

EFFECT OF STRUCTURE ON SECONDARY  
COMPRESSION OF KAOLINITE

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## NOTATION

|            |   |
|------------|---|
| $a_v$      | Coefficient of compressibility          |
| $C_c$      | Compression index                       |
| $C_s$      | Coefficient of secondary compression    |
| $c_v$      | Coefficient of consolidation            |
| $e$        | Void ratio                              |
| $H_s$      | Height of soil solids                   |
| $K$        | Coefficient of permeability             |
| $p$        | Intergranular pressure                  |
| $r_s$      | Secondary compression ratio             |
| $t$        | Time                                    |
| $T$        | Time factor in the consolidation theory |
| $\gamma_w$ | Unit weight of water                    |

## SECTION I

### INTRODUCTION

One of the most important principles in any field of engineering is the full knowledge and understanding of the properties of the materials with which one must work. Those engaged in the fields of soil mechanics and foundation engineering are confronted with a particularly complex problem in this respect because of the innumerable combinations of soils that are involved, and the fact that the properties of many of these soils are not easily discernable.

Soils investigation on a scientific basis is a relatively recent development, but because of strong interest on the part of those engaged in this field, much has been accomplished toward gaining an understanding of soil properties and their engineering behavior. Recognition of the importance of soil investigation is steadily increasing.

Purpose of the Investigation. Fine grained soils, particularly clays, under the influence of superimposed loads or stress increases from other causes, often exhibit a large magnitude of compression. The problem of compression in these soils is further complicated by the fact that resultant settlements are time dependent. Many laboratory investigations and field observations have been conducted to determine the cause of this phenomena. The Terzaghi theory of consolidation has been widely accepted as accounting for that part of compression which occurs, in saturated fine grained materials, as a result of water being squeezed from the soil. An additional compression occurs, however,



beyond the point at which, according to the consolidation theory, compression should be complete. This additional compression is known as secondary compression.

Secondary compression is believed to be the result of a gradual shifting of individual clay particles in the soil mass to a more compact arrangement. This may be the result of the breakdown of edge to face arrangements of soil particles caused by increased intergranular stresses imposed on the soil as consolidation takes place. It has been noted that such a breakdown does occur both as a result of remolding and one dimensional compression of clay samples. If the concept of shifting particles is correct, then it is reasonable to expect that a clay which had initially a dispersed structure, or a very parallel orientation of particles, would exhibit less secondary compression than a clay sample whose particles had a less parallel orientation. The object of this study was to investigate the effect of structure on the secondary compression of kaolinite clay.

Scope of the Investigation. Two groups of kaolinite clay samples were prepared and an attempt was made to induce a more parallel arrangement of particles in one group than in the other. One group of samples was prepared using distilled water as the pore solution, and the other group using deflocculating agents as the pore solutions. Though all samples were remolded as a result of their preparation from powder form, it was anticipated that the relative degree of orientation of particles in the samples with the deflocculating agent would be greater than that for the distilled water samples.

Only indirect means of determining relative structure of the different kaolinite samples were used since the equipment and experience for preparation of specimens for optical examination with a microscope were unavailable. Strengths and permeabilities were used as the basis for determining the structure differences in the samples prepared and tested in this investigation. Relative strengths of the samples were compared by means of Atterberg Limits tests. Laboratory vane shear tests provided values of shear strength and sensitivity. Permeability comparisons were made on the basis of the calculated coefficients obtained from data presented by the consolidation curves of the compression samples.

Test Series A. This series consisted of the compression testing of samples no. 1 through 8, and sample no. 12. Compression tests of two samples from each of four extrusion slugs of material were conducted simultaneously in order to confirm general behavior of the samples, provide a check on the possibility of errors in the test equipment or procedure, and to verify any seemingly unreasonable results that might be obtained. Compression tests on all samples in this series were performed with the axis of compression of the sample coinciding with the axis of extrusion from the Vac-Aire machine. Sample no. 12 was subjected to a maximum pressure of  $52.35 \text{ kg/cm}^2$  to determine data for distilled water samples at low void ratios. All other samples in this series had maximum pressures of approximately  $8.5 \text{ kg/cm}^2$ .

In the first set of tests of this series, those performed on samples no. 1 and 2, the rings, samples, and porous stones were entirely submerged in distilled water during the entire period of testing. In the succeeding

tests on all other samples, drying during testing was prevented by use of a moist paper towel which enclosed the entire compression device, and which was kept moist by means of capillary action of water which was maintained in the base of the apparatus. Figure 1 shows a sketch of the compression device used in these tests.

Test Series B. This series involved the testing of two compression samples, one, a 34.2 percent distilled water sample, the other was a 31.1 percent water content di-sodium phosphate sample. These were designated as samples no. 9 and 10, respectively. The purpose of these tests was to determine directional properties of the samples that may have resulted from the extrusion technique used in the preparation of the samples for testing. The axis of compression of these samples was taken perpendicular to the axis of extrusion from the Vac-Aire machine. The samples were taken from the same slugs of material from which corresponding (same water content) samples of test series A were taken.

Test Series C. This series consisted of a single test on a sample prepared using a 1/40 Molar sodium tetraphosphate solution. Sodium tetraphosphate is known commercially as Quadrofos. Because the characteristic properties cannot be truly indicated by only one test, only limited data will be presented for this sample. This Quadrofos sample was designated as sample no. 11.

Data for all compression samples is included in the Appendix along with the compression curves for all samples tested in these series.

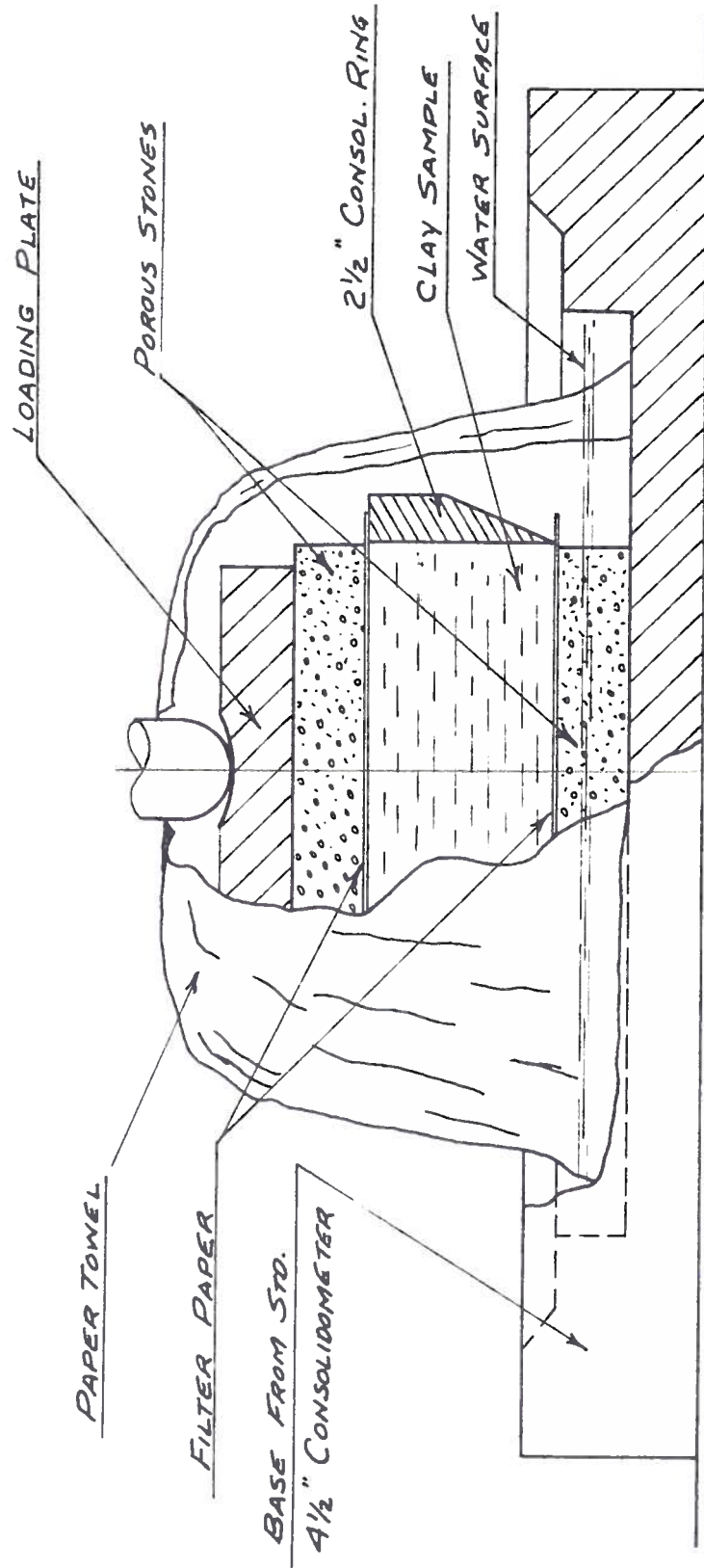


Figure 1. Compression apparatus used in the investigation.

## SECTION II

### SUMMARY OF PREVIOUS WORK

Terzaghi Theory of Consolidation. The consolidation theory presented by Terzaghi (1) considered the compressibility of fine grained soils as a purely mechanical process, in that compression of these materials was a result of volume decrease caused by a flow of water from the soil.

The assumptions on which the consolidation theory is based are:

- a. Water fills all of the voids of the soil.
- b. Both water and soil particles are incompressible.
- c. Darcy's Law is valid for the flow which takes place within the soil.
- d. The time lag involved in the consolidation is due entirely to the low permeability of the soil.
- e. The compressible material is laterally confined.
- f. Both total and effective normal stresses are the same on every horizontal plane through the soil.
- g. An increase in the effective pressure from  $p_1$  to  $p_2$  reduces the void ratio from  $e_1$  to  $e_2$ , and the ratio,  
$$a_v = \frac{e_1 - e_2}{p_2 - p_1}$$
, is assumed constant from  $p_1$  to  $p_2$ . This relationship is called the coefficient of compressibility. Figure 2 shows this relationship.
- h. The coefficient of consolidation,  $c_v$ , is assumed constant from  $p_1$  to  $p_2$ , and is defined by the expression,

$$c_v = \frac{K(1 + e)}{a_v \gamma_w} .$$

When a fully saturated, compressible soil is subjected to an increase in pressure, the pressure is initially carried entirely by the water in

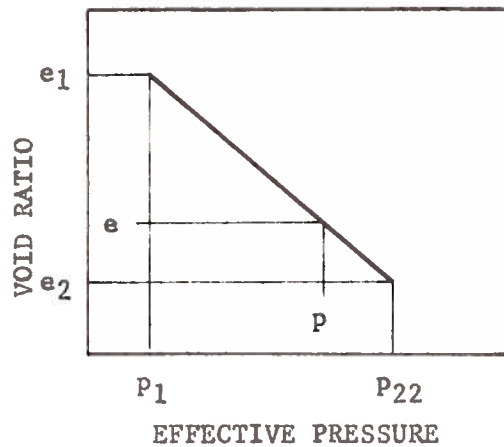


FIGURE 2. Pressure - void ratio relationship assumed in the consolidation theory.

the voids of the soil. A hydraulic gradient exists and water flows from the region of increased head. As the pore water is expelled from the voids of the soil, consolidation takes place and the imposed pressure is gradually taken up by the solid constituents of the soil. The process continues until all of the pressure has been transferred to the soil. Compression is then assumed to be complete. A plot of the theoretical consolidation curve is shown in Figure 3a.

For comparison with the theoretical consolidation curve, a typical laboratory curve is shown plotted in Figure 3b. It may be noted that the curves are very similar over most of the compression, but the laboratory curve plots as a straight line with slope  $\frac{de}{d(\log t)}$  in the latter portion, whereas the theoretical curve approaches a horizontal asymptote at 100 percent consolidation. The location of the point of assumed 100 percent consolidation is generally obtained using a method developed by A. Casagrande. The straight line portion of the laboratory curve is projected back until it intersects the tangent to the compression curve drawn through the point of inflection. The point of intersection of these two



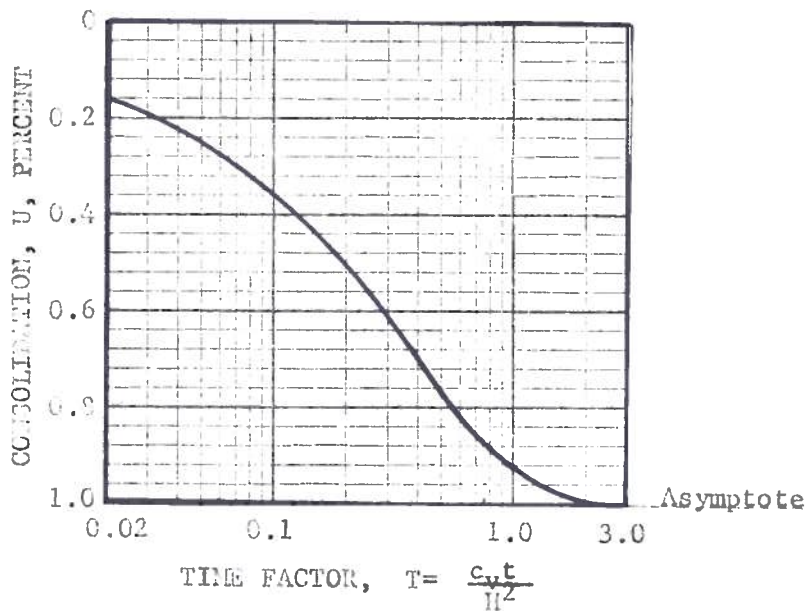


FIGURE 3a. Terzaghi theoretical consolidation curve.

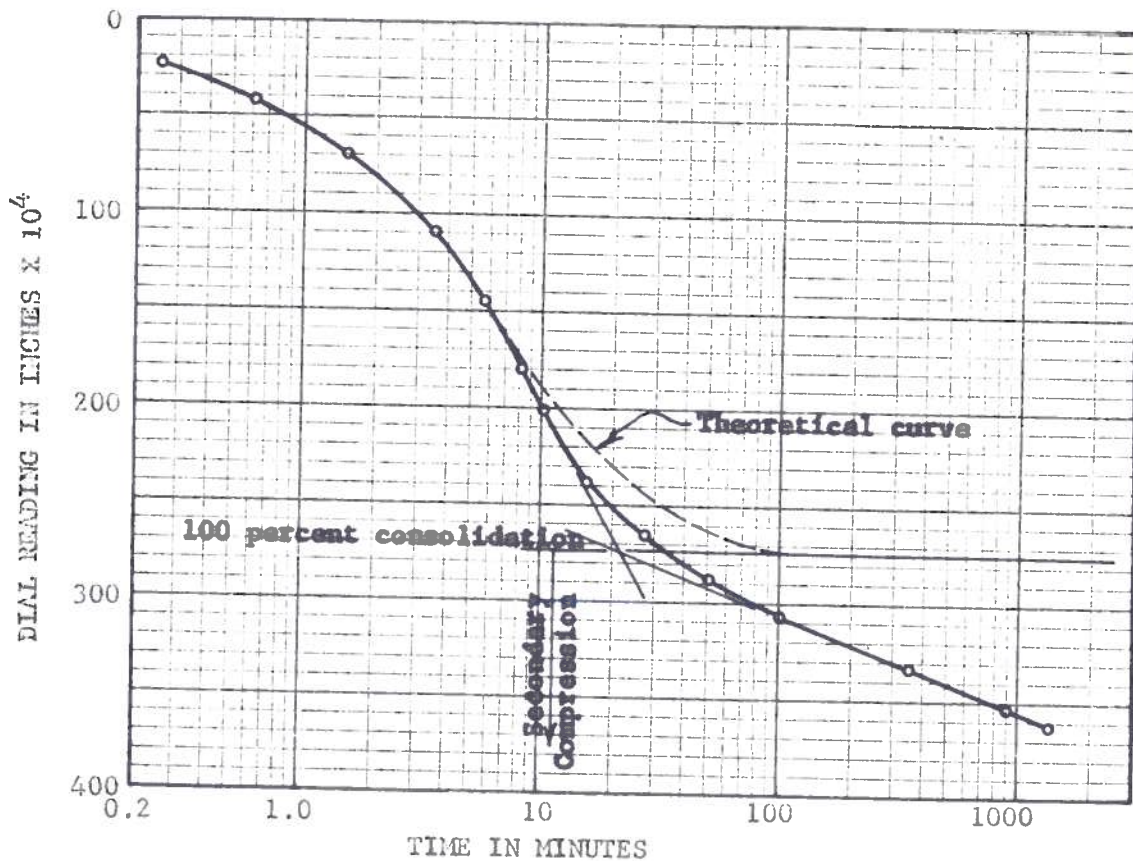


FIGURE 3b. A typical laboratory consolidation curve.

lines is the point of 100 percent consolidation. The construction of the point is shown in Figure 3b. Additional compression occurring beyond the point of 100 percent consolidation is known as secondary compression, and is characterized by the straight line plot as shown in Figure 3b.

Several mathematical treatments of consolidation and the included effects of secondary compression have been advanced. Taylor's theory (2) to account for secondary compression has probably been the most widely discussed.

Taylor's Theory to Account for Secondary Compression. A theory to include the effects of secondary compression was advanced by Taylor (2) in which he noted that the speed at which the void ratio of a fine grained soil undergoes change was the sum of two factors. It was equal to the rate at which it would change if there were no variation in intergranular pressure, plus the speed at which the intergranular pressure underwent change. The first of these, the change in void ratio occurring at constant intergranular pressure, was the rate of secondary compression.

The rate of secondary compression was assumed to follow a law resembling that for viscous flow, or creep. This concept furnished the assumption that secondary compression will develop at a rate proportional to the amount of undeveloped secondary compression. The exact solution of the differential equation resulting from the inclusion of the viscous flow effect had not been obtained at the time of development of the theory, but certain additional assumptions furnished a solution which could be given application. The theory presented was claimed by Taylor (2) to

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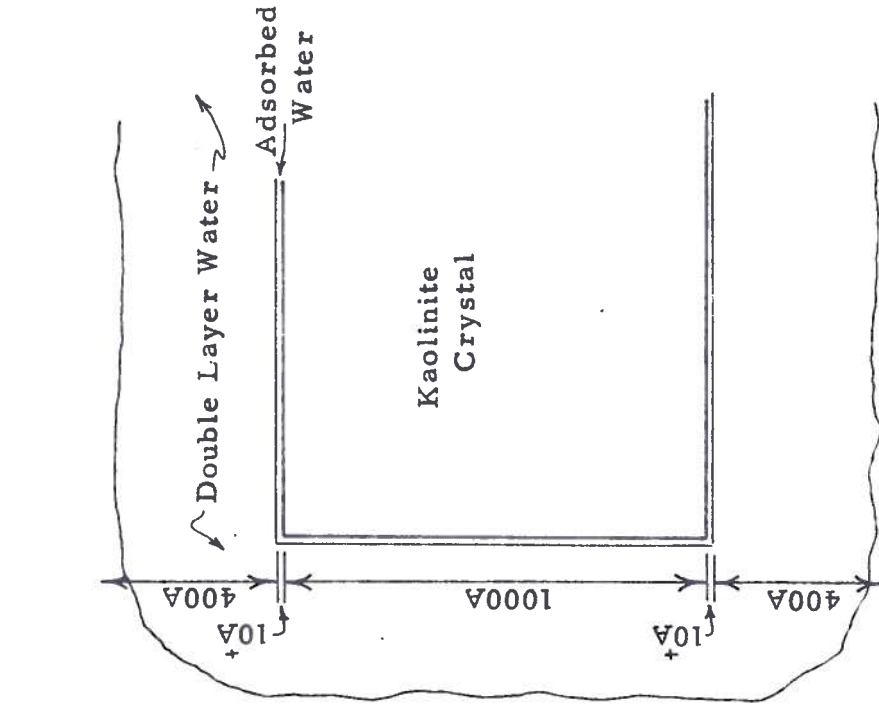


have shown better agreement with laboratory results than did the Terzaghi consolidation theory.

The principal objection to Taylor's theory was his consideration that secondary compression was a result of viscous flow. It was believed, even at the time of presentation of this concept, that the action was more involved than the theory indicated. More recent investigations into the structure of clays and other fine grained materials have supported these objections. Compressibility is now felt to be considerably more than a mere mechanical process.

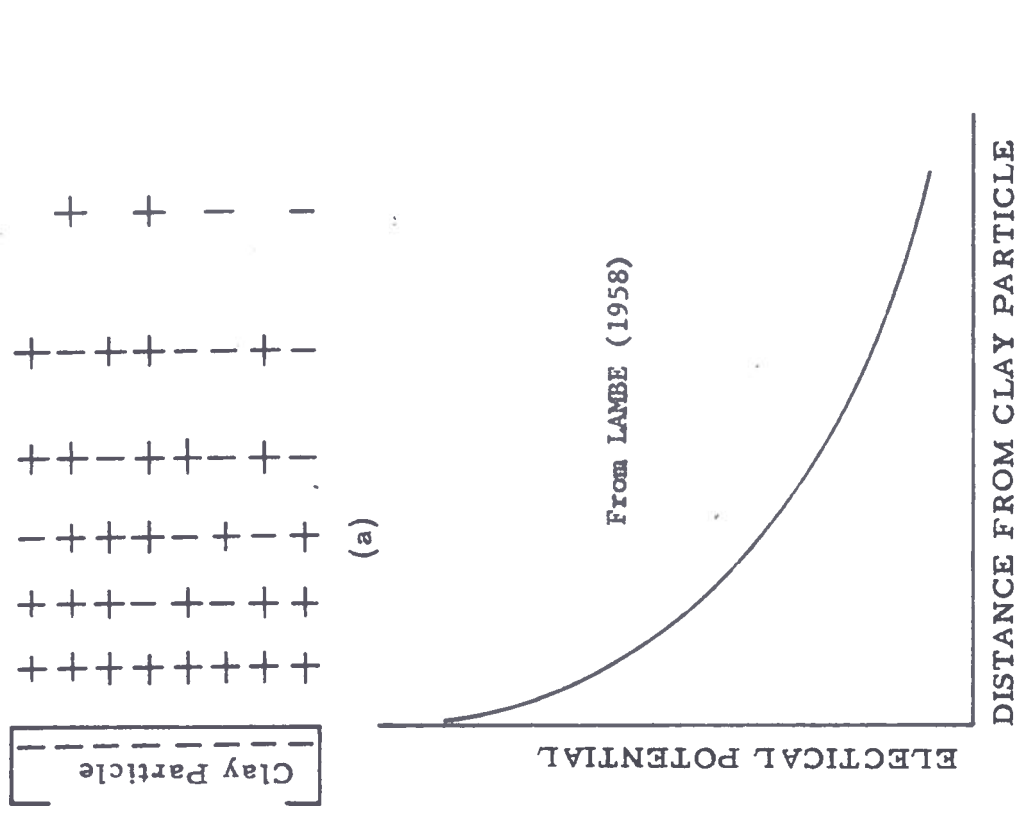
The Structure of Clay. Lambe's (3) compilation of the work of several investigators indicates that the secondary compression phenomena exhibited by clays may be directly related to the structure of the clay. By structure is meant the arrangement of soil particles and the electrical forces acting between them.

A particle which has a specific surface large enough for the electrical forces to dominate the mass forces is called a colloid. Clay particles, whose sizes are of the order of 1 micron to 1 millimicron (10A) fall into the category of colloid. Individual clay particles carry a net negative charge which is balanced by exchangeable cations at or near the surface of the particle. The ionic distribution around a clay particle is illustrated in Figure 4a, and the electrical potential curve for the particle resulting from this distribution is shown in Figure 4b. The net negative charge carried by the clay particles causes them to repel each other. The repulsive force is effective when the double layers of two adjacent particles overlap. The double layer



From LAMBE (1958)

Figure 5. Typical kaolinite particle and extent of double layer water.



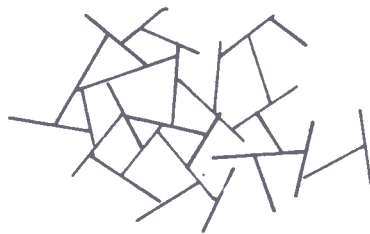
From LAMBE (1958)

Figure 4 a. Ion distribution about clay particle.  
b. Electrical potential of clay particle.

consists of the charge on the clay mineral surface and the swarm of ions surrounding the clay particle, including the water in which they are diffused.

A typical kaolinite particle is shown in Figure 5 with dimensions given for particle size and extent of the double layer. Michaels (4) describes the primary kaolinite particle as being a roughly hexagonal leaflet about 0.1 microns thick and about 1 micron in length or breadth. The edges of the kaolinite particle contain points of positive charge at moderately low values of pH. Michaels indicates that these points of positive charge may be the result of coordination of aluminum ions at the edges of the particle with water.

Because of the negatively charged faces and the points of positive charge on the edges of the particles, a tendency exists for the aggregation of particles to assume an edge to face arrangement within the soil mass. This type of arrangement of clay particles is called a flocculated structure. An arrangement in which the clay leaflets approach parallelism is called a dispersed structure. These two types of structure are shown in Figure 6.



FLOCCULATED STRUCTURE



DISPERSED STRUCTURE

Figure 6. Two types of clay particle structure.

The type of structure exhibited by clay soil masses in nature depends to a large extent on both the conditions existing at the time of formation or deposition, and the conditions to which the clay has been since subjected. Two conditions that may provide significant structure change are leaching, and increased overburden.

According to Lambe (3), some of the variables in the soil water system which increase the tendency toward flocculation are:

1. Increasing -
  - a. Ion valence
  - b. Electrolyte concentration
  - c. Temperature
2. Decreasing -
  - a. Dielectric constant
  - b. Size of hydrated ion
  - c. pH
  - d. Anion adsorption

The effect of decreasing the thickness of the double layer decreases the electric potential and the tendency toward flocculation of the particles is increased.

Effect of One Dimensional Compression and Remolding on Clay Structure.

Salas (5) showed that the orientation of clay particles during the consolidation process can be verified by examination of the samples under a microscope. Clay paste, air dried, did not show any birefringence when observed under polarized light. Though individual particles have high reflective qualities, their random orientation in a clay paste was optically uniform. A clay sample extracted from a consolidometer after being tested showed strong birefringence. Another sample which was subjected to triaxial compression and later viewed under a microscope with the aid of polarized light failed to show any birefringence, indicating that

this sample maintained its initially random structure.

Mitchell (6) states that a more orderly arrangement of clay particles results from remolding an undisturbed sample. Thin sections, 40 microns in thickness, of various clays, principally illites and montmorillonites, were prepared and viewed under polarized light to determine particle orientation. Both undisturbed and remolded samples were examined. It was found that the remolded samples gave a more parallel array of orientation than that exhibited by the undisturbed samples. One dimensional compression tests on remolded clay samples are known to show a lower void ratio corresponding to any given pressure than do undisturbed samples of the same material within the normal range of testing pressures. This is generally attributed to what is believed to be a more efficient packing of clay particles in the compression sample. The compression index,  $C_c$ , which is the slope of the curve of logarithm of pressure versus void ratio, is greater for remolded clay samples than for undisturbed samples at moderate pressures. This is the result of greater void ratio change in a given pressure increment in the case of remolded samples. Mitchell, on the basis of his determination of clay structure change accompanying remolding, suggests that a relationship exists between particle orientation and the compression index of the sample.

If the cause of secondary compression is a result of shifting of particles under stress, the measured values of the secondary compression ratio,  $r_s$ , should bear a relation to the initial particle orientation. The secondary compression ratio is the ratio of secondary compression to total compression. Data was presented by Mitchell (6) which showed that

secondary compression ratio in the undisturbed case was greater than the remolded secondary compression ratio in all but two cases on the samples tested. It was noted, however, that the relative amounts of final particle adjustment that occur during primary and secondary compression are unknown quantities. It is likely that these adjustments are functions of the orientation of particles at time of application of the load, the forces by which the particles are held in orientation, the speed of compression, the time length of the pressure increment, and the pressure to which the clay is subjected. The net effect of these factors was felt to be too complex to be quantitatively expressed by the secondary compression ratio.

Compression Tests on Clay with Organic Liquids. Salas (5) describes the effects of organic liquids on the compressibility of clay. Samples of natural bentonite were oven dried at  $100^{\circ}$  C to remove the hydration water, and ethyl alcohol, methyl alcohol, and carbon tetrachloride were introduced into different dried samples. Permeability coefficients for the samples were obtained by using a consolidometer as a falling head permeameter. The curves shown in Figure 7 are typical of those over the entire range of loading increments. Using the value of permeability determined directly, the value of  $c_v$  was computed and it was found that the time required for 98 percent consolidation was on the average between two and six seconds. Secondary compression ratios over a time interval of five days ranged up to 39 percent for the ethyl alcohol, and up to 73 percent for the methyl alcohol soil solutions.



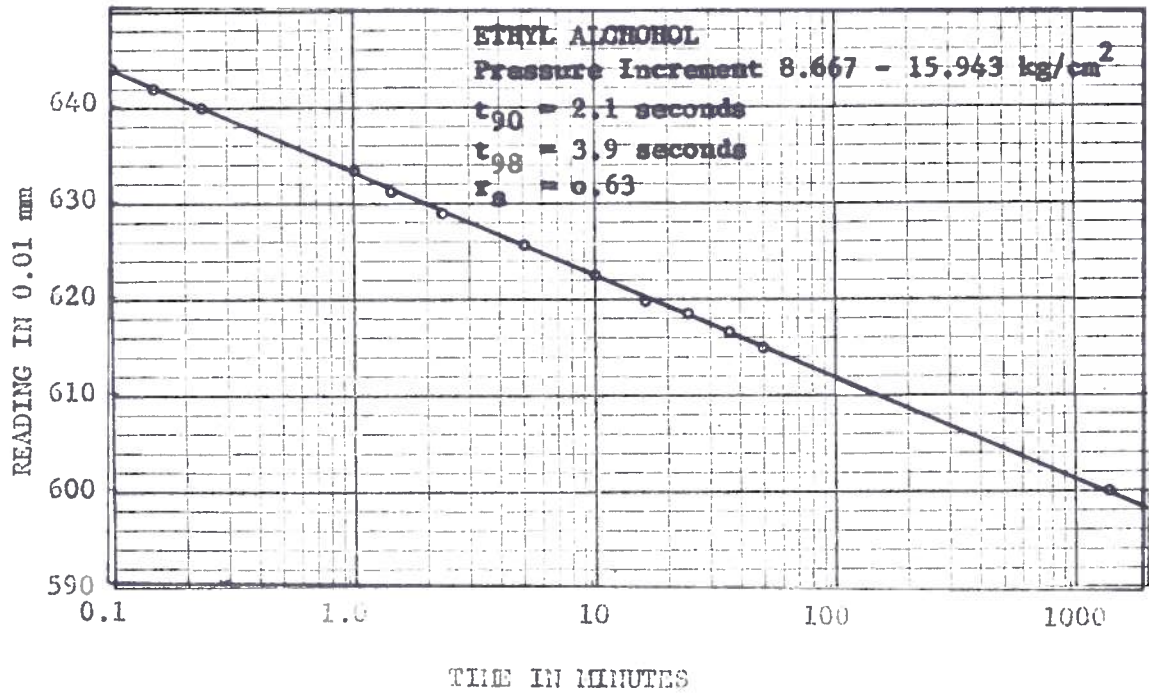
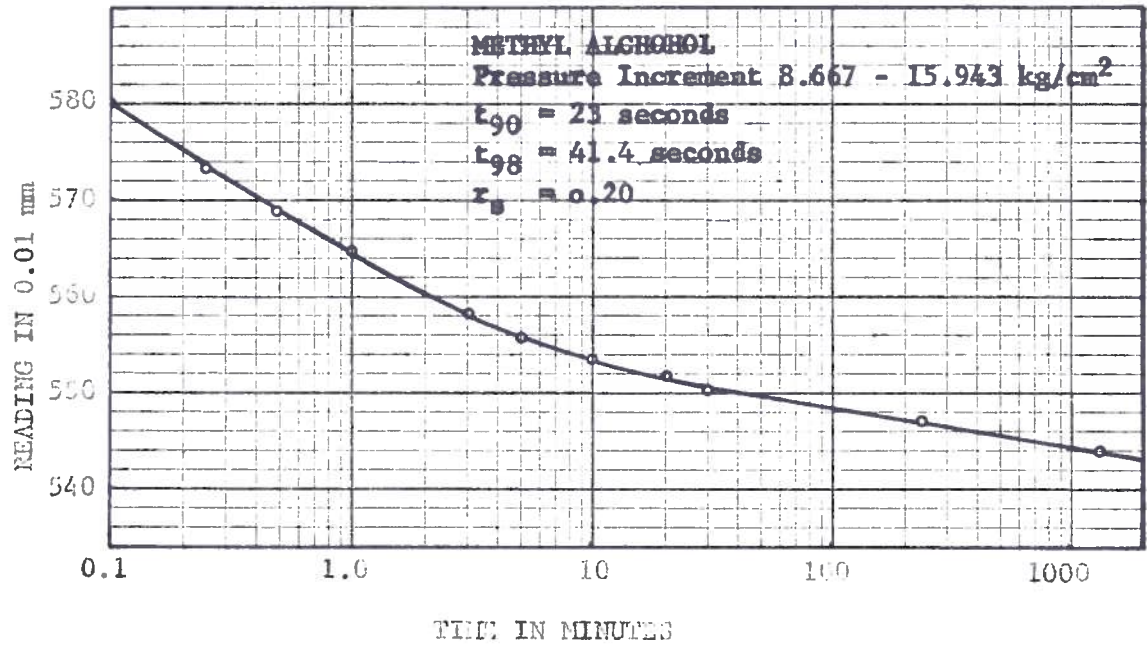


FIGURE 7. Typical results of compression tests on clays with organic pore solutions. (From: SAIAS, 1953)

General Observations of the Nature and Effect of Secondary Compression in Engineering Practice. Secondary compression has been defined as that volume change occurring in compressible soils that is not considered in the classical Terzaghi theory of consolidation. The magnitude of the compression is variable and considerable differences occur with soil type and stress. Because the major part of secondary compression usually occurs after the completion of consolidation, it has assumed increasing importance in recent years with the development of sand drain installations. Sand drains are used as a means for increasing the rate of consolidation in fine grained soil strata. The rate of consolidation varies inversely as the square of the thickness of the soil strata where vertical flow only is considered. Without sand drains, for very thick strata, the time required for completion of consolidation was often of such long length that additional settlements resulting from secondary compression were thought to be of little consequence.

Several aspects of secondary compression have been indicated in a recent study of sand drain installations by Moran, Proctor, Mueser and Rutledge (7). Some of the findings of the report were:

1. Pore water pressures are believed to exist during secondary compression, since a saturated soil requires a flow of water in order for volume change to occur.
2. Pore water pressures during secondary compression are so small that conventional means of measuring them are ineffective.
3. Since the magnitude of secondary compression is related to the intergranular stresses, in natural strata of clay most of the secondary compression should occur in the upper portion where stresses from surface loads are greatest, and should decrease with depth.
4. The rate of secondary compression is independent of soil permeability and the coefficient of consolidation. Permeability of the



soil only affects secondary compression as it affects the point at which consolidation is complete. The more impermeable the soil, the longer is the delay from time of loading to the beginning of observed secondary compression.

The report showed that an effective means by which secondary compression may be reduced in field practice is by the use of surcharge or preloading. It was found that a minor reduction in effective stress caused a delay in the appearance of secondary compression, and that the delay increased with increasing reduction in loading. In tests on laboratory samples, it was determined that a load decrease of 12 percent caused a time delay of 1500 to 3000 seconds, and that a load decrease of 18 percent increased the time delay to about 10000 seconds. After the time delay, secondary compression reappeared even though a volume increase resulted immediately on removal of load. An additional effect noted was a significant decrease in the coefficient of secondary compression,  $C_s$ , on its reappearance. The coefficient of secondary compression is defined as the amount of secondary compression occurring, per unit of thickness of soil, in one logarithmic cycle increment of time.

Kjellman (8) experienced similar effects of surcharge on large scale deep drainage field tests where cardboard wicks were used to accelerate consolidation. In the tests the ground surface was a dry crust one-half meter thick and underlain by a thick strata of soft, fat clay with water content of 118 percent and a liquid limit of 125 percent. A surcharge load of 4.5 tons per square meter was provided by a gravel surcharge. Settlement reached 66 centimeters in 240 days, at which time the surcharge was reduced to 3.1 tons per square meter. A slight swelling of the ground was noticed for several days, then settlement resumed but at a much lower

rate. The rate continued to decrease. Settlement was calculated on the basis of a load of 3.1 tons per square meter and found to be less than 66 centimeters. Therefore, the settlement occurring at the time of load reduction was assumed to be due to secondary compression. The initial rate of secondary compression was determined at 12 centimeters per year, but decreased to about one-tenth this value 450 days later.

There is some question as to whether the straight line plot of secondary compression in laboratory testing is indicative of field settlement rates. Barber (9) reports that observations of settlement of a bridge wing wall over a period of 80 months indicated that secondary compression did not follow the linear relationship exhibited normally in plots of settlement versus logarithm of time but was actually concave upward, indicating a more rapid time-rate decrease than might be expected from laboratory tests. The laboratory curve for a sample of the material underlying the structure was loaded in the laboratory for a period of four days which corresponded to the 80 month field observation, and the compression curve for the sample did exhibit a linear relationship in secondary compression.

### SECTION III

#### MATERIALS AND APPARATUS

Kaolinite Clay used in this Study. The kaolinite used in this investigation was a commercially prepared powder obtained from the Edgar Plastic Kaolin Company, at Edgar, Florida. No analysis of the material was attempted before its use in the preparation of the compression samples for this study, with the exception of water content determinations on the "as received" powder. Kaolinite is given by the chemical formula  $(OH)_3 Al_2 Si_2 O_{10}$ . Kaolinite previously obtained from this source was tested by the National Bureau of Standards (10), and found to be one of the purest commercial preparations available. The results of their studies of the physical, chemical, and mineralogical characteristics of the "as received" Edgar Plastic Kaolinite was summarized as follows:

- A. Physical: "E.P.K. has a uniformly graded distribution of particle sizes, platy morphology, and medium to high surface area."
- B. Chemical: "E.P.K. has a chemical composition closely approximating theoretical kaolinite."
- C. Mineralogical: "As indicated by X-ray analysis, E.P.K. contained predominately kaolinite with some mica contamination."

Deflocculation of Kaolinite by Alkali Phosphates. The ability of certain ionizing substances to provide dispersion of some flocculated systems was described by Michaels (4) as being due to an increase in the electrokinetic potential of the particles. The increased potential energy may be brought about by replacement of polyvalent ions in the double layer by monovalent ions such as sodium.

The cation exchange capacity of kaolinite is believed to be the result of isomorphous substitution of ions such as magnesium for aluminum in the crystal lattice. The cationic sites of kaolinite flakes seem to result from reaction of aluminum ions at the platelet edges with water.

The two most important possible mechanisms of deflocculation of kaolinite proposed by Michaels are:

1. Adsorption of anions on the platelet faces.
2. Adsorption of anions on the platelet edges in excess of the number of cationic sites initially present.

The result of both these mechanisms is to provide all parts of the kaolin particle surface anionic, causing a net interparticle repulsion for all possible particle arrangements.

The use of sodium polyphosphate as a deflocculating device for kaolinite was found effective. Its action provides for an increase in cation exchange capacity and an increase in density at the anionic sites on the kaolinite. The ability of polyphosphates to provide for the deflocculation of kaolinite was found to increase with increasing molecular weight of the deflocculant. Sodium tetrphosphate,  $\text{Na}_6\text{P}_4\text{O}_{13}$ , commercially known as "Quadrofos", appeared to be the most active.

Deflocculating Agents used in this Study. A 1/30 Molar solution of di-sodium phosphate,  $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$ , was used in the preparation of compression samples no. 5, 6, 7, 8, and 10. Sample no. 11 was prepared using a 1/40 Molar solution of sodium tetrphosphate,  $\text{Na}_6\text{P}_4\text{O}_{13}$ , (Quadrofos). The "Quadrofos" was not available for use at the beginning of this study. Time permitted the preparation and testing of only on compression sample using this deflocculant.

Vac-Aire "Experimental" Extrusion Machine. This machine was manufactured by the International Clay Machinery Co. The device consists of a pair of augers , mounted in series, which pass through two identical housings. The material is fed into the hopper of the first chamber and it is forced by means of the first auger into a second chamber which is sealed and held under a vacuum of approximately 27 pounds per square inch. The second auger which is located in the de-aired chamber then forces the material through a die which produces the desired shape of slug as it is extruded. Matlock (11) concludes that the use of this machine can provide test results that can be duplicated with a high degree of precision.

Compression Testing Apparatus. A standard consolidation machine employing an 8:1 mechanical advantage in the lever system was used in the compression testing of all samples with the exception of sample no. 12. Because some of the samples tested were close to their liquid limit and light hangar weights were unavailable, an auxiliary hangar was placed on the machine having a 1:1 mechanical advantage. This permitted the use of hangar weights available for building up gradually the applied loads so as not to induce squeezing of the material between the porous stones and ring. Using this machine, pressures up to about 8.5 kilograms per square centimeter could be applied to the compression samples. For the compression test on sample no. 12, a larger consolidation machine was used in order to obtain higher pressures on the sample. This machine had a 40:1 advantage in the lever system and pressures in excess of 50 kilograms per square centimeter were obtainable.

To minimize the effects of side friction on the sample, a floating type ring was used. The rings were 2.5 inches in diameter and 1 inch in height. They were a special type and employed a tapered outside diameter which permitted them to be used directly in cutting a sample from a larger slug of material.

Porous stones, top and bottom, provided double drainage for the consolidation samples.

To correct excessive squeezing of material from between porous stones an ring, a condition noticed early in the testing, filter paper was placed between the porous stones and the sample. As consolidation took place, the filter paper acted as a seal between porous stones and ring and squeeze out was prevented. It is unlikely that the use of the filter paper caused any restriction of pore water flow at the surface of the samples.

## SECTION IV

### PREPARATION OF COMPRESSION SAMPLES

To determine the concentration of di-sodium phosphate which would facilitate the handling and testing of samples, a series of Atterberg Limits tests were performed on samples with concentrations of solution up to and including 1/20 Molar. These tests indicated the range of water contents in which the clay, at varying concentrations of pore solution, was in the plastic range, and in which it might be prepared for compression testing. Figure 8 indicates the results of these tests. A 1/20 Molar concentration provided a saturated solution in distilled water at room temperature. It was decided to prepare the di-sodium phosphate samples using a 1/30 Molar solution. Beyond this concentration there appeared to be little decrease in the liquid limit. There was also provided as indicated in the curves shown on Figure 8 a slight overlap in the plastic ranges of the distilled water kaolinite and the 1/30 Molar di-sodium phosphate kaolinite preparations. Similar tests were performed on various concentrations of "Quadrofos" solution as shown in Figure 9, and a 1/40 Molar solution was selected for the preparation of sample no.11.

An attempt was made to prepare the di-sodium phosphate samples at water contents of 35 percent and 31 percent. Consideration was given to the existing moisture content of the kaolinite powder, and an allowance was made for a loss of about 3 percent expected to result from evaporation during preparation of the samples. The solution was initially hand mixed with a predetermined weight of kaolinite powder, and extruded several times through the Vac-Aire machine to assure a uniform mixture of the



clay and solution. Extruded slugs, about 6 to 8 inches in length and 2.7 inches in diameter, were cut and dipped immediately in wax to prevent drying. Malted "Petrowax A", a Gulf Oil Corporation product, was used to provide the coating. The slugs were then stored in a moist room. Water content determinations were made from the clay adjacent to the slugs as they were extruded from the Vac-Aire machine. Lengths of slugs were such as to provide at least two compression samples.

Distilled water samples were prepared in the same manner as that described for the di-sodium phosphate samples. The attempted water contents of these samples were 42.5 percent and 35 percent. The single sample with "Quadrofos" pore solution was prepared at an attempted water content of 28 percent.

There was noted a significant loss of moisture during the extrusion process of samples with initial water contents close to their plastic limit. This may be accounted for by the fact that as the clay becomes more stiff, it is more resistant to extrusion, and during such a process partial consolidation takes place and water is forced from the clay. Also, increased heat generated during the extrusion of the lower water content samples increased evaporation losses in these samples. There were visible signs of liquid dripping from the Vac-Aire machine during extrusion of the samples of lower water content of both distilled water and di-sodium phosphate samples.

As the water content of the clay approached the liquid limit of the samples, handling after extrusion became difficult. There is a range in which water contents of this clay must lie in order to be easily prepared by this method of extrusion, and the range is significantly less than the



plastic index of the material. Some of the slugs of kaolinite clay extruded at water contents close to the plastic limit had visible signs of the effect of the wormshaft that forced the material through the extrusion die. Several slugs of material had to be discarded because of cracking along a helical plane after leaving the die.

Slices of approximately 1.5 inches thick were cut from the extruded slugs and these served as the compression samples. The special ring was forced over a slice of the material, and the sharp edge of the ring trimmed off the excess 0.1 inch of the sample radius. This procedure was used in the preparation of all samples in test series A, and the single "Quadrofos" sample of test series C. The axis of compression of these samples was along the axis of extrusion of the slugs. The two samples of test series B were obtained by cutting the extruded slugs lengthwise and taking the compression sample perpendicular to the axis of extrusion.

## SECTION V

### ANALYSIS OF TEST RESULTS

Strength Indications from Atterberg Limits. The determination of the liquid and plastic limits of the distilled water and di-sodium phosphate samples served two principal purposes. First, they indicated the range of plasticity of the samples, and thereby provided a basis for the selection of water contents at which the samples could be prepared. Secondly, obtaining the liquid limit of the samples showed the water content above which the sample is assumed to have zero shearing strength.

Figures 8 and 9 show the liquid and plastic limits of various concentrations of di-sodium phosphate samples and "Quadrofos" samples, respectively. The zero concentration on both figures shows the limits for the distilled water samples. The distilled water kaolinite exhibited a liquid limit at a water content of approximately 52 percent, and a plastic limit at a water content of approximately 33 percent. Corresponding values for the 1/30 Molar di-sodium phosphate samples were approximately 36 percent and 28 percent, and for the 1/40 Molar "Quadrofos" sample, 29 percent and 26 percent.

The fact that distilled water samples exhibited strength at water contents considerably greater than the liquid limits of the samples with the deflocculating agent as the pore solution indicates a greater force of attraction between individual particles. This would indicate a more flocculated arrangement of particles in the distilled water samples.

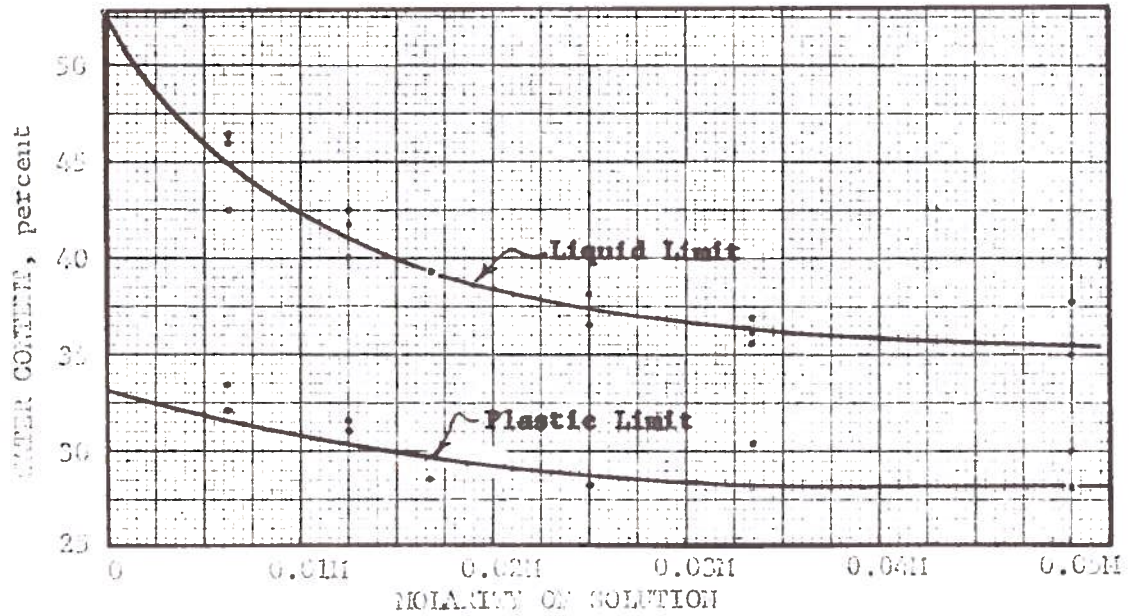


FIGURE 8. Atterberg Limits for kaolinite with di-sodium phosphate solution.

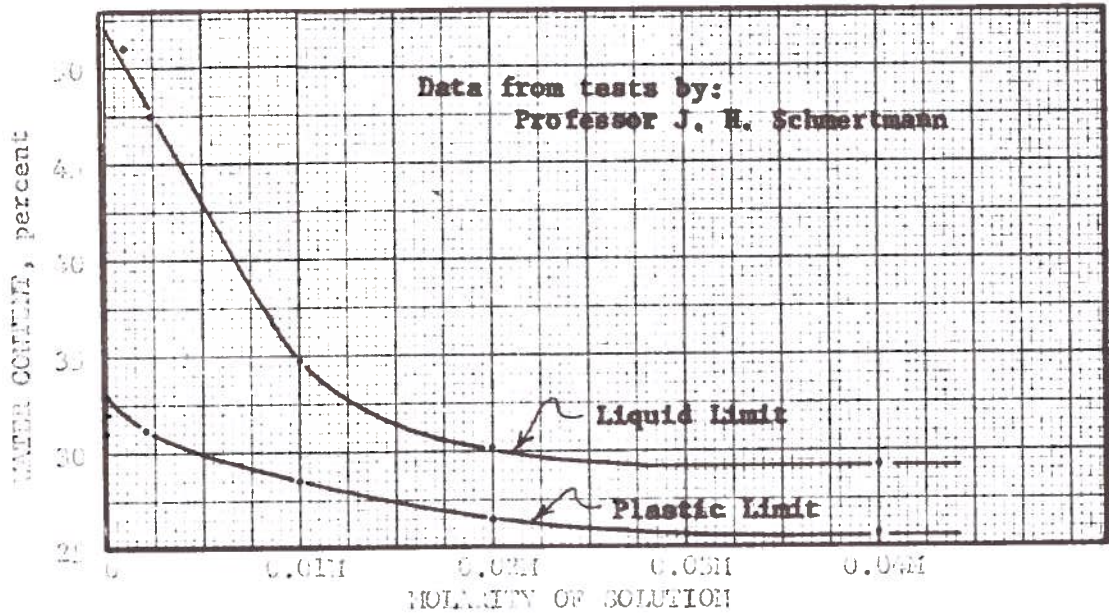


FIGURE 9. Atterberg limits of kaolinite with sodium tetraphosphate sln.

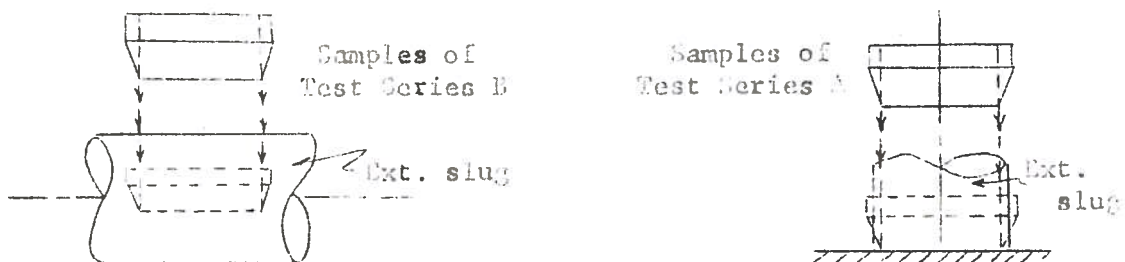


FIGURE 10. Direction of samples with respect to axis of extrusion.

Strength and Sensitivity Comparisons by means of Laboratory Vane Shear Apparatus. Figure 11 shows the "undisturbed" and "remolded" strengths of the samples with distilled water and di-sodium phosphate pore solutions. The points plotted are the approximate average values obtained from many vane shear tests on several samples of the extruded material. The size of the laboratory vane used in these tests was 1/2 inch by 1/2 inch. Duration of the testing was from 2 to 3 minutes. By "undisturbed" strength is meant the initial strength of the extruded sample and should not be confused with the term "undisturbed" as generally used in reference to a soil sample. The "remolded" strength was obtained after rotating the vane 10 times in place before obtaining another shear strength determination. In figure 11, the solid lines join the "undisturbed" points and dashed lines connect the "remolded" points. Because the "Quadrofos" samples were prepared at only one water content, only a single "undisturbed" and "remolded" strength is shown. For both the distilled water and the di-sodium phosphate samples, the trend is an increase in strength with decreasing water content. The sensitivity of both samples increases with decreasing water content. Sensitivity is the ratio of "undisturbed" to "remolded" strengths. The ratio of the strength of the distilled water samples to the di-sodium phosphate samples is not constant. The di-sodium phosphate samples appear to increase in strength with decreasing water content at a more rapid rate than does the distilled water samples. This appearance may result from the straight line assumption of strength increase between points, and is therefore not conclusive. No comparison can be made for the



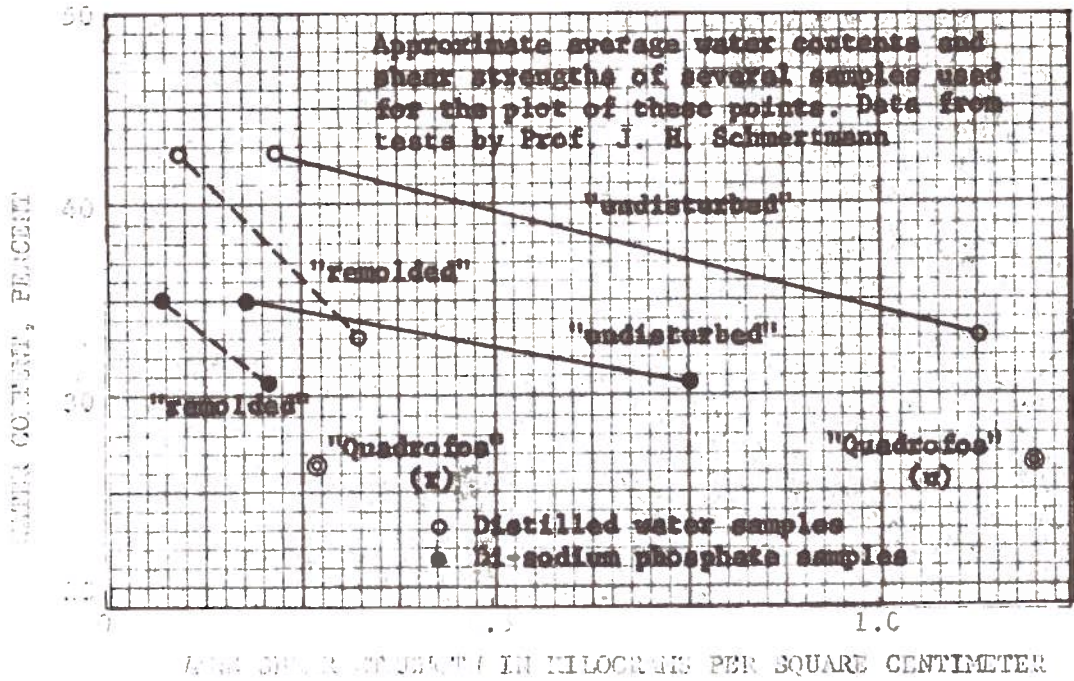


FIGURE 11. Laboratory vane shear strength versus water content for kaolinite with distilled water and di-sodium phosphate pore solutions.

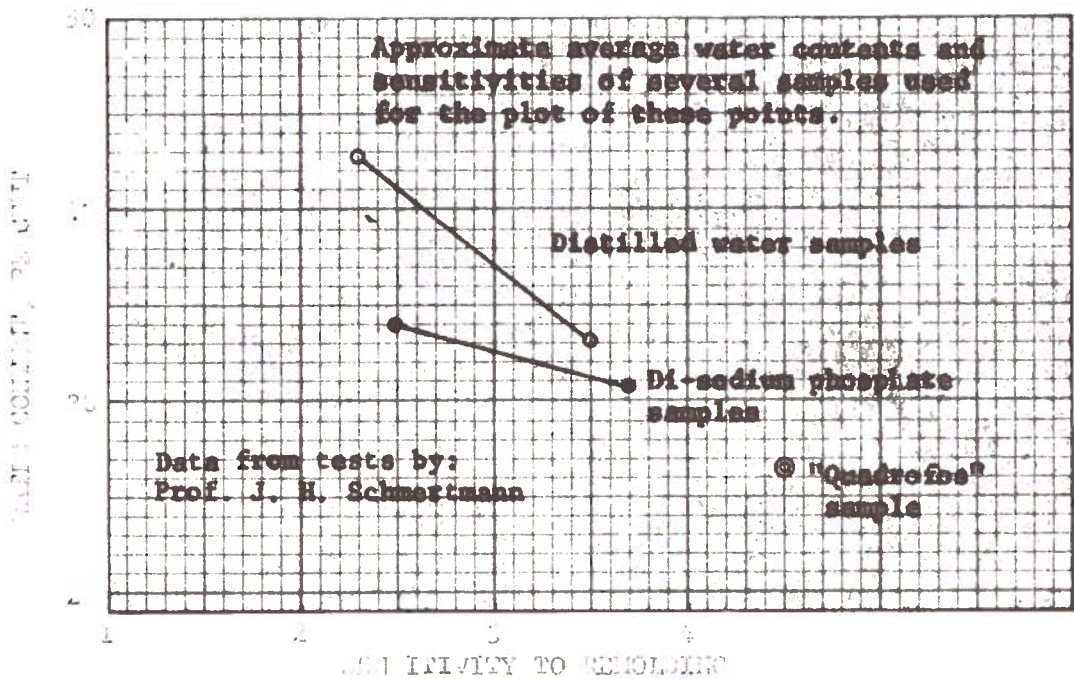


FIGURE 12. Plot of sensitivity versus water content for kaolinite with distilled water and di-sodium phosphate pore solutions.

"Quadrofos" sample since its strength-water content relationship is presently unknown. The strength comparison on the basis of these vane shear results indicate considerably greater strength for the distilled water samples than for the di-sodium phosphate samples.

Sensitivity is indicative of structure in that strength loss is believed to result from a change of structure from a more flocculated to a less flocculated arrangement, or from a less parallel to a more parallel arrangement of particles. One would expect therefore, that a clay sample with a high degree of parallel orientation initially would undergo less strength loss from additional remolding than would a sample with a lesser degree of initial parallel orientation. A comparison of the sensitivities of the distilled water samples and the di-sodium phosphate samples is shown in Figure 12. The ordinate of the plot of points is water content of the sample, but since all samples had about the same degree of saturation, void ratio might easily be superposed as the ordinate. The plot indicates that the di-sodium phosphate samples, at the same water content, are less sensitive than the distilled water samples.

Clay Structure Compared on the Basis of Permeability. Permeability of a soil is a measure of the ease with which a fluid will flow through the soil. Lambe (12) indicates that the permeability is dependent on such soil properties as grain size, properties of the pore fluid, void ratio, shape and arrangement of soil particles, and degree of saturation of the soil. For all these series of tests, grain or particle size can be considered the same for all samples tested. The degree of saturation in all cases was comparable, and at about 100 percent. The effect of

decreasing void ratio is a decrease in the permeability of the soil. Shape and arrangement of particles effects permeability as they effect the path of flow of the pore fluid. A more tortuous path would be encountered in a clay with a dispersed structure if the flow were required to be perpendicular to the parallel arrangement of of clay particles. This would be the case for a consolidating sample in which both axis of loading and direction of flow of the pore fluid were coincident.

The viscosities of both distilled water and the 1/30 Molar di-sodium phosphate solution can be assumed to be about the same.

The permeability of the samples was obtained indirectly from the consolidation tests by means of the expression:

$$K = c_v a_v \gamma_w (1+e)$$
, the value of  $c_v$  being obtained from the logarithm of time fitting method on the compression curves for the samples. The density,  $\gamma_w$ , was assumed to be the same for both distilled water and the di-sodium phosphate pore solutions, and the void ratio,  $e$ , was taken at the point of 50 percent consolidation.

Figure 13 shows a semi-logarithmic plot of permeability versus void ratio for all compression samples of test series A. For both the distilled water samples and the di-sodium phosphate samples, a decrease in permeability occurs with decrease in void ratio. The permeability of the di-sodium phosphate samples at any given void ratio within the range of testing was less than that of the distilled water samples with a ratio of about 2.5:1.

Values of permeability obtained from the "Quadrofos" sample of test series C are given in table 6. These appear to be somewhat inconsistent with the results obtained from other samples tested, but the inconsistency



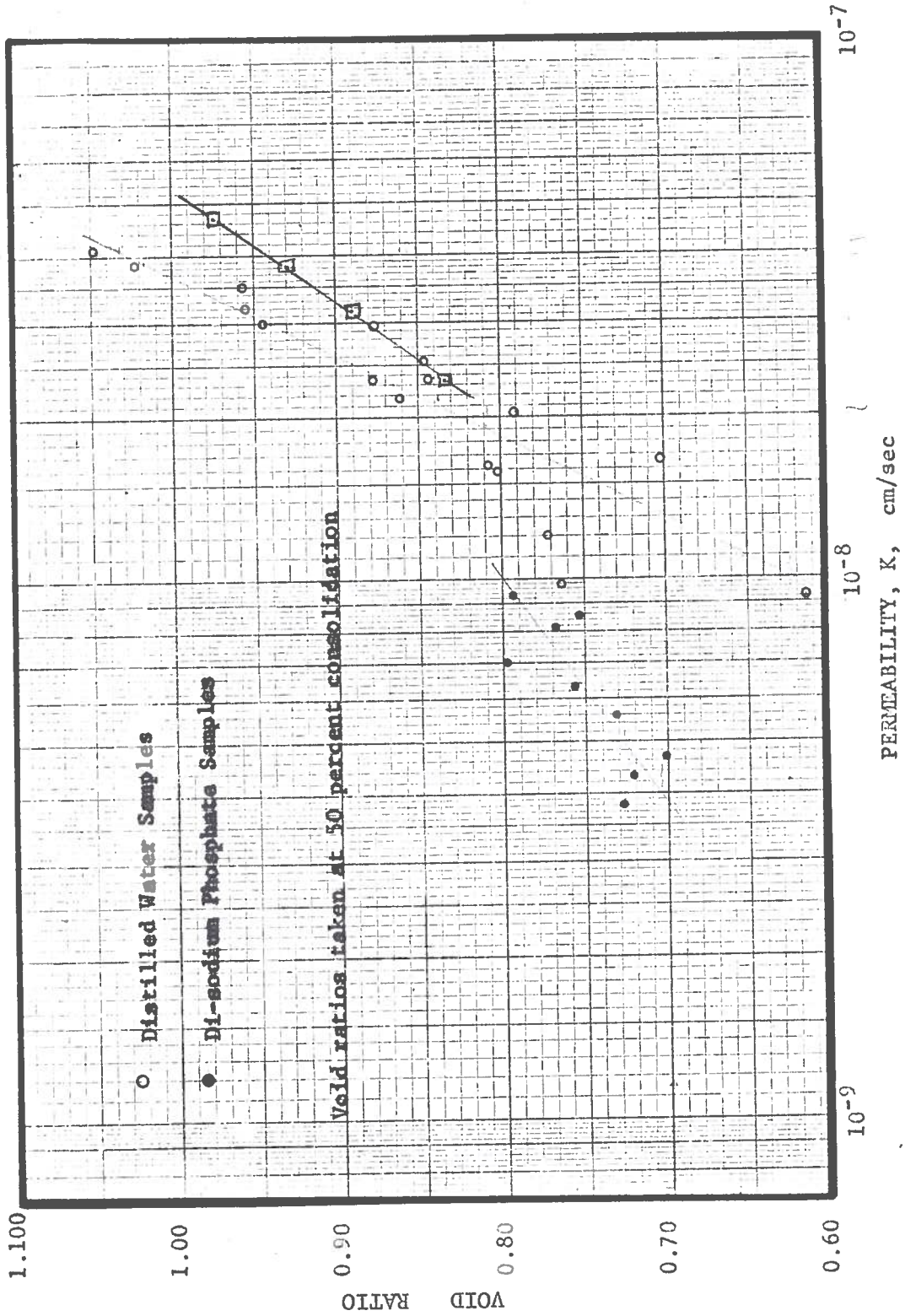


FIGURE 13. Plot of permeability versus void ratio for kaolinite clay with distilled water and di-sodium phosphate pore solutions. (Samples of test series A)



may be the result of erosion of the compression sample which occurred during testing. Since only one test was performed, the results are not conclusive.

Figure 14 is a plot of permeability versus void ratio for the two samples of test series B, and those of the corresponding samples in test series A. Points joined by solid curves are for the test series B samples, and dashed curves connect points for the test series A samples. There appears to be little difference in the permeability of corresponding samples, and the variation shown is probably well within the limits of error afforded by the use of this method of computing permeability. It may be concluded from this plot that directional effects caused by the extrusion method used in the preparation of these samples, insofar as permeability is concerned, is negligible. Refer to Figure 10 for sketch showing direction of sample with respect to axis of extrusion.

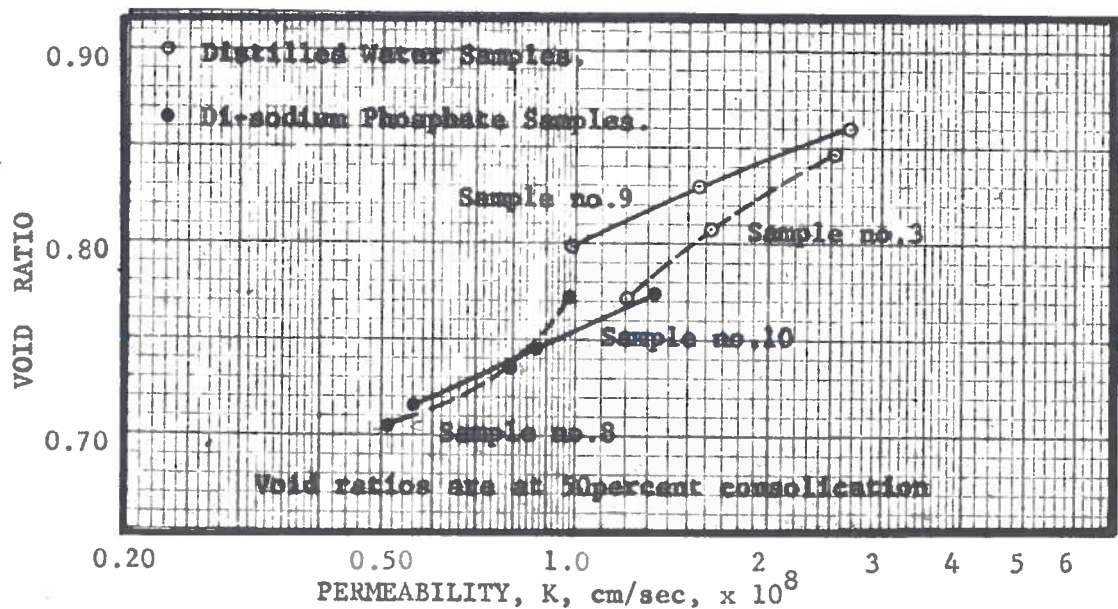


FIGURE 14. Plot of permeability versus void ratio for compression samples no. 3, 8, 9, 10.

Comparison of Curves of Logarithm of Pressure Versus Void Ratio.

Figure 15 shows a semi-logarithmic plot of pressure versus void ratio for samples no. 1, 3, 5, 7, and 12 of test series A, and for the single "Quadrofos" sample of test series C. In Figure 16 is the plot of the other samples in test series A, these being the duplicate tests of the series. It may be noted that the samples of both distilled water and di-sodium phosphate pore solutions which were prepared at the lower water contents exhibit a pseudo-preconsolidation portion in their curves. This is probably the result of the increased resistance that the materials of lower water content displayed during the extrusion process. Partial consolidation of these samples during extrusion is believed to be responsible for the break in the curves of these samples. There is also exhibited a trend for an increase in slope of the rebound curves with decreasing void ratio.

At any given pressure, the void ratio of the di-sodium phosphate samples is less than that of the distilled water samples. This must be due to a more efficient packing of particles, i.e., a more parallel orientation of particles in the di-sodium phosphate samples. There is good agreement of the curves for the duplicate tests as shown in Figure 16. This was to be expected, however, because of the extrusion method of sample preparation.

Figure 17 shows the semi-logarithmic plot of pressure versus void ratio for the two samples of test series B, and the corresponding samples of test series A. Solid curves are for the B samples, and dashed curves represent the corresponding A samples. The total compression of the

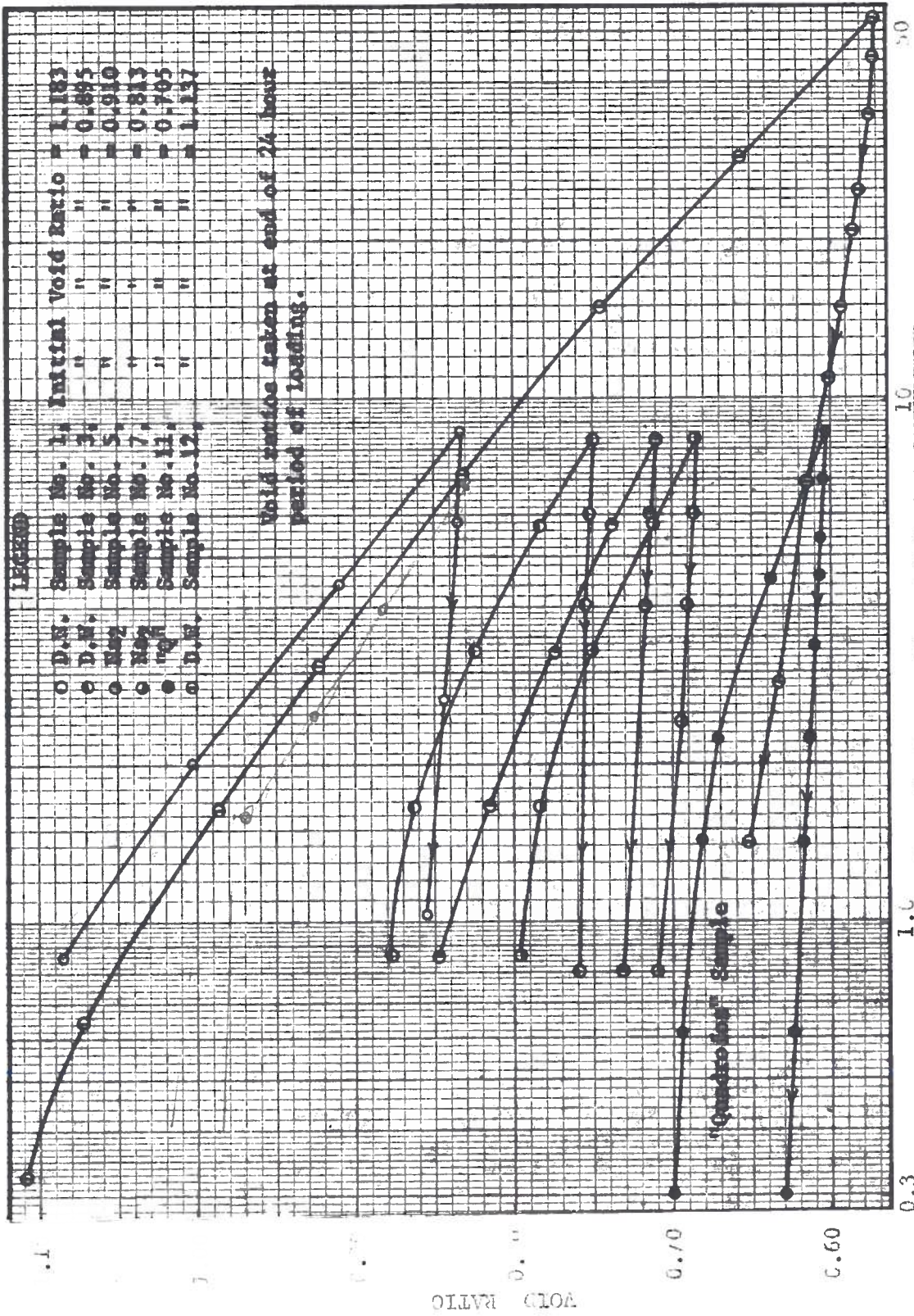


FIGURE 15. Curves of logarithm of pressure versus void ratio for samples no.1,3,5,7,11, and 12.



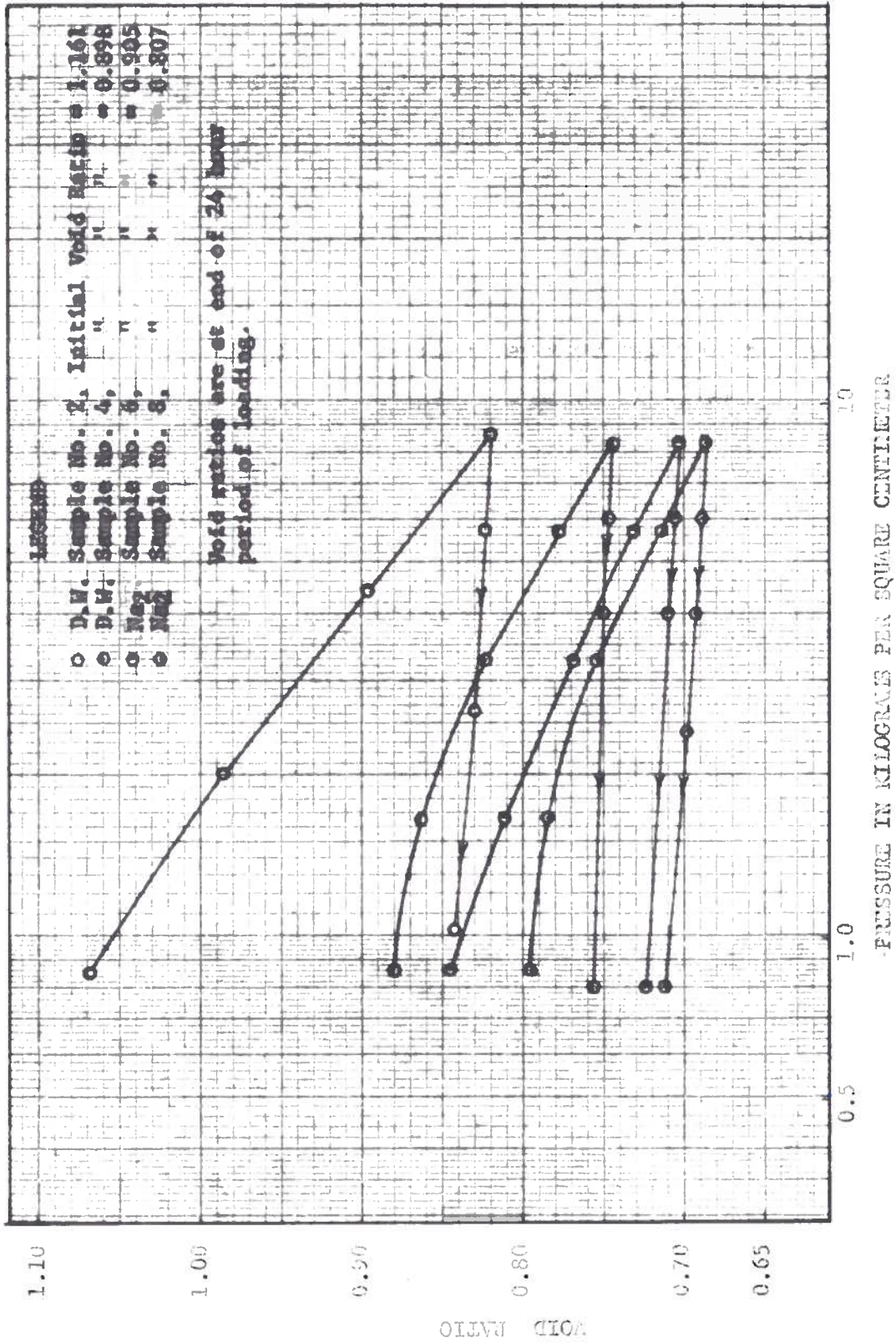


FIGURE 16. Curves of logarithm of pressure versus void ratio for samples no. 2, 4, 6, and 8.

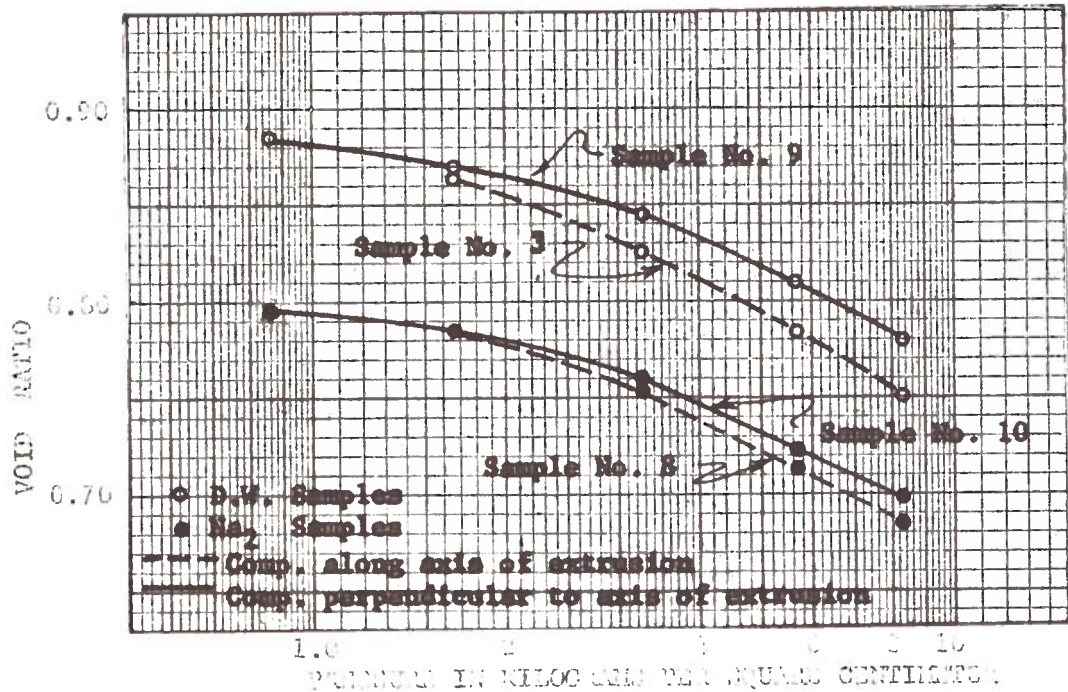


FIGURE 17. Comparison of Logarithm of pressure versus void ratio curves obtained for samples compressed along axis of extrusion and perpendicular to axis of extrusion.

samples in test series B is less than that of the corresponding samples which were compressed along the axis of extrusion. The pressure increments and total load was the same for all samples shown in Figure 17. The void ratio reduction in each pressure increment up to 1.65 kilograms per square centimeter was about the same for corresponding samples of test series A and B. In the pressure increment of 1.65 to 3.28 kilograms per square centimeter, the void ratio change occurring was approximately 30 percent less for the samples compressed perpendicular to the axis of extrusion than the void ratio change of the corresponding samples of test series A that had been compressed along the axis of extrusion. In succeeding increments of pressure, the void ratio change of the samples of test series B was always less than that which had occurred in the same pressure increment for the corresponding samples of test series A. The

magnitude of difference decreased with each succeeding increment, however, and in the final pressure increment of 5.68 to 8.30 kilograms per square centimeter, the average difference in void ratio change for corresponding samples was approximately a 10 percent reduction for the samples of test series B. This comparison indicates that there is a difference in clay particle structure with respect to direction. The particle arrangement on the average must be more parallel in a direction perpendicular to the axis of extrusion.

Summary of Indications of Structure Difference in Distilled Water and Di-sodium Phosphate compression Samples.

1. At a given void ratio, distilled water samples have greater strength as determined from the laboratory vane shear tests. This indicates that they are more resistant to being forced to a parallel structure, and are therefore more flocculated.
2. Sensitivity of the distilled water samples is greater at any given void ratio. This infers a more flocculated initial structure.
3. Distilled water samples require a greater pressure to attain a given void ratio. This implies a more flocculated structure, although the greater strength of these samples could also account for this fact.
4. The distilled water samples exhibit greater permeability at a given void ratio, therefore, discounting possible interference to flow from larger double layer in the di-sodium phosphate samples, a more flocculated structure is indicated.
5. A more parallel arrangement of particles perpendicular to the axis of extrusion is evidenced for both distilled water and di-sodium

phosphate pore solutions. The differences in void ratio change in any given pressure increment, between samples compressed perpendicular to and those compressed along the axis of extrusion strongly point up this conclusion.

It is strongly suggested by the results of the foregoing tests that at a given void ratio, the di-sodium phosphate samples have a more dispersed structure than the distilled water samples of kaolinite clay.

Slope of the Secondary Compression Curves. Several factors may affect the slope of the secondary compression curve. Some of the variables involved are the material, void ratio, size of pressure increment, total magnitude of pressure, amount of secondary compression having previously taken place, and the initial structure of the material. The extent to which these variables are interrelated is unknown.

It was the intent of this investigation to control as many of the variables as possible, and to determine the affect created by some of the others. In these tests, the kaolinite clay for all samples was obtained from the same source and was assumed to have constant properties. The technique of preparation was the same for all samples, and in testing, the pressure increments used on each sample was the same except on samples no. 1, 2, and 12, the distilled water samples of high initial water content. Total load and period of loading were the same for all samples excepting samples no. 1, 2, and 12. The period of loading was 48 hours in each increment for samples no. 1 and 2.

The results of the tests as previously discussed provide a strong indication that a structure difference in the kaolinite clay samples did



result from the use of a deflocculating agent as the pore solution in one group of samples, and that a more parallel orientation of particles was obtained in the di-sodium phosphate samples than in the distilled water samples. On that basis, the effect of structure on the secondary compression of kaolinite may be compared. Slopes of the secondary compression curves will be compared at:

1. Same void ratio.
2. Same average intergranular pressure.

Figure 18 shows a plot of slope of secondary compression curve versus void ratio at the end of a 24 hour pressure increment period. The di-sodium phosphate samples show a trend toward rapidly increasing slope of the secondary compression curve with decrease in void ratio. The slopes of the secondary compression curves for the distilled water samples seem to be affected by the water content at which they were initially prepared. Those prepared at high initial water contents do not exhibit great change in slope with decreasing void ratio. On the other hand, those prepared at water contents close to the plastic limit of the samples show a trend similar to that of the di-sodium phosphate samples, that is, a large increase in slope with small decrease in void ratio. In every case of the samples tested in this investigation, the distilled water samples exhibited a greater slope of secondary compression than did the di-sodium phosphate samples, when compared at any given void ratio.

Figure 19 shows a plot of slope of secondary compression curve versus logarithm of pressure. For the di-sodium phosphate, a wide range of values of slope appear at low pressures. With increase in pressure, the variation between samples is less pronounced and there is a distinct tendency for an

# 11  
1/90-tetra ph

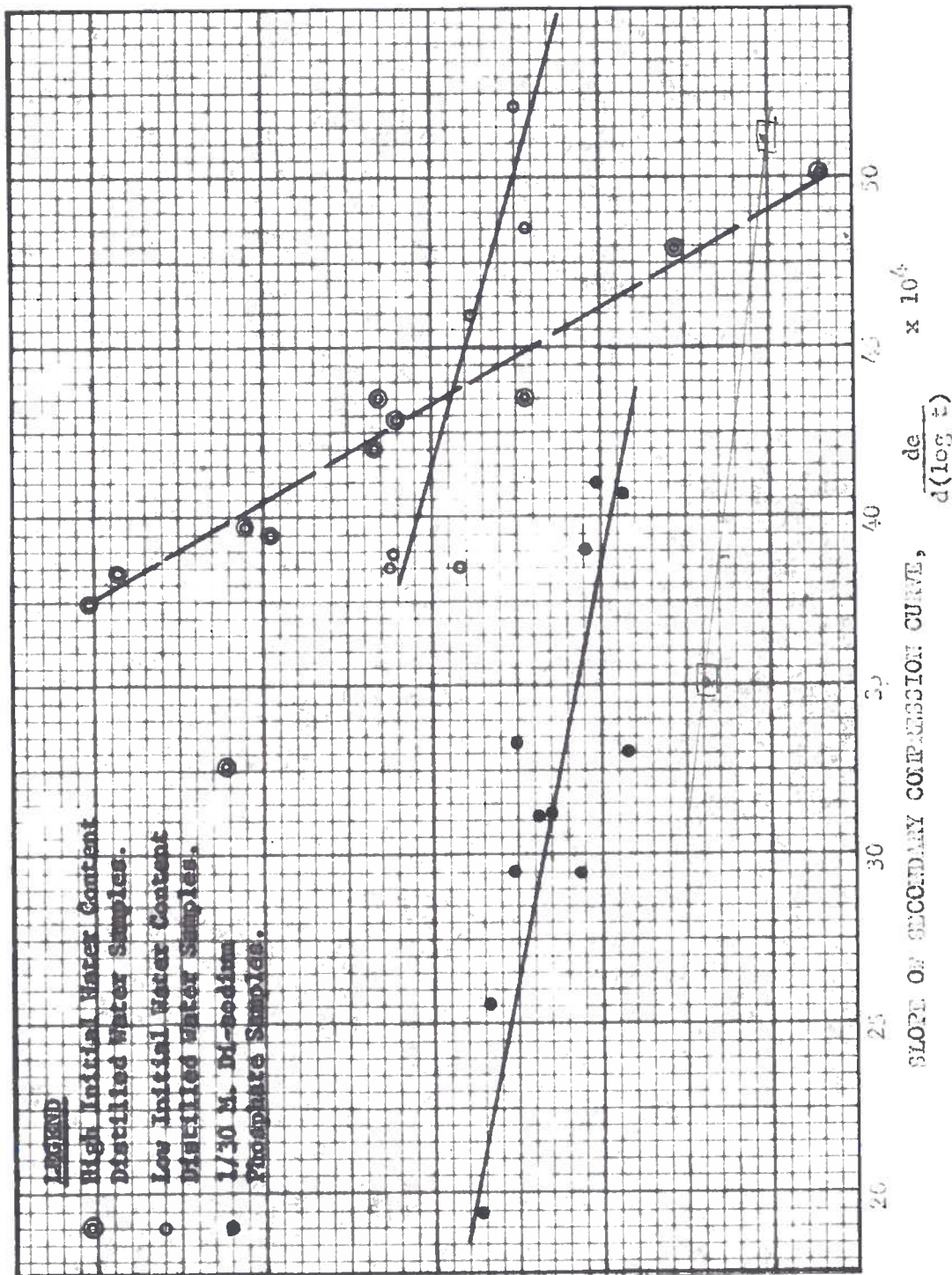


FIGURE 10. Plot of slope of secondary compression curves versus void ratio for kaolinite clay compression samples. (Samples of test series A only)

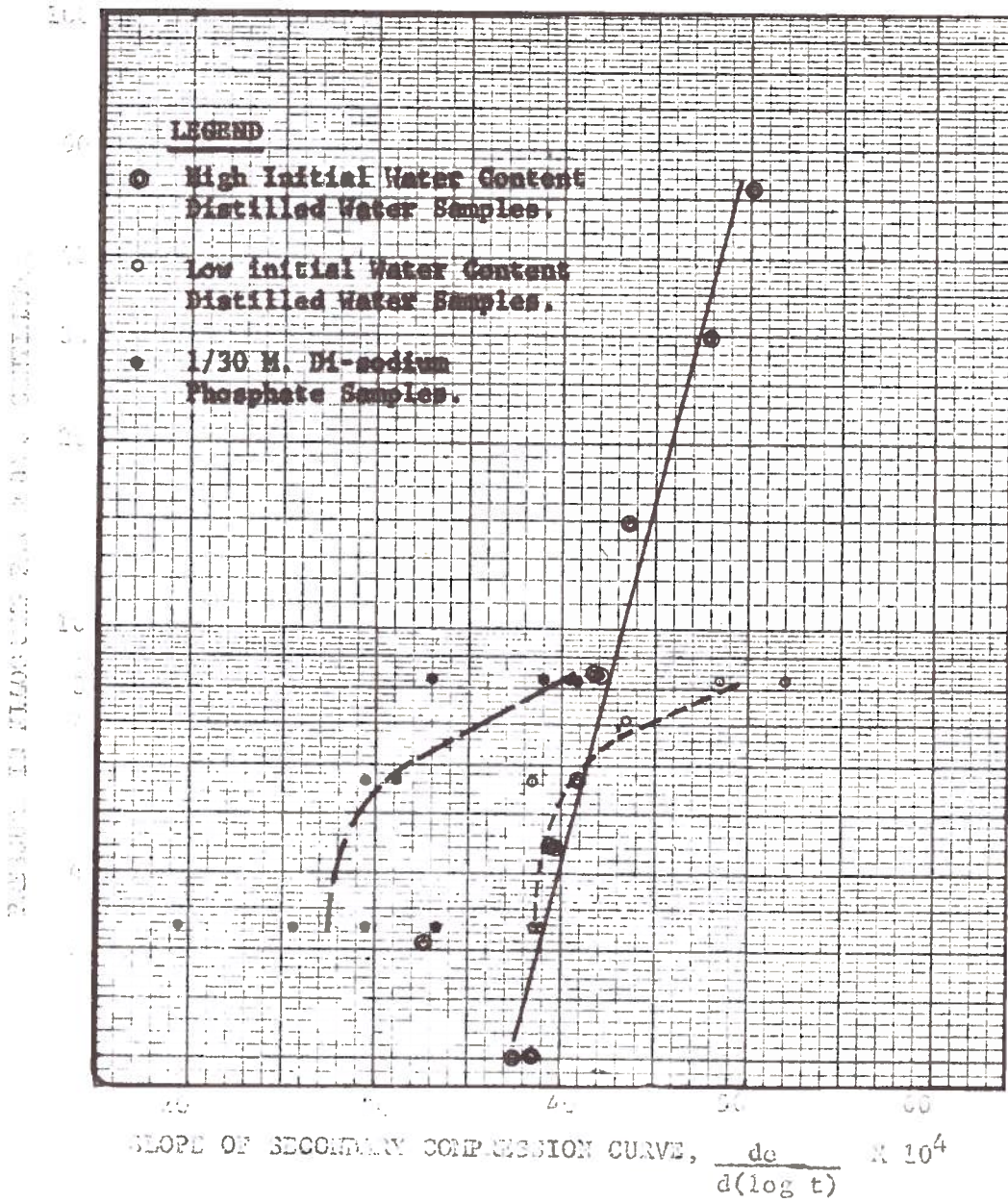


FIGURE 13. Plot of slope of secondary compression curves versus logarithm of pressure for kaolinic clay compression samples.



increase in slope to occur with increasing pressure. For the distilled water samples of low initial water content there appears to be little variation in slope at lower pressures, but the slope increases by a large amount at high pressures. The behavior of these samples at higher pressure is similar to that exhibited by the di-sodium phosphate samples, and the rate of increase of slope of the secondary compression curves is about the same for samples of both pore solutions. Within the range of pressures to which the samples were subjected, at any given pressure, the slope of the secondary compression curve was greater for the distilled water samples than for the di-sodium phosphate samples.

The distilled water samples which were prepared at high initial water contents show an increase in the slope of their secondary compression curves with increasing pressure, but not by as nearly a significant amount as those prepared at low initial water contents. The exact relationship between initial water content and the slope of the secondary compression curve occurring at varying pressures cannot be determined, however, from the tests performed in this investigation.

#### Summary of Results of Secondary Compression Comparisons.

1. At the same pressure, the slopes of the kaolinite clay samples with the distilled water pore solution was greater than slopes of the secondary compression curves for the samples with the di-sodium phosphate pore solution.

2. At the same void ratio, the slopes of the kaolinite clay samples with the distilled water pore solution was greater than slopes of the secondary compression curves for samples with the di-sodium phosphate pore solution.

3. A more flocculated structure will exhibit greater secondary compression , in spite of the weaker bonds which are evident in a more dispersed structure.

4. The slope of the secondary compression curve increases with increasing pressure. The slope increases also with decreasing void ratio. In spite of the fact that the degree of flocculation decreases with decreasing void ratio, secondary compression increases. This may be attributed to increasing pressure producing the void ratio decrease masks the effect of a more parallel particle orientation.

## SECTION IV

### CONCLUSIONS OF THIS INVESTIGATION

The conclusions presented are based on the results of tests performed on a commercial kaolinite powder with distilled water and di-sodium phosphate pore solutions. The findings may or may not be applicable to other types of clay soils whose structural characteristics are not the same as the kaolinite used in this study. It has been concluded from this study that:

1. The structure of kaolinite clay may be altered to a more parallel orientation of particles by the use of di-sodium phosphate as the pore solution in place of distilled water.
2. At a given pressure, a more flocculated structure will provide greater secondary compression than a less flocculated structure.
3. At a given void ratio, a more flocculated arrangement of particles in the clay will provide greater secondary compression than a less flocculated orientation.
4. With increase in pressure there is an increase in the slope of the secondary compression curve, regardless of initial structure.
5. An increase in the slope of the secondary compression curve occurs with decrease in void ratio.



APPENDIX

| Sample   | 1               | 2               |
|--|-----------------|-----------------|
| Pore Solution  | Distilled Water | Distilled Water |
| Initial Void Ratio   | 1.183           | 1.161           |
| Water Content, percent   | Initial         | 44.5            |
|  | Final           | 33.4            |
| Degree of Saturation, percent  | Initial         | 100.5           |
|  | Final           | 106.5           |
| Pressure, kg/cm <sup>2</sup>   | 2.01            | 8.61            |
|  | 1.003           | 0.833           |
| Void Ratio, Final  | 0.910           | 0.820           |
| Coefficient of Consolidation, C <sub>v</sub> , x 10 <sup>4</sup>                         | 2.80            | 6.81            |
|  | 7.22            | 1.83            |
| Coefficient of Compressibility, S <sub>v</sub> , x 10 <sup>2</sup> , cm <sup>2</sup> /kg | 4.15            | 2.34            |
|  | 3.75            | 3.84            |
| Coefficient of Permeability, K, cm/sec, x 10 <sup>8</sup>                                | 3.50            | 3.00            |
|  | 3.97            | 3.95            |
| Slope of Secondary Compression Curve, de/d(log t), x 10 <sup>3</sup>                     | 3.75            | 3.84            |
|  | 3.97            | 4.28            |

TABLE 1.  $\frac{C_d}{C_c} =$  Data sheet for samples no. 1 and 2.  $\frac{C_d}{C_c} = .0141$   $\frac{C_d}{C_c} = .0154$   $\frac{C_d}{C_c} = .0147$   $\frac{C_d}{C_c} = .0155$

C<sub>d</sub> =

| Sample  | 3               | 4               |       |       |       |       |
|---|-----------------|-----------------|-------|-------|-------|-------|
| Pore Solution   | Distilled Water | Distilled Water |       |       |       |       |
| Initial Void Ratio  | 0.895           | 0.898           |       |       |       |       |
| Water Content, percent                                    | Initial         | 34.3            |       |       |       |       |
|   | Final           | 31.6            |       |       |       |       |
| Degree of Saturation, percent                             | Initial         | 100.0           |       |       |       |       |
|   | Final           | 111.0           |       |       |       |       |
| Pressure, kg/cm <sup>2</sup>                              | 3.28            | 5.68            | 8.30  | 3.28  | 5.68  | 8.30  |
|   | 0.825           | 0.783           | 0.750 | 0.822 | 0.778 | 0.744 |
| Coefficient of Consolidation, $c_v$ , x 10 <sup>4</sup>   | 5.83            | 5.11            | 5.39  | 5.19  | 4.83  | 4.30  |
|   | 2.35            | 1.75            | 1.26  | 2.46  | 1.83  | 1.29  |
| Coefficient of Permeability, K, cm/sec, x 10 <sup>8</sup> | 2.54            | 1.62            | 1.20  | 2.35  | 1.59  | 0.98  |
|   | 3.85            | 3.85            | 5.20  | 3.89  | 4.09  | 4.85  |

TABLE 2.

Data sheet for samples no. 3 and 4.

-0.277 -0.777 -0.916 -0.817



| Sample   | 7                           | 8                           |              |              |              |              |
|--|-----------------------------|-----------------------------|--------------|--------------|--------------|--------------|
| Pore Solution  | 1/30 M. Di-sodium Phosphate | 1/30 M. Di-sodium Phosphate |              |              |              |              |
| Initial Void Ratio   | 0.813                       | 0.807                       |              |              |              |              |
| Water Content, percent   | Initial                     | 31.2                        |              |              |              |              |
|  | Final                       | 28.5                        |              |              |              |              |
| Degree of Saturation, percent  | Initial                     | 100.0                       |              |              |              |              |
|  | Final                       | 108.5                       |              |              |              |              |
| Pressure, kg/cm <sup>2</sup>   | 3.28                        | 5.68                        | 8.30         | 3.27         | 5.68         | 8.30         |
|  | 0.751                       | 0.711                       | 0.685        | 0.754        | 0.714        | 0.687        |
| Void Ratio, Final  | $c_c = .166$                | $c_c = .158$                | $c_c = .158$ | $c_c = .164$ | $c_c = .158$ | $c_c = .164$ |
|  | 2.78                        | 1.95                        | 2.88         | 2.89         | 2.74         | 2.89         |
| Coefficient of Consolidation, $c_v$ , x 10 <sup>4</sup>              | 1.97                        | 1.66                        | 0.99         | 1.92         | 1.67         | 1.03         |
|  | 0.82                        | 0.56                        | 0.47         | 0.98         | 0.79         | 0.51         |
| Slope of Secondary Compression Curve, de/d(log t), x 10 <sup>3</sup> | 3.33                        | --                          | 3.30         | 2.95         | 2.95         | 4.06         |

TABLE 4.  $\frac{c_v}{c_c}$  .0197 .0101 .0127 .0214 Data sheet for samples no. 7 and 8.

| Sample Number   | 9               | 10                          |       |       |       |       |
|---|-----------------|-----------------------------|-------|-------|-------|-------|
| Pore Solution   | Distilled Water | 1/30 M. Di-sodium Phosphate |       |       |       |       |
| Initial Void Ratio  | 0.905           | 0.810                       |       |       |       |       |
| Water Content, percent.   | Initial         | 31.1                        |       |       |       |       |
|   | Final           | 28.9                        |       |       |       |       |
| Degree of Saturation, percent.  | Initial         | 100.0                       |       |       |       |       |
|   | Final           | 105.5                       |       |       |       |       |
| Pressure, kg/cm <sup>2</sup>  | 3.28            | 5.68                        | 8.30  | 3.28  | 5.68  | 8.30  |
|   | 0.845           | 0.810                       | 0.779 | 0.760 | 0.724 | 0.699 |
| Void Ratio, Final   |                 |                             |       |       |       |       |
| Coefficient of Consolidation, $c_v$ , x 10 <sup>4</sup>                       | 9.40            | 5.86                        | 4.69  | 5.15  | 3.09  | 3.43  |
|   | 1.54            | 1.46                        | 1.18  | 1.46  | 1.50  | 0.96  |
| Coefficient of Compressibility, $a_v$ , cm <sup>2</sup> /kg x 10 <sup>2</sup> | 2.69            | 1.56                        | 0.99  | 1.33  | 0.87  | 0.56  |
|   | 2.91            | 3.68                        | 4.45  | 2.78  | 4.07  | 3.70  |
| Slope of Secondary Compression Curve, $de/d(\log t)$ , x 10 <sup>3</sup>      |                 |                             |       |       |       |       |

$\frac{d\epsilon}{d\log t} = 0.224$   $c_c = 0.116$   $c_c = 0.127$   $c_c = 0.152$   $c_c = 0.256$

TABLE 5. Data sheet for samples no. 9 and 10.



| Sample   | 11                            | 12              |
|--|-------------------------------|-----------------|
| Pore Solution  | 1/40 M. Sodium Tetraphosphate | Distilled Water |
| Initial Void Ratio   | 0.705                         | 1.137           |
| Water Content, percent   | Initial                       | 43.6            |
|  | Final                         | 27.8            |
| Degree of Saturation, percent  | Initial                       | Assumed 100.0   |
|  | Final                         | -----           |
| Pressure, kg/cm <sup>2</sup>   | 4.51                          | 8.55            |
|  | 0.639                         | 0.602           |
| Void Ratio, Final  | 3.70                          | 4.15            |
|  | 1.39                          | 0.92            |
| Coefficient of Consolidation, $c_v$ , x 10 <sup>4</sup>                        | 3.09                          | 7.11            |
|  | 0.922                         | 0.830           |
| Coefficient of Compressibility, $a_v$ , cm <sup>2</sup> /kg, x 10 <sup>2</sup> | 3.73                          | 7.00            |
|  | 4.45                          | 2.26            |
| Coefficient of Permeability, K, cm/sec, x 10 <sup>8</sup>                      | 3.20                          | 2.96            |
|  | 3.26                          | 4.35            |
| Slope of Secondary Compression Curve, $de/d(\log t)$ , x 10 <sup>3</sup>       | 3.26                          | 4.35            |
|  | 3.26                          | 4.35            |

$C_c =$

$\frac{C_c}{C_c}$

.0328      .0150      .0120      .0144      .0150

TABLE 6. Data sheet for samples no. 11 and 12.

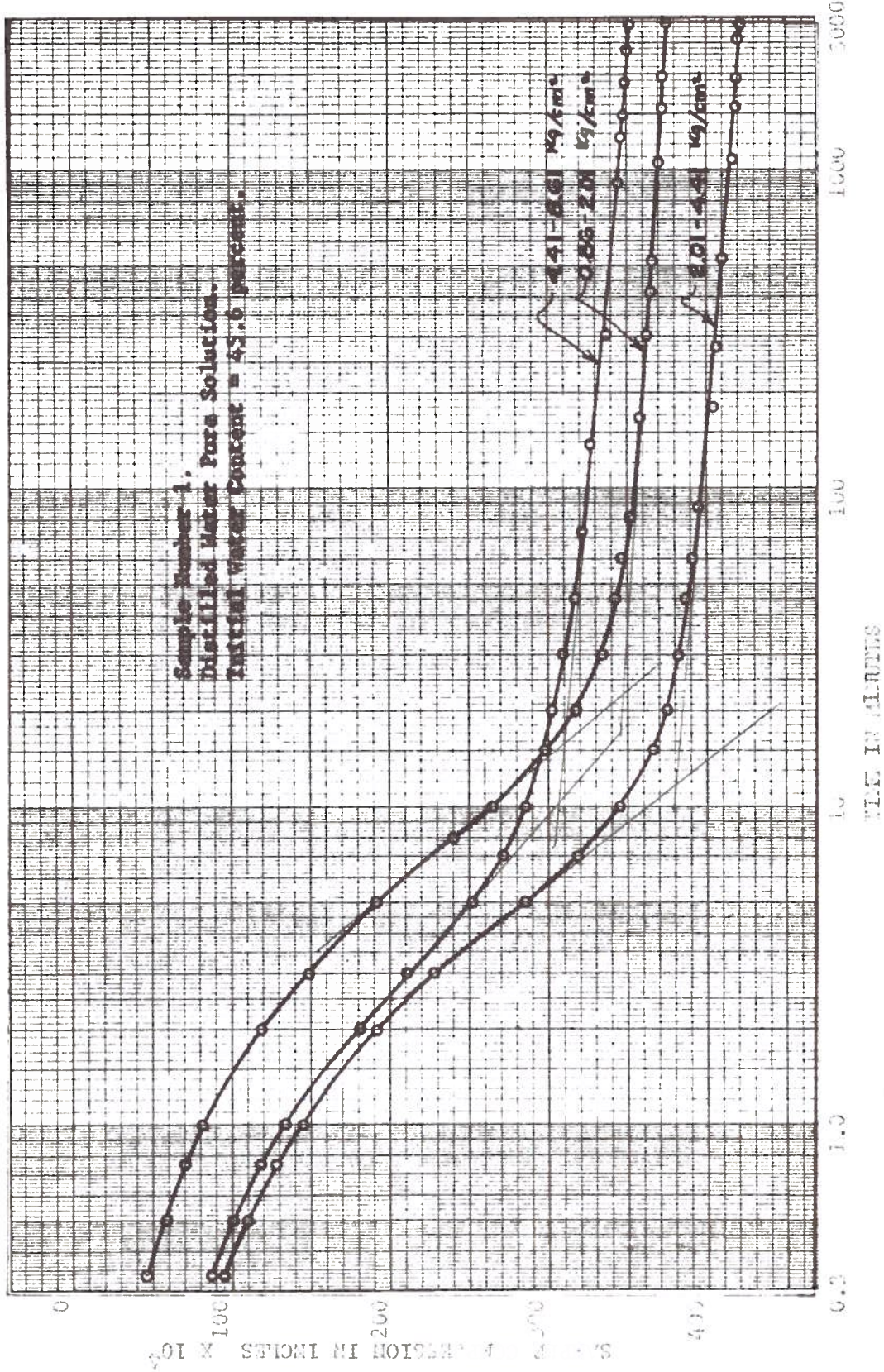


FIGURE 20. Laboratory compression curves for sample no. 1.



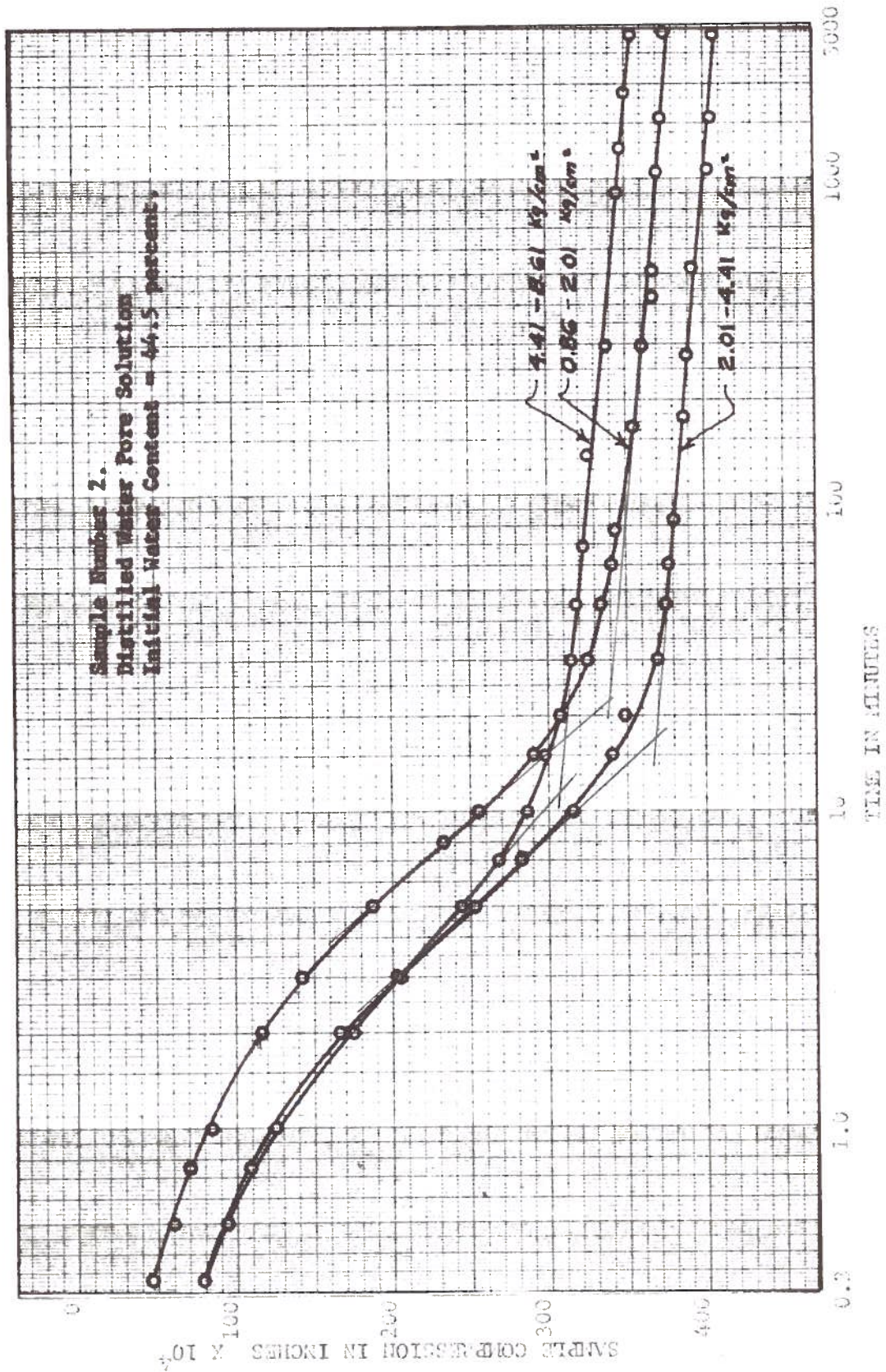


FIGURE 21 Laboratory compression curves for sample no. 2.



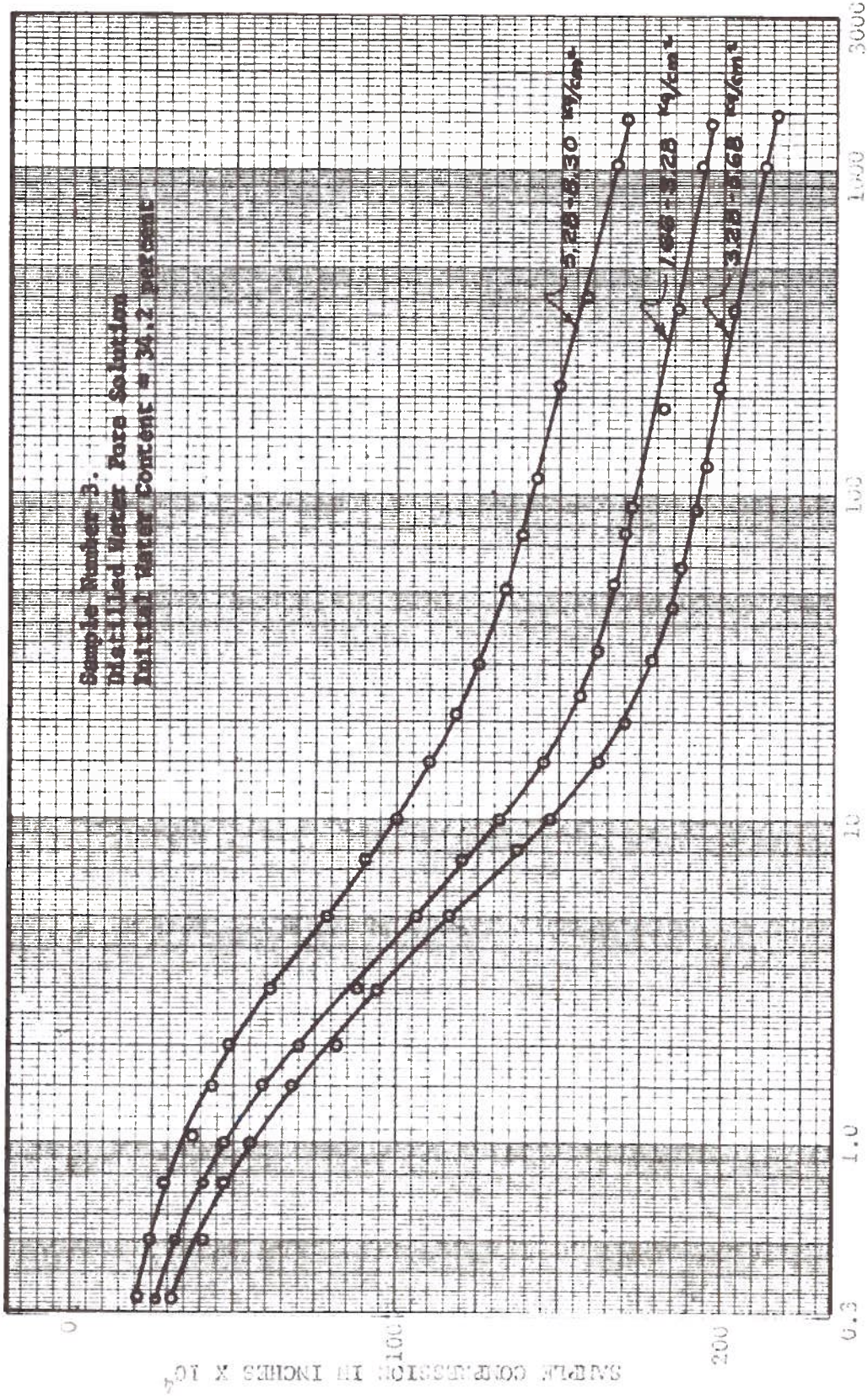


FIGURE 22. Laboratory compression curves for sample no. 3.



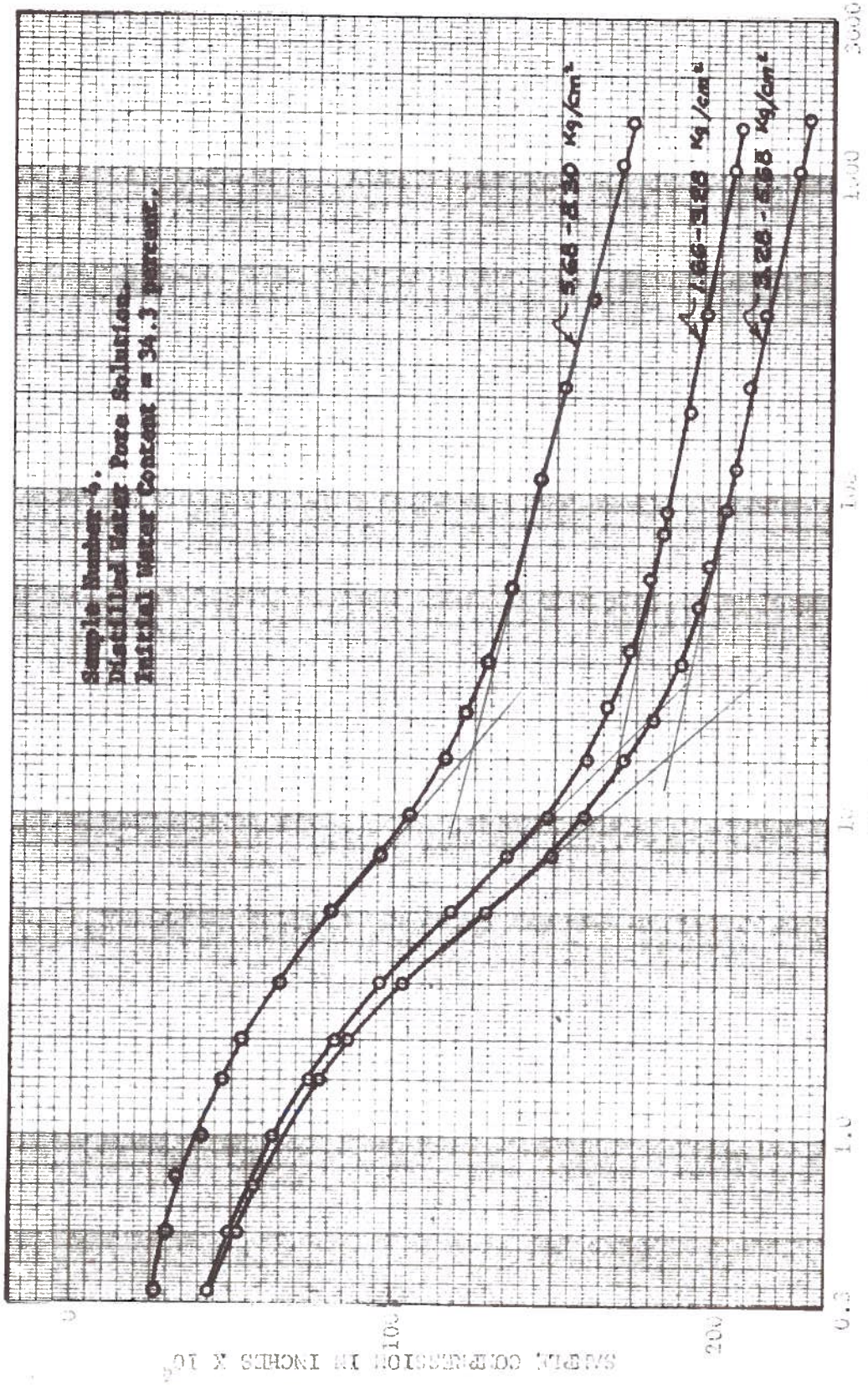


FIGURE 23. Laboratory compression curves for sample no. 4.



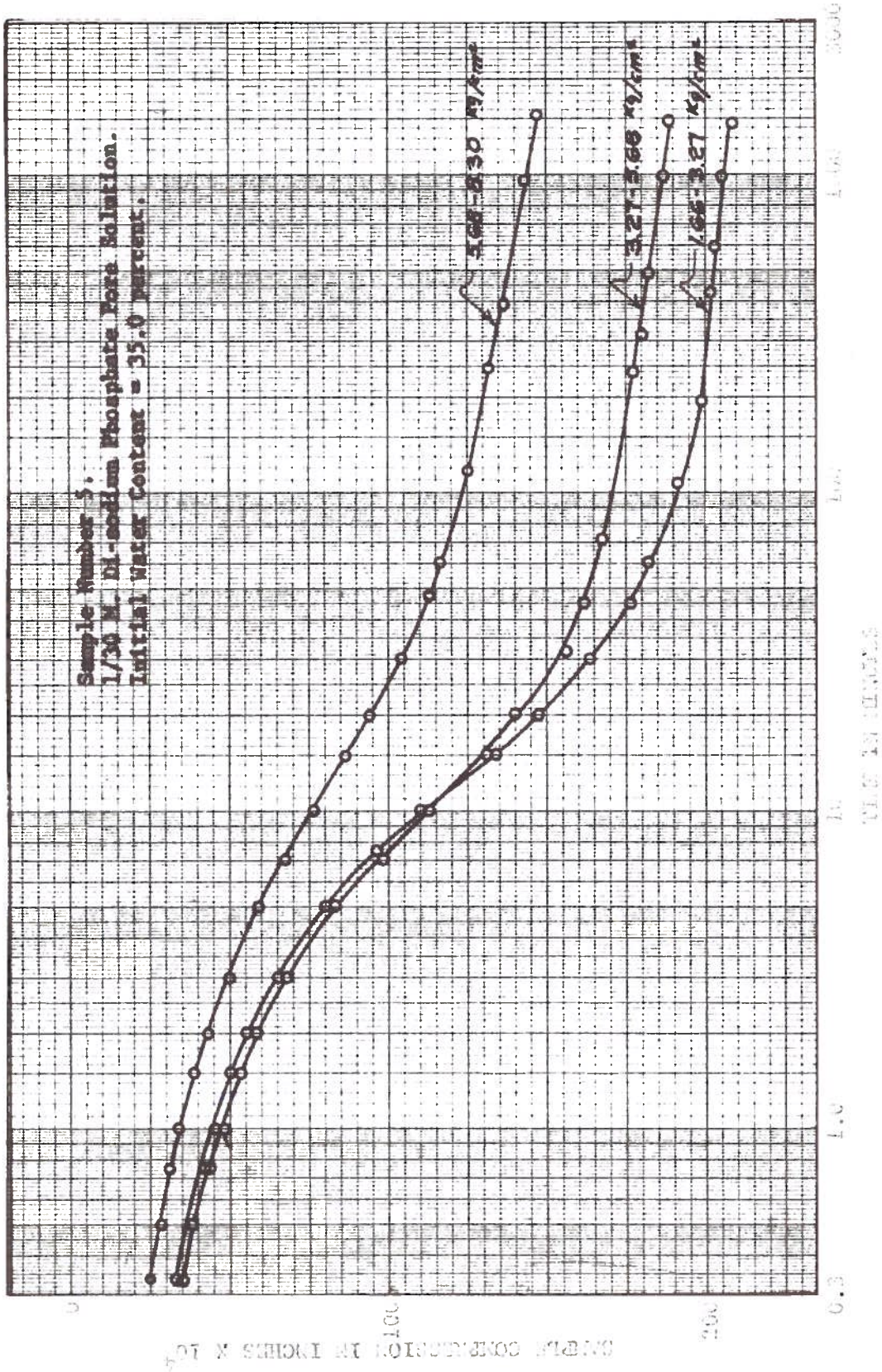


FIGURE 24. Laboratory compression curves for sample no. 5.



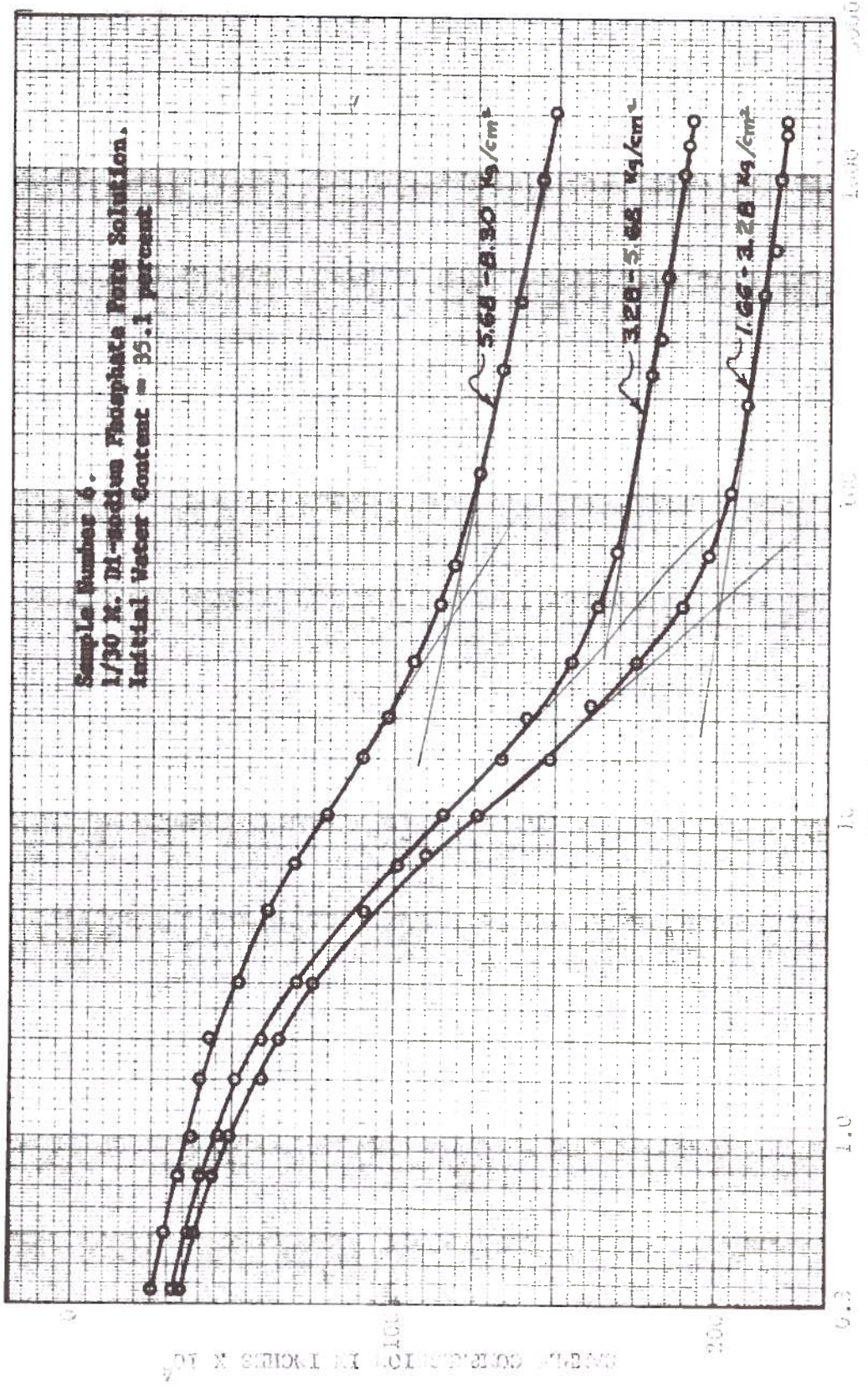


FIGURE 25. Laboratory compression curves for sample no. 6.



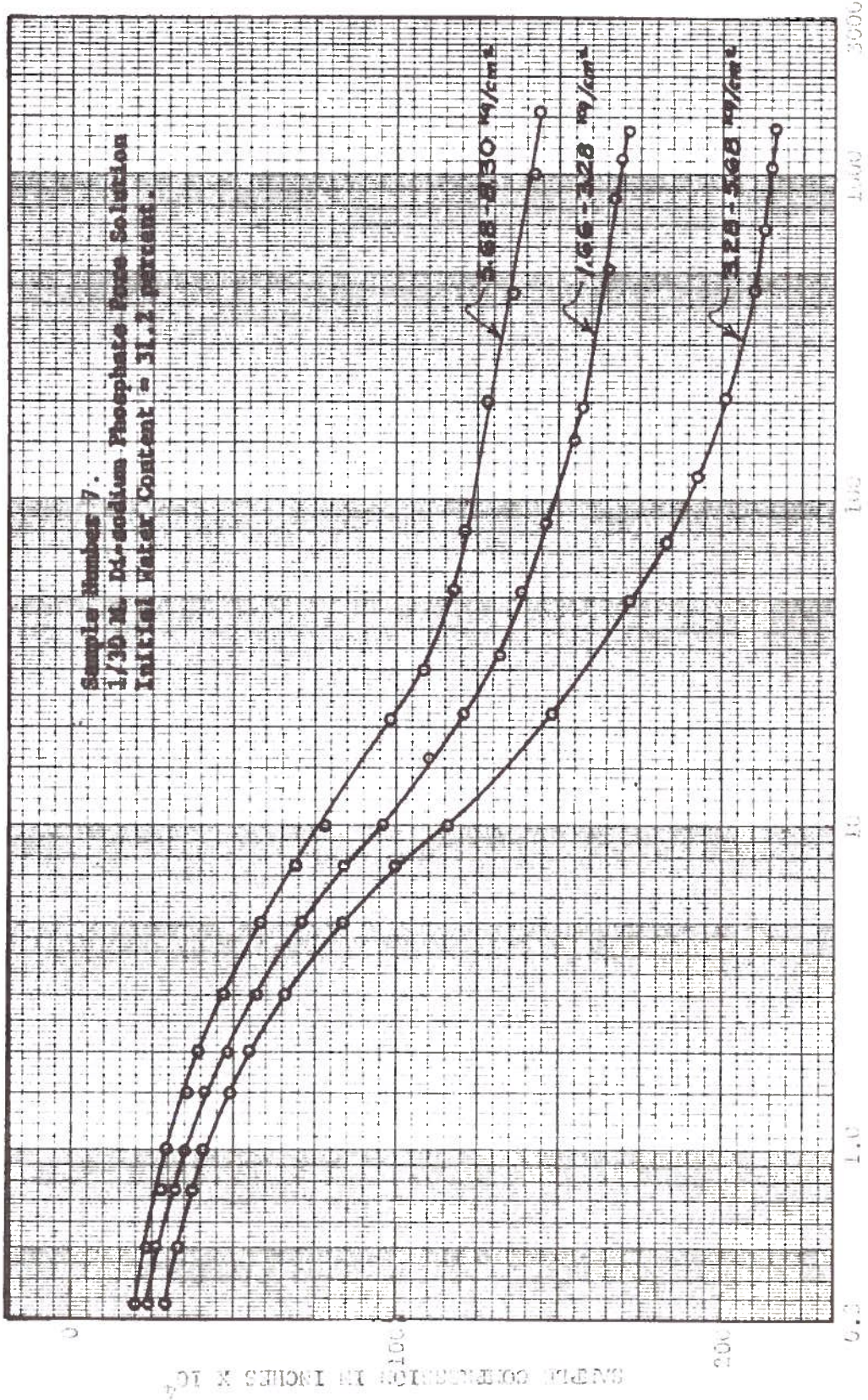


FIGURE 26. Laboratory compression curves for sample no. 7.



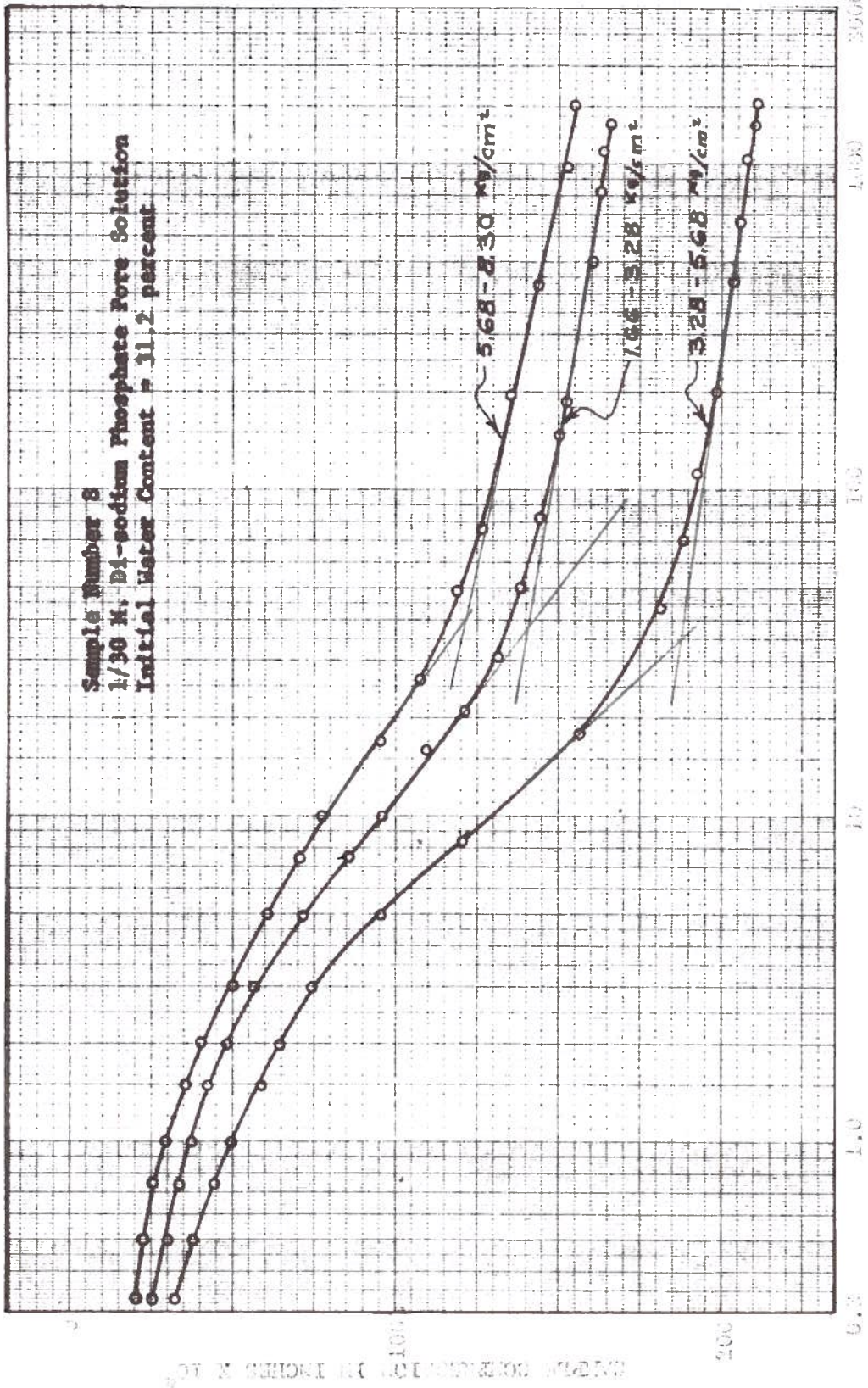


FIGURE 27. Laboratory compression curves for sample no. 8.

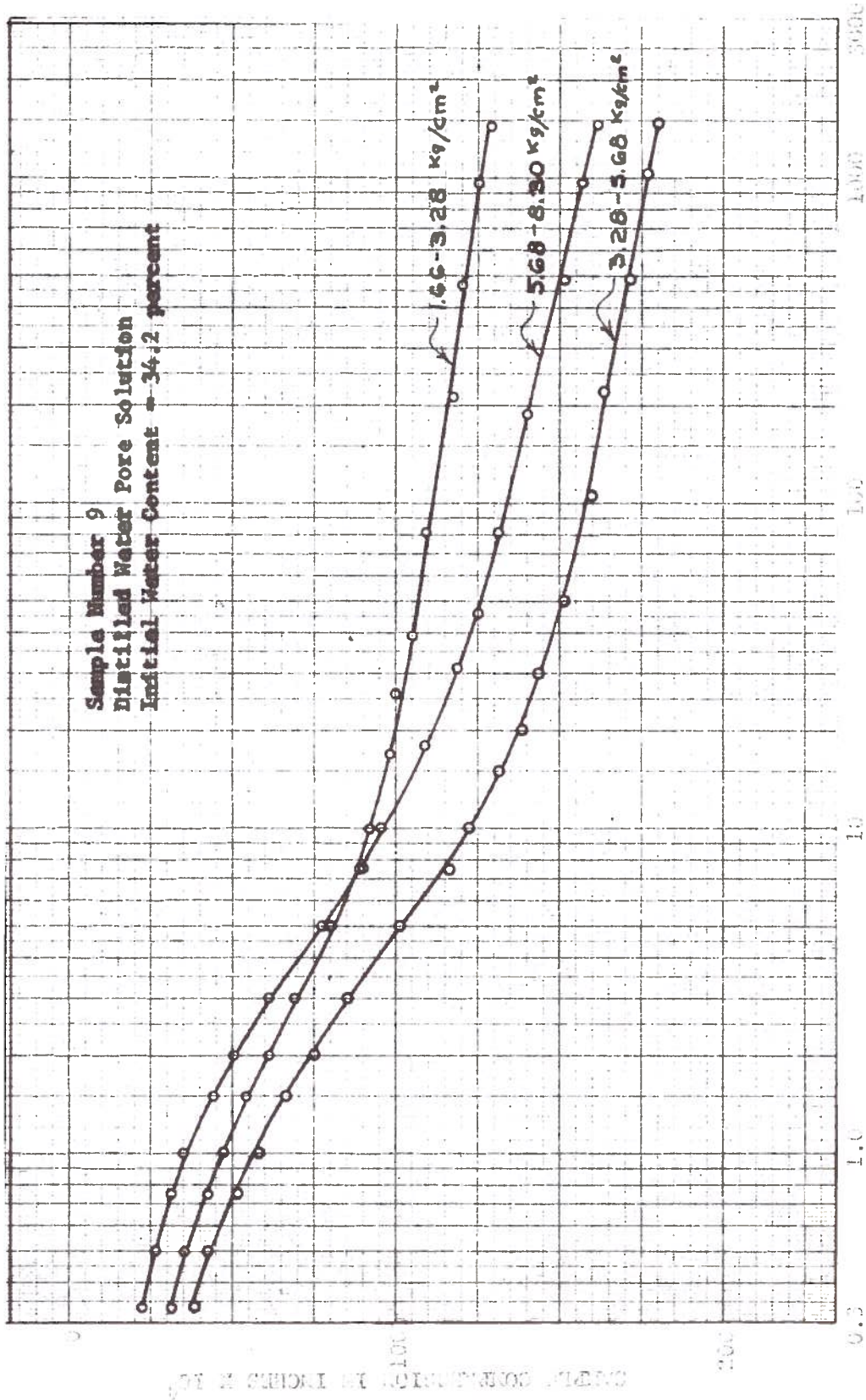


FIGURE 28. Laboratory compression curves for sample no. 9.



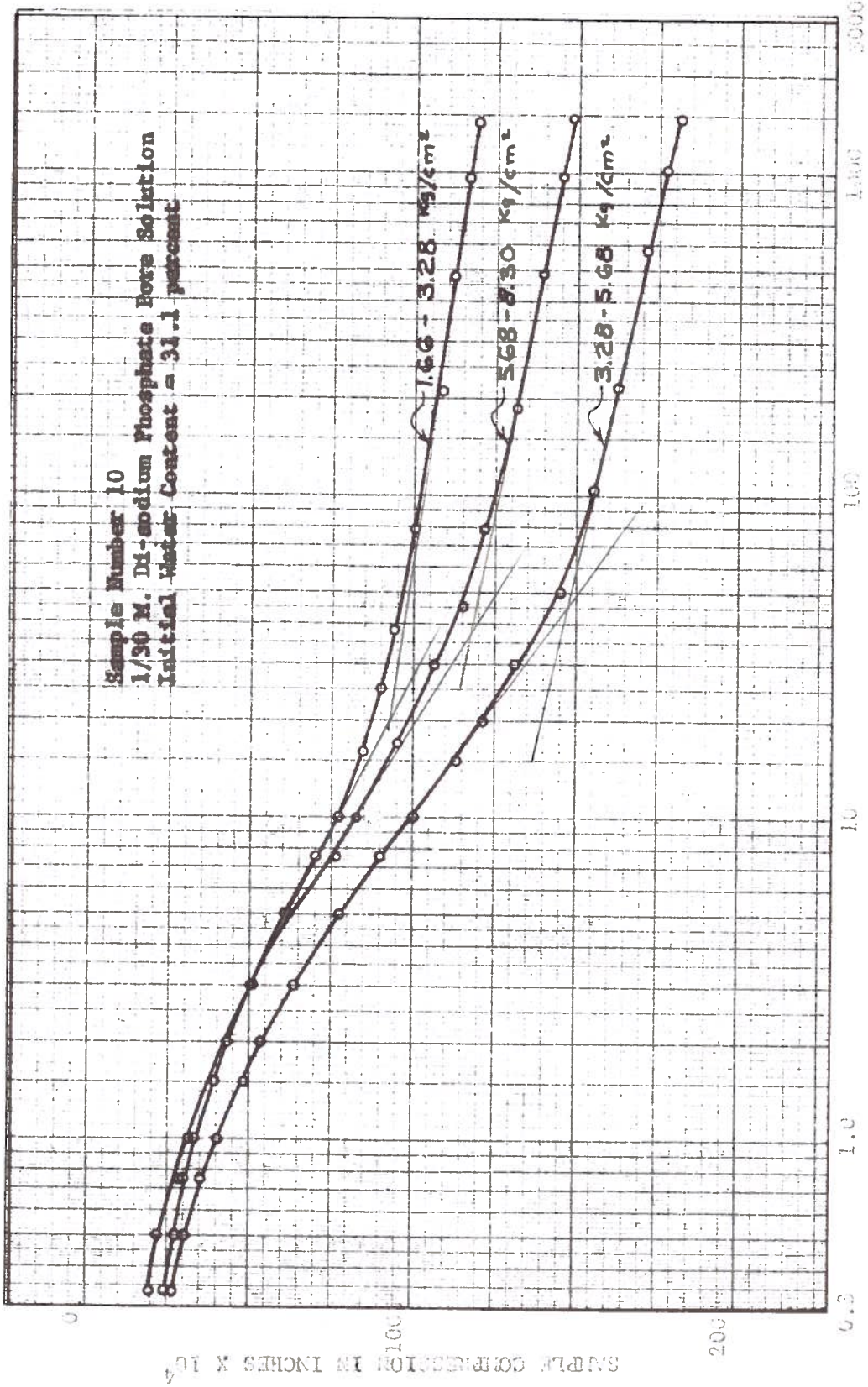


FIGURE 29. Laboratory compression curves for sample no. 10.

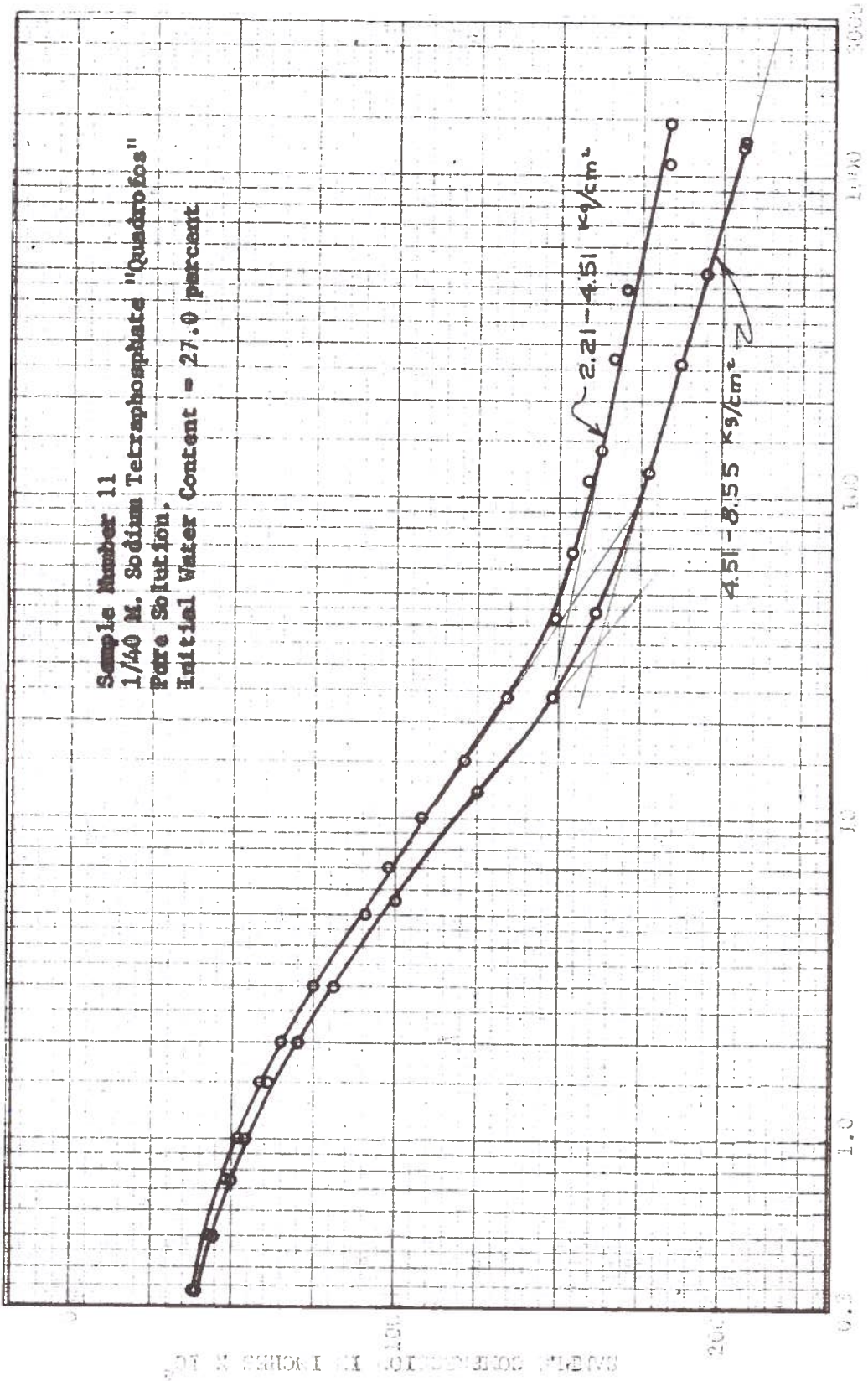


FIGURE 30. Laboratory compression curves for sample no. 11.



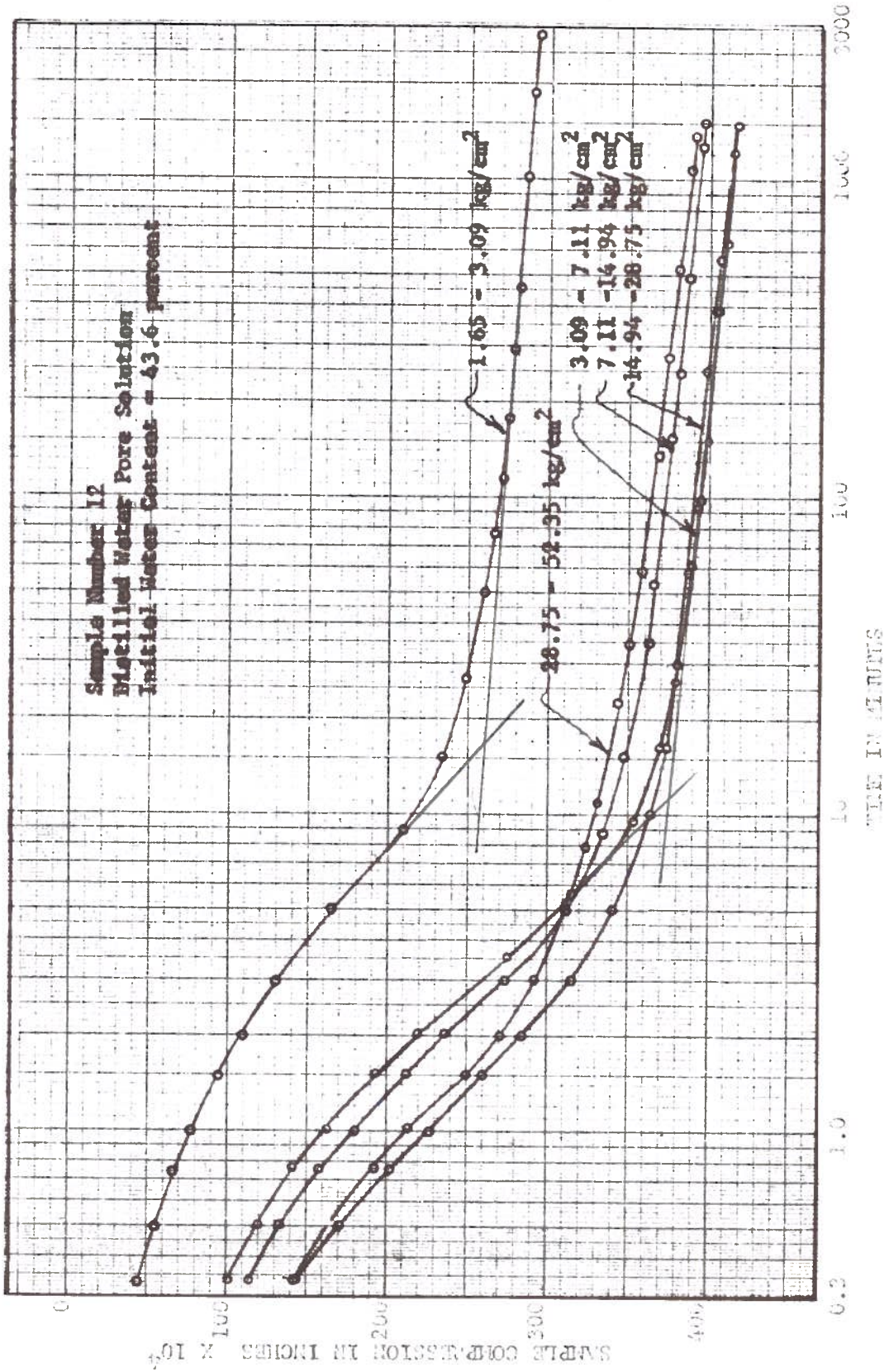


FIGURE 31. Laboratory compression curves for sample no. 12.

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## BIOGRAPHICAL SKETCH

James Wesley Macfarlane was born in Cape May County, New Jersey, August 9, 1930.

He attended high school in Philadelphia, Pennsylvania, and in 1948 enlisted in the United States Army. After serving five years in the service, he was released from active duty in the grade of First Lieutenant in 1953. In February, 1954, he entered Drexel Institute of Technology in Philadelphia, and transferred to the University of Florida in 1956. He received a degree of Bachelor of Civil Engineering from the University of Florida in June, 1958. He was then enrolled in the Graduate School at the University of Florida to continue work towards a Master of Science degree in Civil Engineering.

He is a member of the honorary fraternities of Sigma Tau and Phi Kappa Phi.

He is married and has one daughter.

This thesis was prepared under the direction of the Chairman of the candidate's supervisory committee and has been approved by all members of the committee. It was submitted to the Dean of the College of Engineering and to the Graduate Council and was approved as partial fulfillment of the requirements for the degree of Master of Science in Engineering.

January 31, 1959.

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Dean, College of Engineering

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Dean, Graduate School

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