Influence of Liquid and Clay Mineral Type On Consolidation of Clay-Liquid Systems

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Introductory Remarks by the Chairman

In order to appreciate the special qualities of the water substance, it is advisable to experiment with non-aqueous liquids, especially with pure organic substances of well known molecular and bulk properties. Mr. Waidelich has done this and has determined with established engineering techniques the consolidation behavior, the Atterberg consistency limits and the apparent specific gravities of three clays in combination with six organic liquids and water, respectively. The data obtained and the conclusions drawn therefrom complement and illuminate the findings on soil-water interaction reported by other contributors to this symposium.

●THIS PAPER deals with the influence of physico-chemical factors on the compressibility of clays. It had previously been shown that the presence of exchangeable ions in clays is accompanied by repulsive forces between the particles and that the amount and type of exchangeable ions in a soil material influenced its consolidation behavior. To verify this fact and to learn about other physico-chemical factors, consolidation and supplementary tests were performed with three distinctly different clays and seven liquids; one of these was water, the others were organic liquids differing in molecular structure, dipole moment, and dielectric constants.

To verify Russell's findings (19), concerning the interaction of polar liquids with soil and lack of interaction in the case of non-polar liquids, specific gravity tests were run with all the soil-liquid combinations. It seemed probable that the soil-liquid interaction that shows itself in the specific gravity values of a soil if determined in different liquids would also affect the mechanical properties of soil-liquid systems, especially since Winterkorn had shown the relationship existing between the swelling of expanding lattice type clays and the dielectric constant of the liquid employed.

The experiments showed that the compression indices of the non-expanding lattice clays varied in the same manner as the dipole moment of the liquid used. The expansion indices also varied with the dipole moment of the liquids; in addition, they were affected by the size and structure of the molecules, the effect of the liquid upon the elasticity of the soil particles, and the dielectric constant of the liquid. The specific gravity of the non-expanding clays also varied with the dipole moment but was additionally influenced by the size and structure of the molecules of the liquid.

The compression indices of the expanding lattice clay varied in the same manner as the dielectric constant of the liquids used. The expansion indices were functions of the dielectric constant of the liquid but were additionally affected by the size and structure of the molecules and the other factors previously mentioned. The specific gravity of the expanding lattice clays also varied as the dielectric constant of the liquids but was additionally influenced by the size and structure especially of the larger molecules.

Of course, the physical properties are not the only factors governing the experimental results. The consolidation and expansion mechanism is quite complex and many secondary phenomena are coupled with the primary factors that have been investigated in the present work. A major contribution to the resolving of this complexity is the correlation found in this study between mechanical properties of soil-liquid systems and dipole moments of the liquids in the case of non-expanding lattice clays, and between mechanical properties and dielectric constants for expanding clays.

This investigation was motivated by the desire for a better understanding of the various factors involved in the consolidation of saturated soils upon loading. The general

theory of soil consolidation was developed by Terzaghi (1925) who recognized the analogy between the consolidation of a soil confined between strata of greater permeability by loss of water and the cooling of a hot plate by loss of heat. The mechanism of this type of consolidation is well described by the late Donald H. Taylor (24) who states:

"Any loading applied to a saturated mass of clay causes compression. However, the soil grains and the pore water are relatively incompressible, and as compression requires a reduction of the pore space, it can occur only as fast as pore water is able to escape. At the instant after the application of load, before any pore water has escaped, none of the added load can be carried by the granular network of the soil, since to carry added load this network must undergo compression. The load, therefore, must be carried, temporarily, by a pressure in the water, called 'hydrostatic excess pressure'. If water can escape at the surface of the clay, drainage begins and the hydrostatic excess pressures and their gradients gradually decrease. The stresses imposed by the loading slowly pass from hydrostatic excess pressure to intergranular pressures, with compression of the clay meanwhile occurring at a continuously decreasing rate. In time the load is carried entirely by the grain structure and no hydrostatic excess remains. It is this gradual adjustment process which is known in soil mechanics as 'consolidation'."

The Terzaghi theory as well as the Taylor statement represent only first macromechanical approximations to what is really happening in a consolidating soil. According to this picture the total consolidation is equal to the loss of water and the rate of consolidation is a function of the permeability of the soil system. The inability of this simple picture to account completely for actually observed consolidation phenomena has led to the development of auxiliary theories on secondary consolidation.

Actually, the consolidation process represents a complex interplay between applied stresses on the one hand, and frictional and cohesive resistance forces in the solid-liquid system on the other hand. The resistance factors themselves are functions of the granulometry of the solid components and the surface interactions between the solid and liquid phases composing the soil system. Such interactions fall within the realm of physical chemistry; their character and magnitude are functions of the physico-chemical characteristics of the surfaces of the solid components and of those of the liquid phase. For water as the liquid phase, it has been shown by Winterkorn that the consolidation process and the physical parameters, such as the coefficients of permeability, consolidation and compressibility calculated from the respective experiments, are functions of the type of soil, the type, percentage and base exchange capacity of its clay fraction, and the kind and proportions of exchange ions present (29, 30, 34).

Since water is a unique and complex liquid, its actual role in the consolidation process can be properly understood only by comparable experimentation with other liquids. With respect to interaction of soil mineral surfaces and liquids, it had been shown by Winterkorn and Baver (33) in the case of swelling experiments and E. W. Russell (19) in specific gravity determinations of clay involving various liquids that the polar character and the architecture of the molecules composing the liquids were of primary importance. On the basis of the available information, it was decided that significant data could be obtained by making consolidation experiments using three different well defined clays and seven different liquids with each clay.

EXPERIMENTATION

Materials Used in the Investigation

1. Clay Minerals. Three different commercially available clay materials were employed in the experimental part of this study. They are (a) Georgia Acid Kaolinite, (b) Goose Lake White Clay—predominantly Halloysite and, (c) Na—Bentonite (Montmorillonite) in pellet form.

Mineralogical identification of these materials was made by means of X-ray diffraction (1, 5, 10, 28, 29). A North American Phillips Co. X-ray diffraction machine was used with a Brown potentiometer which is a counter and graphic recorder of the amount of X-rays reflected. The X-ray machine rotated the X-ray beam one deg of arc per min. The graphic record was started at 36 deg, measured from the horizontal, and run to approximately four deg from the horizontal. This proved to be the range of

identifying peaks. Spectrograms were obtained for the three clay materials employed in the investigation as well as for kaolinite and dickite standards. The slides used for this purpose were made in the following manner: The mineral material was first pulverized in a small dish by means of a glass pestle. A small amount of the resulting powder was placed on a glass slide where it was mixed with a few drops of acetone.

A paper clip was used to mix the soil and acetone and also to spread the mixture evenly and thinly over the glass slide surface. The acetone evaporated rapidly and soon the slide was ready to be placed in the X-ray diffraction machine. The apparatus worked automatically once the machine was turned on.

RESULTS OF THE IDENTIFICATION TESTS

a. Georgia acid kaolinite

This material was supplied through the courtesy of the Georgia Kaolin Company, Dry Brand, Georgia. Kaolin, according to Ross and Kerr (18) is the name of a rock composed of white or nearly white clay minerals that have the approximate chemical composition $2H_2O \cdot Al_2O_3 \cdot 2SiO_2$. Kaolinite is the name of the mineral that characterizes most kaolines. Other minerals falling within the same group are nacrite and dickite. The word "kaolin" is a corruption of the Chinese "kauling" meaning "high ridge", the name of a hill near Jauchua Fu, China, where the material was obtained centuries ago for porcelain manufacturing (10). Kaolinite crystallizes in the monoclinic system and in dense crystalline form has a specific gravity of 2.627. In less perfect crystals the specific gravity is smaller and of the order of 2.5. The crystal structure of kaolinite was first generally outlined by Pauling in 1930, worked out more thoroughly by Gruner in 1932, and substantiated by Brindley and his colleagues by X-ray analysis in 1951. It has a 1:1 lattice structure and a silica/sesquioxide ratio of two.

An X-ray diffraction analysis of the Georgia kaolinite used is matched in Figure 1 with that of a pure kaolinite standard and a dickite standard. Representatives of this clay mineral group can be identified as such by the two sharp "first order" peaks seen to be at approximately 7.14 A and 3.57 A. No other clay minerals have first order peaks at this location. The values given above indicate the lattice spacing in Angstroms.
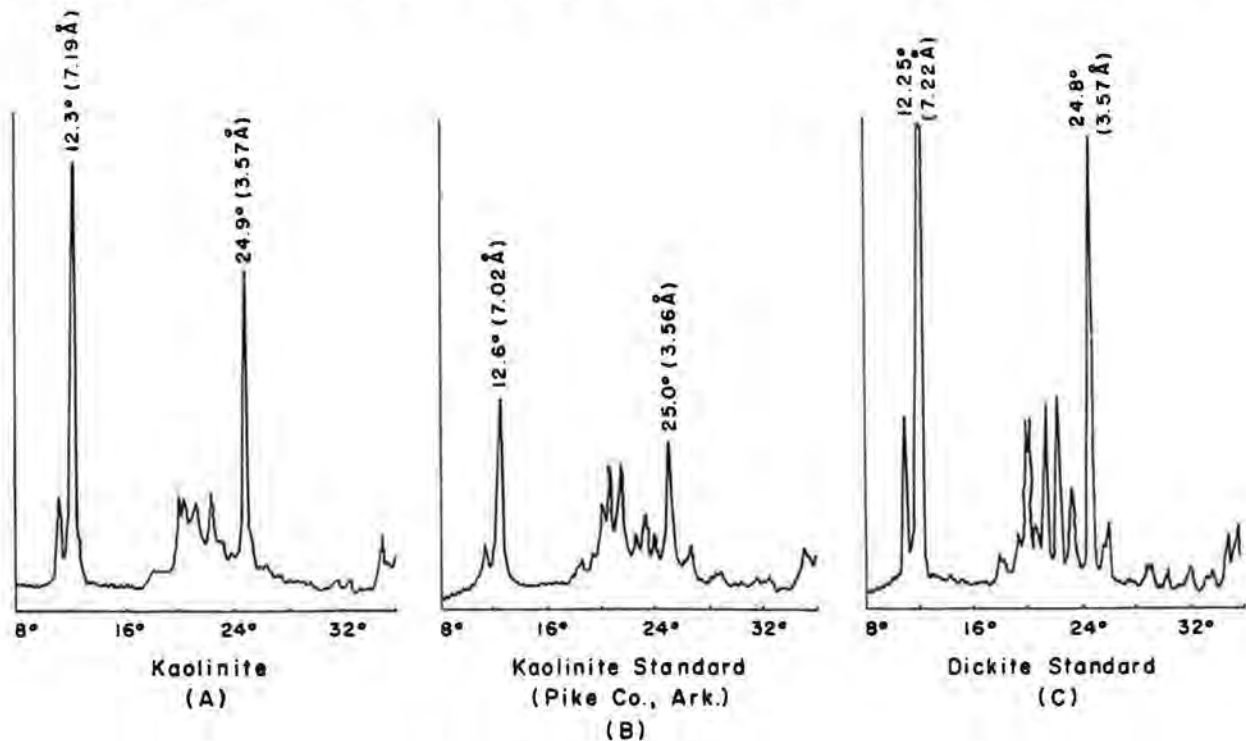

Figure 1.

b. White clay

This clay was supplied through the courtesy of the Illinois Clay Products Company, Joliet, Illinois. According to the supplier this material is composed predominantly of the mineral halloysite. Analytical data furnished by this company are given in Table 1. From these the silica/sesquioxide ratio of the clay was calculated as 1.89. This ratio is 2.0 for kaolinite.

The name halloysite was given by Berthier (4) to a mineral found near Liege, Belgium, in honor of Amalius d' Halloy who had observed this mineral several years previously. Ross and Kerr showed that this material is crystalline and that it is closely related to but distinct from kaolinite. The silica/sesquioxide ratio of the mineral suggests impurities or lattice intergrowth of Al_2O_3. An X-ray diffraction analysis of the white clay is shown in Figure 2. There are no sharp peaks for identification. The "dome" indicates a disorganized structure and signifies a mixed-layer clay. The soil was then treated with ethylene glycol. Treatment with organic compounds permits the detection of small amounts of minerals which would otherwise be missed in complex mixtures. This treatment, however, did not provide any new information concerning the white clay although it did reorient the soil structure (Fig. 2).

TABLE 1

CHEMICAL ANALYSIS OF
GOOSE LAKE WHITE CLAY

Silica	42.59
Alumina	40.56
Iron Oxide	0.62
Titania	Trace
Lime	0.42
Magnesia	0.09
Alkalies	0.11
Ignition Loss	15.51

Workability	Poor
Drying Shrinkage	1.3
Firing Shrinkage at 2550 F	7.3
Fired Modulus of Rupture	127 psi
P. C. E.	35 - 36
Apparent Porosity	59.9%

c. Wyoming bentonite

This clay was supplied through the courtesy of the American Colloid Company of Chicago. The main constituent of this clay is the mineral montmorillonite, named by Damour and Salvetat in 1847 after Montmorillon, France, the place of its first discovery. Montmorillonite has a 2:1 expanding lattice structure and a silica/sesquioxide ratio of four or more. Hofman, Endell, and Wilm established the structure of montmorillonite, showing the expanding-lattice characteristics of the mineral in 1933. This is now generally considered to be an essential characteristic of the montmorillonite group. Other minerals in this group are saponite and nontronite. The difference between these and montmorillonite is the replacement of aluminum by magnesium and iron, respectively.

The X-ray diffraction pattern of the montmorillonite used is shown in Figure 3. Soils from this clay group can be identified as such by the first order peaks at 14.7 A and 7.35 A. From the X-ray graph it is seen that the 7.35 A peak is missing completely and the other peak is located at 12.44 A. This small spacing could be caused by the lattice shrinking due to the oven-drying of the soil. The soil was treated with ethylene glycol to try to bring out some hidden data (Fig. 3) but this did not provide any new information. The Wyoming bentonite used is essentially a Na-montmorillonite; it was received in pellet form insuring uniformity of composition.

2. <u>Liquids</u>. Because water is a complex substance with unique properties it was decided to employ not only water but other liquids in this investigation. The liquids employed can be divided into two groups, viz. (a) water and low molecular weight alcohols and (b) polar aromatic liquids. Specifically, the group contained:

(1)		(2)	
HOH	Water		
$HOCH_3$	Methanol	$C_6H_5NH_2$	Aniline
HOC_2H_5	Ethanol		
HOC_3H_7	Propanol	$C_6H_5NO_2$	Nitrobenzene
HOC_4H_9	Butanol		

Goose Lake White Clay
(A)

Goose Lake White Clay
Treated with Ethylene Glycol
(B)

Figure 2.

7.1° (12.44 Å)

Montmorillonite
(A)

Montmorillonite
Treated with Ethylene Glycol
(B)
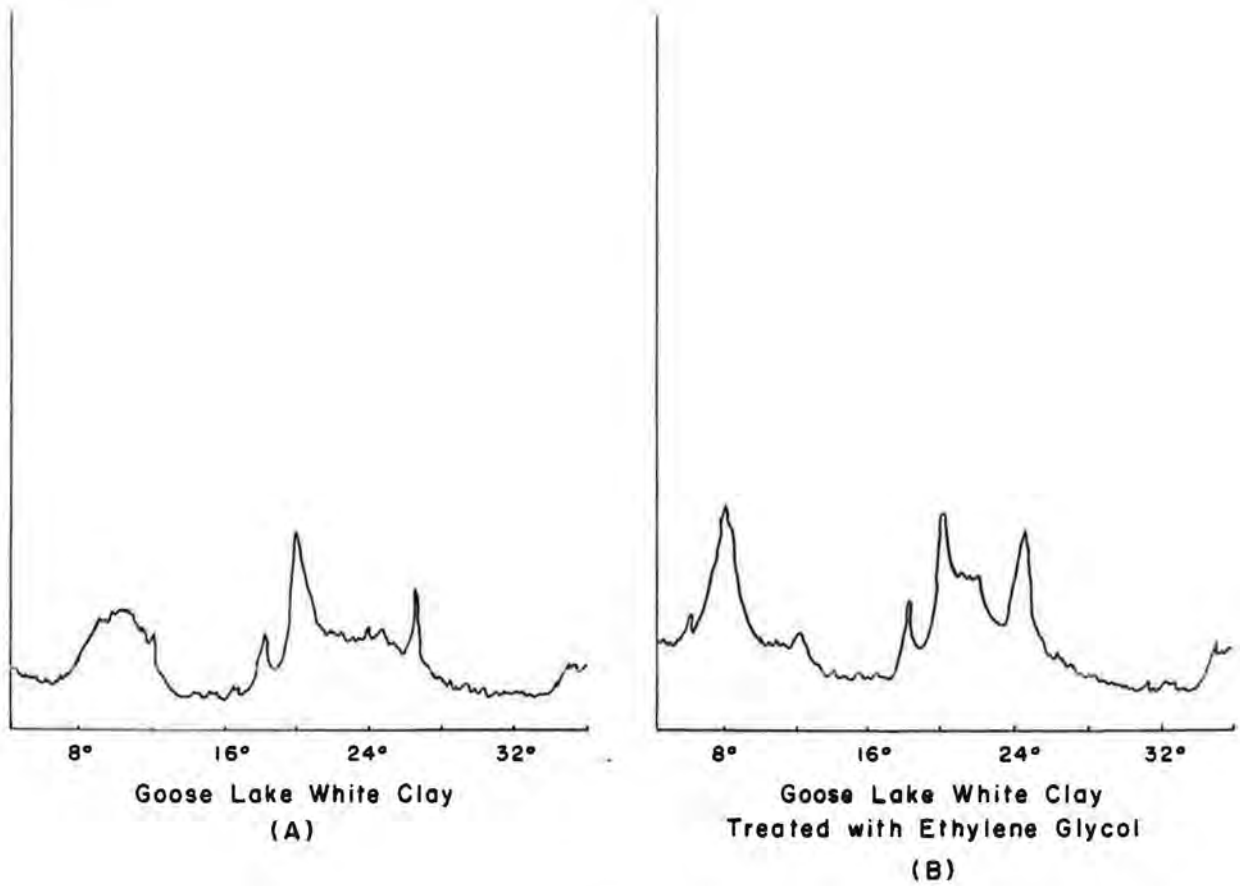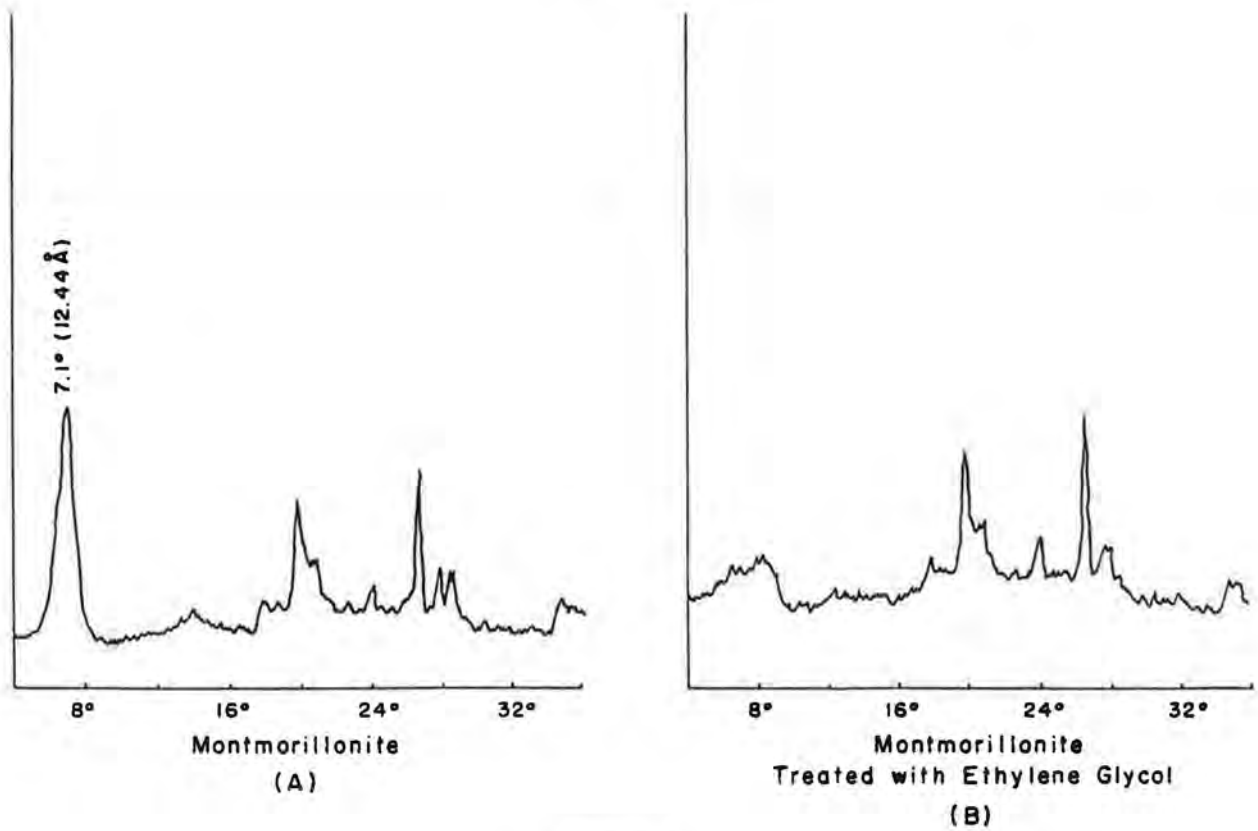
Figure 3.

Significant physical properties of these liquids are given in Table 2. All these are polar liquids; this means that in their respective molecules the center of the positive charges does not coincide with the center of the negative charges. One differentiates between permanent dipoles, which are inherent in the molecules and are due to their normal structure, and induced dipoles, which are due to a deformation of the electron shell when placed in a strong electric field. Dipoles are characterized by the dipole moment which is the product of the electric charge and distance between the center of the charges and by the architecture of the molecule which determines how accessible the charge centers are and how close other ions or molecules can get to the respective centers.

Experiments Performed During the Investigation

Experimentation was concerned primarily with the consolidation test on the above-named mineral-liquid combinations. In addition it appeared worthwhile to determine the specific gravities and the Atterberg limits of the mineral materials with the various liquids.

1. Consolidation Tests. The consolidometers used were of standard type, taking a sample of approximately 2½ in. in diameter and 1 in. in height. A Federal dial, accurate to the nearest ten thousandth of an inch, was employed to measure the vertical movement (compression). On two of the consolidometers, the sealing ring was soldered to the sample barrel to aid in preventing the loss of liquid by leakage at this perimeter. On the other four consolidometers, sodium silicate with a cotton filler was put around this perimeter for the same purpose. This worked well when the organic liquids were used. White lead was employed in place of the cotton filler with the sodium silicate when water was used with the soils.

To prevent the volatile liquids from evaporating, a polyethelene cover was placed around the consolidometer. Also, a flask was placed above the apparatus with two flexible tubes feeding the liquid to the soil when the liquid level dropped below the desirable height. Aluminum foil was wrapped around the bottles to protect photosensitive liquids from sunlight.

The porous stones were soaked in the liquid to be used for at least one day and usually longer.

The soil-liquid mixture was placed in the consolidometer with a spatula. Care was taken to avoid the entrapment of air in the specimun as this would drastically affect the results.

The first load increment was 0.1 ton per square foot (TSF); each successive increment was double the last until one of 6.4 TSF was reached. The unloading decrements

TABLE 2

PHYSICAL CHARACTERISTICS OF LIQUIDS USED (36)

Liquids	Liquid Symbol	Formula	Mol. Wt.	Density^a Gm/cc	Melting Point deg C.	Boiling Point deg C.	Latent Heat of Vapor. Gm-Cal/Gm	Latent Heat of Fusion Gm-Cal/Gm	Viscosity at 20 deg C. Centipoises (Cp.)	Dielectric Constant at 20 deg C.	Dipole Moment
Water	1	HOH	18	0.99823	0	100.0			1.000	81.07	1.8
Aniline	2	$C_6H_5NH_2$	93.12	1.022	- 6.2	184.4	103.68	20.95	4.40	7.25	1.55
Nitrobenzene	3	$C_6H_5NO_2$	123.11	1.19867	5.7	210.9	79.08	22.52	2.03	36.1	3.89
Methyl Alc.	4	CH_3OH	32.04	0.7917	- 97.8	64.65	262.79	16.39	0.597	33.1	1.68
Ethyl Alc.	5	C_2H_5OH	46.07	0.78934	-117.3	78.5	204.26	24.89	1.200	25.8	1.69
Butyl Alc.	6	C_4H_9OH	74.12	0.80978	- 89.2	117.71	141.26	29.93	2.948	7.8	1.67
Propyl Alc.	7	C_3H_7OH	60.09	0.8044	-127.0	97.19	164.36	21.02	2.256	22.2	1.65

^{a}Densities refer to water at 4 deg C., the liquid being at 20 deg C.

were one quarter of the previous load; this unloaded the specimen in three decrements ending with the initial load.

For all the samples, one day was allowed between load stages except for the montmorillonite-water sample, which required two days to complete its primary consolidation and to establish a secondary compression rate. Two days were also allowed for expansion of this sample.

To derive the coefficients of consolidation from the laboratory data, a "fitting method" must be used which correlates the laboratory and the theoretical time-consolidation curves. The "square root of time" fitting method was employed for evaluating all results because of the rapidity of the compression rates (some reaching the ninety percent consolidation point within one minute).

Due to this rapid consolidation rate, the coefficient of consolidation and, therefore, the permeability values obtained were mainly of qualitative value, being important only in judging the order of magnitude of the coefficients involved. The permeability is often considered a material constant and the only liquid property affecting it is assumed to be its viscosity. It should be noted that the viscosities of several of the liquids were higher than that of water, but the permeabilities were also higher, not lower as would be the case if the assumed relationship were true. The cause of this is (a) the effect of liquid on the structural arrangement of the solids, making larger individual pores

$$(\text{for effect see Poisseuille} \quad v = \frac{\pi r^4 \Delta p}{8\eta \, \Delta l} \cdot t);$$

(b) the different thicknesses of the adsorbed or "restrained" liquid layers. (See Figs. 4, 5, and 6 which will indicate the permeability ranges of the three soils graphically.)

2. Specific Gravity. The specific gravity of any solid or liquid substance is the ratio of the unit weight of the substance to the unit weight of water at the same temperature. It is a measure of the heaviness of a material. The true average specific gravity of an actual soil is the weighted average of the specific gravities of all the mineral particles in the soil. A liquid that will not react with the soil in any way should be used to obtain this true specific gravity. E. W. Russell has shown that the specific gravity values obtained for a soil using various liquids will deviate from one another depending on the interaction between the liquid and the soil (19). He also found that "No evidence could be obtained of interaction between clays and non-polar liquids and interaction took place in all the polar liquids examined." To obtain the true specific gravity of the soil, decahydro-naphthalene (decalin), a non-polar liquid, was used.

If the test is run with entrapped air in the soil-liquid system, the apparent weight of the soil, liquid, and pycnometer is less than the true weight since the entrapped air is taking the place of water. Therefore, entrapped air will cause specific gravity values that are too low. A desiccator, provided with an interconnected flask filled with anhydrous calcium chloride attached to a Hyvac oil pump, was used to remove the entrapped air. The pump provided a suction of approximately 28 psi. The pycnometers with the soil-liquid mixture were left under this vacuum for at least one hour. The vacuum was released and the pycnometers were spun manually to aid the removal of entrapped air bubbles. This procedure was continued until, upon spinning, no more air bubbles appeared. The pycnometers were then replaced in the desiccator and remained under vacuum until the next day. This proved to be sufficient for the removal of entrapped air.

When liquids are employed that possess densities greater or smaller than that of water, the density of the dispersed minerals is obtained by using the volume rather than the weight of the liquid displaced by the mineral material. In the metric system, the density thus obtained is numerically equal to the specific gravity.

The density of liquids also varies with temperature changes. Therefore, temperatures were recorded during the test so that the unit weight of the liquid could be determined with regard to one standard temperature. All specific gravity results were standardized to 20 deg C.
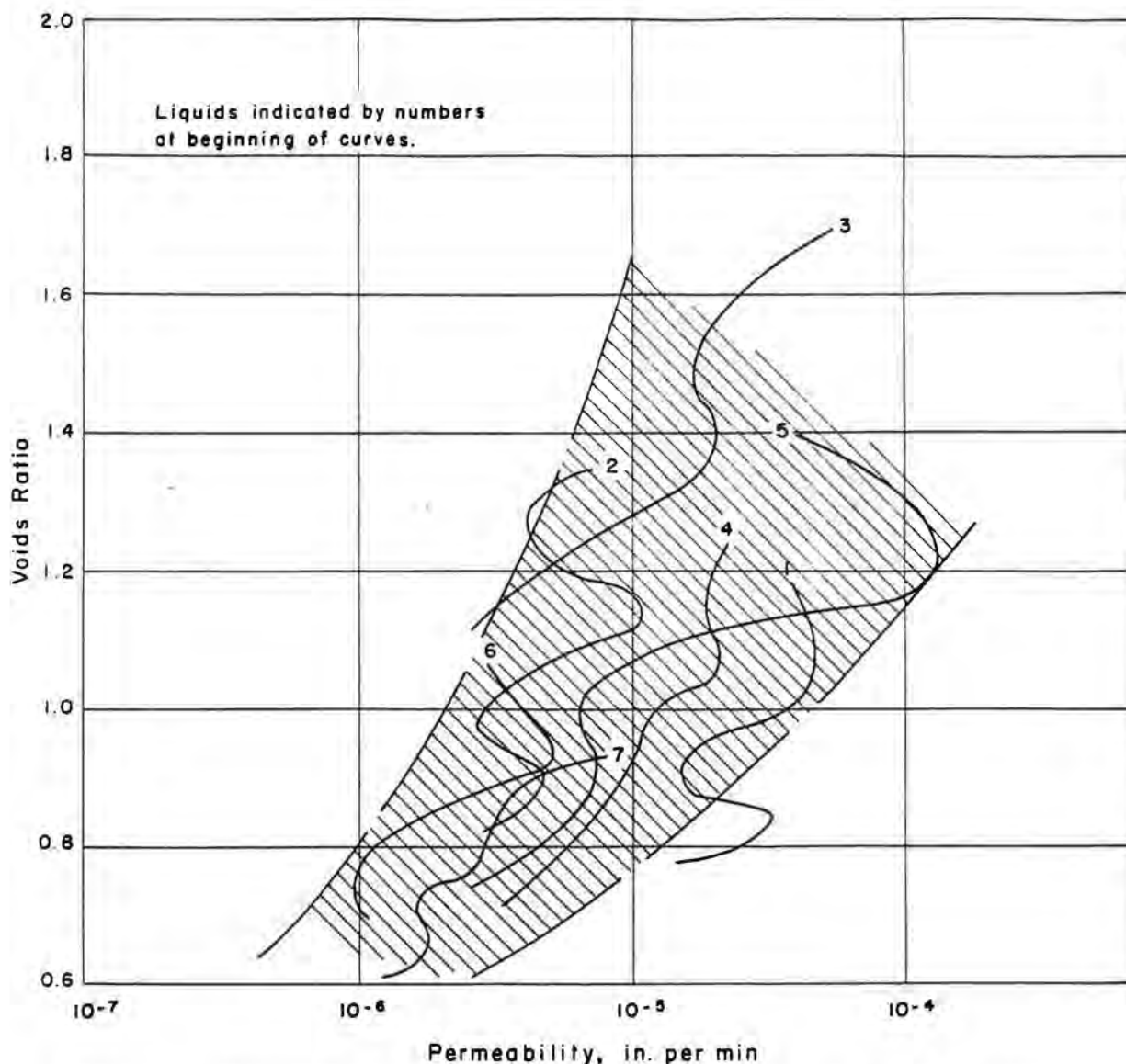
Figure 4. Permeability versus voids ratio using kaolinite with all liquids.

The test procedures with all liquids except water differed from the ASTM standard method (D854-52). The vapors of the various organic liquids had extremely annoying odors plus the fact that the inhaling of some of these vapors might prove harmful. Therefore, the test procedure used was as follows:

1. Weigh the pycnometer, clean and dry; (weighing device is a torsion balance; capacity 120 Gms.; ±.01 Gms.)

2. Fill the pycnometer with liquid and place in desiccator with a vacuum of 28 psi applied to it to remove the dissolved gases the liquid may be holding. One hour seemed to be sufficient to remove these gases. The pycnometer was then filled to the mark with the liquid and the combined weight determined.

3. The pycnometer was then emptied and the little liquid remaining was evaporated by heating.

4. After the pycnometer was dry, it was allowed to cool.

5. The clay sample was placed in the pycnometer and the combined weight determined.

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TABLE 3
RESULTS OF THE SPECIFIC GRAVITY TESTS

Liquid Soil	Water	Aniline	Nitro-Benzene	Methyl Alcohol	Ethyl Alcohol	Butyl Alcohol	Propyl Alcohol	Decolin
Kaolinite	2.560	2.481	2.577	2.585	2.569	2.628	2.588	2.530
White Clay	2.324	2.170	2.230	2.289	2.244	2.247	2.228	2.191
Bentonite	2.394	2.247	2.261	2.360	2.359	2.298	2.332	2.167

6. The liquid was then added; subsequently, the entrapped air was removed as previously explained, and the weight of the combined mixture taken.

The time interval that the liquid spent in the desiccator aided it to adjust itself to room temperature. The temperature of the main supply of the liquid, of the liquid in the pycnometer, and the room were within one degree of each other at all times, and did not vary more than one degree during a test run.

The results of the specific gravity tests are given in Table 3.
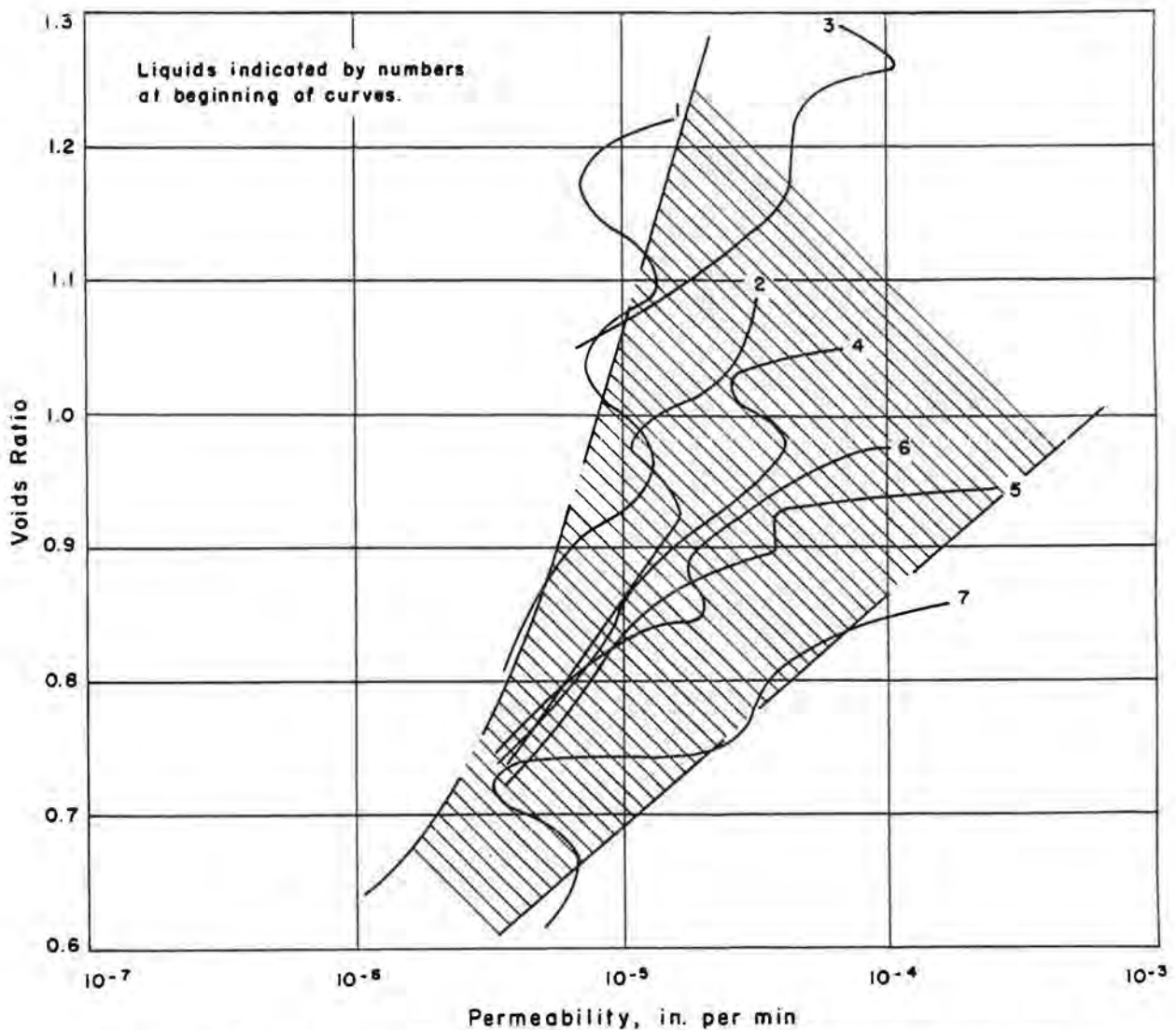
Figure 5. Permeability versus voids ratio with White Clay and all liquids.

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were cut into the brass dish, perpendicular to the direction of sliding. It was hoped that these grooves would provide a gripping surface for the soil. The grooves did not affect the liquid values of the kaolinite samples but did aid in obtaining better experimental data for the White Clay. Occasionally, the White Clay would slip along the spherical surface of the dish, thus losing the advantage of the grooves. Accordingly, the results of the Atterberg limits using White Clay with all the organic liquids were erratic and must be interpreted with care.

The temperature used to dry the soil samples was 110 deg C. This proved sufficient in all cases even though the boiling point of some of the liquids was well above this figure.

<p style="text-align:center">RESULTS</p>

Consolidation Tests

Consolidation tests were run with the three clays and the seven liquids. The compression and expansion indices were obtained from the slopes of the log pressure versus voids ratio curves. Seven curves for each of the three soils are plotted on four graphs (Figs. 7, 8, 9, and 10); the compression and expansion indices are given in Table 5. The data in this table show that the respective indices for the clays with non-expanding lattices (kaolinite and White Clay) vary with the dipole moment. For the kaolinite, the larger the dipole moment of the liquid used, the larger is the slope of the compression curve (compression index). For the White Clay, however, the larger is the dipole moment of the liquid used, the smaller is the slope of the compression curve. This is in

<p style="text-align:center">TABLE 4</p>
<p style="text-align:center">ATTERBERG LIMITS OF SOILS USED [a]</p>

Soil	Liquid Limit	Plastic Limit	Plastic Index	Flow Index	Toughness Index
1-A	41.1	29.7	11.4	10.0	1.14
1-B	50.2	38.3	11.9	3.9	3.05
1-C	490.0	46.6	443.4	107.0	4.14
2-A	47.0			16.5	
2-B					
2-C					
3-A	67.5			17.0	
3-B					
3-C					
4-A	40.0	33.9	6.1	15.0	4.06
4-B	41.6			7.6	
4-C					
5-A	41.75	34.6	7.2	9.3	0.77
5-B	39.20			7.0	
5-C					
6-A	35.50	21.5	14.0	8.0	1.75
6-B	38.2			4.6	
6-C					
7-A	40.0	25.7	14.3	10.0	1.43
7-B	38.2			4.8	
7-C					

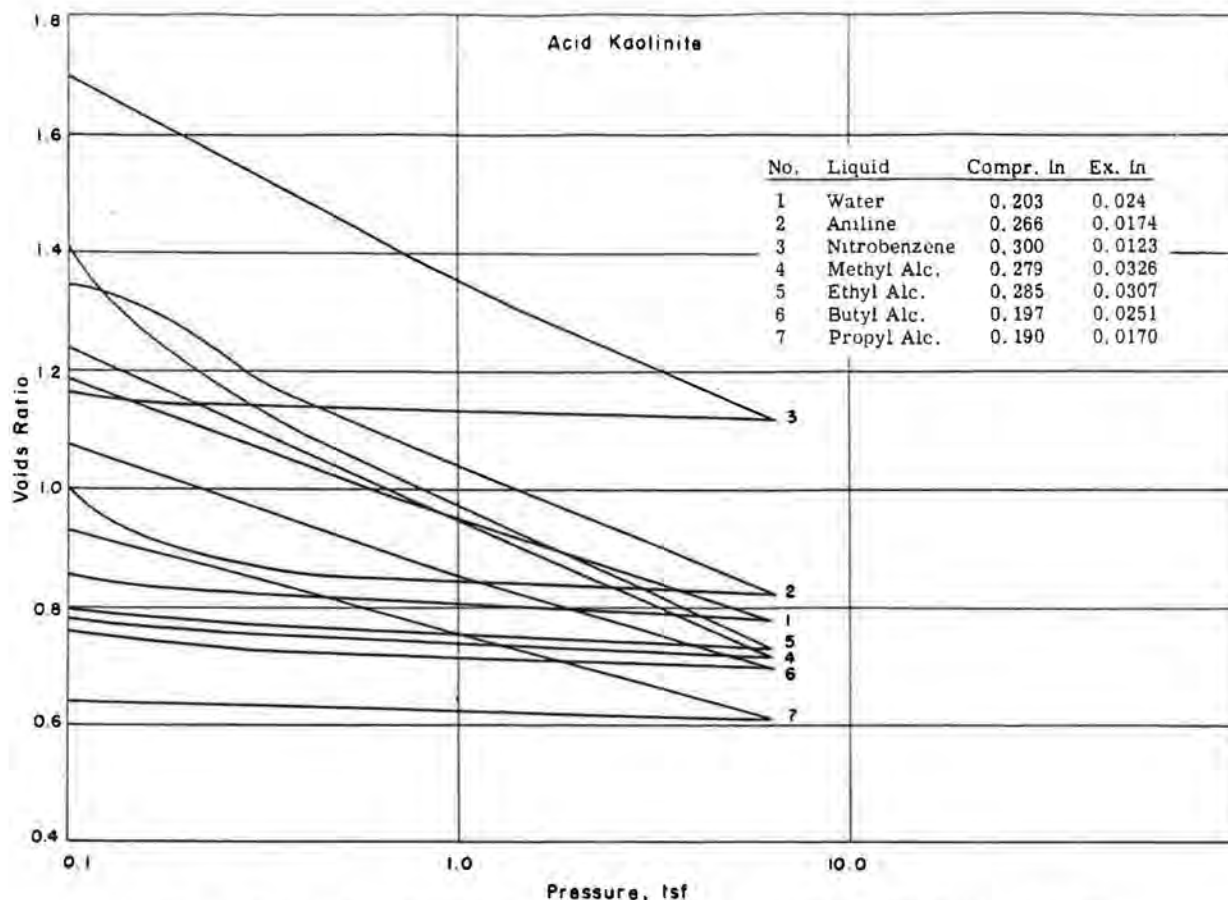[a] Missing values could not be gotten due to soil structure.

Figure 7. Pressure versus voids ratio for kaolinite with all liquids.

line with previous observations on absorption of organic liquids on lateritic clays that have SiO_2/R_2O_3 ratios smaller than two.

The liquids aniline and water are two exceptions common to both soils. It is possible that the aniline engaged in base exchange with the two non-expanding soils causing the formation of anilinium soils.

Water is the other exception to the observation. Water is one of the most common liquids, and yet, very little is really known about it. Its oddities are apparent but few are completely explainable. Methyl alcohol is another exception in the case of the White Clay. This liquid, having a molecular structure closely resembling water, acts similar to water on occasions.

TABLE 5

EXPERIMENTAL RESULTS TABULATED AGAINST THE DIPOLE MOMENT

| Dipole Moment	Liquid	Kaolinite			White Clay			Bentonite		
		Compr. Index	Expan. Index	Sp. Gr.	Compr. Index	Expan. Index	Sp. Gr.	Compr. Index	Expan. Index	Sp. Gr.
3.89	Nitrobenzene	0.300	0.0125	2.577	0.195	0.0111	2.230	0.660	0.0216	2.261
1.8	Water	0.203	0.0240	2.560	0.246	0.0025	2.324	4.480	1.8320	2.394
1.69	Ethyl Alc.	0.285	0.0307	2.569	0.154	0.0072	2.244	0.326	0.0286	2.359
1.68	Methyl Alc.	0.279	0.0326	2.585	0.218	0.0115	2.289	0.398	0.0390	2.360
1.67	Butyl Alc.	0.197	0.0251	2.628	0.172	0.0083	2.247	0.534	0.0194	2.298
1.65	Propyl Alc.	0.190	0.0170	2.588	0.182	0.0106	2.228	0.614	0.0148	2.332
1.55	Aniline	0.266	0.0174	2.481	0.226	0.0028	2.170	0.610	0.0296	2.247
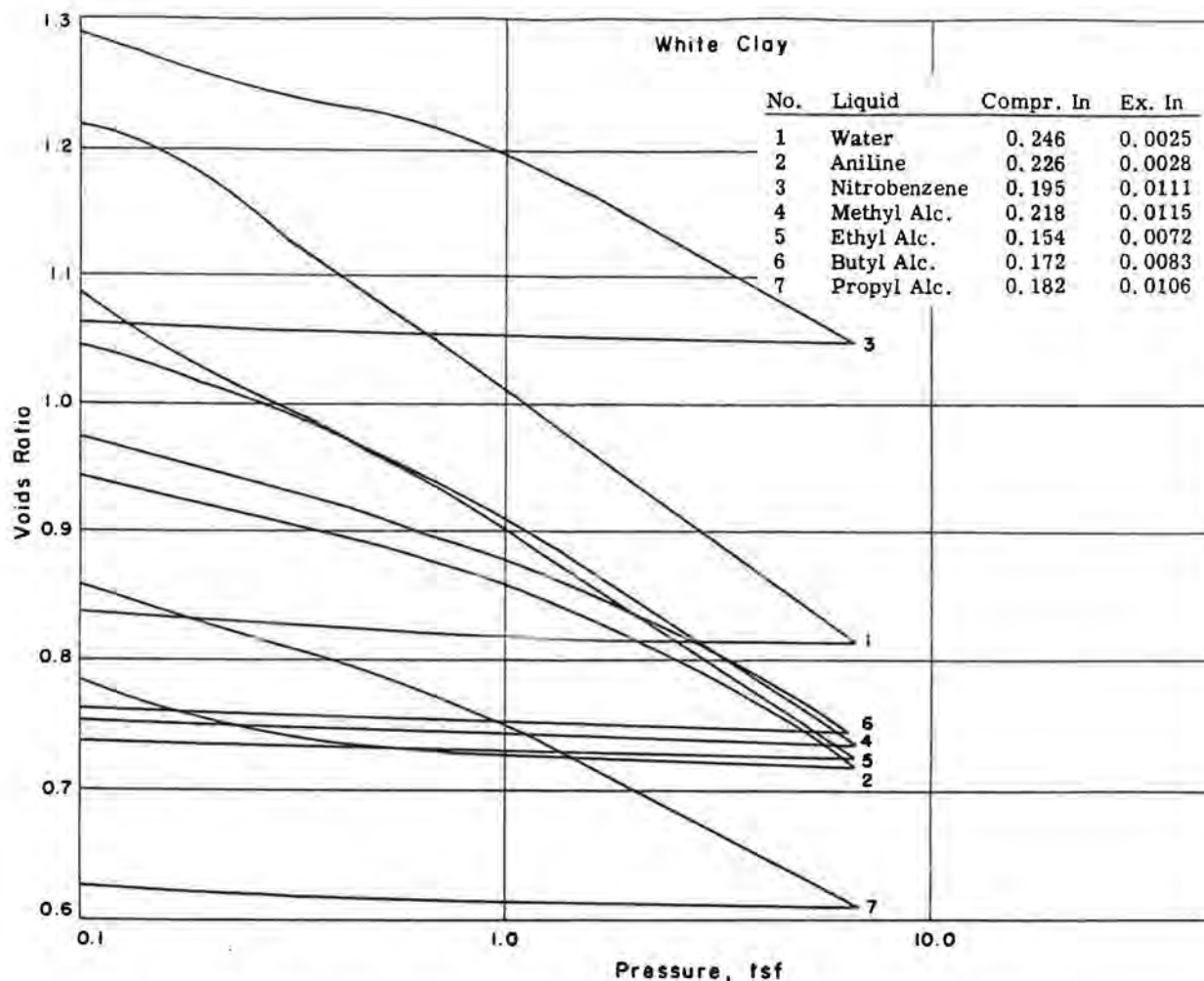
Figure 8. Pressure versus voids ratio for White Clay with all liquids.

At this point, it should be mentioned that the molecular size and structure of the liquid in addition to the dipole moment influences the rate of consolidation and, therefore, the compression index. If the alcohols and water are considered as a separate group, better correlation of the data for the non-expanding clays is obtained. Nitrobenzene, having an exceptionally large dipole moment and exposed oxygen atoms, should be considered individually.

From the previous definition, the dipole moment can be seen to be a localized force couple within the molecule itself. The particles of a non-expanding clay do not absorb liquids within the lattice as an expanding clay will.

Montmorillonite clay, which possesses an expanding lattice, is affected by the dipole moment to a lesser extent than the clays with a non-expanding lattice. Rather, the dielectric constant, which is an integral function of the dipole moment and molecular structure, seems to have a more dominating influence on this type of clay mineral (Table 6).

To explain the effect of the dielectric constant, an example will here be given. The dielectric constant of liquid water at room temperature is approximately 80. This means that two opposite electrical charges in water will attract each other with a force that is $\frac{1}{80}$ as strong as in a vacuum. With this great reduction of the attraction forces, the inherent kinetic energy of the exchange ions is sufficient to overcome the attraction forces and cause an ionic atmosphere to be formed around the clay particles and between the expanding layers. Clays with expanding lattices possess high base exchange capacities or a high surface concentration of adsorbed ions. The higher the dielectric constant
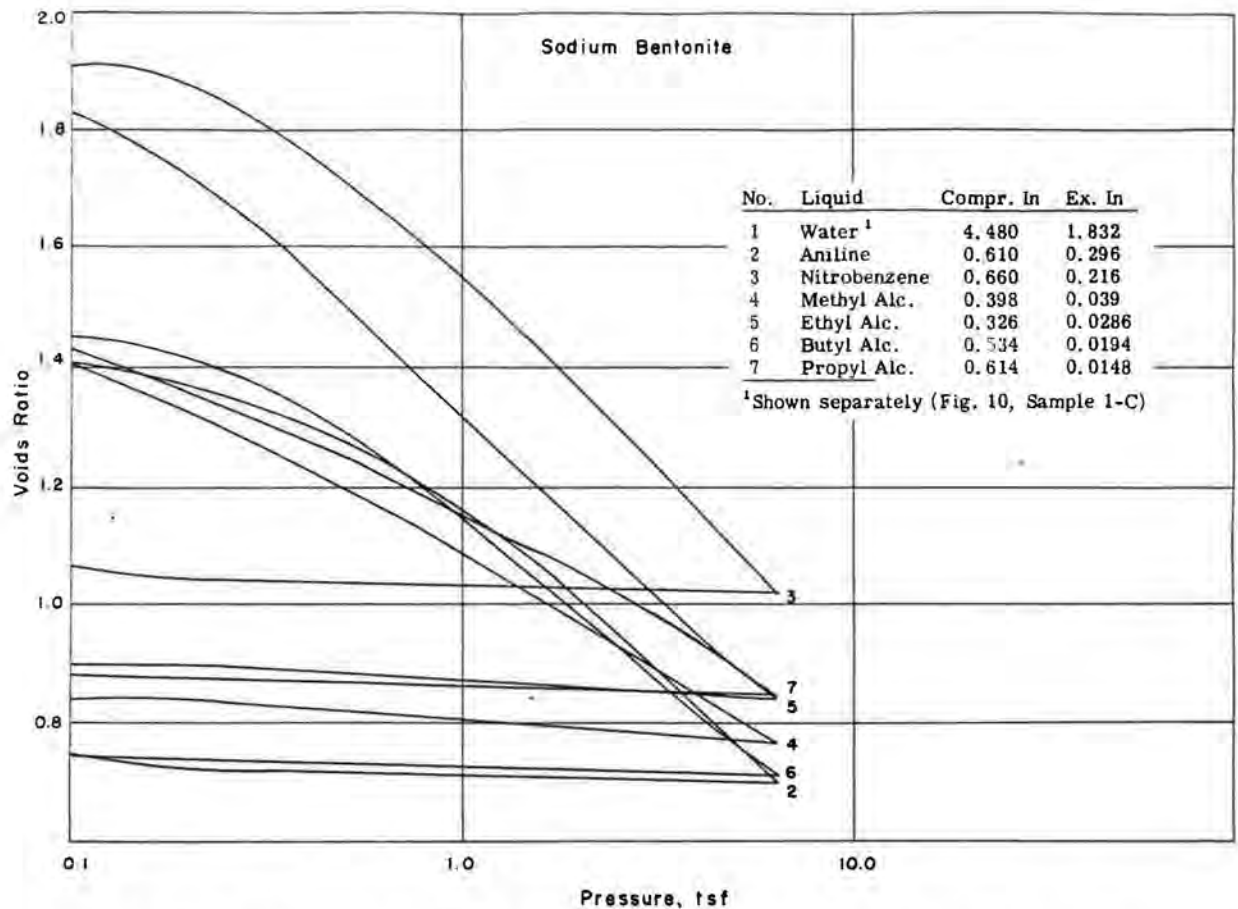
Figure 9. Pressure versus voids ratio for bentonite with all liquids.

of the liquid, the more exchangeable ions will enter the liquid resulting in a swarm of positive ions surrounding negatively charged clay particles. As Winterkorn has shown in 1932, the swelling of such systems is directly proportional to the dielectric constant of liquids having molecules of similar architecture. This is exemplified by the water-alcohol series with montmorillonite. However, when lower dielectric constants are accompanied by larger molecular size (propanol and butanol), deviations from the proportionality occur. As the dielectric constant gets smaller, the ion concentration and the distance over which the electric field of the particles acts is reduced. Therefore,

TABLE 6
EXPERIMENTAL RESULTS TABULATED AGAINST THE DIELECTRIC CONSTANT

| Dielectric Constant	Liquid	Kaolinite			White Clay			Bentonite		
		Compr. Index	Expan. Index	Sp. Gr.	Compr. Index	Expan. Index	Sp. Gr.	Compr. Index	Expan. Index	Sp. Gr.
81.07	Water	0.203	0.0240	2.560	0.246	0.0025	2.324	4.480	1.8320	2.394
36.1	Nitrobenzene	0.300	0.0125	2.577	0.195	0.0111	2.230	0.660	0.0216	2.261
33.1	Methyl Alc.	0.279	0.0326	2.585	0.218	0.0115	2.289	0.398	0.0390	2.360
25.8	Ethyl Alc.	0.285	0.0307	2.569	0.154	0.0072	2.244	0.326	0.0286	2.359
22.2	Propyl Alc.	0.190	0.0170	2.588	0.182	0.0106	2.228	0.614	0.0148	2.332
7.8	Butyl Alc.	0.197	0.0251	2.628	0.172	0.0083	2.247	0.534	0.0194	2.298
7.25	Aniline	0.266	0.0174	2.481	0.226	0.0028	2.170	0.610	0.0296	2.247
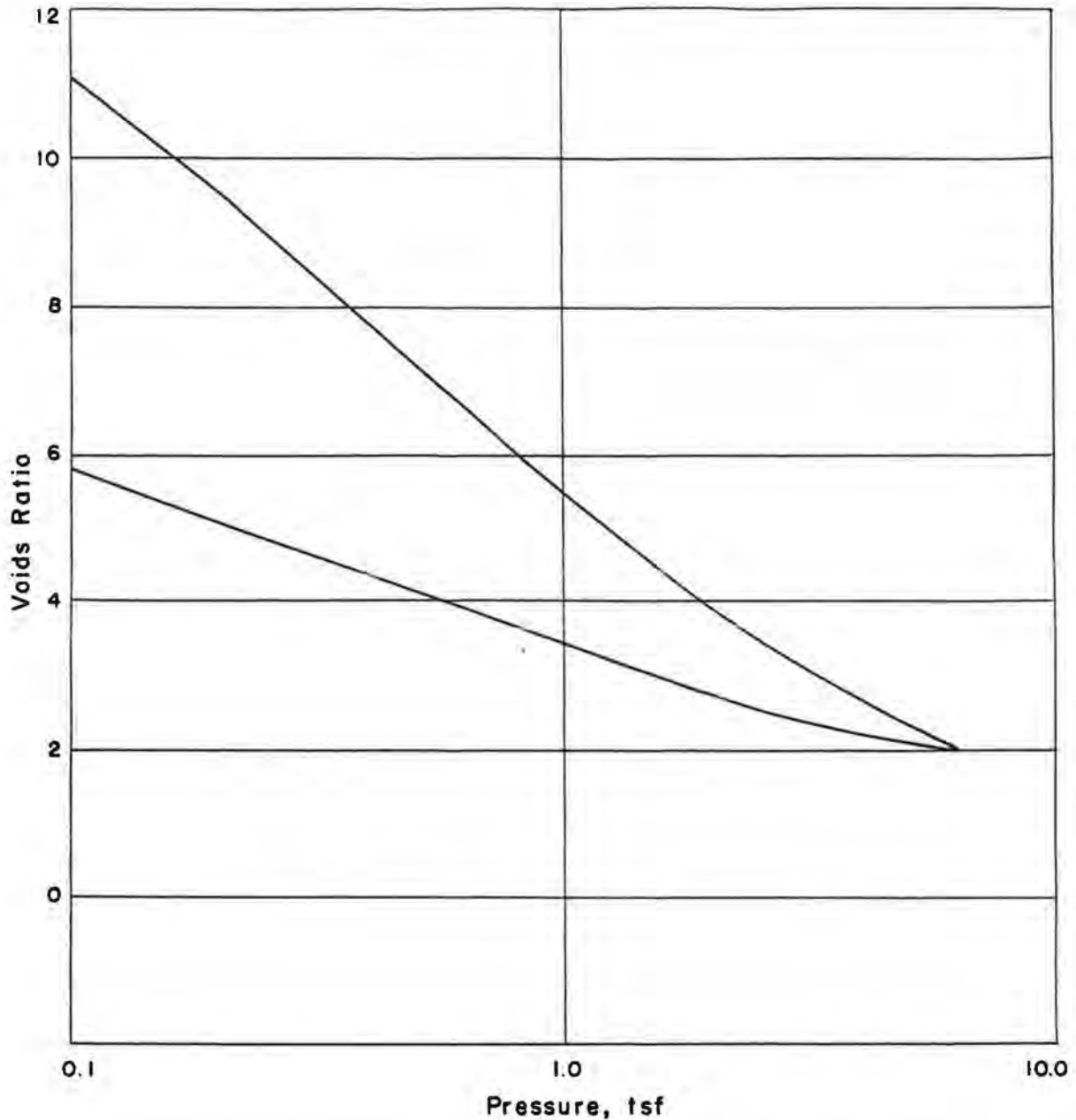
Figure 10.

the clay flakes can be forced closer together, permitting the size of the liquid molecules to influence the extent to which the clay flakes can be compressed. Flocculation phenomena may further complicate the picture.

Again, the results obtained with the aniline are of a different character, first because of the possible occurrence of base exchange phenomena, and second because of the specific polar character of the $-NH_2$ group.

The expansion indices of the various soil-liquid mixtures are influenced by factors similar to those that affect the compression indices. The major factors that have a pronounced affect on the expansion properties of a soil-liquid mixture are (a) the dipole moment, (b) the dielectric constant, (c) the effect of the sorbed liquid on the elastic rebound properties of the soil flakes, and (d) the size and structure of the liquid molecules. Of course, the four factors mentioned are not the only ones affecting the expansion. The above factors will vary with each liquid and with each soil and, therefore, it is difficult to state exactly what part each factor will play in influencing soil expansion.

Therefore, the correlation between the expansion indices and the dipole moment for the non-expanding lattice clays, and the dielectric constant for the expanding lattice clays are not as apparent as for the compression indices.

One of the factors mentioned above seems to affect particularly the rate of secondary compression. That is, the size of the liquid molecule and also another factor not mentioned previously, the viscosity of the liquid, appears to have an effect on the amount and rate of secondary consolidation. A number of other rheological factors are undoubtedly involved in this phenomenon; however, the type of apparatus used precluded a study of these factors in the present investigation.

Upon removing and drying the compressed soil-liquid samples from the consolidometer, it was noticed that occasionally the samples went through a color change (Table 7). It was also apparent that the structure of the bentonite samples was affected to different extents by the various liquids.

Specific Gravity

About 25 years ago E. W. Russell showed that the specific gravity of clay varied with the character of the liquid employed in the respective tests. Depending upon the electric surface structure of the clay minerals and the polar and structural characteristics of the liquids, the molecules of the latter can make structural arrangements on the solid-liquid interfaces which differ from the arrangements in the bulk of the liquid. Because of this, the adsorbed layers may have densities either larger or smaller than that of the bulk liquid. Since the latter density is used for calculation of the volume displaced by the clay particles, the specific gravity of the clays will be calculated either too large or too small. Thus the specific gravities determined for different clays using different liquids can serve as indicators of the degree of interaction between the mineral surfaces and the liquids involved. For this reason the specific gravities of the three clays investigated were determined in each of the liquids used in the consolidation study. The results are given in Table 8. From the data on the specific gravity of the clays using various liquids, it is apparent that the dipole moment has a noticeable effect on the variation of the specific gravity of the non-expanding clays and the dielectric constant has a noticeable effect on the variation of the specific gravity of the expanding clays. However, the size and structure of the liquid molecule is seen also to have a major effect on the specific gravity (Table 8). If water and the alcohols are listed in order of their molecular weights, it is apparent that the larger is the molecular weight, the larger is the specific gravity for the kaolinite, but the specific gravity decreases with increasing molecular weight of

TABLE 7
COLORS AND VISUAL STRUCTURE OF DRIED CONSOLIDATED SOIL

| Soils | Liquids | | | | | | |
	Water	Aniline	Nitro-benzene	Methyl Alcohol	Ethyl Alcohol	Butyl Alcohol	Propyl Alcohol
Kaolinite	White (crumbled) Fine[a]	Light Violet Fine	Beige Fine	White (crumbled) Fine	White Fine	White Fine	White Fine
White Clay	Orange Yellow Fine	Dark Brown Fine	Brown Fine	Orange Fine	Beige Fine	Green Orange Fine	Brown Orange Fine
Bentonite	Green Very Fine	Dark Brown Coarse	Yellow Green Coarse	Green Fine	Yellow Medium	Green Coarse	Pale Yellow Coarse

[a] Indicates visual soil particle size.

TABLE 8

SPECIFIC GRAVITY TABULATED AGAINST MOLECULAR WEIGHT

Molecular Weights	Liquid	Kaolinite	White Clay	Bentonite
123.11	Nitrobenzene	2.577	2.230	2.261
93.12	Aniline	2.481	2.170	2.247
74.12	Butyl Alc.	2.628	2.247	2.298
60.09	Propyl Alc.	2.588	2.228	2.332
46.07	Ethyl Alc.	2.569	2.244	2.359
32.04	Methyl Alc.	2.585	2.289	2.360
18	Water	2.560	2.324	2.394

the liquid in the case of White Clay and the montmorillonite. It should be noticed that this same reversal took place previously in the case of the compression and expansion indices.

Nitrobenzene and aniline have a different molecular structure than the previously mentioned liquids and, therefore, should be considered separately. The nitrobenzene gives greater specific gravities than the aniline indicating a different type of reaction of the $-NO_2$ group as compared with that of the $-NH_2$ group on the benzene ring. In the case of the aniline there is probably an additional effect due to the formation of anilinium clays.

ACKNOWLEDGMENTS

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