THE INFLUENCE OF COMPACTION METHOD
ON FABRIC OF COMPACTED CLAY

by

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A Thesis Submitted to the Faculty of the
DEPARTMENT OF CIVIL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1964
STATEMENT BY AUTHOR

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ACKNOWLEDGMENTS

The author expresses his appreciation to Professor Richard L. Sloane, who suggested the problem for this thesis. Professor Sloane spent considerable time studying and analyzing the replicas in the electron microscope and preparing the micrographs for this thesis.

The author also expresses his appreciation to his wife, Nelda, who helped make this thesis a success. Nelda spent many hours assisting with the photography; typing rough drafts; and typing the finished copy of this thesis.
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ABSTRACT

A laboratory investigation of compacted kaolinite was made for the purpose of analyzing the fabric of clay soils produced by different compaction methods at different moisture contents. The study of the clay fabric was carried out using electron microscopy of replicas of fracture surfaces in compacted clay specimens. It was found that compacted clay consists of packets in random and oriented fabric rather than individual platelets postulated by others. Kneading and impact compaction produces essentially the same fabric for a given moisture content and compactive effort. Static pressure was found to produce a different fabric than the other two methods. The degree of orientation was found to increase with increase in molding water content for the three methods of compaction; however, static pressure was the only method that caused an oriented fabric normal to the direction of loading.
Chapter 1
INTRODUCTION

The effect of remolding on the particle arrangement in clay soils (fabric) has been given considerable attention during the past forty years. It has been found that the engineering properties of a remolded clay soil are changed considerably from what they were in their undisturbed state. The changeable properties such as shear strength, swelling and shrinkage characteristics, compressibility, permeability, etc. are very important in the field of construction. To be able to predict the properties of a clay soil after compaction is fundamental in the design of safe, economical structures.

Because of its importance, engineers have intensively studied the effect of remolding on the physical properties of clay soils since 1925. From this effort, a sizeable amount of valuable scientific data on the fabric of clay soils has accumulated. The results of previous research have shown that the fabric of a clay soil governs all of its mechanical properties. In an effort to develop a sound theory of soil fabric, considering both natural development and the results of man-made disturbances (remolding), the subject has been studied from a variety of viewpoints. Most of the studies have used an indirect
approach, consisting of measurement of physical properties before and after compaction, and then prediction of the fabric from the data gathered.

1.1 History of Development

The present theory of clay soil fabric has evolved through forty years of research and from the efforts of many researchers. Terzaghi has been credited with the first working theory of clay soil fabric.\(^1\) His writings, published in 1925, discuss the bonds and the fabric in cohesive soils. According to Rosenqvist,\(^1\) Terzaghi suggested that the minerals stick to each other at the points of contact with forces sufficiently strong to build up a honeycomb fabric. As a result, comparatively large amounts of water could be enclosed within voids built up of aggregates of minerals glued to each other by the adhesion forces. Thus, each cell in the honeycomb structure was supposed to be made up of numerous single mineral grains.

About the same time Terzaghi published his work, a geo-chemist, V. M. Goldschmidt,\(^1\) was performing experiments with mixtures of clay minerals and various liquids such as water, benzene, carbon tetrachloride, liquid sulphur dioxide, and ammonia. He was studying the effect of non-polar liquids versus polar liquids on the plasticity of clays. Clay mixed with a non-polar liquid was found to exhibit non-plastic characteristics in contrast to the plasticity of the
same clay mixed with a polar liquid. In 1926, Goldschmidt presented a
theory that clay properties were due to crystalline minerals surrounded
by a film of adsorbed water molecules and that the water molecules
stuck to each other and to the minerals because of their dipole moment.
He further expressed the opinion that the flaky minerals in the highly
sensitive clays were arranged in unstable "cardhouse" fabric.
Goldschmidt also postulated that the surplus water was enclosed in the
space between a few mineral flakes leaning upon one another and that
the difference between clays of high and low sensitivity was the denser
arrangement of the minerals in the clays of low sensitivity. This
concept is slightly different from that postulated by Terzaghi.

A. Casagrande\textsuperscript{2} expanded the ideas put forth by Terzaghi
to form a more general concept of soil fabric. In his theory,
Casagrande considered a soil consisting of colloids and granular (silt-
size) particles. According to him, flocs of colloidal clay particles
would link with larger clay particles and silt grains to form a
flocculent fabric.

In 1953, Lambe\textsuperscript{3} presented a more comprehensive theory
of the development of fabric in inorganic soils. His theory was based
on the electrical properties of the clay colloids. For the undisturbed
marine clays an open structure similar to Goldschmidt's cardhouse
structure was shown, whereas in fresh water sediments the structure
was thought to be denser. According to his theory, in a marine
environment the positively charged edges of the clay platelets would be attracted to the negatively charged faces of the other clay platelets forming edge-to-face contacts, thus causing a haphazard or random arrangement of particles resembling a house of cards. In a fresh water environment (low cation concentration causing non-flocculating conditions) repulsion between the negatively charged faces would tend to produce a parallel arrangement, at least for a short range within the clay soil, until interfered with by larger silt grains. Silt grains would tend to disrupt the long-range order resulting in some degree of randomness in the fabric. Remolding of these clays would tend to cause parallelism so that a more parallel (oriented) fabric would result. Lambe's concepts are shown in Figure 1.

Some later studies by Mitchell added to the knowledge of clay soil fabric and helped substantiate Lambe's ideas. In his work, Mitchell studied the effect of remolding on the fabric of clay. Fourteen clays from various locations on the North American Continent were studied. Half of the clays were of marine and the other half of fresh water origin. For his studies, Mitchell prepared thin sections of each soil by replacing soil moisture with a high molecular weight wax. This technique enabled him to make direct observations of the samples under polarized light.

The microscopic study of thin sections of the selected clays, at natural water contents in both the undisturbed and remolded state,
Figure 1 - The Goldschmidt-Lambe concept of cardhouse fabric (after T. W. Lambe)
gave information on the fabric. It was found that the remolding of marine clays led to a small but detectable improvement in the clay orientation within small areas. The effect of remolding on the fabric of fresh water clays was found to depend on the intensity of parallel clay orientation, and the amount of precompression in the undisturbed sample. The magnitudes of the differences between the undisturbed and remolded engineering properties of both marine and fresh water clays were found to correlate, in general, with differences between the undisturbed and remolded fabrics. Mitchell found that, the more oriented the remolded clay was in comparison to the undisturbed clay, the greater were the differences between the undisturbed and the remolded engineering properties. He reported the following conclusions from his studies:

1. The greater the orientation improvement with remolding, the greater the loss of strength.
2. The greater the orientation improvement caused by remolding, the steeper the slope of the straight-line portion of the compression curve for the undisturbed clay with respect to the slope of the compression curve for the remolded clay.
3. The greater the orientation improvement caused by remolding, the greater the difference between the undisturbed and remolded void ratio at any pressure.
4. The secondary compression of clays having a high degree of parallel clay orientation was less than the secondary compression of poorly oriented clays.
5. The ratio of permeability in a horizontal direction to that in a vertical direction was directly related to the amount of particle orientation parallel to the horizontal.
It has been stated, however, that the limitations of microscopic resolution prevented Mitchell from making reliable determination of particle orientation in zones smaller than 10 microns wide. Under this limitation, Mitchell was forced to make some assumptions about the orientation below 10 microns based on the behavior of larger areas.

In 1956, Bolt presented a theory of consolidation based on the physico-chemical properties of clay soils. One of his main assumptions in the theory was a parallel alignment of clay platelets.

In 1957, Tan presented an imaginary three-dimensional picture of a random clay soil network. He believed that mutual contact between clay particles could be subdivided into three groups: (1) corner to flat surface contact; (2) edge to flat surface contact; and (3) flat surface to flat surface contact.

In 1958, Lambe expanded his theory and incorporated the findings of others. At this time, he presented a characteristic plot of molding water content versus compacted density (Figure 2). The lower plot is for a lower compactive effort than the upper curve. The two curves are shown as a representation of the effect of different amounts of compactive effort.

Lambe first discussed the concept of "water deficiency" as an aid to understanding the development of clay soil fabric.
Figure 2 - Effects of Compaction on the Fabric of Clay (after T.W. Lambe)
This concept recognizes that any given soil particle under any given state of stresses requires a certain amount of water to develop fully its double layer. The difference between this needed water and the existing water is deficient water which the particle will try to imbibe. The amount of water used in clay compaction is almost always less than that wanted by the soil; nearly all compacted plastic soils in the as-molded state have a deficiency in water.

Lambe's theory postulates that at (A) in Figure 2, there is not sufficient water to fully develop the diffuse double layers of the soil colloids. It is believed that the small amount of water present at (A) gives a very high concentration of the electrolyte, which depresses the double layer, and thereby reduces the inter-particle repulsion which results in a tendency toward flocculation of the colloids. Flocculation in this sense generally means a low degree of particle orientation accompanied by a low density. The low density and random or "card-house" particle arrangement is illustrated in Figure 2.

As the moisture content is increased from (A) to (B), the double layers around the soil particles expand and are fully developed. This expansion is believed to be due to the reduction in the electrolyte concentration caused by increasing the moisture content. As the thickness of the double layer increases, the tendency toward flocculation decreases. The reduced degree of flocculation permits a more orderly arrangement of the particles and a higher density. Lambe uses the term "lubrication" to describe the effect of the increased inter-particle
repulsion which permits the particles to slide past one another into a more oriented and denser bed.

He further suggested that as the water content is increased from (B) to (C), the double layer expands more, accompanied by a continued reduction in the net attractive forces between particles. Although a more orderly arrangement of particles exist at (C) than (B), there is a decrease in density. It is believed that the decrease in density, going from (B) to (C), is due to the added water that has diluted the soil particles per volume.

Figure 2 also illustrates another important characteristic of compaction and its effect on the fabric of soil. When the compactive effort is increased, the compacted density is increased. The greater the input of work, the more nearly parallel are the clay particles, and usually the closer together they are.

As the input of work increases, the clay particles become more parallel to each other. The increased input of work also tends to compress the clay particles closer together. Lambe believes that at high molding water contents (and high degree of saturation), increased compactive effort may merely align particles without significantly altering the particle spacing. He did not insinuate that the previously stated theory holds true for all soils. In fact, he stated that some soils will be found that show an extreme variation going from random to parallel orientation, as illustrated in Figure 2. Other soils will
exhibit only slight improvement of orientation with increased molding water. It is Lambe's belief that this slight variation arises with soils that are either fairly well dispersed dry of optimum, or are still partly flocculated wet of optimum. Lambe postulated that an improvement in orientation occurs as the molding water increases for these soils. The improvement, however, is less than the extreme case shown in Figure 2.

In a succeeding paper, Lambe presented additional data to substantiate his theory. Tests were run which examined the effect of compacted clay fabric on permeability. The test data which was gathered indicated a much higher permeability for a soil compacted dry of optimum than for a soil compacted wet of optimum. After analyzing the data, it was concluded that the samples compacted dry of optimum had a more randomly-oriented particle arrangement resulting in a higher void ratio and, therefore, a higher permeability. The samples compacted wet of optimum had a more parallel particle arrangement resulting in a lower void ratio and, therefore, lower permeability.

In the same paper, Lambe presented an analysis of clay particle reorientation due to one-dimensional consolidation. Figure 3 illustrates the effect of one-dimensional compression on the structure of compacted clays. The upper part of the figure shows what would happen to the particle orientations under a one-dimensional compression. The orientation in the circles show that a load tends to align the
Figure 3 - Effect of One-Dimensional Compression on the Fabric (after T.W. Lambe)
particles in a parallel array. In the case of the remolded or wet-side compacted clay, in which the particles are already parallel, a load merely brings them closer together. The lower half of Figure 3 suggests what would happen to particle orientation under very high pressures.

For the dry-side compacted sample the pressure orients the particles normal to the direction of compression and decreases the spacing between them. For the wet-side compacted clay in which the particles are already oriented the pressure reduces the spacing between the particles. Theoretically, a large enough pressure would make the structure of the wet-side compacted sample identical to that of the dry-side compacted sample. Upon load release from this pressure the two samples would follow the same rebound. During rebound the spacing between particles increases, but only negligible changes in orientation occur.

Seed and Chan studied the effect of fabric on the shrinkage characteristics of compacted clay resulting from kneading and impact compaction methods. Kaolinite clay was compacted at different moisture contents and the shrinkage for each determined. It was concluded that the shrinkage might possibly be used as a measure of particle orientation. It was found that samples compacted dry of optimum, and therefore having essentially flocculated fabric, exhibited considerably less shrinkage than samples of the same composition compacted wet of optimum.

Other studies were carried out in which swell pressures were measured. It was found that samples compacted dry of optimum
moisture content exhibited less swell pressure than those compacted wet of optimum.

Seed and Chan\textsuperscript{9} also studied the effect of shear strain on particle orientation. They suggested that shear strains, developed during the kneading and impact methods of compaction, could change a flocculated fabric to a dispersed fabric. This was based on a study of deformation characteristics of compacted specimens. It was found that, when compacted specimens were subjected to repeated load applications, a marked increase in resistance to deformation developed. This was attributed to the change in soil fabric during the loading application.

If shear strain after compaction can change the fabric of a compacted clay, then the shear strains which occur during compaction are also likely to have a marked effect on the initial fabric. This line of thinking has been justified by analyzing the movement of soil during kneading and impact compactions. When a sample of clay is compacted dry of optimum, there is usually no appreciable penetration of the compaction hammer or tamping foot once the soil has been rammed into a compact mass from its original loose state. Under these circumstances, there is no appreciable shear deformation during compaction. Therefore, a soil which tends to flocculate will retain a flocculated fabric even after compaction. On the other hand, compaction of the same soil wet of optimum usually results in appreciable penetration of
the compacting hammer or tamping foot even after the maximum
density has been attained, producing considerable shear strain in the
soil.

Seed and Chan applied their ideas of shear strain to the
accepted theory of compaction set forth by Lambe. They believed that
shear strains in clays will cause orientation of clay platelets. A com­
plete general theory that incorporates Lambe's concepts and Seed and
Chan's concepts is as follows:

At low water contents the high electrolyte concentra­
tion prevents the double layer from developing fully result­
ing in low inter-particle repulsion and consequently, for
most soils, a tendency for flocculation of the clay particles. An increase in water content causes a decrease in electro­
lyte concentration, expansion of the double layer, and
therefore increased repulsion between clay particles to­
gether with a tendency for higher pore-water pressures to
develop when the tamping pressure is applied; consequently
it leads to a decrease in shear strength. The somewhat
reduced tendency to flocculate but more particularly the
greater shear deformations under the tamping foot which
result from the reduction in shear strength can lead to an
increased degree of dispersion or an increased degree of
orientation of the clay particles in the compacted soil. 9

Based on the above hypothesis, Seed and Chan concluded
that a compaction procedure involving large shear deformations and
one involving negligible shear deformations could be compared as
follows: the sample compacted with high shear deformations (kneading
compaction) would have a relatively dispersed fabric, while the sample
compacted with low shear deformations (static compaction) would have
a relatively flocculated or less dispersed fabric.
Trollope and Chan\(^8\) studied clay soil fabric from a more general approach, similar to that of Terzaghi and Casagrande. Rather than consider clay as a material consisting only of clay platelets, they took a realistic approach and considered a clay as consisting of both granular and colloidal particles. In their work a phenomenon was studied which they called "step-strain". To develop a theory of step-strain in clay soils, the fundamental clay fabric was considered.

In considering the clay fabric, the possibility of a buildup of "packets" of clay particles to form an oriented arrangement was considered. Trollope and Chan suggested that the colloidal particles, referred to by previous researchers, may consist of one or many colloidal crystals arranged in "packets" or oriented fabric.

They also explained how the buildup of a "cardhouse" structure could occur under natural environmental conditions. Two cases were considered: one in which the existing pore-water was a weak electrolyte; the other in which the pore-water was a strong electrolyte. A particle fabric, characteristic of each case, was said to result. The fabric developed in the first case would be an expansive system when acted upon by external forces. The fabric, in the second case, would be a contractive system, under the same forces.

Trollope and Chan\(^8\) also discussed the subject of remolding, and defined the terms "complete remolding" and "partial remolding". It was stated that complete remolding would occur only if a
cardhouse fabric, within a clay, is completely transformed into an oriented fabric. In light of the past research and developed theory, complete remolding was said to occur only in areas where large shear strains developed. This, of course, was said to be within the zones of shear failure along failure planes. Therefore, compacted clay soils, which had previously been considered remolded soils, were said to be only partially remolded. Their conception of a compacted clay soil is one containing coarse (sand and silt) grains distributed at random in a colloidal matrix consisting of zones of "oriented" fabric surrounded by zones of "cardhouse" fabric. Trollope and Chan further stated that, when a compacted clay soil is subjected to shear strains sufficient to cause failure, complete remolding will develop along the resulting failure plane. The yield of a colloidal fabric along a failure plane was said to be synonymous with complete remolding. It could also be said that yield occurs when an oriented fabric is developed along a continuous surface throughout the soil mass.

This condition of matrix yield is achieved when applied shear stresses are sufficient to force the colloidal particles into such a position that they tend to be oriented parallel to one another and in the direction of the potential failure surface.\textsuperscript{10}

After some previously successful electron microscope studies using replica techniques, Rosenqvist\textsuperscript{11} produced an electron micrograph of blue Oslo clay which showed a very close resemblance to the picture of clay fabric put forth previously by Tan.\textsuperscript{6} Rosenqvist's
electron microscope studies have proven the existence of both parallel and cardhouse types of fabric.

In extending the above idea, one may consider the possibility of a clay soil fabric consisting of small regions or groups of parallel oriented clay platelets which themselves are arranged in a more-or-less random fabric. Trollope and Chan, Trolley and Quirk, Aylmore and Quirk, and Michaels among others, have suggested such a possible fabric. The small groups of oriented clay platelets have been called packets, books, domains, among other terms; but all terms have the same basic concept. Aylmore and Quirk, using the electron microscope and replica techniques, showed such packets to exist.

1.2 Scope

From the review that has been presented, one may conclude that the theory of clay soil fabric is complete. This is not the case, however, for there are many questions yet to be answered. The present ideas on clay soil fabric resulting from different compactive methods are not complete. Theory postulates that compaction of clay produces a flocculent or "cardhouse" fabric for moisture contents below optimum moisture, and a dispersed or parallel fabric for moisture contents above optimum moisture. The transition from a flocculent to a dispersed fabric is presumed to occur at or near optimum moisture. This theory of compacted clay fabric has been developed primarily
through examination of the mechanical properties of compacted clay soils. A detailed visual observation of compacted clay fabric is needed to substantiate or modify the present theory. Some of the questions that need to be answered are: (1) Is the term "cardhouse" properly descriptive or is it misleading when considering a compacted clay soil? (2) Will orientation of clay platelets occur without developed shear strain? (3) Does orientation occur at or near optimum moisture? (4) How should the term "oriented" be defined? (5) Can a single theory be developed to adequately define all methods of compaction?

The purpose of this investigation is to study the fabric resulting from various compaction methods and different moisture contents. An attempt will be made to answer some of the questions raised by existing theory and to clarify some of the present concepts.
2.1 General Approach

A selected kaolinite was compacted by kneading, impact, and static compaction at three different moisture contents: 3 per cent below optimum; at or near optimum; and 3 per cent above optimum. In order to have a close comparison between the three methods, clay cylinders were compacted to the same density by each method of compaction for a given moisture content.

The compacted cylinders were first air dried, then vacuum dried for moisture and density determinations. This method of drying was used to eliminate the possible effect of heat on the fabric of the compacted clay.

Platinum-carbon replicas were prepared from specimens taken from the centers of the clay specimens. Representative sections were sawed from the centers of the compacted clay cylinders. These sections were fractured to produce fracture surfaces both parallel and normal to the longitudinal axis of the compacted cylinders. Platinum-carbon replicas of the fracture surfaces were then prepared.

The platinum-carbon replicas were mounted on 1/8 inch diameter electron microscope grids and viewed in an electron
microscope. Each replica was studied to determine the fabric resulting from the different methods of compaction and moisture content. A representative area of each replica was selected and micrographs of the selected area taken. Micrographs were enlarged, and a detailed fabric study performed.

2.2 Equipment

The following equipment was used in the laboratory studies:

1. Harvard miniature compaction apparatus with special compaction mold
2. Special impact compaction apparatus
3. Hand operated unconfined compression apparatus
4. Vacuum desiccator with high-vacuum rotary pump
5. Mikros VE-10 Thin-film Vacuum Evaporator
6. Ladd carbon evaporation apparatus

2.3 Materials

A special kaolinite, processed by the Georgia Kaolin Company, Dry Branch, Georgia, was selected for this study. This kaolinite, sold under the trade name Hydrite-UF, possesses characteristics making it eminently suitable for electron microscopic studies. Hydrite-UF has a well-defined, platey, hexagonal shape, and a high degree of crystallinity. The fabric, resulting from the different
compaction methods at different moisture contents, is easily identified because of these characteristics. Hydrite-UF also has a very small particle size (UF means ultra fine), and exhibits low shrinkage characteristics when compacted and dried. It is free of mineral impurities which cause identification difficulties in electron microscopic studies of other kaolinite clays. All chemicals used in this study were reagent grade as defined by the American Chemical Society. Electron microscope supplies such as grids, shadowing materials, etc. were obtained from reputable suppliers.

2.4 Optimum Moisture Content Determination

Before compaction of the test specimens, the optimum moisture content of the Hydrite-UF had to be determined. This was accomplished using the Harvard miniature compaction apparatus. Individual 200 gram samples of dry kaolinite were mixed with calculated quantities of distilled water and placed in polyethylene bags. The bags were sealed with rubber bands and stored for a curing period of thirty-six hours. After curing, samples were compacted using the Harvard miniature compaction apparatus. Each clay sample was compacted in five layers, by twenty-five tamps per layer using a forty pound spring in the special tamper. Results of the moisture-density determination are shown in Figure 4. The Harvard miniature compaction apparatus is shown in Figure 5.
Max. Dry Density = 83.0 lb/ft$^3$

Optimum Moisture = 34.5%

$S = 100\%$

Figure 4 - Moisture Density Curve for Georgia Kaolinite (Hydrite-UF)
Figure 5 - Photograph of the Harvard Miniature Compaction Apparatus used in the optimum moisture determination of the Georgia kaolinite.
2.5 Specific Gravity Determination

The specific gravity of the clay was determined by the standard pycnometer method, ASTM Designation: D854-52. The test was performed according to the indicated standard, using a volumetric flask having a capacity of 100 milliliters. Results of the specific gravity determination (Sp. Gr. = 2.74) were used to calculate the 100 per cent saturation curve shown in Figure 4.

2.6 Preparation of Kaolinite for Compaction

Three batches of Hydrite-UF plus distilled mixing water were prepared at 31.5, 34.5 and 37.5 per cent moisture contents. Each batch contained 600 grams of dry kaolinite plus the calculated quantity of distilled water required to yield the desired moisture content. Several trials were required to perfect a process by which the desired moisture contents could be obtained at the time of compaction. It was found that the clay could be prepared to meet the stated conditions within reasonable limits (plus or minus 0.3 of the desired moisture per cent) using the detailed process described below.

Six hundred grams of Hydrite-UF were weighed on the triple beam balance and placed in a stainless steel mixing pan. The calculated quantity of distilled water, required to bring the clay to the desired moisture content, was measured in a 500 ml. graduated cylinder. The water was placed in a polyethylene squeeze bottle and
sprayed on the clay, while mixing by hand. After the measured quantity of water had been added to the clay, and mixed thoroughly, the container and wet clay were weighed on the triple beam balance. The difference between the initial total weight before mixing and the total weight after mixing was the volume of water which had evaporated during the mixing process. This additional water was mixed with the clay, as before, to compensate for the evaporation. Immediately after the mixing process, the clay batch was placed in a polyethylene bag, sealed at the top with a rubber band, and placed in a sealed metal container for a thirty-six hour curing period.

2.7 Compaction

After curing, each of the three batches of clay and water was compacted by the three different methods of compaction. Each batch was divided into three parts: one part for kneading compaction; one part for impact compaction; and one part for static compaction. The kneading compaction method was considered to be the standard method, and the other two methods were adapted to give comparable density results. It was decided that an impact compaction procedure yielding the same wet weight after compaction as the kneading method would be comparable enough for the purpose of fabric studies. For the static compaction, a different technique was used. In this case, a
compacted specimen having the same wet weight and volume as the specimen compacted by kneading compaction was considered to be comparable.

The same special mold was used in all three compaction methods. The mold (Figure 6) is a split type designed so that compacted cohesive soils can be removed from the mold without disturbance. Disturbance of a compacted clay specimen during ejection from the standard Harvard miniature mold could alter the fabric being studied; therefore, the special split mold was used.

2.7.1 Kneading Compaction Procedure - The prepared clay was compacted in the special mold in five layers, by means of the kneading compactor from the Harvard miniature compaction apparatus (Figure 7), using a 40 lb. spring and twenty-five tamps per layer. One compacted specimen was prepared (for each moisture content) by this method.

2.7.2 Impact Compaction Procedure - A special impact compactor was constructed consisting of a 1/2 inch diameter rod, a 1.71 lb. rammer, and a dropping height of 12 inches (Figure 8). Trial and error procedures were performed to determine the number of layers and blows per layer required to yield the same wet weight as the kneading compaction specimen. It was found that the desired wet weight could be obtained if the clay was compacted in three layers with twenty-five blows per layer.
Figure 6 - Photograph of the miniature compaction mold used in the three compaction processes. The mold, constructed as shown, permitted the removal of the compacted cylinders with a minimum of disturbance. The volume of the mold is 1/454 cu. ft.
Figure 7 - Photograph of the kneading compaction apparatus. The kneading compactor, shown, is the compactor from the Harvard Miniature Compaction Apparatus.
Figure 8 - Photograph of the impact compaction apparatus.
The compaction device consist of a 1.7 lb. weight
with a 1.0 ft. fall. The tamping rod has a diameter
of 0.5 inches.
2.7.3 Static Compaction Procedure - From the third section of the batch, a quantity of material (equal to the wet weight of the kneading compaction specimen) was weighed on the torsion balance. This material was placed in the compaction mold, and compacted with the static compactor. Since the cylinder was of a given uniform diameter and moisture content, the only variable in this process was the height of the compacted specimen. The clay was compressed inside the cylindrical mold by static pressure until the final specimen height was equal to the height of the sample compacted by the kneading process. The result was assumed to be comparable since the clay was from the same batch and the same wet weight was obtained. (Figure 9)

2.8 Drying Method

At the completion of each compaction process, the clay cylinders were weighed on the torsion balance, measured for shrinkage determination, and placed in an open-air storage bin for drying. The cylinders were allowed to air dry for a four day period. After this time, they were placed in the vacuum desiccator (Figure 10) for final drying. Final drying of the compacted specimens was completed in a vacuum of approximately $10^{-3}$ mm of mercury pressure. Drying required approximately four days. The clay cylinders were removed from the vacuum desiccator and reweighed for moisture-density determinations and remeasured for shrinkage. They were then placed
Figure 9 - Photograph of the static compaction apparatus. The static load is transmitted to the clay through the proving ring.
Figure 10 - Photograph of the vacuum desiccator used to dry the compacted specimens. This desiccator was also used to "out-gas" the fractured specimens prior to the platinum-carbon replication process.
in labeled plastic bags, sealed with rubber bands, and stored until replication could be accomplished.

2.9 Preparation of Fracture Surfaces

In order to have representative samples for the replication process, sections were taken from the centers of the compacted, vacuum-dried clay cylinders. Sections were sawed from the centers of the cylinders as shown in Figure 11. Each section was scored around the outside with a razor blade, then fractured along the scored groove as indicated in Figure 11. Each fracture specimen was trimmed of excess material to form an approximate one centimeter cube. Fracture surfaces were cleaned by blowing gently upon them. Prepared fracture specimens were placed in covered plastic Petri dishes to prevent dust contamination. Because a complete picture of the effect of compaction method on the fabric of the clay was being studied, fracture surfaces both normal and parallel to the axis of the compacted clay cylinder were prepared.

2.10 Replicating Methods

The first ten fracture specimens were replicated by shadow-casting with 20 per cent palladium - 80 per cent platinum using William and Wyckoff's method and an evaporated carbon film deposited according to Bradley's technique. The remaining eight
Figure 11 - Photograph of the steps for preparing a fracture surface for replication: (1) compacted clay cylinder; (2) representative sample sawed from the center of the cylinder; (3) sample fractured with a razor blade; (4) fractured sample ready for trimming; (5) trimmed fracture specimens stored in Petri dish until replicating process.
specimens were shadow-cast using the platinum-carbon pellet technique reported by Bradley and replicated by an evaporated carbon film.

The replicas were removed from the clay by two different techniques. In the first and second methods, the replicas were reinforced with polystyrene applied to the replica in liquid form. The replicas were removed from their embedment by dissolving the plastic in ethylene dichloride. This technique is a modification of the method suggested by Bates and Comer. In the third method, Victawet was used to aid in the stripping procedure. The replicas were reinforced using polystyrene pellets and removed from their embedment by the Bates and Comer method.

2.10.1 Method 1 - The Petri dishes, containing the previously prepared clay specimens, were placed in the vacuum desiccator and "out-gassed" at a pressure of $10^{-3}\text{mm}$ of mercury. The specimens were allowed to remain under vacuum for approximately four hours prior to the platinum-carbon replicating process. This technique was used to speed up the pump-down time in the metal shadow-casting and carbon replicating processes.

Out-gassed specimens were placed on the rotating table of the Mikros VE-10 Vacuum Evaporator (Figure 12), fracture surfaces up. Small 1.5 centimeter square lead shields with 0.5 centimeter square openings were placed over the fracture surfaces. The shields
Figure 12 - Photograph of the Mikros VE-10 Vacuum Evaporator used in the platinum-carbon replicating process. The evaporation of platinum and carbon is carried out inside the basket-covered bell-jar.
were used to allow only the 0.5 centimeter square areas to be shadow-cast and carbon replicated. Handling of the fracture specimens after they were prepared and replicated was minimized to protect the fracture surfaces from disturbance. Clay specimens, resting on the rotating table with the lead shields in place, are shown in Figure 13.

A length of 4 mil. platinum-palladium wire (80% Pt-20% Pd), approximately 2 centimeters long, was shaped into a ball and placed in a tungsten wire basket. The basket was connected to two electrodes so the wire basket would be approximately 5 centimeters above and 15 centimeters away from the clay specimens, as shown in Figure 13. The bell-jar was sealed and evacuated to a pressure of 10^-6 millimeters of mercury. Platinum-palladium was evaporated by heating the tungsten basket by means of high-amperage, low voltage direct current. Upon completion of metal shadowing, the bell-jar was then returned to atmospheric pressure, opened, and the wire basket removed.

Carbon rod holders were placed so that carbon could be evaporated from 10 centimeters above the center of the rotating table. Clay specimens were placed on the outer edge of the rotating table, with the lead shields in place as before. Two 1/8 inch diameter carbon rods, one with a special necked-down point, were inserted in the holders. The set-up is shown in Figure 14.

The bell-jar was replaced, and evacuated to 10^-6 mm of mercury pressure. The necked-down portion of the carbon rod was
Figure 13 - Photograph showing the first method used to platinum shadow-cast fracture surfaces. Platinum-palladium wire is evaporated in the tungsten wire basket, shown at the upper left of the picture, under a pressure of $10^{-6}$ mm of mercury. The specimens are shown in the foreground with the lead shields in place.
Figure 14 - Photograph of the carbon evaporation apparatus. The necked-down section of the carbon electrode, shown at the top, is evaporated under a pressure of $10^{-6}$ mm of mercury. The fractured samples are rotated on the rotating table, under the carbon arc, to yield a continuous carbon coating on the fracture surface.
evaporated by passing high amperage, low voltage direct current through the two electrodes. As the carbon was evaporated, the samples were rotated beneath the arc on the rotating table. Rotation of the clay specimens below the evaporating carbon allowed the shadow-cast rough fracture surfaces to be coated with a uniform carbon film. The thickness of the evaporated film was not determined, but it was estimated to be between 100 - 150 angstroms from appearance of the micrographs. It was found that the required thickness was determined by the surface roughness of the clay fracture surface. To avoid breakage of the replicas, thicker films of carbon must be applied to a rough surface than to a smooth surface.

In order to avoid break-up of the platinum-carbon replicas during removal of the clay, it was necessary to reinforce them by embedment in a plastic base. A modification of the polystyrene pellet method suggested by Bates and Comer,\(^1^5\) was used. Each replica was coated with liquid polystyrene and allowed to dry. When dry the polystyrene-embedded replica was broken free of the clay specimen. A thin layer of clay usually remained attached to the replica, and required further treatment with an acid solution for removal.

An acid solution was prepared consisting of 60 per cent phosphoric, 25 per cent hydrofluoric, 10 per cent nitric, and 5 per cent acetic acid. A small quantity of this solution was placed in a polyethylene container, while working under a ventilated fume hood. The
plastic-embedded replica was placed on the surface of the solution, replica side down. The replica was allowed to wash in the acid solution for eight to ten hours. At the end of this period, it was transferred to a fresh container of acid solution and washed for an additional six to eight hours. It was then washed by floating on the surface of several changes of distilled water and finally allowed to dry.

The cleaned replica was scored into 2 mm squares by means of a sharp clean razor blade. The replica was removed from the hardened plastic by dissolving the polystyrene in ethylene dichloride. The scored, plastic-embedded replica was placed on the surface of clean ethylene dichloride, contained in a small polyethylene dish, replica side up. The polystyrene dissolved in approximately thirty minutes, leaving the squares of replica floating on the surface. The replica squares were removed to a fresh dish of solvent by means of a section of stainless steel screening and washed by floating on the fluid surface for another thirty minutes. This process was repeated for a third washing before picking up the replicas on 400-mesh 1/8 inch diameter electron microscope grids.

Some of the replicas were rolled and folded, as a result of the ethylene dichloride washings. These replicas were picked up from the last ethylene dichloride bath and transferred to a container of carbon film straightener solution, where they soaked for one minute. They were then removed from the straightener solution and placed on top of
a solution of 25 per cent ethyl alcohol and 75 per cent distilled water. The greater surface tension of the alcohol-water solution snapped the replicas plane. Replicas were picked up on 400-mesh 1/8 inch specimen grids as before.

Each mounted replica was viewed with an 80X binocular microscope to determine its quality. The presence of folds and fractures in the film were detected in this manner. The best quality replicas were placed in No. 5 gelatin capsules and the capsules were glued to microscopic specimen plates for storage until they could be viewed in the electron microscope.

2.10.2 Method 2 - This method of replication was suggested by D. E. Bradley. It consists of a simultaneous evaporation of platinum and carbon for the metal shadow-casting process rather than the evaporation of a metal wire as described in the first method. Small pellets of carbon containing a high percentage of finely-divided platinum were used for shadow-casting. The special carbon evaporation apparatus (Figure 14) was used for this method. The evaporation was carried out inside the evacuated bell-jar as in Method 1.

Clay specimens were placed on the base of the special apparatus, directly below the top set of electrodes, and adjacent to the lower set of electrodes. Lead shields were placed on the fracture surfaces, as before. This setup is shown in Figure 15. Carbon rods,
Figure 15 - Photograph of the platinum-carbon evaporation apparatus used in the second replicating method. Platinum-carbon pellets are evaporated in the lower position and carbon is evaporated in the upper position. The clay specimens are placed in position at A for the replicating process.
one with a necked-down end, were inserted in the top electrode holders. A platinum-carbon pellet was held between the two electrodes in the lower position.

2. 10. 3 Method 3 - Six of the replicas prepared by Methods 1 and 2 were found to be unsatisfactory when viewed in the electron microscope. These replicas were remade using a third method. Surface replication was accomplished as in the second method. Replicas were reinforced by the polystyrene pellet method suggested by Bates and Comer. Recovery of the replicas was accomplished by their method.

Before replicating the clay surfaces, a thin film of dehydrated Victawet wetting agent was evaporated onto the fracture surfaces. (Similar to platinum-palladium wire evaporation setup in Figure 13). Clay specimens were placed directly below the basket, fracture surfaces up, the bell-jar evacuated, and the Victawet evaporated. Specimens were shadow-cast and carbon replicated as in Method 2.

The Bates and Comer method, used in removing the replicas from the clay specimens, was performed as follows: the clay specimen plus replica was gently pressed into a heat-softened polystyrene disc, replica side down, and allowed to cool to room temperature. The reinforced replica plus clay was placed in a dish of 48 percent hydrofluoric acid (replica side up) for as long as necessary to
remove the clay from the replica. After separation of the clay and embedded replica, the replica was placed in a fresh acid bath for one hour, then thoroughly washed in distilled water and allowed to dry. When dry, the embedded replica was scored into 2 mm squares, placed in a dish of ethylene dichloride, replica side up, and pushed to the bottom. The plastic adhered to the bottom, and remained there until the replicas floated free. The replicas were picked up from the ethylene dichloride and transferred to a fresh container of ethylene dichloride for washing. The replicas were handled as described in Method 2 for the remainder of the treatment.

2.11 Electron Microscope Studies

The platinum-carbon replicas, prepared by the three methods, were studied in a Philips EM-100B Electron Microscope (Figure 16). The fabric produced by the different compaction methods and moisture contents, as seen in the replicas, was studied thoroughly by scanning the entire surface of each replica. From this scan, a representative area was selected to be photographed at a magnification of 10,400X. The photographic plate, for each representative area photographed, was developed and a 2X enlargement made. The enlarged prints were studied in detail, and the fabric shown in each was analyzed.
Figure 16 - Photograph of the Philips EM-100B Electron Microscope used to study the platinum-carbon replicas. The plate camera, attached to the microscope as shown, was used to produce the micrographs accompanying this thesis.
Chapter 3

RESULTS

3.1 Moisture-Density

Special batching and compaction techniques were used to permit comparison of fabric resulting from the three different compaction methods at selected moisture contents.

The technique developed for batching the Hydrite-UF did not yield completely accurate results. Variable factors, such as relative humidity and handling time during compaction, influenced the amount of evaporation prior to weighing. The maximum deviation from a pre-selected moisture content occurred on the dry side of optimum moisture content using the impact compaction method. A moisture content of 31.9 per cent was obtained rather than the selected value of 31.5 per cent.

The kneading compaction method was used as the standard, and both impact and static compaction techniques were developed to yield comparable dry densities among the three methods. Although the specimens were compacted to the same wet weight before drying, the weights after drying were not the same. However, all of the cylinders compacted by impact and static methods were within 0.3 lbs. per cu. ft. of the dry density obtained by kneading. The results of the
moisture-density determinations for the three methods of compaction are shown in Table I of the Appendix.

3.2 Shrinkage After Compaction

Shrinkage measurements were made across the diameter of each compacted cylinder. Shrinkage of the cylinders varied from 1.2 per cent, for moisture contents dry of optimum, to 5.1 per cent, for moisture contents wet of optimum. All compaction methods showed similar results. A correlation of shrinkage versus fabric was not attempted.

3.3 Sample Preparation

The accuracy of replica studies depends, to a great extent, on the methods of sample preparation. The center sections of the clay cylinders were fractured gently to produce a minimum of relief on the fracture face. Each specimen was trimmed with caution to prevent disturbance of the prepared surface, then gently blown clean of loose clay fragments. The technique was time consuming but produced fracture surfaces of good quality.

3.4 Replication

Method 3 of the replication techniques produced the most satisfactory replicas. Difficulty with methods 1 and 2 was encountered during the cleaning process, while the replica was embedded in the
polystyrene. A film of partially-dissolved altered clay remained attached to the surface of the replica after the final cleaning. As a result, the replicas for electron microscopy were of poor quality. The Victawet wetting agent, used in Method 3, eliminated the problem, and clean replicas with satisfactory resolution resulted.

3.5 Micrographs

Some of the micrographs shown in Figures 20, 21 and 22 are difficult to analyze. This is due, primarily, to the replica cleaning processes discussed in Methods 1 and 2 of Chapter 2. Some of the replicas were not cleaned sufficiently and areas suitable for photographing, that were completely free of foreign matter, could not be found in the scan. Some areas had to be photographed that included foreign matter so representative fabric could be shown. Although this condition was not suitable, the micrographs produced were of sufficient quality for fabric analysis and they did not effect the over-all results of this study.
Chapter 4

CONCLUSIONS

4.1 General

Although sources of error were present in the laboratory methods, the over-all results are sufficiently satisfactory for adequate determination of fabric.

4.1.1 Moisture-Density - The small deviation in the moisture contents (paragraph 3.1) during the compaction processes are not considered significant. Because the three methods of compaction yielded similar results for moisture content versus dry density, the effects of moisture content variation on the fabric produced by the different methods is considered to be negligible.

4.1.2 Shrinkage - The shrinkage of the clay cylinders during drying (paragraph 3.2) is considered to be too small to have a significant effect on the fabric. Shrinkage will cause small displacements and orientations which will not change the character of the fabric. The fabric determined from electron microscopy of the platinum-carbon replicas is considered to reflect the influence of the compaction methods and moisture contents.
4.2 Definitions of Terms

In order for the reader to fully grasp the meaning of the replica analysis that follows, some special terms should be clarified.

4.2.1 Packets and/or Books - Groups of oriented clay platelets have been called domains, packets, books and oriented aggregates. The terms "packets" and "books" are used in this paper to describe groups of clay platelets aggregated with basal planes parallel to one another.

4.2.2 Oriented Fabric - The term "oriented fabric" is used to describe packets aligned parallel to one another. An analogue to this definition would be books of different sizes stacked one on top of another, back to back, with adjacent stacks interlocking to form a continuous wall of books. (Figure 17-a).

4.2.3 Random Fabric - The term "random fabric" is used to describe packets situated in a haphazard arrangement relative to one another. An analogue to this definition would be books of different sizes lying on or against adjacent books, as shown in Figure 17-b, with no apparent pattern.

4.2.4 Horizontal and Vertical Sections - Fracture surfaces were prepared of horizontal and vertical sections of the compacted clay cylinders. A horizontal section is defined as a section normal to the longitudinal axis of the compacted clay cylinder. A vertical section is
Figure 17 - Sketches Showing Analogy Between Books and Packets of Clay Platelets
defined as a section parallel to the longitudinal axis of the compacted clay cylinder.

4.3 Replica Analysis

Details of the fabric produced at each moisture content by each method of compaction were determined from the micrographs as noted in paragraph 2.11.

4.3.1 Fabric Produced by Kneading - A characteristic common to all the replicas studied, both from horizontal and vertical sections, was recognized. Zones of oriented fabric were found to exist at all three moisture contents. The oriented zones (Figure 20) are thought to result primarily from the shear strains produced by the kneading action of the compaction process. This is in accord with the conclusions made by Seed and Chan.\(^9\) If one considers the movement of the clay under the action of the tamping rod of the kneading compactor, the existence of the fabric shown would seem logical. Based on the Terzaghi-Prandtl bearing capacity theory\(^{17}\) (Figure 18), shear planes would develop in the clay from the kneading action. Each tamp of the rammer would create zones of shear in the following places: (1) along the boundaries of zone I, (2) along the boundaries of zone II; (3) along the boundaries of zone III and (4) after zones I, II, and III have failed and the rod moves through the clay, a zone of shear would be located along the surface of the tamping rod (Figure 19). The shear strains
Figure - 18 - Sketch of the Terzaghi-Prandtl Bearing Capacity Theory

Figure - 19 - Sketch of Shear Zone Along Wall of Rammer
within the zones of shear cause orientation of the clay platelets, creating oriented fabric. The kneading action (5 layers with 25 tamps per layer) mixes the oriented fabric caused by one tamp with that resulting from the previous tamps. This action is responsible for the zones of oriented fabric shown in the micrographs (Figure 20).

The zones of oriented fabric appear to increase in extent with the increase in molding water content. The replicas were scanned in the electron microscope in an effort to obtain a general idea of the over-all fabric. It appeared from the scan that the extent of the oriented zones increased from dry of optimum to wet of optimum. The micrographs included in this paper are of high magnification, showing only a small portion of each replica, and therefore do not give as good an over-all picture of the fabric as a complete scan of the replica in the electron microscope. However, the increased penetration of the tamping rammer, which results from the increase in moisture content, should produce more zones of shear and, hence, more oriented zones, than would result from a dryer material. Based on this reasoning, a soil that is compacted wet of optimum would be more oriented than one compacted dry of optimum.

Micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by kneading compaction are shown in Figure 20. Zones of oriented packets with their edges exposed are shown at A in micrographs a thru f. Zones of oriented packets
Figure 20—Micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by kneading compaction. Micrographs a, c, and e are horizontal sections. Micrographs b, d, and f are vertical sections. Micrographs a & b show specimens compacted at 31.2% moisture content, c & d at 34.7%, and e & f at 37.6%. 15,000 X
with their basal planes exposed are shown at B in micrographs a thru f. The oriented zones indicated are due primarily to shear strains which developed during the kneading compaction process.

4.3.2 Fabric Produced by Impact - The fabric study of the impact compacted specimens showed little or no difference from the fabric produced by kneading. Many areas of each replica were scanned and the same characteristic zones of oriented fabric were seen. During the compaction process (for a given moisture content) the impact rammer was observed to have less penetration than the kneading rammer. Based on the electron microscopy of the platinum-carbon replicas and the observation of the rammer for the two compaction methods, the following conclusions can be made: the impact compaction produces essentially the same fabric as the kneading method; however, the fabric resulting from impact will be less oriented than that caused by kneading for the same moisture content and compactive effort. Since the penetration of the rammer is less for impact compaction, fewer zones of shear strain will be produced. The smaller degree of orientation of the samples compacted by impact is therefore concluded to be a function of the penetration of the rammer.

Micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by impact compaction are shown in Figure 21. Zones of oriented packets with their edges exposed are
Figure 21—Micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by impact compaction. Micrographs a, c, and e are horizontal sections. Micrographs b, d, and f are vertical sections. Micrographs a & b show specimens compacted at 31.9% moisture content, c & d at 34.5%, and e & f at 37.7%. 15,000X
shown at A in micrographs a thru f. Zones of oriented packets with their basal planes exposed are shown at B in micrographs a thru f. The oriented zones are due primarily to shear strains which developed during the impact compaction process.

4.3.3 Fabric Produced by Static Pressure - A marked difference was noticed in the fabric produced by static pressure from those produced by the kneading and impact compaction methods. A significant difference was the absence of oriented zones like the ones caused by shear strains in the other two methods. Another difference was the apparent trend toward general orientation perpendicular to the direction of loading.

Figure 22 shows micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by static compaction. Packets with their edges exposed are shown at A in micrographs a thru f. Packets with their basal planes exposed are shown at B in micrographs b thru f. The oriented zones shown in micrographs a and d appear different than the oriented zones shown in micrographs of Figures 20 and 21. More edge-to-face contact between adjacent packets can be seen in the zones of micrographs a and d of Figure 22.

The scan of the eighteen replicas revealed another difference: the oriented zones (edges of packets exposed) of the kneading and impact compacted specimens appeared as segments of trajectories. The
Figure 22 - Micrographs of platinum-carbon replicas of fracture surfaces in kaolinite compacted by static compaction. Micrographs a, c, and e are horizontal sections. Micrographs b, d, and f are vertical sections. Micrographs a & b show specimens compacted at 31.6% moisture content, c & d at 34.7%, and e & f at 37.7%. 15,000X
trajectory-like pattern was not seen in the scan of the replicas of static compacted specimens. Packets arranged in a haphazard pattern (random fabric) were seen in specimens compacted below optimum moisture content, and wide zones of oriented packets (oriented fabric) were seen in specimens compacted above optimum moisture.

Based on the electron microscopy of the platinum-carbon replicas the following conclusions can be made: oriented fabric is produced in the absence of shear strains. The difference between the oriented fabric produced by kneading and impact compactions from that produced by static compaction is a function of the compaction method and the per cent molding water. The oriented fabric in Figures 20 and 21 is due primarily to shear strains. The oriented fabric in Figure 22 is thought to result from the mixing of distilled water with the dry kaolinite. This condition would develop according to Lambe's theory based on the diffuse double layer. When distilled water is mixed with the dry clay, the moisture distribution is non-uniform causing areas of high and low moisture contents. In the areas of high moisture contents more water is present than is needed and the double layers around the clay platelets are fully developed. Under this condition, the clay platelets tend to disperse or become aligned in an oriented fabric. In the areas of low moisture contents the relatively higher cation concentration prevents the double layer from developing fully
resulting in low inter-particle repulsion and consequently a tendency for flocculation of the clay particles. These two conditions can exist within a few microns of one another. The writer concluded that this is the explanation for the edge-to-face contacts among the packets within zones of oriented fabric below optimum moisture content. As the molding water increases, the double layers become fully developed, causing a higher degree of dispersion, resulting in the wide zones of orientation that occur above optimum moisture.

After an examination of the micrographs for the static method of compaction, a trend toward over-all orientation became apparent. The fabric produced by compaction dry of optimum moisture content is random, as well as can be discerned, in both horizontal and vertical sections. The fabric produced at optimum moisture content appears to tend toward an orientation perpendicular to the direction of loading. The orientation is more pronounced wet of optimum moisture content than at dryer moisture content, as shown in Figure 22. This was concluded after analyzing how the fabric would appear in a horizontal and vertical section. If the packets were becoming more oriented at right angles to the direction of loading, it would be apparent in the two different sections: a vertical section would show a greater quantity of packets on edge, while a horizontal section would show a greater quantity of packets having their basal planes normal to the direction of viewing. The increased orientation became apparent after scanning the
replicas and studying the micrographs of the clay compacted wet of optimum moisture content. This condition is shown in Figure 22 e and f and is in complete accord with Lambe's hypothesis of the consolidation effect on fabric of clays (See Figure 3).

4.4 Conclusions Summarized

There appears to be a similarity between the fabrics produced by kneading and impact compaction methods. It is believed that the kneading method of compaction produces a greater degree of orientation than the impact method for a given moisture content. This was concluded after observing the difference in penetration of the rammer between the two methods, and the appearance of replicas in the electron microscopy study. The orientation increases with moisture content because of the increased penetration of the tamping rammer and attendant larger shear strains. The oriented edge-on zones appear in trajectory-like patterns and the zones of oriented platelets themselves appear to lie in a random relation to one another.

The static method of compaction produces a different fabric from that produced by the other methods of compaction. The zones of orientation, which occur in the other methods as a result of shear strains, are not present in the fabric produced by static compaction. The packets appear to become oriented normal to the direction of applied pressure as the amount of molding water increases.
4.5 Recommendations

The writer concludes that the electron microscopy study of the fabric of compacted clay, as presented in this thesis, is a qualified success. Due to time limitations the writer was unable to re-do some of the micrographs of lesser quality. Although some of the micrographs included in this report are difficult to interpret, the overall quality is sufficient for the fabric analysis. The studies have shown that most of the ideas presented by previous researchers are essentially correct, with a few exceptions. In view of the findings of this study, several recommendations are made:

(1) The term "cardhouse" should not be used to define "random fabric" of a compacted clay soil because edge-to-face contacts between individual particles do not occur in compacted kaolinite. The suggested term "bookhouse" would seem more descriptive.

(2) An oriented fabric should be thought of as one where the clay basal planes are aligned face-to-face. Oriented fabric should not be considered as oriented in any particular direction except when a clay is compacted by static pressure. In this case, oriented fabric could mean both orientation with respect to basal planes and perpendicular to the direction of loading.
The use of electron microscopy and replica methods have been shown to be an effective method for fabric analysis of compacted kaolinite. Other studies of natural clay soil fabric could be performed using these techniques. Shear strain has been shown by this study to produce oriented fabric in zones of shear failure. Shear failure zones are absent in clay compacted wet of optimum by static pressure. Kaolinite could be compacted at different moisture contents by static pressure, and failed by direct shear or in unconfined compression to generate extensive zones of shear strain. Replica methods could be used to study the fabric within the failure zone to determine the kind of orientation resulting from shear strains at different moisture contents.
APPENDIX
<table>
<thead>
<tr>
<th>COMPACTION METHOD</th>
<th>Kneading</th>
<th>Impact</th>
<th>Static</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Below Optimum Moisture Content</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Moisture Content</td>
<td>31.8%</td>
<td>31.9%</td>
<td>31.6%</td>
</tr>
<tr>
<td>b. Dry Density</td>
<td>81.8#/ft³</td>
<td>82.1#/ft³</td>
<td>81.7#/ft³</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Moisture Content</td>
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<td>34.5%</td>
<td>34.7%</td>
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<tr>
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<td>83.2#/ft³</td>
<td>83.0#/ft³</td>
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<tr>
<td><strong>Above Optimum Moisture Content</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Moisture Content</td>
<td>37.6%</td>
<td>37.7%</td>
<td>37.7%</td>
</tr>
<tr>
<td>b. Dry Density</td>
<td>79.1#/ft³</td>
<td>79.3#/ft³</td>
<td>79.0#/ft³</td>
</tr>
</tbody>
</table>

Note: Optimum Moisture Content = 34.5%
Maximum Dry Density = 83.0#/ft³

Table I - Results of Moisture-Density Determination for the Three Compaction Methods
REFERENCES CITED


