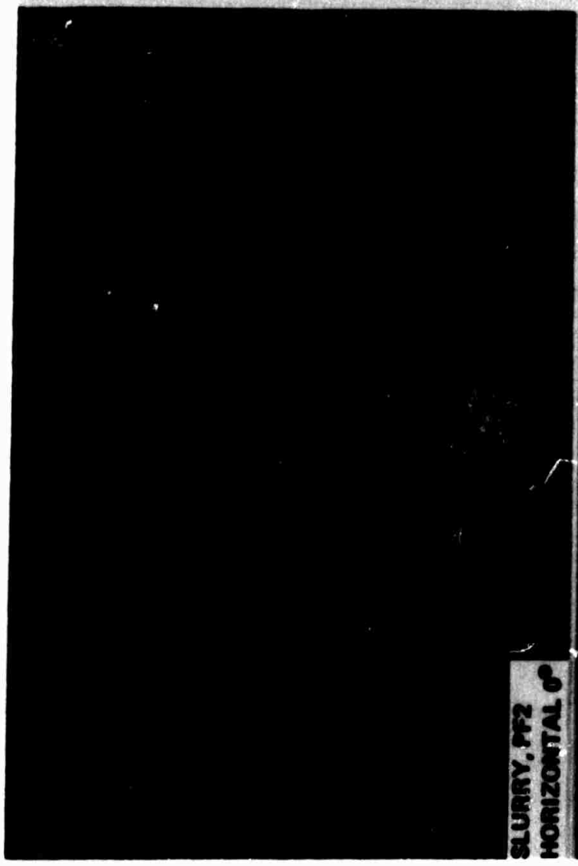
PLATE 7



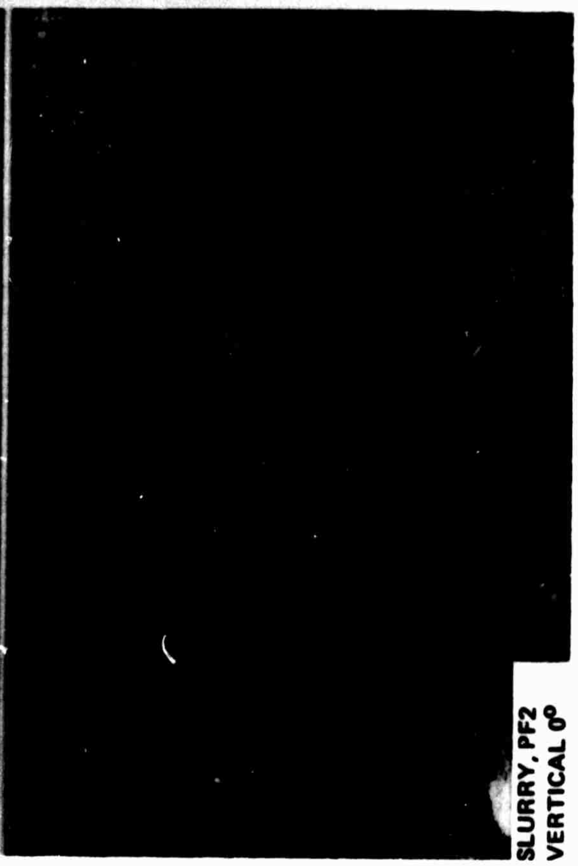
SLURRY, PF2
HORIZONTAL 90°



SLURRY, PF2
VERTICAL 90°



SLURRY, PF2
HORIZONTAL 0°



SLURRY, PF2
VERTICAL 0°

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A soil bin equipped for measuring the time-displacement behavior of representative particles under a moving load is recapitulated from eariler reports. Methods of preparing soils and placement of particle position markers are described with emphasis on problems associated with preparing fully saturated clay beds. For a series of driven wheel tests, the test parameters, test procedures, and the results of auxiliary tri-axial tests are reported. For towed wheel tests, strain rate fields are tabulated.

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Plate 1

Interchange Titles "Oriented, PF1 Horizontal 0°"

and "Oriented PF1 Horizontal 90°"