The Fabric of Natural Clays and its Relation to Engineering Properties[1]

JAMES K. MITCHELL, *Engineer*,[2]
Soils Division, Waterways Experiment Station,
Corps of Engineers, U. S. Army, Vicksburg, Mississippi

The fabric of an earth material may be defined as the appearance or pattern produced by the shapes or arrangement of the soil grains, independently of the external boundaries of the material. Theoretical considerations and available data indicate that the flocculation of clays is caused by negative particle surface to positive particle edge electrostatic attractive forces, resulting in a random particle orientation. Dispersion, caused by high repulsive forces between particles, leads to a parallel association of particles, at least within small zones. Interparticle forces at the time of deposition as well as subsequent history of the deposit are believed responsible for the fabric of natural clays.

The microscopic study of thin sections, prepared by a special technique, from several clays at natural water content in both the undisturbed and remolded state has yielded direct information on the fabric. Photomicrographs are presented indicating various fabric features such as parallel clay orientation. The fabrics formed in the undisturbed and remolded clays are explained in terms of the interparticle forces and history of the material subsequent to deposition or remolding.

The remolding of the marine clays studied led to a small but detectable improvement of the clay orientation within small areas. The effect of remolding on the fabrics of fresh water clays was largely dependent on the intensity of parallel clay orientation and the amount of precompression in the undisturbed sample. The magnitudes of the differences between undisturbed and remolded engineering properties of both the marine and fresh water clays were found to correlate, in general, with the differences between the undisturbed and remolded fabric. The more oriented the remolded clay with respect to the undisturbed, the greater were the differences between the undisturbed and remolded engineering properties.

● FOR many years engineers have been concerned with the effects of remolding on the structure of clay. Strength losses and compressibility increases accompanying the remolding of an undisturbed clay are important considerations in design and construction on clay soils. The structure of a clay is defined as the fabric of the clay and the resistance of this fabric to alteration by physical, chemical, or electrical means. The fabric of an earth material may be defined as the appearance or pattern produced by the shapes and arrangement of the mineral grains, independently of the external boundaries of the material. Important in making up the fabric are particle orientation, or the positions of adjacent particles relative to each other, and texture, or the appearance of groups of particles.

Heretofore, direct observations of clay fabrics have been impossible because of the small size of clay particles and the lack of a procedure for the preparation of undisturbed samples for study. This paper describes a

[1] The research from which this paper has been prepared is taken from a thesis entitled, "The Importance of Structure to the Engineering Behavior of Clay," submitted in partial fulfillment of the requirements for the degree of Doctor of Science in Civil Engineering at the Massachusetts Institute of Technology, January 1956. Thesis supervisor was Dr. T. William Lambe; his assistance during the conduct of the research and in the preparation of this paper is gratefully acknowledged.

[2] Currently on active duty, U. S. Army, Fort Belvoir, Va.

method whereby thin sections of undisturbed and remolded clays may be prepared and studied with the aid of a petrographic microscope. The results of a detailed experimental and theoretical study of several clays in both the undisturbed and remolded states are presented and explained in terms of interparticle forces and the history of the material. The changes in engineering properties as a result of remolding are shown to correlate with the changes in fabric. Finally, further applications of the direct optical study of clay fabrics to problems in soil engineering are pointed out.

BACKGROUND AND THEORETICAL MATERIAL

Lambe (*6*), Skempton and Northey (*13*), Rosenqvist (*10, 11*), Bjerrum (*1*), and Bolt (*2*) have recently given close attention to the structure of fine-grained soils. The facts the clay particles are colloids and generally have the shape of thin, flat plates or rods have formed the basis for their considerations. Then, considering the types of interparticle attractive and repulsive forces in a clay-water-electrolyte system, theories of soil structure have been built up. Detailed considerations of these interparticle forces are beyond the scope of this paper. The interested reader is referred to the work of Lambe (*6*) and Bolt (*2*). It will be sufficient to keep in mind the following concepts:

1. A clay suspension will flocculate when attractive forces exceed repulsive forces.
2. Interparticle repulsive forces generally decrease with increasing electrolyte concentration and increasing cation valence.
3. Clay particles usually flocculate when suspended in solutions of high salt content. The exact salt concentration required to cause flocculation is dependent on clay mineral type, pH, and type of dissolved salt. Concentrations of NaCl greater than 0.1 to 0.2 molar are generally sufficient to flocculate a clay.

The theory of soil structure as presented by Lambe (*6*) is predicated, in part, on assumptions relative to the fabric induced by the particle orientation within undisturbed fresh and salt water clay deposits and in remolded clays. The orientation of particles within small areas is believed of prime importance. The two basic premises of particle orientation are that a dispersed system consists of particles in a parallel arrangement and a flocculated system consists of particles in a random arrangement. The parallel particle orientation in a dispersed system was predicted from the principles of colloidal theory (*6, 2, 3, 18*), as a parallel arrangement of particles puts them in their most stable positions.

Recent work has indicated that flocculation of clay probably occurs through simple electrostatic attraction between positively charged particle edges and negative particle surfaces. Theissen (*15*) presents electron photomicrographs which show negatively charged colloidal gold adsorbed only on the edges of kaolinite particles; whereas, positively charged silver was adsorbed only on the negative particle surfaces. Van Olphen (*16, 17*) was among the first to suggest the possibility of flocculation through edge to surface attraction. Subsequently, Schofield and Samson (*12*) and Bolt (*2*) have obtained experimental data in support of this hypothesis. The flocculation of plate-shaped particles by this mechanism will lead to a random arrangement of particles. Indirect evidences obtained from observations of such properties as sediment density and permeability also lend support to the concept of a random orientation in a floc.

Three important differences between a dispersed and a flocculated clay which aid in the explanation of engineering property differences between the two materials may be listed as follows:

1. At any consolidation pressure, a given weight of clay occupies a smaller volume in the dispersed (oriented) state than in the flocculated (random) state.
2. The particles within a dispersed clay are distributed more uniformly throughout the volume than are the particles in a flocculated clay.
3. A given increment of pressure applied to two clays, one dispersed and one flocculated, previously consolidated to the same pressure, causes a greater shifting of particles relative to each other in the flocculated clay than in the dispersed clay. This shifting is toward more parallel orientation.

Lambe (*6*) has schematically presented pictures of the fabrics as envisioned for undisturbed-salt and fresh-water clays and for remolded clay as shown in Figure 1. He postulates that when a sediment is dumped into a salt-water body, the sudden increase in

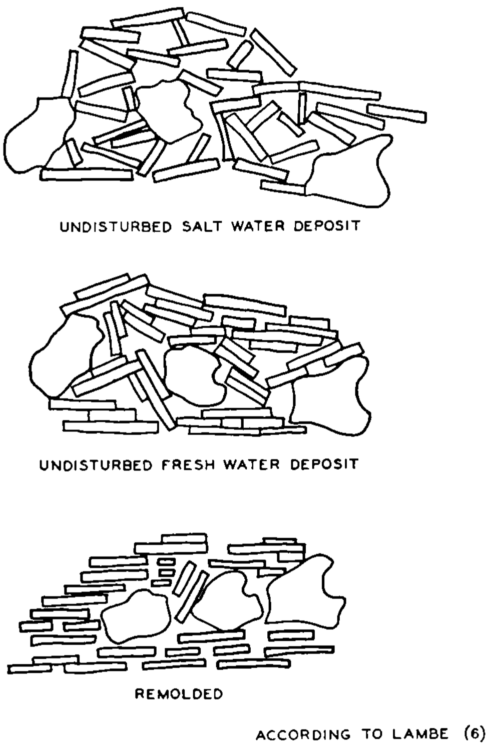

Figure 1. Schematic representations of particle orientation in clays.

electrolyte concentration and the reduction in velocity of the transporting water flocculates the clay particles, causing them to settle simultaneously with the silt and fine sand forming a loose, porous fabric. On the other hand, clay particles when dumped into fresh water, remain dispersed and settle with a slower velocity and a much higher degree of parallel orientation, at least within small areas.

The work of Skempton and Northey (*13*), Rosenqvist (*9, 11*), Bjerrum (*1*), and Lambe (*6*) has conclusively shown the relation between the leaching of marine clays and sensitivity.[3] The greater the salt content reduction as a result of leaching, the higher the sensitivity of a clay to remolding. After a leaching of the salt content, but before remolding, the particles remain in their flocculated positions. When the clay is remolded, however, the low electrolyte content tends to cause dispersion or at least a reduction of the degree of flocculation of the particles and results in a fabric as indicated in Figure 1.

[3] Sensitivity is defined as the ratio of undisturbed to remolded strength.

EXPERIMENTAL

Theory of Optical Study of Clay Particles

In order to obtain conclusive data for the purposes of confirming and, if found correct, expanding Lambe's picture of fabric and the effects of remolding thereon, an optical method for the direct observation of samples was developed.

Since individual clay particles are submicroscopic in size under magnifications up to 350×, which was found to be a practical limit in this study, the optical properties of a randomly oriented group of particles are indeterminate. Such a group of particles appears uniformly gray when rotated in plane polarized light. If, however, the particles are aligned parallel to each other, they behave optically as one large particle and have definite optical properties.

For plate-shaped particles, the refractive indices in the directions of the long axes (a and b) are approximately equal, but are significantly different from the refractive index in the direction of the short axis (c). If a group of oriented particles is viewed under polarized light, looking down the short axis, a uniform grayness of the field is observed as the sample is rotated about the short axis. If the group of particles is observed normal to the short axis, four stages of illumination and extinction are observed as the sample is rotated through 360 degrees.[4] Groups of oriented clay particles observed at any other angles to these axes show four stages of illumination and extinction during a 360-degree rotation; however, the intensities are less and changes from illumination to extinction are not as abrupt as in the case of observation normal to the short axis of the particles. Therefore, when a clay sample is to be studied optically, it is necessary to prepare two specimens for observation; each taken in a plane normal to the other. Orientation at any angle other than 90 degrees to the plane of one of the specimens should then be detectable in both sections.

[4] In the case of rod-shaped particles in parallel orientation, a uniform grayness is observed looking down the long axis, whereas, illumination and extinction are observed looking normal to this axis.

Preparation of Thin Sections

In order to apply the optical procedure to the study of clay fabric, it was necessary to develop a method for the preparation of thin sections from undisturbed and remolded clays. Weatherhead (*19*) describes a procedure whereby thin sections could be prepared from very soft rock by impregnating a dried surface with pyroxlin (a plastic material) and peeling off sections for study. Williamson (*21*) and Weymouth and Williamson (*20*) improved this procedure and successfully applied it to the study of dried kaolinite surfaces. The present author was able to apply this technique to other clay soils; however, the use of dry samples was undesirable since the effects of drying on fabric are unknown. A method was sought, therefore, which could be applied to clays at natural water content.

Rosenqvist (*10, 11*) describes a method whereby the water in a clay was replaced by sulphonated alcohol, or a similar substance at 60°C. After cooling the impregnated clay, he was able to cut sections down to 2 microns thickness with a biological microtome. He was successful in applying the procedure to Norwegian clays, although the preparation of such thin slices probably disrupted some of the coarser particles. It is not likely that the microtome blade could cut directly through silt and fine sand particles.

A satisfactory method was developed in the investigation described herein which involved the replacement of soil moisture with a high molecular weight polyethylene glycol compound (Carbowax 6000, produced by the Carbide and Carbon Chemical Company). This material is hard at ordinary temperatures, melts at about 55°C and is soluble in water in all proportions. A small cube of the wet clay to be studied was placed in the melted material at 60°C. At the end of three days, the water in the clay and the melted Carbowax had formed a uniform mixture by diffusion;[5] the sample was removed from the Carbowax and allowed to cool. The cooled impregnated sample had a hardness comparable to that of talc. Thin sections of approximately 40 microns thickness were then prepared using a procedure similar to that used for the preparation of rock thin sections. The only necessary modifications of the usual procedure were that kerosene instead of water was used for all grinding and cleaning operations and that the cement used for sticking the sample to the microscope slide did not employ heat for application. This procedure was found very satisfactory. The effects of the water replacement on the clay are believed to be negligible since no volume changes were observed on treatment, and it is felt that the thin sections gave an accurate picture of the fabrics of the clays studied.

Clays Studied

A study was made of 14 clays from various locations on the North American continent. Seven of these soils are reported in the literature to be of marine or brackish-water origin, and seven are believed to be of fresh-water origin. A brief description of these clays, their index properties, and compositions are listed in Table 1.[6] The following thin sections were prepared for each clay:

1. A section parallel and a section perpendicular to the horizontal plane through the clay as it existed in nature from the undisturbed clay at natural water content.
2. One section in a random direction from the clay remolded at natural water content.
3. A section parallel and a section perpendicular to the horizontal plane through the clay as it existed in nature from the undisturbed clay compressed one-dimensionally to 2 kg./cm.^{2} The direction of applied pressure was normal to the horizontal.
4. A section parallel and a section perpendicular to the direction of one-dimensional consolidation from the remolded clay compressed to 2 kg./cm.^{2}

The Study of Thin Sections

All sections were studied using a petrographic microscopic equipped with a 7.5× micrometer eyepiece in combination with 10× and 45× objectives. The 10× objective gave a field size of 1500 microns diameter and permitted the study of detail down to about 15 microns. The 45× objective gave a field size of 330 microns diameter and permitted detailed study down to about 3 microns. Plane

[5] Since the amount of Carbowax greatly exceeded the amount of water, the properties of the resultant mixture were nearly the same as those of the pure Carbowax.

[6] The author gratefully acknowledges the assistance of Dr. R. T. Martin of the M. I. T. Soil Stabilization Laboratory who performed the compositional analyses of these clays.

TABLE 1
CLAY INDEX PROPERTIES AND COMPOSITIONAL DATA

Clay and Location	Appearance	Natural Water Content %	Liquid Limit	Plastic Limit	Percent by Weight: Finer than 2μ	Percent by Weight: Illite	Percent by Weight: Chlorite	Percent by Weight: Montmorillonoid	Percent by Weight: Quartz	Cation Exchange Capacity Me/100gm	Pore Water Electrolyte Concentration (M)	Predominant Cation	Depositional Environment
Boston Blue, (Cambridge, Mass.)	Homogeneous, medium gray	35.6	41.1	20.2	52	30	5	—	15	13.6	0.04	Na	Marine
Boston Blue, (Charlestown, Mass.)	Homogeneous, medium gray	37.5	48.7	26.0	56	45	5	—	20	11.2	0.24	Na	Marine
Fore River, (Portland, Maine)	Silty, medium gray	41.5	48.8	21.0	43	40	5	—	20	11.4	0.08	Na—25%; mg (?)	Marine
Goose Bay, (Goose Bay, Labrador)	Brown, stiff, some silt	29.0	28.1	18.3	42	20	5	—	20	9.4	0.05	Na	Marine
Chicago, (Chicago, Illinois, subway)	Medium gray, very homogeneous	39.7	57.9	20.6	64	65	15	—	20	3.8	0.12	Ca	Lacustrine
Beauharnois, (Beauharnois, Quebec)	Soft, sensitive, dark gray	61.3	56.0	22.0	56	30	8	—	15	14.3	0.10	Ca	Marine
St. Lawrence, (Site unknown)	Medium homogeneous, dark gray	53.6	55.2	22.1	77	35	5	—	10	14.3	0.05	Na	Marine
Dow Field, (Bangor, Maine)	Silty, gray-green, very stiff	23.9	33.2	16.7	23	30	2	—	30	11.0	0.03	Na	Marine (?)
Mexico City, (Mexico City, Mex.)	Soft, plastic, red clay some fissures	356	416	102	29	—	—	Trace	—	37.8	0.03	—	Lacustrine
Cincinnati, (Cincinnati, Ohio)	Very silty, reddish-brown, stiff	23.2	30.2	12.3	20	50	—	10	35	13.5	0.02	Mg (?)	Fresh water
New Orleans, (New Orleans, La.)	Stiff, gray, contained sand lenses	51.0	78.5	26.0	—	20	—	20	40	17.2	0.02	Na	Fresh water
Texas, (Site unknown)	Very stiff, fissured yellow	19.1	80.0	24.9	47	50	—	30	10	26.1	0.06	Na—60%	Fresh water
Louisiana, (Bayou Cocodrie, La.)	Stiff, dark gray	40.0	73.8	25.8	40	35	—	35	15	29.2	0.04	Na—50%	Fresh water
Pump site, (Unknown)	Soft, spongy, yellow	27.0	32.0	18.5	18	15	—	20	40	16.4	0.05	Na	Fresh water (?)—possibly residual

polarized light was used with the degree of illumination varied to afford the best conditions for the study of detail. A gypsum or sensitive tint plate (550 millimicrons retardation of light waves) was found useful for picking out some details not readily visible in the ordinary black, white, and grey tones of the thin sections. With the tint plate extinction appeared purple, and illumination was either yellow or green depending on the quadrant of the crystal axes with respect to the plane of polarization of the light.

The procedure for the study of thin sections was established in such a way that a clear and concise description of the fabric could be obtained, and so that numerical ratings could be attached to the features making up the fabric. The general scheme of study was as follows:

- Fabric
  - Particle Orientation (Clay)
    - Small Areas (<1500 μ diameter)
    - Large Areas (>1500 μ diameter)
      - Direction
    - Orientation of Clay around Silt
  - Particle Orientation (Silt)
    - Orientation of Clay around Silt
  - Texture
    - Regularity of Components
    - Transition between components

Each thin section was studied systematically and in detail. After a preliminary scanning of the entire section, five distinct fields were studied. All items listed in the above diagram were determined for each field. Rating scales from 0 to 100 were arbitrarily established for most of the features. At the conclusion of the study, the values for the individual fields were averaged to give one value for the sample.

Particle Orientation. The degree to which clay particles were oriented in a parallel arrangement could be determined by the intensity of illumination and extinction as the microscope stage was rotated. Orientation intensity was determined both over areas larger and smaller than 1500 microns diameter. Numerical intensity ratings increase from 0 to 100 as the particle orientation changes from random to perfect parallelism. Photomicrographs of well-oriented Texas clay having an orientation rating of 75 are shown in Figure 2. Photomigrographs of randomly oriented Goose Bay clay, orientation rating 0, are shown in Figure 3. The angle of the plane in which clay was oriented with respect to a horizontal plane through the clay as it existed in nature was determined where possible.

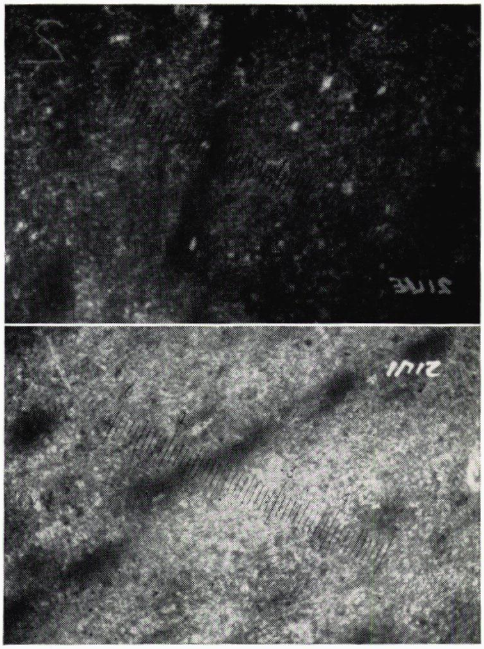

Figure 2. Photomicrographs of well oriented Texas clay (undisturbed). Above: Extinction. Below: Illumination. Large difference in intensity between extinction and illumination indicates that clay is well oriented.

Texture: Regularity of Components. The regularity of components refers to the arrangement of the components of the field on a large scale (greater than 500 micron-diameter areas), and is dependent on the distribution of silt, and the size and distribution of oriented areas. Low regularity ratings indicate a very heterogeneous fabric with irregular distribution of oriented patches, irregular silt distribution, or orientation in some areas and none in others. High regularity ratings are indicative of homogeneous appearing fields. Photomicrographs of clays exhibiting low and high regularity are shown in Figures 4 and 5, respectively.

Texture: Transition Between Textural Components. Transition refers to the manner in which oriented areas extend across the sections and the change from one area to another. Good interconnection over the field or a smooth transition from orientation in one direction to orientation in another area are indications of good transition (high numerical rating). Isolation of oriented areas, abrupt changes in orientation direction, and narrow veins of clay oriented in a different direction than the rest of the clay are indications of poor transitions (low numerical rating). Photomicrographs of clays exhibiting high and low transition ratings are shown in Figures 6 and 7, respectively.

Silt Orientation and the Orientation of Clay Around Silt. The orientation of silt particles was random in almost all cases; consequently, this feature was not rated numerically. The degree of orientation of clay particles around silt particles was observed, since it is possible that during compression in nature, clay particles may be pressed around the surfaces of silt particles and the action of remolding may tend to orient clay particles around silt.

The results of the fabric analysis are listed in Table 2. The values listed in Table 2 are averaged from 10 observations—5 for each of the two sections studied from any sample, with the exception of those for the remolded clay at natural water content where only one thin section was prepared for each clay.

THE FABRICS OF UNDISTURBED AND REMOLDED CLAYS

General

At the conclusion of the examination of the 14 undisturbed and remolded clay soils in thin section, it was noted that several features were common to the majority of the clays. These features are evidently independent of grain size, composition, or mode of formation of the clay.

1. Silt particles did not touch each other either in the undisturbed or remolded clays. This was true even in those clays, such as Dow Field clay, Cincinnati clay, and Pump Site clay, all of which had less than 25 percent finer than 2 microns. Since silt particles do not touch each other but "float" in a matrix of clay, they probably have little influence on the strength properties of the material.

2. The variability between the size and intensity of oriented areas, regularity, and transition from one field to another is greater in the undisturbed clays than in the remolded clays. This would be expected since the remolding process tends to homogenize the fabric.

3. The improvement in parallel clay orientation as a result of one-dimensional compression from natural water content to 2 kg./cm.^{2} is much greater for remolded clays than for undisturbed clays. This may be explained

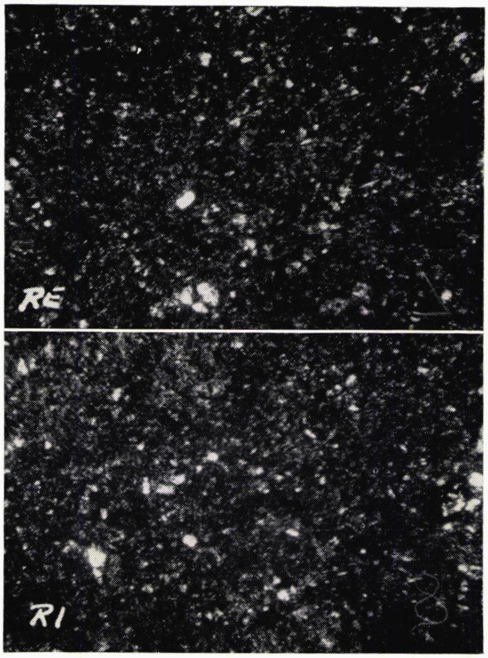

Figure 3. Photomicrographs of randomly oriented Goose Bay clay (undisturbed). Above: Extinction. Below: Illumination. No difference in intensity between extinction and illumination indicates that clay is randomly oriented.

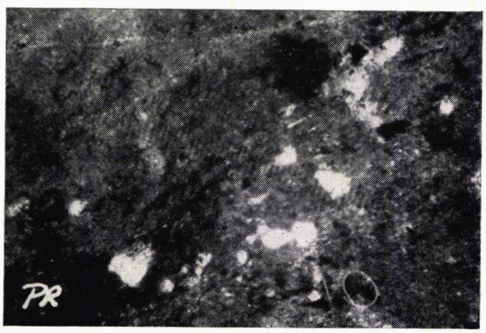

Figure 4. Photomicrograph of undisturbed New Orleans clay exhibiting an irregular fabric. Note irregular silt distribution.

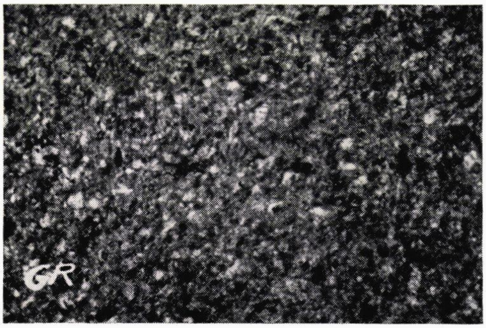

Figure 5. Photomicrograph of undisturbed Pump Site clay exhibiting a regular fabric.

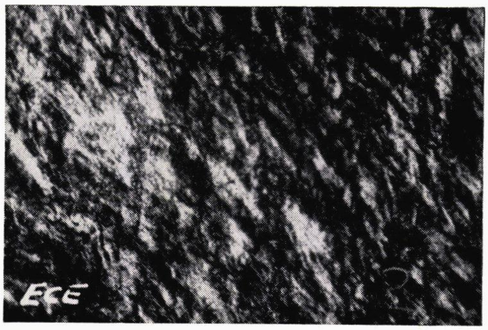

Figure 6. Photomicrograph of sodium kaolinite exhibiting smooth transitions from one area to another.

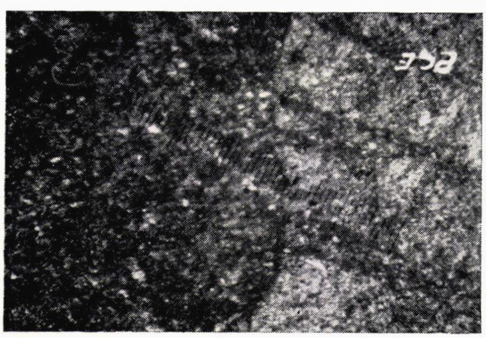

Figure 7. Photomicrograph of undisturbed Boston blue clay exhibiting abrupt transitions from one area to another. Note vertical discontinuity, center, and veins across right half.

by the fact that the undisturbed clays studied, in most cases, had been compressed to a pressure greater than 2 kg./cm.^{2} in nature; therefore, the void ratio change during the laboratory recompression was small. The remolded clays, however, due to their lower strengths, underwent an appreciable void ratio change as a result of compression; consequently, the change in particle orientation was appreciable.

4. In remolded clays at natural water content, orientation of clay particles parallel to one plane is not good over large areas; however, the orientation intensity within small areas ($<350\mu$) is good, and oriented areas shift smoothly from orientation in one direction to orientation in another. The kneading action of the remolding process is responsible for this, since during remolding, shear stresses are constantly shifting from plane to plane and there is no force tending to align particles parallel to any one direction.

Fabrics of the Individual Clays

The clays studied may be broken down into three groups on the basis of the effects of remolding on their fabrics.

Group	Description	Clays
1	Undisturbed material shows some parallel orientation of the clay. Remolding improves orientation in small areas, removes discontinuities, and improves the regularity of texture.	Boston blue (Cambridge); Boston blue (Charlestown); Fore River; Goose Bay; Chicago; Beauharnois; St. Lawrence
2	Undisturbed material shows good parallel orientation in large and/or small areas. Remolding has little effect on the intensity of orientation	New Orleans; Texas; Louisiana
3	Undisturbed material above random orientation except in a few small areas. Little or no change in orientation with remolding	Mexico City; Cincinnati; Dow Field; Pump site

Group 1 Clays. With the exception of Chicago clay, all the clays in this group are believed to have been formed in a marine or brackish environment. Photomicrographs of undisturbed and remolded Boston blue clay (Cambridge) are shown as a typical example of the clays in this group in Figure 8. It may be noted that the differences between the intensities of illumination and extinction are the greatest for the remolded clay indicating that the clay in the remolded material is better oriented.

The results of the study of these clays were somewhat surprising in that all the undisturbed clays exhibited some degree of parallel orientation. This would not be expected on the

TABLE 2
RESULTS OF THIN SECTION STUDY

Clay	State*		Parallel Orientation Intensity in Large Areas (>1500 μ)	Direction of Orientation in Large Areas†	Size of Small Oriented Areas μ	Intensity of Small Oriented Areas	Regularity of Texture	Transition between Components	Orientation of Clay around Silt	Remarks
Boston Blue (Cambridge)	U	Natural *w*	47	0°	30–100	50	30	30	Random	Definite predominance of clay oriented parallel to horizontal.
	R	Natural *w*	43	—	30–>350	70	65	60	Oriented >5 μ layer	
	U	2 kg./sq. cm.	65	−7°	20–150	66	68	50	Oriented on some	Sections split. Directions in error.
	R	2 kg./sq. cm.	80	17°	>350, 60% area	85	87	75	Parallel to matrix	Section split. Directions in error.
Boston Blue (Charlestown)	U	Natural *w*	45	0°	50–150	57	21	18	Random	150 μ wide vein across section clay at right angles to mass.
	R	Natural *w*	15		10–25	65	72	54	Oriented	
	U	2 kg./sq. cm.	75	10°	75–>350	75	51	26	5 μ layer on some	Sharp discontinuities.
	R	2 kg./sq. cm.	81	11°	40–>350	84	84	75	5 μ layer on some	Interconnected patches (10% area) to 150 μ diameter at 90° to main body.
Mexico City	U	2 kg./sq. cm.	58	2°	20–150, 50% area	71	90	82	Oriented	Black fibers 15 × 150 μ parallel to 5°.
	R	2 kg./sq. cm.	0	—	20–40, 20% area	58	68	68	Random	Brown spots to 150 μ diameter.
Fore River	U	Natural *w*	Patches < Field	—	50–300	44	60	38	Random	Patchy texture.
	R	Natural *w*	43	—	70–>350, 60% area	65	75	72	Slightly oriented	
	U	2 kg./sq. cm.	0	—	20–>350, 50% area	51	90	77	3 μ layer on some	Patchy texture.
	R	2 kg./sq. cm.	52	10°	50–>350, 60% area	84	90	90	Mostly parallel to 10%	
Goose Bay	U	Natural *w*	10	10°	100–400	36	60	21	oriented on some	Patchy texture.
	R	Natural *w*	50	—	70–300	60	60	60	Random	
	U	2 kg./sq. cm.	5	—	15–30, 40% area	34	81	42	Random	
	R	2 kg./sq. cm.	30	12°	20–>350, 60% area	54	90	87	Some parallel to 12°	
Chicago	U	2 kg./sq. cm.	5	—	10–20, 50% area	43	66	45	—	
	R	2 kg./sq. cm.	55	0°	15, 50% area	95	84	81	—	
Beauharnois	U	Natural *w*	0	—	to 500	36	60	39	Oriented on some	Fissured, weakly oriented patches of all sizes and shapes
	R	Natural *w*	20	—	to 300	55	42	54	Oriented on some	Patchy texture.
	U	2 kg./sq. cm.	0	—	30–450	56	81	50	Oriented on some	
	R	2 kg./sq. cm.	65	25°	20–>350, 60% field	80	81	77	Oriented on some	

TABLE 2—*Continued*

Clay	State*	Parallel Orientation Intensity in Large Areas (>1500μ)	Direction of Orientation in Large Areas†	Size of Small Oriented Areas	Intensity of Small Oriented Areas	Regularity of Texture	Transition between Components	Orientation of Clay around Silt	Remarks
Cincinnati	U Natural *w*	5	0°	10–30, 30% field	37	40	48	—	Silt distribution not uniform.
	R Natural *w*	0	—	20–30	35	60	60	Oriented	
	U 2 kg./sq. cm.	10	10°	20–30	35	81	57	Oriented on some	
St. Lawrence	U Natural *w*	42	—	150–750	34	45	41	—	Section split up, direction uncertain.
	R Natural *w*	10	—	10–300	75	63	78	—	
	U 2 kg./sq. cm.	60	15°	>350	50	63	32	—	20 μ wide streak across section.
	R 2 kg./sq. cm.	37	−5°	20–100	72	90	50	—	
New Orleans	U 2 kg./sq. cm.	53	0°	150–450	100	60	69	Random	Streak of clay oriented in different direction than rest of material.
	R 2 kg./sq. cm.	55	15°	15–>350, 50% area	76	72	78	Oriented on some	
Dow Field	U Natural *w*	0	—	200–400, 10% area	10	60	45	Random	
	R Natural *w*	5	—	15, 10% area	5	66	66	Random	
	U 2 kg./sq. cm.	25	11°	20–30, 15% area	45	72	38	Random	Very silty.
Texas	U Natural *w*	75	11°	>350, 90% area	85	84	84	Parallel to 11°	
	R Natural *w*	50	Varies	Bands to 300	83	57	72	Oriented on some	
Louisiana	U Natural *w*	15	42°	10–150, 50% area	72	66	38	Random	
	R Natural *w*	30	—	15–500, 50% area	80	69	63	Random	
	U 2 kg./sq. cm.	28	16°	15–>350, 50% area	55	60	36	Oriented on some	
	R 2 kg./sq. cm.	73	21°	15–800, 60% area	75	60	51	Parallel to matrix	
Pump site	U Natural *w*	0	—	15	10	90	63	—	
	R Natural *w*	20	—	20, 25% area	20	78	78	—	
	U 2 kg./sq. cm.	0	—	0	—	90	56	3 μ layer on some	
	R 2 kg./sq. cm.	5	—	15–>350, 20% area	25	90	84	Random	

* U = Undisturbed; R = remolded. 2 kg./sq. cm. = After one-dimensional compression to 2 kg./sq. cm.
† Angle of orientation with respect to a horizontal plane.

basis of the flocculating nature of salt water as outlined previously. Rosenqvist (*11*) found that the clay particles in highly sensitive Norwegian marine clays were almost completely randomly distributed. However, he also points out that the consolidation of these clays has never been very great. Table 3 indicates that all of the group 1 clays, with the exception of Beauharnois clay, had undergone at least 2.9 kg./cm.^{2} precompression in nature. Since compressions in nature are essentially one-dimensional, considerable orientation of clay particles could result.

In order to test further the orienting effect

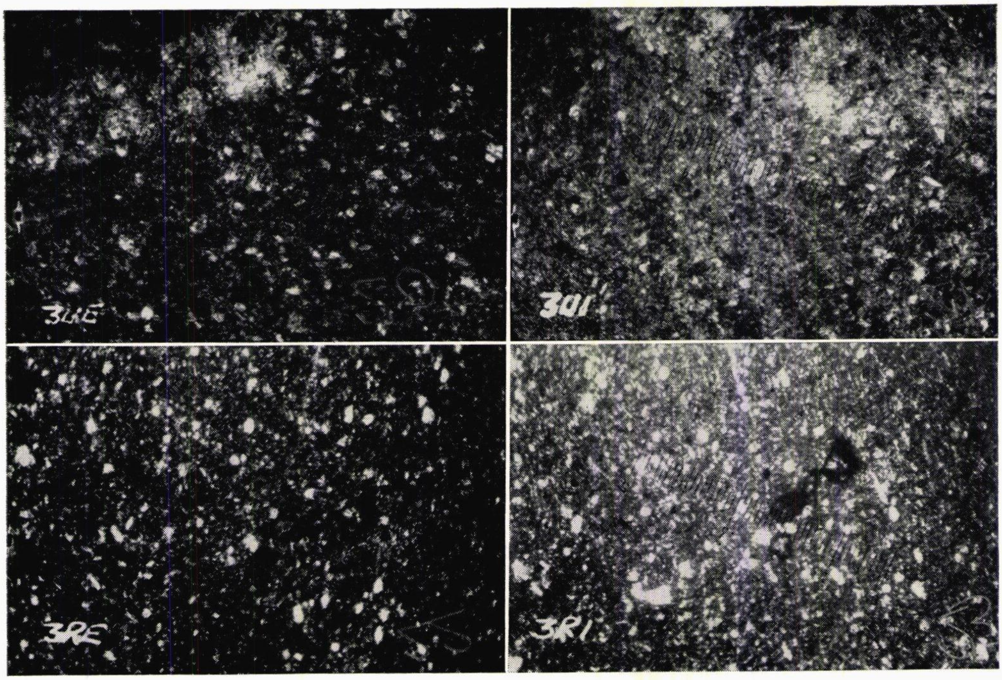

Figure 8. Photomicrographs of undisturbed and remolded Boston blue clay (Cambridge). Above: Undisturbed—Left: Extinction; Right: Illumination. Below: Remolded—Left: Extinction; Right: Illumination.

of pressure on an initially random sample, air-dried, powdered Boston blue clay was thoroughly mixed with sea water and compressed one-dimensionally to 4 kg./cm.^{2} (a typical precompression load for Boston blue clay). The compression curve for this sample, Figure 9, follows a line having the same slope as the virgin curve of the undisturbed material, and at any pressure the void ratio is only slightly less than the undisturbed void ratio. Consequently, this laboratory sample was probably a reasonable duplication of the undisturbed clay. Photomicrographs of thin sections prepared from this sample are shown in Figure 10. It may be seen by the differences in intensity between the illumination and extinction position that this sample was well oriented. A considerable part of the orientation in undisturbed marine clays, therefore, may be attributed to precompression.

The Fore River, Goose Bay, and Beauharnois clays all exhibited a patchy fabric. In these undisturbed clays, orientation parallel to any one direction persisted only over areas of 50 to 500μ diameter. In all three clays some of the patchy nature of the undisturbed clay remained after remolding. A probable reason for this is that some of the oriented areas are too tightly bonded internally to be broken down during remolding. Lambe and Martin (7), in their studies of the relationship between soil properties and composition, have found many cases where clay aggregates are too strongly cemented by carbonates and iron and aluminum oxides to be broken up. It is believed that these oriented zones represent cemented groups of particles that were dumped intact into the sediment during its formation since they were oriented in random directions. These clusters of oriented particles could possibly be fragments of eroded shales from which a part of the sediment was derived.

The majority of the clays in this group were characterized by the presence of abrupt discontinuities and narrow veins of clay oriented in a direction different from that of the remainder of the material. These veins and discontinuities could represent old fissures or

TABLE 3
ENGINEERING DATA

Clay	Strength* Undist. Lb./sq.ft.	Strength* Remolded Lb./sq.ft.	† Sensitivity	Void Ratio at Maximum Past Pressure e_U‡	Void Ratio at Maximum Past Pressure e_R§	¶C_cU	‖ C_cR	**Maximum Past Pressure kg./sq.cm.	†† r_U	‡‡ r_R	Permeability §§ Undisturbed k_x cm/sec	Permeability §§ Undisturbed k_z cm/sec	Permeability §§ Remolded k_x cm/sec	Permeability §§ Remolded k_z cm/sec
Boston Blue (Cambridge)	1152	170	6.80	0.88	0.67	0.38	0.21	4.9	0.31	0.17	2.75×10^{-7} 5.00×10^{-7}	1.57×10^{-7} 6.95×10^{-8}	1.45×10^{-7} 6.11×10^{-8}	1.37×10^{-7} 1.22×10^{-8}
Boston Blue (Charlestown)	1150	200	5.75	0.94	0.79	0.33	0.21	4.5	0.30	0.20	3.80×10^{-7} 2.14×10^{-7}	1.05×15^{-7} 3.14×10^{-8}	1.43×10^{-7} 1.00×10^{-7}	6.06×10^{-8} 1.86×10^{-8}
Mexico City	425	216	1.97	—	—	—	—	—	—	—	1.51×10^{-7} 9.54×10^{-8}	2.51×10^{-7} 2.09×10^{-8}	8.59×10^{-8} 8.80×10^{-9}	6.61×10^{-8} 4.64×10^{-9}
Fore River	900	201	4.50	1.06	0.81	0.37	0.26	3.3	0.30	0.11	1.65×10^{-7} 1.29×10^{-7}	7.51×10^{-8} 5.75×10^{-8}	4.91×10^{-8} 4.87×10^{-8}	4.91×10^{-8} 1.66×10^{-8}
Goose Bay	1400	—	—	—	—	—	—	—	—	—	9.10×10^{-8} 9.25×10^{-8}	2.68×10^{-8} 1.90×10^{-8}	1.26×10^{-7} 6.17×10^{-8}	9.33×10^{-8} 1.50×10^{-8}
Chicago	965	286	3.38	1.05	0.84	0.44	0.22	3.8	0.25	0.14	6.71×10^{-8} 9.30×10^{-8}	4.80×10^{-8} 3.55×10^{-8}	1.25×10^{-7} 1.45×10^{-7}	2.54×10^{-9} 1.44×10^{-8}
Beauharnois	350	64	4.70	1.68	1.48	0.55	0.41	0.5	0.34	0.24	2.71×10^{-7} 1.60×10^{-7}	1.17×10^{-7} 6.94×10^{-8}	2.50×10^{-7} 1.22×10^{-7}	3.12×10^{-7} 3.84×10^{-8}
Cincinnati	1190	501	2.37	0.65	0.60	0.17	0.15	2.7	0.17	0.20	2.28×10^{-7} 2.18×10^{-7}	1.03×10^{-7} 6.45×10^{-8}	1.88×10^{-7} 1.66×10^{-7}	5.22×10^{-8} 2.81×10^{-8}
St. Lawrence	910	170	5.35	1.64	1.22	0.67	0.40	2.9	0.38	0.18	1.60×10^{-7} 1.76×10^{-7}	1.07×10^{-7} 4.40×10^{-8}	— —	— —
New Orleans	1800	740	2.44	0.85	0.73	0.28	0.25	3.5	0.20	0.09	— —	— —	1.72×10^{-8} 5.90×10^{-9}	1.53×10^{-8} 5.90×10^{-9}
Dow Field	1800	725	2.60	—	—	—	—	—	—	—	5.79×10^{-7} 4.10×10^{-7}	4.75×10^{-7} 2.93×10^{-7}	4.94×10^{-8} 2.37×10^{-8}	3.80×10^{-8} 1.97×10^{-8}
Texas	>1800	—	—	—	—	—	—	—	—	—	1.21×10^{-7} —	3.10×10^{-8} —	— —	— —
Louisiana	1780	895	1.99	1.03	0.85	0.34	0.28	2.2	0.32	0.14	4.35×10^{-8} 5.22×10^{-8}	4.81×10^{-8} 1.80×10^{-8}	2.64×10^{-8} 1.17×10^{-8}	6.30×10^{-9} 1.81×10^{-9}
Pump site	410	232	1.77	0.79	0.68	0.15	0.13	0.5	0.34	0.44	2.08×10^{-7} 1.34×10^{-7}	6.91×10^{-7} 3.34×10^{-7}	3.48×10^{-8} 1.98×10^{-8}	1.95×10^{-8} 9.90×10^{-9}

* At natural water content. Determination with laboratory vane apparatus.
† Undisturbed strength/remolded strength.
‡ Void ratio of undisturbed clay at maximum past pressure.
§ Void ratio of remolded clay at maximum past pressure of undisturbed clay.
¶ Compression index of straight line portion of undisturbed compression curve.
‖ Compression index of remolded clay; $c_c = \frac{d\,e}{d(\log_{10} p)}$ = Negative slope of e—log p curve.
** Maximum precompression of undisturbed clay.
†† Secondary compression ratio of undisturbed clay at maximum past pressure.
‡‡ Secondary compression ratio of remolded clay at same pressure as listed for undisturbed clay.
§§ k_x = horizontal permeability, k_z = vertical permeability. First value is for clay at natural water content, second value was determined after vertical compression to 2 kg./sq. cm.

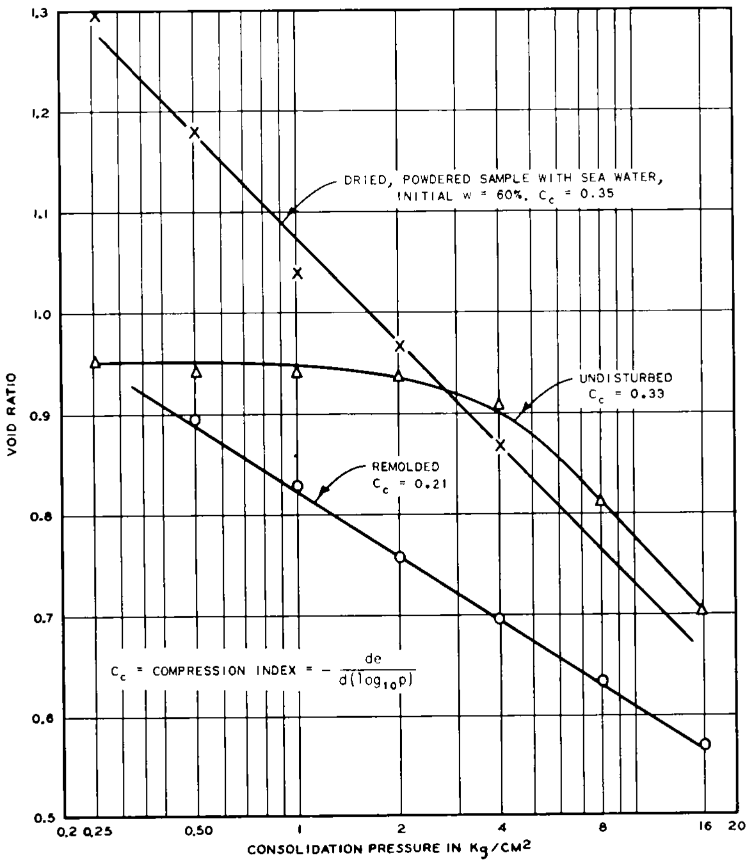

Figure 9. Consolidation of different samples of Boston blue clay.

shear planes resulting from ground movements.

The overall randomness of the particle orientation noted in the undisturbed Chicago clay was somewhat surprising since this material is thought to have formed in a fresh water environment where flocculation would be at a minimum. However, the "fresh" waters in the Chicago area are known to be high in dissolved calcium and magnesium carbonates. At the time of deposition, the clay was undoubtedly either in the calcium or magnesium form in which case flocculation could easily have occurred.

Remolding the clays in this group homogenized the fabric and increased the intensity of parallel orientation in small areas. After compression to 2 kg./cm.^{2}, the clay orientation was generally very good over large areas.

Group 2 Clays. Both the Texas and New Orleans clays were very stiff and heavily precompressed. Photomicrographs of undisturbed and remolded New Orleans clay are shown in Figure 11, where it may be noted that the differences between extinction and illumination are about the same for the undisturbed and remolded clay. The high intensity of parallel orientation in the undisturbed materials would be anticipated as a result of their fresh water origin and heavy precompression. The undisturbed Louisiana clay showed reasonably good orientation in small areas, but not over large areas. The precompression of this clay was significantly less than in either the New Orleans or Texas clays.

Group 3 Clays. Cincinnati, Dow Field, and Pump Site clays all contained more than 75 percent silt and fine sand. Particle orientation in these materials was restricted to areas

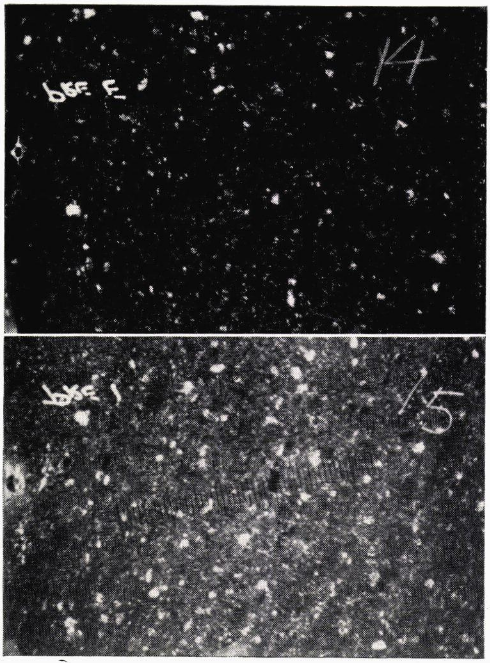

Figure 10. Photomicrographs of powdered Boston blue clay consolidated one-dimensionally to 4 kg/cm^2 in sea water. Above: Extinction. Below: Illumination. Large difference in intensity between extinction and illumination indicates parallel orientation of clay particles.

generally less than 50μ in diameter. Photomicrographs of Dow Field clay, Figure 12, are characteristic of these clays. These materials had low sensitivities and showed little change in orientation due to remolding. Most likely the high percentage of coarse particles prevented the development of orientation parallel to any one direction over large areas. The Mexico City clay was found to have a very random fabric. This material was formed as a result of wind-blown volcanic ash being dumped into a fresh water basin. The most detailed mineralogical investigation carried out on this particular sample has failed to show more than a trace of montmorillonite and no other clay minerals. The greatest percentage of material is believed to be a weathered volcanic ash, probably changing to montmorillonite. Since volcanic ash particles are definitely not plate-shaped, orientation of particles would not be expected.

THE RELATION BETWEEN BEHAVIOR AND FABRIC

The discussion in the preceding section and the data in Table 2 have shown that the fabrics of undisturbed clays may assume various forms, particularly regarding the orientation of clay particles. In addition, the change in fabric as a result of remolding varies from clay to clay. This section will show how the fabrics are related to the engineering properties of undisturbed and remolded clays.

In Table 3 are listed strength, permeability, and compressibility data for the clays studied. Shearing strengths were obtained with the laboratory vane apparatus described by Kusnitz (*4*). Compressibility data were obtained using standard consolidation testing methods as given by Lambe (*5*). Permeabilities in a horizontal and vertical direction through a clay were determined using a special apparatus developed by the author and described in reference *8*.

Composition

Compositionally the clays fall into three groups: illite-chlorite clays, illite-montmorillonoid clays, and Mexico City clay, which is a weathered volcanic glass. It may be noted that the marine clays belong to the illite-chlorite group, whereas, the majority of the fresh water clays belong to the illite-montmorillonoid group. The marine clays undergo the greatest changes in particle orientation and engineering properties as a result of remolding.

Electrolyte Content of the Pore Water

The effect of high electrolyte concentration in depositional waters on the flocculation of clay suspensions has been pointed out. Lambe (*6*), Skempton and Northey (*13*), Bjerrum (*1*), and Rosenqvist (*9*) have shown that changes in electrolyte content subsequent to deposition have some, but not a large effect on the properties of the undisturbed clay, but that the remolded properties are affected to a high degree. The marine clays listed in Table 1, with the exception of the Boston blue clay from Charlestown, all have a present electrolyte content of about 0.05 molar which is considerably less than the 0.4-molar NaCl concentration of sea water. These clays showed the greatest changes in fabric and engineering properties due to remolding.

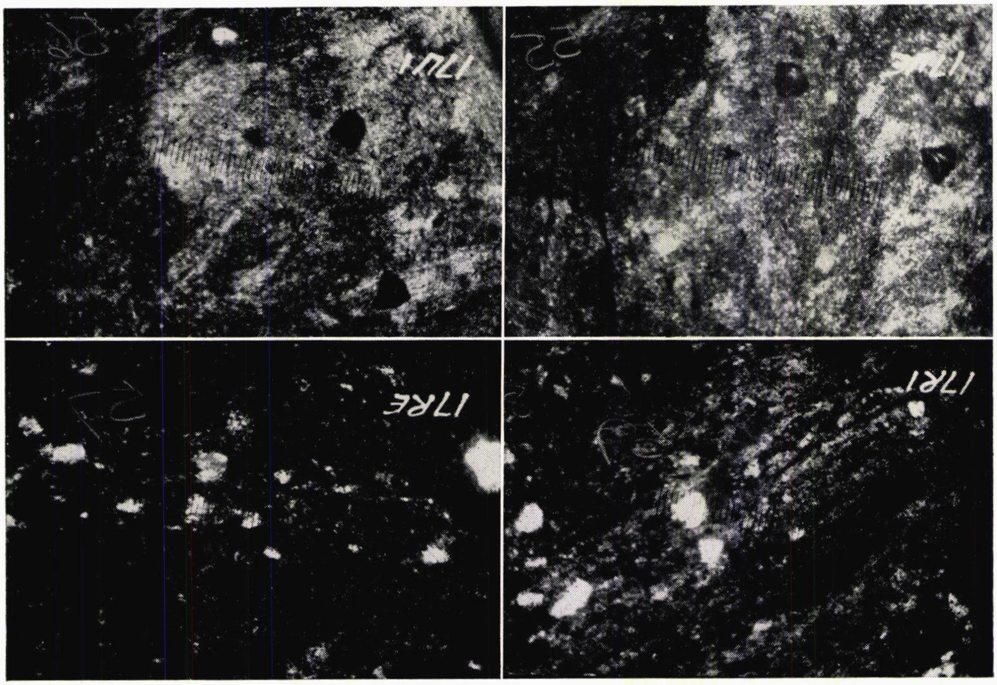

Figure 11. Photomicrographs of undisturbed and remolded New Orleans clay. Above: Undisturbed—Left: Extinction; Right: Illumination. Below: Remolded—Left: Extinction; Right: Illumination.

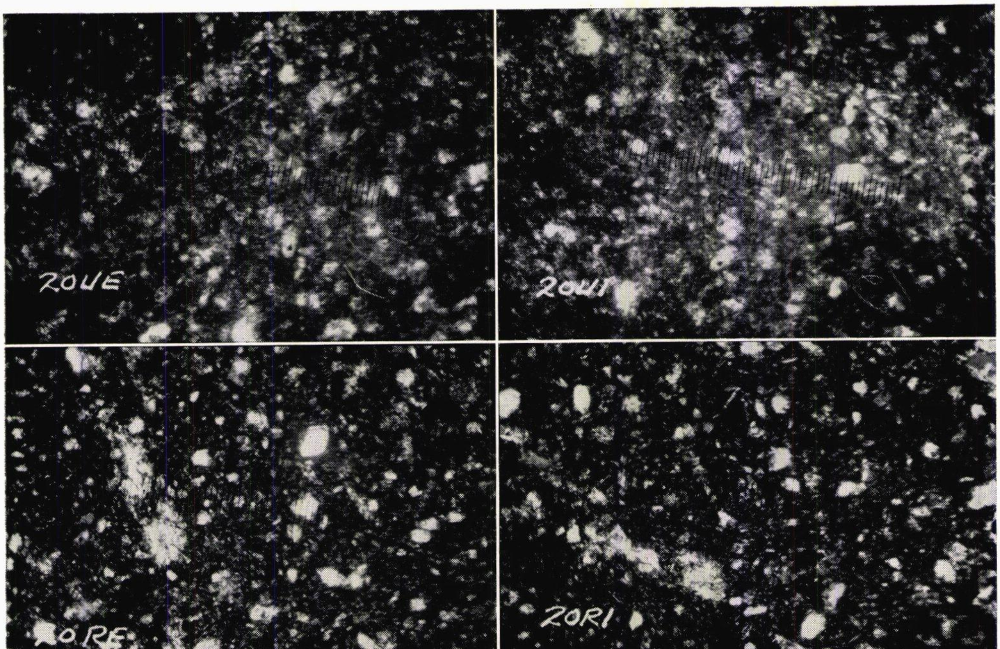

Figure 12. Photomicrographs of undisturbed and remolded Dow Field clay. Above: Undisturbed—Left: Extinction; Right: Illumination. Below: Remolded—Left: Extinction; Right: Illumination.

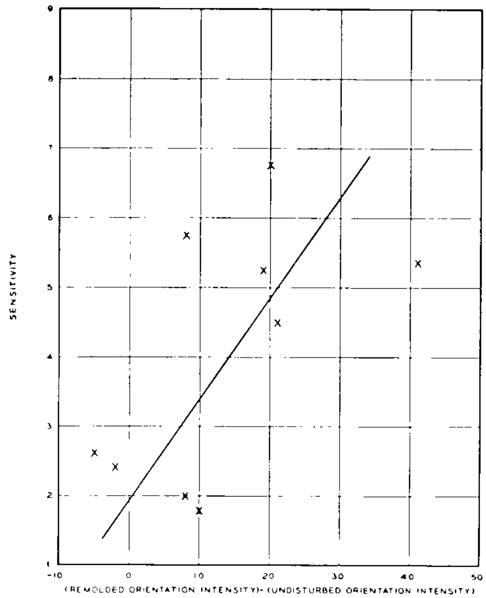

Figure 13. Sensitivity vs. improvement in particle orientation in small areas due to remolding.

Sensitivity

Sensitivity[7] is plotted in Figure 13 as a function of the improvement in parallel orientation intensity within small zones caused by remolding. A definite relation is far from defined by Figure 13; however, there is a trend between increasing sensitivity with orientation improvement. A clay of high sensitivity may be considered as a flocculated material (random orientation) in the undisturbed state and as a dispersed material (parallel orientation) in the remolded state. Observations have repeatedly confirmed the fact that a flocculated clay has a higher strength than a dispersed clay at the same void ratio.

Compressibility

The consolidation constants for the undisturbed and remolded clays are listed in Table 3. The compression index (C_c) values represent the slope of the straight line portion of the void ratio-log pressure curve. Secondary compression ratios were determined by the square root of time fitting method (*14*). The values of secondary compression ratio listed in Table 3 are those corresponding to a consolidation pressure equal to the precompression load on the undisturbed clay in nature.

For each clay, the remolded C_c value is less than the undisturbed C_c value. Since the interparticle repulsions in a remolded clay are higher than in the undisturbed and, therefore, the particles may pack efficiently, the clay undergoes significant void ratio decrease under low loads. The undisturbed clay compresses very little until the pressure exceeds the precompression load. When both materials have been consolidated to a pressure equal to the precompression load, the void ratio of the remolded clay is significantly less than the void ratio of the undisturbed clay, as indicated by the void ratio values in Table 3. There is a minimum void ratio to which a given clay can be compressed regardless of pressure or initial orientation. This void ratio will be greater than zero due to irregularities in particle shapes and surfaces. At the maximum past pressure, the remolded clay is closer to the minimum possible void ratio than is the undisturbed clay. Due to this denser and more efficient packing in the remolded clay, a given increment of pressure causes a smaller void ratio decrease than occurs in the undisturbed sample under the same increment of pressure. Therefore, the slope of the straight-line portion of the undisturbed curve is steeper than that for the remolded clay.

On the basis of these considerations, one would expect a correlation between the improvement in orientation caused by remolding and both (1) the difference between the undisturbed and remolded void ratios at a pressure equal to the maximum precompression, and (2) the differences between the undisturbed and remolded C_c values. Figures 14 and 15 show these expectations to be correct. Figure 14 shows the ratio of undisturbed to remolded compression index to increase with the improvement in orientation intensity due to remolding. Figure 15 indicates that the ratio of undisturbed to remolded void ratios at the maximum past pressure increases as the improvement in orientation intensity due to remolding increases.

Secondary compression, or that void ratio decrease that occurs after excess hydrostatic pressure in the pore water is dissipated, has been attributed by Lambe (*6*) to the break down of aggregates and the shifting of particles

[7] Determined as the ratio of the peak strength of the undisturbed clay divided by the remolded strength at the same strain.

under stress. He also points out that there is undoubtedly extrusion of adsorbed water from between particles at a very slow rate; however, this process can occur with negligible volume change. If secondary compression is indeed caused by these factors, then the measured values of secondary compression ratio should bear some relation to the orientation.

The data in Table 3 indicate that the undisturbed secondary compression ratio is greater than the remolded secondary compression ratio in all but two cases. The data in Table 2 show that, in general, the undisturbed clays have a more random particle orientation than do the remolded. Since the remolded clays are more efficiently packed than the undisturbed clays, the amount of particle shifting during compression is less than occurs in the undisturbed clays. The difference between undisturbed and remolded secondary compression ratios is shown in Figure 16 as a function of the orientation change due to remolding. No clear-cut relation is defined. The scatter of these points may possibly be due to the fact that the effects of time are not considered. The relative amounts of final particle adjustment that occur during primary and secondary compression are unknown quantities. It is quite likely, however, that these adjustments are functions of the orientation of particles before load application, the forces by which these particles are held in this orientation, the speed of compression, and the pressure to which the clay is subjected. The net effect of these factors is probably much too complex to be quantitatively expressed by the secondary compression ratio.

Permeability

Directly measured permeability values for the undisturbed and remolded clays at natural water content and after compression to 2 kg./cm.² are listed in Table 3. It may be noted that, in general, remolding decreases the permeability at natural water content by a factor of from 1 to 15 with a reduction to half the undisturbed value typical for many of the materials. Permeability decrease due to remolding would be expected on the basis of the fabric changes. It was previously noted (Table 2) that remolding homogenized the fabric and improved the parallel orientation of particles. As a result the remolded material represents a more uniform space distribution

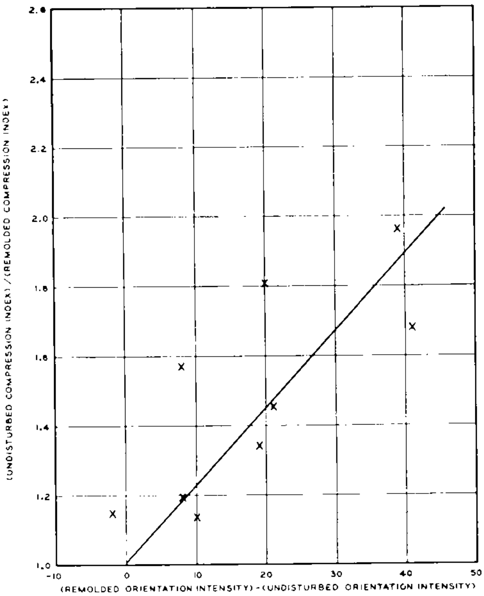

Figure 14. Ratio of undisturbed to remolded compression index as a function of orientation improvement due to remolding.

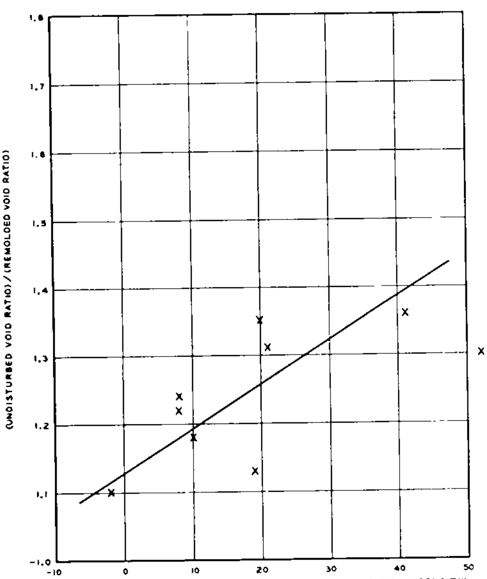

Figure 15. Ratio of undisturbed to remolded void ratios at maximum past pressure as a function of the improvement in orientation in small areas due to remolding.

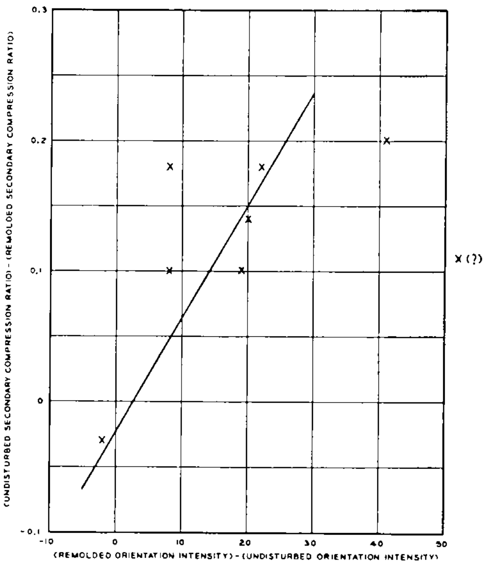

Figure 16. Difference between undisturbed and remolded secondary compression ratio as a function of improvement in orientation intensity due to remolding.

of particles than does the undisturbed. Therefore, the average pore diameter in the remolded clay is lower than in the undisturbed and the resistance to water permeation is higher, resulting in lower permeability values for the remolded clay.

The data in Table 3 also show that the permeability in a horizontal direction through a clay is, in most cases, higher than the permeability in a vertical direction, particularly after the clay has been compressed one-dimensionally. Two factors can be responsible for a higher horizontal than vertical permeability: stratification and orientation of platy clay particles with their long axes parallel to

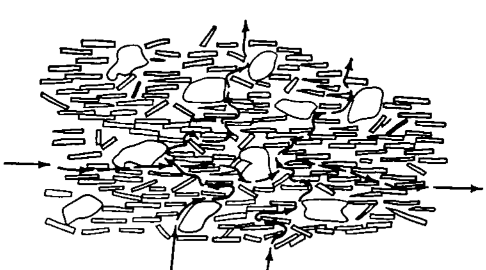

Figure 17. Schematic diagram of water flow through oriented clay.

the horizontal. The effect of stratification on the ratio of horizontal to vertical permeability is obvious; the effect of orientation is illustrated by Figure 17. This schematic drawing indicates that water flowing vertically must follow a much more tortuous path than water flowing horizontally. As a result, the horizontal permeability is higher than the vertical.

Stratification cannot be a factor in the case of the remolded samples; however, it can influence greatly the permeability of undisturbed clays. Care was taken in the tests summarized in Table 3 to avoid using samples showing any evidence of sand or silt lenses; however, stratification cannot always be seen; in addition, it is possible to have discontinuities between layers of the same material, representing periods of erosion or no deposition, along which water could easily flow.

The relation between directional permeability and particle orientation may be examined using the data in Tables 2 and 3. The ratio of the horizontal to vertical permeability, k_x/k_z, will be considered as a function of the orientation intensity and direction. In order to obtain comparable orientation values, the average intensities over large areas were multiplied by the cosine of the angle to the horizontal at which the clay was oriented and plotted vs. k_x/k_z in Figure 18. Thus, if orientation were very good, but at a large angle to the horizontal, the resultant value would be low and should correspond to a low k_x/k_z ratio. Although the scatter in Figure 18 is quite large, a straight line may be fitted through the points which shows a definite increase in the k_x/k_z ratio with increasing orientation intensity parallel to the horizontal. From these data, it appears that stratification in the undisturbed samples had little effect on the horizontal permeability since the points in Figure 18 for the undisturbed clays do not scatter any more than the points for the remolded clays.

FURTHER APPLICATIONS OF THE OPTICAL STUDY OF CLAY FABRIC

The preparation of thin sections from wet soils offers a new tool to aid the engineer or researcher in his study of soil phenomena. In addition to permitting the study of the fabrics of soils as they occur in nature, the procedure

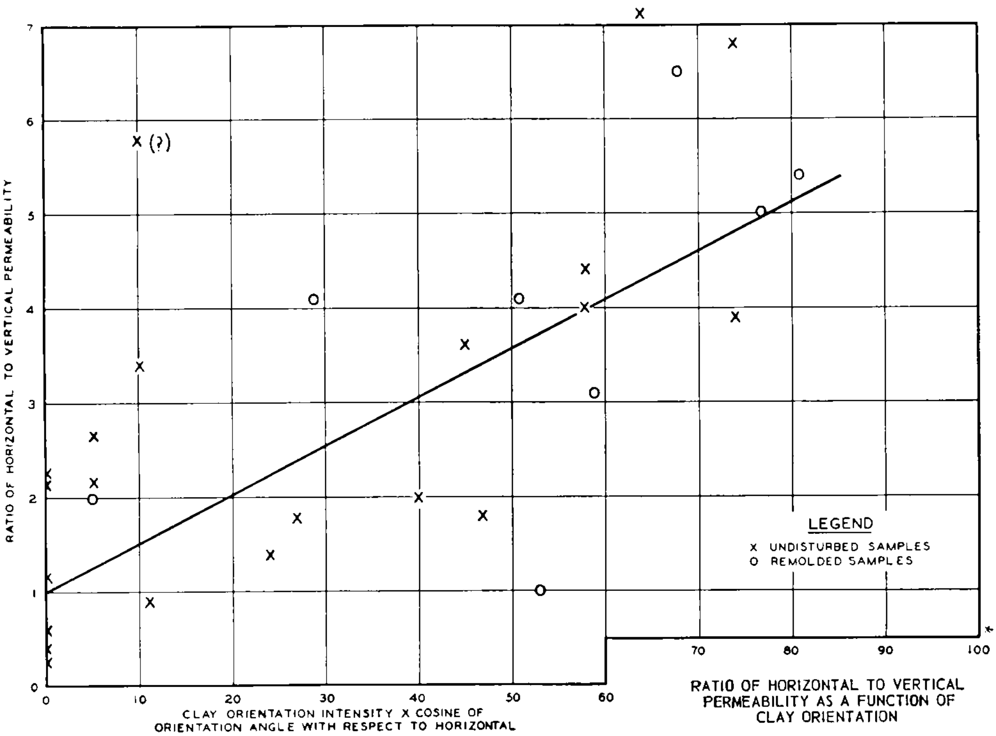

Figure 18.

could be applied to several more specific soil problems.

Strength

The study of strength specimens before and after testing could provide information relative to the effects of shearing stress on the orientation of particles and conditions within failure zones.

Compaction

Previous investigations have shown that the mechanical properties of samples compacted on the dry side of optimum are considerably different than those for samples compacted on the wet side. A thin section study of compacted soils could aid in the explanation of these differences.

Soil Stabilization

Thin sections of soils treated with different stabilizers could be used to give information concerning the relations between the stabilizer and the soil, such as, the effect of additives on the orientation of particles and the distribution of the additive within the soil.

SUMMARY AND CONCLUSIONS

A new procedure for the preparation of thin sections from wet clays has been described. This technique was found to be simple, applicable to a range of soils, and gave thin sections that contained particles in the same positions as in the original wet clay. By means of this technique, it is now possible to examine directly the fabrics of fine-grained soils as they exist in nature or after disturbance. The procedure is potentially applicable to other soil problems.

The optical study of thin sections prepared from 14 clays in both the undisturbed and remolded states furnished several important conclusions relative to the fabric of the clays themselves and the importance of fabric in influencing the engineering properties.

The schematic representation of particle orientation within undisturbed and remolded marine and fresh water clays, previously presented by Lambe (*6*) and reproduced in Figure 1, is basically correct. In addition, the results of the present investigation permit certain modifications and expansions of Lambe's concepts.

In none of the clays, either undisturbed or remolded, did silt particles touch each other, except for an occasional isolated pair. Therefore, the silt probably has little effect on the strength properties of the clay.

The undisturbed clays were found to exhibit abrupt discontinuities, irregular silt distribution, local zones of oriented clay within a random mass, narrow veins of clay oriented at angles to the remainder of the material, and other irregularities. These features are attributable to the history of the material.

Significant amounts of parallel clay orientation were noted in the undisturbed marine clays studied in spite of the fact that the material probably was initially deposited in a completely random, flocculated state. This orientation may be the result of two factors; the presence of tightly bonded oriented aggregates which may be remnants of the parent rock and of essentially one-dimensional compression in nature. Remolding these clays, all of which had had a high percentage of the salt leached out subsequent to deposition, led to improved parallel orientation of the clay particles, particularly within small zones. One-dimensional compression of the remolded clay induced a greater intensity of parallel orientation over large areas than was present in the undisturbed clay. A further effect of remolding was, of course, to homogenize the fabric.

The study of fresh water clays suggests that account must be taken of such factors as impurities in the depositional water and the nature of the adsorbed cations and their effect on the dispersion of the clay particles at the time of deposition. Formation of a deposit in "fresh" water does not, of itself, insure a dispersed oriented clay fabric. The changes in fabrics of these materials due to remolding were not as pronounced as in the case of the marine clays.

Correlations were found between the engineering properties and the clay fabric. The most important fabric component influencing properties was the clay orientation. The following relationships were found:

1. The greater the orientation improvement with remolding, the greater the loss of strength.
2. The greater the orientation improvement caused by remolding, the steeper the slope of the straight-line portion of the compression curve for the undisturbed clay with respect to the slope of the compression curve for the remolded clay.
3. The greater the orientation improvement caused by remolding, the greater the difference between the undisturbed and remolded void ratios at any pressure.
4. The secondary compression of clays having a high degree of parallel clay orientation was less than the secondary compression of poorly oriented clays.
5. The ratio of permeability in a horizontal direction to that in a vertical direction was directly related to the amount of particle orientation parallel to the horizontal.

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