INVESTIGATION OF THE CONSOLIDATION AND SHEAR STRENGTH CHARACTERISTICS OF TWO CLAY MINERALS

Thesis for the Degree of M. S.
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Murl Harry Webster
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This is to certify that the

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INVESTIGATION OF THE CONSOLIDATION AND
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OF TWO CLAY MINERALS

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MURL HARRY WEBSTER

has been accepted towards fulfillment
of the requirements for

MASTER OF SCIENCE degree in CIVIL ENGINEERING

Major professor

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INVESTIGATION OF THE CONSOLIDATION AND SHEAR STRENGTH CHARACTERISTICS OF TWO CLAY MINERALS

by

Murl Harry Webster

AN ABSTRACT

Submitted to the College of Engineering
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Civil and Sanitary Engineering

June 1959

Approved: ______________________

MURL HARRY WEBSTER ABSTRACT

This paper is concerned with the effect of the sodium and calcium ions on the consolidation, orientation, and shear strength of the clay minerals grundite and kaolinite.

Experiments were conducted with the clay minerals saturated with sodium or calcium ions. The clays were artifically sedimented and consolidated to various pressures. The shear strengths, consolidation characteristics, and orientation were then studied at these various pressures.

The optical studies showed that particle orientation is increased by consolidation. From the consolidation tests, it was found that the sodium clay showed a higher void ratio than the calcium clay at the same pressures.

The strength tests showed that the ions affect the shear strength. Sodium clays are found to have less strength than calcium clays.

The remolded strength of a soil is much less than the undisturbed strength. This may be explained by the high initial pore pressure in the remolded soil.

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LISTING OF SYMBOLS

A - electrical attractive force per unit area
a_v - coefficient of compressibility (1/gms.)
C - undisturbed shear strength (kg/cm^2)
C_{rem} - remolded shear strength (kg/cm^2)
c_v - coefficient of consolidation (cm^3/sec)
D - deviator stress (kg/cm^2)
dc - compression dial reading at zero time
d_{50} - compression dial reading at 50% primary compression
d_{100} - compression dial reading at 100% primary compression
e - void ratio
k - permeability (cm/sec)
LL - liquid limit
PI - plasticity index
PL - plastic limit
P_o - preconsolidation pressure (kg/cm^2)
qu - unconfined compression strength (kg/cm^2)
R - electrical repulsive force per unit area
u - porewater pressure (kg/cm^2)
w - water content %
σ - total normal stress (kg/cm^2)
$\bar{\sigma}$ - effective normal stress (kg/cm^2)
σ_1 - major principle stress (kg/cm^2)
σ_3 - minor principle stress (kg/cm^2)
τ - shear stress on a plane (kg/cm^2)
ϕe - true angle of internal friction (degrees)

I. DEVELOPMENT OF CURRENT KNOWLEDGE

Soil Structure

Soil structure is a property that has been recognized to be of importance for many years [Terzaghi 1925, Cassagrande 1932, and Hvorslev 1938 (6)*]. Originally the structure of a soil referred only to the arrangement of the particles. However, at present, when referring to a clay soil, structure encompasses the particle arrangement as well as the electrical forces acting between particles. Baver (1) states that both chemical and physical properties seem to be controlled by the surface activity of the soil particles.

Forces Acting Between Soil Particles

The forces between soil particles may be divided into three main groups; primary valence bonds, hydrogen bonds, and secondary valence bonds.

Primary valence bonds are defined as the forces that hold the atoms together in the basic mineral units. This group is further subdivided into three subgroups; ionic bonds, covalent bonds, and heterpolar bonds.

Another type of bond that can be classified as a primary bond is that of electrostatic attractions and

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*Numbers in parentheses are references listed at the end of this paper.

repulsions. Clay particles are negatively charged along their plates and may or may not be positively charged along the edges. Thus, if cations are present they will be attracted to the plate. These ions are called adsorbed ions or counterions. Water molecules will also be adsorbed by the clay particles. This happens because the water molecule is a dipole. The adsorption of water takes place in the presence of cations and the adsorbed water layer is affected by the presence of the ions.

Secondary valence bonds, also known as van der Waals forces, arise from electrical moments within the existing units. It should be noted that the net effect is attraction.

Since the clay particles have a net negative charge, the particles repel each other. Using the Gouy Chapman theory, an expression for the electrical repulsion can be written. However, the actual case is not so simple, as secondary valence forces also act. By combining repulsive and attractive forces chemists have developed expressions relating the potential and the net repulsion to the interparticle spacing. This information was published recently by Krutz,1952 and Bolt,1955(6).

The Gouy Chapman theory assumes that the charges are distributed evenly over the entire particle. If the charges on the edges are ignored the theory shows that flocculation with parallel orientation results if the attractive forces exceed the repulsive forces. However, not all flocculation will produce parallel orientation. This is because of the fact that often the edges carry a plus charge, thus tending to cause flocculation in an edge to plate array.

Volume Changes in the Soil

For volume changes to take place, a particle rearrangement must take place. If the soil is loaded and the rearrangement of the particles takes place, decreasing the volume, the rearrangement must have forced the particles into a more orderly array. When a volume decrease takes place due to compression as above, it is largely non-recoverable.

Consider now the hypothesis of equilibrium presented by Lambe (6). To maintain equilibrium the externally applied intergranular stress ($\bar{\sigma}$) plus the electrical attraction (A) must equal the electrostatic repulsion (R). Now if a pressure increase is applied ($\Delta\bar{\sigma}$), for equilibrium to be maintained the colloidal particles must move closer together with an increase in the net repulsion. Some water between the particle is forced out by this movement. Now examine the case when the load is removed from the mass. For equilibrium there must be an increase in the distance between particles to allow the net repulsive force to decrease by the amount ($\Delta\bar{\sigma}$). This type of volume increase is almost the sole contributor to the rebound of a soil, as was stated by Bolt (3).

Shear Strength

When considering the shear strength of a soil one usually recalls the Coulomb equation $S = C + \tan \phi$. It states that the strength is made up of two parts, cohesion and internal friction. When one examines the shear strength of a system of clay particles, one must consider the same forces that are discussed under "Volume Changes in the Soil," ($\bar{\sigma}$), (A) and (R). As was stated earlier for equilibrium ($\bar{\sigma} + A = R$) must exist.

According to Lambe (6), shear strength of a colloid is primarily determined by the electrical forces acting between particles; however, he also mentions four factors other than electrical that have some effect. They are respectively: (a) particle spacing, (b) orientation, (c) external loads ($\bar{\sigma}$), and (d) characteristics of the water system.

In natural clays a decrease in particle spacing increases the shear strength. This supports Leonards, 1955 (9) and Rutledge, 1948 (7), who state that the closer the particle spacing the denser the soil and the greater the shear strength.

Orientation of Clay Particles

Under the topic of strength was mentioned orientation of clay particles. Generally one associates a random type of orientation with flocculation. It is also possible to have parallel orientation in a flocculated material, depending upon the forces that are responsible for flocculation.

In 1956 Mitchell (10) published an extensive article on a study of the fabric of clays. This article showed that the improvement in orientation by remolding increases with increasing sensitivity of the clay.

Summary

The foregoing discussion indicates that the consolidation and shear strength characteristics are controlled to a very large extent by the physical chemical forces that act between the particles. The review also brought out the fact that outside of the fundamental laws on potential and repulsive forces between particles, little is known about these forces and their effects on consolidation and shear strength characteristics.

II. METHOD OF INVESTIGATION

Objective

The primary objective of this research was to attempt to evaluate the physical-chemical forces that are important to the mechanical properties of clays. The consolidation characteristics, the undisturbed and remolded shear strengths and their relationships with the adsorbed ion and with the particle orientation were studied. Two minerals, kaolinite and grundite, and two ions sodium and calcium, were chosen. Consolidation studies were made on laboratory sedimented clays. The shear strengths were measured by the unconfined compression test and the triaxial test, performed on clays preconsolidated to various pressures. From this data the ratio of the shear strength to the preconsolidation pressure, $^{C}/P_{o}$ was computed. The orientation of the clay particles were studied by examination of thin sections with a petrographic microscope.

Soil Studied

This study used two clay minerals, kaolinite and grundite. The grundite is a mineral of the illite family, which has a general formula

$(OH)_4 K_y (Si_{8-y} \cdot Al) (Al_4 \cdot Fe_4 \cdot Mg_4 \cdot Mg_6) O_{20}$ (4).

The grundite has a slightly more expanding structure than the Fithian illite. Illite being a general term proposed by Grim, et al. (4) in 1937 for a mica like clay commonly found in the state of Illinois.

The grain size characteristics of the clays are shown in Figure 1. Table 1 is a tabulation of the Atterberg Limits of the clays studied.

Preparation of the Clay Minerals

The general procedure used in the preparation of both clay minerals was identical. First the clay was put into suspension with a standard Waring blender. Approximately 100 grams of soil was mixed with 1 liter of distilled water. After the suspended soil had flocculated, the clear water on top of the soil was poured off. Next the container, a 3 liter beaker, was filled with 1 normal HCl. The clay was vigorously stirred until all clay was in suspension. Again the clay was allowed to flocculate and the liquid poured off. This procedure was repeated until no green color was observed in the liquid above the soil. At this point all the exchangeable ions had been replaced with hydrogen ions. The HCl washes were discontinued, and the clay was washed with distilled water approximately five times. After completion of the washings, the clay was poured onto a number fifty filter paper in an 18.5 centimeter Buchner funnel. The Buchner funnels were supported by 4 liter vacuum flasks which were evacuated by a vacuum pump. Enough clay was poured on the filter paper to form a pat approximately one-eighth of an inch thick. During this phase a continual wash of distilled water was run through the clay until no chlorine ions could be detected in the wash water. The silver nitrate test was used to detect chlorine ions.

After completion of the washing the clays were titrated with a base until pH7 was maintained. This usually required 7 to 10 days. The two bases used were sodium hydroxide [NaOH] and calcium hydroxide [$Ca(OH)_2$]. The titration produced clays saturated with Na and Ca ions. In the remainder of this paper the clays will be referred to as sodium kaolinite, calcium kaolinite, sodium grundite or calcium grundite.

Consolidation Tests

The clay was mixed into a dilute suspension ($w = 800\%$ to 1200%) and placed in a modified consolidometer fitted with a tall lucite standpipe. In a matter of about 24 hours the clay had flocculated to allow clear water to be decanted off the top and the standpipes refilled. This was repeated until 6 to 8 inches of flocculated material had accumulated at the bottom of the standpipe. After 72 hours a porous stone was lowered to the top of the clay. At this point standard consolidation loading was started. The first load was 0.04 kg/cm^2.

The sodium grundite when mixed in a dilute suspension remained dispersed so it was treated slightly differently.

Instead of mixing the clay into a dilute suspension it was mixed into a thin paste ($w = 400\%$ to 600%) and placed in the apparatus. The procedure followed henceforth was identical to the procedure just described.

For all consolidation tests a complete record of time-consolidation readings was kept. A plot of a typical time-consolidation curve is shown in Figure 2.

Study of Optical Properties

The fabric of the clays was studied in various states of consolidation. The unconsolidated clay was allowed to flocculate in small glass jars ($P_o = 0$). To impregnate the clay the porewater was displaced by a 1:3 solution of carbowax and water. The flocculated soil was kept in this dilute carbowax solution for about a week at a temperature of 65°C. Then the water was allowed to evaporate and after another week the specimen was removed from the oven and the carbowax allowed to solidify.

The study also includes consolidated clays. One specimen being preconsolidated to 1 kilogram per square centimeter ($P_o = 1$ kg/cm^2), and the other preconsolidated to 40 kilograms per square centimeter ($P_o = 40$ kg/cm^2). The impregnation of the consolidated clays for thin sections was identical with that described by Mitchell, 1956 (11). A piece of the clay was placed in a bottle containing liquid carbowax and placed in an oven at 65°C for a period of two weeks. At the end of this time the carbowax had replaced all of the porewater in the clay. Following this the bottles were removed from the oven, allowing the carbowax to solidify. When cooled, the clay was ready to be sliced into thin sections.

The thin sections were prepared by Mr. George Rev of Columbia University.

Optical Studies

The thin sections were studied under the petrographic microscope. Using a vertical section of a clay with parallel orientation, four alternate stages of illumination and extinction could be observed when placed between crossed nicol prisms. (Light passed through crossed nicols vibrates in two planes only.) The horizontal sections showed no illumination because the a_1 and a_2 axes lie in all directions. (See Figure 3.) In a vertical section, random oriented particles show no illumination or extinction as none of the axes of the individual particles are oriented in a particular direction.

The method used by Wu (14) to measure the degree of orientation is as follows: the light transmitted at both extinction and illumination is measured by the use of a photo tube attached to the petrographic microscope eyepiece. Then the ratio of the light at illumination to that at extinction is designated as the orientation factor.

Strength Tests

Unconfined compression tests.

The clays were consolidated to a certain pressure, extracted from the consolidometer and specimens one inch square and two inches long were trimmed from the cake. Both the undisturbed and remolded clays were tested using approximately 2% strain per minute.

Drained triaxial tests. For the determination of the true angle of internal friction the drained triaxial test was used. The specimen of remolded soil was placed into the rubber membrane supported by the membrane jacket. A specimen one inch in diameter and three inches in length was obtained. Two sets of three samples each were used. One set had an initial water content of 71% and the second set an initial water content of 61%. The chamber pressures used were 0.25 kg/cm^2, 0.50 kg/cm^2, 1.0 kg/cm^2, 1.50 kg/cm^2, and 4.0 kg/cm^2.

Consolidated quick triaxial tests. The procedure for preparation of the undisturbed specimens for the consolidated quick test was similar to that used in the consolidation tests. In this case standpipes with a 4 inch inside diameter were used. The specimens were consolidated to 4.0 kg/cm^2 before being trimmed for the test. A standard triaxial cell modified for pore-pressure measurements (Figure 4) was used.

Quick triaxial tests. Preparation of the undisturbed specimen used in the triaxial quick test was identical to the procedure followed for the consolidated quick triaxial test.

III. RESULTS

Consolidation Tests

Pressure-void ratio curves obtained from the consolidation tests are presented in Figures 5, 6, and 7. It will be seen that the adsorbed ions, exerts an effect on the pressure-void ratio curves. At a given void ratio the curves for both the sodium grundite and sodium kaolinite show higher pressures than their calcium counterparts. This means that the net repulsive forces between particles is greater in the sodium clays than it is in the calcium clays. This is in agreement with the results of theoretical calculations by Bolt (3).

When the two minerals are compared one finds that the void ratio of the grundites is always greater than that of the kaolinites.

One may also consider the activity of the minerals. Activity is defined as the plasticity index divided by the per cent finer than 2 microns. Referring to Table 1, one sees that the grundite is more active than the kaolinite. The activity of a mineral is indicative of the net charge of the clay particles and the magnitude of the surface forces. Thus, it can be concluded that the activity of the mineral reflects accurately the consolidation characteristics of the clay mineral.

Figure 2 is a representative time-consolidation curve and illustrates the calculation of the coefficient of consolidation and permeability by the Logarithmic method. The relationship between the permeability and void ratio for the four soils are plotted in Figures 8 and 9.

Optical Studies

The orientation of the soils as measured through the petrographic microscope is given in Table 2. The optical studies indicate a definite trend for the orientation ratio to increase with increased consolidation pressure. This is reasonable and is expected because the clay particles are forced closer together and are slightly rearranged during consolidation. Average values are given in the tables. The kaolinites exhibit a considerable range in orientation. The calcium kaolinites, at $P_o = 1$ kg/cm^2, has a range from 1.5 to 2.2, while at $P_o = 40$ kg/cm^2 the range is from 1.4 to 2.0. As can be seen from this data the orientation is initially improved but after consolidation to 1 kg/cm^2 little improvement can be expected. The range in measured orientation for the two grundites is very small and the average values in the table are representative of a fairly uniform condition throughout the specimens. Figures 10 and 11 show photomicrographs of the thin sections at both illumination and extinction.

Strength Tests

Unconfined compression tests. Tables 4 and 5 give the results of the unconfined compression tests on undisturbed and remolded soils. One can see that the adsorbed ion effects the $^{C}/P_{o}$ ratio considerably less than does the mineral itself. Again it can be concluded that the clay mineral has a much greater effect upon the characteristics of the soil than do the exchangeable ions. Figure 12 shows typical unconfined compression stress-strain curves for both undisturbed and remolded soils.

Drained triaxial tests. The drained triaxial tests were performed on remolded sodium kaolinite. From the results obtained, the true angle of internal friction was determined. In Figure 13 is plotted the water content at failure vs. the chamber pressure σ_3 . Directly below this Mohr's envelops are drawn. The graphical construction to compute ϕ_e is also shown in the figure. The value of ϕ_e is found to be 15 degrees.

Consolidated quick triaxial tests. Consolidated quick triaxial tests were performed on laboratory sedimented and consolidated specimens of sodium kaolinite. The stress-strain and porewater pressure-strain curves are shown in Figures 14 to 17. From the test results the effective normal stress and the shear stress on the failure plane were computed and are plotted in Figure 18. The true cohesion of the soil ranged from 0.03 kg/cm^2 to 0.10 kg/cm^2.

Quick triaxial tests. Triaxial quick tests with porewater pressure measurements were performed on the sodium kaolinite. An undisturbed specimen preconsolidated to 4.0 kg/cm^2 was tested. After this the specimen was remolded and tested again. The stress and porewater pressure vs strain curves are shown in Figure 19. One sees that the pore pressure in the undisturbed test is about equal to the chamber pressure. This is expected of a saturated clay when placed in a triaxial cell. As the deviator stress is increased, the pore pressure decreased slightly. This may be due to movement of soil particles along the failure plane causing a slight expansion of the structure.

In the remolded specimen an initial porewater pressure of 0.03 kg/cm^2 at zero chamber pressure was measured. When the chamber pressure of 0.50 kg/cm^2 was applied the pore pressure increased by an amount equal to the chamber pressure. Thus it is evident (refer to Figure 18) that the effective stress $\bar{\sigma}_n$ is negative. If Figure 18 is referred to one sees that the remolded test falls mostly in the second quadrant. The failure point plots in the first quadrant with τ equal to 0.033 kg/cm^2. This indicates that the remolding of the soil destroys the structure such that an initial porewater pressure is set up. It can be concluded that the remolded strength of a soil is low because no internal friction is active.

IV. SUMMARY OF RESULTS

Consolidation of the Soils

From the information gathered on the consolidation of the soils certain general conclusions may be drawn. In Figures 8 and 9 and Table 3 the permeability vs. void ratio relationships are given. The data from the grundite shows that the permeability of the sodium clay is always smaller than that of the calcium clay. This is also true of the kaolinites when the void ratios are less than 1.3. However, as the void ratios increase the reverse takes place. The small difference can be explained by the fact that the kaolinite has so small an ion exchange capacity that the material does not adsorb many ions. Therefore, the small number of ions have little effect on the permeability. The reason the sodium clay has the smaller permeability can be explained by the fact that it is more active than the calcium clay. The double layer that contains the adsorbed ions and adsorbed water has a greater thickness in the sodium clay. Since the adsorbed water is immobile, its greater thickness reduces the void space open to flow of water. When the clay thus surrounds itself with this thick water layer its permeability is consequently reduced.

It is interesting to note the general relationship of the permeability to the PI. From Tables 1 and 3 one sees that the sodium clay has higher PI values than the calcium clay; the permeabilities of the sodium clays are lower than the calcium clays.

Orientation of Clays

In Table 2 are given the orientation factors for the calcium kaolinite and grundite. These results show that in general consolidation increases orientation of the clay particles. However, the kaolinite seems to reach an optimum orientation at a preconsolidation pressure of 1 kg/cm^2.

Shear Strength of Clays

In Figure 20 the shear strengths measured by the unconfined compression test are plotted against the water content of the specimens. It shows that at equal water contents the calcium clays possess greater strength than the sodium clays. Also the grundites have a greater strength than the kaolinites. If the influence of the adsorbed ions are considered one finds that the sodium clays with the thicker double layer has less strength. From this one may conclude that the shear strength does not depend upon the thickness of the adsorbed water. Furthermore the shear strength is controlled by factors other than those that control the permeability and consolidation characteristics.

An interesting point can be seen from the quick triaxial test data presented in Figure 19. From this data a possible explanation as to the reason for the low remolded strengths can be presented. It was found that the remolded soil had such a high porewater pressure that the effective normal stress on the failure plane was negative for the greater portion of the test. At failure the $\bar{\sigma}_n$ was positive, but the strength developed approximated the true cohesion value for the clay. Thus the conclusion is that a remolded soil only develops the cohesive component of the shear strength.

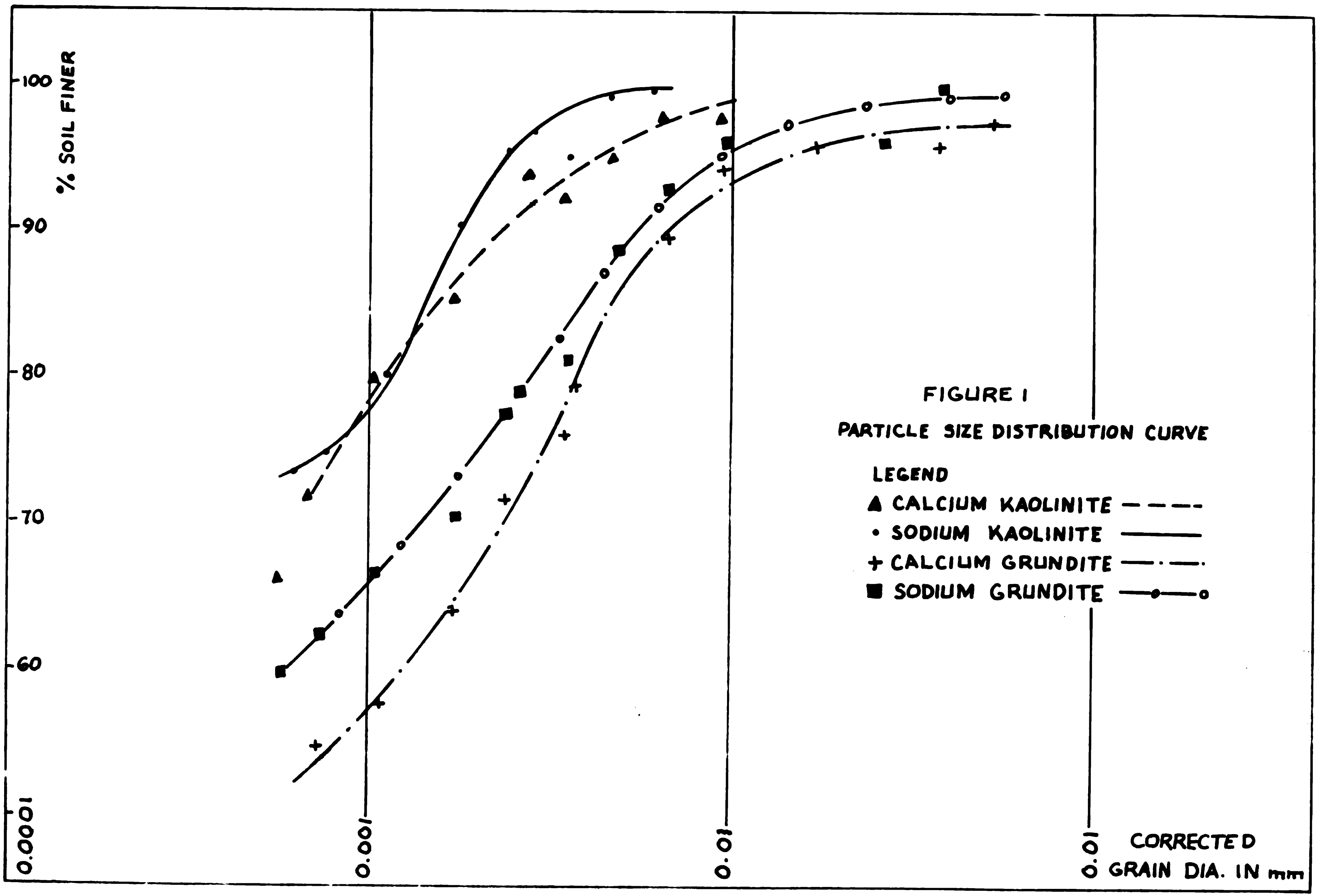
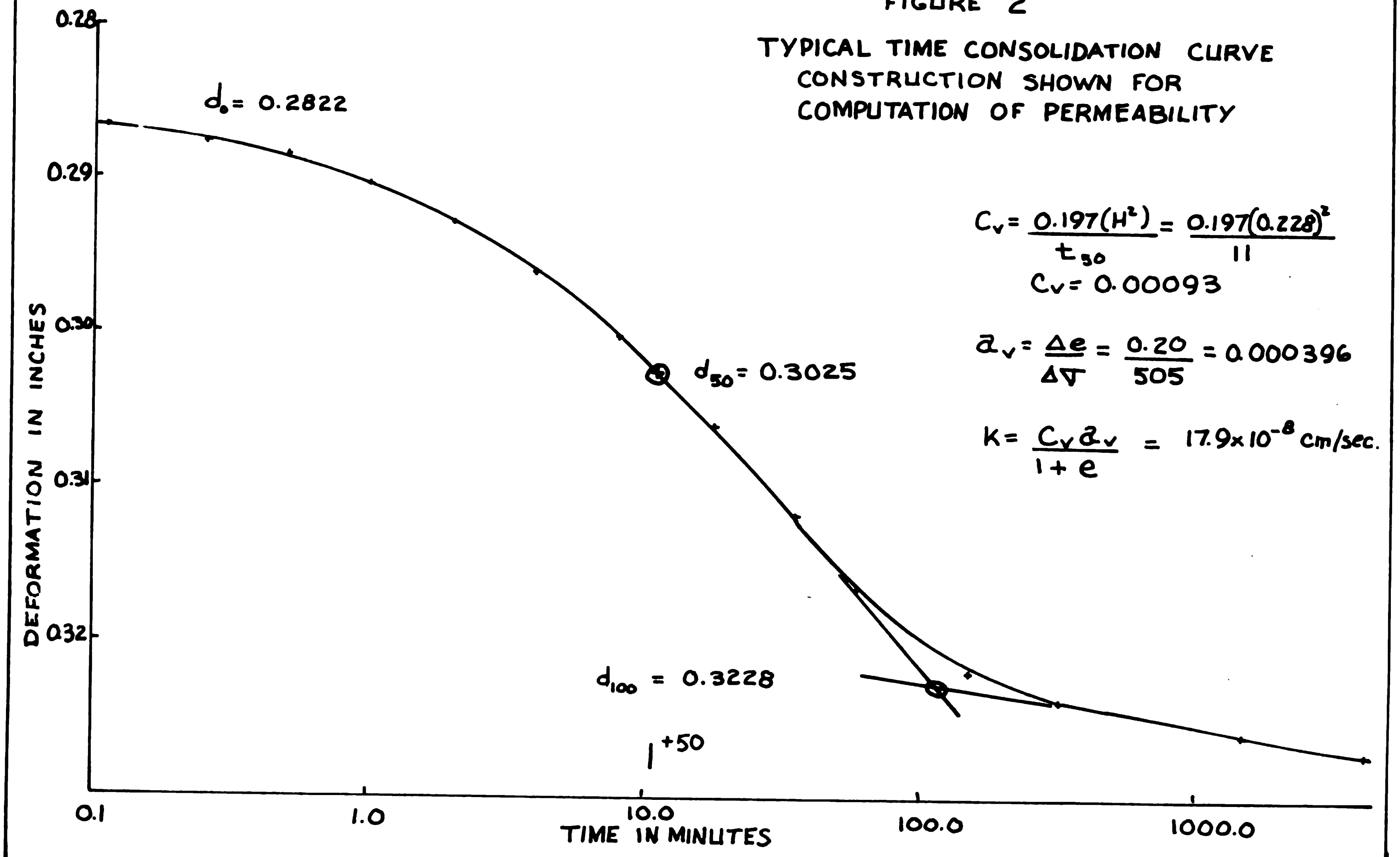


FIGURE I

PARTICLE SIZE DISTRIBUTION CURVE

FIGURE 2

TYPICAL TIME CONSOLIDATION CURVE
CONSTRUCTION SHOWN FOR
COMPUTATION OF PERMEABILITY

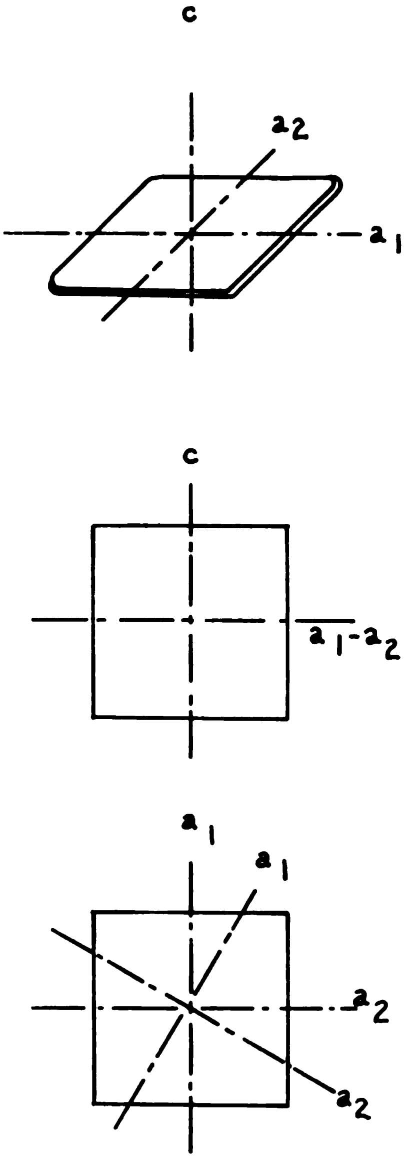


$$C_v = \frac{0.197(H^2)}{t_{50}} = \frac{0.197(0.228)^2}{11}$$

$$C_v = 0.00093$$

$$a_v = \frac{\Delta e}{\Delta \nabla} = \frac{0.20}{505} = 0.000396$$

$$K = \frac{C_v a_v}{1+e} = 17.9 \times 10^{-8} \text{ cm/sec.}$$



a. Optical axes of a clay mineral

b. Optical axes of a vertical section through a mass of oriented particles

c. Optical axes of a horizontal section through a mass of oriented particles

FIGURE 3

Optical Axes of Clays

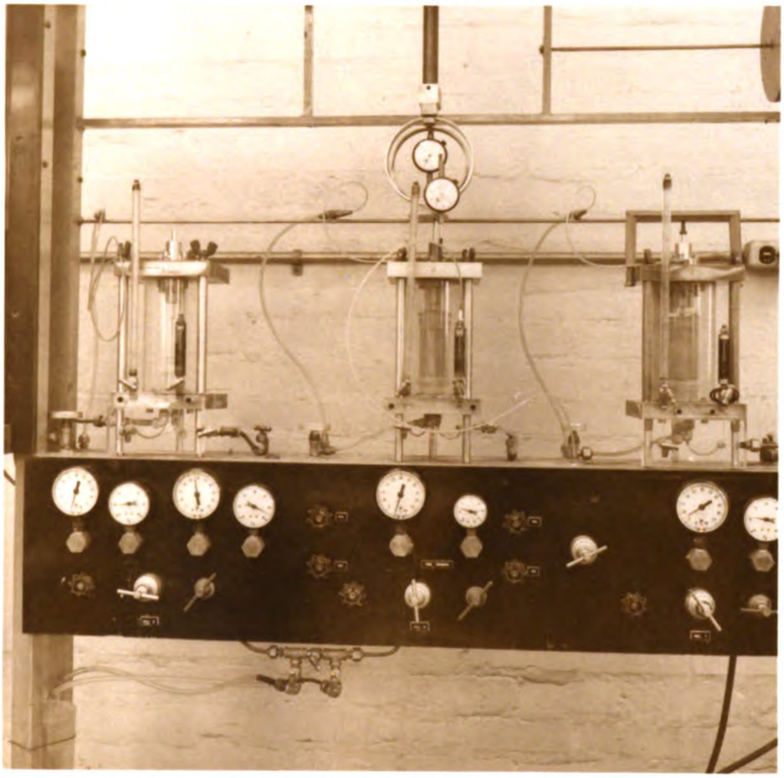
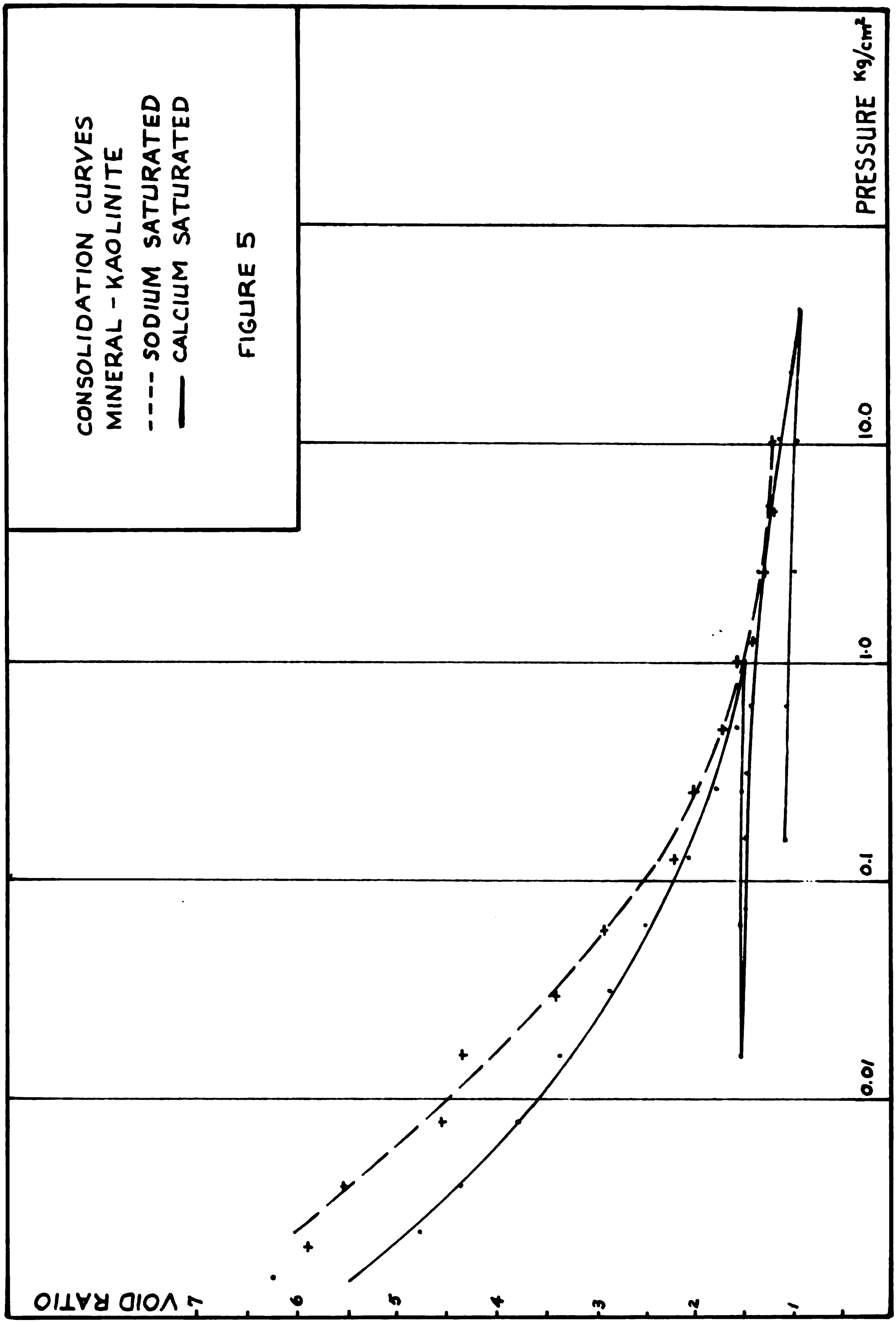
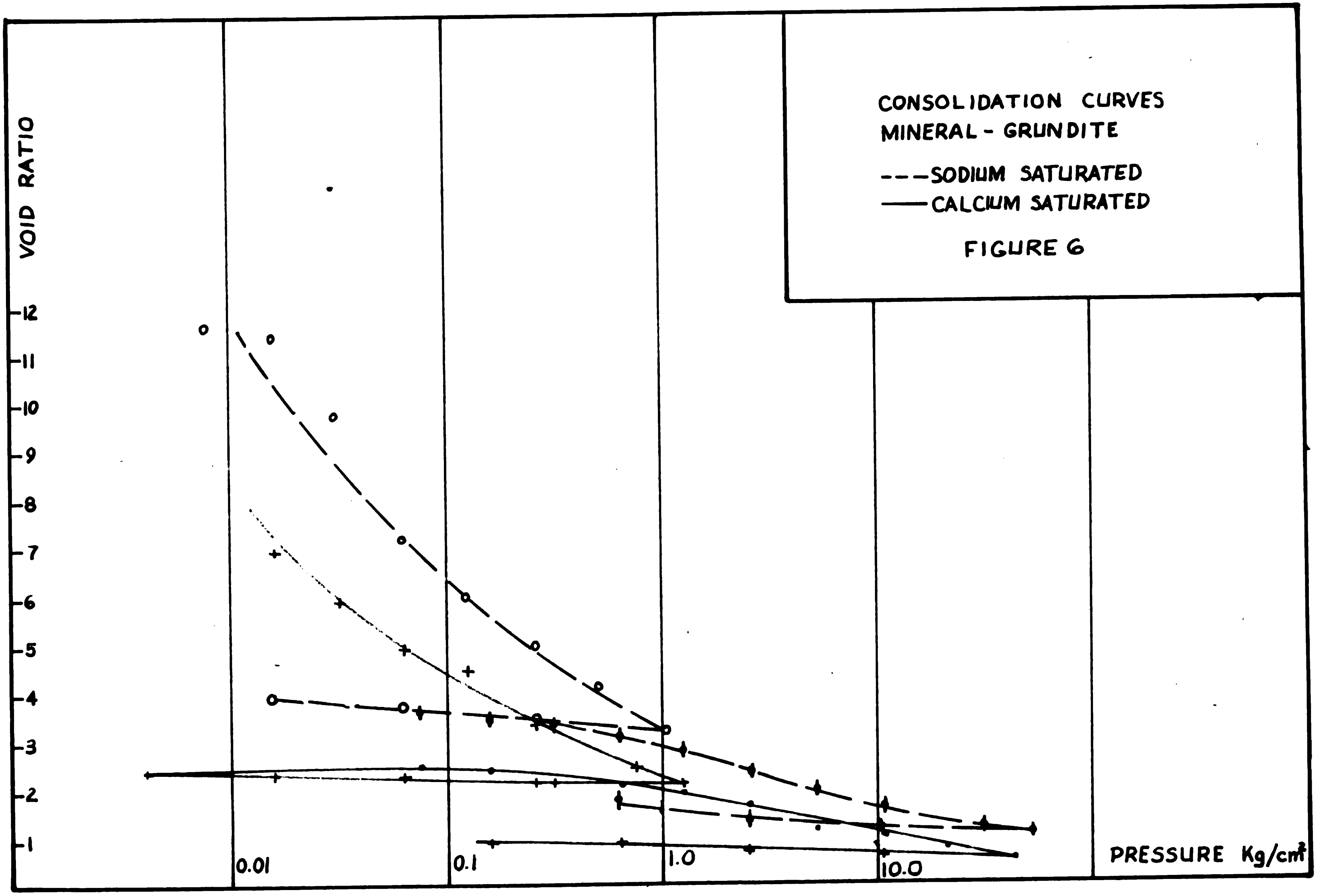


FIGURE 4
TRIAXIAL CELL



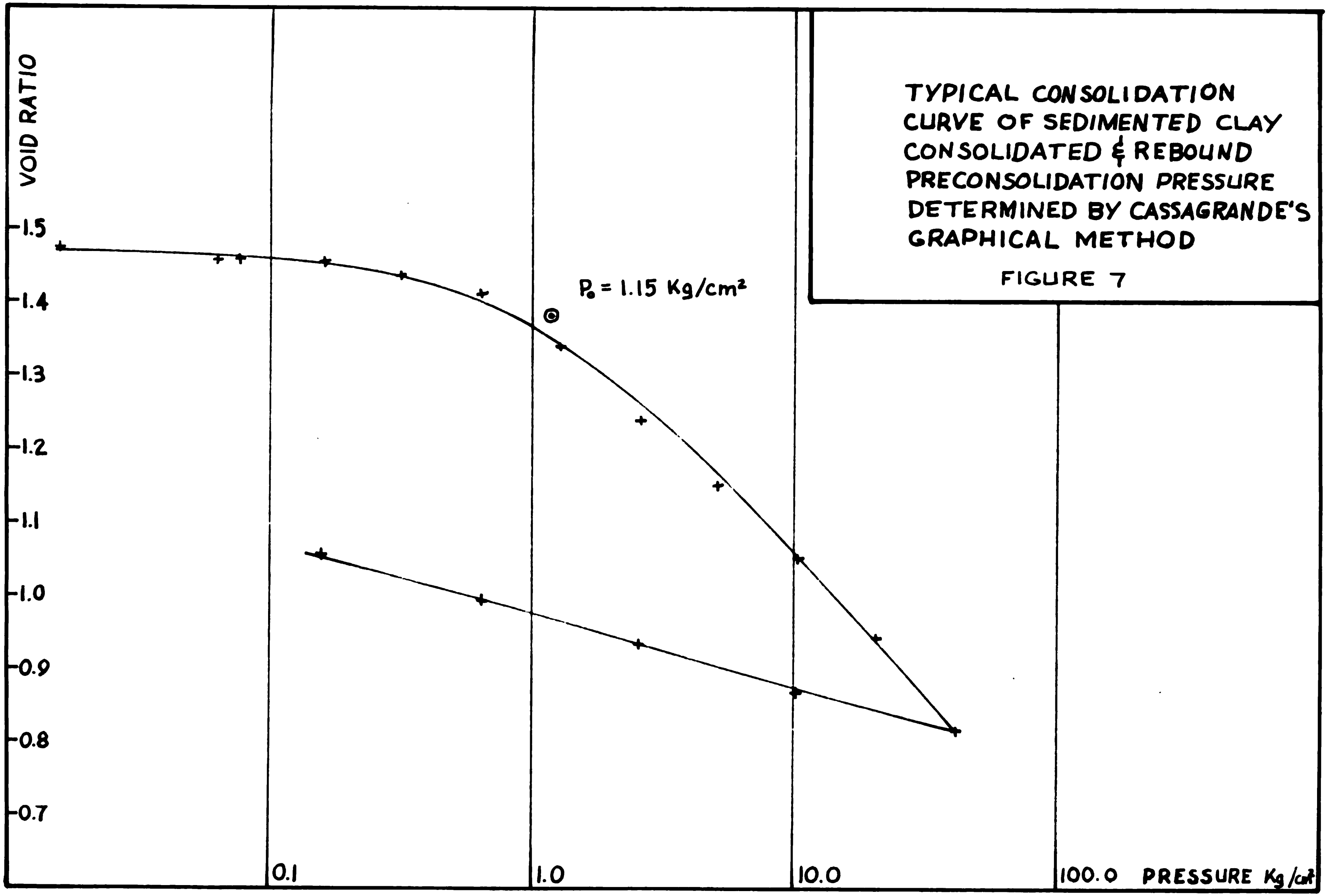
CONSOLIDATION CURVES
MINERAL - KAOLINITE
---- SODIUM SATURATED
— CALCIUM SATURATED

FIGURE 5



CONSOLIDATION CURVES
MINERAL - GRUNDITE

FIGURE 6



TYPICAL CONSOLIDATION
CURVE OF SEDIMENTED CLAY
CONSOLIDATED & REBOUND
PRECONSOLIDATION PRESSURE
DETERMINED BY CASSAGRANDE'S
GRAPHICAL METHOD

FIGURE 7

FIGURE 8
VOID RATIO VS PERMEABILITY
KAOLINITE

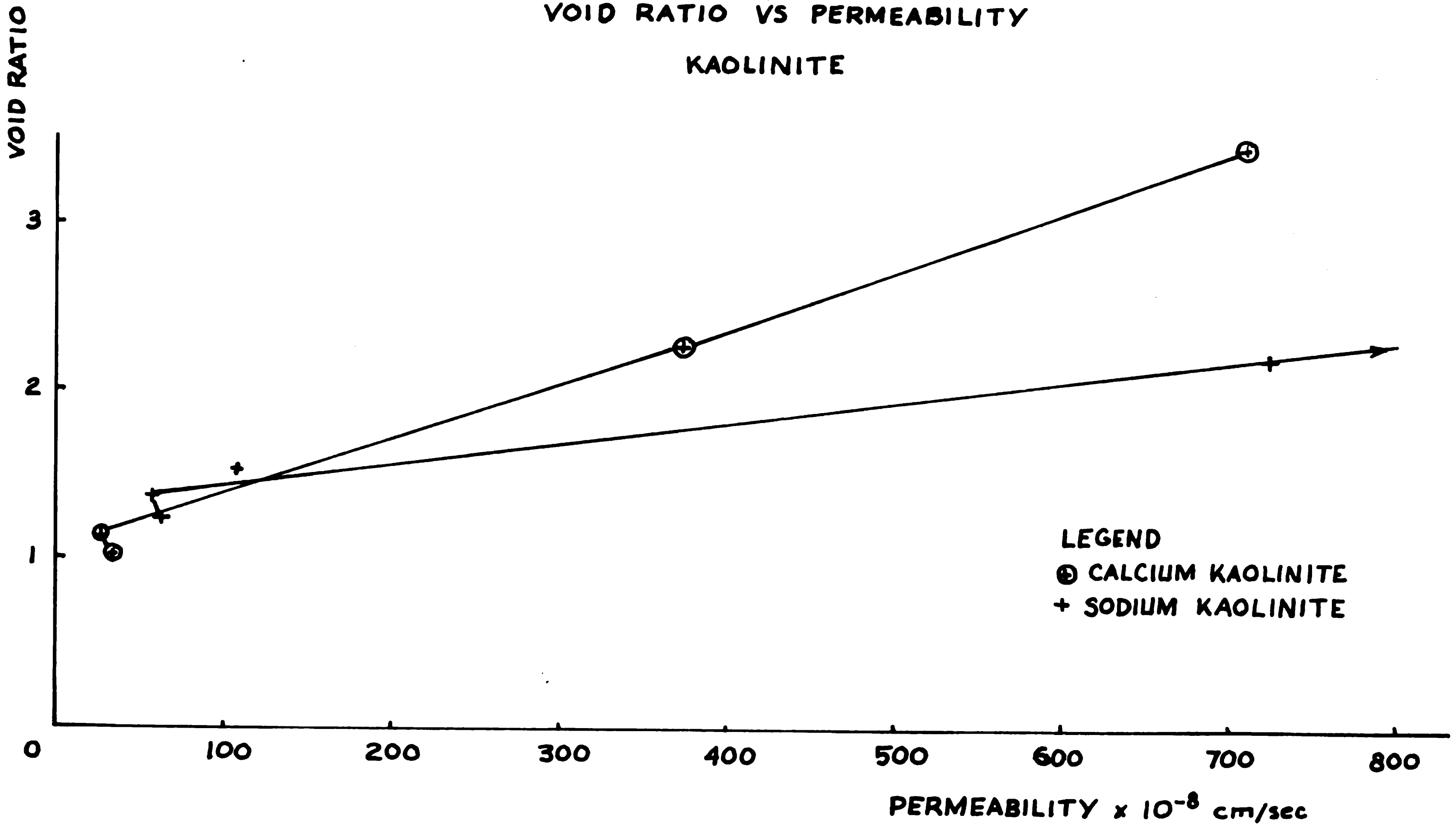
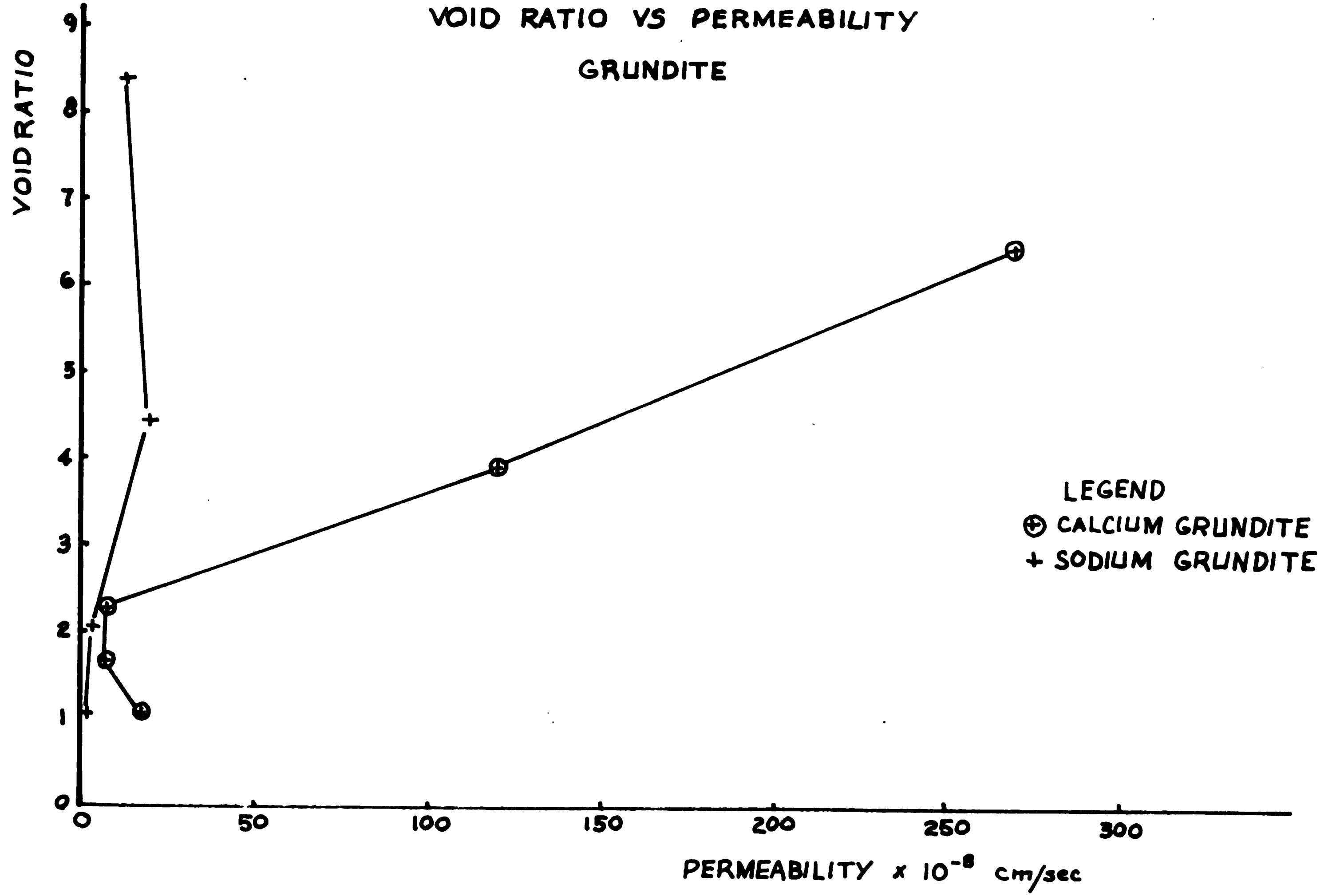


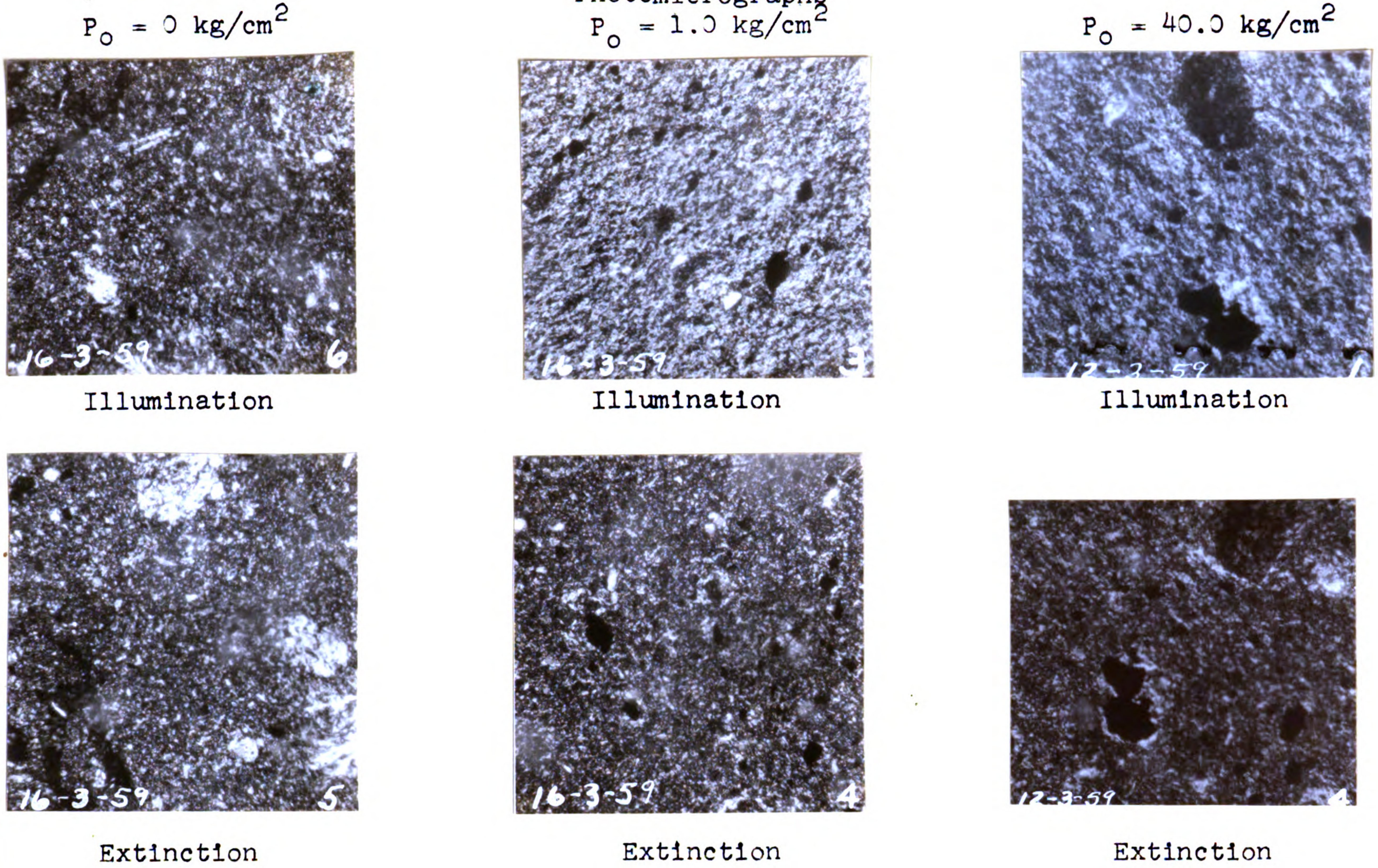
FIGURE 9

VOID RATIO VS PERMEABILITY

GRUNDITE



Calcium Grundite
Photomicrographs



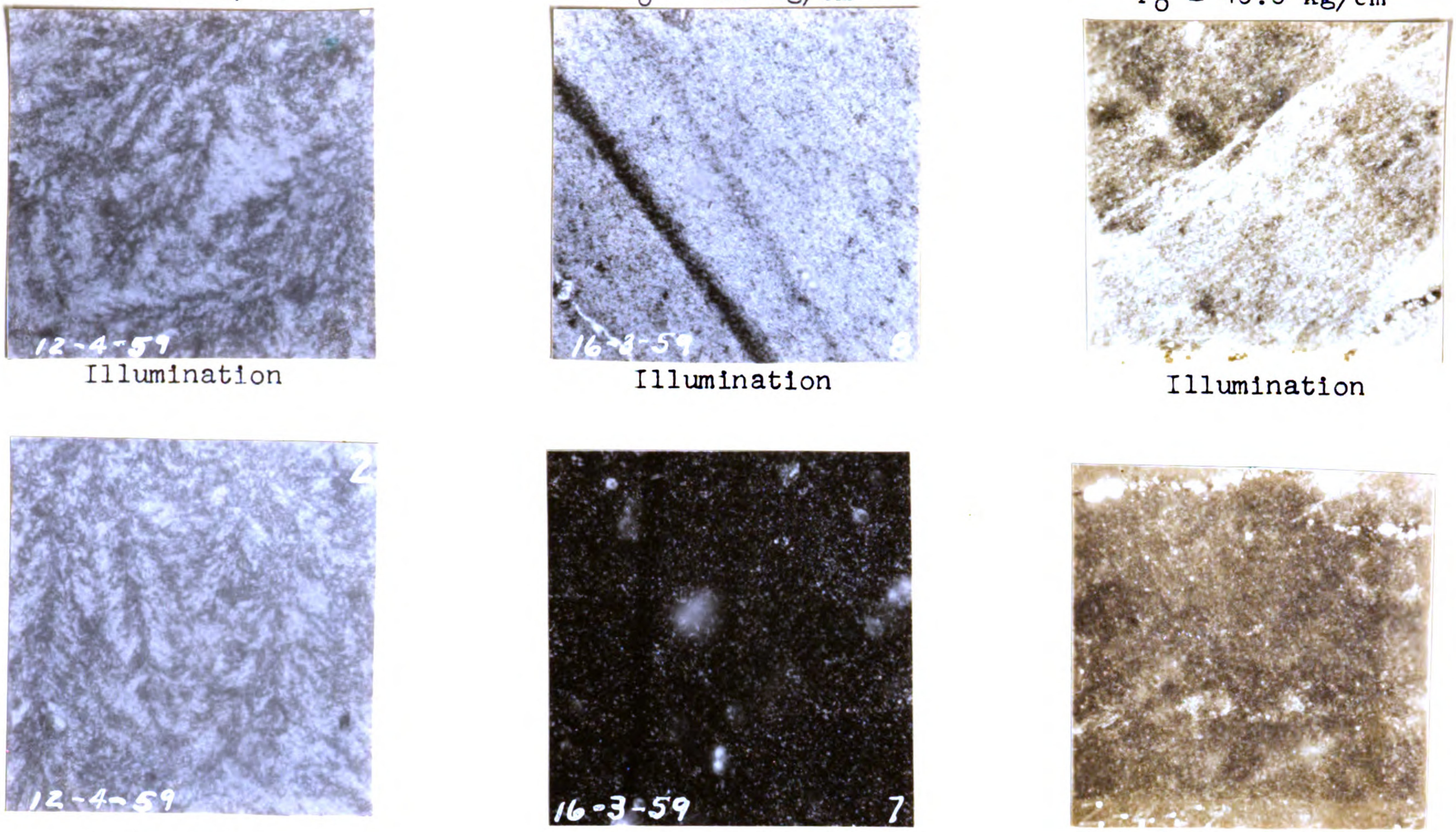
$P_o = 0$ kg/cm^2 — Illumination; Extinction

$P_o = 1.0$ kg/cm^2 — Illumination; Extinction

$P_o = 40.0$ kg/cm^2 — Illumination; Extinction

Figure 10

Calcium Kaolinite
Photomicrographs



$P_o = 0$ kg/cm^2 — Illumination, Extinction

$P_o = 1.0$ kg/cm^2 — Illumination, Extinction

$P_o = 40.0$ kg/cm^2 — Illumination, Extinction

Figure 11

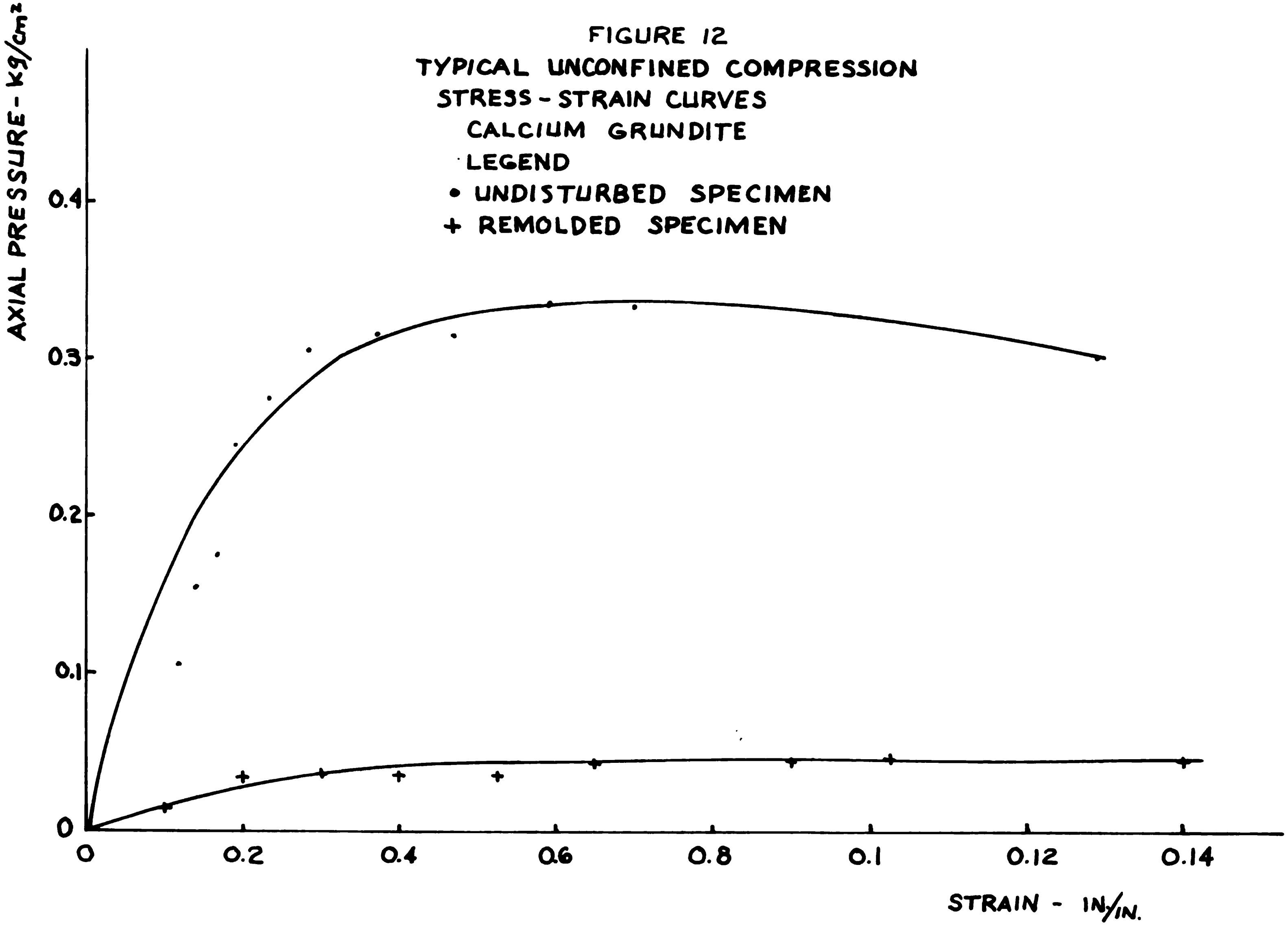


FIGURE 12
TYPICAL UNCONFINED COMPRESSION
STRESS - STRAIN CURVES
CALCIUM GRUNDITE

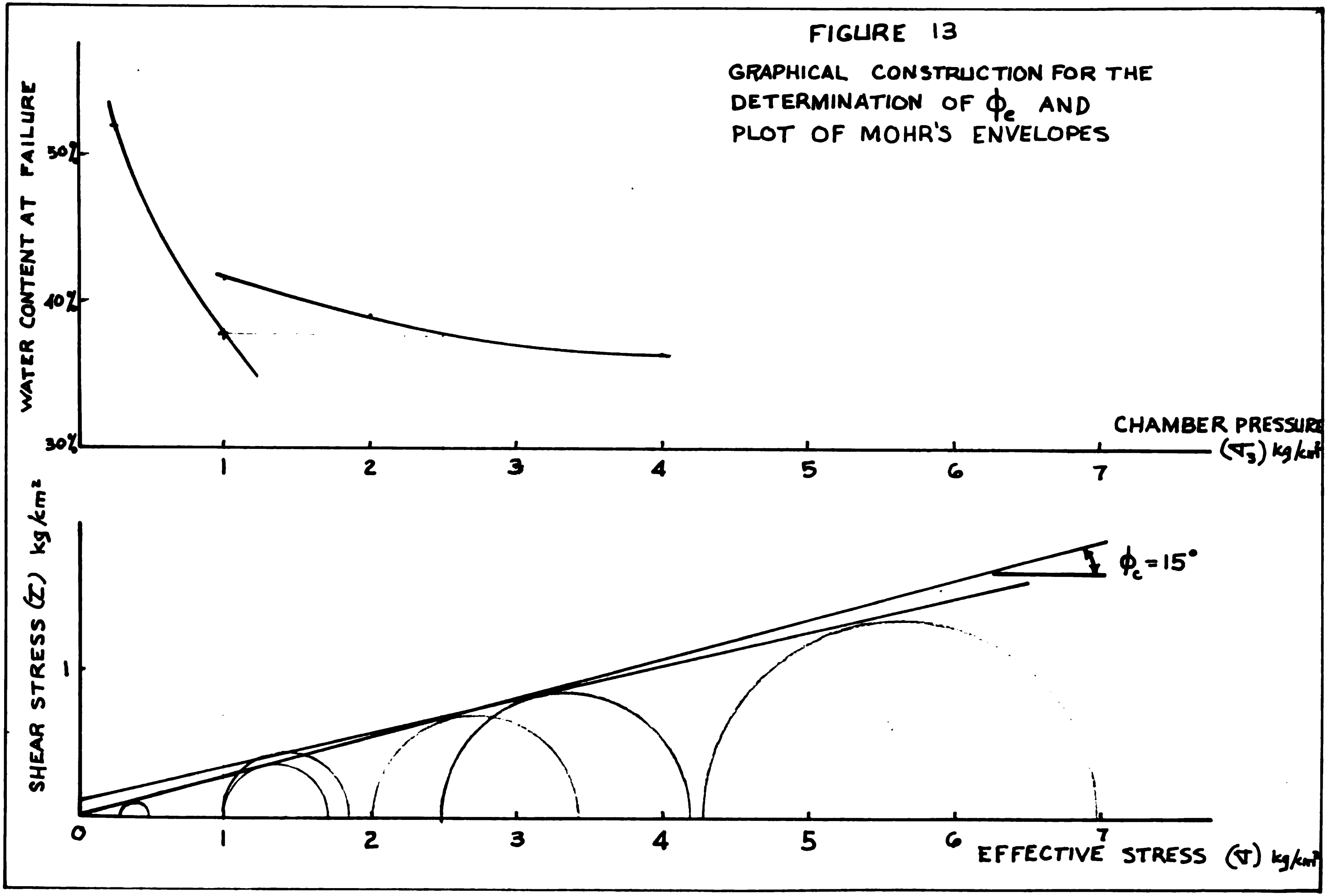


FIGURE 13

GRAPHICAL CONSTRUCTION FOR THE DETERMINATION OF ϕ_e AND PLOT OF MOHR'S ENVELOPES

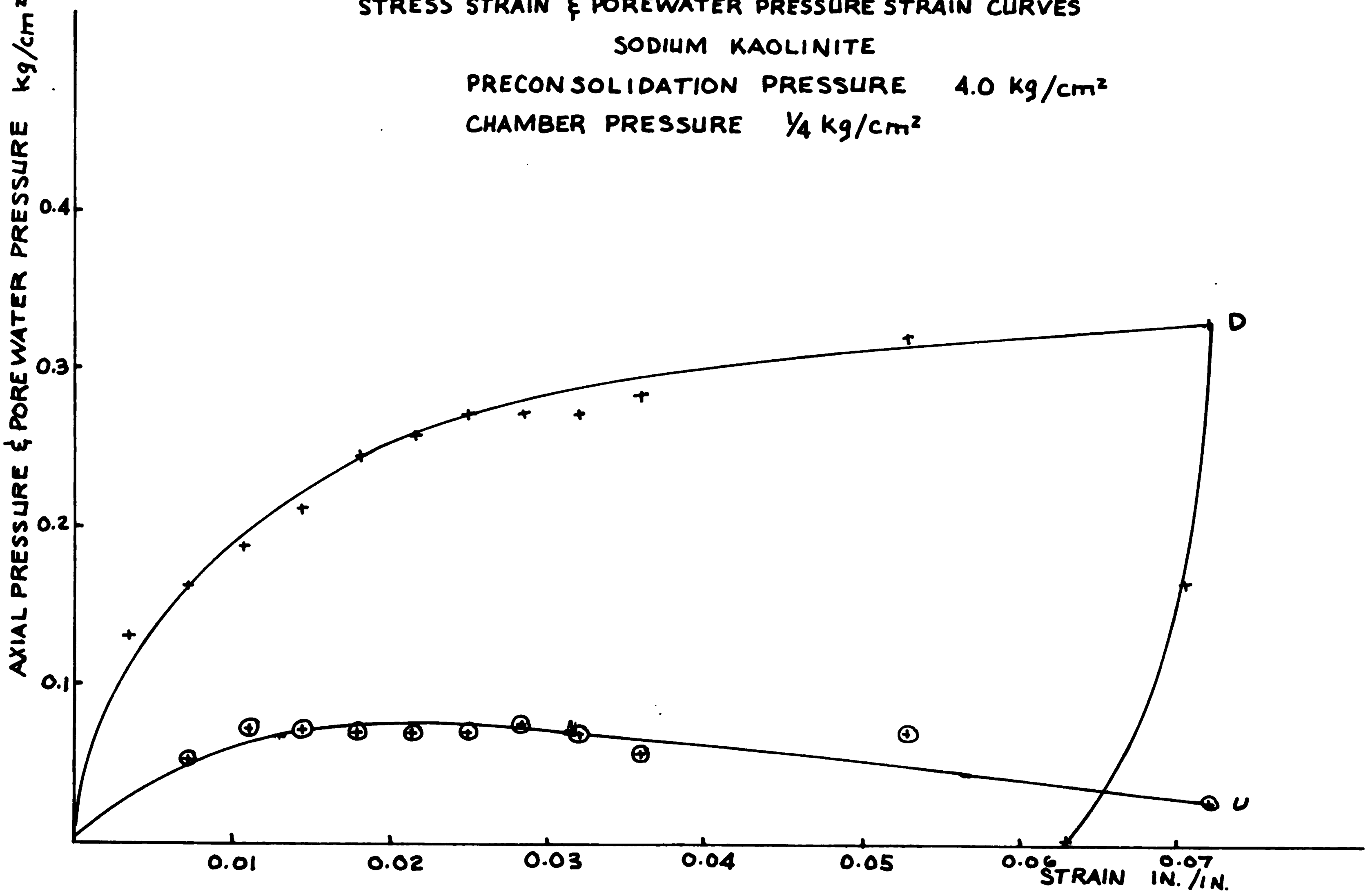
FIGURE 14

STRESS STRAIN & POREWATER PRESSURE STRAIN CURVES

SODIUM KAOLINITE

PRECONSOLIDATION PRESSURE 4.0 kg/cm²

CHAMBER PRESSURE 1/4 kg/cm²



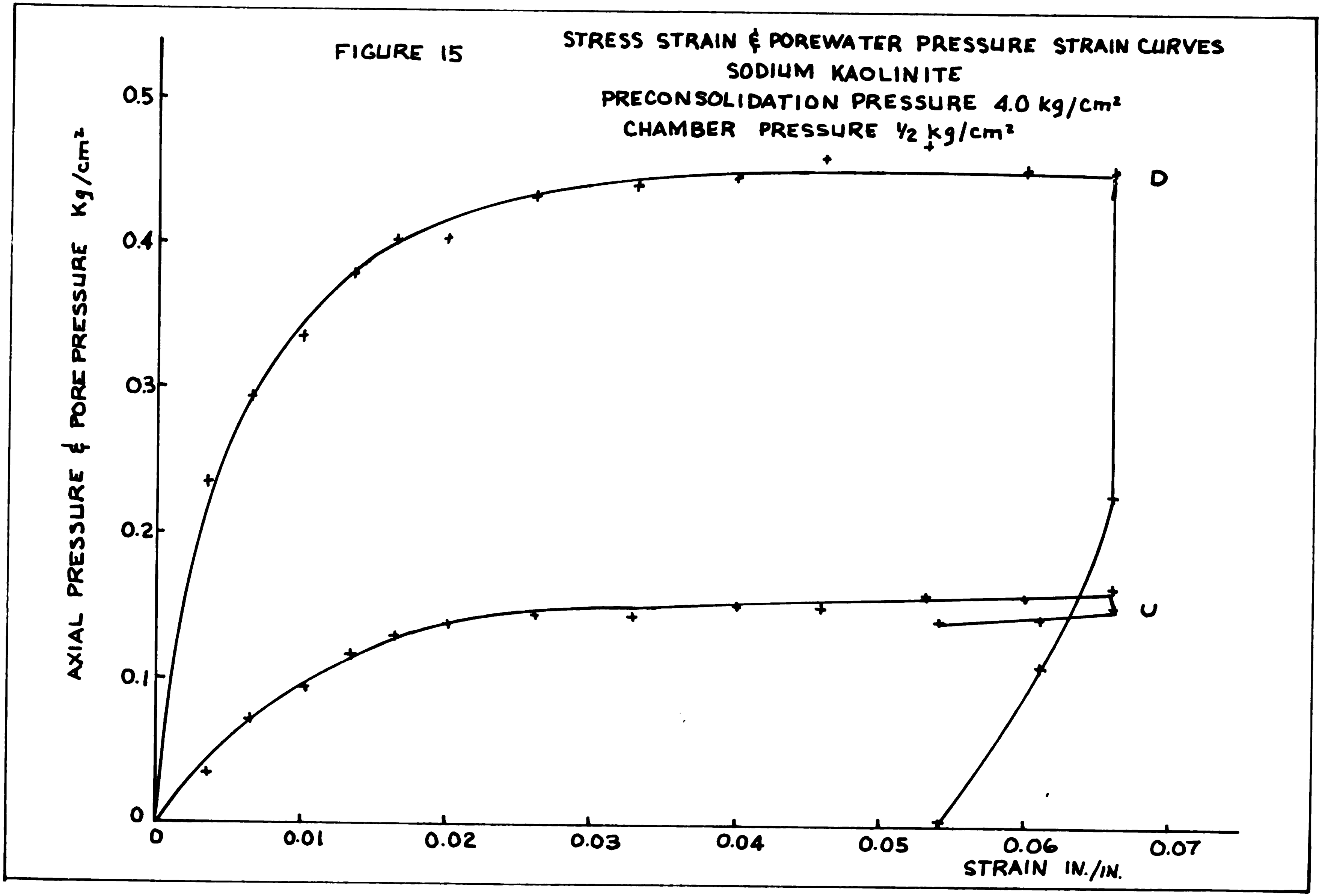
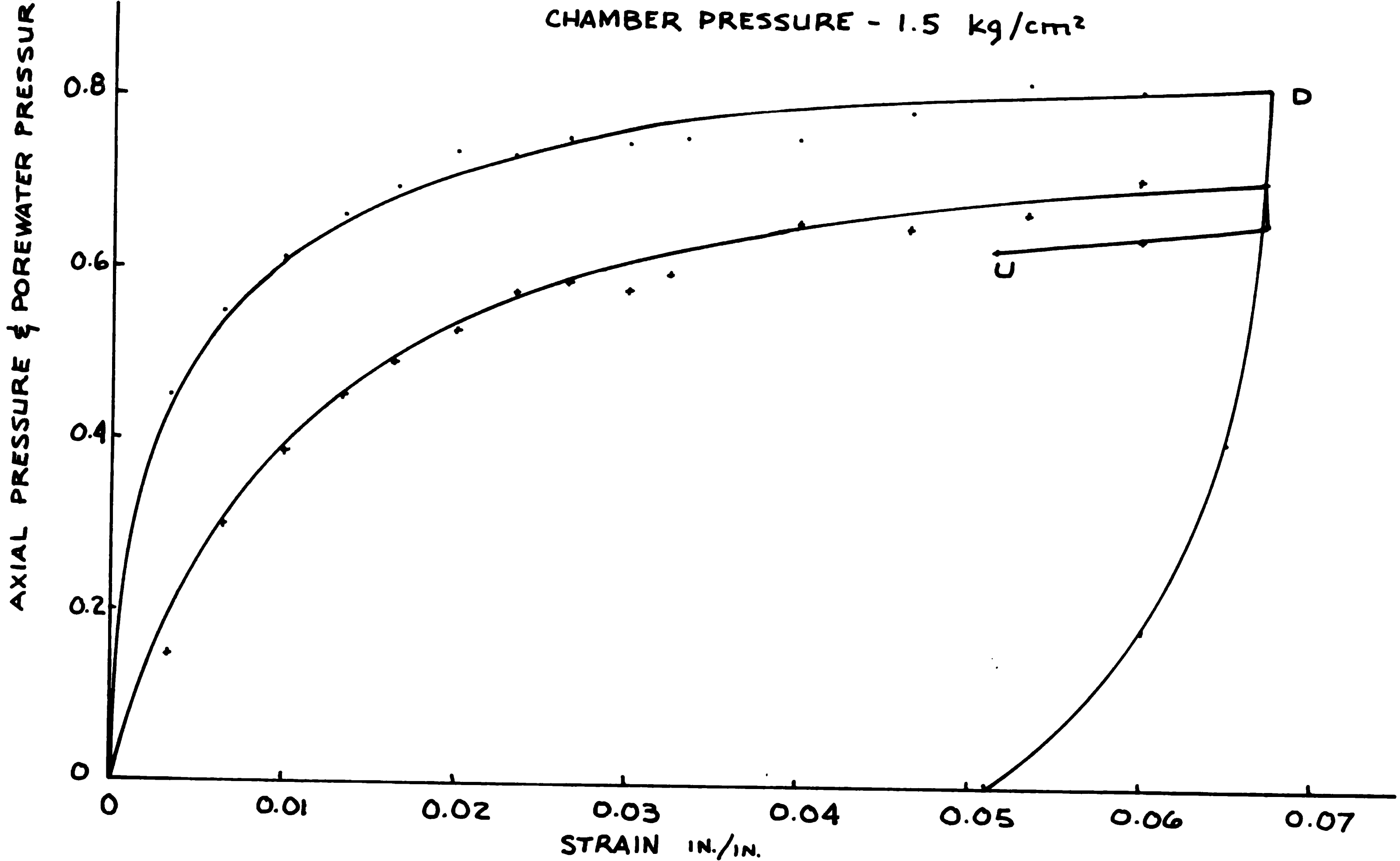


FIGURE 15

STRESS STRAIN & POREWATER PRESSURE STRAIN CURVES
SODIUM KAOLINITE
PRECONSOLIDATION PRESSURE 4.0 kg/cm²
CHAMBER PRESSURE ½ kg/cm²

FIGURE 16

STRESS-STRAIN & POREWATER PRESSURE - STRAIN CURVE
PRECONSOLIDATION PRESSURE = 4 kg/cm²
SODIUM KAOLINITE
CHAMBER PRESSURE - 1.5 kg/cm²



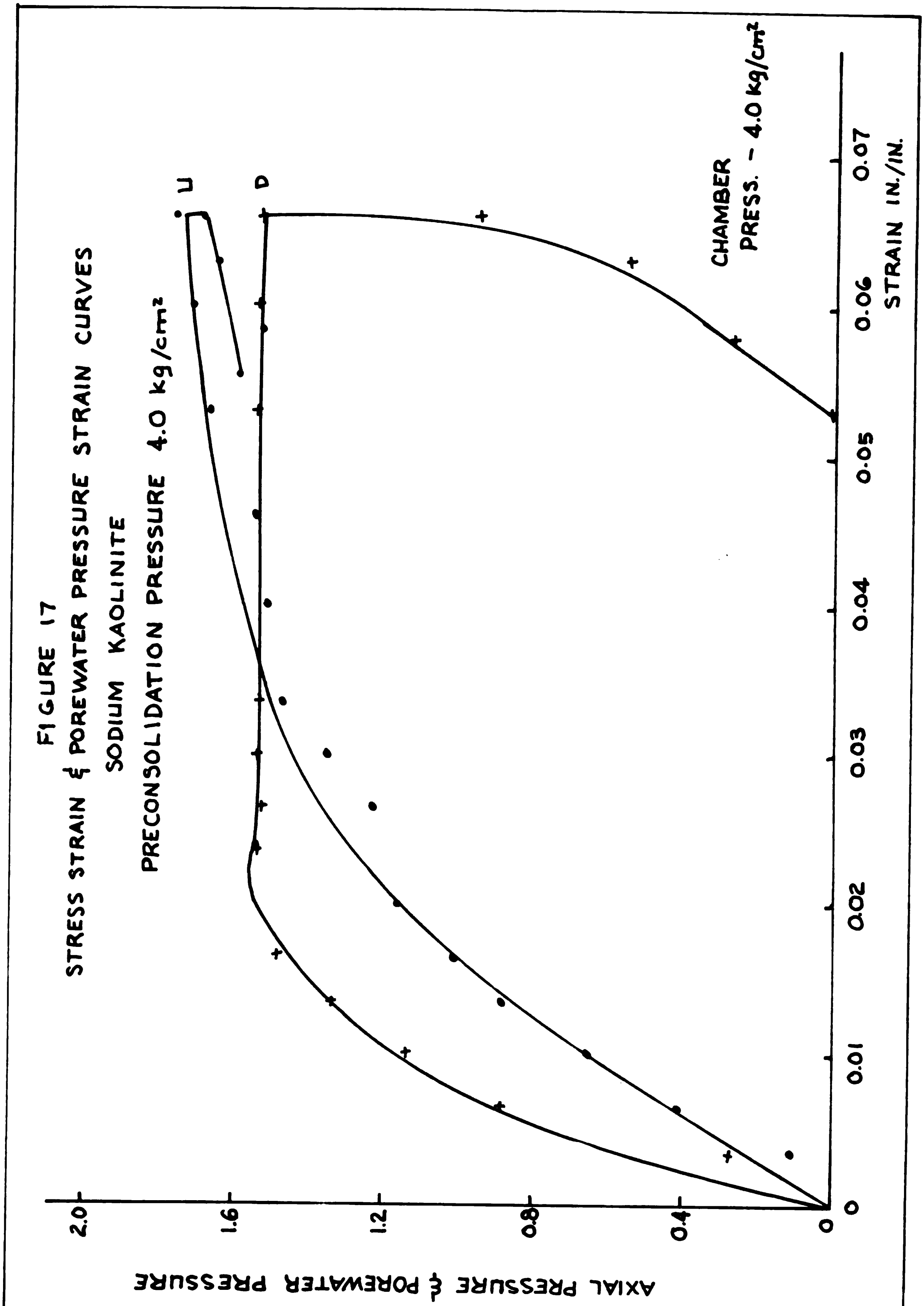


FIGURE 17

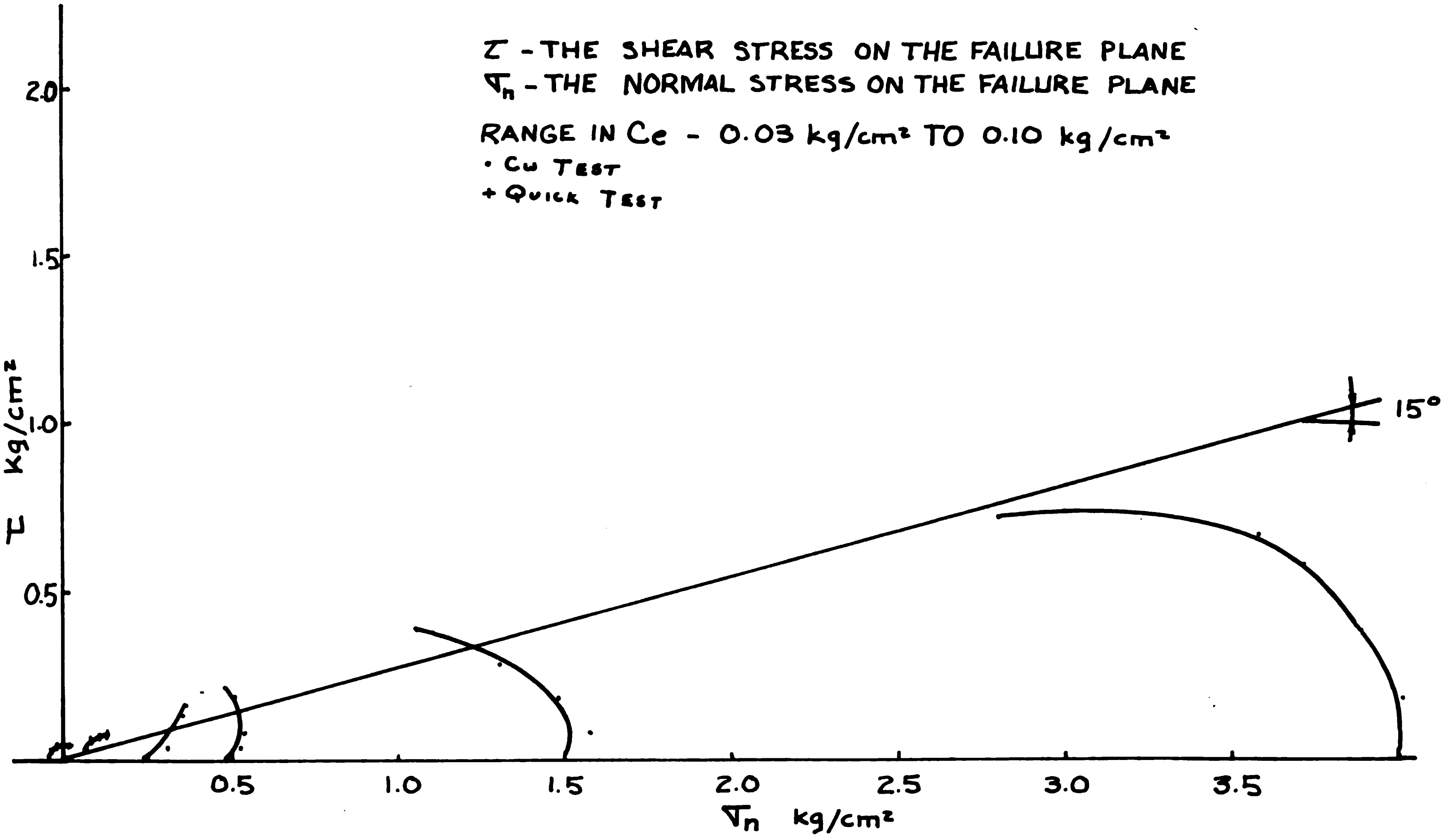
STRESS STRAIN & POREWATER PRESSURE STRAIN CURVES

SODIUM KAOLINITE

PRECONSOLIDATION PRESSURE 4.0 kg/cm²

FIGURE 18

GRAPHICAL CONSTRUCTION FOR THE DETERMINATION OF THE TRUE COHESION



τ - THE SHEAR STRESS ON THE FAILURE PLANE

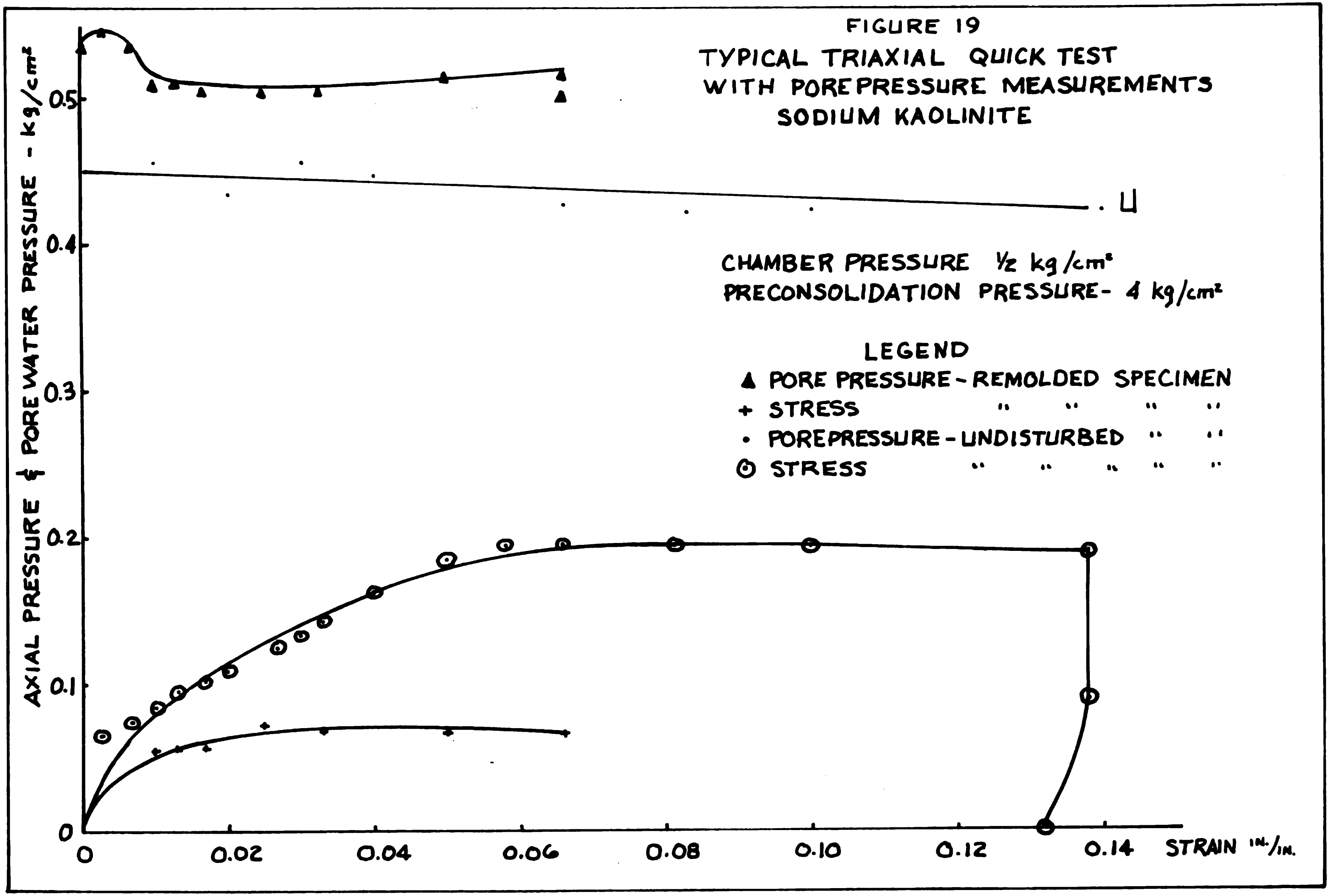
σ_n - THE NORMAL STRESS ON THE FAILURE PLANE

RANGE IN C_e - 0.03 kg/cm² TO 0.10 kg/cm²

- · Cu TEST
- + QUICK TEST

FIGURE 19

TYPICAL TRIAXIAL QUICK TEST
WITH POREPRESSURE MEASUREMENTS
SODIUM KAOLINITE



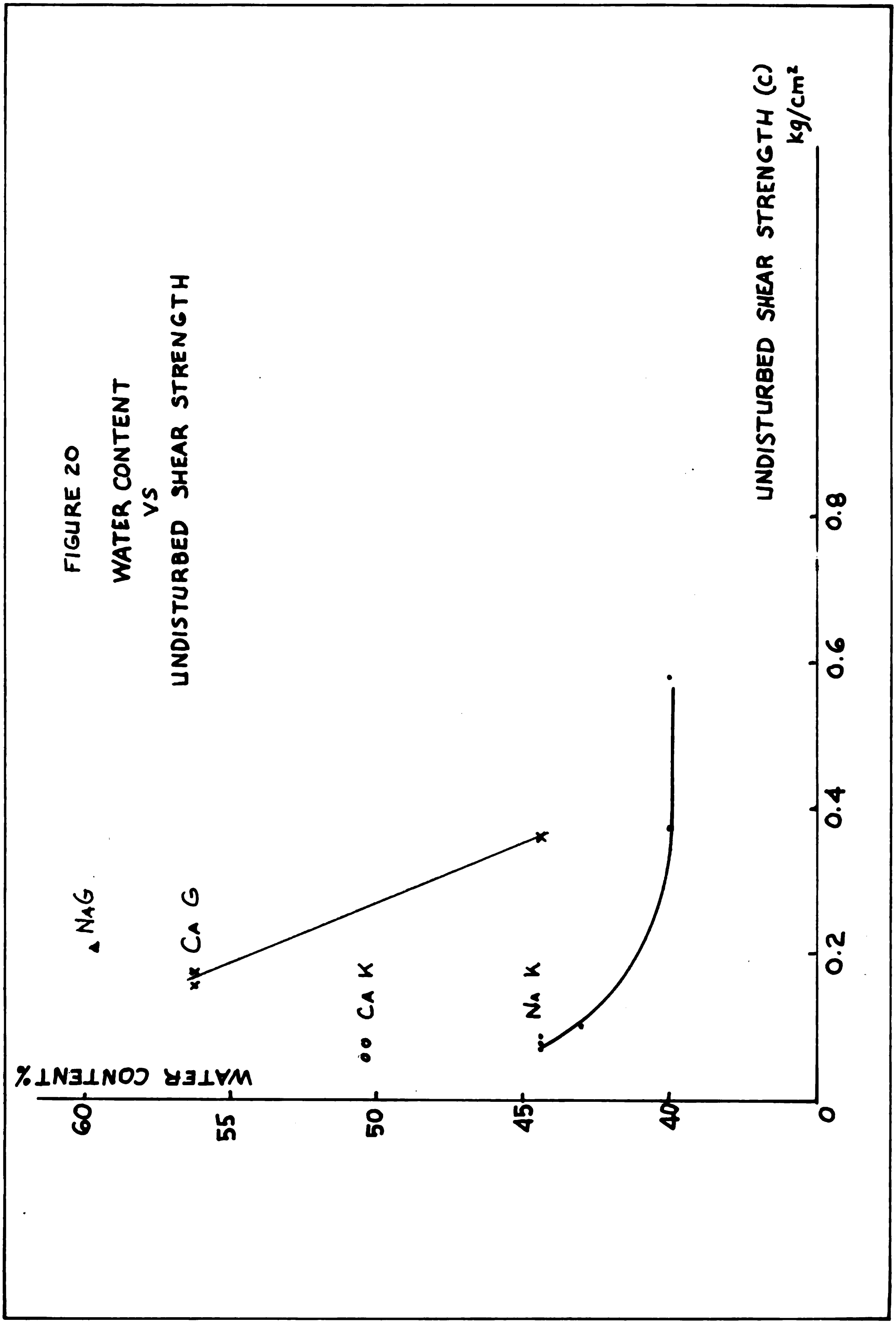


FIGURE 20

WATER CONTENT
VS
UNDISTURBED SHEAR STRENGTH

TABLE 1

CLAY	ACTIVITY	L.L.	P.L.	P.I.
SODIUM GRUNDITE	0.814	84.2%	23.2%	61%
CALCIUM GRUNDITE	0.677	74%	28.7%	45.3%
SODIUM KAOLINITE	0.267	50.8%	26%	24.8%
CALCIUM KAOLINITE	0.202	47.5%	29.5%	18.0%

TABLE 2

CLAY	PRECONSOLIDATION PRESSURE kg/cm²	ORIENTATION FACTOR
CALCIUM GRUNDITE	0	1.00
CALCIUM GRUNDITE	1	1.80
CALCIUM GRUNDITE	40	2.80
CALCIUM KAOLINITE	0	1.00
CALCIUM KAOLINITE	1	1.70
CALCIUM KAOLINITE	40	1.60

TABLE 3

CLAY	VOID RATIO	PERMEABILITY x 10^{-8} cm/sec
CALCIUM GRUNDITE	6.42	270
	3.87	121
	2.27	6.26
	1.71	6.09
	1.05	18.0
SODIUM GRUNDITE	8.36	13.0
	4.43	19.5
	2.09	2.5
	1.09	0.14
CALCIUM KAOLINITE	2.33	374
	1.33	27.3
	1.15	39.3
	3.44	713.0
SODIUM KAOLINITE	3.15	5650
	2.22	726
	1.36	67.5
	1.26	62.4

TABLE 4
KAOLINITE

ION	P_o kg/cm^2	C kg/cm^2	C_{rem} kg/cm^2	C/P_o	W %
SODIUM	2.0	0.084	0.0181	0.042	44.3
	2.0	0.073	0.0181	0.038	44.3
	4.0	0.098	0.023	0.025	43.0
	8.0	0.37	0.0393	0.046	40.1
	8.0	0.58	0.0448	0.072	40.1
CALCIUM	1.0	0.074	0.027	0.074	50.5
	1.0	0.059	0.027	0.059	50.5

TABLE 5
GRUNDITE

ION	P_o kg/cm^2	C kg/cm^2	C_{rem} kg/cm^2	C/P_o	W %
CALCIUM	1.0	0.169	0.047	0.169	56.4
	1.0	0.154	0.047	0.154	56.4
	2.0	0.360	0.230	0.180	44.4
SODIUM	1.0	0.095	0.070	0.095	77.0
	2.0	0.210	0.187	0.105	59.8

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