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COMPRESSIBILITY AND REBOUND CHARACTERISTICS OF COMPACTED CLAYS

by

Yousef Matri Massanat

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THE UNIVERSITY OF ARIZONA

GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction by Yousef Matri Massanat entitled Compressibility and Rebound Characteristics of Compacted Clays be accepted as fulfilling the dissertation requirement of the degree of Doctor of Philosophy

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ABSTRACT

This investigation was carried out to study the effects of method of compaction, molding water content, and dry density on the compressibility and rebound characteristics of compacted kaolinite clay samples. The samples were compacted by the kneading and static methods at two compaction efforts and three molding water contents: dry of optimum, optimum, and wet of optimum. The samples were consolidated in three states: (1) as compacted, (2) soaked with volume change, and (3) soaked without volume change.

The effects of method of compaction, molding water content, dry density, and consolidation stress on the fabric characteristics of compacted clays were expressed quantitatively in terms of the orientation indices of the carbowax-impregnated sections of the tested samples by using the x-ray diffraction technique, and qualitatively by the electron microscopy examination of the Pt-Pd shadowed carbon replicas of the tested samples.

It was found that there is an increase in the fabric orientation of a compacted soil sample with the increase in the molding water content except for the kneading samples which showed a decrease in the orientation index from the optimum water content to wet of optimum water content. The kneading samples showed higher orientation indices than the static samples at all molding water contents except at wet of

optimum water content. This might be due to the inclination of the shear strain planes in the kneading samples compacted at wet of optimum to the horizontal plane caused by the high penetration of the tamping foot.

An increase in fabric orientation occurs upon the increase in the compactive effort, and also upon the change of the consolidation stress of the compacted samples through the transition zone from the flat portion to the steep portion of the consolidation curve. However, all the tested samples regardless of their method of compaction, dry density, molding water content, and consolidation stress lie on the random side of the continuum from the random state to the perfectly oriented state. Electron microscopy examination showed that the fabric of compacted clays generally consist of platelets and packets that exist at tilted positions to each other. Parabolic planes consisting of zones of oriented kaolinite packets were encountered in the kneading samples mainly due to the shear action of the tamping foot. This type of orientation pattern was not encountered in the static samples.

The static samples were found more compressible at the dry of optimum water content and less compressible at optimum and wet of optimum water contents than the kneading compacted samples in two cases, (1) consolidation in the as-compacted state and (2) consolidation after soaking without volume change. This is mainly due to the collapse of the large size pores in the static samples compacted at dry of optimum during the consolidation process. Upon soaking with volume change the static samples swelled more and compressed more than the kneading samples at all molding water contents. In the case of a small increase in the dry density, the increase in the compactive effort may cause an increase in the compressibility of the compacted samples.

It was found that the higher the stress at which rebound starts the higher is the swelling index and the steeper is the rebound curve. The rebound curves of the samples consolidated in the as-compacted state were concave downward while those of the samples consolidated after being soaked with volume change are generally concave upward.

CHAPTER 1

INTRODUCTION

The term "compaction" as used in soil mechanics and engineering practice refers to the rapid reduction in the volume of a disturbed soil mass by rolling, tamping, vibrating or other means. This process of densification aims essentially at improving the mechanical properties of the soil mass and thus its engineering performance. Proctor (1933) was the first to show that there is a definite relationship between dry density, compactive effort, and moisture content of the soil during compaction. The moisture content at which a given soil attains its maximum dry density for a certain compactive effort is called the optimum moisture content. At that time, the compactive effort used in the laboratory test by Proctor was equivalent to that produced by field compaction equipment. The ASTM Committee E-10 on Standards (1961) gave this test a tentative standard status. The standards of ASTM D 698 and AASHO T 99 for soils use a compactive energy and procedure that closely simulate the field compaction by tamping rollers. With the advent of new heavier compaction equipment after the second World War, a modified laboratory test procedure was adopted by the Corps of Engineers. The designations given to this modified laboratory test are ASTM D 1557 and AASHO T 180.

The main factors that control the density a clay soil can attain by compaction include: (1) the moisture content; (2) the nature of the soil, i.e., its mechanical and physiochemical properties: (3) the type and magnitude of the compactive effort: (4) the environmental conditions under which compaction is performed and the chemical quality of the water used in compaction. It follows that many factors can influence the mechanical and physical properties and thus the engineering performance of a compacted clay soil. This has been indicated and partially explained in work conducted previously by several investigators, e.g., Lambe (1958a, 1958b), Seed and Chan (1959a, 1959b) and Mitchell (1956). The need for optimizing field compaction as a principal and cheap stabilization process stimulated the efforts to investigate the role of the different factors in determining the resulting soil structure (fabric plus the electrokinematic forces in the soil-water system) and thus the engineering behavior of compacted clays under the different environmental conditions to which these soils may be exposed. This research work necessitated new laboratory compaction techniques to simulate the mechanical actions of the various field compactors, i.e., compaction by kneading, impact, vibration and static methods. It was postulated that the different methods of compaction induce different magnitudes of shear strains and thus result in soils with different engineering properties. Also, the variaiton in the compaction effort at the same moisture content will result in compacted clays that differ in their dry densities as well as in their fabric.

History of Previous Research

In 1925, Terzaghi was among the first soil scientists who tried to investigate soil structure in an attempt to interpret its physical properties (Rosenqvist, 1959). He postulated that soil is made up of aggregates of minerals linked together by the adhesive forces at their points of contact with large voids among these aggregates developing what he called a honeycomb structure. Goldschmidt (1926) conducted a series of experiments with mixtures of clay minerals and various liquids such as water, benzine, carbon tetrachloride, liquid sulphur dioxide and amonia. He concluded that clay properties are dependent upon both the crystal chemistry of the mineral phase and the atomic structure of the liquid phase.

In 1926, Goldschmidt described clay soils as being built up of crystalline minerals with thin films of water molecules strongly attached to them due to the dipolar properties of water molecules (Rosenqvist, 1959). He also expressed his opinion that the flaky minerals in highly sensitive clays are arranged in unstable "cardhouse" structures and that the increase in density of the arrangement of the minerals in the clay is accompanied by a decrease in their degree of sensitivity.

Arthur Casagrande (1932) assumed that clay soils consist of flocs of colloidal particles, larger clay particles, and silt size grains all of which are linked together developing a flocculent structure. Lambe (1953) presented a theory to explain the variation in soil fabric with the environment of deposition. He showed the role of the electrical forces acting among the clay particles in determining the resulting structure of naturally deposited soils. In a marine environment with a high electrolyte concentration, where the attractive forces dominate, the deposited soils have commonly a random or edge-to-face fabric, while in a fresh water environment the deposited soils have commonly a more oriented fabric due to the net repulsive forces between the clay particles. He presented schematic representations of the fabric of undisturbed salt and freshwater clays and remolded clays as shown in Figure 1.

Mitchell (1956) studied thin sections of fourteen types of marine and fresh water clay soils after replacing their moisture with carbowax 6000. He found that remolding results in an increase in the homogeneity of clay fabric as well as in its degree of orientation. However, the improvement in the orientation of clay fabric as a result of remolding was more pronounced in the marine clays than in the fresh water clays. The improvement in the orientation of clay fabric as a result of one-dimensional compression, up to 2 kg./cm^2, was much greater for the remolded clays than for the undisturbed clays due to the higher compression of the remolded clays. Mitchell (1956) found also some correlations between the clay fabric and its engineering properties. The increase in the orientation of clay fabric as a result of remolding is commonly accompanied by the following changes in its engineering properties as found by Mitchell and summarized by the author:

1. A decrease in the strength of soil.
2. A decrease in the slope of the straight line portion of the e-log p curve.

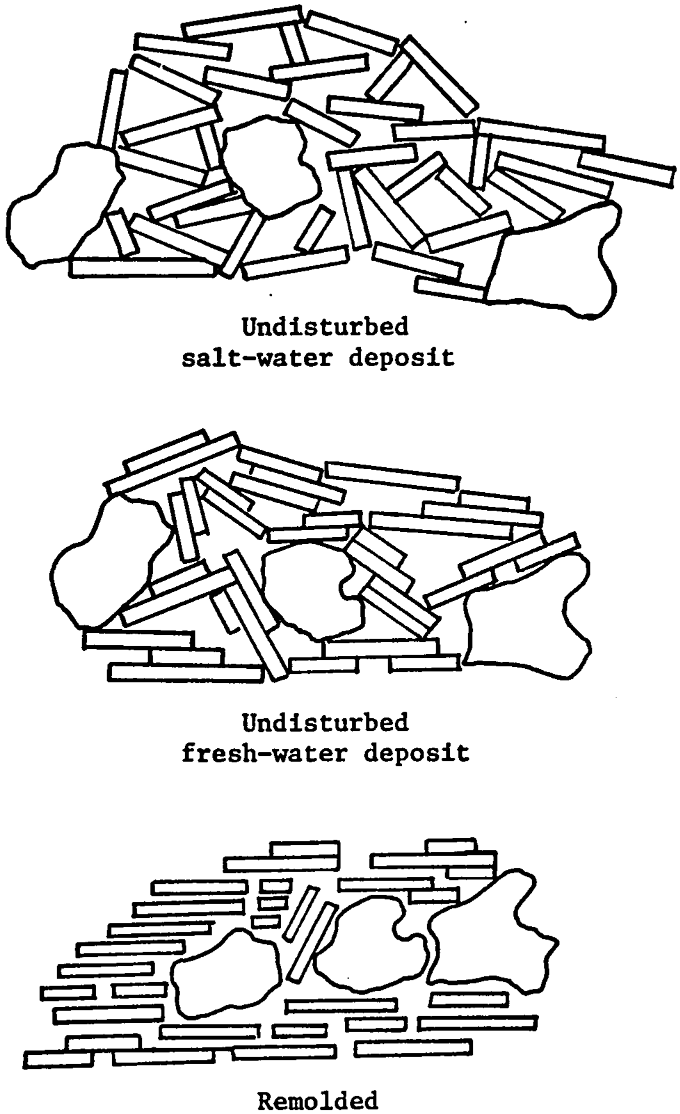


Figure 1 Schematic Representation of Fabric of Clays (Lambe, 1953)

3. A decrease in the equilibrium void ratio at any particular stress level.
4. A decrease in the secondary compression, and
5. An increase in the ratio of horizontal to vertical permeability.

Mitchell also found that remolding causes a decrease in the permeability at natural water content by a factor of from 1 to 15 with a reduction to half the undisturbed value and that this is typical for many of the materials. He explained this by the increased homogeneity of clay fabric and the decreased average pore diameter in the remolding clay as compared with the undisturbed clay. He also found, as mentioned before, a definite increase in the ratio of horizontal to vertical permeability with the increase in the orientation of clay particles in the horizontal plane.

Lambe (1958a) used the double layer theory and the water deficiency concept to explain his hypothesis concerning the variation in the structure of compacted clays with the molding water content. As shown in Figure 2, he presented a plot of the compacted dry density versus the molding water content for two different compaction efforts to explain the change in the soil structure along the compaction curve. He used the term "water deficiency" to indicate the difference between the water needed by the soil particle under any given state of stress to develop fully its double layer and the existing water. He also used the term "structure" to indicate both the arrangement of soil particles and the electrical forces acting between adjacent particles. By

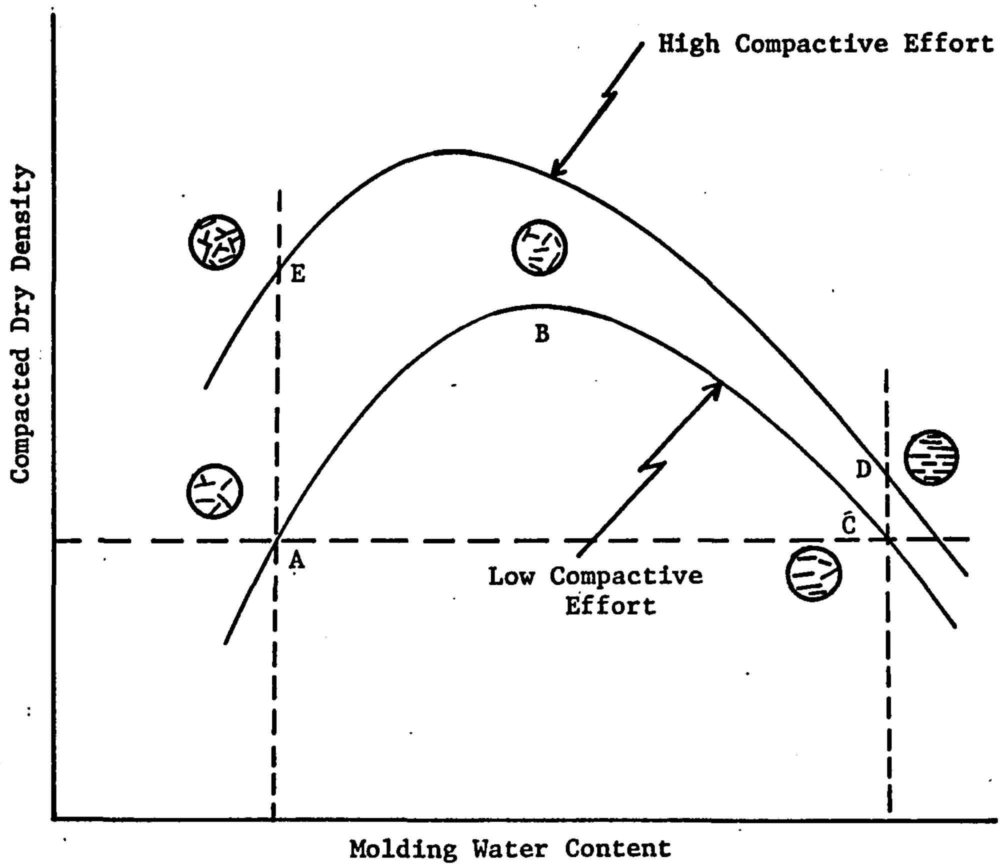
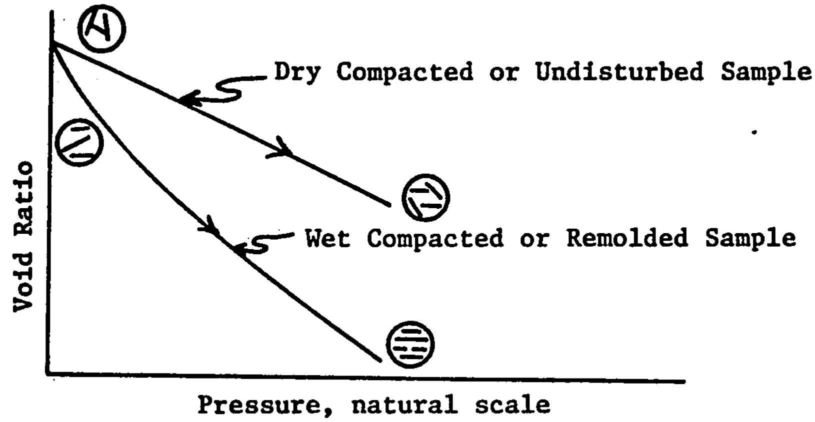


Figure 2 Effects of Compaction on Structure
(Lambe, 1958a)

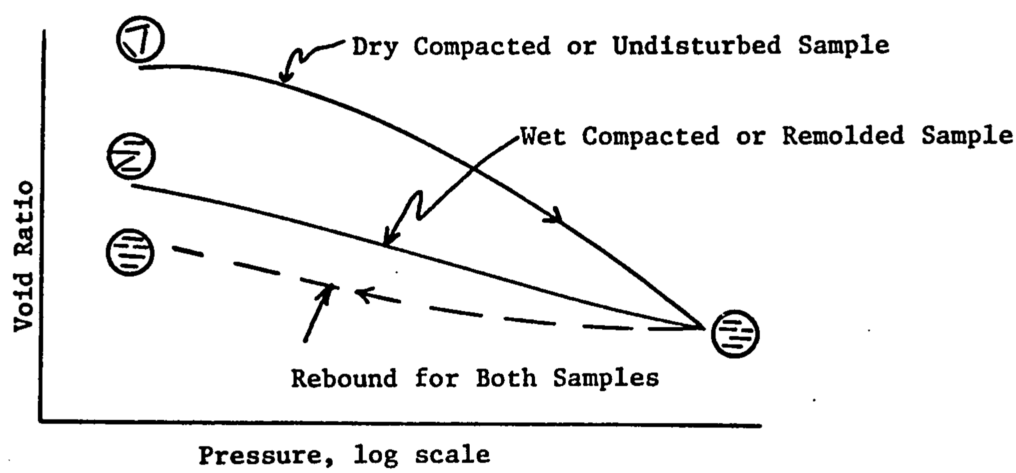
considering the information in Figure 2 Lambe postulated that, for a given compaction effort, the clay soil compacted at point A on the dry side of optimum assumes a "flocculated" structure with a random orientation of clay particles and that the degree of randomness decreases with the increase in the molding water content from point A to point B and then to point C resulting in a "dispersed" structure with a high degree of orientation of clay particles for the soil at point C compacted on the wet side of optimum. This was explained by indicating that for the soil compacted at A there exists a higher deficiency in water content, a higher electrolyte concentration, a reduction in the thickness of double layer, and thus a net dominating attractive force causing a random arrangement of clay particles. The increase in the molding water content for the soil compacted wet of optimum (Point C) accompanied by a decrease in the electrolyte concentration and an increase in the repulsive forces causing a more oriented arrangement of the clay particles. However, the degree of improvement in the orientation of soil particles with the increase in the molding water content for a certain compaction effort is not the same for all soils but it varies from one soil type to another. The increase in the magnitude of compactive effort also results in an increase in the orientation of clay particles and a decrease in the spacings between them as we compare the soil at Point A with the soil at Point E. However, at a high molding water content the increase in the compactive effort may merely align the clay particles without significantly altering the particle spacing as we compare the soil at Point C with the soil at Point D. Lambe also indicated that shrinkage characteristics, swelling pressure, and slaking characteristics could be used as useful indicators to the structure of compacted clay.

Lambe (1958b) found that soils compacted at dry side of optimum have higher permeability than soils compacted at wet side of optimum. Such a result supports the previous findings of Mitchell (1956) concerning the effect of soil structure on the permeability of compacted clays. Lambe (1958b) also tried to evaluate the effect of one-dimensional compression on the fabric of compacted clays. He emphasized the importance of particle re-orientation and the change in the size of water micelles in the one-dimensional compression of compacted clays. He mentioned that the experimental work shows that the compression of saturated clay resulting from an increase in the applied stress is mainly due to the re-orientation of particles and to the decrease in the size of micelles, and that the rebound upon load release is due almost entirely to an increase in the size of micelles.

Lambe (1958b) presented Figure 3 to show the effect of one-dimensional compression on clay structure. Figure 2 shows that at a low stress level the sample compacted on the wet side of optimum is more compressible than the one compacted on the dry side of optimum. It also shows that for the soil compacted dry of optimum there is an improvement in the orientation of clay particles with the increase in the applied stress, while for the soil compacted wet of optimum the increase in stress merely brings the particles closer together. Figure 3b shows that at a high stress level the straight line portion of the e-log p curve is steeper for the sample compacted dry of optimum than for the sample compacted wet of optimum. It also shows that both soils



a. Low Pressure Consolidation



b. High Pressure Consolidation

Figure 3 Effect of One Dimensional Compression on Structure (Lambe, 1958b) will assume identical structure at a high stress level and thus they will follow the same rebound upon load release. Lambe (1958b) also assumed that during rebound the spacing between particles increases, but only negligible changes in orientation occur.

Seed and Chan (1959a) found that clay samples compacted dry of optimum exhibit significantly less shrinkage than clay samples having the same dry density but compacted wet of optimum. They also found that clays compacted dry of optimum exhibit a stress-strain relationship synonymous to that of brittle materials while the same clays compacted wet of optimum exhibit a stress-strain relationship synonymous to that of plastic materials. Based on the strength and deformation characteristics of clays compacted by different methods of compaction, Seed and Chan (1959a) indicated that the kneading compaction results in the highest degree of particle orientation while the static compaction results in the least degree of particle orientation for the compacted clays that have the same dry density. In his study of the fabric of montmorillonite, Meade (1961) used the term "peak-height ratio" as the ratio of the height of the 15-angstrom peak to that of the 4.4-angstrom peak. He also used the term "orientation ratio" as the ratio of the peak-height ratio in the horizontal section to the peak-height ratio in the vertical section. An orientation ratio of 1.0 indicates an ideally random orientation, while higher values indicate more orientation of clay particles in the horizontal section than in the vertical section.

Mitchell (1956) developed a new procedure to prepare thin sections of a wet clay soil for X-ray study without disrupting the original fabric of the soil. This is done by submerging the wet clay soil in molten carbowax 6000 at 65° C where a gradual replacement of the soil water by wax takes place. Upon cooling the specimens solidify with a hardness equal to 1 on Moh's scale where they can be ground to a very flat surface for X-ray diffraction study. This technique was adopted later on by Martin (1966) and Martin and Ladd (1970) the fabric of consolidated kaolinite. Martin (1966) used a Norelco diffractometer equipped with a pole figure device and a Geiger detector to measure by reflection the diffracted intensity of the 002 and 020 kaolinite reflections. He used the peak ratio PR which is the ratio of the amplitude of the 002 peak to the amplitude of the 020 peak to quantitatively express the particle orientation at any chosen angle to the specimen surface. He found a peak ratio of 2.0 for a random fabric produced by dumping dry clay into molten carbowax, and a peak ratio of 200 for a thoroughly dispersed slurry dried slowly on a glass slide.

Meade (1964) indicated that there is little evidence to support formation of oriented fabrics during the natural consolidation of shales. However, he mentioned that preferred oriented fabrics normal to the direction of applied stress were produced in laboratory experiments by many researchers only under great pressures.

In their electron microscopy study of direct platinum-shadowed carbon replicas of compacted kaolinite, Sloane and Kell (1966) did not find oriented fabric or edge-to-face random fabric of individual particles. Instead, they indicated that regardless of the compaction method the fabric was found to consist of parallel and random arrangements of packets of kaolin flakes and that the increase in molding water content is accompanied with an increase in the parallel packet orientation. They also found that both impact and kneading compaction produced essentially the same fabric consisting of trajectories of parallel packets within essentially randomly oriented zones of packets and that static load compaction produced a fabric in which there is some tendency of the packets to orient normal to the direction of load. Sloane and Kell also proposed the use of the term "bookhouse" as an analog to the "cardhouse" fabric, and the term "parallel packet" to describe the oriented fabric.

Martin (1965) studied the variation in the fabric of compacted Georgia kaolinite samples as a result of consolidation in their partially saturated state. From his measurements of the orientation indices, he found that the fabric becomes more random at the end of primary consolidation on planes both parallel and normal to the loading direction than at the start of the consolidation process. He attributed this decrease in the orientation of clay particles to the hydrodynamic gradient of pore water during the primary consolidation. He, therefore, concluded that if preferential orientation does exist at the end of complete consolidation, it must have occurred during secondary compression.

In his revision of soil structure in the electron microscope, Smart (1969) adopted the following meanings for domains and packets:

> Domains are aggregates of platy particles, laths or tubes, large in comparison with the particles, in which almost all the particles are approximately parallel to a smooth surface, plane or curved.

> Packets are aggregates in which platy particles are almost parallel, extend across the packet, and are capable of admitting water between themselves.

Figure 4 shows the types of soil structures as given by Smart (1969).

El-Rousstom (1969) studied the settlement characteristics of compacted Georgia kaolinite after soaking. The kaolinite samples were compacted by kneading and by the static methods at the same molding water content and to the same dry density. He found that at dry of optimum, the statically compacted samples settled more than the kneading compacted samples. The reverse was true when compacted wet of optimum. He found also that for the statically compacted samples, those compacted dry of optimum settled more than those compacted wet of optimum. The same behaviour occurred for the kneading samples when stressed beyond 2 tsf. Since the compaction process destroys the stress history of compacted clays, El-Rousstom concluded that the method of compaction does not affect the value of computed P_p.

Olson and Mesri (1970) tried to study the applicability of what they called the "mechanical model" and the "physico-chemical" model to the analysis of the compressibility characteristics of the different types of clays. The term "mechanical" was used to denote short-range particle interaction in which compressibility is controlled by the physical properties of the mineral particles such as the particle shape, geometric arrangement of particles, and surface friction. The term "physico-chemical" was used to denote relatively long-range particle interaction and which involves electrical forces of the double layer and

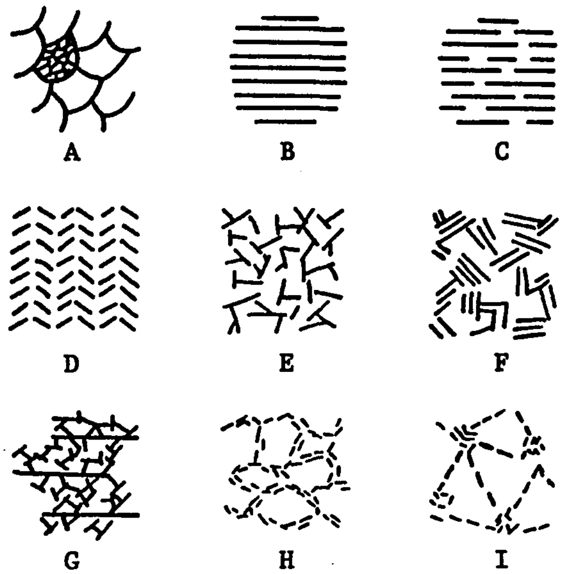


Figure 4 Types of Structures. A. Kidney structure, sketch. B. Packet, cross-section, each stroke represents a platy particle. C. Domain, cross-section. D. Herringbone structure, cross-section. E. Cardhouse structure, two-dimensional analog. F. Salt flocculated structure, analog. G. Brounian structure, analog. H. Flocculent structure, cross-section. I. Pusch's structure, cross-section. (Smart, 1969)

Van der Waals type. They performed one-dimensional consolidation tests on samples of ground muscovite, kaolinite, illite, and smectite. The experiments showed that the virgin compression curves of kaolinite and illite were controlled by the mechanical effects, while those of smectite were physico-chemically controlled. They explained these results by indicating that the particles of kaolinite and illite tend to be large and stiff and are at large angles to each other, while those of smectite are very thin and highly flexible with a high surface area causing the double layer effects to dominate over the mechanical effects.

Diamond (1971) investigated the microstructures of impact-compacted kaolinite and illite clays, after drying, by pore size distribution measurements, x-ray orientation determination, and scanning electron microscopy. He found that clays compacted on the dry side of optimum moisture content exhibited, after drying, a domain structure with the domains touching each other only at peripheral points leaving large interdomain spaces, while clays compacted at or above the optimum moisture content exhibited a more nearly massive structure with the domains in closer contact leaving small interdomain spaces. He also introduced the term "degree of orientation" and defined it as:

$$\text{Degree of orientation} = \frac{\text{Orientation index of sample surface} - \text{Orientation index of random mount}}{\text{Orientation index of fully oriented mount} - \text{Orientation index of random mount}}$$

He found that there was only a small degree of overall preferential orientation normal to the compaction axis as compared with planes parallel to the compaction axis. The result indicated that the degree of orientation for all compacted samples did not exceed 4 percent and that there was no considerable difference in the degree of orientation for the samples compacted at or above optimum moisture content as compared with those compacted dry of optimum.

From their experimental work on the directional properties of consolidated kaolin, Kirkpatrick and Rennie (1972) found that the anisotropically consolidated samples (Ko-condition) have a high degree of preferential orientation in the direction normal to the major consolidation pressure (horizontal plane). They found also that the anisotropically consolidated samples were isotropic with respect to their strength, but were found more compressible in the horizontal direction than in the vertical direction. They explained the higher compressibility in the horizontal direction by indicating that a pressure in the horizontal direction would cause the platelets to slide over and in between other platelets in the same way as one would sort an untidy pack of cards.

Scope of the Research

Variations in the soil fabric are usually manifested by variations in its engineering properties especially its permeability, strength, and compressibility characteristics.

Previous investigations were mainly concerned with the strength and stress-strain characteristics of compacted clays. The settlement characteristics of compacted clays did not receive equal attention. The rapidly growing field of urban planning and the construction of highways, and elevated free-ways, and the increasing number of high embankments for earth dams stimulate the need for more investigations to acquire a better understanding of the influence of the different factors involved in the compaction process on the fabric and thus on the settlement and rebound characteristics of compacted clays. This research work aims at clarifying the effect of molding water content, method of compaction, and the magnitude of the compactive effort on the settlement and rebound characteristics of compacted clays. This study will try to check some of the findings of previous investigations regarding the rebound characteristics of clayey soils. The behavior of compacted clays will be explained in view of the changes that occur in their fabric with an attempt to evaluate these changes by means of x-ray diffraction analysis and electron microscopy examination. The result of this research work on the settlement and rebound characteristics of compacted clays when combined with the results of the previous investigations on the hydraulic and strength characteristics of compacted clays would reveal more clearly the significance of the different factors involved in the compaction process. This will undoubtedly form a better basis for establishing design criteria to be followed in writing construction specifications for compacted fills.

CHAPTER 2

EQUIPMENT AND MATERIALS

Different types of equipment were used at different stages of this research work. These include mechanical compaction machines, consolidometers, and fabric study apparatus. However, only one material was used in this research which was Georgia Kaolinite, Hydrite 10.

Mechanical Compaction Machines

Kneading Compactor

The kneading compaction of soil was achieved by using the kneading compactor described in test Method No. Calif. 301-F, September 1964. Compaction is accomplished by applying a kneading-like pressure to the soil specimen through a tamping foot by means of a controlled slow speed dynamic force. The kinetic energy required for compaction is developed from an electric motor, and the magnitude of the dynamic force used in compaction is controlled by the load transmitted to a pressure regulating cylinder. The pressure is applied to a small area (about 3.2 square inches) of the specimen through a semi-triangular tamping foot, while the rest of the specimen is free to move. The tamping foot moves up and down through a distance of about 4 inches, alternately applying and releasing a pressure on the specimen according to a fixed cycle. The time required for each stroke of the tamping foot is 2 seconds.

Static Compactor (Soiltest Model AP-350 Versa-Tester)

This is a hydraulically operated machine that can be used to apply a compression force up to 30,000 lbs. It can be operated in three states: loading, neutral, and unloading, as well as in different rates of crosshead movement ranging from 0 to 5 inches per minute regulated by a loading rate valve. The machine is controlled by a main power switch and a reset switch and is calibrated by a proving ring certified by the U.S. Bureau of Standards.

Consolidation Apparatus

Two types of consolidometers were used. The first type is the levermatic consolidometer where the load is carried on a 20:1 lever system. The load is applied on a $2\frac{1}{2}$ inch diameter soil sample in increments from $\frac{1}{8}$ to 16 tons/sq. ft. The second type is the Karol-Warner Conbel, model 351. This pneumatically operated consolidometer allows an instantaneous load application on the $2\frac{1}{2}$ - inch diameter soil sample by opening a toggle valve. The load can be held indefinitely by a precision air regulator and recorded on a sensitive test gauge. This consolidometer is also provided with a bleeder valve for the rapid reduction of air pressure in the system when the test is concluded.

Pressures up to 0.5 tons/sq. ft. were applied according to calibrated manometer readings using an indicating fluid in the manometer (Meriam No. D-8325) of a specific gravity of 1.75. Pressures from 1.0 to 16.0 tons/sq. ft. were applied according to the gauge readings of the consolidometer. The readings of the manometer and the gauge were calibrated in the laboratory using a pressure load-cell by Arizona Certified Electronics, Tucson, Arizona.

Fabric Study Apparatus

X-ray Diffractometer

A General Electric XRD-5 diffractometer was used. The copper radiated x-ray beam produced by 35 kv and 23 ma is modified by a 1° beam slit before its incidence on the goniometer-mounted specimen. The diffracted beam then passes through a medium resolution collimator, a 0.1° detector slit and a nickel filter before it reaches the SPG-6 xenon-filled counter tube. A time constant of two seconds was used and the goniometer was driven at an angular velocity of two degrees 2θ per minute.

Vacuum Desiccators

Vacuum desiccators were used to dry the fractured compacted specimens before replication. Vacuum up to 10^{-3} mm of mercury pressure was developed by the use of a electrically operated high vacuum rotary pump.

Mikros VE-10 Thin-film Vacuum Evaporator

This evaporator has automatic, pre-programmed circuitry to the vacuum system. It is provided by three push buttons on the control panel: operate, change, and stop. A switch is provided to select any of three electrical feed-throughs within the bell jar. A vacuum system capable of developing a vacuum in the bell jar to approximately 10^{-5} mm of mercury consists of a high capacity rotary pump and a very high capacity, air-cooled, oil diffusion pump. Vacuum is read on a meter in mm mercury as sensed by a Pirani gauge in the vacuum manifold. Power to the selected electrical feed-through is controlled by a Variac at a constant 15 volts and variable DC amperage.

The Electron Microscope

An Hitachi HS-7 Electron Microscope was used to study the replicas of fractured kaolinite specimens. This microscope has a resolution of 8 angstroms and optical magnification from 1,500 to 84,000X. An internal camera is used to take the electron photomicrographs on $3\frac{1}{4}$ x 4 inch glass plates.

Material

The clay material used in this research work is a commercial kaolinite, Hydrite 10, sold by the Georgia Kaolin Company. It has a specific gravity of 2.63, a liquid limit of 59, a plastic limit of 33, and a plasticity index of 26. Its natural water content ranges from 0.47 percent to 0.68 percent depending on the climatic conditions. This material was chosen because (1) it is free from impurities, (2) it has a high degree of crystallinity, (3) it does not swell appreciably upon soaking in water, and (4) it can be easily molded.

CHAPTER 3

TEST PROCEDURES

One thousand grams of air-dried kaolinite were weighed and placed in a 10 x 15 inches polyethylene bag. A calculated amount of water was added to the kaolinite to reach the desired value of molding water content. The bag was manually freed from air, sealed with a rubber band, and the soil was then thoroughly mixed with the water by kneading. This bag , in turn, was placed in another plastic bag and sealed tightly. The sample was then placed in a pan with a plastic cover and kept in a humidity room for 48 hours to temper. The amount of water needed to reach a certain molding water content was determined after many trials for the samples compacted by both the kneading and static methods.

Determination of Compaction Curves

The consolidation tests and fabric study analyses were conducted on soil samples that were compacted by both the kneading and static methods at the same water content and to the same dry density. The tested samples were compacted at three molding water contents: dry of optimum, optimum, and wet of optimum. Two different compaction efforts were used for the preparation of the samples tested in this research. Soil samples were first compacted by kneading, then equivalent weights of wet kaolinite at the same molding water content were statically compressed to the same volume as their corresponding samples compacted by kneading to reach the same dry density.

In order to determine the appropriate molding water contents of the tested samples and the compaction efforts to be used in preparing these samples it was found desirable to first determine the Standard AASHO and Modified AASHO compaction curves of this soil.

Impact Compaction

The procedures followed in compacting the soil by impact to determine its Standard AASHO and Modified AASHO compaction curves are as described in Lambe's book (Soil Testing for Engineers, 1967), and which are similar to the ASTM D698 and ASTM D1557 methods, respectively. Eleven tests were found sufficient to adequately define each of these compaction curves. For the Standard AASHO compaction curve the optimum molding water content was 37.3 percent and the maximum dry density 81.3 pcf, while for the Modified AASHO compaction curve the optimum molding water content was 29.5 percent and the maximum dry density 89.5 pcf.

Kneading Compaction

Several trials were made following the procedure described in Test Method No. Calif. 301-F, September 14, 1964, but using different compaction efforts in order to establish two compaction curves as close as possible to the Standard AASHO and Modified AASHO compaction curves to be used in preparing the compacted soil samples for this research.

A 4-inch diameter mold was placed in the mold holder that had a rubber disc $3\frac{15}{16}$ inch in diameter and $\frac{1}{8}$-inch in thickness cemented to the base plate. The well mixed wet kaolinite sample was placed in the compactor feeder trough with the loose material distributed evenly along the full length. The feeder was divided into 17 portions with the first portion 3 inches long and the rest of the feeder divided into 16 equal portions. The compactor was started and the pressure indicator was adjusted to the desired reading as will be specified later. After the tamping foot reached its lowest position, the first three inches of material were pushed into the mold. The compactor was operated and the rest of the material was pushed into the mold in 16 equal parts while the mold and its holder were rotating. Ten additional blows were allowed to level and set the material in the mold. The compactor foot was raised and cleaned and a rubber disc, $3\frac{15}{16}$ inch diameter and $\frac{1}{8}$-inch thick, was placed on top of the specimen. The air pressure gauge was adjusted to a new reading and a certain number of tamps were applied to the specimen. The motor was stopped and the specimen trimmed in the mold flush with the upper surface and then weighed. A representative portion of the whole sample was then trimmed for the determination of the molding water content. The compaction curves are as follows:

1. The lower compaction curve was produced by placing the soil material in 17 increments in the compaction mold as mentioned before. Each increment received one tamp from the compactor foot. Then the whole specimen received

ten additional tamps before placing the upper rubber disc and 105 tamps ($3\frac{1}{2}$ minutes) after placing the rubber disc. All tamps were applied at 8 psi on the air pressure gauge. The compaction curve was determined by running twelve compaction tests. The optimum molding water content was found to be 36.1 percent and the maximum dry density 80 pcf.

2. The higher compaction curve was produced by placing the soil material in 17 increments in the compaction mold where each increment received two tamps with the air pressure indicator at 18 psi. The air pressure was then reduced to 14 psi and 10 tamps were applied to the whole specimen before placing the upper rubber disc and 150 tamps (5 minutes) after placing it. The compaction curve was determined by running twelve compaction tests. The optimum molding water content was found to be 31.1 percent and the maximum dry density 86.3 pcf. These compaction curves are shown in Figure 5.

Static Compaction

The wet kaolinite mixture consisting of 1000 grams of air-dried kaolinite plus the calculated amount of molding water was placed in the 4-inch diameter compaction mold in three equal layers. Each layer was slightly compressed from top and bottom sides before placing the next layer. The whole specimen was then compressed from both ends to the calculated volume that would give the same dry density as that of the corresponding kneading-compacted specimen having the same molding

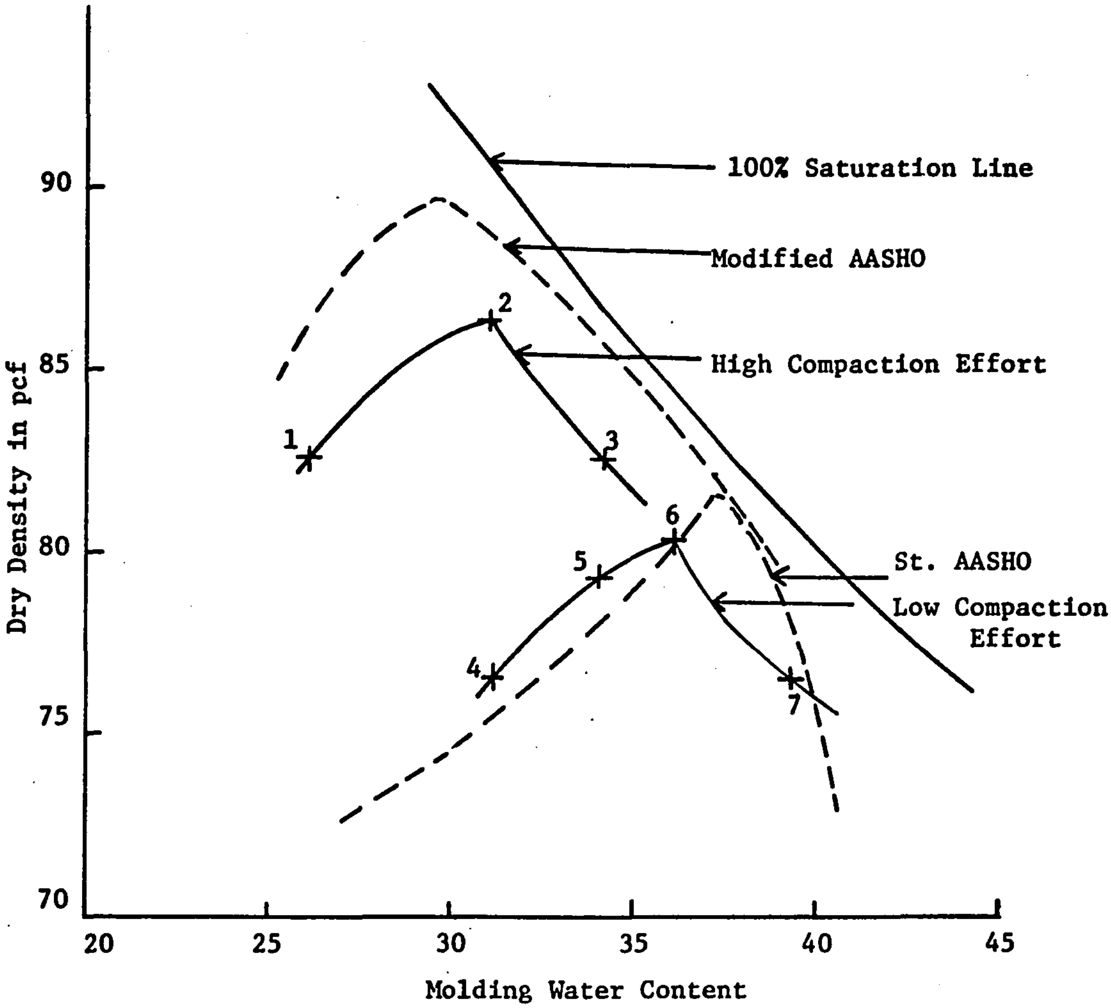


Figure 5 The Relative Position of the Low and High Compaction Efforts Curves with Respect to the Standard and Modified AASHO Compaction Curves. The Numbers Indicate the Positions of the Tested Samples as Defined in Appendix A.

water content. The static load was kept applied on the sample for five minutes. If a noticeable magnitude of rebound took place after the removal of the static load the specimen was loaded again till the rebound was reduced to a negligible magnitude of less than $\frac{1}{16}$ of an inch.

Consolidation Test

The 4-inch diameter compacted sample was trimmed into two $2\frac{1}{2}$ inch diameter samples, each about 1 to $1\frac{1}{4}$ inches in height. One sample was used for determining the molding water content, and the other sample for running the consolidation test. Trimming to a $2\frac{1}{2}$ inch diameter sample was done by pushing a $2\frac{1}{2}$ inch inside diameter sampler with a sharp cutting edge and $\frac{1}{16}$ inch wall thickness to a depth of about 2 inches in the approximately 4 inch high compacted sample. The whole assembly was then extruded from the compaction mold and then placed on a motorized soil lathe, model 400. A fine wire saw was used to trim the remaining 2 inch high portion of the compacted sample to a slightly greater than $2\frac{1}{2}$ inch diameter sample. This exposed portion was then trimmed horizontally and separated from the sampler. A teflon lined $2\frac{1}{2}$ inch diameter consolidometer ring was placed on a horizontal surface with its bottom up where the teflon liner is flush with the aluminium wall of the ring. The trimmed sample was then placed over the ring and pushed into it uniformly by a slight finger pressure on a glass plate placed above the sample. The final trimming was then achieved by the sharp edge of the teflon liner of the consolidometer ring. The sample was then trimmed horizontally to its final height. The sample height was measured using a one-inch gauge with a dial accurate to the nearest 0.001 inch. The sample and its consolidometer ring were then weighed to the nearest 0.1 gram. Two filter papers were placed on top and bottom of the sample. A large porous stone was placed below the sample, and a tapered one-inch high and $2\frac{1}{2}$ inch diameter porous stone was placed above it within the consolidometer ring. The whole assembly was then placed in a large brass container. In the case of samples to be consolidated in the as-compacted state the brass container was sealed with a saran sheet after placing small water-filled cups inside the container to minimize moisture loss during consolidation.

Consolidation Test Procedure

For the samples that were consolidated in the as-compacted state the consolidation test was performed immediately after the preparation of the sample to avoid moisture loss and thixotropic effects. For the samples that were tested after saturation, the samples were soaked in water for at least 48 hours before the consolidation test was performed. It was found that the swelling of the soaked samples practically stops after 36 hours. An additional twelve hours were allowed to attain a high degree of sample saturation. Dial gauge readings were recorded before and after soaking to calculate the magnitude of swell experienced by the soaked samples. The weight of the consolidometer ring and the sample was measured after consolidation for all the consolidated samples. The specimen's final water contents after consolidation were determined.

The consolidation tests conducted in this research were the conventional incremental odometer tests with a load increment ratio of unity. Each load was applied for 90 minutes starting with $\frac{1}{4}$ tsf, and dial readings were recorded at appropriate intervals during the entire period of load application. It was found from preliminary testing that the 90 minute period was enough to insure that the primary consolidation was completed and that the secondary consolidation reached the straight line portion of the deformation versus log time curve of the secondary consolidation stage. The unloading cycle was performed by decreasing the load to one-fourth the previous load applied on the sample every 90 minutes. Dial gauge readings were recorded after $\frac{1}{2}$, 1, 5 and 90 minutes after the rebound had started. Using the square root of time vs. deformation fitting method the primary compression as well as the coefficient of consolidation (cv) were determined for each load. The vertical strain $\frac{\Delta H}{Ho}$, where ΔH is the deformation up to the end of primary compression and Ho is the initial height of the sample, was computed for each load. The cumulative vertical strain (ε_v) versus log-consolidation stress was plotted as the consolidation curve rather than the void ratio versus log-consolidation stress. This was done following the recommendation mentioned in the draft copy of Highway Research Board Subcommittee of Committee A2L02 (Jonas et al., 1971) for the following quoted reasons:

1. Strains are easier to compute than void ratios.
2. Samples may exhibit quite different void ratio vs. log stress plots, because of differences in initial void ratio, but almost identical strain vs. log stress plots.

3. Settlements are directly proportional to strain, whereas use of Δe data requires a knowledge of $(1 + e_o)$. Thus the latter introduces two variables, Δe and $(1 + e_o)$.

4. It is easier to standardize strain plots than void ratio plots.

These curves could be used to compute the compression index (C_c) and the swelling index (C_s) because of our knowledge of the initial void ratio (e_o) of the compacted samples where the change in void ratio Δe is equal to the vertical strain times $(1 + e_o)$, i.e.,

$$\frac{\Delta e}{(1 + e_o)} = \frac{\Delta H}{H_o} \quad , \quad \text{thus}$$

$$\Delta e = \frac{\Delta H}{H_o} (1 + e_o) = \varepsilon_v (1 + e_o) \quad .$$

Consolidation Samples

Consolidation tests were performed to study the effect of molding water content, dry density, method of compaction, saturation with volume change, and saturation without volume change on the compressibility and rebound characteristics of compacted clays. Therefore, consolidation tests were conducted on samples compacted by two methods: static and kneading, under the following conditions which will be discussed in detail in the following chapter:

1. Low Compaction Curve: Consolidation tests were conducted on samples compacted at the following molding water contents and dry densities: (a) 31.1%, 76.5 pcf, (b) 36.1%, 80.0 pcf, and (c) 39.2%, 76.5 pcf. Consolidation tests were performed

under three states of compacted samples: (a) in the as-compacted state, (b) soaked with volume change, and (c) soaked without volume change. Samples were consolidated under the following maximum consolidation stresses before rebound starts: (a) 1 tsf, (b) 4 tsf, and (c) 16 tsf.

2. High Compaction Curve: Consolidation tests were performed only on the kneading-compacted samples in two states: (a) soaked without volume change up to 16 tsf and (b) in the as-compacted state up to 16 tsf. The molding water contents and dry densities of the compacted samples are: (a) 26.1%, 82.5 pcf, (b) 31.1%, 86.3 pcf, and (c) 34.0%, 82.5 pcf.

The positions of all the tested samples on their respective compaction curves were indicated by numbers in Figure 5.

X-ray Diffraction Study

Sample Preparation

X-ray diffraction study was conducted on the compacted samples before consolidation and after consolidation to study the effect of molding water content, dry density, method of compaction, and consolidation stress on the fabric of compacted clays. The samples were chosen from the middle portion of the 4-inch diameter compacted samples. Two rectangular vertical sections and two rectangular horizontal sections, each about $\frac{1}{4}$ inch in thickness and 1 inch in height, were cut from the center portion of the sample by means of a wire saw.

These sections were placed immediately after being trimmed in molten carbowax 6000 in a constant temperature oven at 65° C for a period of about two weeks with periodic exchange for fresh wax. Carbowax 6000 is a high molecular weight wax that can replace the water in the sample by diffusion without disrupting the initial fabric of the soil (Mitchell, 1956). This water soluble wax is manufactured by Union Carbide Corporation. At the end of the soaking period the vertical and horizontal sections were removed from the molten wax and left in the open atmosphere to harden for about two days. The resulting sections have a hardness of one on the Moh Scale of hardness.

The specimen sections were first polished on a coarse garnet paper to remove the irregularities from the surface. Then, the sections were polished on medium fine carborundum paper, and finally wet polished using unidirectional movement with a slight finger pressure applied. The sections were considered appropriate for x-ray diffraction study when it could be determined that, upon examination under a light microscope at 80 x magnification, their polished surfaces were flat, smooth, and free from hairline-cracks.

It has been found experimentally that the removal of 0.06 inches of the surface of the studied section in the successive stages of grinding and polishing secures a relatively disturbance free surface for fabric study. Martin (1966) demonstrated experimentally that neither the standardized impregnation procedure nor the normal grinding procedure has an adverse effect upon clay fabric.

X-ray Diffraction Technique

Upon the examination of the x-ray diffraction traces of powdered kaolinite, Carbowax 6000, and Carbowax impregnated compacted kaolinite samples it was found appropriate to use the 020 and 002 peak counts for the qualitative expression of the degree of particle orientation in the compacted kaolinite samples. Martin (1966) mentioned that the three reasons for choosing the 020 and the 002 kaolinite reflections to express the peak ratio, PR, are that these x-ray reflections are:

1. Strong reflections and thus provide a sensitive measure of fabric,
2. distinct from other reflections, and
3. close enough together that approximately the same volume will be irradiated in the determination of the peak amplitudes for both peaks.

Nowatzki (1966) found this method satisfactory for expressing the fabric of sheared compacted kaolinite specimens. In this study, the fabric of the tested kaolinite specimens was quantitatively expressed in terms of the "orientation index", O.I., which is defined as:

$$\text{O.I.} = \frac{\text{Average peak count at (002) - Background at (002)}}{\text{Average peak count at (020) - Background at (020)}}$$

From the x-ray diffraction trace it was easy to determine the approximate 2θ angle for both the (020) peak and (002) peak. It was found that the (020) peak occurs at about $2\theta = 19.82°$, and that the (002) peak occurs at about $2\theta = 24.83°$. Therefore, the following procedure was used to obtain the peak count at the (020) peak:

1. The goniometer was manually advanced from a 2θ angle of 19.50° at a rate of about 0.5° per minute keeping track of the x-ray diffraction trace and the rate meter reading in the x-ray diffractometer.
2. When the diffraction trace reached its maximum, the goniometer was advanced further until the trace began to fall off.
3. The goniometer was then driven slowly back and forth to determine with a reasonable degree of accuracy the 2θ angle at which the peak occurs.
4. A series of 10-second counts were taken at the 2θ angle determined in the previous step, and at several 2θ angles very close to it to determine with a high degree of accuracy the exact 2θ angle of the peak.
5. Ten 10-second random counts were taken at the peak angle, and the average peak count computed.
6. The specimen was rotated 180° in the specimen holder and the above steps (1) through (5) were repeated.
7. The average peak count for the section was then computed for the (020) peak.
8. The same procedure was followed in computing the average peak count for the (002) peak except that the goniometer was first manually advanced from a 2θ angle of 24.50°.

The background count corresponding to each peak was determined from the x-ray diffraction trace of the section. The background count did not change significantly from one section to another.

The net peak counts were computed and the orientation indices were determined for both the horizontal and vertical sections of the tested samples. A typical x-ray diffraction trace of a compacted kaolinite sample is shown in Figure 6.

X-ray Study Samples

Fabric study using the x-ray diffraction technique was conducted on the samples that were compacted at the three molding water contents: dry of optimum, optimum, and wet of optimum by both compaction methods, kneading and static, at the low compaction effort. This study was conducted also on the kneading-compacted samples (low compactive effort) that have been soaked with volume change and consolidated under 1 tsf, 4 tsf, and 16 tsf. Fabric study was also performed on the samples compacted by kneading at the high compaction effort and at the three molding water contents: dry of optimum, optimum, and wet of optimum.

These fabric studies were intended to reveal the effect of molding water content, dry density, method of compaction, and consolidation stress on the fabric of compacted clays. This was done to test the hypothesis developed by Lambe (1958a) and adopted by Seed and Chan (1959a) which suggests that clays compacted at molding water contents less than optimum would tend to have a "flocculated" or edge-to-face structure, while samples compacted at molding water

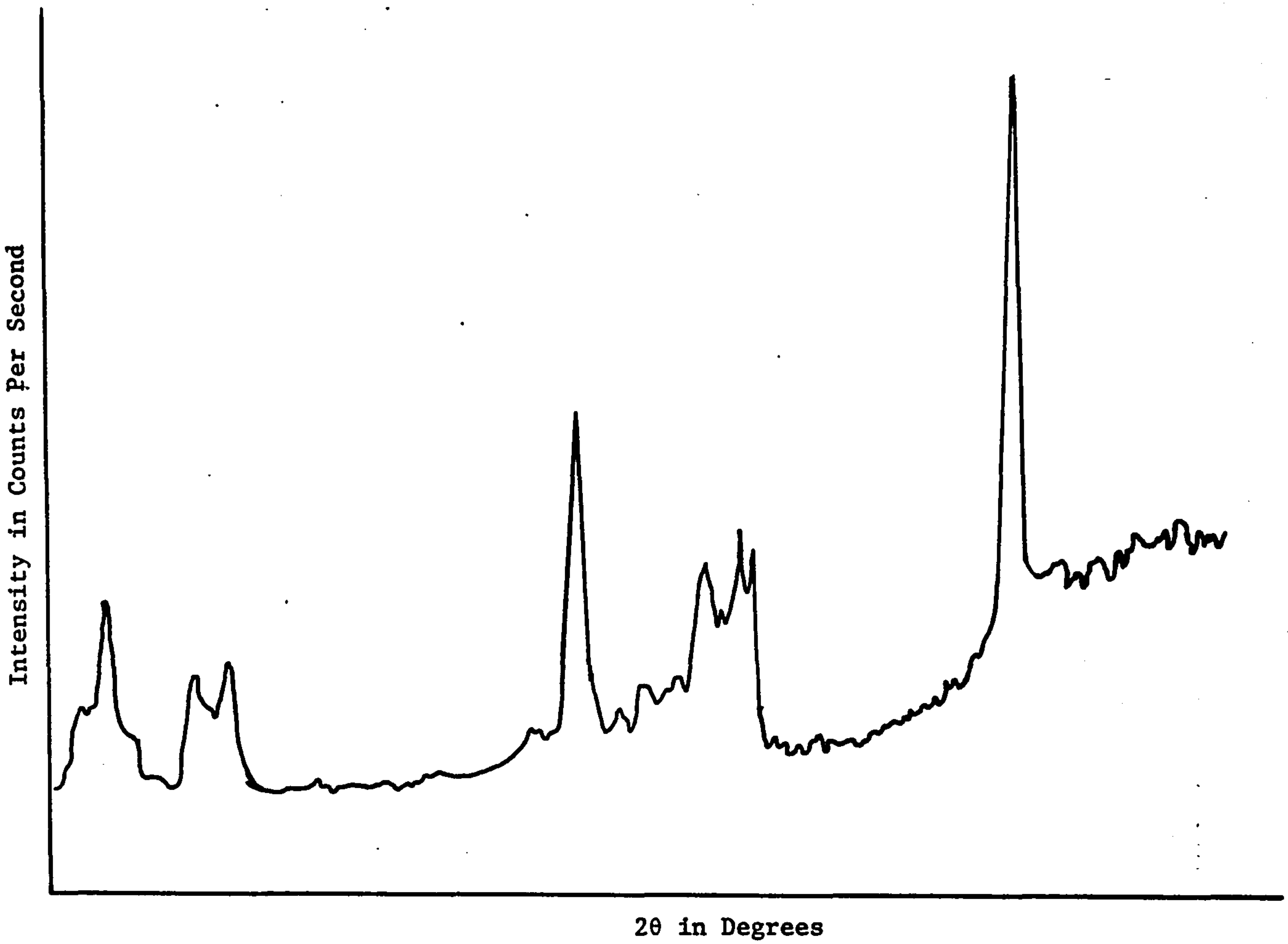


Figure 6 Typical X-ray Diffraction Trace of a Compacted Kaolinite Sample

contents greater than the optimum would tend to have a "dispersed" structure with a considerable improvement in the orientation of clay particles in a direction perpendicular to the axis of compaction.

To express the extent to which the fabric of a particular sample surface is oriented relative to the best experimental estimate of the orientation of perfectly oriented and randomly oriented fabric for a particular soil, Diamond (1971) introduced the term "degree of orientation", D.O., defined as follows:

$$\text{D.O.} = \frac{\text{O.I. of sample surface} - \text{O.I. of random mount}}{\text{O.I. of "fully"-oriented mount} - \text{O.I. of random mount}}$$

The orientation indices of fully oriented and fully random mounts were determined following the technique suggested by Professor R. L. Sloane, University of Arizona, Tucson, Arizona. The fully oriented mount was developed by the centrifugal precipitation (2000 rpm, for 5 minutes) of kaolinite particles from a suspension of 1.5% concentration on a porous plate in three cycles. The fully random mount was developed by sieving a powdered kaolinite to fill a slide cavity with the kaolinite particles passing 63 microns. A very thin film was made by dropping a few drops of flexible collodion mixed with some castor oil and amyl acetate on the surface of clean water. The film was carefully picked up on a 3-inch diameter ring of soft iron wire. The film was fixed over the slide to hold the "random" mount in place.

Martin's method (1966) of dumping air-dried kaolinite into molten wax of 1:2 kaolinite to wax ratio to produce a random mount was also tried and the results were compared with the above technique.

Electron Microscope Study

This study aims at clarifying the effect of water content, dry density, method of compaction, and consolidation stress on the fabric of compacted clays. This study provides a visual evidence that will either support or modify the current hypothesis about the effect of the above factors on the fabric of compacted clays.

Sample Preparation

As many sections as possible were cut from the $2\frac{1}{2}$ inch diameter samples by means of a wire saw. The approximate dimensions were 1.2 cms x 2 cms for the vertically fractured sections and 1.2 cms x 1.2 cms for the horizontally fractured sections. These were first air-dried for two days and then placed in a vacuum desiccator for four days for final drying. Each section was then scored on the outside by a sharp razor blade and fractured along the scored grooves. The sections were fractured horizontally and vertically to study the fabric in both directions: normal and parallel to the compaction axis, and to the applied consolidation stress for the consolidated-compacted samples. The fractured samples were then trimmed to approximately one centimeter cubes.

Replication Procedure

The trimmed cubic sample was mounted on a glass slide, fracture surface up. A thin lead-foil mask with about half centimeter square opening was placed over the fracture surface. The bell jar of the Makros VE-10 Vacuum Evaporator was evacuated to an operating pressure of approximately 10^{-5} mm of Hg. The bell jar was then brought back to atmospheric pressure, and two $\frac{1}{8}$-inch diameter carbon rods, one with a special necked down point, were installed in the carbon holders, and a 2 centimeter long platinum-palladium wire (80% Pt - 20% Pd) was folded into a v-shape and placed in the tungsten wire basket. The fractured sample was placed on the rotating table directly below the contact point of the carbon rods. The bell jar was closed and evacuated to 10^{-5} mm of Hg. The electrode selector was switched to the front pair of feed-throughs for the metal shadow-casting of the fracture surface. The platinum-palladium wire was evaporated by heating the tungsten basket with a high-amperage, low voltage direct current. The electrode selector was then switched to the rear pair of feed-throughs for carbon-replicating of the fracture surface by evaporating the necked-down portion of the carbon rod with a high amperage, low voltage direct current. The replica was reinforced by the following method: a polystyrene disc was placed on a glass slide and heated till it became like a viscous liquid. The clay sample was pressed into the heated polystyrene disc, replica side down, and then allowed to cool to room temperature. The clay sample was easily separated from the replica which adhered tightly to the polystyrene disc. The disc was removed from the glass slide by wetting it with a few drops of ethyl alcohol. The polystyrene-embedded replica was then placed in a hydrofluoric acid solution, replica side down, for about 45 minutes. The replica was then washed with water before placing it in a diluted sodium hydroxide for ten minutes. The replica was again washed with water and placed in the acid solution. Five cycles of washing were generally sufficient for an adequate removal of the clay attached to the replica. All washings were carefully performed under a ventilated fume hood. The cleaned polystyrene-embedded replica was then scored into 2 mm squares by a sharp clean razor blade. The scored replica was placed in a polyethylene dish filled with ethylene dichloride, and pushed to the bottom replica side up. The replicas floated free to the top of the solution where they were picked up by a stainless steel screening and transferred to a second container and then to a third container of fresh ethylene dichloride for washing. The replicas were then picked up on 400-mesh, $\frac{1}{8}$-inch diameter copper electron microscope grids. The replicas were viewed under an 80 x binocular microscope, where the best four or five replicas were chosen and placed in gelatine capsules glued to identified glass microscope specimen slides for storage until they were needed for examination under the electron microscope.

Electron Microscope Samples

The electron microscope study was conducted on the same sequence of samples as those used in the x-ray diffraction study.

CHAPTER 4

FABRIC CHARACTERISTICS

The term "fabric" is used in this research as that component of the soil structure that describes the spatial geometrical arrangement of the soil particles and/or groups of particles and their associated void spaces. This definition was adopted by many investigators among which are: Mitchell (1956), Lambe (1958a), Brewer and Sleeman (1960), Meade (1964), Martin (1966), and Martin and Ladd (1970). The other component of soil structure is the electrokinematic force acting between the soil particles. Extensive research work was carried out to study the effect of the different factors on soil structure both for undisturbed natural soils and for disturbed soil samples in the laboratory. Most of the previous research work was essentially qualitative in its nature. The importance of soil structure and especially its effect on the engineering behaviour of clay soils stimulated the efforts to develop new techniques for better qualitative and quantitative evaluation of soil structure. New methods, both direct and indirect, have been developed to achieve this purpose. These methods include the use of the petrographic microscope, the use of the electron microscope, the x-ray diffraction measurement techniques, as well as the engineering characteristics of soil behaviour such as the shrinkage characteristics, the slaking characteristics, and the swelling potential of soil upon soaking.

The current research work employed both the x-ray diffraction measurement techniques and the electron microscope examination to study the effect of the different factors involved in the compaction process on the fabric characteristics of compacted clays. These factors include the molding water content, dry density, method of compaction as well as the effect of consolidation under different stress levels.

X-ray Diffraction Study

Since previous investigations demonstrated experimentally that the engineering behaviour of clayey soils is structure-dependent, a quantitative expression of soil structure becomes highly important. Soil fabric that describes the spatial arrangement of soil particles and their associated voids is the component of soil structure that is more amenable to measurement. Two interrelated problems concerning the measurement of soil fabric were mentioned by Martin (1966): (1) to prepare for examination a specimen that preserves the fabric of the original sample, and (2) to examine some property of the clay crystallites that quantitatively expresses their geometrical arrangement. The technique that was used in preparing the sections of the x-ray diffraction study and the method of measuring the degree of orientation in these sections were described in Chapter 3.

In order to evaluate the effect of the different variables involved in the compaction process on the fabric characteristics of compacted clays, it was found appropriate to measure the orientation indices of the perfectly random and perfectly oriented samples. This will enable us to examine the orientation state of the tested samples on the continuum from the perfectly random to the perfectly oriented states. The procedures of preparing the samples with the practically extreme cases of randomness and orientation were described in Chapter 3. It was found experimentally that the orientation index of the perfectly random sample was 1.91 using the technique described in this research, and that of the perfectly oriented sample was 230. Using the technique described by Martin (1966), the orientation index for the perfectly random sample was 2.26.

For the easy reference to the different samples tested in this research, symbols were used to identify each sample. These symbols, along with some given examples, are explained in Appendix A.

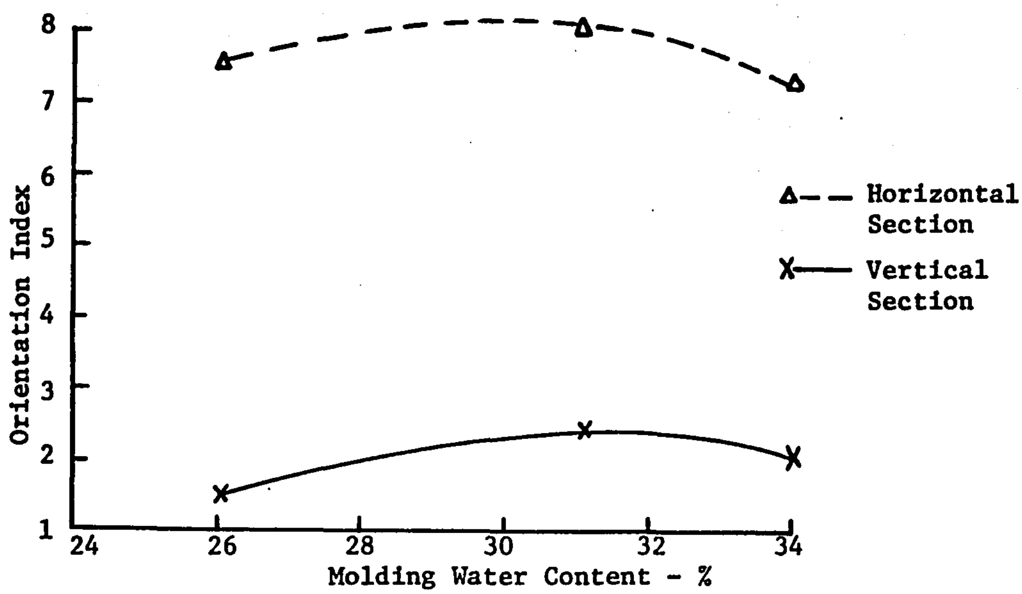
Effect of Molding Water Content

Based on the engineering behaviour of compacted clays Lambe (1958a, 1958b) presented his hypothesis that the degree of orientation of clay particles in compacted clays increases with the increase in the molding water content. According to Lambe's hypothesis it can be concluded that, in general, a clay soil compacted at dry of optimum will assume a random fabric while the same soil compacted at wet of optimum will assume an oriented fabric. The research work of Seed and Chan (1959a) on the structure and strength characteristics of compacted clays supported the general views of Lambe. However, later investigations such as the research work of Diamond (1971) on the microstructure and pore structure of impact compacted clays showed that the views of Lambe were not essentially all true.

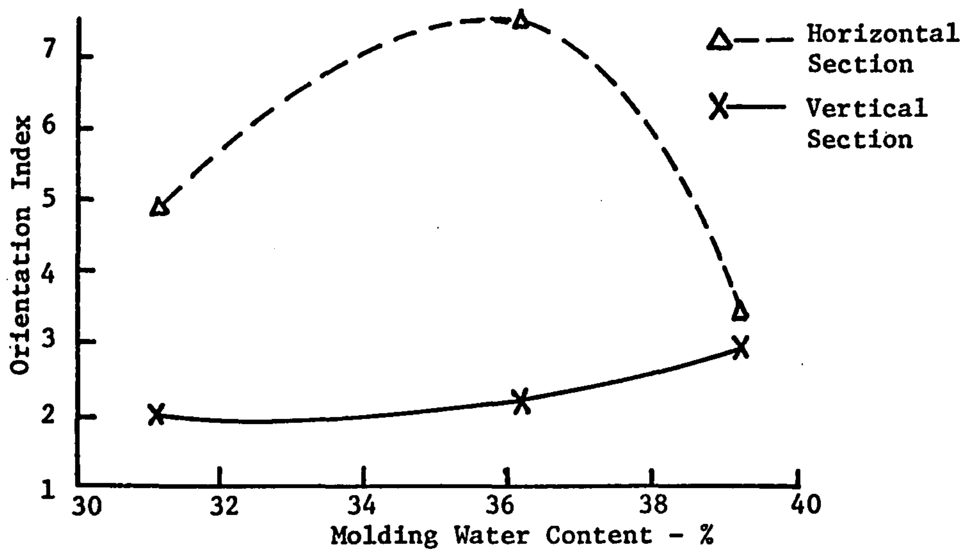
In this research the variation of the orientation index with the molding water content was studied for both the kneading and static compacted samples at the low compaction effort, and only for the kneading compacted samples at the high compaction effort as shown in Figures 7 and 8.

Figure 7 shows that for the kneading compacted samples at the low compaction effort the orientation index in the horizontal section increased from 4.89 at dry of optimum to 7.56 at optimum, and then decreased to 3.45 at wet of optimum. In the vertical section, the orientation index increased from 2.04 at dry of optimum to 2.20 at optimum, and then to 3.01 at wet of optimum. For the samples compacted by kneading at the high compaction effort the orientation index in the horizontal section increased from 7.58 at dry of optimum to 8.09 at optimum, and then decreased to 7.31 at wet of optimum. In the vertical section, the orientation index increased from 1.50 at dry of optimum to 2.44 at optimum, and then decreased to 2.10 at wet of optimum.

Figure 8 shows that for the static samples, the orientation index in the horizontal section increased from 3.79 at dry of optimum to 4.90 at optimum, and then to 6.97 at wet of optimum. In the vertical section, the orientation index increased from 1.93 at dry of optimum to 2.53 at optimum, and then to 3.24 at wet of optimum.



a. High Compaction Effort



b. Low Compaction Effort

Figure 7 Variation of the Orientation Index with the Molding Water Content for the Kneading Compacted Samples

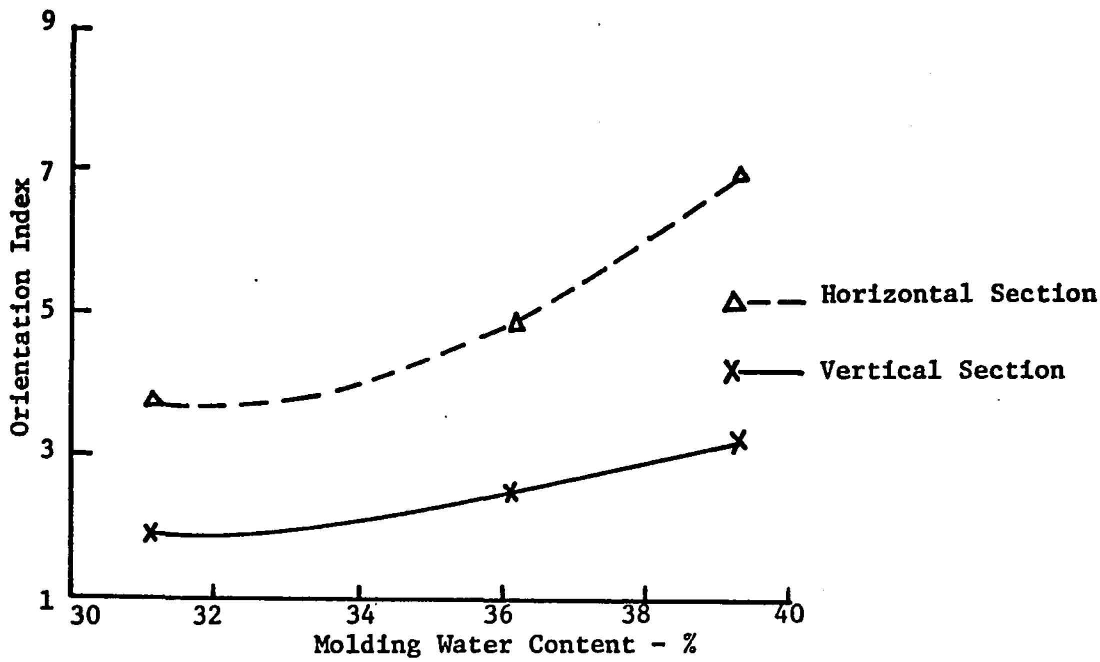


Figure 8 Variation of the Orientation Index with the Molding Water Content for the Static Compacted Samples , Low Compaction Effort

This shows that there is an improvement in the orientation of clay particles in the horizontal section in the statically compacted samples with the increase in the molding water content. This result is in conformity with Lambe's hypothesis where there is an increase in the thickness of the double layer and the repulsive force will be the dominating one with the increase in the molding water content which will increase the mobility of clay particles to align themselves with their faces normal to the direction of the compaction axis. On the other hand, there is an appreciable decrease in the orientation index in the horizontal section in the kneading compacted samples with the increase in the molding water content from optimum to wet of optimum water content. This might be due to the fact that at the high molding water content at wet of optimum the tamping foot of the kneading compactor develops numerous and discontinuous planes of shear strain in the compacted samples. These shear planes often exist at different angles of inclination to the horizontal plane. These angles of inclination are steeper in the samples compacted at wet of optimum than in the samples compacted at optimum or dry of optimum. Thus any horizontal section for x-ray diffraction study will have a high probability of intersecting these shear planes at some inclination angle that will reduce the orientation index in that section.

The research of Diamond (1971) showed that the orientation indices of the impact compaction kaolinite specimens were higher for the specimens compacted at the optimum water content than for those compacted at wet of optimum water content. Such results are in conformity with the results of this research particularly since it has been shown, Kell (1964), that the fabric characteristics of impact compacted clays are very similar to those of the kneading compacted clays.

The variations in the orientation indices in the vertical sections for both the static and kneading compacted samples are small, and the general trend seems to indicate an increased degree of orientation with increased molding moisture content. However, since no reliable conclusions should be derived by comparing the small variations of these values no further discussion will be made concerning the orientation indices in the vertical section. Thus the orientation indices that will be discussed will be those of the horizontal sections unless specified otherwise.

Effect of Method of Compaction

In their research work on the structure and strength characteristics of compacted clays, Seed and Chan (1959a) made the conclusion that among the known methods of compaction the kneading compaction results in a soil fabric with maximum orientation while the static compaction results in a soil fabric with minimum orientation.

By comparing the orientation indices of the kneading and statically compacted samples, as found in this research, we notice that the orientation indices of the statically compacted samples are less than those of the kneading compacted samples at dry of optimum water content (3.79 for the static versus 4.89 for the kneading), and also at optimum water content (4.90 for the static versus 7.56 for the kneading). This is expected and in conformity with the conclusions by Seed and Chan (1959a) where the kneading action of the tamping rammer will allow more orientation of the clay particles in the kneading-compacted samples. Yet, the molding water content at dry of optimum and at optimum is not high enough to allow the development of shear planes that are highly irregular or steeply inclined to the horizontal plane as would be expected at the wet of optimum molding water content. Therefore, there is a greater chance for the horizontal section of the x-ray diffraction study to reveal the orientation of clay particles in the fabric of the kneading compacted samples. The molding water contents at dry of optimum and at optimum are also not high enough for the static load to align the clay particles in the horizontal plane, and thus the statically compacted samples show less orientation than their corresponding samples compacted by kneading.

At the wet of optimum molding water content the orientation index of the static samples is higher than that of the kneading samples (6.97 for the static versus 3.45 for the kneading). This is mainly due to the fact, as mentioned before, that the tamping rammer of the kneading compactor with its deeper penetration at such a high molding water content causes the development of numerous, irregular, and discontinuous shear planes that are inclined to the horizontal plane at steeper angles of inclination than those produced at optimum or dry of optimum molding water contents. Therefore, any horizontal section has a high probability of intersecting these shear planes at a relatively steep angle of inclination, and thus will reveal a lower degree of orientation than the expected one. On the other hand, the wet of optimum molding water content will be sufficient for the static load to align the clay particles in a direction normal to the compaction axis. Due to the mechanism of static compaction and as was confirmed by Kell (1964), no such planes of shear strain as those developed by kneading compaction will develop in the statically compacted samples. Therefore, a horizontal section in the statically compacted samples will reveal under the x-ray diffraction study a higher orientation index than the horizontal section in the corresponding kneading compacted sample.

Effect of Consolidation

Lambe (1958b) assumed that the effect of consolidation in the soil compacted at dry of optimum water content will comprise both the decrease in the spacings between soil particles as well as the reorientation of soil particles. Thus a soil that has initially a random fabric, such as the one compacted at dry of optimum water content, will assume an oriented fabric at the end of consolidation under a high applied pressure. For the soil that has initially an oriented fabric, such as the one compacted at wet of optimum water content, the consolidation effect will be mainly the decrease in the spacings between soil particles.

The present study showed that this is not necessarily the case. The fabric characteristics of the samples compacted by kneading at low compaction effort at the dry of optimum and wet of optimum molding water contents were tested before consolidation and after applying consolidation stresses of 1, 4, and 16 tons/sq. foot on the samples after being soaked with volume change as shown in Figure 9.

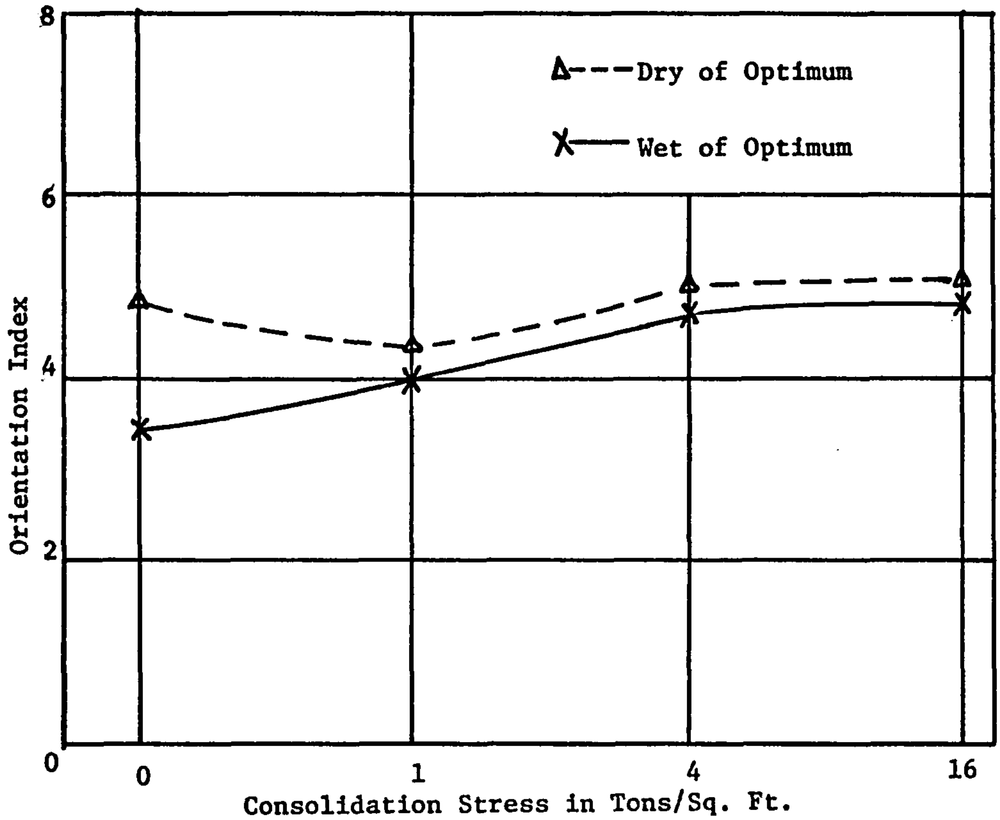


Figure 9 Variation of the Orientation Index with the Consolidation Stress for the Horizontal Sections of the Samples Compacted by Kneading at the Low Compaction Effort. Consolidation Stresses Were Applied on the Samples After Being Soaked With Volume Change.

Many factors involved in the consolidation process may have a significant effect on the fabric of compacted clays after consolidation. Such factors include: (a) the initial fabric of compacted clay before consolidation, (b) the magnitude of the applied consolidation stress, (c) time of consolidation, (d) the hydraulic gradient that may develop upon the application of a certain consolidation stress, (e) the magnitude of consolidation that the sample undergoes during the consolidation process, and (f) any changes in the consolidation and fabric that may occur upon load release. As far as the last factor is concerned, Lambe (1958b) assumed that during rebound the spacing between particles increases but only negligible changes in orientation occur. Such an assumption is accepted until further research work is carried out to clarify the effect of rebound on soil fabric.

By studying the variations in the orientation indices with the consolidation stress as presented in Figure 9 we notice the following:

1. The variation in soil fabric upon the application of a consolidation stress of 1 tsf depends on the initial fabric of the compacted sample. The slight decrease in the orientation index of the kneading sample compacted at dry of optimum is mainly due to the effect of the hydrodynamic gradient. The slight increase in the orientation index of the kneading sample compacted at wet of optimum may be mainly due to the improvement in the macrofabric of the compacted sample. The term "macrofabric" refers here to the gross properties or features of the tested samples

that can be visualized by the naked eye or with the help of a simple magnifier. The presence of planes of shear strain and their characteristics which include the number, spacing, continuity, orientation, and surface characteristics of these planes form an important element of the macrofabric of the compacted samples. The shear planes that developed at some angle of inclination to the horizontal plane during the kneading compaction will become closer to the horizontal plane during the consolidation process, and thus will reveal more orientation in soil fabric. Also, since the flow of pore water in the consolidated samples is generally in the vertical direction, the effect of the hydrodynamic gradient on the disruption of soil fabric increases with the decrease in permeability in the vertical direction i.e., with the increase in the orientation of soil fabric in the horizontal direction. Thus, the role of the hydrodynamic gradient in decreasing the orientation of soil fabric might be of less importance in the sample compacted at wet of optimum water content (O.I. = 3.45) than in the sample compacted at dry of optimum water content (O.I. = 4.89).

2. An improvement in soil fabric occurs upon the application of a consolidation stress of 4 tsf for the samples compacted at dry of optimum and wet of optimum molding water contents. This is mainly due to the high compression of the samples where the major steepening in the vertical strain (ε_v) versus log consolidation stress (log P) curve

occurs upon changing the consolidation stress applied on the sample from 1 tsf to 4 tsf.

3. Only a very slight change in soil fabric occurs upon changing the consolidation stress from 4 tsf to 16 tsf for the samples compacted at dry of optimum and wet of optimum molding water contents. This is mainly due to the effect of the hydrodynamic gradient that develops upon the application of the 16 tsf consolidation stress. Any probable improvement in soil fabric due to the consolidation of the samples may be offset by the disrupting effect of the hydrodynamic gradient.

Thus we can conclude that the greatest improvement in the orientation of consolidated compacted clays occurs upon the increase in the consolidation stress from a stress below the equivalent pre-consolidation stress (P_p) to one above it, i.e., when the stress state of the sample passes through the transition zone from the flat portion to the straight line portion of the consolidation curve. We can also state that since the flow of pore water during the primary consolidation is essentially in the vertical direction, and since the permeability in the vertical direction decreases with the increase in the degree of orientation in the horizontal direction, the disruption of soil fabric due to the effect of the hydrodynamic gradient will increase with the increase in the preferential orientation in the horizontal direction.

However, we can state that all the tested samples regardless of their dry density, molding water content, consolidation stress, and method of compaction are on the random side of the continuum from the perfectly random state (O.I. = 1.91) to the perfectly oriented state (O.I. = 230). Thus, these little differences in the orientation indices between the samples compacted at dry of optimum and those compacted at wet of optimum look relatively insignificant. Yet, there is a significant variation in their mechanical properties and engineering behaviour. The writer concludes from this that it is not only the micro-fabric of the soil that determines its engineering behaviour but also its macro-fabric whose importance should be more emphasized in any future investigations. This macro-fabric does not refer to the particle-to-particle or packet-to-packet relationship, but as mentioned before, to the gross properties and features of the compacted samples and especially to the characteristics of any shear strain planes that may exist in the tested samples.

Electron Microscopy Study

Although electron microscopy study is admittedly a qualitative one, it constitutes a powerful tool for fabric study analysis. It permits rapid visualization and examination of the arrangement of soil particles and/or groups of particles and the different patterns of orientation zones within the tested soil samples. When combined with the x-ray diffraction measurements of fabric orientation and with the pore-size distribution analysis, the electron microscopy study can provide a more integrated picture of the microstructure of the studied soil samples. However, this type of study involves the use of diversified kinds of apparatus, and requires the detailed study and examination of a large number of electron micrographs to come up with applicable concepts about the effect of the different factors on soil fabric.

The procedure of preparing the platinum-palladium (Pt-Pd) shadowed carbon replicas of the kaolinite samples for this study was described in Chapter 3. Four or five replicas were prepared for each sample and all of them were viewed under the petrographic microscope and the best one was chosen for examination under the electron microscope. After a thorough scan of the replicas under the electron microscope a certain area that was found representative of the whole fabric was photographed at a magnification of 5000. A chosen representative area of the photograph was then enlarged to a magnification of 10,000. These enlarged electron micrographs are the ones presented in this study for fabric analysis.

Effect of Molding Water Content

The literature is rich in the terms that were developed and extensively used by the investigators to describe soil fabric. The writer finds it appropriate to mention and adopt some of the terms used by Kell (1964) in describing the fabric of compacted soils. Kell used the term "packet" to describe a group of clay platelets aggregated with basal planes parallel to one another. He also used the term "oriented fabric" to describe packets aligned parallel to one another, and the term "random fabric" to describe packets situated in a haphazard arrangement relative to one another. Since he did not find edge-to-face contacts between individual particles, Kell (1964) suggested the use of the term "bookhouse" instead of the term "cardhouse" to define the "random" fabric of a compacted clay soil.

Electron micrographs were taken of the Pt-Pd shadowed carbon replicas of the horizontal and vertical sections of the fractured samples. These samples were compacted by the kneading and static methods at three molding water contents: dry of optimum, optimum, and wet of optimum water contents. The kneading samples were compacted at the low and high compaction efforts while the static ones were compacted at the low compaction effort.

In describing the fabric of the compacted samples both the horizontal and vertical sections were thoroughly scanned under the electron microscope. The more the compacted samples were oriented in a direction normal to the compaction axis the greater is the quantity of kaolinite platelets and/or packets that will appear on edge in the vertical section, and on basal plane in the horizontal section. Although these electron micrographs at such a high magnification (10,000 x) do not present as good an over-all idea about the different features of soil fabric as the complete scan of the replicas under the electron microscope, they are of sufficient quality to give a general picture of the fabric of compacted soils.

A common characteristic to the electron micrographs of the horizontal and vertical fracture surfaces of compacted clays was the absence of edge-to-face contacts between the individual clay platelets. The presence of packets or domains consisting of kaolinite platelets aggregated along their basal planes, and individual clay platelets or crystallites was recognized. Zones of orientation of kaolinite packets were recognized in the kneading compacted samples at the three molding water contents. However, these zones were more frequent at the wet of optimum and optimum water contents than at the dry of optimum. This is mainly due to the greater penetration of the tamping foot at the wet of optimum and optimum water contents than at the dry of optimum water content. The electron micrographs of the kneading samples presented in Figures 10 and 11 show a greater quantity of kaolinite platelets and packets exposed on their basal planes in the horizontal sections, and a greater quantity of kaolinite platelets and packets on edge in the vertical sections. Although there does not appear a significant degree of preferential orientation in the horizontal sections with respect to the vertical sections, the difference in fabric is more pronounced at the optimum water content than at the dry of optimum or wet of optimum water contents. This may be due to the greater penetration of the tamping foot at the optimum than at the dry of optimum water content, and thus creating more planes of shear strain and consequently more zones of preferential orientation. At the same time these planes of shear strain, although being less in number, have the chance of being more preserved and of greater extension at the optimum than at the wet of optimum water content where there is a considerable degree of mixing in the soil fabric produced by one tamp by that produced in subsequent tamps as was indicated also by Kell (1964). Adjacent packets or domains in the kneading samples appear to be slightly tilted to each other rather than being aligned in one direction.

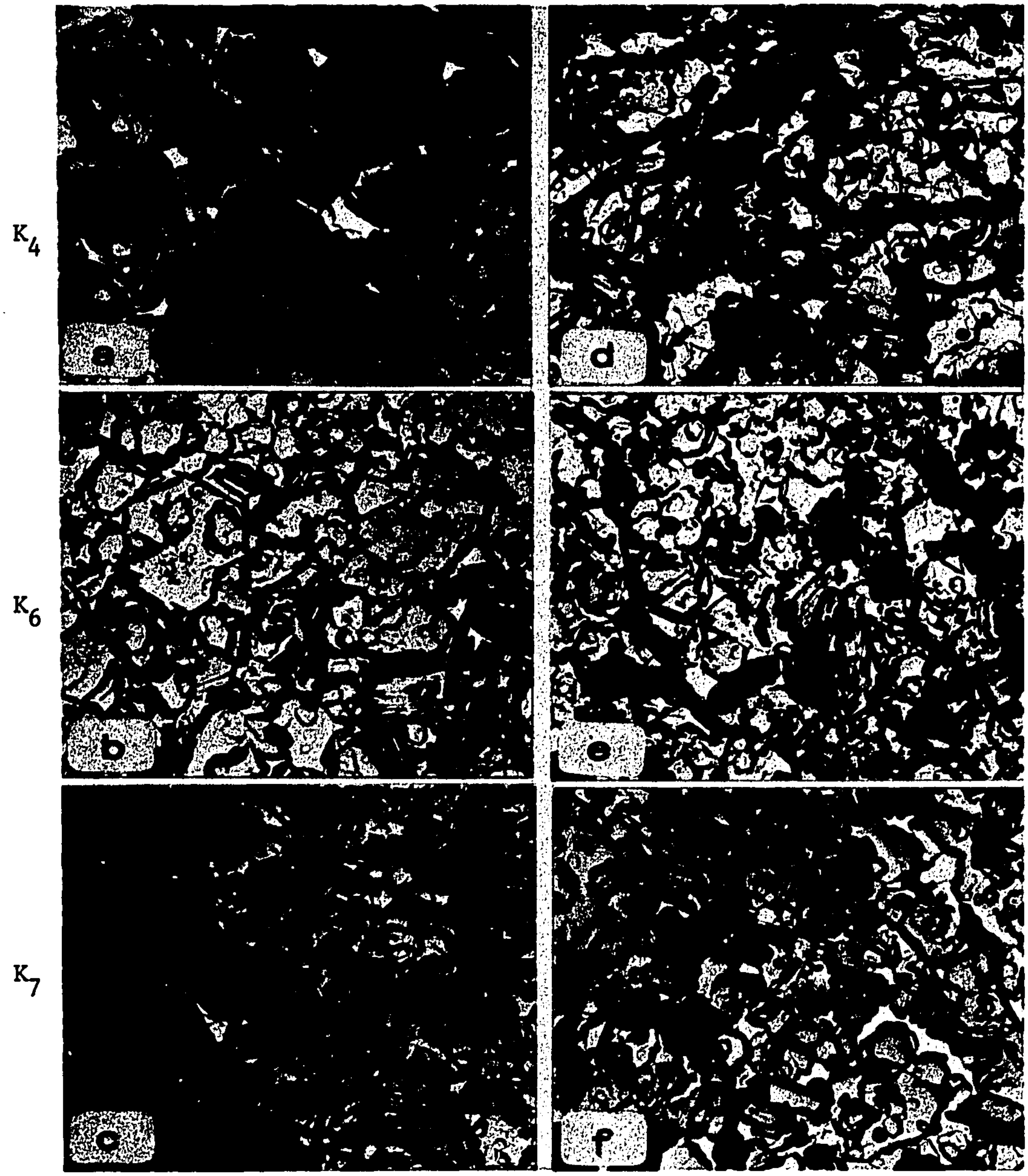


Figure 10 Micrographs a, b, and c Are the Horizontal Sections, d, e, and f Are the Vertical Sections of the Samples K_4, K_6, and K_7 Respectively

(10,000X)

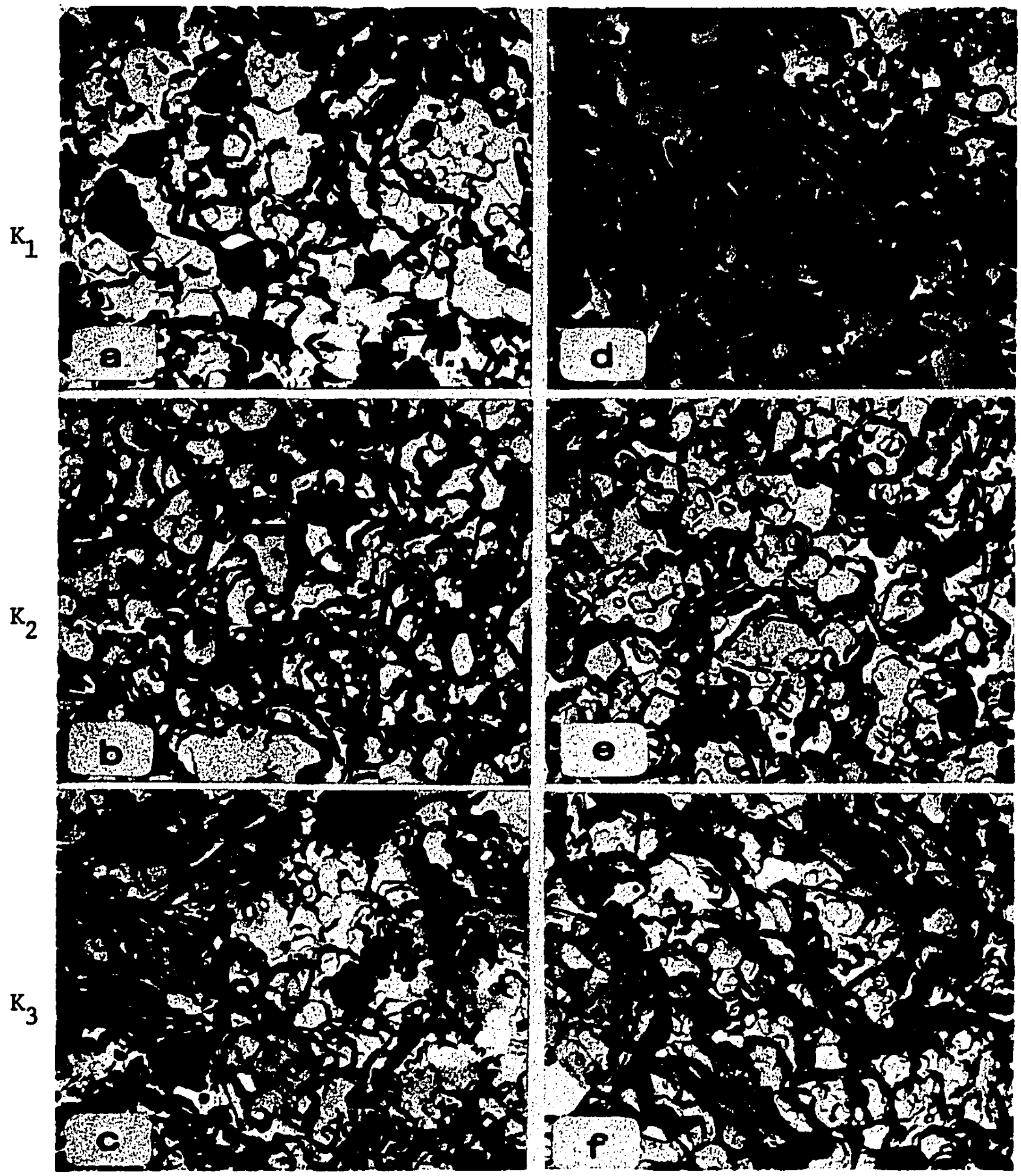


Figure 11 Micrographs a, b, and c Are the Horizontal Sections, d, e, and f Are the Vertical Sections of the Samples K_1, K_2, and K_3 Respectively

(10,000X)

Zones of orientation of packets exist at slightly curved planes, generally parabolic in shape, which are thought to be produced by the kneading action of the tamping foot.

In the statically compacted samples the electron micrographs of the horizontal sections show also a greater quantity of kaolinite platelets and packets exposed on basal plane than those of the vertical sections as shown in Figure 12. Kaolinite platelets and intervening void spaces seem larger at the dry of optimum than at the optimum or wet of optimum water contents. This observation corroborates the findings of Diamond (1971) who found that the kaolinite and illite samples impact-compacted at dry of optimum water content exhibited a domain structure with adjacent domains separated by micrometer-size interdomain voids, while those compacted at optimum or wet of optimum water content showed a more massive structure with the large interdomain voids being absent. In contrast to the findings of the x-ray measurements the difference of soil fabric, as shown in the electron micrographs presented in Figure 12, between the horizontal and vertical fracture sections and thus the degree of orientation is more pronounced at the optimum than at the wet of optimum water content. This is mainly due to the fact that the replicated fracture surfaces are not ideally horizontal or vertical as the sections of the x-ray diffraction measurement. The samples were fractured in such a way that the fracture surfaces form along the weakest bonds rather than being forced in a certain direction to avoid any disturbance to soil fabric. Thus many local deviations from the horizontal or vertical direction may

S_4

S_6

S_7

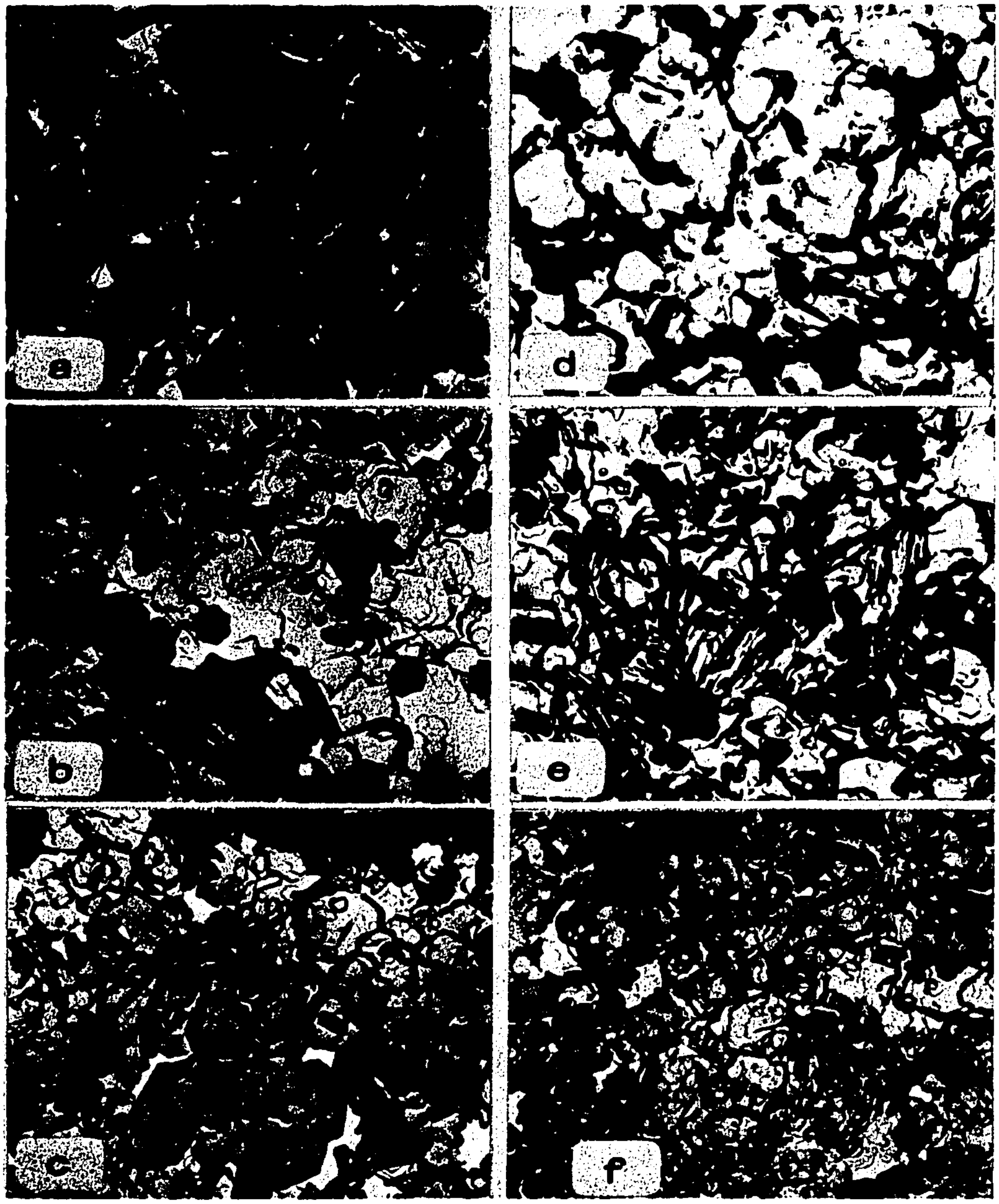


Figure 12 Micrographs a, b, and c Are the Horizontal Sections; d, e, and f Are the Vertical Sections of the Samples S_4, S_6, and S_7 Respectively (10,000X)

occur, and electron microscope replicas may have been taken of such spots. The high magnification of the electron micrographs as well as the limited number of kaolinite particles involved in this study render the x-ray diffraction measurement of the orientation of soil fabric, where a very high number of kaolinite particles is involved, far more sensitive and reliable. This is in addition to the fact that the electron microscopy examination is essentially a qualitative one.

Effect of Method of Compaction

Seed and Chan (1959a) indicated that the data obtained from their experimental research work on the structure and strength characteristics of compacted clays are in excellent accordance with the concept that the shear strain during compaction is primarily responsible for the influence of method of compaction on soil properties. They also indicated that for samples of the same composition prepared at wet of optimum the kneading compaction causes the largest shear strain during compaction while the static compaction causes little shear strain during compaction.

The present electron microscopy study shows that the statically compacted samples have a more open fabric than the corresponding kneading compacted samples especially at the dry side of optimum. The static samples have larger void spaces and larger size of aggregates that did not have the same chance, like those of the kneading samples, to undergo shear strains and thus orientation under the effect of the tamping foot of the kneading compactor. In the static samples, packets of kaolinite platelets exposed on edge and on basal planes can be seen in the electron micrographs of the horizontal and vertical fracture surfaces. However, zones of orientation along parabolic planes of shear strain like those of the kneading samples are not encountered. Instead, zones of orientation are very localized and sporadic, presumably at spots of aggregates of relatively larger water contents. The packets and platelets are generally tilted to each other at greater angles than in the case of the kneading compacted samples.

Effect of Consolidation

The data obtained from the x-ray diffraction study on the fabric orientation of compacted clays demonstrates that the effect of consolidation on the improvement of the orientation of compacted soil fabric is relatively insignificant. Thus, compacted samples which were initially on the random side of the continuum from the random state to the perfectly oriented state remained so even after being consolidated under a consolidation stress of 16 tsf. This study proved the fallacy of the assumption that consolidation, up to the level used in this research, causes a significant improvement in the orientation of soil fabric. Electron microscopy study was carried out to provide a visual evidence on what actually happens to soil fabric upon consolidation under different stress levels.

Electron micrographs were taken of the Pt-Pd shadowed carbon replicas of the horizontal and vertical fracture surfaces of the kneading compacted samples. These samples were compacted at the low compaction effort at the dry of optimum and wet of optimum water contents and consolidated under 1, 4 and 16 tsf consolidation stresses applied on the samples after being soaked with volume change. These electron micrographs are presented in Figure 13 and 14.

The electron micrographs support the x-ray diffraction study results that all the consolidated compacted samples are far from being perfectly oriented regardless of the consolidation stress applied on the samples. The slight variations in soil fabric with the applied stress are not noticeable in the electron micrographs except in the case of samples consolidated under 4 tsf where there is a clear contrast in soil fabric as evidenced from the electron micrographs of the horizontal and vertical sections. An improvement in the orientation of soil fabric could be noticed where the electron micrographs of the horizontal sections are dominated by the kaolinite platelets and packets exposed on basal plane, while those of the vertical sections are dominated by the platelets and packets exposed on edge. This is especially true in the case of samples compacted at the dry side of optimum. No considerable change in fabric is noticed in the electron micrographs of the compacted samples consolidated at 16 tsf from those consolidated at 4 tsf, or in those consolidated at 1 tsf from those in the as-compacted state. No other appreciable variations in the fabric characteristics of compacted clays with consolidation were detected in the electron microscopy study.

K_4TV-1

K_4TV-4

K_4TV-16

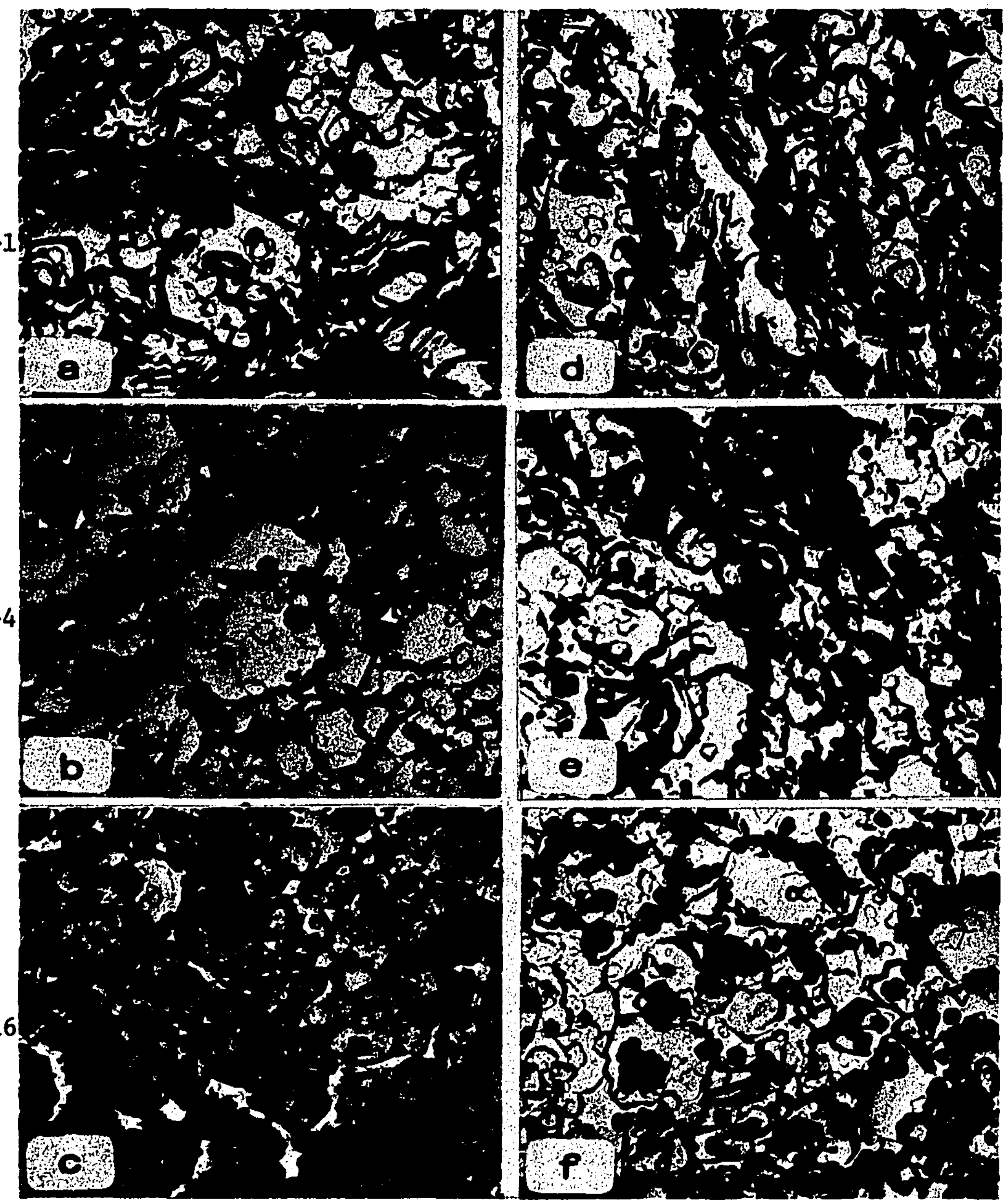


Figure 13 Micrographs a, b, and c Are the Horizontal Sections, d, e, and f Are the Vertical Sections of the Samples K_4TV-1, K_4TV-4, and K_4TV-16

(10,000X)

K_7TV-1

K_7TV-4

K_7TV-16

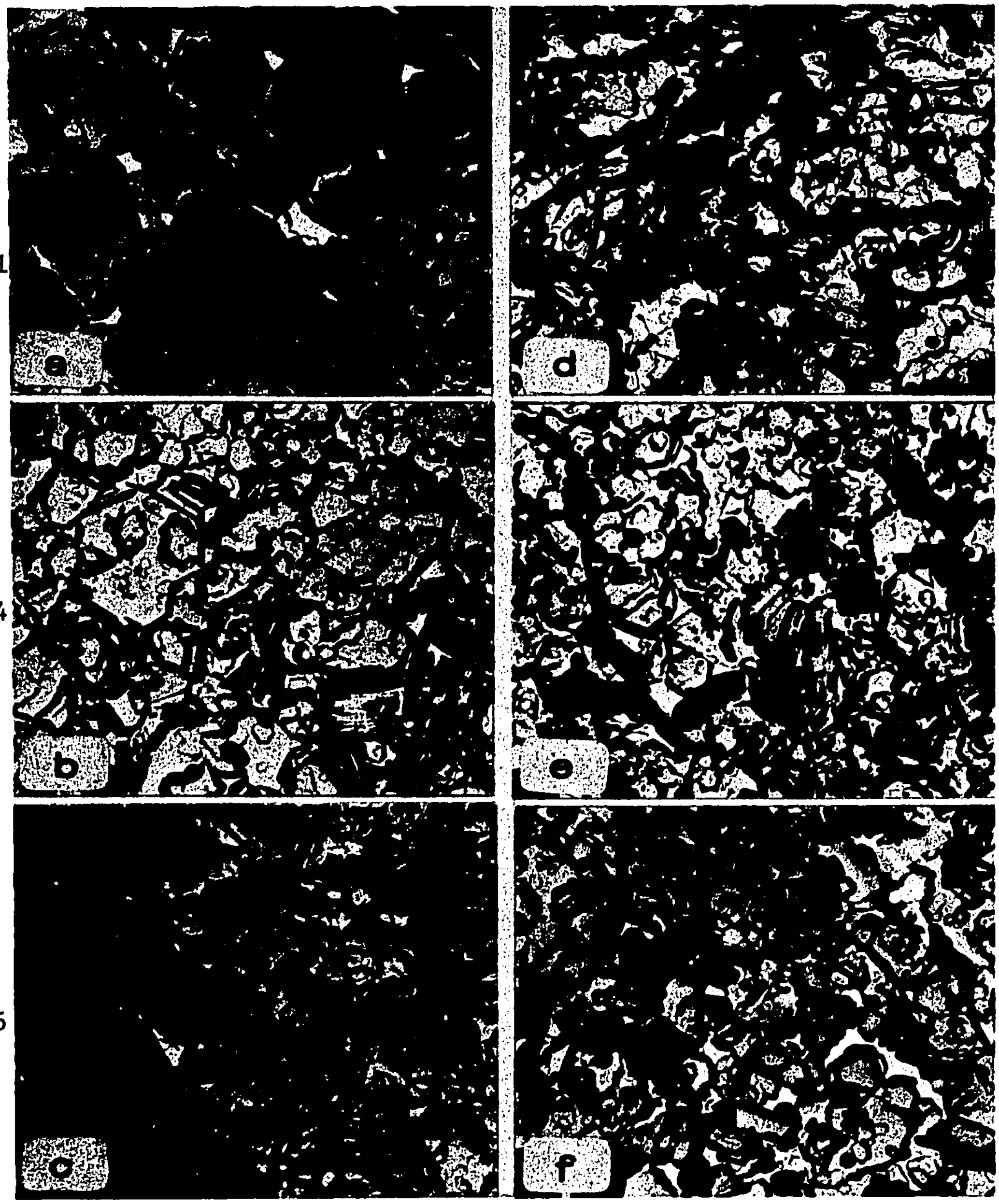


Figure 14 Micrographs a, b, and c Are the Horizontal Sections, d, e, and f Are the Vertical Sections of the Samples K_7TV-1, K_7TV-4, and K_7TV-16 Respectively (10,000X)

CHAPTER 5

COMPRESSIBILITY CHARACTERISTICS

Extensive research work had been carried out to formulate some working theories that can adequately explain the behaviour of compacted clays especially their strength, hydraulic, and compressibility characteristics. Among these main attempts was the development of Lambe's hypothesis (1958a) concerning the change in soil fabric with the molding water content, and which was then adopted and expanded by Seed and Chan (1959a) to include the effect of the different methods of compaction of soil fabric and thus on the engineering behaviour of compacted clays. Techniques were also developed to prepare and measure the fabric of both disturbed and undisturbed soil samples. New terms were used and new parameters were devised to quantitatively and qualitatively better express soil fabric and the variation in this fabric with the different environmental and laboratory factors involved in the preparation of the tested soil samples.

This study aims at testing the applicability of these concepts and primarily the hypothesis of Lambe concerning the compressibility characteristics of compacted clays and to evaluate the effect of some of the factors that may influence such characteristics. This research involves the study of the consolidation characteristics of the static and kneading compacted kaolinite samples both in the as-compacted state and after being soaked with and without volume change. The samples are compacted at two different compaction efforts, and at three molding water contents for each compaction curve: at dry of optimum, at optimum, and at wet of optimum. This research aims at evaluating the effect of such factors as the method of compaction, molding water content, and dry density on the compressibility characteristics of compacted clays in three cases: (1) consolidation in the as-compacted state; (2) consolidation after soaking the compacted samples allowing volume change; and (3) consolidation after soaking the compacted samples without volume change. All the consolidation curves of the tested samples are included in Appendix B.

Effect of Molding Water Content

In the As-compacted State

By comparing the compressibilities of the samples compacted at dry of optimum with the compressibilities of the samples compacted at wet of optimum as shown in Figures 15, 16 and 17 (Appendix B) it can be noticed that the samples compacted at wet of optimum compressed more than those compacted at dry of optimum. This is true for the samples compacted by the kneading and static methods. For the static and kneading samples compacted at the low compaction effort, it can be noticed that the difference in vertical strain between the samples compacted at wet of optimum and those compacted at dry of optimum continued to increase until 8 tsf and then decreased upon the application of 16 tsf consolidation stress. This could be explained by the fact that the sample compacted at wet of optimum has undergone a much higher compression and thus attained a higher dry density than that compacted at dry of optimum. The higher compression of the sample compacted at wet of optimum till 8 tsf will lead also to higher cation concentration and thus to the hardening of soil structure. The higher dry density and the increase in rigidity of soil structure are believed to be the main causes of the above compressibility behaviour.

At the high compaction effort, the difference in vertical strain between the sample compacted by kneading at wet of optimum and that compacted at dry of optimum continued to increase until 16 tsf, Figure 17. This may be attributed to the fact that no collapse or large compression occurred in the kneading sample compacted at dry of optimum at the high compaction effort as it occurred in the kneading sample compacted at dry of optimum at the low compaction effort due to the higher dry density of the former.

Soaked with Volume Change

The consolidation curves of the kneading and static samples compacted at the low compaction effort and consolidated up to 16 tsf after being soaked with volume change are shown in Figures 18 and 19 (Appendix B). These curves indicate that the samples compacted at dry of optimum consolidated more than those compacted at wet of optimum. This difference in consolidation is mainly due to the higher swelling percentage of the samples compacted at dry of optimum as compared with the swelling percentages of the samples compacted at wet of optimum as shown in Table 1. The difference in the average swelling percentages between the samples compacted at dry of optimum and those compacted at

Table 1

Average Swelling Percentages of the Static and Kneading Compacted Samples

Sample	Average Swelling (%)
Kneading, dry of optimum	10.11
Static, dry of optimum	11.29
Kneading, optimum	6.06
Static, optimum	10.60
Kneading, wet of optimum	2.74
Static, wet of optimum	5.71

wet of optimum is 5.58 percent for the static samples and 7.37 percent for the kneading samples.

Soaked without Volume Change

The consolidation curves of the kneading and static samples compacted at the low compaction effort and consolidated up to 4 tsf after being soaked without volume change are shown in Figures 20 and 21 (Appendix B), and those of the kneading samples compacted at the high compaction effort are shown in Figure 22. These curves clearly indicate that the samples compacted at wet of optimum consolidated much more than those compacted at dry of optimum. This is mainly due to the higher swelling pressure that the samples compacted at dry of optimum had attained during their soaking in water without volume change before consolidation. In the case of the samples compacted at the low compaction effort the increase in the water content to reach the saturation state is 12.7 percent for the samples compacted at dry of optimum and only 4.6 percent for the samples compacted at wet of optimum. In the case of the samples compacted at the high compaction effort the increase in water content to reach the saturation state is 11.6 percent for the samples compacted at dry of optimum and only 3.7 percent for the samples compacted at wet of optimum. The swelling pressure of the samples compacted at dry of optimum, as estimated from the consolidation test at the commencement of consolidation of the samples, reached about 1 tsf for the kneading samples at the low compaction effort, about 0.5 tsf for the static samples at the low compaction effort, and about 4 tsf for the kneading samples at the high effort. All the samples compacted at wet of optimum started to consolidate upon the application of 0.25 tsf.

Effect of Method of Compaction

In the As-compacted State

The consolidation curves of the kneading and static samples compacted at the low compaction effort at the three molding water contents and consolidated up to 16 tsf in the as-compacted state are shown in Figures 25, 28 and 31 (Appendix B). Figure 25 shows that at dry of optimum water content the static sample consolidated more than the kneading sample. The difference in vertical strain between the two samples increased considerably upon increasing the applied consolidation stress from 8tsf to 16 tsf. The higher compressibility of the static samples is mainly due to the collapse of the large-size pores that exist among the soil aggregates in the static samples. The larger pores are the ones that collapse at the low stress level and the smaller pores are the ones that collapse at the high stress level. The presence of such large-size pores results form the mechanism of static compaction where the static load, especially at a low molding water content, does not break the individual soil aggregates and thus leaves some large pores in between these aggregates that start to break down during the consolidation process. These rather large-size pores in the static samples were seen during the electron microscopy examination and are clear in the electron micrographs of Figure 12. A smaller degree of collapse occurred also in the kneading sample compacted at dry of optimum upon the application of a 16 tsf consolidation stress. For comparison, the incremental vertical strain upon changing the consolidation stress from 8 tsf to 16 tsf was 549 x 10^{-4} for the static sample, and only 328 x 10^{-4} for the kneading sample.

Figures 28 and 31 show that at optimum and wet of optimum water contents, respectively, the kneading samples consolidated more than the static samples. At the optimum water content the difference in vertical strain between the kneading and static samples increased with the applied consolidation stress till 8 tsf and then decreased upon the application of 16 tsf consolidation stress. This is due to the higher compression of the static sample where the incremental vertical strain between 8 tsf and 16 tsf was 290 x 10^{-4} for the static sample and only 259 x 10^{-4} for the kneading sample. At the wet of optimum water content the difference in vertical strain between the kneading and static samples continued to increase till 4 tsf and then started to decrease. This is also due to the higher compression of the static sample at consolidation stresses above 4 tsf. The incremental vertical strain of the static sample between 4 tsf and 8 tsf was 319 x 10^{-4} and between 8 and 16 tsf 340 x 10^{-4}, while the incremental vertical strain of the kneading sample at the corresponding consolidation stresses were 226 x 10^{-4} and 260 x 10^{-4} respectively. These results are essentially in agreement with Lambe's hypothesis where the more oriented samples compressed more than the less oriented samples at the low stress level and less at the high stress level. The collapse phenomenon of the large-size pores is of much less significance because the existence of such large-size pores become less probable with the increase in the molding water content or dry density or both. The electron microscopy examination and the electron micrographs of the static samples presented in Figure 12 show that the large-size pores at optimum and wet of optimum water contents, if they exist, are less than those at the dry of optimum water content.

Soaked with Volume Change

The consolidation curves of the kneading and static samples compacted at the low compaction effort at dry of optimum, optimum, and wet of optimum molding water contents and consolidated up to 16 tsf after being soaked with volume change are shown in Figures 34, 37, and 40 (Appendix B), respectively. These figures show that the static samples consolidated more than the kneading samples with the greatest difference being at the optimum molding water content. Also, in the case of samples compacted at wet of optimum water content the static sample consolidated more than the kneading sample till 4 tsf, then the kneading sample consolidated slightly more than the static sample under 8 tsf and 16 tsf. The main reason that the static samples consolidated more than the kneading samples is that the average swelling percentages of the static samples are higher than those of the kneading samples at the three molding water contents as shown in Table 1. However, the greatest difference in swelling percentages was at the optimum water content where it reached 4.54 percent which explains the greatest difference in vertical strain between the static and kneading samples being at the optimum water content also.

Soaked without Volume Change

The consolidation curves of the static and kneading samples compacted at the low compaction effort at the dry of optimum and wet of optimum water contents and consolidated up to 4 tsf after being soaked without volume change are shown in Figures 41 and 42 (Appendix B). Figure 41 shows that at the dry of optimum water content the static sample consolidated more than the kneading sample. Both samples have the same dry density and water content before consolidation. Therefore, the fabric of the samples will be the controlling factor in their consolidation behaviour. Although the average swelling percentage of the static sample at dry of optimum is 11.29 percent while it is 10.11 percent for the kneading sample and from which we expect a higher swelling pressure from the static sample, the static sample started to consolidate under 1 tsf. This clearly shows that there has been some sort of collapse in the fabric of the static sample enhanced by the soaking of the sample before consolidation. Figure 42 shows that at the wet of optimum water content the kneading sample consolidated more than the static sample. Such behaviour is similar to that of the static and kneading samples consolidated in the as-compacted state where the static sample consolidated more than the kneading sample at the dry of optimum water content, and less at the wet of optimum water content. While the collapse of the large-size pores accounts for the higher consolidation of the static samples at dry of optimum water content, such a phenomenon does not appreciably influence the consolidation characteristics of the samples compacted at wet of optimum water content. Although the kneading samples showed less orientation in the horizontal plane than the static samples at the wet of optimum water content, they behaved as being more oriented than the static ones. At the wet of optimum water content the average swelling percentage of the kneading samples was 2.74 percent while that of the static samples was 5.71 percent. Also, the electron microscopy examination as well as the mechanism of the kneading compaction indicate a higher degree of fabric orientation in the kneading samples but at planes inclined to the horizontal plane.

The previous results are generally in a good agreement with the conclusion of Seed and Chan (1959a) that the swelling of the static samples is higher than that of the kneading samples especially at wet of optimum molding water content, and with Lambe's hypothesis that the oriented samples tend to consolidate more than the random samples at a low stress level.

Effect of Dry Density

In the As-compacted State

Figure 43 (Appendix B) shows the consolidation curves of the sample compacted by kneading at the low compaction effort at the dry of optimum water content (K_4C - 16), and of the sample compacted by kneading at the high compaction effort at optimum water content (K_2C - 16) after both samples were consolidated up to 16 tsf in the as-compacted state. Both samples have the same molding water content (31.1%), and the dry density of the sample (K_4C - 16) was 76.5 pcf while that of the sample (K_2C - 16) was 86.3 pcf. This figure shows that the sample compacted at the high compaction effort (K_2C - 16) consolidated slightly more than the sample compacted at the low compaction effort (K_4C - 16) till about 6.5 tsf. However, upon increasing the consolidation stress from 8 tsf to 16 tsf a sudden collapse occurred in the sample compacted at the low compaction effort while no comparative collapse occurred in the sample compacted at the high compaction effort. The incremental vertical strain of the sample (K_4C - 16) upon changing the consolidation stress from 8 tsf to 16 tsf was 328 x 10^{-4}, while it was only 113 x 10^{-4} for the sample (K_2C - 16). The orientation index of the sample (K_4C - 16) was 4.89 while that of the sample (K_2C - 16) was 8.09. This again clearly shows that the probability of the collapse of soil fabric upon the application of a certain consolidation stress decreases with the increase in the dry density of the soil. The previous result also shows that while the soil fabric was a dominating factor in the consolidation of soil samples at the low and medium stress levels that it could offset the effect of the difference in dry density (9.8 pcf), the dry density became the dominating factor at the high stress level.

Figure 44 (Appendix B) shows the consolidation curves of the samples compacted by kneading at the low compaction effort at the dry of optimum water content (K_5C - 16), and of the sample compacted by kneading at the high compaction effort at the wet of optimum water content (K_3C - 16) after both samples were consolidated up to 16 tsf in the as-compacted state. The dry density of the sample (K_5C - 16) was 79.0 pcf, while that of the sample (K_3C - 16) was 82.5 pcf. The molding water content for both samples was 34.0 percent. The orientation index of the sample (K_5C - 16) was 5.20 while that of the sample (K_3C - 16) was 7.31. This figure shows that the sample compacted at the high compaction effort (K_3C - 16) consolidated more than the sample compacted at the low compaction effort (K_5C - 16). This indicates that since the difference in dry density between the two samples (3.5 pcf) is relatively small when compared with that of the previous samples (K_2C - 16 and K_4C - 16) which was 9.8 pcf, the fabric of the samples (K_3C - 16 and K_5C - 16) became the dominating factor in affecting their consolidation characteristics. However, it was mentioned before that the fabric study conducted by using the x-ray diffraction technique had amply demonstrated that all the tested samples were on the random side of the continuum from the random state to the perfectly oriented state. Therefore, a difference in orientation index of 2.11 (between the samples K_3C - 16 and K_5C - 16) when compared with the possible range in orientation index from the random state to the perfectly oriented state which is approximately 228 does not seem high enough to account for this difference in compressibility characteristics. This suggests one or more of the following possibilities:

1. There was some experimental error in the laboratory consolidation test or its computations. This possibility is eliminated because the consolidation test was repeated with extreme care and the results were approximately the same with essentially no change in the comparative compressibility behaviour of the above mentioned samples.

2. The x-ray diffraction technique is not adequate to reveal the whole elements of the micro- and macro-fabric of the tested soil samples which may affect their compressibility characteristics e.g., the number, continuity, and orientation of the shear failure planes, or the pore-size distribution of the tested samples.
3. A considerable change occurs in the fabric orientation of the consolidated samples upon load release which is contradictory to what Lambe had suggested and subsequent investigators had adopted that the rebound is mainly due to the increase in the spacings between soil particles with negligible change in their orientation. Some new technique is needed which involves the preservation of soil fabric as it is under the applied consolidation stress where no change occurs in the volume of the sample or its fabric after load release. Such a technique, if developed, will clarify the effect of rebound on the fabric orientation of consolidated samples and will render the explanation of testing results more reliable and persuasive.

Soaked without Volume Change

Figure 45 (Appendix B) shows the consolidation curves of the sample compacted by kneading at the low compaction effort at dry of optimum (K_4TO - 16), and of the sample compacted by kneading at the high compaction effort at optimum water content (K_2TO - 16) after both samples were consolidated up to 16 tsf after being soaked without volume change. This figure shows that the sample compacted at the low compaction effort (K_4TO - 16) consolidated more than the sample compacted at the high compaction effort (K_2TO - 16). The greatest difference in consolidation between the two samples occurred upon changing the consolidation stress form 8 tsf to 16 tsf where the incremental vertical strain of the sample K_4TO - 16 was 295 x 10^{-4} while that of the sample K_2TO - 16 was only 181 x 10^{-4}. The difference in consolidation between the two samples is mainly due to the fact that the sample K_2TO - 16 has a significantly higher dry density and lower water content after saturation than the sample K_4TO - 16 which dominated over the effect of higher orientation of the sample K_2TO - 16. This result supports the conclusion mentioned before that the probability of a significant compression in the fabric of a compacted soil increases with the decrease in its dry density.

Figure 46 (Appendix B) shows the consolidation curves of the sample compacted by kneading at the low compaction effort at dry of optimum (K_5TO - 16), and the sample compacted by kneading at the high compaction effort at wet of optimum (K_3TO - 16) after both samples were consolidated up to 16 tsf after being soaked without volume change. This figure shows that the sample compacted at the high compaction effort (K_3TO - 16) consolidated more than the sample compacted at the low compaction effort K_5TO - 16. This shows again, as in the case of consolidation in the as-compacted state, that the fabric of soil rather than the small difference in dry density (3.5 pcf) is the controlling factor in consolidation especially at the low consolidation stress level.

Most of the difference in consolidation occurred at a stress level below 2 tsf. Upon changing the consolidation stress from 8 to 16 tsf the incremental vertical strain of the sample K_5TO - 16 was 267 x 10^{-4} while that of the sample K_3TO - 16 was only 201 x 10^{-4}. This also confirms the previous conclusion that the probability of the collapse of soil fabric under a certain stress level increases with the decrease in the dry density of the soil.

Coefficient of Consolidation

Using the square root time fitting method, the coefficient of consolidation (Cv) was computed for the samples compacted by the static and kneading methods at the low compaction effort at the dry and wet of optimum water contents. The samples were consolidated both in the as-compacted state and after being soaked with volume change. Figures 47, 48, 49, and 50 (Appendix B) show the variation of the coefficient of consolidation with the applied consolidation stress for the above tested samples. Figures 47 and 48 indicate that the coefficients of consolidation for the kneading and static samples consolidated in the as-compacted state do not show any specific trend except that they are generally higher at the low stress level (less than 1 tsf) and at the high stress level (greater than 4 tsf) than at the medium stress level (1 - 4 tsf). Figures 49 and 50 indicate that the coefficient of consolidation for the compacted samples that were soaked with volume change before consolidation tends to increase with the increase in the consolidation stress.

No definite conclusion can be made regarding the effect of method of compaction or molding water content on the coefficient of consolidation. This is mainly due to the fact that the variability of the Cv-value with the consolidation stress for any individual sample is high enough to over-shadow the difference in the Cv-value between two differently compacted samples due to the effect of method of compaction.

CHAPTER 6

REBOUND CHARACTERISTICS

The rebound characteristics of consolidated compacted clays did not receive an attention equal to the one that the compressibility and other engineering characteristics of compacted clays had received in any of the previously mentioned investigations. However, attention was paid to the slope of the rebound curves of the natural undisturbed soils by Schmertmann (1955a), and by Crisp (1955) in his discussion of Schmertmann's paper on the consolidation behaviour of undisturbed clay. Schmertmann (1955a) indicated in his paper that rebound slopes do not appear to be significantly altered by sample disturbance. In his discussion of Schmertmann's paper, Crisp presented plots of laboratory testing data for samples subjected to cyclic loading which indicated that the slope of the rebound curve tends to increase with the increase in the applied stress, and that the slope of the recompression curve approximates the slope of the rebound curve only when the rebound curve is very flat. In his discussion of Crisp's comments, Schmertmann agreed that the rebound slope varies with the physical and mineralogical structure of the clay and with the void ratio or consolidation stress from which the rebound starts. Based on the data obtained from many individual consolidation tests on preconsolidated clays that were slightly disturbed, Schmertmann indicated that the slope of the rebound curve is approximately 87 percent of the average slope of the subsequent recompression curve, i.e., the Cx/Cr is approximately 1.15 where the Cr is the slope of the rebound curve and Cx is the slope of the subsequent recompression curve.

The present study intends to examine the effects of such factors as the method of compaction, molding water content, and consolidation stress on the rebound characteristics of compacted clays. These characteristics will be expressed in terms of rebound ratio, ratios between rebound magnitudes at different stress levels, and the swelling indices of the consolidated samples upon their rebound from different stress levels.

Rebound Ratio

This term is developed and used to study the rate at which a consolidated compacted soil sample reaches its equilibrium size under any consolidation stress during the unloading cycle.

It is defined herein as:

$$\text{Rebound Ratio (R.R.)} = \frac{\text{Rebound magnitude in 1st minute after unloading}}{\text{Rebound magnitude in 90 minutes after unloading}}$$

The 90-minutes period was chosen because it was found from the initial experiments that for most of the samples more than 90 percent of the total rebound (during 24 hours after load release) takes place within the first 90 minutes. The first minute period was also chosen to indicate the magnitude of rebound that takes place within a relatively short period of time after load release.

By examining the rebound ratios of the consolidated compacted samples after load release from different stress levels as shown in Tables 2 and 3 the following conclusions can be derived:

1. For any consolidated sample the rebound ratio decreases with the decrease in the stress at which rebound takes place e.g., the rebound ratio from 16 tsf to 4 tsf is higher than that from 4 tsf to 1 tsf and this in turn is higher than that from 1 tsf to 0.25 tsf.
2. The rebound ratio from a certain stress level to a lower stress level decreases with the increase in the maximum consolidation stress under which the sample was consolidated e.g., the rebound ratio from 1 tsf to 0.25 tsf is higher for the sample consolidated under 1 tsf than for the sample consolidated under 4 tsf, and this in turn is higher than for the sample consolidated under 16 tsf.
3. The rebound ratios of the samples that were soaked with volume change before consolidation are generally lower than those of the corresponding samples consolidated in the as-compacted state. This means that the saturation of consolidated samples renders their rebound upon load release more time-dependent.
4. The molding water content does not seem to have a noticeable effect on the rebound ratios of the consolidated samples.

Table 2

Rebound Ratios of the Samples Consolidated in the As-compacted State for the Indicated Consolidation Stress Rebounds

Sample	Consolidation Stress Rebounds		
	From 16 tsf to 4 tsf	From 4 tsf to 1 tsf	From 1 tsf to 0.25 tsf
K_4C-1			0.92
K_4C-4		0.88	0.74
K_4C-16	0.95	0.84	0.60
S_4C-1			0.92
S_4C-4		0.90	0.72
S_4C-16	0.96	0.84	0.53
K_6C-1			0.89
K_6C-4		0.94	0.82
K_6C-16	0.82	0.41	0.28
S_6C-1			0.92
S_6C-4		0.92	0.85
S_6C-16	0.96	0.83	0.63
K_7C-1			0.96
K_7C-4		0.99	0.77
K_7C-16	0.85	0.77	0.67
S_7C-1			0.87
S_7C-4		0.94	0.79
S_7C-16	0.86	0.88	0.72

Table 3

Rebound Ratios of the Samples Consolidated After Being Soaked with Volume Change for the Indicated Consolidation Stress Rebounds

Sample	Consolidation Stress Rebounds		
	From 16 tsf to 4 tsf	From 4 tsf to 1 tsf	From 1 tsf to 0.25 tsf
K_4C-1			0.74
K_4C-4		0.68	0.36
K_4C-16	0.84	0.54	0.31
S_4C-1			0.76
S_4C-4		0.77	0.45
S_4C-16	0.89	0.61	0.35
K_6C-1			0.72
K_6C-4		0.78	0.53
K_6C-16	0.84	0.55	0.32
S_6C-1			0.69
S_6C-4		0.82	0.59
S_6C-16	0.88	0.60	0.39
K_7C-1			0.82
K_7C-4		0.79	0.50
K_7C-16	0.85	0.58	0.35
S_7C-1			0.82
S_7C-4		0.82	0.56
S_7C-16	0.88	0.61	0.36

5. For the samples that were soaked with volume change before consolidation, the rebound ratios of the static samples are consistently higher than those of the kneading samples. For the samples that were consolidated in the as-compacted state, the rebound ratios of the static samples are generally but not consistently higher than those of the kneading samples. This indicates that the rebound behaviour of the kneading samples is more time-dependent than that of the static samples.

Shape of the Rebound Curve

From the consolidation curves of the compacted samples it can be noticed that the general shape of the rebound curves of the samples consolidated in the as-compacted state is different form that of the rebound curves of the samples that were soaked with or without volume change before consolidation.

The shape of the rebound curves can be defined by computing the ratios of rebound magnitudes of the consolidated samples between different stress levels, and by comparing the swelling indices of the samples consolidated to, and rebound from, different stress levels.

In the As-compacted State

Table 4 shows the ratios of rebound magnitudes: from 16 tsf to 4 tsf; from 4 tsf to 1 tsf; from 1 tsf to 0.25 tsf for the static and kneading compacted samples consolidated up to 16 tsf in the as-compacted state. These ratios indicate the following:

Table 4

Ratios of Rebound Magnitudes of the Consolidated Compacted Samples for the Stress Rebounds:
From 16 tsf to 4 tsf ; From 4 tsf to 1 tsf;
From 1 tsf to 0.25 tsf Respectively

Samples	Ratios of Rebound Magnitudes
K_4C-16	2.73:1.87:1.00
K_6C-16	1.94:1.16:1.00
K_7C-16	4.33:2.94:1.00
S_4C-16	3.31:2.33:1.00
S_6C-16	2.44:1.65:1.00
S_7C-16	6.71:1.88:1.00
K_4TV-16	0.75:0.95:1.00
K_6TV-16	0.86:1.03:1.00
K_7TV-16	0.73:0.96:1.00
S_4TV-16	0.78:0.95:1.00
S_6TV-16	0.84:1.01:1.00
S_7TV-16	0.90:1.06:1.00

1. The rebound curves of the compacted samples that were consolidated in the as-compacted state are concaved downward.
2. The degree of concavity of the rebound curves is higher in the static samples than in the kneading samples.

Table 5 shows the swelling indices (Cs) of the compacted samples that were consolidated in the as-compacted state to 1 tsf, 4 tsf, and 16 tsf. These swelling indices indicate the following:

1. The swelling index is a function of the stress at which rebound takes place. The higher the stress at which rebound takes place the higher is the swelling index and the steeper is the rebound curve. This is true for both the static and kneading samples.
2. The swelling indices of the static samples are, in general, slightly higher than those of the kneading samples.

Soaked with Volume Change

Table 4 shows the ratios of rebound magnitudes: from 16 tsf to 4 tsf; from 4 tsf to 1 tsf; from 1 tsf to 0.25 tsf for the static and kneading compacted samples consolidated up to 16 tsf after being soaked with volume change. These ratios indicate the following:

1. The rebound curves of the compacted samples that were consolidated after being soaked with volume change generally consist of two portions. The initial portion (16 tsf to about 2 tsf) is concaved upward, while the last portion (2 tsf to 0.25 tsf) approaches a straight line.

Table 5

Swelling Indices of the Compacted Samples that Were Consolidated in the As-compacted State

Sample	Swelling Index ($C_s \times 10^{-4}$)
S_4C-1	107
S_4C-4	322
S_4C-16	369
K_4C-1	77
K_4C-4	241
K_4C-16	301
S_6C-1	109
S_6C-4	172
S_6C-16	296
K_6C-1	131
K_6C-4	158
K_6C-16	209
S_7C-1	79
S_7C-4	189
S_7C-16	333
K_7C-1	82
K_7C-4	163
K_7C-16	309

2. The degree of concavity of the rebound curves is higher in the kneading samples than in the static samples at the dry and wet of optimum water contents and about the same at the optimum water content.

Table 6 shows the swelling indices of the compacted samples that were consolidated after being soaked with volume change. These indices indicate the following:

1. The swelling index is a function of the stress at which rebound takes place. The higher the stress at which rebound takes place the higher is the swelling index and the steeper is the rebound curve. This is true for all the static and kneading compacted samples.
2. There is no significant effect of the compaction method on the values of the swelling indices of the consolidated compacted samples.
3. Samples compacted at dry of optimum have slightly higher values of swelling indices than those compacted at wet of optimum for both the static and kneading compacted samples.

During the initial trial tests of this study a kneading compactive curve was established with an optimum molding water content of 32.0 percent and a maximum dry density of 85.7 pcf as shown in Figure 51 (Appendix B). A sample compacted at dry of optimum with a molding water content of 28.9 percent and a dry density of 84.4 pcf was subjected to a cyclic consolidation test after being soaked with volume change. The cyclic consolidation test was performed by first

Table 6

Swelling Indices of the Compacted Samples that Were Consolidated After Being Soaked with Volume Change

Sample	Swelling Index ($C_s \times 10^{-4}$)
S_4TV-1	213
S_4TV-4	477
S_4TV-16	732
K_4TV-1	228
K_4TV-4	515
K_4TV-16	730
S_6TV-1	259
S_6TV-4	519
S_6TV-16	690
K_6TV-1	246
K_6TV-4	453
K_6TV-16	630
S_7TV-1	191
S_7TV-4	482
S_7TV-16	687
K_7TV-1	185
K_7TV-4	498
K_7TV-16	687

consolidating the sample up to 1 tsf and then releasing the load to 0.25 tsf, and then reconsolidating the sample up to 4 tsf and then releasing the load to 0.25 tsf, and then reconsolidating the sample up to 16 tsf and then releasing the load to 0.25 tsf and then reconsolidating the sample back again to 16 tsf, and finally releasing the load to 0.25 tsf. In all these steps, the load increment ratio was a unity and the load release was to a stress that equals one fourth of the applied stress as was done in the other conslidation tests. The consolidation and rebound curves of this sample which is designated as KYTV-16 are shown in Figure 52 (Appendix B). The slopes of the rebound curves are shown in the same figure. The computed slopes of the rebound curves and subsequent recompression curves and the ratios between these slopes are shown in Table 7. These rebound curves indicate the following:

1. The slope of the rebound curve increases with the increase in the consolidation stress at which rebound starts; a result that supports the previous conclusion mentioned in the other consolidation tests.
2. The slope of the rebound curve from a certain stress level might decrease progressively upon the cyclic consolidation and rebound from the same stress level. This is indicated in Figure 52 (Appendix B) where the first rebound curve (No. 3) from the 16 tsf consolidation stress has a steeper slope than the second rebound curve (No. 4) from the same stress level. However, more tests are needed to support and quantify this conclusion.

Table 7

The Slopes of the Rebound and
Subsequent Recompression Curves of the Sample KYTV-16

Change in Consolidation Stress (tsf)	Rebound Slope ($C_r \times 10^{-4}$)	Recompression Slope ($C_x \times 10^{-4}$)	C_x/C_r
0.25 - 1	291	315	1.08
0.25 - 4	757	838	1.11
0.25 - 16	1425*	1590	1.12
0.25 - 16	1349*		

*Slope of the first rebound curve from 16 tsf to 0.25 tsf

**Slope of second rebound curve from 16 tsf to 0.25 tsf

3. The ratio of the slope of the recompression curve to the slope of the proceding rebound curve (Cx/Cr) approximates the average value indicated by Schmertmann (1955b) which is approximately equal to 1.15.

From the previous data it can be concluded that the presence of water enhances the rebound of the soaked consolidated samples at a low stress level thus causing their rebound curves to be concaved upwards. The absence of enough water, on the other hand, hinders the samples consolidated in the as-compacted state from undergoing an appreciable rebound at a low stress level thus causing their rebound curves to be concaved downward. This is due to the fact that upon load release the sample starts to expand. With this increase in the size of the consolidated sample some new void spaces develop and some previously existing void spaces tend to expand thus decreasing the degree of saturation of the sample and increasing its moisture-deficiency and subsequently increasing the soil-moisture tension. In the case that water is available as in the soaked samples the soil-moisture tension is suppressed by the gradual saturation of the new void spaces and further rebound is allowed. In the case that water is not available as in the samples consolidated in the as-compacted state soil-moisture tension developes to such an extent that it holds any further rebound of the consolidated sample.

It can be noticed also that the presence of water causes the rebound behaviour of the consolidated samples to become more time-dependent. This is indicated by the rebound ratios of the soaked consolidated samples being smaller than those of the samples consolidated in the as-compacted state.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The present investigations included the study of the effect of such factors as method of compaction, molding water content, dry density, and stress level on the compressibility and rebound characteristics of compacted kaolinite samples in three cases (1) consolidation in the as-compacted state, (2) consolidation after being soaked with volume change, and (3) consolidation after being soaked without volume change.

The results were analyzed in view of the changes that might occur in the fabric of compacted samples under the effect of the above factors. Variations in soil fabric were quantitatively expressed in terms of orientation indices using the x-ray diffraction technique. The x-ray diffraction study of soil fabric was supplemented with the electron-microscopy examination for a qualitative evaluation and examination of the fabric patterns of the different tested samples. The main conclusions of this study are summarized below.

Fabric Characteristics

1. According to the technique used in evaluating the fabric of the tested soil samples all the samples tested in this investigation regardless of their method of compaction, dry density or consolidation stress lie on the random

side of the continuum from the random state to the perfectly oriented state.

2. There is an increase in the fabric orientation of a compacted soil sample with the increase in the molding water content except for the kneading compacted samples which showed a decrease in the fabric orientation from the optimum water content to the wet of optimum water content. It has been indicated before that this might be due to the fact that at the wet of optimum water content the planes of shear strain of the kneading samples often exist at varying angles of inclination to the horizontal plane along which the orientation indices are measured.

3. Consolidation, up to the level used in this research, does not result in an appreciable improvement in the fabric orientation of the compacted soil samples. On the contrary, consolidation may lead to the disruption of soil fabric due to the rapid development of a high hydrodynamic gradient which was found also by Martin (1966). However, the results of this research indicate that an improvement in fabric orientation occurs when the stress state of the sample passes through the transition zone from the flat portion to the straight line portion of the consolidation curve.

4. The kneading compaction results in samples with a higher degree of fabric orientation than the static compaction at

the dry of optimum and at optimum water contents. At the wet of optimum water content the fabric orientation in the horizontal plane is less in the kneading samples than in the static samples due to the inclination of the planes of shear strain in the kneading samples to the horizontal plane. However, the swelling characteristics indicate a higher degree of orientation in the kneading samples than in the static samples at all molding water contents.

5. The increase in compaction effort results in an increase in the fabric orientation of the samples compacted by the same method and at the same molding water content.
6. The electron microscopy examination revealed the absence of the edge-to-face contact between individual kaolinite particles. Instead, it showed that the fabric of compacted soil samples generally consist of platelets and packets that exist at tilted positions with respect to each other.
7. Zones of oriented packets within essentially a random fabric appears frequently in the kneading compacted samples presumably as a result of the kneading action of the tamping foot. This parabolic type of oriented zones along the planes of shear strain do not exist in the static samples.
8. Larger-size pores exist in the samples compacted at dry of optimum water content as compared with the samples compacted at wet of optimum water content, and in the static samples

as compared with the kneading samples. The increase in fabric orientation with the increase in the molding water content or dry density of the compacted clay samples is essentially in agreement with Lambe's hypothesis (1958a), although the magnitude of such an improvement is much less than what was postulated by Lambe.

Compressibility Characteristics

In the As-compacted State

1. The samples compacted at wet of optimum water content compressed more than those having the same dry density but compacted at dry of optimum water content. This indicates that the increase in molding water content, at the same dry density, causes an increase in the compressibility of the compacted soil samples.
2. The static samples compressed more than the kneading samples at the dry of optimum water content and less at the optimum and wet of optimum water contents. This emphasized the importance of the larger-size pores that exist in the static samples compacted at dry of optimum water content and which start to collapse during the consolidation process. However, although the cumulative vertical strains of the static samples were less than those of the kneading samples at the optimum and wet of optimum water contents, the incremental vertical strains

of the static samples were, at a high stress level (> 8 tsf), higher than those of the kneading samples. This result is essentially in good agreement with Lambe's hypothesis that at a low stress level the randomly oriented sample compresses less than the more oriented sample; while at a high stress level the straight line portion of the consolidation curve is steeper for the randomly oriented sample than for the more oriented one. The incremental vertical strains were used in this study rather than the compression indices (C_c) because the straight line portion of the consolidation curves was not reached up to a stress level of 16 tsf.

3. The increase in dry density of a compacted clay sample does not necessarily result in a decrease in its compressibility characteristics of compacted clays especially when the difference in the dry density of the compacted samples is relatively small.

Soaked with Volume Change

1. All the samples compacted by the kneading and static methods at the dry of optimum water content consolidated more than the sample having the same dry density but compacted at wet of optimum water content. This is mainly due to the higher swelling percentages of the samples compacted at dry of optimum as compared with those of the samples compacted at wet of optimum.

2. The static samples swelled more and thus consolidated more than the kneading samples at all molding water contents. It has been noticed also that the difference in swelling between the samples compacted at dry of optimum and those compacted at wet of optimum is greater in the kneading samples than in the static samples. This indicates that the variation in soil fabric with the variation in molding water content is greater in the kneading samples than in the static samples. These results are in good agreement with the testing results of Seed and Chan (1959a) about the effects of kneading and static compaction on the swelling characteristics of compacted sandy clay samples.

Soaked without Volume Change

1. Samples compacted by the kneading and static methods at the dry of optimum water content consolidated less than those compacted at the wet of optimum water content. This is due to the fact that the samples compacted at dry of optimum water content exhibited a higher swelling pressure than those compacted at wet of optimum water content, which again supports the testing results of Lambe (1958b), and of Seed and Chan (1959a) about the effect of molding water content, and thus soil fabric, on swell pressure.

2. The static samples compressed more at the dry of optimum water content and less at the wet of optimum water content than the kneading samples that have the same molding water content and dry density. This behavior is similar to that in the as-compacted state where the collapse of the large-size pores in the static samples compacted at dry of optimum water content contributes to the higher compressibility of the static samples.
3. The increase in dry density of a compacted soil sample does not necessarily result in a decrease in its compressibility especially when the difference in the dry density of the samples compacted at the same molding water content is relatively small. This conclusion was also reached at in the case of samples consolidated in the as-compacted state.

It can be noticed that the numerical differences in the orientation indices between the different tested samples are too small to account for the noticeable differences in their compressibility characteristics. This suggests that some other factors other than the degree of orientation, as expressed by the orientation indices, influence the compressibility characteristics of compacted clays. These may include the patterns of orientation of soil fabric, the number, continuity or extension, and orientation of any existing planes of shear strain, and the pore-size distribution of the compacted samples.

Rebound Characteristics

1. Rebound Ratio:

   a. The rebound of consolidated compacted samples, as indicated by the rebound ratios, becomes more time-dependent with the decrease in the consolidation stress at which rebound starts.

   b. The presence of water causes the rebound of consolidated compacted samples to be more time-dependent.

   c. The rate of rebound of the statically compacted samples is generally higher than that of the kneading compacted samples.

2. Shape of the Rebound Curve:

   a. The rebound curves of the compacted samples that were consolidated in the as-compacted state are concaved downward, while those of the compacted samples that were consolidated after being soaked with volume change are concaved upward in their initial portion and approach a straight line in their last portion.

   b. The higher the stress at which rebound takes place the higher is the swelling index and the steeper is the rebound curve. This applies for both the static and kneading compacted samples whether they were consolidated in the as-compacted state or after being soaked with volume change.

   c. The limited data obtained from this research indicate that the slope of the rebound curve from a certain stress level may decrease progressively upon cyclic consolidation and rebound from the same stress level.

The rebound characteristics as found in this research are essentially in agreement with what had been indicated by Crisp (1955) that the slope of the rebound curve tends to increase with the increase in the consolidation stress at which rebound starts.

The ratios of the slopes of the rebound curves to the slopes of the subsequent recompression curves also approximate the ratio indicated by Schmertmann (1955b) which is 0.87.

Recommendations

In view of the experimental results of this study regarding the fabric, compressibility, and rebound characteristics of compacted clays, the writer recommends that more research work be carried out in order to expand, confirm, or modify the presently existing concepts concerning the above characteristics of compacted clays. Future research work may involve the following:

1. Similar consolidation tests may be performed on clay soils of different physico-chemical properties to test the applicability of the results of this research to other types of soils.
2. Studying the variations in soil fabric at the different stages of the consolidation test, i.e., before, at, and after the primary consolidation is completed. This is

recommended to be done under different applied consolidation stresses, say 1 tsf, 4 tsf, and 16 tsf.

3. Studying the variations in soil fabric orientation with direction. This can be done by measuring the orientation indices in sections inclined at different angles to the horizontal plane. This is particularly important in the samples compacted by kneading at the wet of optimum water content where the fabric may be more oriented in some inclined planes other than in the horizontal plane. A large number of tests is needed to render the results of such a research statistically reliable.
4. Some new technique should be developed by which the fabric of the consolidated samples can be preserved without being affected by the increase in the volume of the consolidated samples upon load release.
5. Inundation consolidation tests are recommended to be conducted on the samples compacted by the kneading and static methods at the dry and wet of optimum water contents under low, medium, and high consolidation stress levels. These tests will clarify the effect of method of compaction, molding water content, and dry density on the collapse of the fabric of the compacted soil samples upon their inundation in water.

6. Conducting more cyclic consolidation tests to quantify the relationship between the slopes of the rebound curves and the recompression curves, and to evaluate the effect of cyclic loading and unloading on the slope of the rebound curve from a certain stress level.

APPENDIX A

NOTATION

The following symbols are used in this study as explained below:

K	=	Sample Compacted by the kneading method
S	=	Sample compacted by the static method
Kx or Sx	=	The number x indicates the position (dry density and molding water content) of the sample on the compaction curves (Figure 5)
C	=	Consolidation in the as-compacted state
TV	=	Consolidation after soaking the sample allowing volume change
TO	=	Consolidation after soaking the sample without volume change
Y	=	Cyclic consolidation
O.I.	=	Orientation index
R.R.	=	Rebound Ratio
KxC-N	=	The number N indicates the maximum consolidation stress of the sample
Cv	=	Coefficient of consolidation
Cc	=	Compression index

Cs = Swelling index

ε_v = Cummulative vertical strain

$\Delta\varepsilon_v$ = Difference in cummulative vertical strain

Examples:

K_1TO-16 = Sample compacted by kneading at dry of optimum water content at the high compaction effort and consolidated up to 16 tsf after being soaked without volume change

S_7C-4 = Sample compacted by static loading at wet of optimum molding water content at the low compaction effort and consolidated up to 4 tsf in the as-compacted state

APPENDIX B

CONSOLIDATION CURVES

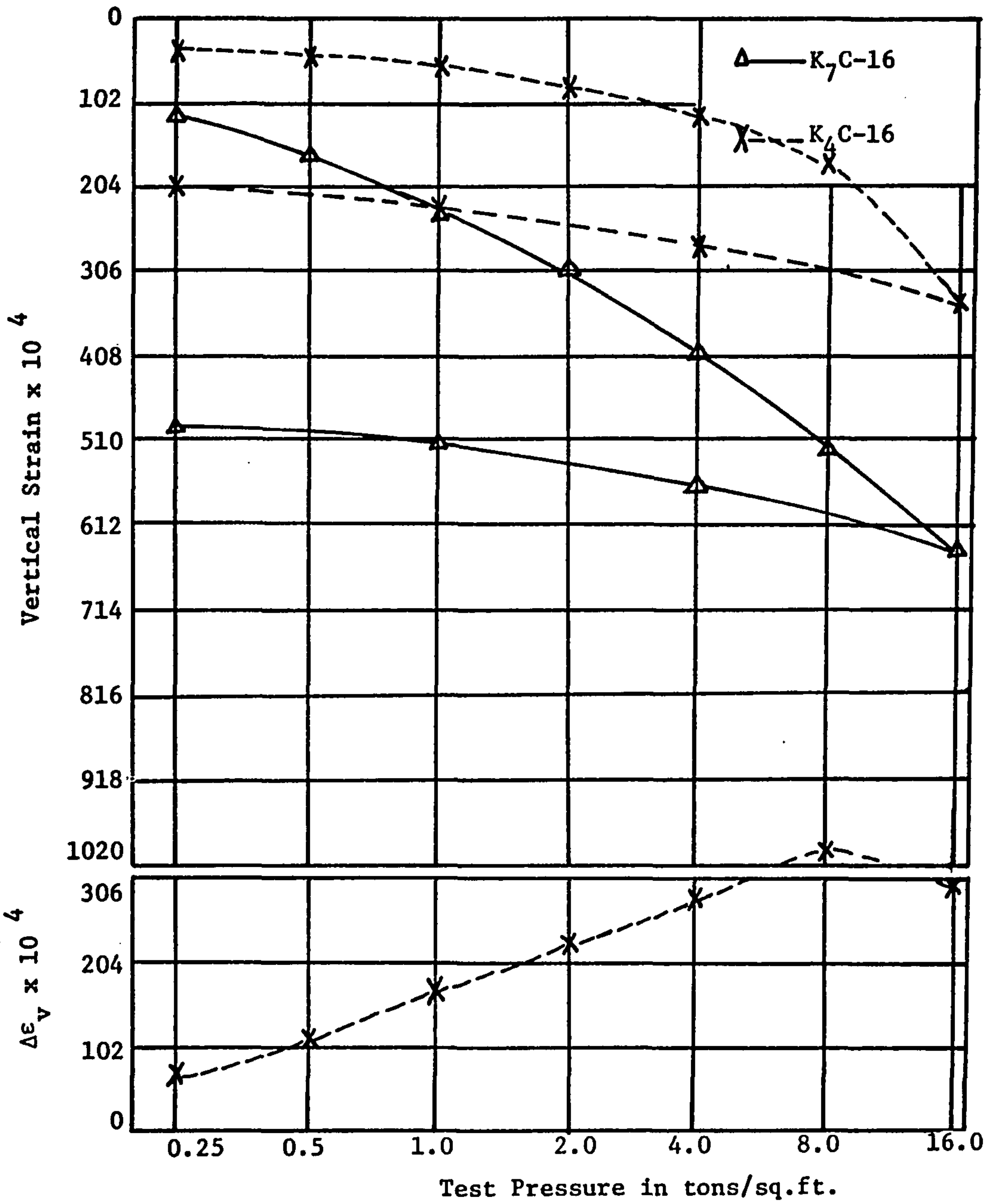


Figure 15 Consolidation Curves of the Samples K_4C-16 and K_7C-16

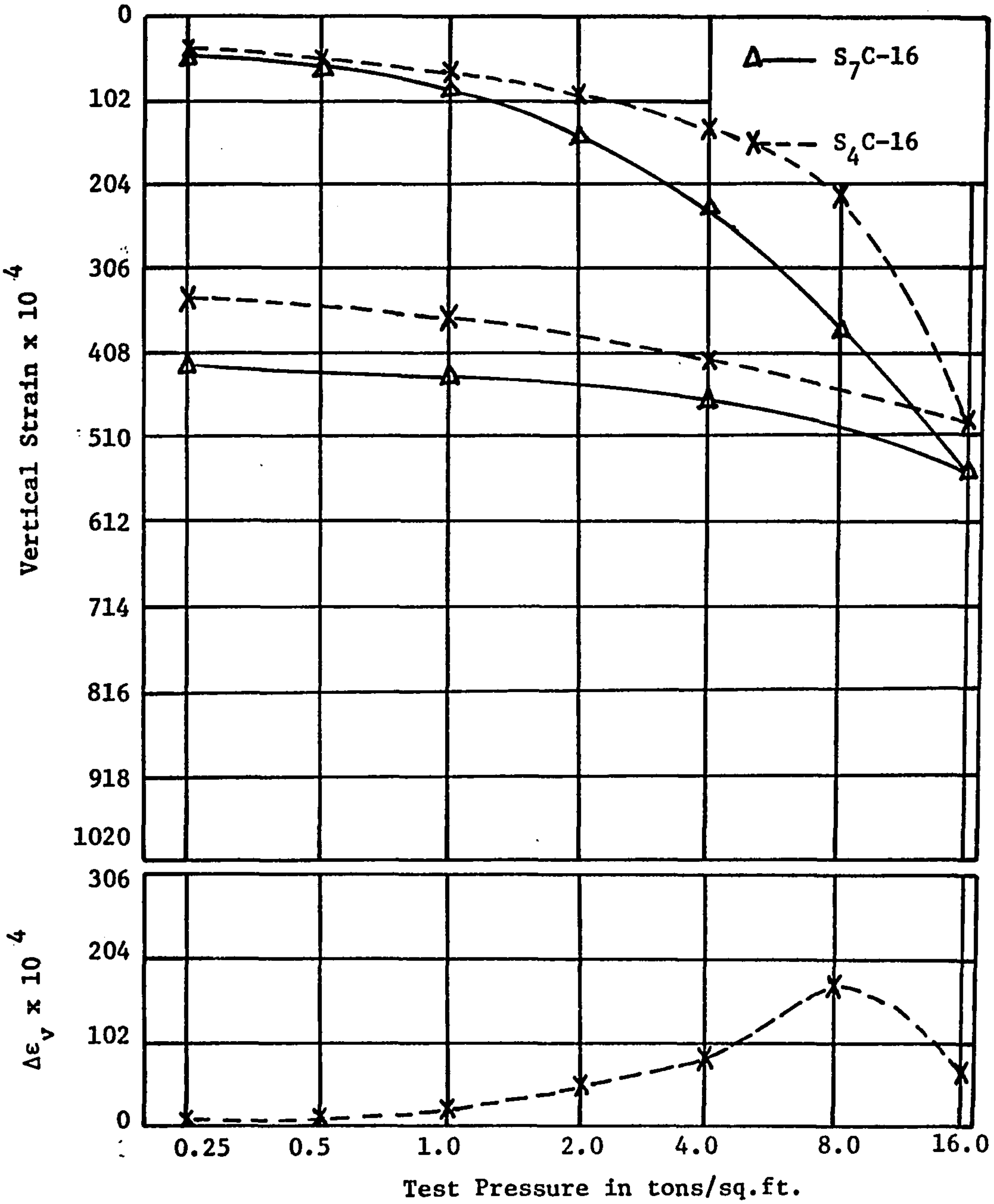


Figure 16 Consolidation Curves of the Samples S_4C-16 and S_7C-16

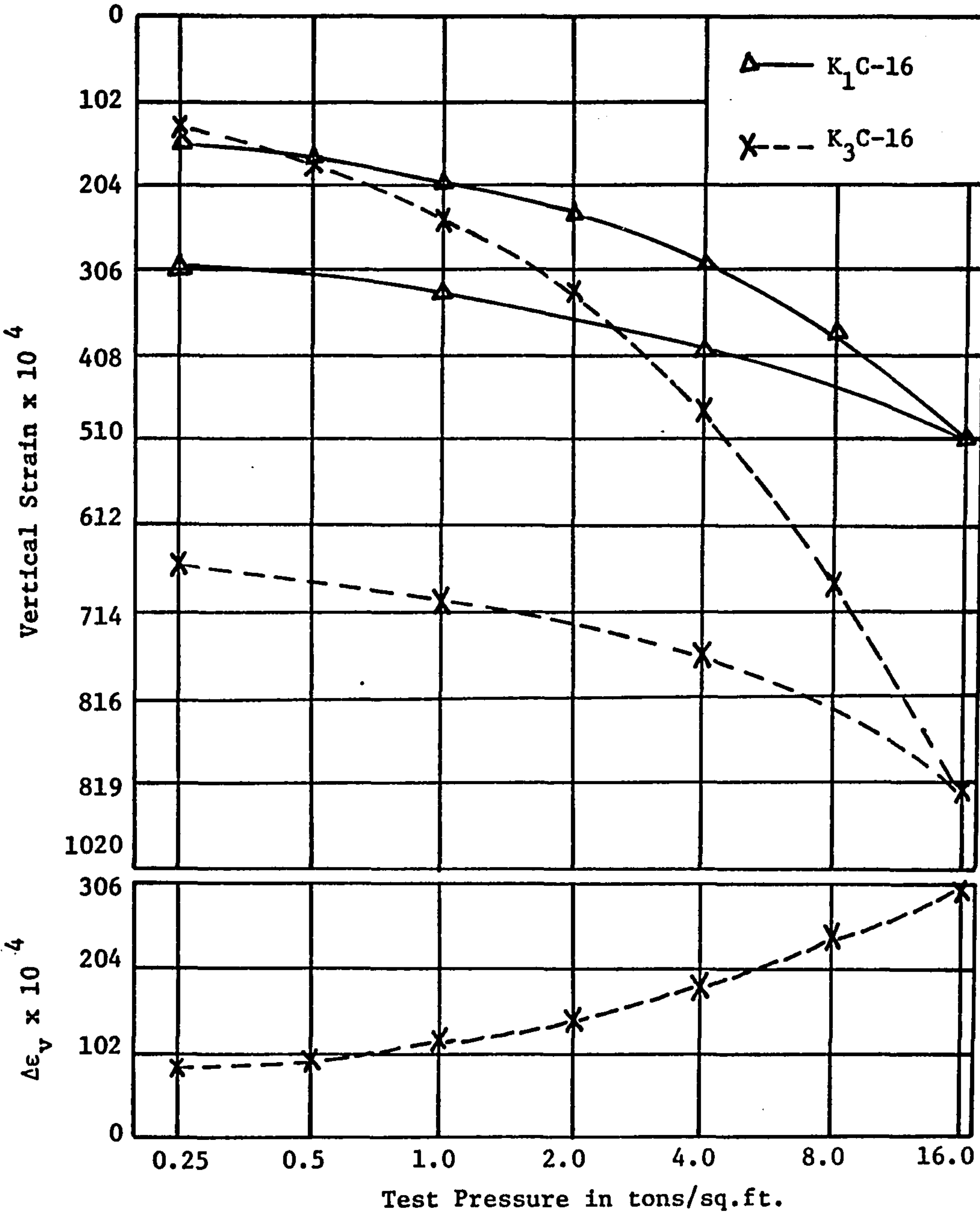


Figure 17 Consolidation Curves of the Samples K_1C-16 and K_3C-16

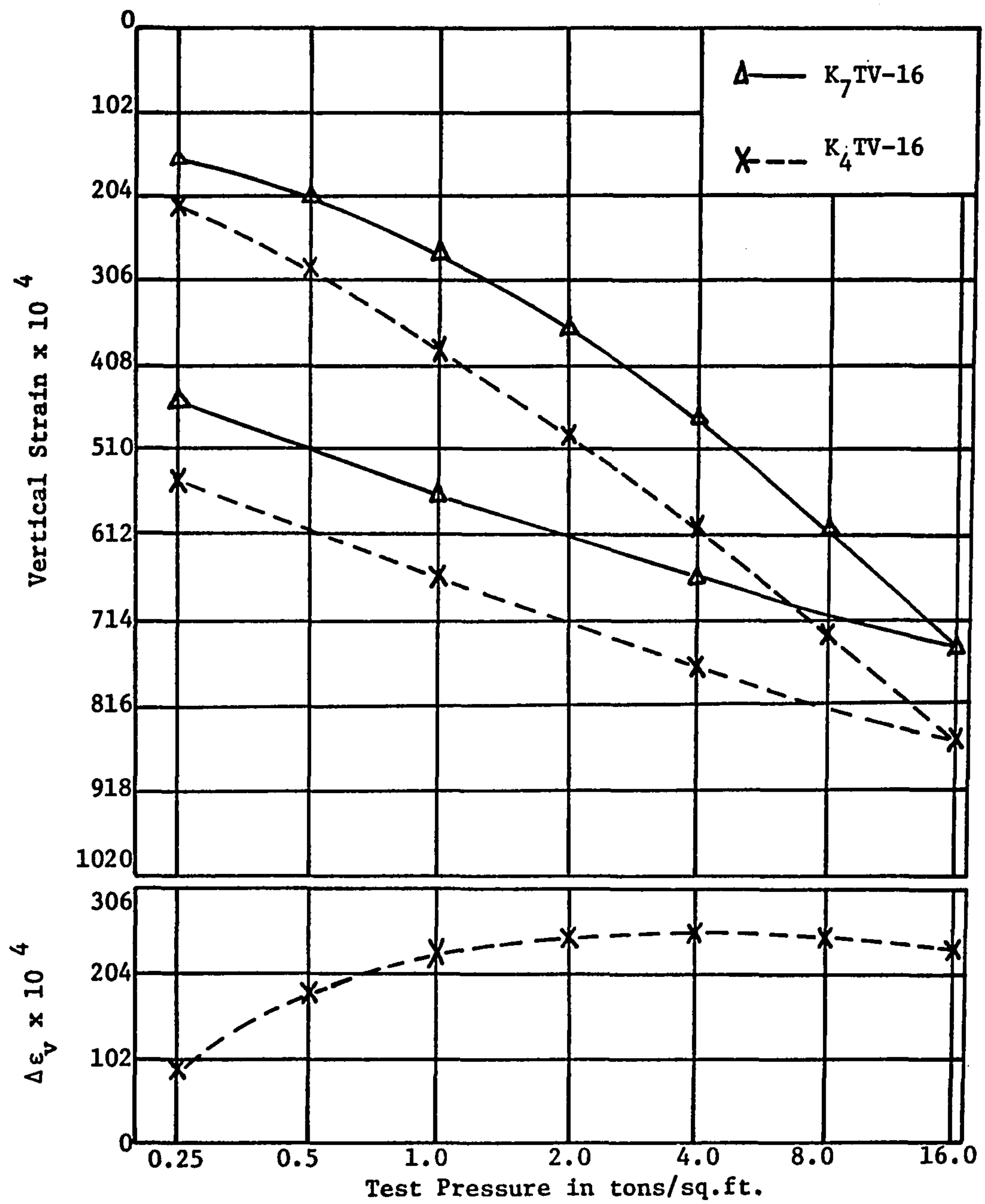


Figure 18 Consolidation Curves for the Samples K_4TV-16 and K_7TV-16

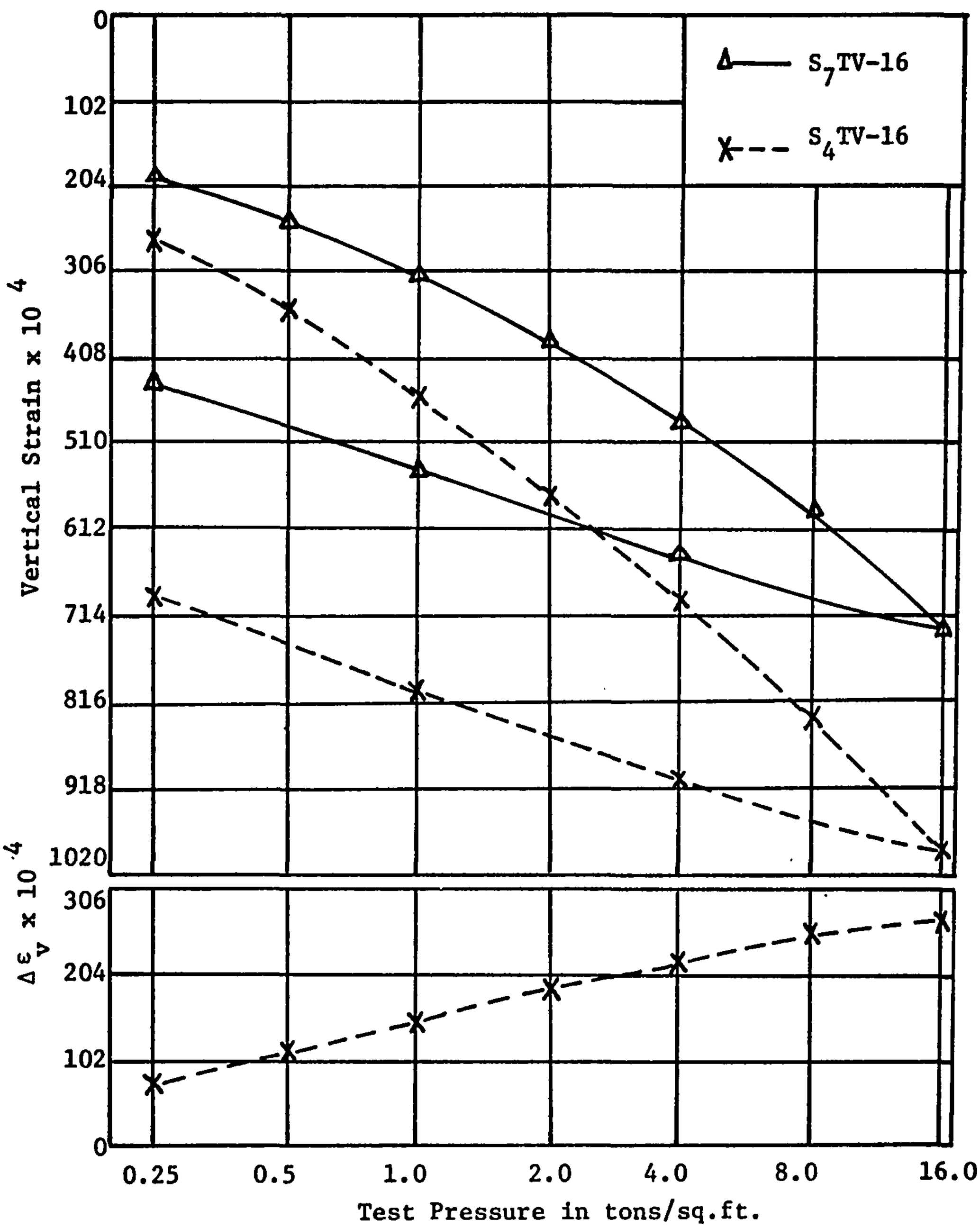


Figure 19 Consolidation Curves of the Samples S_4TV-16 and S_7TV-16

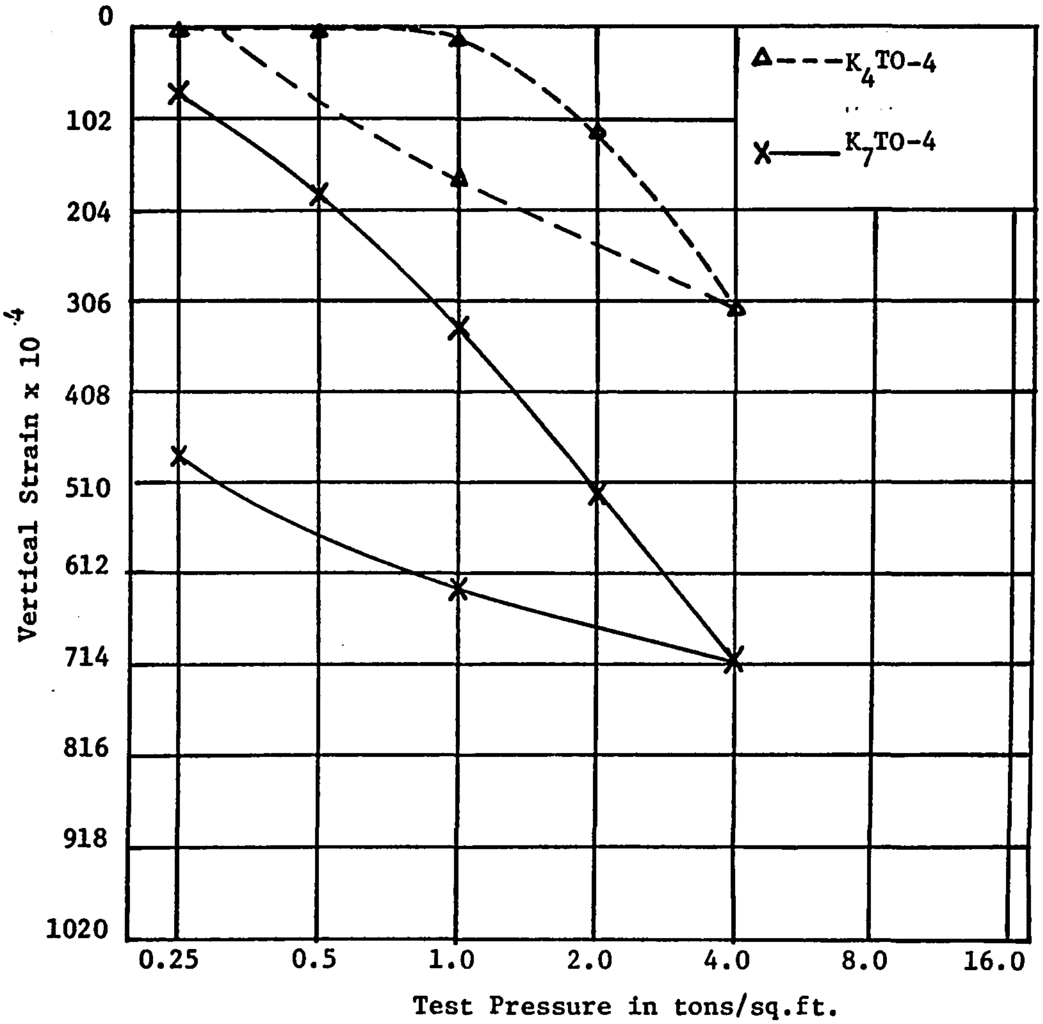


Figure 20 Consolidation Curves of the Samples K_4TO -4 and K_7 TO-4

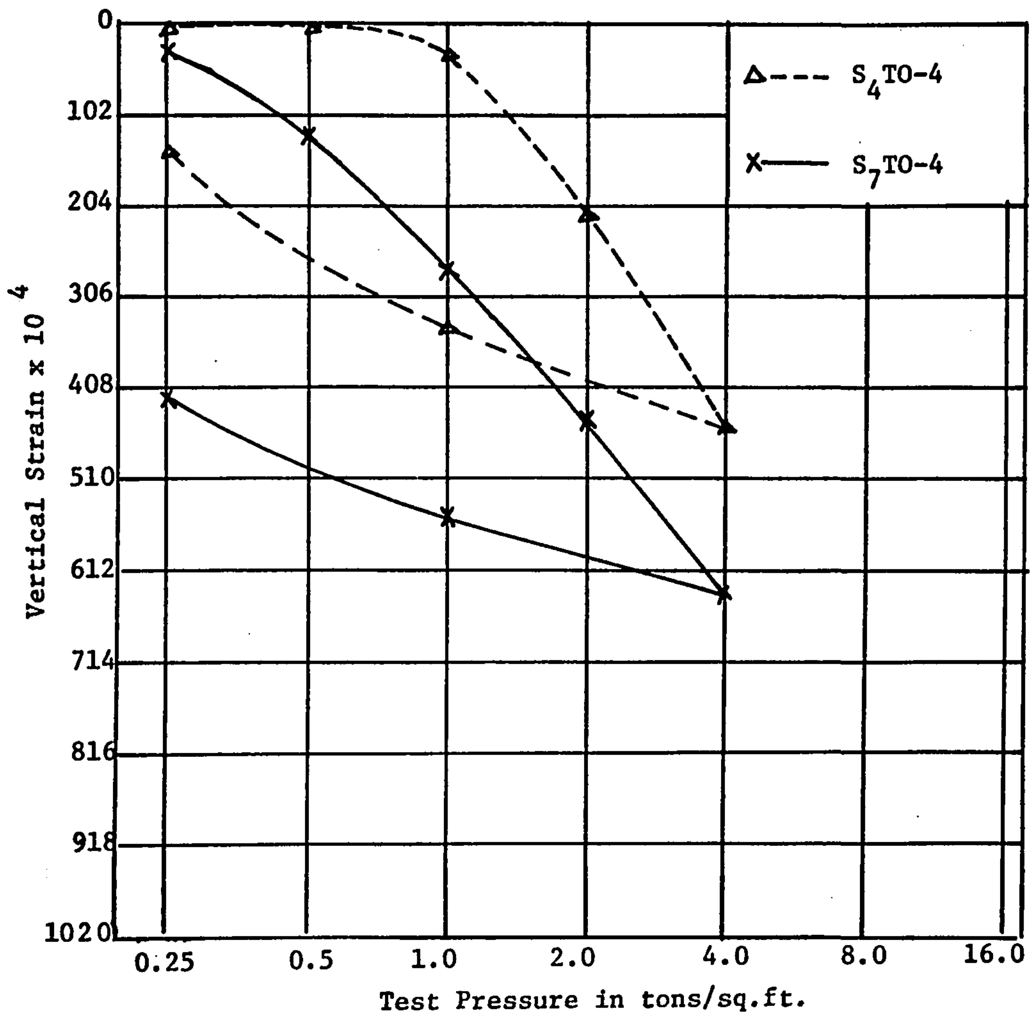


Figure 21 Consolidation Curves of the Samples S_4TO-4 and S_7TO-4

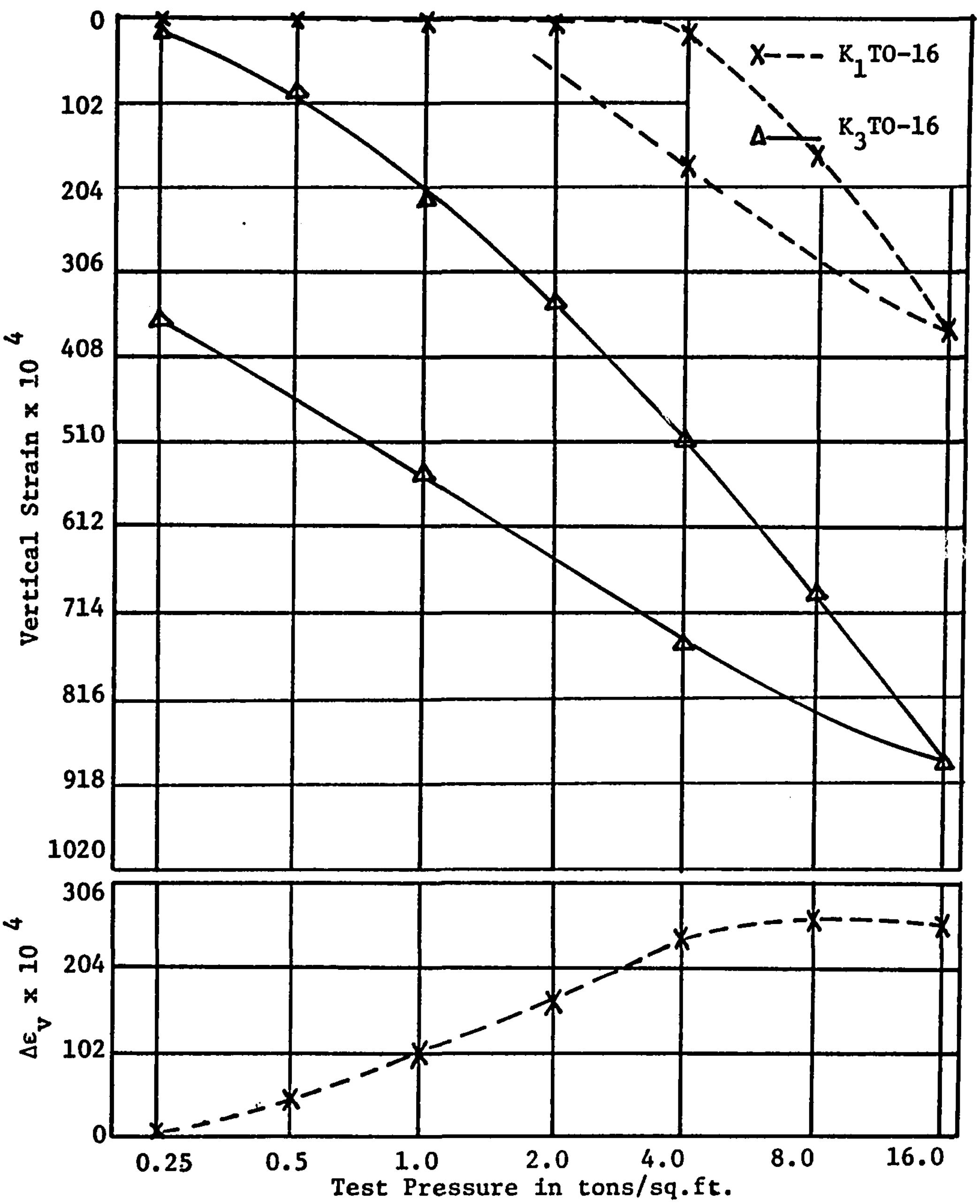


Figure 22 Consolidation Curves of the Samples K_1TO-16 and K_3TO-16

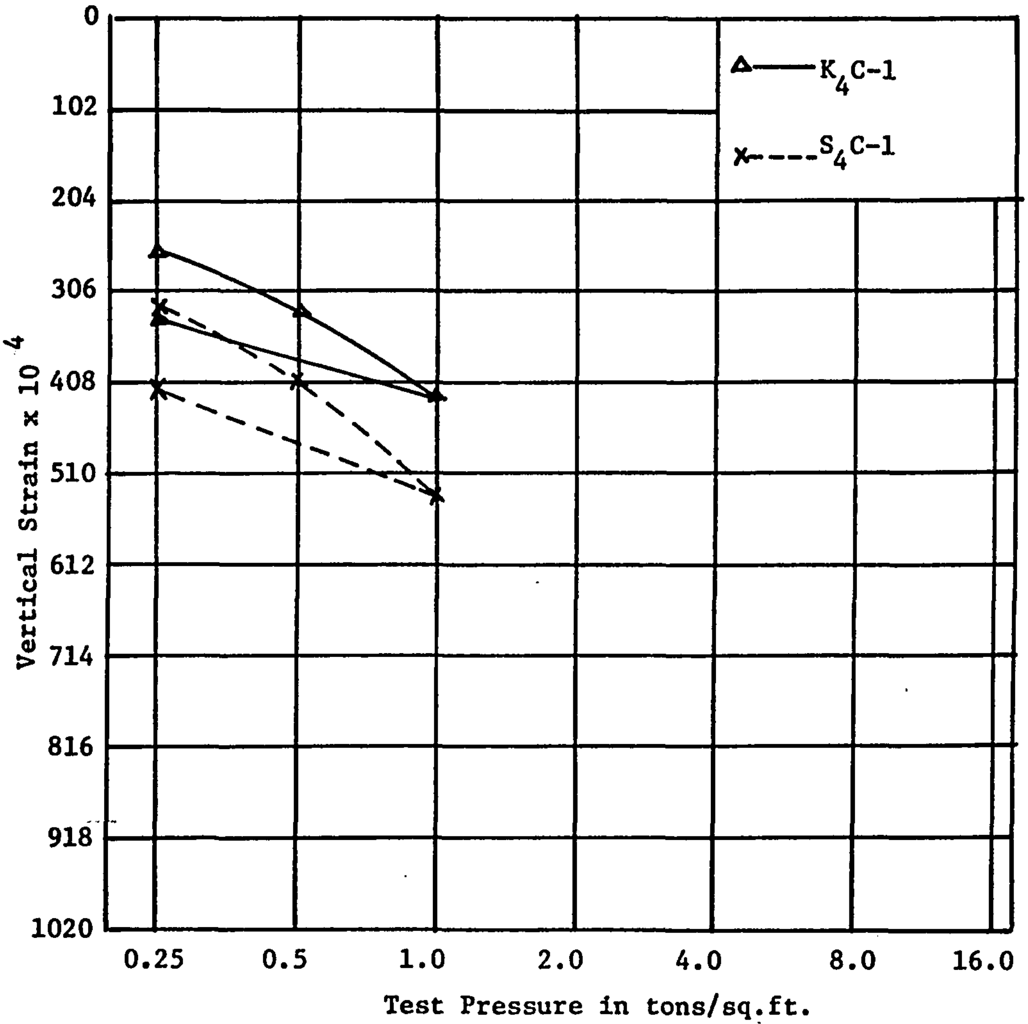


Figure 23 Consolidation Curves of the Samples K_4C-1 and S_4C-1

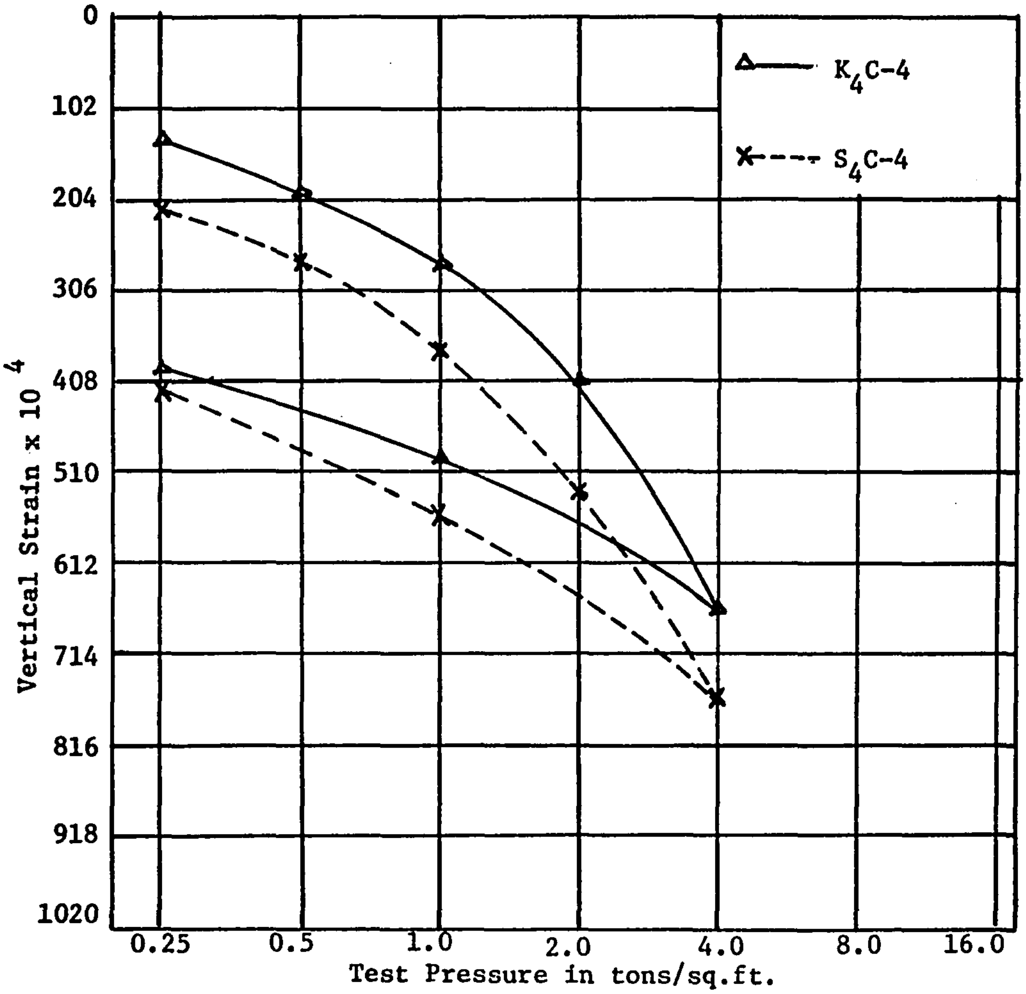


Figure 24 Consolidation Curves of the Samples K_4C-4 and S_4C-4

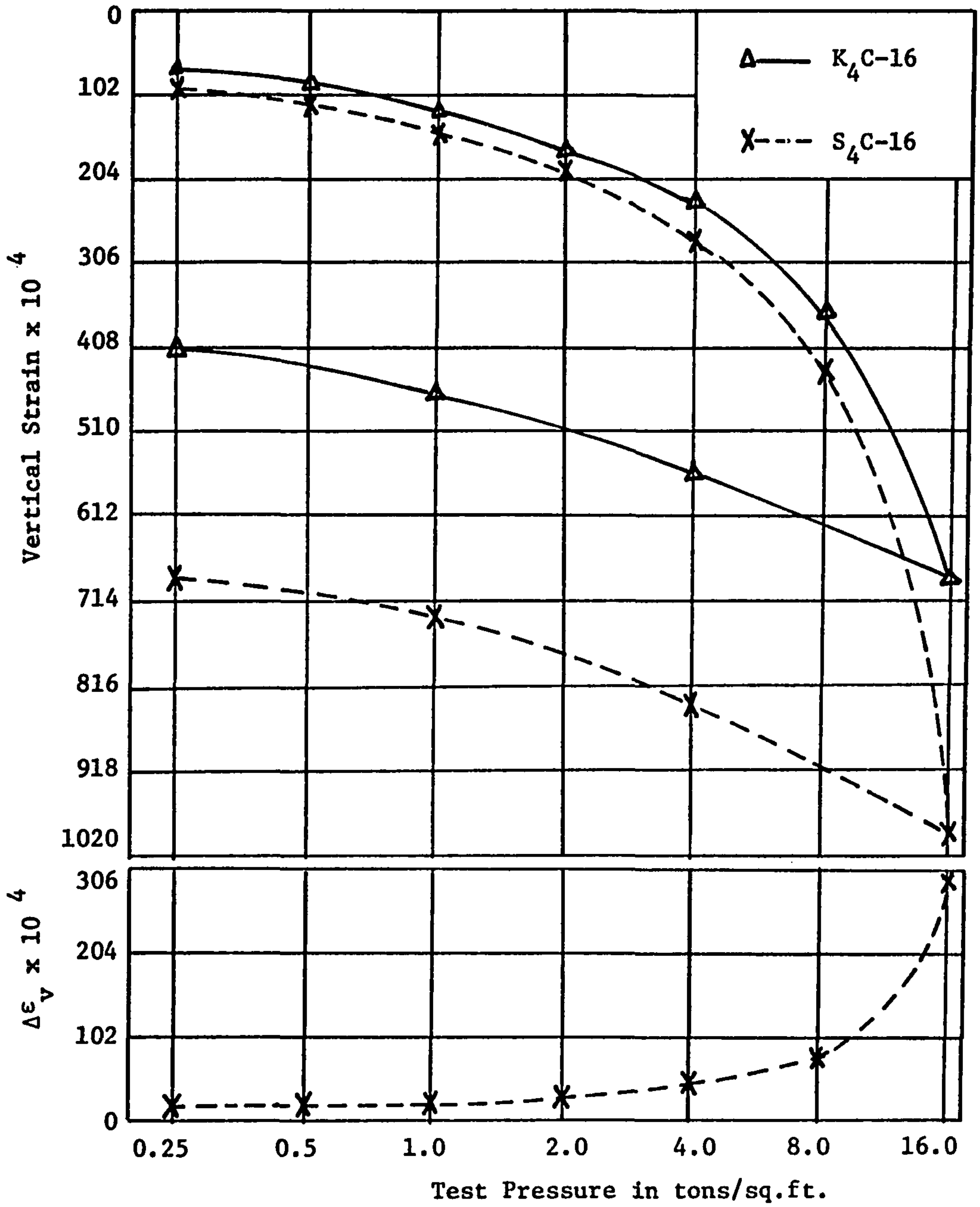


Figure 25 Consolidation Curves of the Samples K_4C-16 and S_4C-16

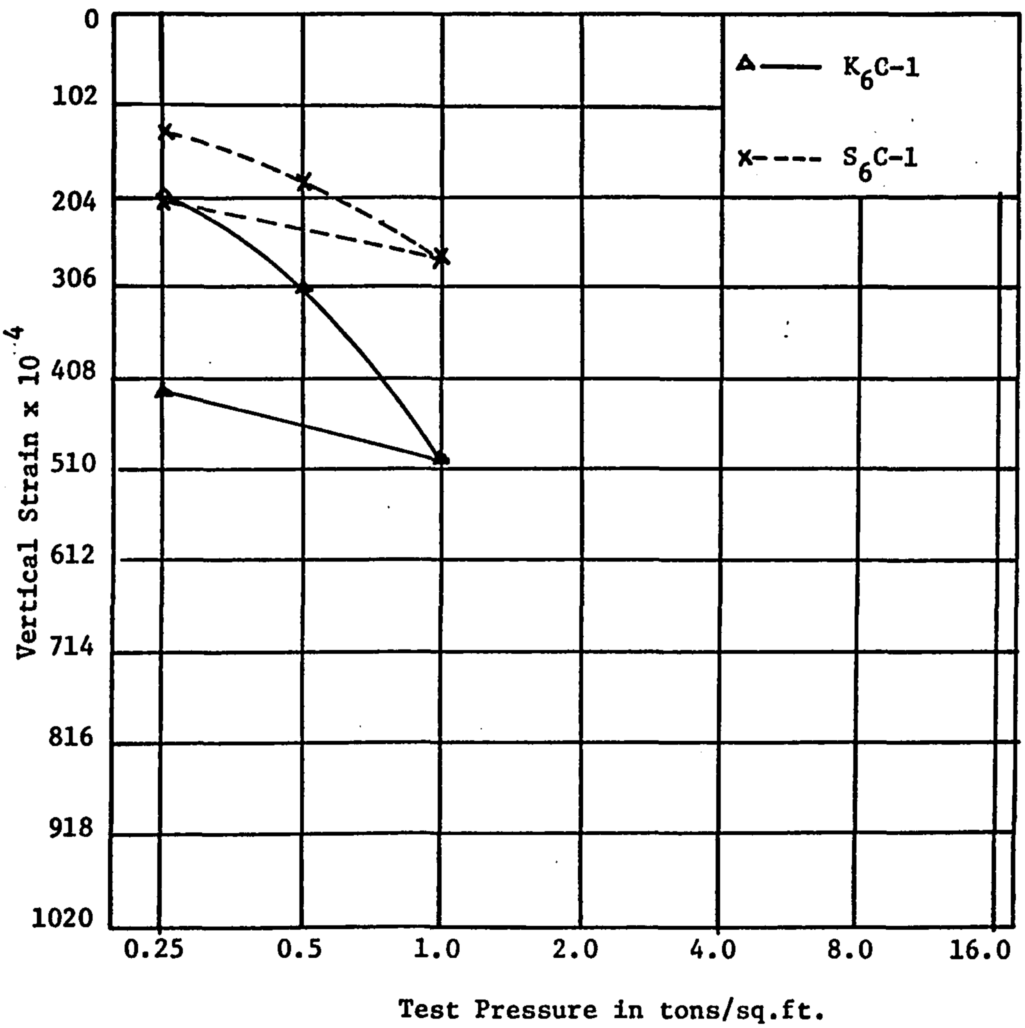


Figure 26 Consolidation Curves of the Samples K_6C-1 and S_6C-1

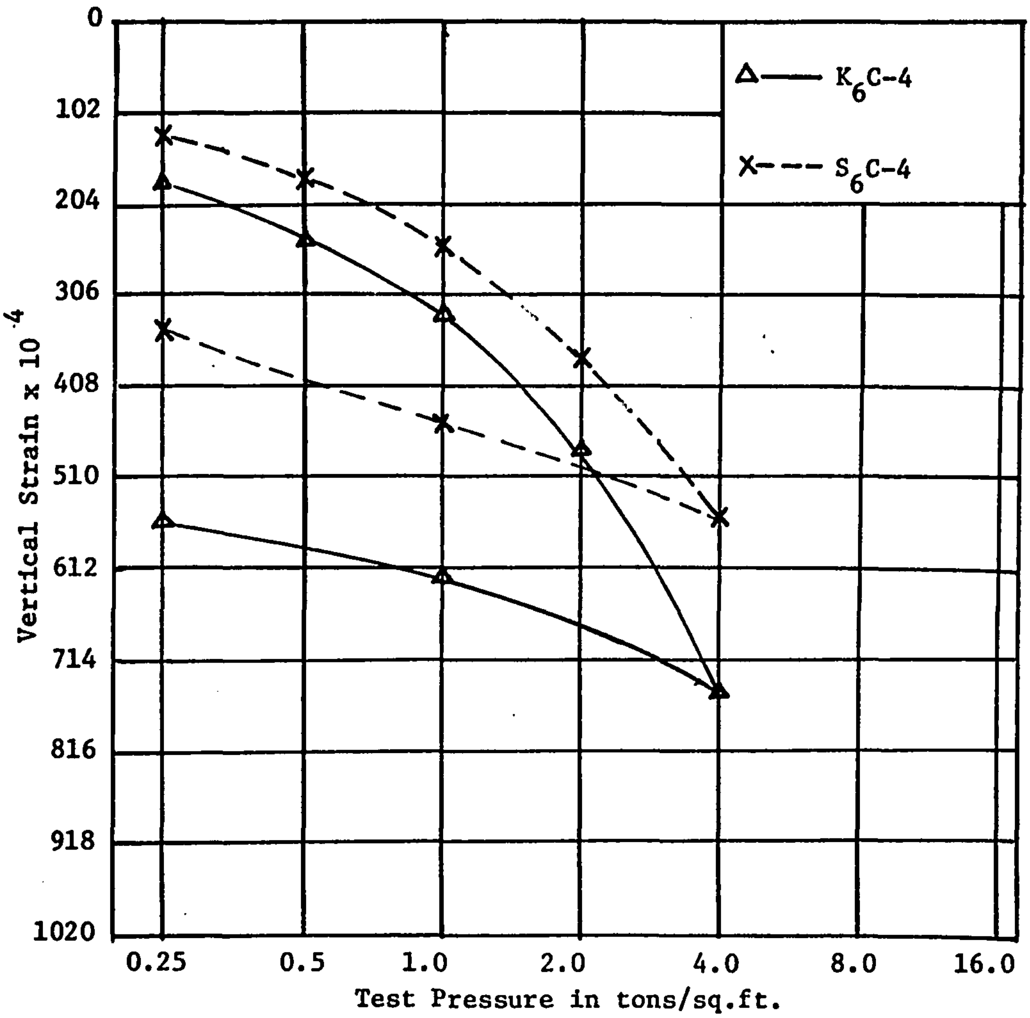


Figure 27 Consolidation Curves of the Samples K_6C-4 and S_6C-4

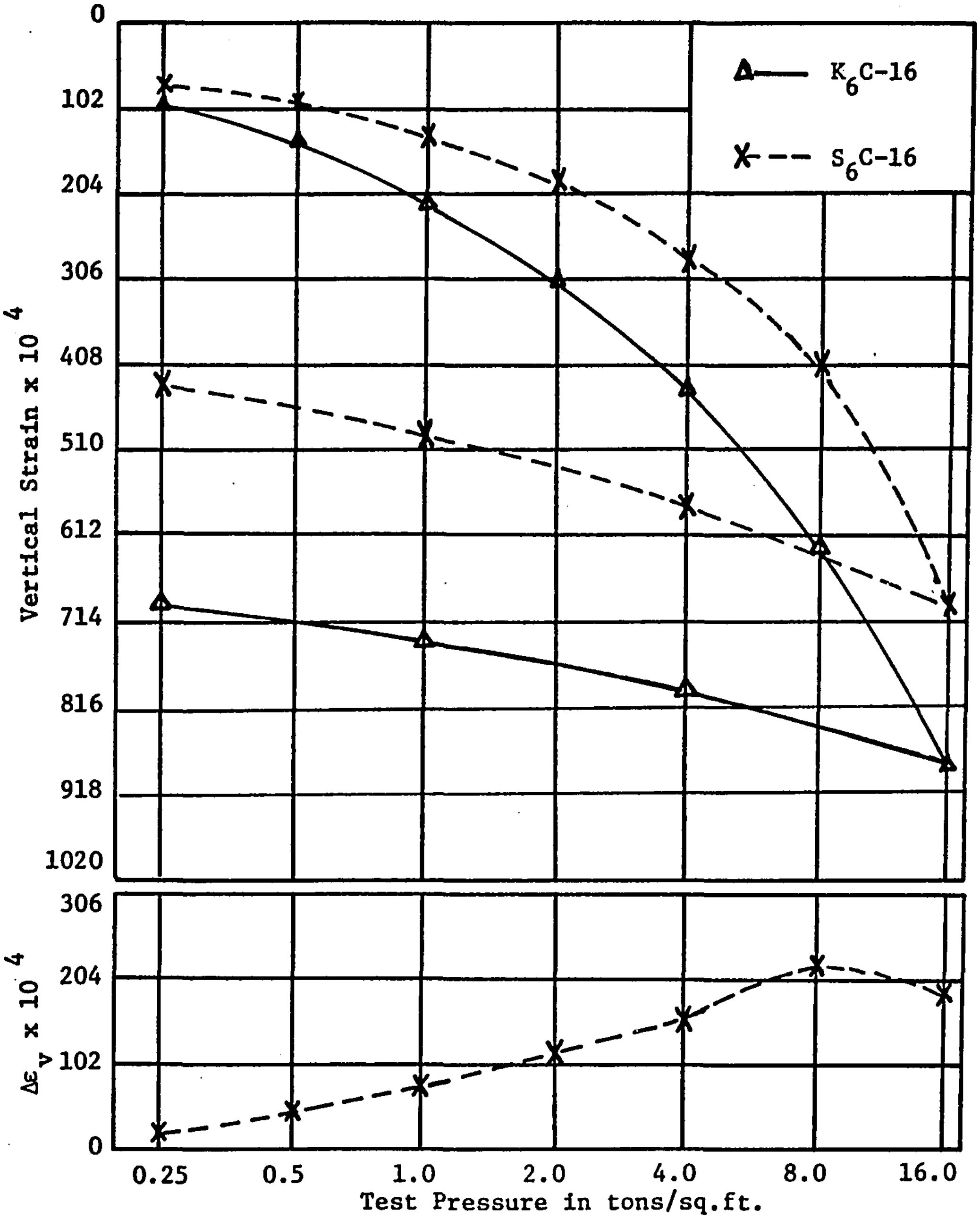


Figure 28 Consolidation Curves of the Samples K_6C-16 and S_6C-16

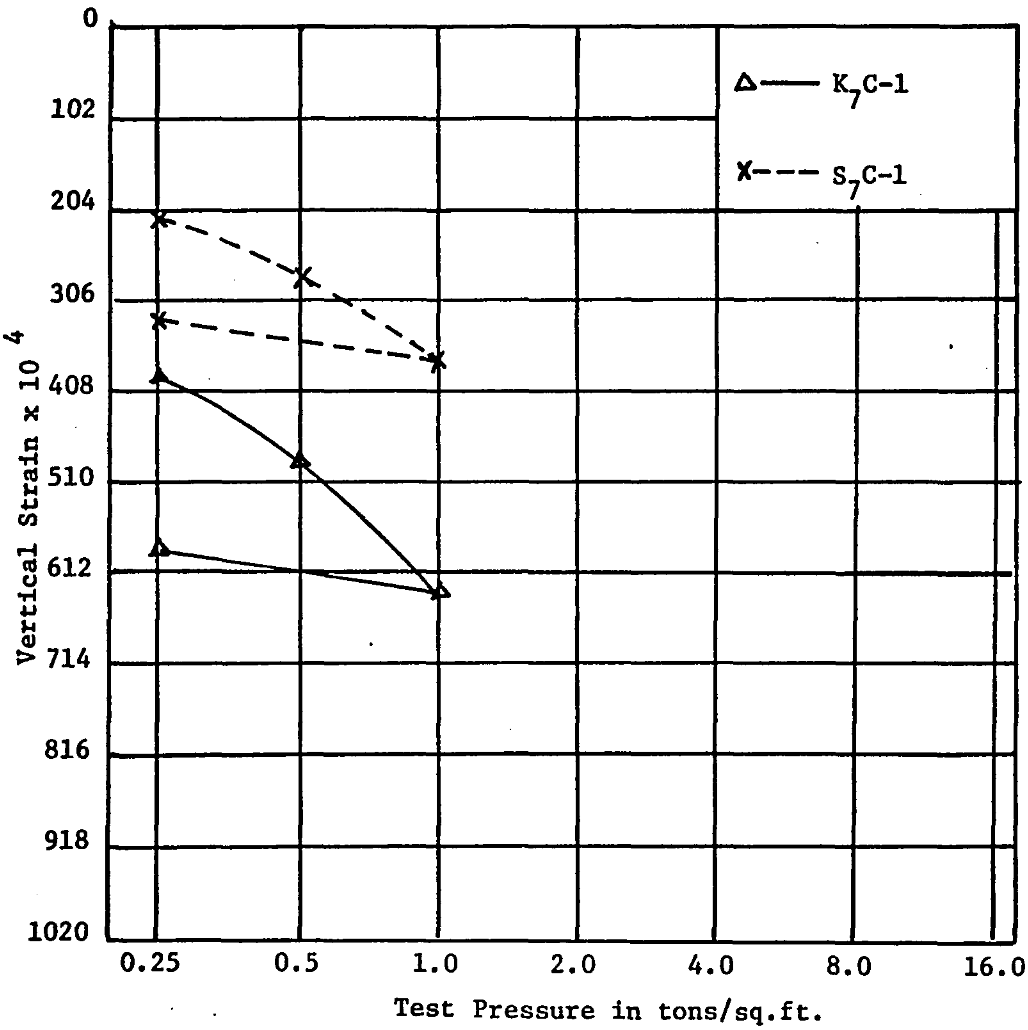


Figure 29 Consolidation Curves of the Samples K_7C-1 and S_7C-1

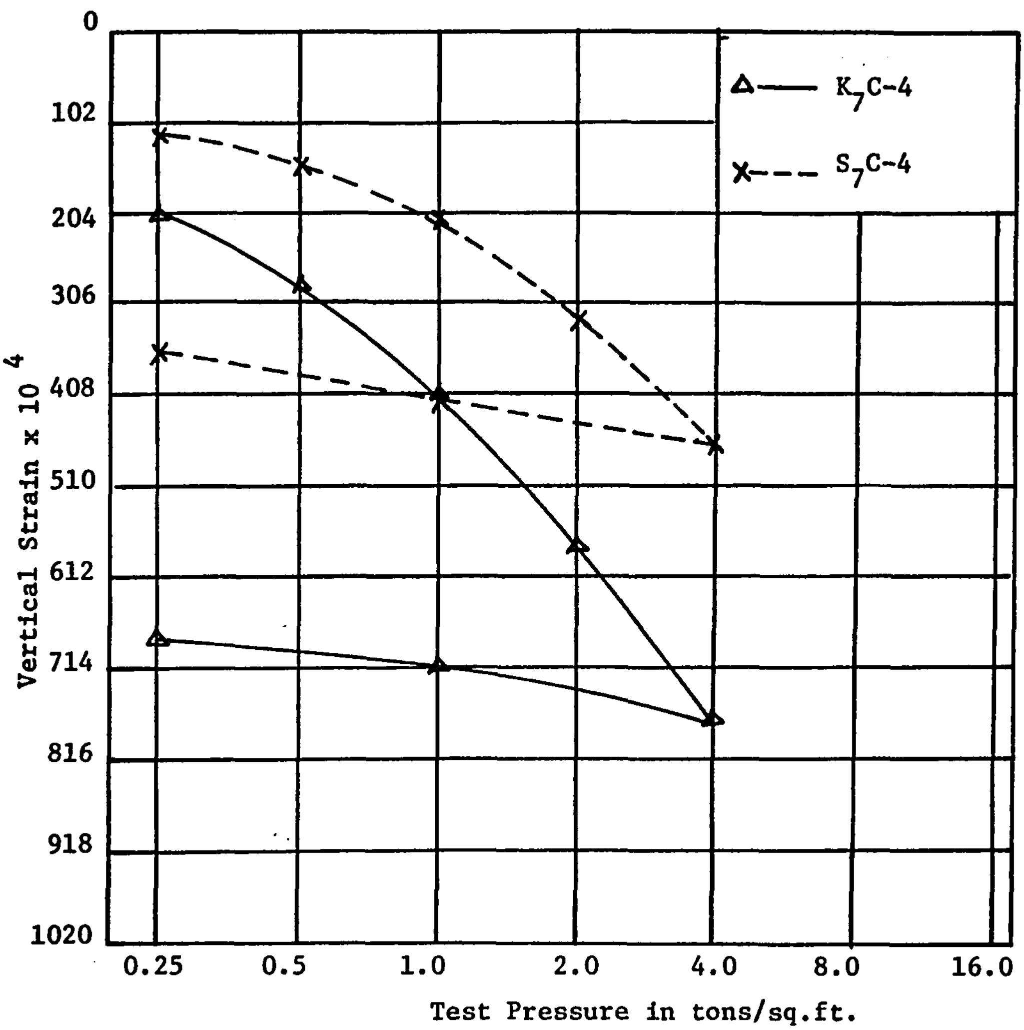


Figure 30 Consolidation Curves of the Samples K_7C-4 and S_7C-4

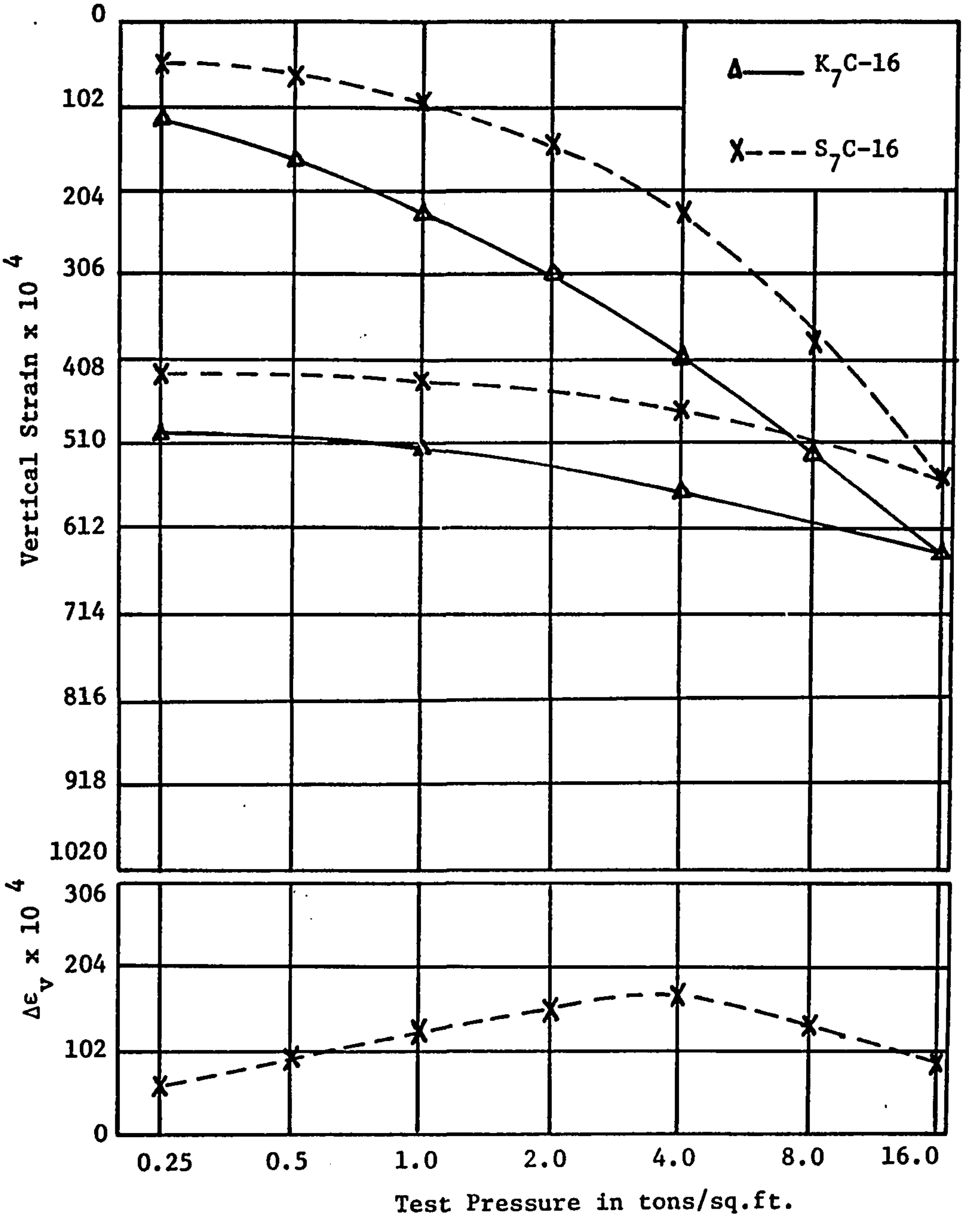


Figure 31 Consolidation Curves of the Samples K_7C-16 and S_7C-16

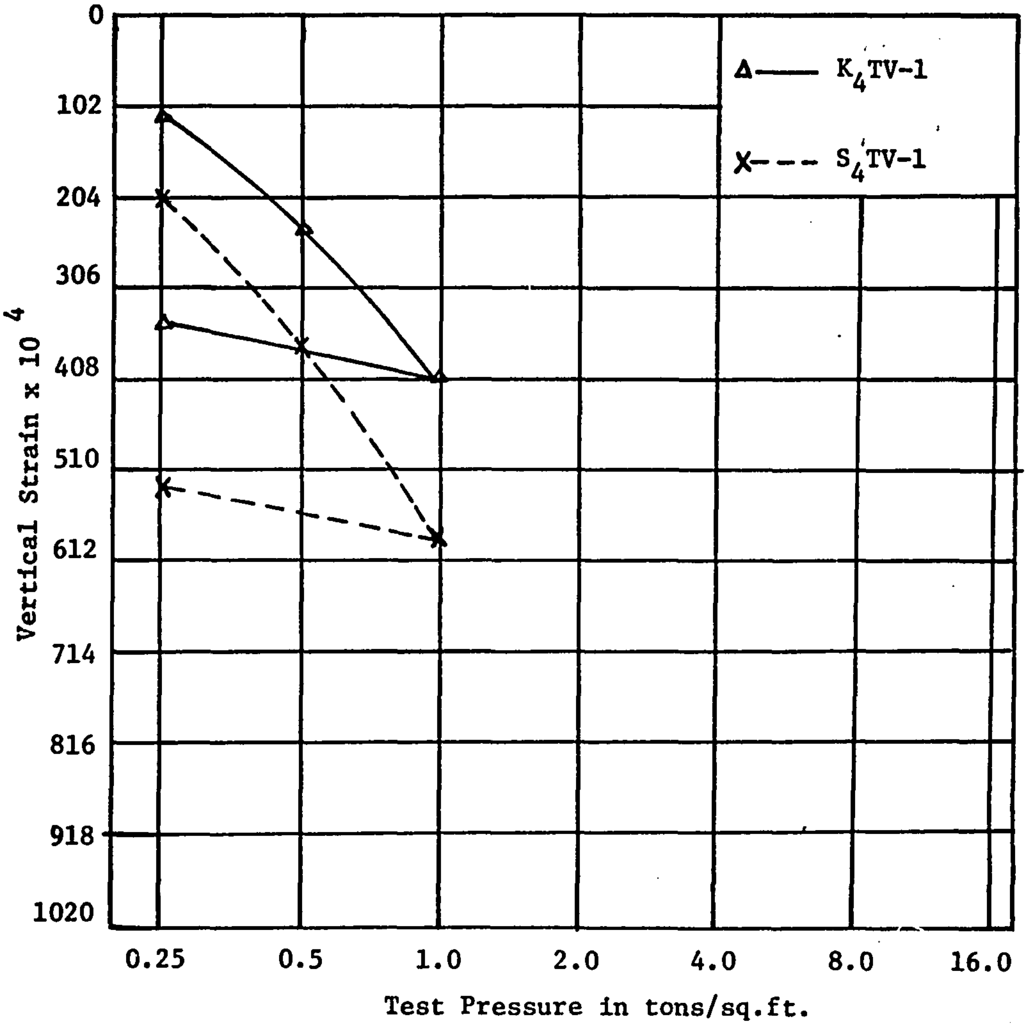


Figure 32 Consolidation Curves of the Samples K_4TV-1 and S_4TV-1

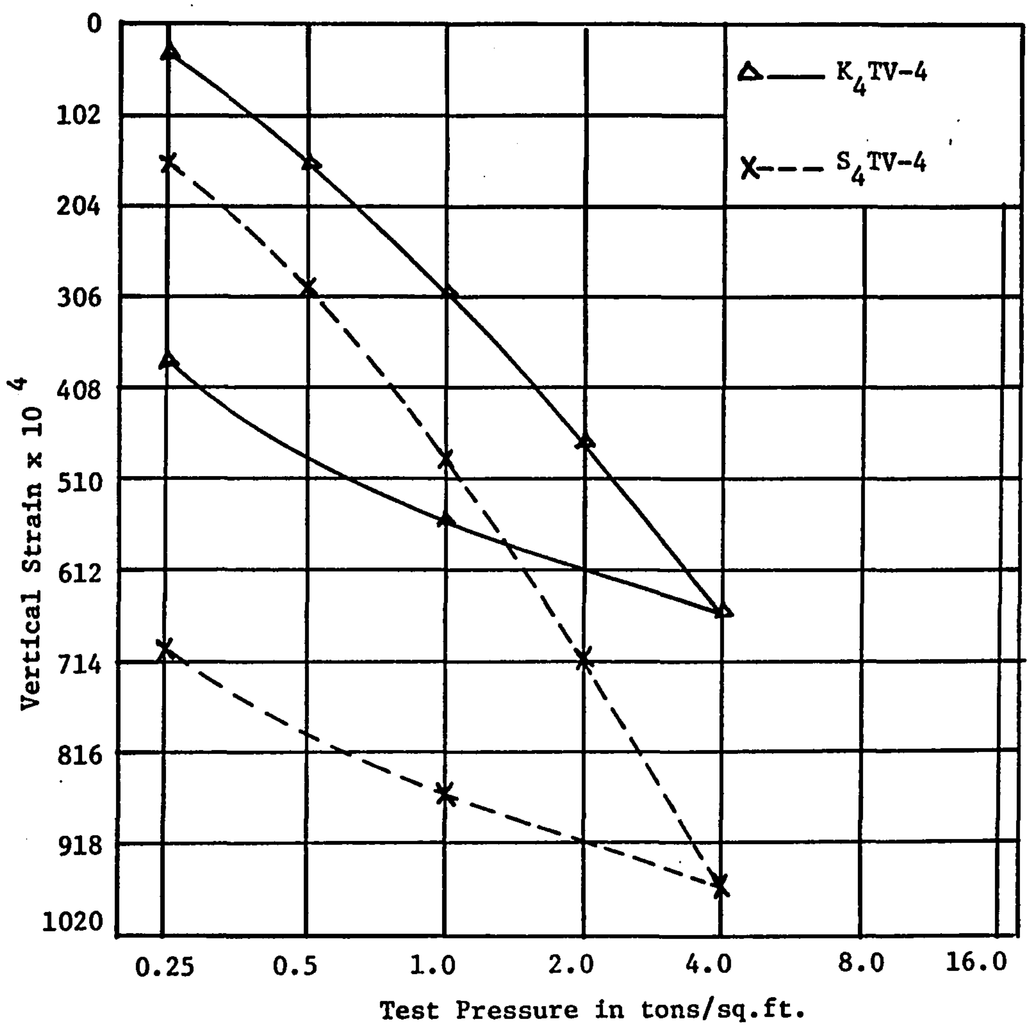


Figure 33 Consolidation Curves of the Samples K_4TV-4 and S_4TV-4

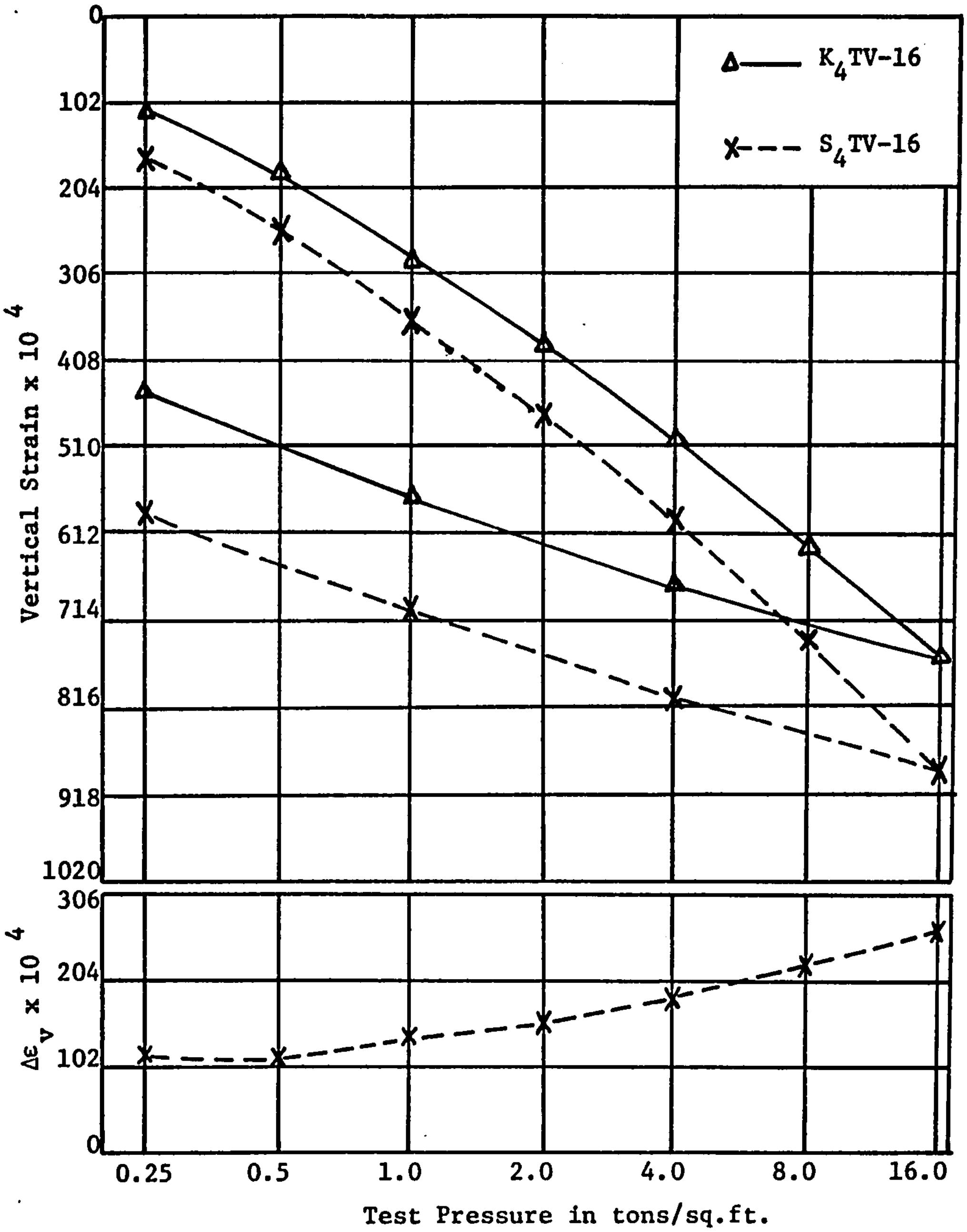


Figure 34 Consolidation Curves of the Samples K_4TV-16 and S_4TV-16

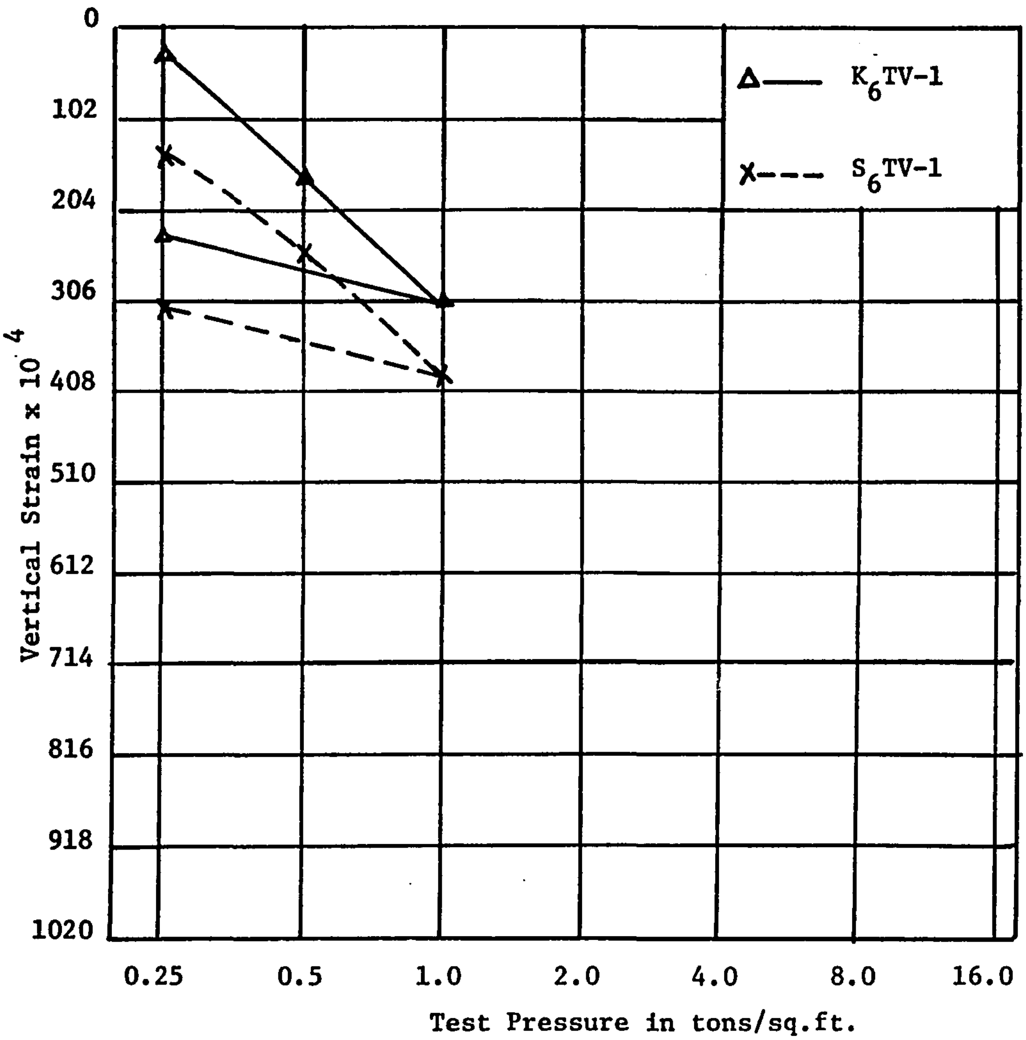


Figure 35 Consolidation Curves of the Samples K_6TV-1 and S_6TV-1

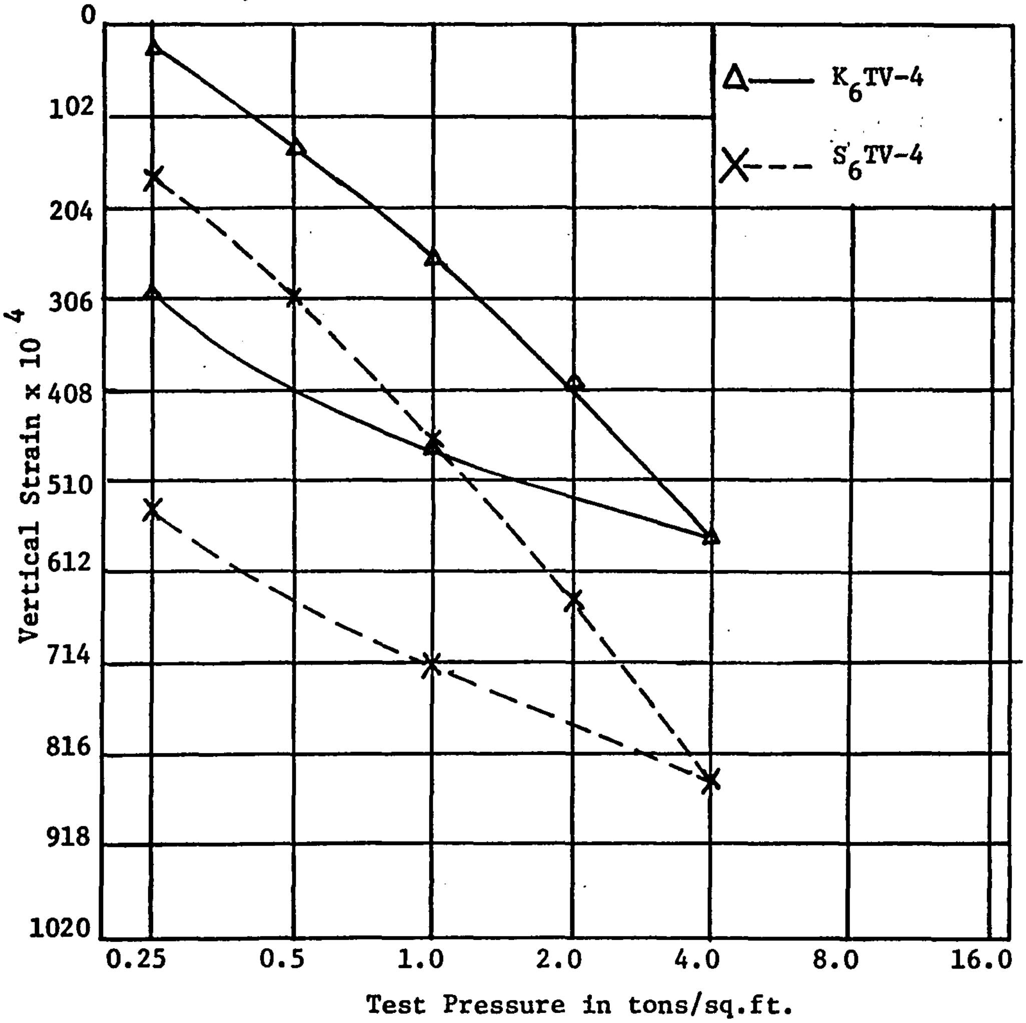


Figure 36 Consolidation Curves of the Samples K_6TV-4 and S_6TV-4

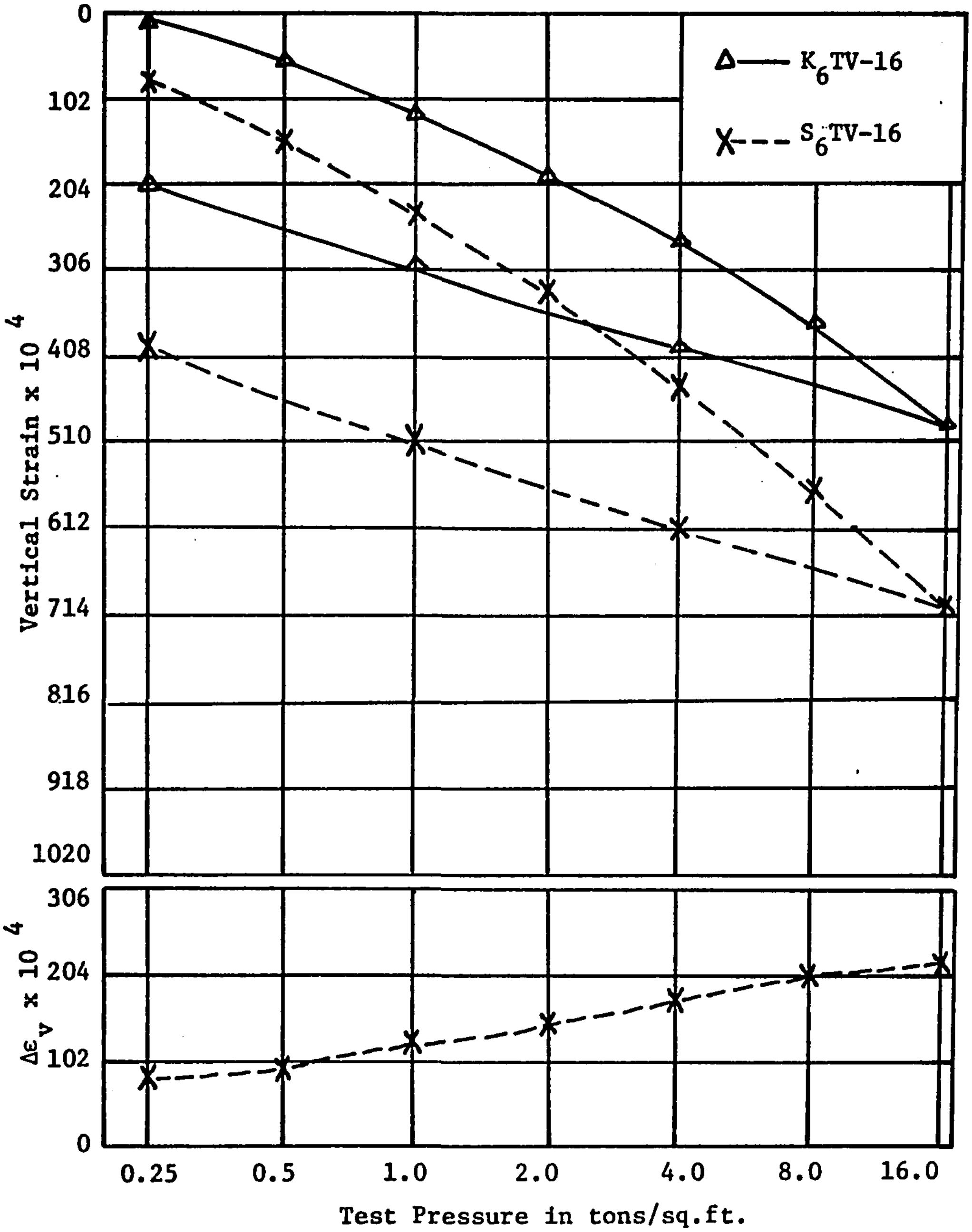


Figure 37 Consolidation Curves of the Samples K_6TV-16 and S_6TV-16

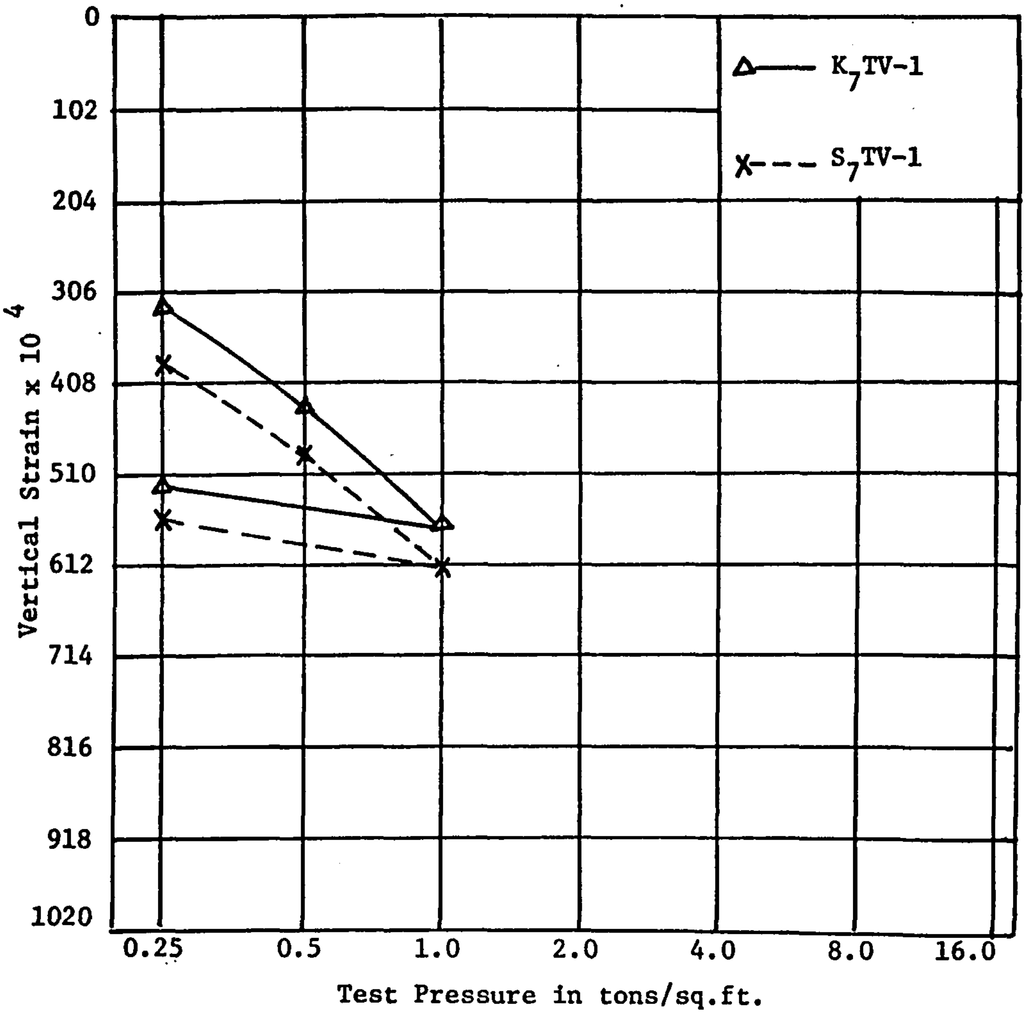


Figure 38 Consolidation Curves of the Samples K_7TV-1 and S_7TV-1

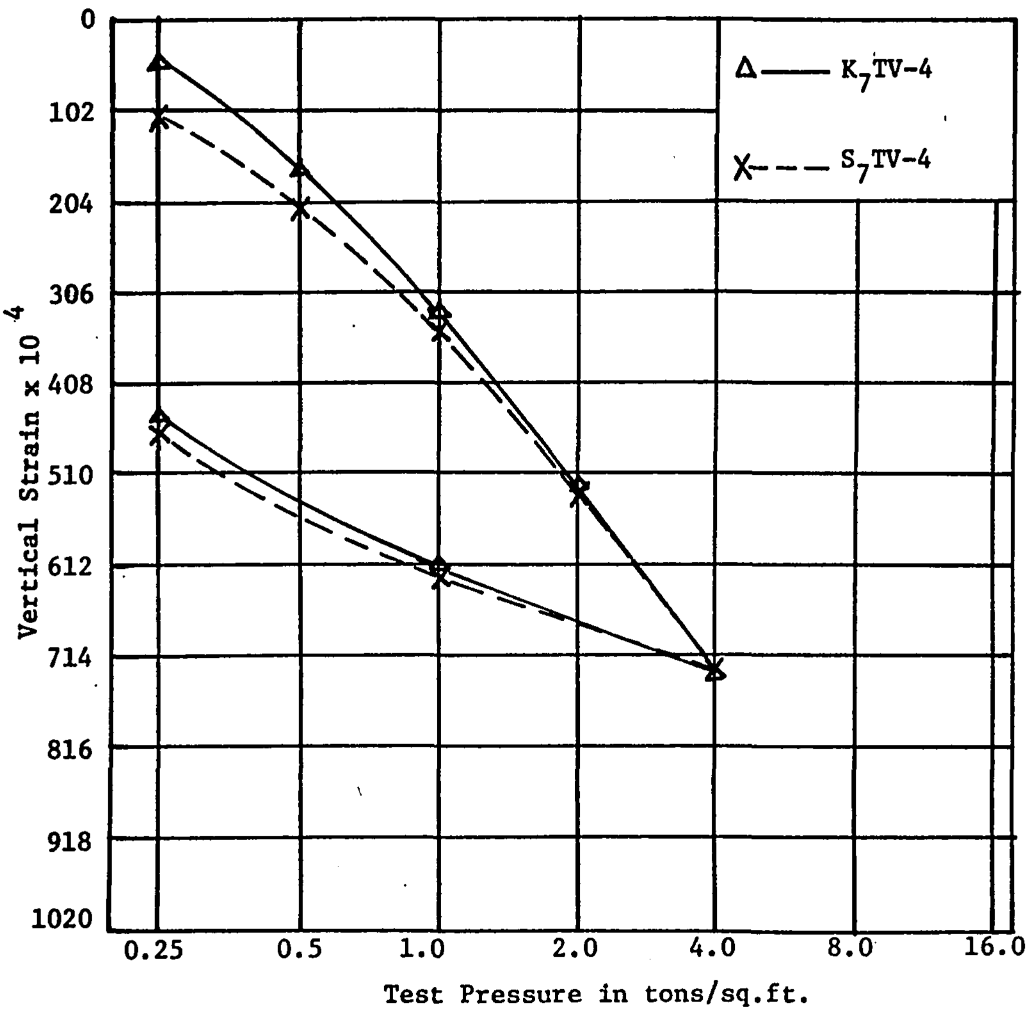


Figure 39 Consolidation Curves of the Samples K_7TV-4 and S_7TV-4

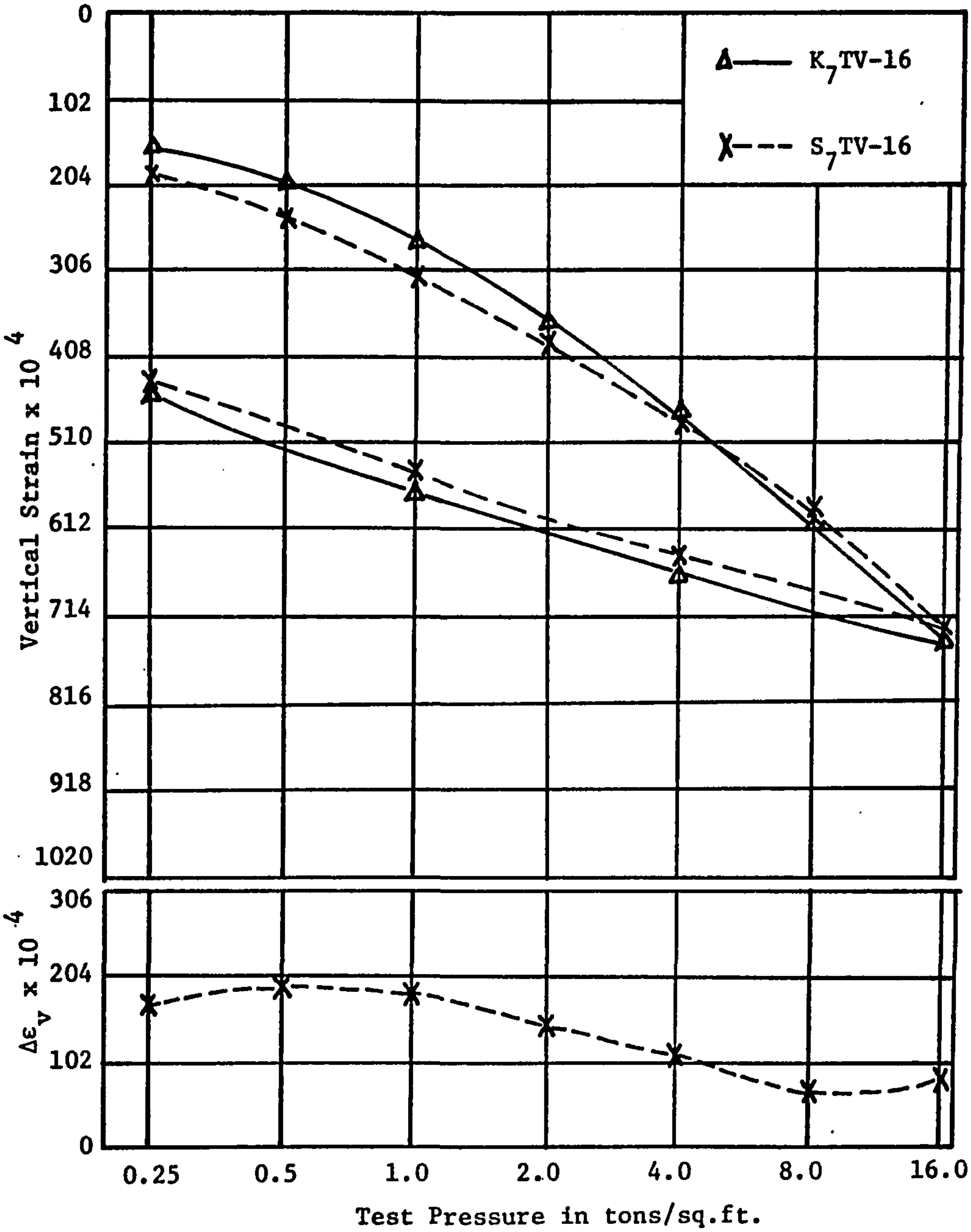


Figure 40 Consolidation Curves of the Samples K_7TV-16 and S_7TV-16

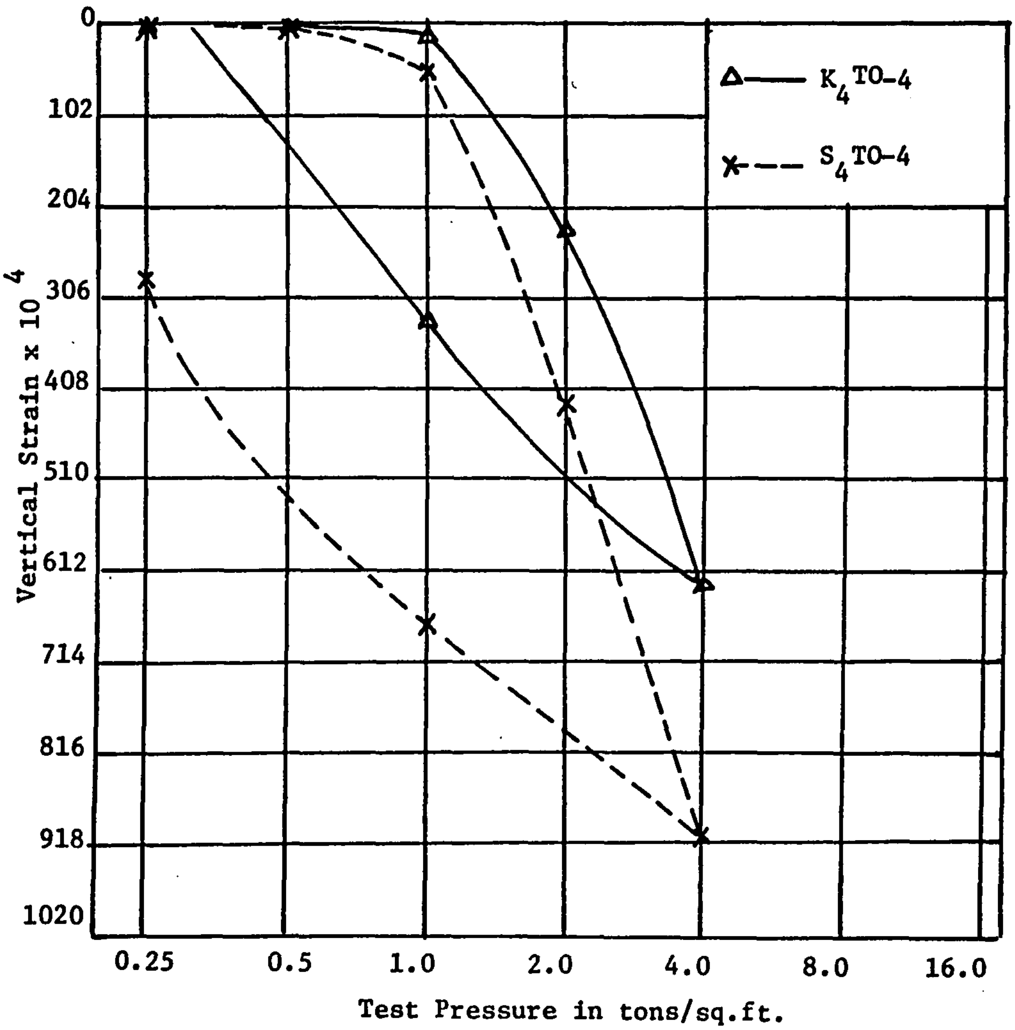


Figure 41 Consolidation Curves of the Samples K_4TO-4 and S_4TO-4

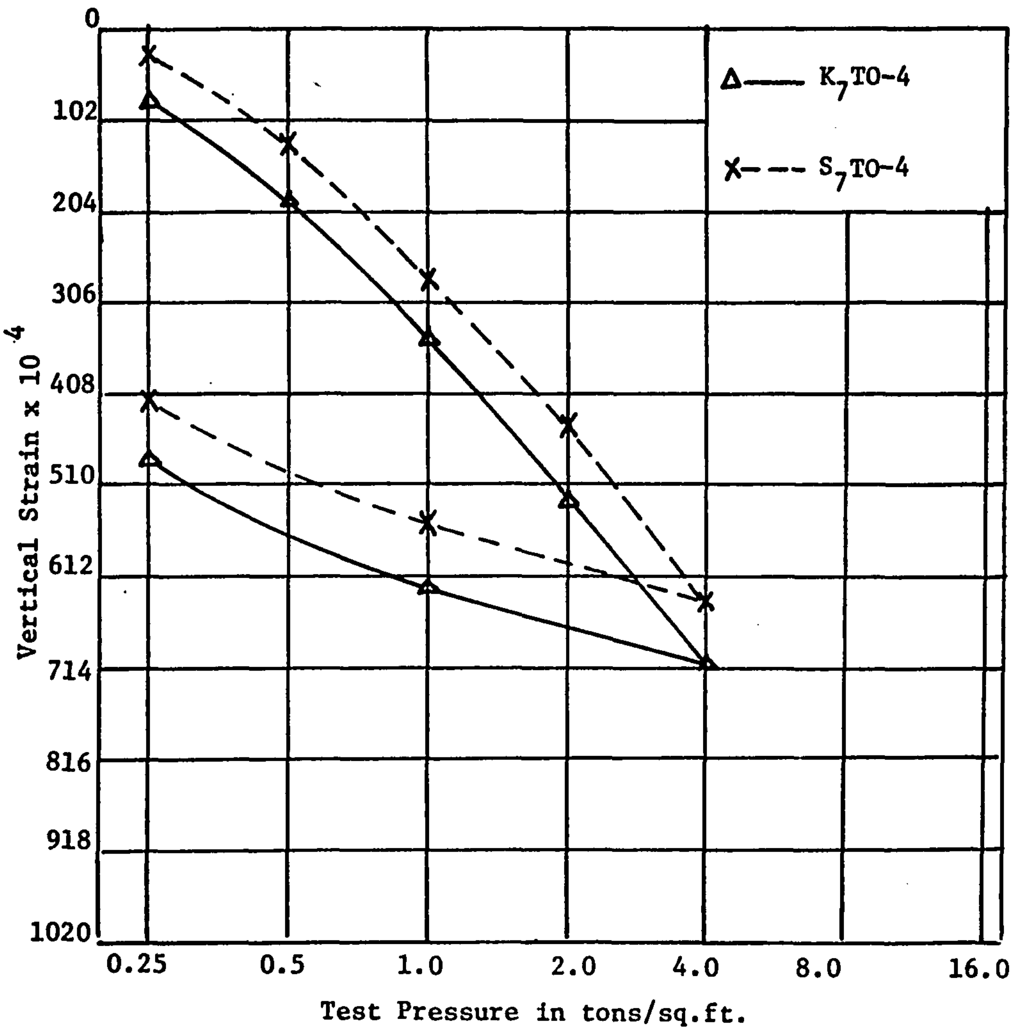


Figure 42 Consolidation Curves of the Samples K_7TO-4 and S_7TO-4

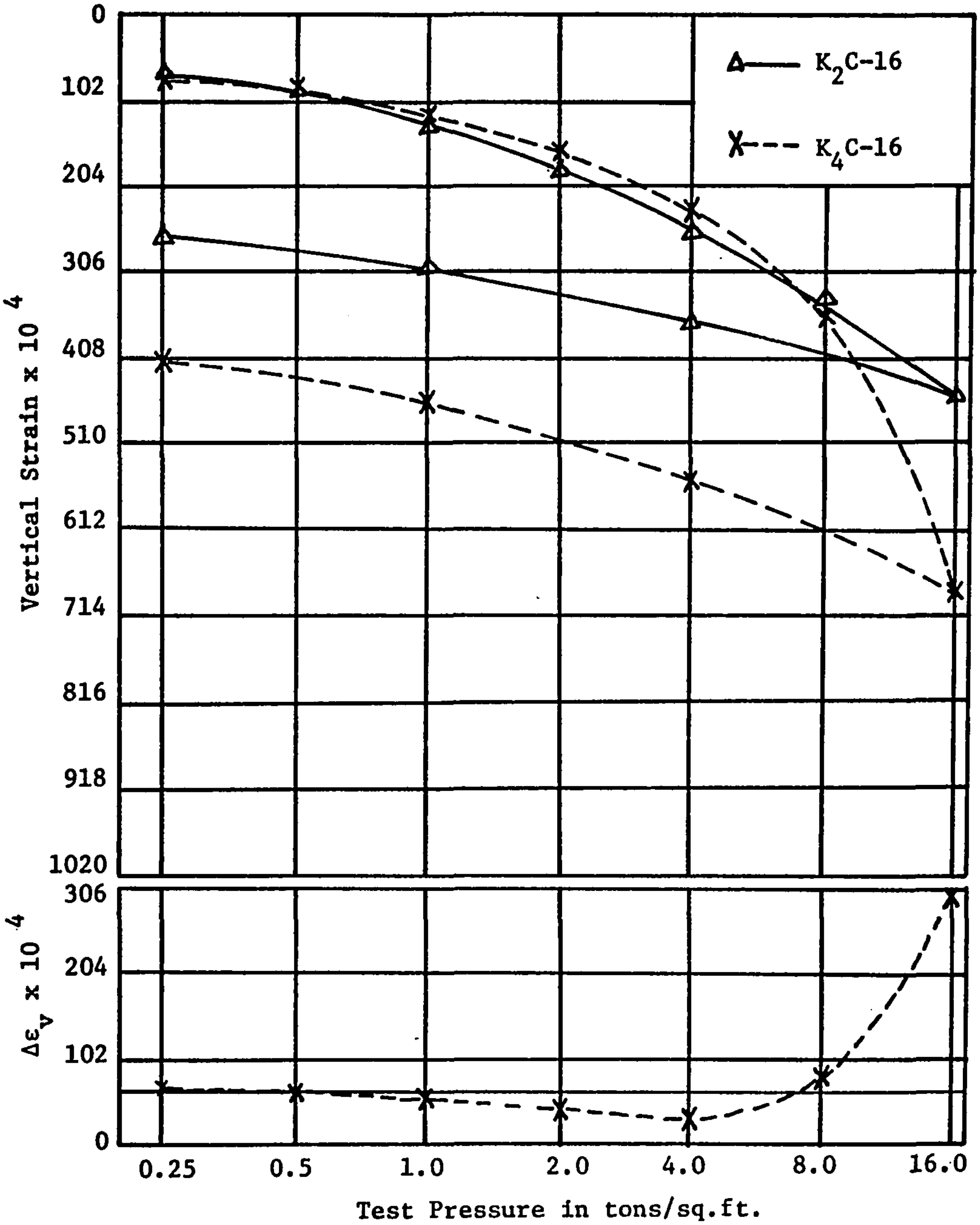


Figure 43 Consolidation Curves of the Samples K_2C-16 and K_4C-16

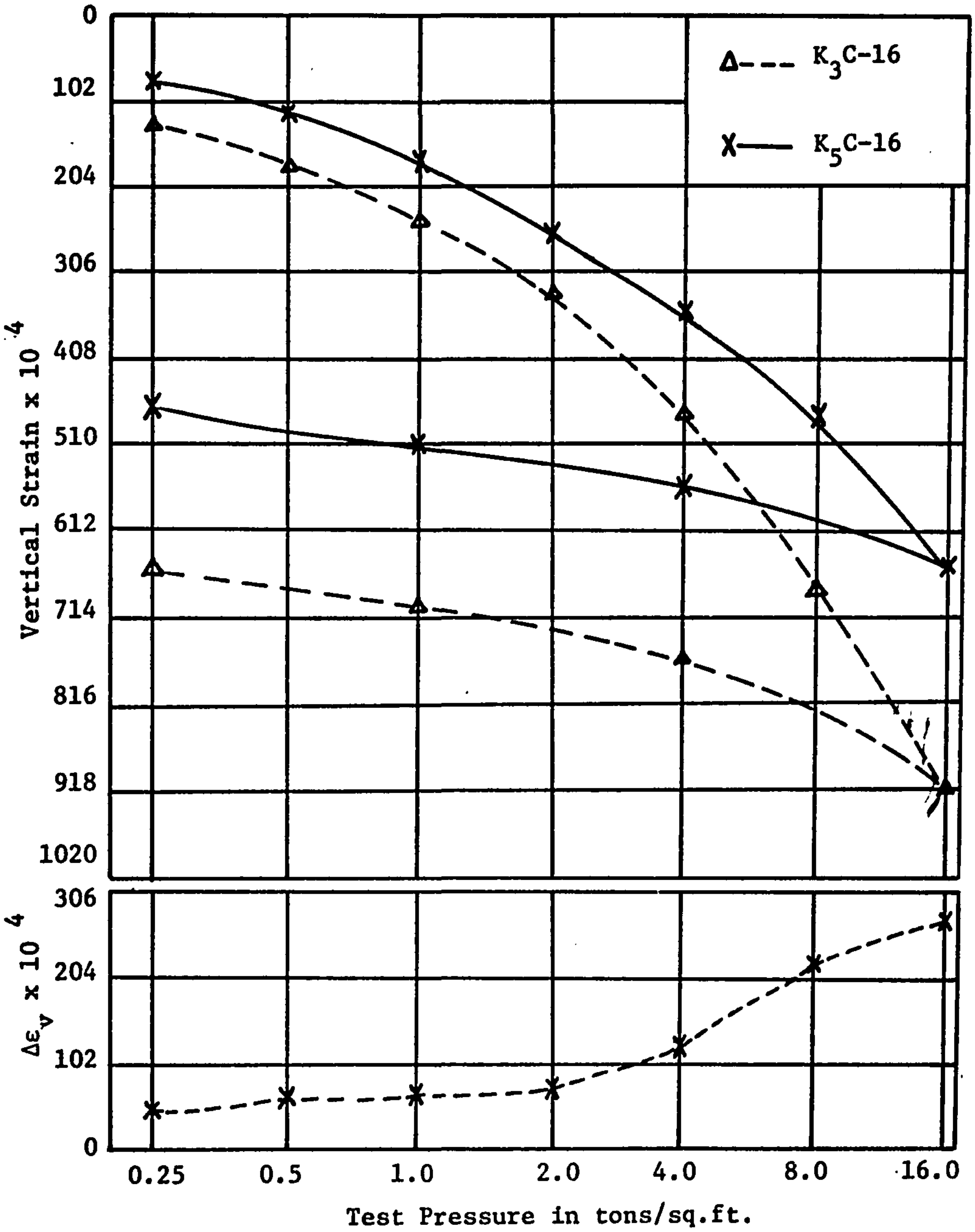


Figure 44 Consolidation Curves of the Samples K_3C-16 and K_5C-16

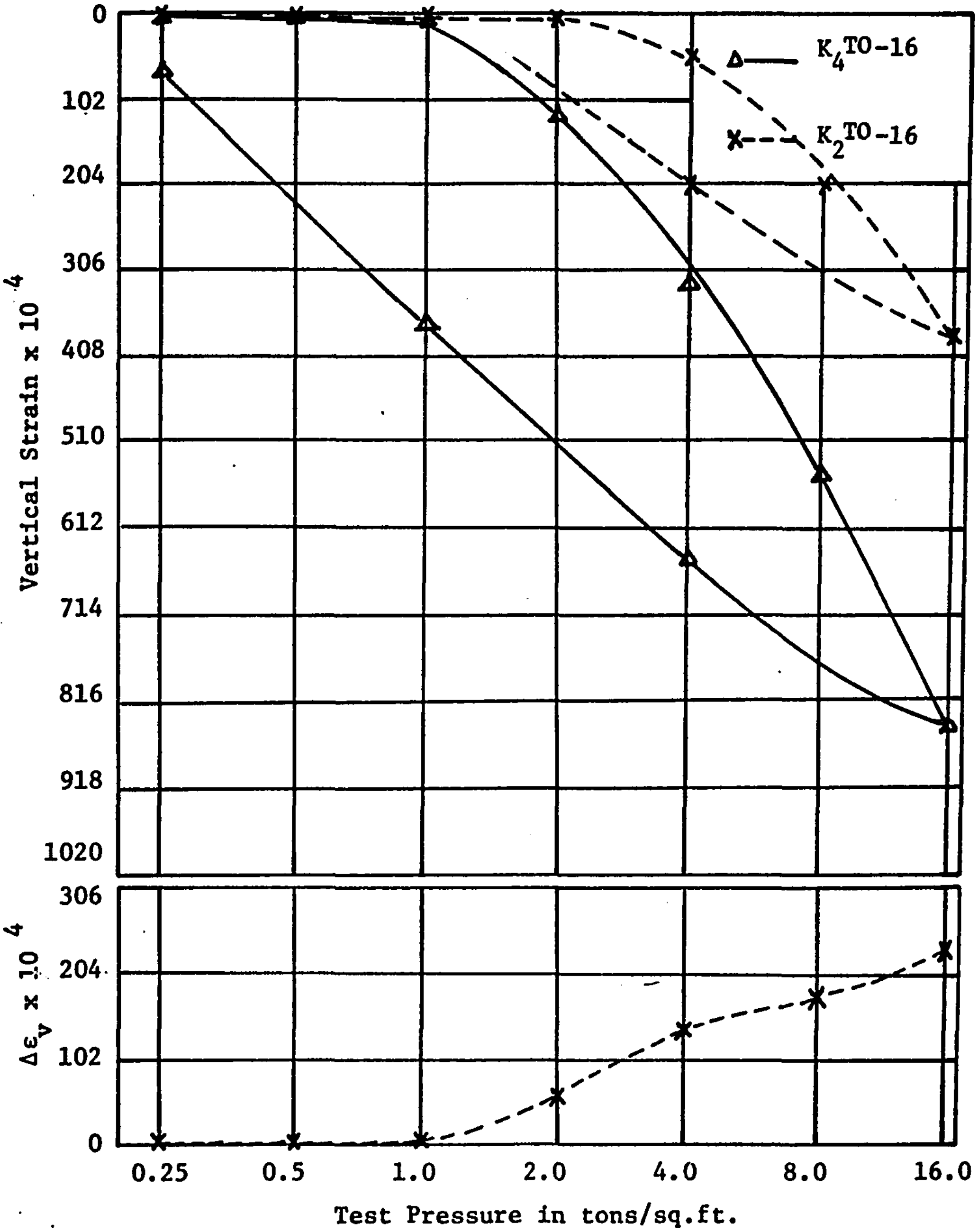


Figure 45 Consolidation Curves of the Samples K_2TO-16 and K_4TO-16

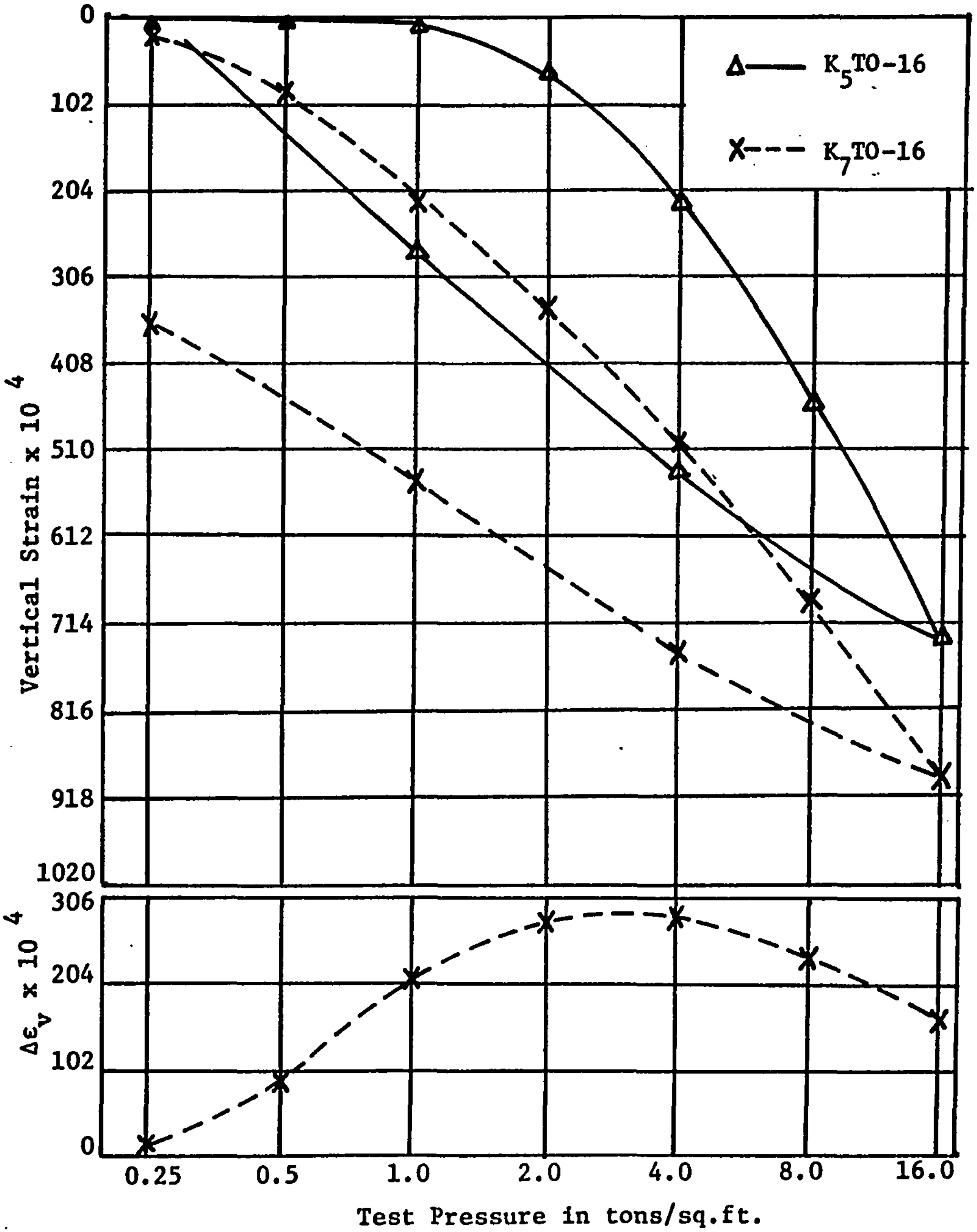


Figure 46 Consolidation Curves of the Samples K_3TO-16 and K_5TO-16

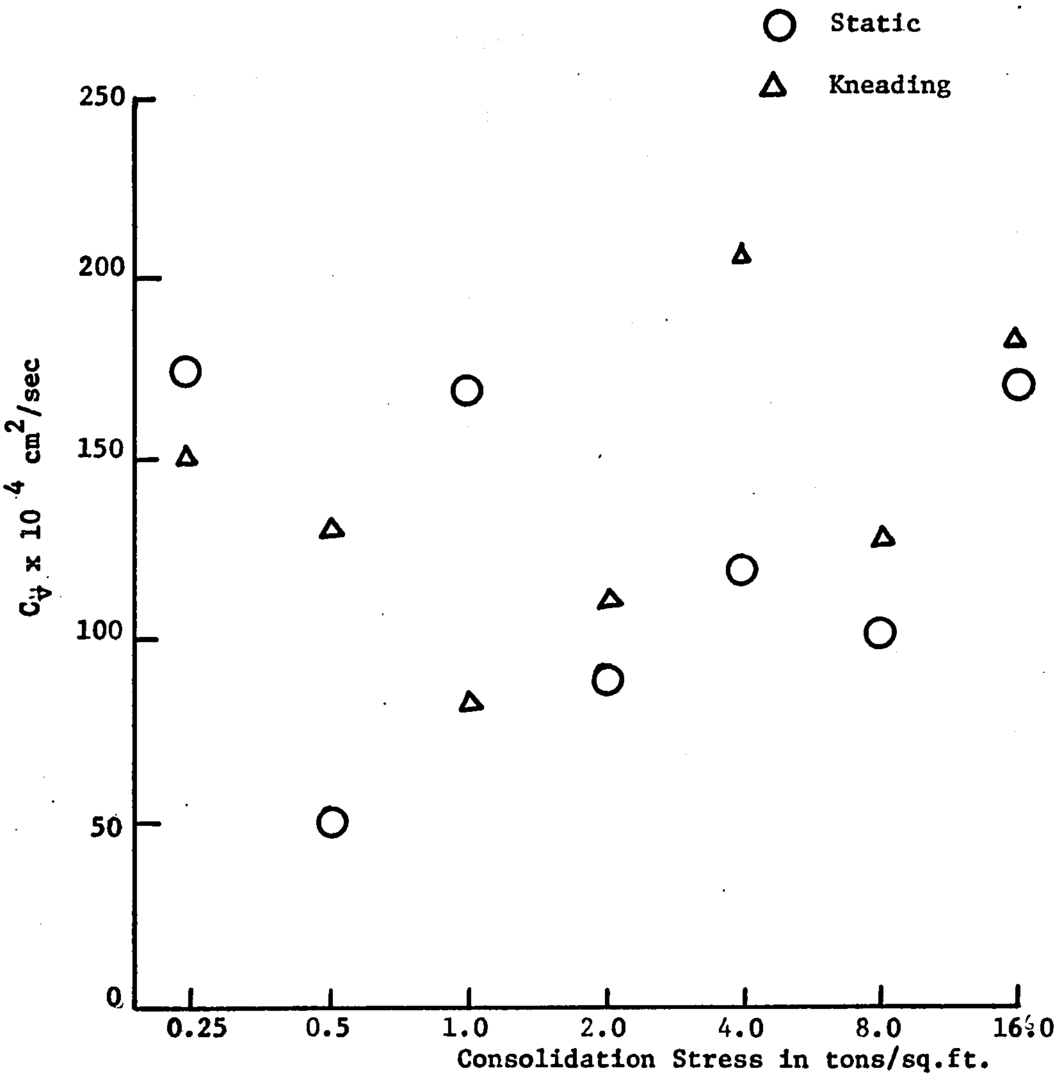


Figure 47 Coefficient of Consolidation versus the Consolidation Stress for the Samples K_4C-16 and S_4C-16

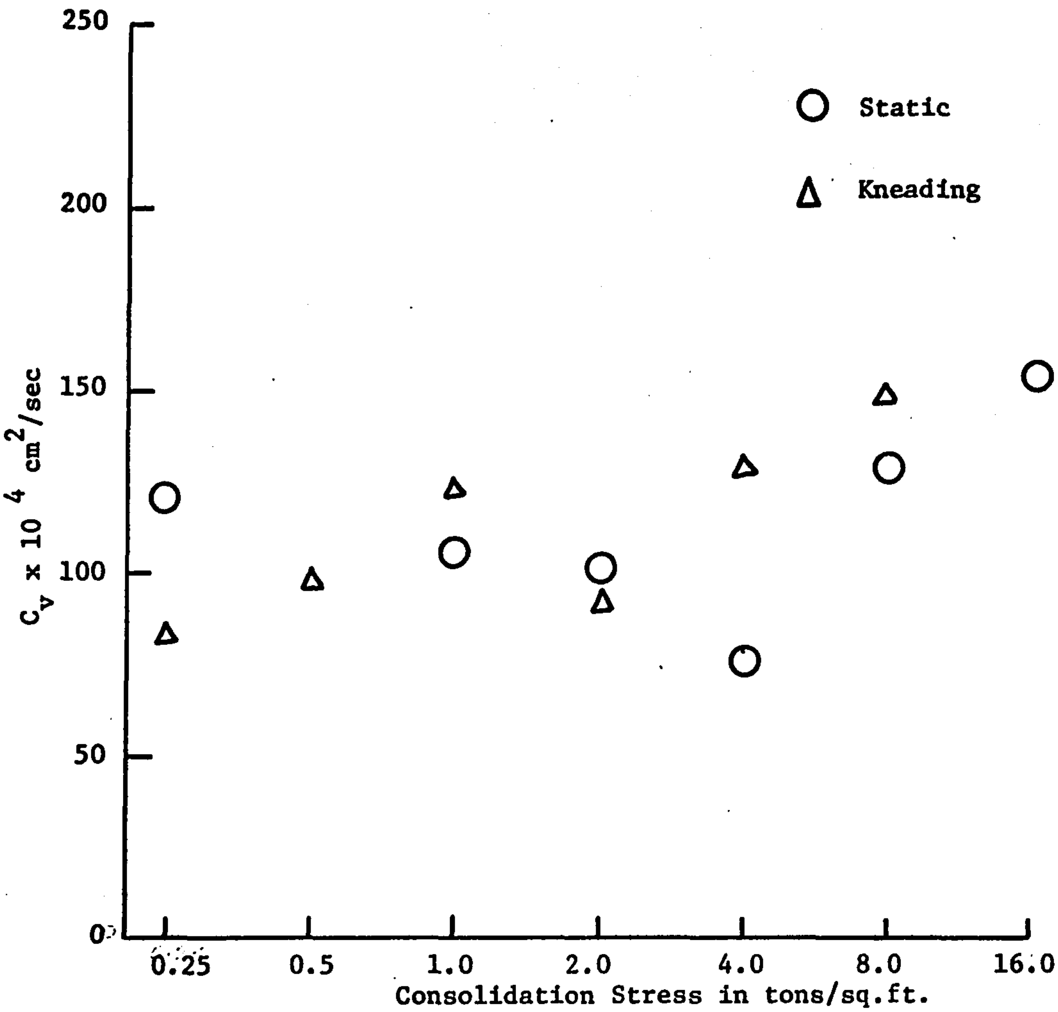


Figure 48 Coefficient of Consolidation versus the Consolidation Stress for the Samples K_7C-16 and S_7C-16

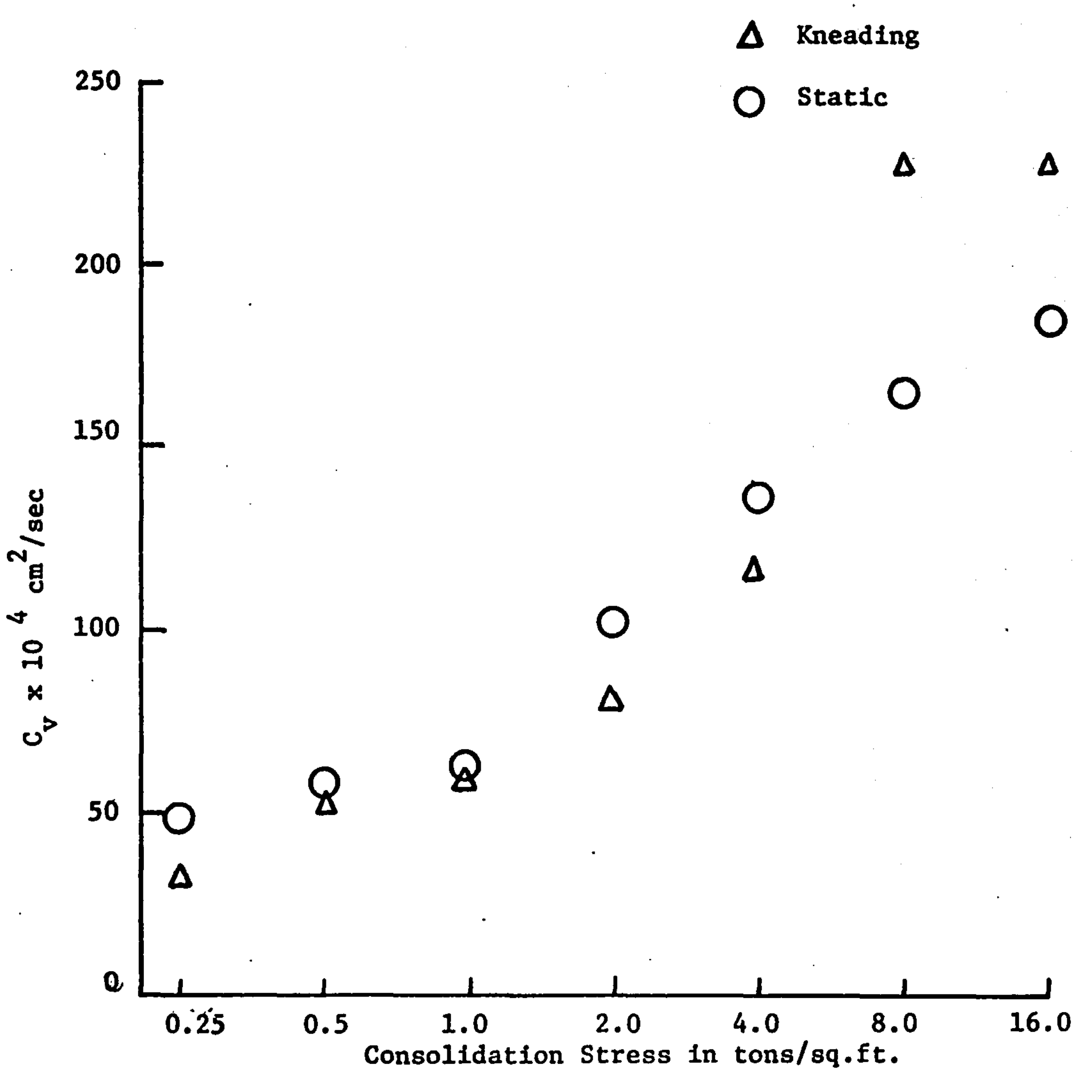


Figure 49 Coefficient of Consolidation versus the Consolidation Stress for the Samples K_4TV-16 and S_4TV-16

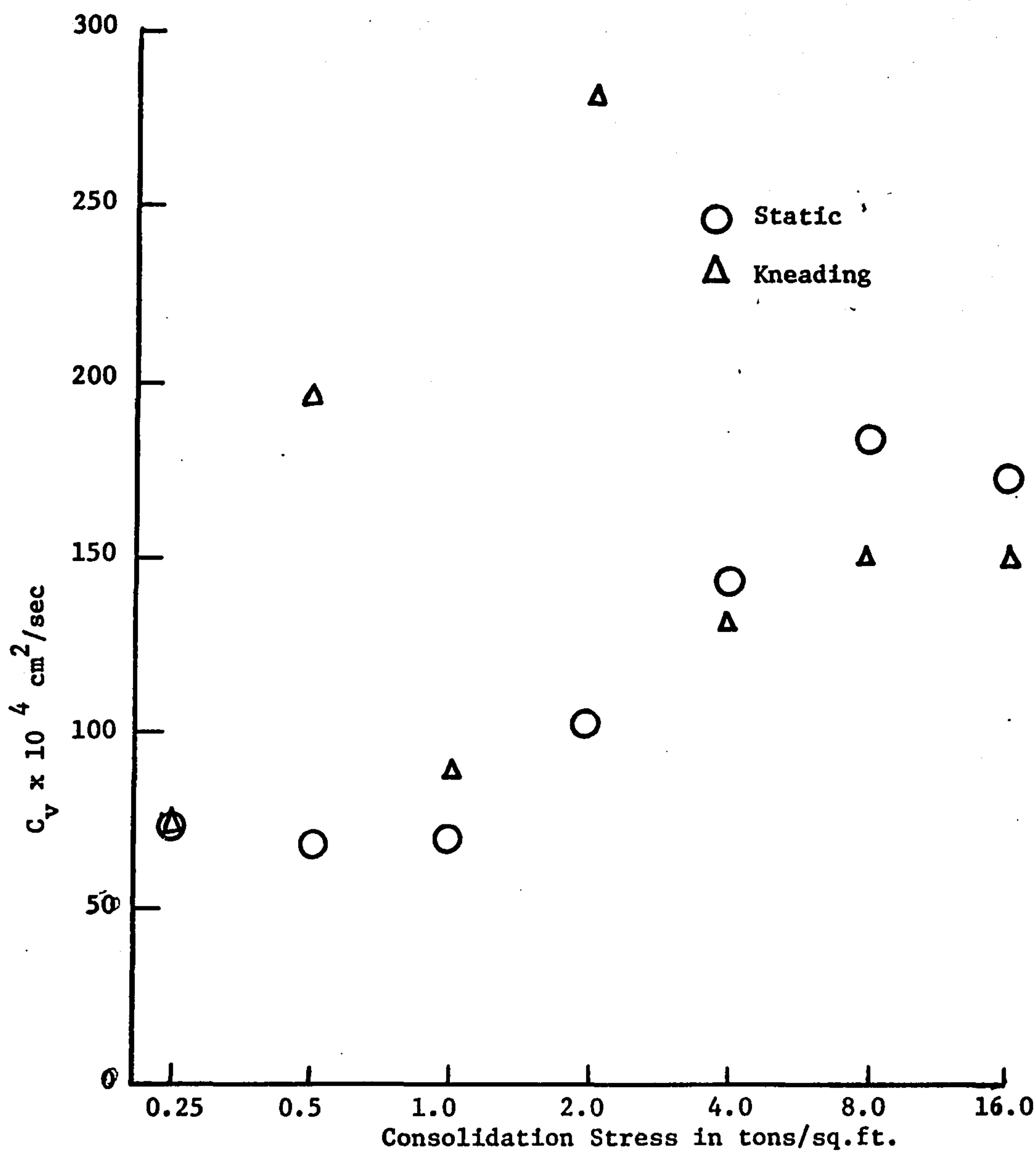


Figure 50 Coefficient of Consolidation versus the Consolidation Stress for the Samples K_7TV-16 and S_7TV-16

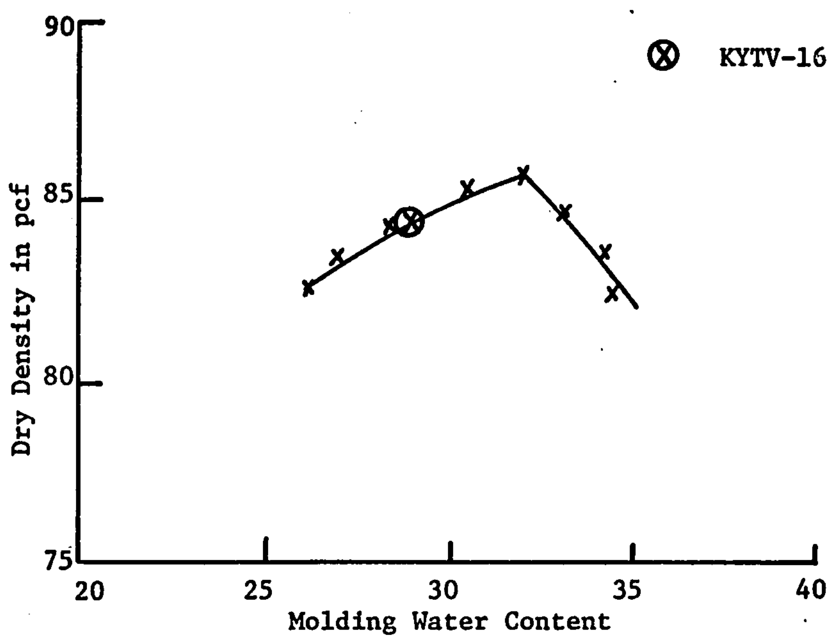


Figure 51 The Initial Trial Kneading Compaction Curve Showing the Position of the Sample LYTV-16

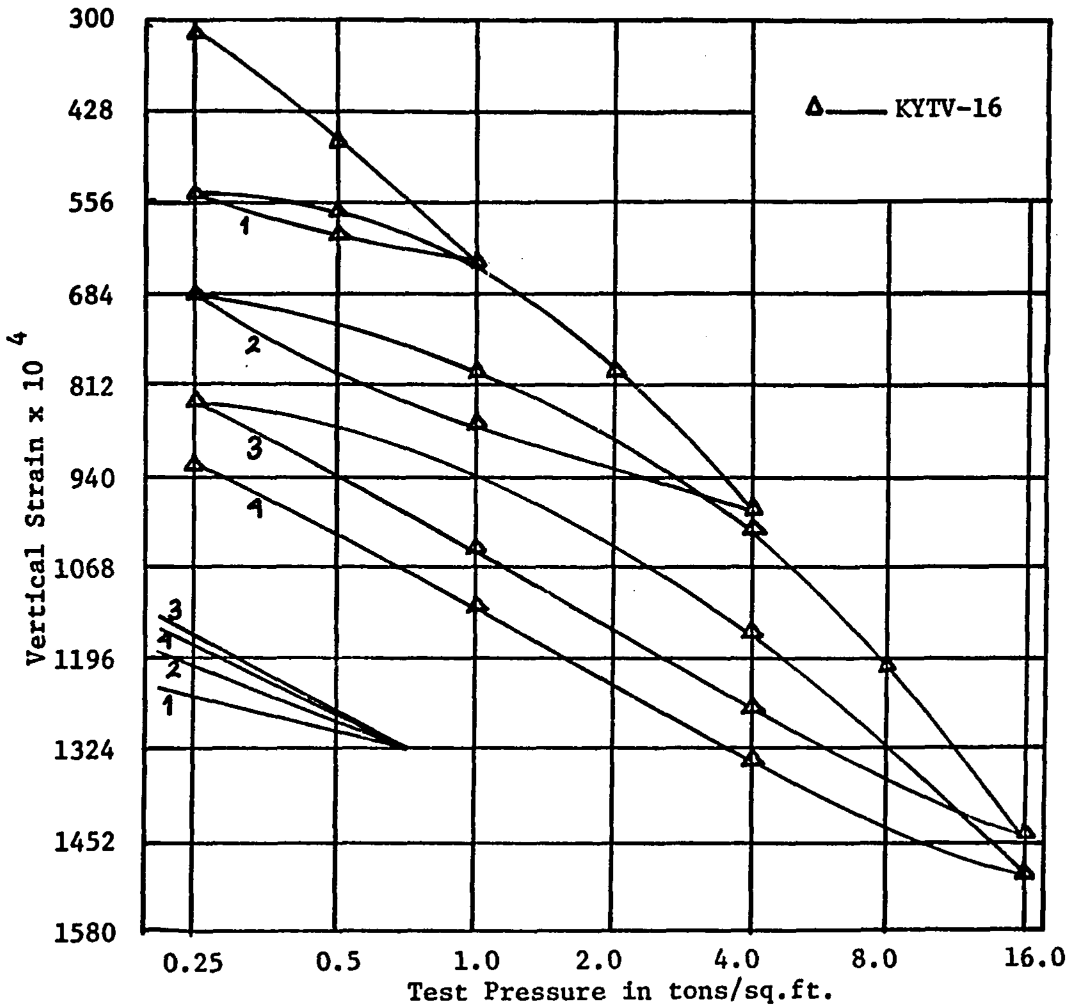


Figure 52 Cyclic Consolidation Curve of the Sample KYTV-16

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