GEOTECHNICS AND GEOTECHNICAL RESEARCH

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SYNOPSIS

Physicochemical reactivities are associated with surfaces. If the particles are sufficiently small, i.e., approaching colloidal dimensions the surface reactivities are a major factor in determining the properties of a mass of the particles. Fine grained soil problems, therefore, involve the concepts of soil chemistry and soil physics as well as soil mechanics. The definitions of soil mechanics, soil physics, soil chemistry, and mineralogy are well established and generally mutually exclusive. It is proposed, therefore, to use the term geotechnics to designate the application of the principles of mechanics, physical chemistry, physics, and mineralogy to problems associated with the use of soils.

Relatively few engineers have maintained a ready familiarity with the concepts of physical chemistry. It appeared desirable, therefore, to present some of the fundamental concepts as briefly and simply as possible. Ions, space lattices, base exchange, and electrosmosis are presented principally from a structural rather than a chemical point of view. The different types of clay are described and their behavior explained in terms of their physicochemistry.

An impressive volume of evidence of the significance of the physicochemical properties of fine grained soils is already available and both laboratory and full scale applications are described. Included are data concerning a very recent experiment in electrosmotic consolidation which appear to have considerable significance.

The program of geotechnical research of the Engineering Laboratory, Washington District, Corps of Engineers has been actively underway for about two years, most of which has been devoted to basic research. As might be expected many of the methods and devices that have been adopted are quite foreign to the usual soil laboratory. Electrokinetic apparatus, X-ray diffraction, and similar devices, therefore, are described together with a large scale tank with an automatic loading device by means of which a 25,000-lb. wheel load may be tracked back and forth in a temperature which may be reduced as low as zero F.

Among the many problems associated with the use of soil as an engineering material none are more perplexing than the relationship of the properties and the behavior of the finegrained types. Encouraging progress toward reasonably rationalized solutions for these problems has been made possible by the concepts of contemporary soil mechanics. There is reason to believe, however, that some of the most difficult problems must be approached from a somewhat different direction, i.e., from the point of view of the mechanics of a chemically active rather than an inert material.

The developmental period of modern soil mechanics, which now may be considered to span the past 20 years, has been paralleled by a period of equally significant development in the concepts of clay mineralogy. The electron microscope and differential thermal analysis, together with the somewhat earlier x-ray diffraction, have disclosed the crystalline structure of clay minerals and have provided an understanding of the physicochemical nature of many of their properties.

As a general rule civil engineers do not have occasion to keep up an easy familiarity with the concepts of chemistry and physical chemistry. It is quite understandable, therefore, why some of the pertinent developments have been overlooked or have been considered to be completely foreign to engineering interests.

It seems quite logical to believe that any physical or chemical characteristic of a material which affects its properties must be of interest whatever use will be made of the material. This should apply no less to soil than it does to the processed materials that the engineer uses as, for example, steel and portland cement. There is the important difference in the case of soil, however, that the engineer is the processor of the raw material.

The introduction of the physical chemistry of soils into engineering problems presents a question of terminology. Soil mechanics has been defined as the application of the principles of mechanics and hydraulics to engineering soil problems. This definition is both adequate and well established and no useful purpose can be served by disturbing it now. On the other hand, the application of the principles of soil chemistry and mineralogy to engineering problems is quite outside the limits set for soil mechanics. It is proposed, therefore, to use the term "geotechnics" to designate the coordinated application of the principles of mechanics, hydraulics, physics, chemistry, and mineralogy to the problems associated with the use of soil as an engineering material. This use is consistent with the precedent established in Sweden and it serves a definitely useful purpose.

The geotechnical research program to be discussed here was initiated by the Airfields Branch of the Office, Chief of Engineers about two years ago. As the name implies it is concerned with the relationship of the physicochemical and mechanical properties of soils and particularly with the practical application of these relationships to electrical drainage and electrochemical stabilization.

A considerable volume of related research has already been accomplished and reported, particularly in the agricultural and ceramic journals. The collection and correlation of the widely dispersed data concerning both the principles and their application represents the initial step of the program and the subject of this paper.

It should be borne in mind in reading the following text that we are concerned here with a two component system consisting of soil and water. General statements should, therefore, be interpreted with respect to this specific system and these materials. For example, the terms solid and solvent should be taken to refer to soil and water, respectively, unless an exception is specifically indicated.

PHYSICOCHEMICAL REACTIVITIES

Atomic and Molecular Compounds—An atom consists of a nucleus around which electrons are arranged in an orderly manner in a series of orbits. It is convenient, and at the same time, sufficiently accurate for the purpose of this discussion, to visualize an atomic structure as shown conventionally in Figure 1.

Electrons are unit negative electrical charges and the number of electrons associated with a particular atom is equal to the total positive charge possessed by that atom. The total positive charge, all of which resides in the nucleus, is equal to the atomic number of the element and this, in turn, is a unique property of each individual element. Since an atom has an equality of positive and negative electrical charges, it is electrically neutral.

TABLE 1 ATOMIC STRUCTURE OF INERT GASES

Element		Ato- mic					
Liement	1	2	3	4	5	6	ber
Helium Neon Argon Krypton Xenon Radon	2 2 2 2 2 2 2 2	8 8 8 8	8 18 18 18	8 18 32	8 18	8	2 10 18 36 54 86
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-	_				_		x /
HELIUM		NEON				-	

Figure 1. Atomic Structure of Certain Inert Elements

The electronic arrangements of several very stable, inert elements are given in Table 1. Two things in particular are to be noted in this table, first, the consistent pattern of the electrons in the various orbits and, second, that each one of these inert elements, with the exception of helium, has a complete outermost orbit of eight electrons. It may be inferred from this that stability is related to a complete outermost orbit.

If the conventionalized structures given in Figure 1 are examined in the light of the information in Table 1 it will be apparent that those elements whose atomic numbers fall in between those of the inert elements, e.g., three to nine or eleven to seventeen, both inclusive, cannot have a complete outermost orbit. Sodium and chlorine, Figure 2, are typical examples of this.

Atoms which do not have a complete outermost orbit are chemically active and they tend to gain stability by acquiring completeness. This may be accomplished by yielding, gaining or sharing electrons. Generally, if there is but one or two electrons in the outer orbit, e.g., sodium, Figure 2a, the atom tends to yield these atoms and thus make the next



inner complete orbit its outermost one. If the atom has more than four, e.g., chlorine, Figure 2b, it tends to gain enough additional electrons to complete its outermost orbit. Such a transfer of electrons is indicated in the formation of sodium chloride, Figure 2c.

The third way of acquiring completeness is by sharing electrons. Energy is required to remove an electron from its orbit and when the outer orbit has three or four electrons, e.g., carbon, Figure 3, the available energy is generally inadequate to accomplish the removal. In such a case the atoms tend to share electrons as, for example, in the formation of carbon tetrachloride, Figure 3.

Three terms that will occur very frequently in the following discussion are associated with the foregoing reactions. These are ion, molecule, and valence. When an atom loses or gains electrons, as illustrated in the formation of sodium chloride, it is called an ion. The positive charge on the nucleus is not affected by such a transfer therefore either a loss or a gain of electrons, the negative charges, must result in a net excess of positive charges or of negative charges, respectively. An ion, therefore, will have a net positive or a net negative charge. Ions retain their individual identity, i.e., they do not unite structurally to form a molecule.



When atoms share electrons the atomic structures must merge at the shared electrons. The open circles surrounding the carbon atom in Figure 3 represent such a condition. Combination by sharing, then, results in secondary structures, i.e., molecules. Since no electrons are lost or gained in this process the atoms remain electrically neutral and the molecule, therefore, does not have a charge. It will have one or more unsatisfied valences however, if it does not complete its outer orbit which will behave in many respects similar to a charge.

One definition of valence is that it is the number of electrons which an element must yield, gain or share in order to complete its outermost orbit. If the atom loses electrons and acquires a net positive charge it has a positive valence. The sodium atom, Figure 2a has a valence of +1. Conversely, the chlorine atom, Figure 2b, has a valence of -1.

Generally, it will be more convenient to regard ions in terms of charge rather than valence and to reserve the latter term to molecules. The valences of metallic and non-metallic atoms are positive and negative, respectively. In Figure 3, then, the valence numbers of carbon and chlorine are +4 and -1 respectively.

In order to visualize a valence acting in the manner of an unbalanced charge assume that only three chlorine atoms are available in the reaction illustrated in Figure 3. This is, of course, chemically incomplete but it will serve to illustrate the point. Three of the valences of the carbon atom will be satisfied or saturated. The fourth valence, however, would be unsaturated and it would act as an attractive force to attach an additional chlorine atom. We may, therefore, think of both the excess charge on an ion and an unsatisfied valence on a molecule as the source of electrostatic attractive forces.

Compounds composed of ions are called ionic or electrovalent compounds. The individual ions are arranged side by side in an alternating pattern and are held together by electrostatic forces called, in this case, electrovalent bonds. If the electrovalent bonds are broken, as happens when the compound is dissolved, the individual ions become independently mobile, i.e., they are free to move about in the solution. This separation of the ions is called dissociation and the individual ions are said to be dissociated.

Compounds composed of molecules are called molecular or covalent compounds. Both the atoms composing the molecules and the molecules themselves are held together by electrostatic forces called covalent bonds. This type of bonding usually is represented by short lines as alternately illustrated in Figure 3, each line representing an individual bond.

When atoms combine covalently the electrons may be closer to one than the other atomic nuclei of the molecule. In such a case the electrical center of all the negative charges may not coincide with the electrical center of all the positive charges. This relative displacement of the two electrical centers will result in a moment of electrical force called a dipole moment. The water molecule is a typical example, Figure 4. A molecule which has a dipole moment is called a dipole and it behaves as though it were a small bar magnet, positive at one and negative at the other. In the vicinity of a positive or a negative ion, i.e., in an electrostatic field of force, these dipoles tend to orient themselves just as a compass needle would do under similar circumstances, Figure 5.





An electrolyte is a substance which, when dissolved in a suitable solvent, will conduct a current of electricity.

When dissociated ions are in an electrical field the positive ions tend to migrate to the negative terminal or cathode and the negative ions to the positive terminal or anode because of the charge which they individually carry. It is this migration which transports the electrical current through the solution, hence, ionic compounds are electrolytes. Molecules, on the other hand, having no net charge, tend to orient themselves rather than migrate in an electrical field; consequently molecular compounds, e. g., water, generally are nonelectrolytes, although some mixtures of molecular compounds frequently will act as conductors.

It might be pointed out here that the atoms which combine to form either an electrovalent or a covalent compound are electrically neutral, i.e., there is an equality of positive



Figure 6. Sodium Chloride Space Lattice



and negative charges. While individual atoms may gain or lose charges the totalities of the two charges, with respect to the compound as a whole, must be equal and consequently a solution must be electrically neutral, i.e., it cannot have a charge. However, if the ions in the solution are not uniformly distributed throughout the entire volume, concentrations of ions will result and a difference of potential can exist between such concentrations even though the solution as a whole is electrically neutral.

Space Lattice—When ions or molecules combine to form a crystalline solid, and clays are crystalline, they tend to group themselves in that geometrical arrangement which will result in the greatest possible degree of electrical neutralization, i.e., so that the electostatic forces will be balanced within the structure. The most elementary grouping of this sort is called a unit cell. A typical ionic lattice structure, sodium chloride, is illustrated in Figure 6.

The silicon-oxygen tetrahedron and the aluminum-hydroxyl octahedron, Figure 7, are typical covalent unit cells and these are the principal constituents of the lattices of the various clay minerals. Bonded together by electrostatic forces these cells produce the elementary lattice structures called the tetrahedral silicon sheet, Figure 8, and the gibbsite sheet, Figure 9, respectively.

Keeping in mind that the electrostatic bonds which hold the atoms together are due to the valences of the individual atoms it may be seen that a cell will be electrically neutral if all the valences are balanced or saturated. If they are not, the cell will be electrically unbalanced and it will tend to establish a bond with any other compatible atom within its field of attraction.

Consider the silicon-oxygen tetrahedron. Figure 7, for example. As illustrated each of the four plus valences of the silicon atom is satisfied by a single covalent bond to each one of the four oxygen atoms. Each oxygen atom, however, has one unsatisfied negative valence and the surface of the cell will, therefore, exert an attractive electrostatic force on any atoms or ions in its environment having an unsatisfied positive valence or positive charge respectively. If, on the other hand, the tetrahedron could exchange its oxygen atoms for hydroxyl units, each of which has a valence of minus one, the tetrahedron would become electrically neutral and consequently indifferent to other ions or atoms.

Both Figures 8 and 9 illustrate an additional source of unbalanced electrostatic forces. In both figures the atoms at the ends of the sheets have unsatisfied valences simply because there are no adjacent atoms. A similar situation would exist if the silicon atoms of Figure 8 were located in a surface and, as a result of this, the four upper oxygen atoms were absent.

Electrostatic forces which may be exerted by a crystalline particle on its environment are seen to be due principally to unbalanced charges or unsatisfied valences located in the surfaces, edges, and corners of the particle.



Since surfaces, edges and corners are structural discontinuities it may be stated that the greater the number of discontinuities for a

given volume of matter the more active the matter will be electrostatically. This is the same as saying that the greater the number of discontinuities per unit volume, Table 2, the more active the matter will be electrochemically and, consequently, the more the physicochemical characteristics will determine the mechanical properties of the matter.

Clay Minerals—Based upon the character of their lattice structure, clay minerals may be classified in three groups. Each group takes its name from its principal member, Table 3. The kaolinite lattice, Figure 10, consists of a gibbsite sheet and a tetrahedral silicon sheet. This structure has an equality of plus and minus valences and, in addition, there is considerable affinity between the adjacent oxygen and hydroxyl layers at the interfaces between the lattices, B—B. These characteristics contribute to tight bonding not only within the individual lattices but also between adjacent lattices.

The montmorillonite lattice, Figure 11, consists of a kaolinite type lattice with an additional tetrahedral silicon sheet. The addition of this sheet produces a marked change in the characteristics. In this structure both of the surface layers at the lattice

 TABLE 2

 PARTICLE SIZE—SURFACE RELATIONSHIP FOR A

 CONSTANT VOLUME = 1 cu mm.

Particle Size		Total Area	Number of Edges	Total Length of Edges		
mm.	μ	mμ	sq. mm.	_	mm.	
1.0			6	12	12	
0.5	500		12	96	48	
0.1	100	1	60	12,000	1,200	
0.05	50		120	96,000	4.800	
0.01	10		600	12 million	120,000	
0.005	5		1.200	96 million	480,000	
0 001	Ĭ	1 000	6 000	12 hillion	12 million	
0.0005	0.5	500	12,000	96 billion	48 million]	

TABLE 3 CLAY MINERAL GROUPS

Type of Lattice	Mineral				
Kaolinite	Kaolinite Dickite				
Montmorillonite	Nacrite Montmorillonıte Talc				
Illite (Hydrous Micas)	Nontronite Illite				

interfaces are composed of oxygen atoms and these have little affinity for each other. Adjacent lattices, therefore, are not bound together and oriented water dipoles occupy the space between them. The amount of water may vary considerably, as a result of which the overall thickness of a lattice may vary more than 100 percent. In the ideal structure illustrated the plus and minus valences are balanced but in actual soils the aluminum and silicon may be replaced by atoms of other bases having a different valence causing an overall electrical unbalance.

The illite lattice, Figure 12, is generally similar to the montmorillonite lattice with the exception that some of the +4 silicon atoms

may be replaced by +3 aluminum atoms. This tendency toward electrical unbalance is compensated for, more or less, however, by overall structure is relatively strong and water cannot penetrate into the interfacial zones. With respect to structural strength,



Figure 11. Montmorillonite (21)

the addition of potassium atoms situated in the interface between adjacent lattices. Some of the aluminum of the gibbsite sheet, also, may be replaced by iron or magnesium. The then, illite lies between the stronger kaolinite and the weaker montmorillonite.

The basal cleavage planes of the three types of clay minerals lie in the interfaces

between adjacent lattices. These are designated B—B in each of the illustrations. Separation along these planes does not result in the breaking of the valence bonds consequently this form of separation does not tend to increase the total surface attractive forces. Fracturing parallel to the C—C lines, Figures 10, 11, and 12 always accompanies basal cleavage plane separation, however. These fractures must sever valence bonds and thereby increase the number of unsatisfied valences. of two-phase interfaces are possible in a soilwater-air system, i.e., solid-solid, solid-liquid, solid-gaseous, liquid-liquid and liquid-gaseous. We are interested here in but one of these interfaces, solid-liquid, because the unique properties of clays are all associated with some degree of wetness.

The surface of a solid, as has been explained, is the seat of electrostatic forces that manifest themselves in a number of processes which, collectively, are generally called capillary



Edges of clay particles, then, are much greater contributors to the electrostatic forces than are the cleavage surfaces.

Relative particle size is an especially important element since, as is shown in Table 2, the total surface area increases tremendously as a given volume of matter is reduced progressively to smaller and smaller particles. Other things being equal the number of unsatisfied valences should be proportional to the total surface area.

Solid-Liquid Interface Reactivity-Five types

chemistry. In soil mechanics the term capillary has a very specific meaning and, in order to avoid confusion, the term interface reactivities will be used here to designate these processes.

Free surface energy is the work that must be done to increase the surface of a liquid against the force of surface tension. Since a liquid tends to diminish its surface area it follows that the free surface energy tends to be as small as possible.

A solution can diminish its free surface energy in two ways, either by diminishing its surface area or by a change in the concentration of the solute in the boundary film of the solution. The latter process is called adsorption. With respect to a solid-liquid interface this may be described as the tendency of the solid to attach to its surface a layer of the solute from the solution with which it is in contact resulting in a greater concentration of the solute in this layer than in the bulk solution.

Assume that we have a crystalline solid in contact with an electrolytic solution. From what has been stated before, the solvent in this case will be water and the solute will be the dissociated ions. There will be a tendency



Figure 13. Preferential Adsorption—13a on Left, 13b on Right

for the solid to adsorb ions on its surface, i.e., at the solid-liquid interface, such that the concentration of ions in this vicinity will be greater than it is well out in the body of the liquid beyond the influence of the interfacial forces.

The line C—C of Figure 11 which represents a typical fracture normal to the cleavage planes is seen to result in both positive and negative unsaturated valences. Moreover, it has been pointed out that there is an equality of positive and negative ions in a solution. It might be expected, then, that the anions, the negative ions, would be adsorbed by the unsaturated positive valences and the cations, the positive ions, by the negative valences in essentially equal amounts. This, however, would not be the case. Nature always tends to produce matter having the smallest possible amount of free surface energy and, of two possible combinations, that producing the least soluble compound will have the least free energy. Adsorption of ions by a solid from a solution is, therefore, a preferential process.

As an illustration of preferential adsorption consider what occurs when silver bromide, AgBr, is in contact, first, with a silver nitrate solution and, second, a potassium bromide solution, Figure 13. Both silver nitrate and potassium bromide are ionic compounds which dissolve in water, i.e., the compound dissociates.

In the first case, Figure 13a, there are two possibilities, either the silver cations of the solid might adsorb the nitrate anions in the solution or the bromine anions of the solid might adsorb the silver cations of the solution. Since silver bromide is less soluble than silver nitrate the silver cations of the solution will be preferentially adsorbed and the surface of the solid will acquire a preponderantly positive charge. In the second case, Figure 13b, silver bromide is less soluble than potassium bromide, the bromine anions will be preferentially adsorbed and the surface charge will be a negative one.

In Figures 13a and b the unadsorbed ions are shown a short distance away from the adsorbed layer. Just as the electrostatic forces emanating from the surface of the solid attract to it any compatible ions in its environment, this adsorbed layer also attracts oppositely charged ions called counter ions. Both attractive and repulsive forces exist in the environment, however, and the counter ions tend to form a layer separated from the adsorbed layer of greater or lesser depth. The adsorbed layer and its counter layer are generally known as the double layer. Since there is a difference in sign between the two sides of this double layer a potential difference must exist across them. This potential is largely responsible for the variations to be observed in those properties which are associated with the solid-liquid interface reactivities of which plasticity is an example.

Ionic or Base Exchange—In order to provide a basis for dimensional visualization, assume that a clay particle is one micron in thickness, i.e., the C—C axis in Figure 10, and that its length and width, parallel and normal, respectively, to the B—B axis are, say, eight microns. The total surface area, which will be called the primary interface, would consist of 128 square microns of cleavage surface and 32 square microns of edge surface, a total of 160 square microns. Assume, further, that each lattice layer is 10 Angstrom units in thickness. The one micron particle would have, then, approximately 1000 such layers. The interfaces between these stacked lattice sheets will be called the secondary interfaces simply to distinguish them from the overall outer surface or primary interface.

Assume, further, that this clay particle is suspended in an ionic solution so that an adequate supply of ions are available to form a double layer wherever there are unsaturated valences on the surface of the particle. If the particle is kaolinite there will be little if any double layer formation on the secondary interfaces because both the hydroxyl and the oxygen atoms are saturated. There will be broken bonds and, consequently, unsaturated valences at the edge surfaces however, and while the primary interface as a whole will not, the edge surfaces will have an appreciable double layer.

It was pointed out that the lattice layers are very tightly bound together and that water cannot enter between them. If there is no water there can be no solid-liquid interface; hence these secondary interfaces will have no adsorbed or counter ions. Therefore, if the particle is kaolinite there will be adsorbed and counter ions on the broken edge surfaces only.

Assume, now, that the particle is montmorillonite, Figure 11. It has been stated that some of the silicon or aluminum atoms may be replaced by atoms of different valence upsetting the electrical neutrality of the lattice. Unsaturated valences may, therefore, exist in the cleavage surfaces of the primary interface. Moreover, water can enter between the lattices at the secondary interfaces. With montmorillonite, then, adsorbed and counter ions may be associated with the primary interface as a whole and also with the secondary interfaces.

The illite particle, Figure 12, does have unsaturated valences at the secondary interfaces but these are balanced by the potassium ions and the lattice layers are tightly bound together. The cleavage areas of the primary interface, however, would be more or less active as would be the edge surfaces. Therefore, adsorbed and counter ions would be associated with the primary interface as a whole.

So far we have assumed that the ionic solution in contact with the solid has but two kinds of ions, one of which is preferentially adsorbed and the other of which forms the counter layer. Suppose, now, that the original solution is replaced by one containing entirely different ions. If it will result in a decrease in the degree of hydration or in a lower net charge the new ions may replace the ions of the original double layer either in part or in whole. This is called base exchange.

TABLE 4 BASE EXCHANGE CAPACITY

Soil Type			Capacity Ma Equivalents per			
Kaolinite Illite Montmorillonite	•	•		3- 15 20- 40 60-100		

There are three types of base exchange which may be classified as follows:

- 1. Exchange within the lattice structure;
- 2. Exchange external to the lattice,
 - a. At the primary and secondary interfaces,
 - b. At the primary interfaces only,
 - c. At the edge surfaces only; and,
- 3. Upon negative organic groups.

The replacement of the aluminum or silicon atoms in the montmorillonite and illite lattices is an example of the first type and, quantitatively, it is relatively unimportant with respect to base exchange capacity. The third type may be omitted from consideration here.

Recalling the discussion of the three clay particles at the beginning of this section, it is seen that montmorillonite, illite and kaolinite are examples of the three sub-types a, b, and c, respectively, of external exchange. Moreover, consideration of the relative dimensions shows that, quantitatively, base exchange should follow the series kaolinite < illite < montmorillonite. The average limits are given in Table 4.

The ease with which ions in the double layer may be exchanged depends, among other things, on how firmly they are held in place. This in turn depends upon the strength of the electrostatic forces holding them and the size of the ions, small ions being held more firmly than large ones.

We are dealing here with solid-liquid interfaces and ions in solution. Since the degree of hydration of an ion depends on its charge and the amount of water available it may be taken for granted that they will be fully hydrated, i.e., that the adsorbed husk will be as thick as possible. With respect to the firmness of attachment, the ionic size to be considered is that of the ion together with its husk rather than that of the atomic size. In

TABLE 5 IONIC RADII

		Angstrom Units					
	Li+	Na+	' K+	Rb ⁺	Cs+		
Crystal Lattice Radii Radii of Hydrated Ions	0.78 10.03	0.98	1.33	1.49	1.65 5.05		



Figure 14. Interface Volume Ratio-Grain Size Relationship—Datum 1-mm. Cube

the light of this consideration the data in Table 5 (56)¹ make it quite clear why lithium for example, which is a relatively small ion is more readily exchanged than others of greater ionic dimension.

Base exchange with respect to soil is essentially a solid-liquid interface reactivity. Since the total interfacial area for a given volume is a function of particle size it follows that the greater the interface-volume ratio the greater the exchange capacity, other things being equal. It is well known that

¹ Italicized figures in parentheses refer to list of references at the end of the paper.

the base exchange capacity of sand is a negligible quantity and that the exchange capacity of colloidal particles may be very high. Somewhere between these two limits, then, is a boundary between soils having important interface reactivity and those that do not. To distinguish them they will be called fine-grained and coarse-grained.

The relationship between particle size and the interface-volume ratio, based on a reference cube 1 mm. on edge, is shown in Figure Brownian movement, which is one of 14. the familiar manifestations of interface reactivity, does not occur when the particles are larger than about four microns. The corresponding interface-volume ratio, is about There is reason to believe, however, 1050. that the boundary between fine grained active and coarse grained inert soils lies at a somewhat larger limiting size. For the purpose of this discussion it will be taken tentatively to be approximately 30 microns or at an interface-volume ratio of 200.

ELECTROKINETICS

The solid-liquid interface reactivities so far considered, i.e., ionic exchange, adsorption, free surface energy, etc., might be thought of as static reactivities because they do not depend upon a relative displacement of the solid and liquid phases. The electrokinetic phenomena, on the other hand, are always associated with the relative displacement of one phase with respect to the other and may, therefore, be considered to be dynamic reactivities.

In the discussion of the formation of a double layer of ions at the solid-liquid interface it was pointed out that one layer consists of ions which are preferentially adsorbed by the unsaturated charges or valences located in the surface of the solid and, for convenience, it will be designated the fixed layer. It should be visualized as a rigid layer of ions and oriented water dipoles the thickness of which is variable and depends largely upon the nature of the ions, the strength of the electrostatic forces, and the amount of adsorbed water. Since it is fixed to the surface of the solid any movement of the bulk of the liquid must be against the face of the fixed layer rather than against the face of the solid.

The other layer of the double layer consists of counter ions, i.e., ions having a charge opposite to that of the fixed layer. From a practical point of view this counter laverand the fixed layer also for that matterincludes both negative and positive ions. One sign, however, is predominant in each layer and, as has been stated, these are opposite in the two layers. In order to avoid complicated qualifications which would serve no useful purpose, the layers will be discussed as though they were composed of their predominant ions alone.

Helmholtz (58) presented the first mathematical treatment of the double layer which he assumed consisted of a negative charge in the surface of a glass capillary and an opposite charge in the liquid, the two layers being parallel and separated by an exceedingly small distance. He visualized this structure as essentially similar to a condenser and, by the application of the condenser principles, he obtained a mathematical solution of the potential across the double layer called the electrokinetic or zeta potential.

While the modern mathematical treatment is still based upon the assumptions of Helmholtz, it may be seen that the concept of the structure of the double layer has been modified considerably. It is generally accepted now that the rigid laver is relatively thin and attached to the surface of the solid phase, and that the diffuse or counter layer extends outward from the attached layer into the liquid phase a varying distance. The first is represented by the dimension A in Figure 15 and the second by B. The boundary between them is also the boundary between the immobile and the mobile water.

The maximum potential difference between a solid and the solution with which it is in contact is called the thermodynamic potential. This should be visualized as a potential difference between the bulk of the solid and the liquid, respectively, well beyond the zone of influence of the double layer.

The quantitative relationship between the zeta and total or thermodynamic potentials is shown diagrammatically in Figure 16. In this figure the ordinates and the abscissae represent potential and distance outward from the solid-liquid interface, respectively.

There is a sharp decrease of potential across the rigid layer and a more gradual

decrease across the diffuse layer. The zeta potential is that portion of the potential drop that exists between the boundary separating the rigid and diffuse layers on one side and the outer limit of the diffuse layer on the other.







Figure 16. Diagrammatic Representation of Zeta Potential. $\zeta = Zeta$ Potential $\epsilon = Thermo$ dynamic Potential.

It may be seen that the zeta potential must depend quantitatively upon the total potential, the thickness of the adsorbed layer, and the thickness of the diffuse layer. The total potential will, in turn, depend upon the character of the solid and the solution with which it is in contact.

The thickness of the adsorbed layer, as has been stated, depends upon the nature of the adsorbed ions, the strength of the electrostatic forces and the amount of adsorbed water. It also depends to some extent upon the concentration of ions in the bulk of the solution as will be shown.

The conditions illustrated in Figure 16 refer to a very dilute solution, i.e., a solution in which the ions in the bulk of the solution are so distant one from another that they exert no electrostatic influence upon each other. If the concentration is increased there



Figure 17. Relationships of Zeta Potential to Certain Variables. Upper Graph, Water-Cellulose Interface (60), Lower Graph, Water-powdered Glass Interface (59)

will be an increase in the number of counter ions, particularly in the vicinity of the diffuse side of the boundary. Any increase in the number of ions in the diffuse layer will tend to decrease the effective thickness of both the rigid and the diffuse layers. This will be accompanied by a decrease in the zeta potential.

If the concentration is made great enough the sign of the zeta potential may be reversed. This may be due to a neutralization of the charge on the particle or to such a decrease in the thickness of the double layer that it eventually collapses and reforms with the charges reversed (29).

It has been found that a zeta potential may exist even when the liquid is a nonconductor, i.e., a non-ionic solution. The reason for this is as yet obscure but it may be associated with oriented polar molecules or an actual separation of electrons in some manner (29). It has been suggested also that it may be related to the fact that a substance acquires a charge when it is in contact with a material of higher or lower dielectric constant than itself. Whatever the reason, it is not too important with respect to soil-water systems at this time although, of course, it may be later.

The graphs given in Figure 17 provide an indication of the relative effect on the zeta potential of such variables as concentration of solution, type of solution and type of solid. The data for the water-powdered glass interface were derived from measurement of the electrosmotic flow due to an externally applied potential (59). In the case of the watercellulose interface the data were derived from measurement of the streaming potential due to an externally applied hydrostatic pressure (60). Since two different methods were used the two sets of data are not directly comparable. They are, however, qualitatively indicative of the relationships.

The electrokinetic phenomena may be classified conveniently in two systems, first, with respect to the movable and the stationary phases and, second, with respect to whether an electromotive force is applied externally or developed internally. These will be designated the Stationary Phase System and the EMF System respectively. The two systems are outlined in Table 6.

When an external emf is applied across a solid-liquid interface the movable diffuse layer of the double layer is displaced tangentially with respect to the fixed layer. This is electrosmosis. If the diffuse layer is composed of positive ions or cations the displacement will be toward the negative electrode. If this movement occurs in a capillary the water in the capillary will be dragged along with the moving diffuse layer and a thread of water will be discharged from the capillary. This is electrosmotic flow in its simplest terms.

Before continuing with the discussion of the electrokinetic phenomena it seems desirable to point out the difference between osmosis and electrosmosis. If two solutions of different concentration are separated by a suitable semi-permeable membrane the molecules of the solvent, but not those of the solute, will tend to pass through the membrane from the solution of the lower to that of the higher solution. This is called osmosis. There are a number of explanations for this reaction but generally it may be considered to be due to the tendency of molecules of the solvent to migrate through pores or capillaries which are too fine to permit passage of the solute molecules. Osmosis then, depends upon two

TABLE 6 CLASSIFICATION OF THE ELECTROKINETIC PHENOMENA

Stationary Phase System

- Soil forms a stationary mass and water moves in pores 1. An externally applied electromotive force produces movement of the liquid relative to the solid-electrosmosis
 - 2. Movement of the liquid relative to the solid due to hydrostatic pressure produces an electromotive force --streaming potential
- B. Liquid is stationary and suspended particles move
 - 1. An externally applied electromotive force produces movement of the particles—electrophoresis
 2. Suspended particles moving through liquid as in sedimentation produces an electromotive force— migration potential

EMF System

- C. An externally applied EMF produces movement 1. Of the liquid with respect to the solid—electrosmosis 2. Of the solid with respect to the liquid—electrophoresis D. An externally caused movement produces an EMF
 - 1. Of the liquid with respect to the solid-streaming
 - otential 2. Of the solid with respect to the liquid-migration potential

conditions, first, solutions of different concentrations and, second, a suitable semipermeable membrane. Obviously, osmosis and electrosmosis are completely different, unrelated phenomena.

From the discussion of the nature of the double layer it may be seen that the rate of discharge for a given external emf must depend upon the magnitude of the zeta potential which in turn is dependent upon the relative balance of the several factors that enter into the development of the double layer. It should be borne in mind that anything which tends to decrease the thickness of the double layer tends also to reduce the magnitude of the zeta potential. If the double layer is collapsed the zeta potential will be zero; if the sign of the diffuse layer is reversed the sign of the zeta potential will be reversed also and flow will occur in an opposite direction.

If the liquid in a capillary is caused to

move by hydrostatic pressure the boundary of the moving liquid will be at the boundary between the fixed and diffuse layers, Figure This will produce a tangential displace-15. ment of the diffuse layer with respect to the fixed layer as a result of which an emf will be developed.

The mathematics of the electrokinetic phenomena as derived by Helmholtz, as has been stated, are based upon the assumption that the fixed and diffused layers are similar to the parallel plates of a condenser spaced a distance, d, apart and each of which carries a charge, e, per unit area. The space between the hypothetical plates is occupied by a liquid having a dielectric constant, D, and the potential between the plates is ;, the zeta potential. Using these terms, the fundamental relationship upon which the quantitative treatment of all the electrokinetic phenomena are based may be written,

$$\zeta = \frac{4\pi ed}{D}$$

Among the relationships that may be derived from this fundamental equation only two will be discussed here, the volume of electrosmotic flow and the pressure-zeta potential relationship. These are the most important with respect to fine-grained soil problems at this time.

Where in addition to the foregoing nomenclature.

- E_{ϵ} = the applied potential gradient (electrosmosis)
- E_{\bullet} = the developed potential (streaming potential)
- = coefficient of viscosity of the liquid 77
- = the area of a group of capillaries q
- V = volume of electrosmotic flow in **a** given time
- P = the hydrostatic pressure difference between the two ends of the flow area
- L =the length of the flow area
- = zeta or electrokinetic potential ۲

$$V = \frac{q\zeta E_{\bullet} D}{4\pi \eta}$$

and

$$\zeta = \frac{Pq}{2E_*DL}$$

From these equations it is seen that the electrosmotic flow is directly proportional to the area, the product of the applied and the zeta potentials, and the dielectric constant. It is inversely proportional to the viscosity of the liquid and independent of the length of the flow path.

Although the zeta potential is generally derived from a measured discharge volume it is believed that the streaming potential provides an equally suitable and perhaps a better means of determining this quantity. According to the second of these relationships, the zeta potential varies directly as the hydrostatic pressure and the flow area and inversely as the streaming potential, the dielectric constant and the length of the flow path.



Figure 18. Railway Cut, Salzgitter, Before Electrical Drainage

Although the studies presently underway have not progressed sufficiently to permit of even tentative conclusions it is apparent that the reactivities associated with electrosmosis extend beyond the mere transport of a volume of liquid. Changes in the overall structure of a soil mass occur which, at least so far, seem to be more or less irreversible and appear to be in the direction of measurably increased stability of the soil mass under a load.

APPLICATION

It was stated that the properties of a fine-grained soil are determined for the most part by the physicochemical characteristics of the surfaces of the particles. Later a description of the physicochemical reactivities was given. It remains to furnish some typical examples of the application of these concepts.

One of the most common examples of the

control of soil structure through physicochemical manipulation occurs when lime is spread on farmland. Plants exchange hydrogen for the nutrients adsorbed on the soil particle surfaces producing a hydrogen saturated soil. A soil of this type tends to become dense and unworkable. A calcium soil is much more friable, consequently calcium ions are provided through the application of lime to replace the hydrogen and, among other reasons, to improve the workability.

The second example makes use of base exchange capacity to remove undesirable calcium. Hard water is brought into intimate contact with a sodium saturated adsorbent and the calcium ions which impart hardness to water are exchanged for the sodium ions. When the available supply of sodium ions is exhausted the adsorbent is flushed with brine from which sodium ions are adsorbed in exchange for the calcium ions which are flushed out. The apparatus is then ready to begin another cycle of calcium ion removal.

Two very interesting applications of the principles of electrosmosis have been reported by Dr. Leo Casagrande (25). The first was in connection with the excavation of a railway roadbed through a very fine-grained, saturated soil near Salzgitter, Germany. A cut 21 ft. deep was required. When it reached a depth of about six feet the unstable side slopes flowed readily. It was apparent that further excavation could be carried on only if the side slopes were very flat and this would have increased the excavation quantity tremendously.

A potential was placed across the soil between rows of electrodes, Figure 18, one of which consisted of well points. This changed the direction of the water movement from the surface to the well points as a result of which the flow served to increase the stability rather than diminish it. The excavation was then carried out with steep, stable slopes, Figure 19. At the completion of the construction the bottom and slopes of the excavation were blanketed with a relatively thick layer of sand and the electrodes were withdrawn.

An even more impressive application of the same principles was made by Dr. Casagrande in connection with the construction of the U-boat pens at Trondhjem, Norway. These pens were constructed on a rather flat area extending into a fiord, the surface of which was but a few feet above the nearby water surface. An excavation 52 ft. deep was required, most of which was below the ground water level in a clayey silt.



Figure 19. Excavation with Electrosmosis, Salzgitter

continued in spite of this, however, until it reached a depth of about 25 ft. At this depth the soil flowed into the excavation as fast as it was being removed and the work came to a halt.

Well points were then used as one electrode and the steel piling as the other, with the direction of the flow of electrical current such



Figure 20. Installation for Electrosmosis, Trondnjem



Figure 21. Excavation with Electrosmosis, Trondhjem

The area in which the deep cut was to be made was enclosed in a sheet pile cofferdam 60 ft. deep. When the excavation reached a depth of about 15 ft. the unbalanced hydrostatic head produced a considerable flow of water upward into the excavation which resulted in deep-seated slides and partial collapse of the cofferdam. Excavation was that the water would tend to move toward the well points, Figure 20. Since the well points were below the excavation the flow was reversed in direction and, as before, tended to increase the natural stability. The excavation was then carried down to the necessary depth without further difficulty, Figure 21. It is to be noted in this case that the stability was a function of the direction of flow. Another example will be cited later in which the installation was similar but the stabilizing reaction was quite different.



Figure 22. Base Exchange—Effect on the Pressure-Void Ratio Curves of Wyoming Bentonite.

An extensive research program is now being carried on in England by Dr. Casagrande at the Building Research Station, Department of Scientific and Industrial Research under the general direction of Mr. L. F. Cooling. This program has already led to several very interesting conclusions which, unfortunately, are not yet available for general discussion.

Mr. Cooling has also carried on an investigation of the effect of base exchange on the consolidation of bentonite and his data, Figure 22, demonstrate quite clearly, first, that the consolidation and rebound characteristics of a fine-grained soil are a function of its surface physicochemistry and, second, that these characteristics may be altered either by intentional or natural base exchange.

Extensive clay deposits occur in Sweden which are very deep and very soft. Time has developed a crust on the surface of these deposits about 3 feet to 6 feet in depth. Recently, Dr. Gunnar Beskow of the Vaginstitut in Stockholm investigated the possibility of increasing the thickness of the crust by electrosmotic processes as an alternate to the construction of a deep, load-distributing pad of selected fill on top of the crust. His studies, while more limited in extent than he considered desirable, demonstrated that the cost of the alternate procedures would be approximately equal.

Digressing briefly, the costs of the projects so far undertaken do not as yet provide a suitable indication of the eventual costs. Electrosmotic flow depends, among other things, on the character of the soil, the character of the soil water, the type of electrode, the electrode pattern, the potential, the manner in which the potential is applied and the end purpose of the application. The most efficient design has not yet been determined for any one of these elements and, consequently, present installation costs must be considered essentially developmental in character.

Little is known concerning applications in Switzerland or Russia although one can hear rather substantial rumors in Europe that field applications have been made in the first-named and a report of work in the second as far back as 1941 will be referred to presently. Early in 1947 W. Schaad and Dr. R. Haefeli published a series of papers (22) in which some original investigation was reported but the only applications referred to were those of Dr. Leo Casagrande which have been discussed here in part.

Solntzev and Borkov (24) reported an investigation which was undertaken in Russia about 1936 to determine the method of applying the electrosmotic and base exchange processes to the stabilization of a railroad roadbed in which frost heaving frequently reached 15 in. In this investigation samples were subjected to electrosmotic flow alone, to saturation with a solution of calcium chloride, and to saturation with a solution of sodium chloride. The samples were then stored in a temperature below zero C. for 600 hr. following which they were alternately frozen and thawed for an additional 300 hr.

The reduction in swelling due to the ionic exchange is shown in Figure 23. At the same time the liquid limit and plastic indices of the two exchanged soils were appreciably lowered in value. Although freezing was complete throughout all the samples and ice lenses formed in the raw soil, there was no lens-ice accumulation in the electrochemically stabilized soils. These laboratory results were later confirmed by full-scale in-situ installations.

Rzhanitzin (23) has reported a second investigation in Russia, presumably concurrent with the foregoing, which included a study of the possibility of increasing the bearing power of piles by ionic exchange. Dr. Leo Casagrande also reported a similar investigation about the same time but in somewhat less detail. In both cases an aluminum pile or an aluminum encased pile was used as one of the electrodes. According to both reports aluminum atoms were stripped from the pile and transferred to the surrounding soil particles resulting in a substantial solidification of the soil in the vicinity of the piles. The published data, however, leave much to be learned concerning the nature of this reactivity.

Rzhanitzin also reported an extensive study of electrochemical stabilization in the same paper (23). Laboratory studies had shown that the application of the electrosmotic processes alone tended to stabilize a soil mass and that soaking for months thereafter indicated that the stabilization was not reversible. This study was extended to include base exchange also in which the reagents were forced through the soil by electrosmotic forces. It was found that this tended to develop a particularly dense condition in the soil, especially in the vicinity of the anode.

This process was then applied to the construction of a trench which was to be excavated to some depth below the water table, the elevation of which was about 25 ft. below the ground surface. Excavation in a sheeted trench to the ground water elevation presented no difficulty but below this the saturated soil flowed upward into the excavation as fast as it was removed.

A test section was selected where the required bottom was about 11 ft. below ground water surface. The trench was excavated to the saturation line and then anodes were inserted into the unstable soil along both sides of the trench as shown in Figure 24. A potential was applied for several hours after which an attempt was made to drive sheeting ahead of the excavation as a safety measure. It was found, however, that the soil was sufficiently stabilized to



make driving difficult and the excavation was then carried on by hand to a depth of about 24 ft. below the normal ground water level with light timbering only.

It is interesting to compare this application with that at Trondhjem. In both cases electrosmosis was used to stabilize an otherwise unstable excavation. In one case stabilization was accomplished by reversing the direction of flow of the ground water; in the other case it was accomplished by an electrosmotically induced modification of the soil structure. In the first case the stabilization depended upon the continuance of electrosmotic flow; in the second case the stabilization was more or less permanent.



[Figure 24. Electrosmotic Stabilization of a Trench Excavation (23)



Figure 25. Effect of Nature of Clay Mineral on Absorption (21)

Endell (21), pointed out that the definitions of clays are completely inadequate not only for construction purposes but for the other fields of applied science as well and his data with respect to the relationship between the physicochemical properties of soil and adsorbed water, capillary pressure and frost





heave, Figures 25, 26, and 27, respectively, are particularly significant.

A number of valuable contributions have orginated in the United States which include reports of investigations directly related to the engineer's problems. Among these are the papers by Dr. Winterkorn, some of which have appeared in the Proceedings of the



Figure 28. Effect of Ion Exchange on Torsional Resistance of a Clay

Highway Research Board (5, 6) and are so readily available that discussion of them is not necessary here. Others are listed in the selected bibliography which is part of this paper.

John D. Sullivan (2) has reported a very extensive investigation which, while directed principally to the ceramic industry, contains some very interesting data with respect to the physicochemical—shear relationship. In this investigation the material was first converted to a hydrogen saturated clay by base exchange processes. The same processes were then used to prepare samples saturated with



Figure 29. Increase of Electrosmotic Flow with Potential Gradient

lithium, sodium, calcium, magnesium, barium, aluminum, potassium, iron, and ammonium. Bars of soil were prepared by extrusion and then were tested in torsion. The data, of which those shown in Figure 28 are typical indicate that shear strength is related to the physicochemical properties of the soil. This was implied in the discussion of the reports by Solntzen and Borkov and by Rzhanitzin.

The studies presently underway in the laboratory of the Washington District have not reached a stage of completion which will permit the presentation of correlated data at this time. Certain typical results, however, will serve to illustrate trends which, in the case of consolidation, have not been reported previously.

When electrosmosis is applied to a soil mass a certain amount of consolidation accompanies the other reactions. Both gravitational and electrosmotic permeabilities are, therefore, variable, at least until electrosmotic consolidation for a given set of conditions is completed.

The ordinate values in Figures 29 and 30 are designated Ratio of Electrosmotic and Natural Permeability and, for convenience



Figure 30. Time Studies of Electrosmosis Note: Void ratio of sample decreased from 2.56 to 1.92 during electrosmosis. Resistance increased from 810 to 8100 ohms during electrosmosis. Natural permeability of soil, approximately 1.5×10^{-7} cm. per sec.

this will be referred to as the permeability ratio in the following discussion. The principal value of stating the permeability in this manner is that the product of an applied potential and the corresponding ratio value is equal to the hydrostatic head that would be required for equal flow under gravitational drainage alone. The ratio has, therefore, a very practical significance.

Gravitational permeability was determined first, following which the electrosmotic permeability was determined for different potential gradients. A relationship between the permeability ratio and the potential gradient is shown in Figure 29. The soil used for this series of tests was a sandy silt having little if any organic matter and the liquid was distilled water. The ratio corresponding to a unit potential gradient is seen to be approximately 2.7. This means that under a potential gradient of 1 volt per cm. the electrosmotic permeability was 2.7 times greater than was the original gravitational permeability.

A relationship between the permeability ratio and time is shown in Figure 30. The soil used for this series of tests was an organic, clayey silt and the liquid was a synthesized solution of sodium chloride which chemically reproduced the ground water extracted from undisturbed samples. At ten minutes the electrosmotic permeability was approximately 2400 times as great as the original gravitational permeability and the final, steady value is seen to be approximately 160 times as great.

It is interesting to compare the data given in Figure 30, which was obtained throughout under a unit potential gradient, with the permeability ratio for a unit potential gradient in Figure 29. It is seen that the equivalent head for flow through the organic clayey silt is approximately 60 times as great as that for a coarser, inorganic soil. In other words, the electrosmotic head in the strongly active system is about 60 times that in the very weakly active one.

Many of the electrosmotic flow studies are made in a lucite-lined tank 48 by 36 in. in plan, and 20 in. deep. The distance between the upper and the draining electrodes, Figure 46, was approximately 10 in. In the tests to be discussed the soil in the tank was maintained under a constant head until it was thoroughly saturated and gravitational drainage had reached a constant rate. The water supply was then cut off and the sample was permitted to drain until no further gravitational drainage occurred. At the end of the draining period, the model contained nongravitational water only.

A series of gradually increasing potentials were then applied, each potential remaining for a period of 60 min. The discharge of non-gravitational water due to an externally applied potential is shown in Figure 31. It is obvious from these data that water under negative pressure can be removed electrosmotically and that a supply of gravitational free water is not necessarily essential to the electrokinetic phenomena.



Figure 31. Electrosmotic Removal of Non-Gravitational Water



A void ratio-pressure curve is shown in

Figure 32 which represents a case in which electrosmotic and static consolidation were applied alternately. In each loading the consolidation under the static load alone was permitted to come to completion before the electrosmotic force was applied. The latter loading is seen to have a consolidating effect which may be considered as equivalent to an additional static load.

The few studies of this nature that have so far been completed appear to indicate that the electrosmotic consolidation may be more or less independent of the prior state of consolidation. For the time being, however, it is necessary to consider this statement as applying only to the set of conditions under



Figure 33. Effect of Electrosmosis on Normal Loading Branch

which the tests were performed because sufficient data are not yet available to determine the quantitative effect of the physicochemical activity of the soil and soil water. That this activity is an essential factor has already been pointed out in connection with the discussion of the permeability ratio.

It is to be noted also that the electrosmotic consolidation appears to have a maximum limit. This also, will be found to depend more or less upon the particular set of conditions in all probability. In Figure 32, however, the maximum is in the neighborhood of an equivalent 10-ton per sq. ft. loading which is considerably greater than the generally accepted load bearing capacity of finegrained soil deposits. From a practical point of view, then, it appears that consolidation under a given load can be increased by electrosmotic means. This opens up a number of very interesting possibilities.

Electrosmosis appears to have a stabilizing effect, also, which is distinct from the increase in stability due to consolidation alone. Pairs of consolidation samples were prepared as nearly identical as possible. One sample was consolidated under static loads only and the void ratio-pressure graph of this sample is designated the "normal" curve in Figure 33. The other sample was consolidated under both static loads and electrosmosis.

A series of static loads was applied between the first and second applications of electrosmosis and the curve for this loading procedure is superimposed upon the normal curve in Figure 33. It is to be noted that the consolidation under equal static loads is materially decreased after the electrosmotic consolidation.

The same effect is to be seen in the relative rebound and reloading curves of Figure 34. In this graph the solid lines designated S12-1 represent a sample which was consolidated by both static and electrosmotic loadings. The broken lines, S12-2, represent a sample consolidated by static loading only. At the beginning of the unloading cycle the external potential on S12-1 was removed and it was not again applied. The rebound and reloading curves for both samples, therefore, were obtained with static loading only.

It can be seen in the graph that the percentages of initial rebound, additional consolidation, and final rebound of the electrosmotically consolidated sample are less than one half the corresponding values for the sample consolidated by static loading alone. It is apparent from these data that the sample which was consolidated in part by electrosmosis acquired a certain degree of stability that was in excess of that due simply to a quantitatively equal mechanical consolidation.

The studies appear to indicate that electrosmotic consolidation is a function of the physicochemical reactivity of the soil and the water, the potential gradient, and the manner in which the potential is applied. These relationships do not appear to be overly complex, however, and it is expected that the studies now underway will provide a guide to the practical evaluation of these factors.

A GEOTECHNICAL RESEARCH PROGRAM

The first research project assigned to the Engineering Laboratory of the Washington District, Corps of Engineers, was concerned with electrical drainage, i.e., the practical application of electrosmosis. Subsequently, soil stabilization by electrochemical, thermal, and other essentially physicochemical means was added as an individual and, presumably, parallel investigation. As the two studies of which is concerned with a specific field, has its own unique methods and procedures, and requires special training and facilities. These include three basic groups, engineering, physics, and chemistry. Engineering was sub-divided into soil mechanics, hydraulics, and construction, i.e., large scale installations; chemistry into analytical chemistry and physical chemistry; and physics into mechanics, thermodynamics, and electricity.



Figure 34. Load and Rebound Characteristics After Electrosmosis Note: Specimen S12-1 was subjected to electrosmosis during virgin loading only. Specimen S12-2 was never subjected to electrosmosis.

have progressed, however, they have become more and more interrelated so that it is no longer possible to define a boundary between them. This is particularly apparent in the consolidation studies in which, as has been pointed out, the electrosmotic drainage and the electrosmotic consolidation are one and the same.

The need of a suitable designation for the overall program became apparent when the pattern of the program was laid out. Consideration of the problem as a whole indicated that it would involve the coordination of a number of individual technical disciplines each As has been pointed out any single subordinate term such as soil mechanics, physical chemistry, or physics is not in itself broad enough to include the others. A comprehensive study was made of each term and of all known related ones to include their definitions, actual usage, implied limitations, and conflicts. The term adopted as a result of this analysis was geotechnics, geo, a combining prefix signifying earth, ground, and soil, and technic or technical, implying the correlation of the various technical skills. The longstanding precedent for this use was established in Sweden and, so far as can be learned, it is completely free of conflict with other terms or with other uses of itself.

The principal objective of the research is the development of practical means and methods for stabilizing fine-grained soil masses through: first, the practical development of the relationship between the physicochemical and mechanical properties of fine-grained soils and their behavior as engineering construction materials; second, the development of methods to evaluate the relationship; and third, the development of methods of practical application.

The program is divided into two general categories: first, the laboratory small scale studies; and second, the larger scale experimental installations. The first includes,

TABLE 7 SCHEDULE OF TESTS FOR THE DETERMINATION OF SOIL CHARACTERISTICS AND PROPERTIES

among other items, the determination of the effect of ionic substitution on such properties as shear strength, compressibility, swelling, and compaction; relationship of physicochemical characteristics to the suitability of inorganic and organic stabilizing agents; the effect of sonic and super-sonic vibrations on interface reactivities; and other problems of the same nature.

The large scale installations studies include the relationship of plate bearing, CBR, and traffic tests to the properties and behaviors referred to in the laboratory program; the effects of freezing and their prevention; and the correlation of laboratory results with large scale installations.

A comprehensive group of soils already collected is being enlarged continually as additional types can be obtained. The basic soils are theoretical clay minerals of the various groups listed in Table 3. Although deposits of these minerals do occur in a rather elementary state, engineering soil problems are almost invariably concerned with complex mixtures. The theoretical types, therefore, while not overly significant in a practical sense from a construction point of view, except in certain limited areas, do provide a means of approaching the study of complex mixtures in a systematic manner.

A series of tests is being performed with the simple minerals and this is being followed by similar studies of controlled mixtures. Natural mixtures, also, are being investigated for comparison with the theoretical mixtures. Such a program involves a tremendous amount of work which, until enough data are available to suggest correlations, is almost completely devoid of spectacular results. Unfortunately, a short cut is inconsistent with the very nature of the problem.

Soils are studied both in their natural or raw condition and in a state of controlled base saturation. The modified soils are first reduced to a state of hydrogen saturation and then the individual samples are saturated with such bases as lithium, sodium, calcium, potassium, etc. essentially in the manner given by Sullivan (2).

The test program with respect to individual samples consists presently of the three groups shown in Table 7. Many of these tests follow standard procedures and make use of the ordinary types of apparatus and need not be described here. Some, however, involve both procedures and apparatus which are quite foreign to those usually associated with an engineering soil laboratory.

The method followed in the chemical analysis of soils is the fusion method of the Division of Soil Chemistry and Physics, Department of Agriculture (63). Spectrographic analysis is used as a correlative determination. In the determination of the base exchange capacity of each soil and the exchangeable bases present, either in its initial or modified state, the soil is first leached with ammonuim acetate. The exchange capacity is then determined by the Kjeldahl method and the individual bases are determined by gravimetric analysis.

As has already been pointed out, the chemical analysis alone is not sufficient to determine the type of mineral since type is largely a matter of lattice structure. Two methods are used to identify the structure, X-ray diffraction analysis and differential thermal analysis. In the X-ray method use is made of the fact that fibre glass of the Coleman block is essentially inert. Extensive tests are underway to determine the effect of ionic solutions on both types of blocks.



Figure 35. X-Ray Diffraction Pattern

the crystal planes, i.e., the layers of atoms, Figures 10, 11, and 12, will diffract X-rays. The diffracted rays are registered on photographic film, Figure 35, and the dimensional relationships of these lines are used as a basis for computing the plane spacing. The cameras and the source of X-rays are shown in Figure 36.

In the differential thermal method the sample is heated to 1000 C. at a uniformly increasing rate in the course of which reactions occur which in some cases give off heat and in others absorb it, i.e., exothermic and endothermic reactions, respectively. The pattern of the reactions for a particular sample, of which Figure 37 is typical, provides a good guide to the identification of the mineral or minerals, present in a great majority of cases. The various parts of a differential thermal apparatus are shown in Figure 38.

The water-retention properties of soil at various water contents, expressed in terms of pressure or pF, is related to free energy changes. Several methods are available for the determination of the related elements, including the tensiometer for high water contents and the Bouyoucos and Coleman blocks for low water contents. The tensiometer has already been described (61). The Bouyoucos block, Figure 39, consists of two terminals sealed in a plaster block and the resistance of the block is a function of its moisture content.

The Coleman block, also, is based on the relationship between water content and electrical resistance. This block, however, consists of fibre glass and has a thermistor mounted in the block to permit temperature determination. The two blocks, because of the material of which each is constructed, differ considerably from an electrochemical point of view. The calcium sulphate of the Bouyoucos block is chemically active; the



Figure 36. X-Ray Diffraction Apparatus



Figure 37. Typical Thermal Reaction Curve

The pressure-water retention characteristics are determined by an adaptation of the pressure method developed at Purdue University and which was described in the Subsurface Drainage Investigation Report of 1946–1947 by the New England Division, Corps of Engineers. The adaptation consists of a small, open-ended lucite cylinder which has been turned down to fit tightly in a small Beuchner funnel, Figure 40. Capillary rise is determined by a method reported by Carman (53).



Figure 38. Differential Thermal Apparatus



Figure 39. Resistance Block and Bridge

The effect of electrosmosis on the shear and consolidation characteristics both incorporate the same provisions. The consolidometers are shown in Figure 41. The usual metal soil retaining ring has been replaced by a retaining ring of lucite. Brass filter plates at each end of the sample replace the usual filter stones and act as electrodes. Since electrosmotic drainage must occur from one side to the other across the full thickness of the sample, provisions are made so that the drainage under static load consolidation will be comparable. A number of cells, Figure 42, have been constructed for the determination of the electrosmotic characteristics. The first cells were constructed of glass with adjustable electrodes. Generally, however, lucite tubing has been found to be much more convenient to use because of the ease with which it may be machined and sealed.

The electrosmotic cells are used for electrophoresis studies. The purpose of this test is to determine the sign of the charge on the



Figure 40. Water Retention Apparatus

suspended particles. Positively charged particles in a colloidal suspension will migrate to the cathode and negatively charged particles will migrate to the anode.

The streaming potential is extremely sensitive to polarization and even the small current draw of a galvanometer is sufficient to completely destroy it. In order to avoid this difficulty a Lindemann electrometer, Figure 43, is used as a null indicator in a potentiometric circuit. There is no flow of current in this circuit during adjustment and this has practically eliminated the difficulty with polarization.

Electrode design and patterns have been investigated extensively. The two-dimensional electrical analogy tray (62) with an alternating current of not less than 1000 cycles per second is used for some studies but, for the

The accurate determination of conductivity is essential to the use of experimental electrokinetic data. A very sensitive circuit, Figure



Figure 41. Electrical Consolidation Apparatus



Figure 42. Soil Cells for Electrosmosis and Streaming Potential Measurements

most part, small three-dimensional models, Figure 44, immersed in an electrolyte of known specific conductance are used. 45, has been built up around a Campbell-Shackleton ratio box and precision capacitances. The conductivity cell is immersed in transformer oil to prevent electrical losses and maintained at 25 ± 0.02 C.

Both small and medium sized models are used in the study of the electrokinetic reThe principal purpose of the models is to furnish a basis for the correlation of the cell studies with large scale applications in which the current density and hence the electros-



Figure 43. Apparatus for Measuring Streaming Potential



Figure 44. Three-Dimensional Model of Electrode Patterns

activities, Figure 46. In the electrosmotic cells, Figure 42, the electrodes are the same area as the interior of the cell, consequently, the current flow through the sample is essentially straight line. When the electrodes are located in a large mass of soil the current distribution obviously is completely different in pattern.



Figure 45. Apparatus for Determining Conductivity of Solutions

motic effects are non-uniform. In addition to this the tanks also permit variation in the dimensions and types of stratification in the soil as well as a wider range of electrode pat-



Figure 46. Large and Small Model Tanks

load for bearing tests. This device also runs on the tank walls. Opposite pairs of deeply anchored plates are provided in the top of the wall through which heavy pins may be inserted to anchor the reaction beam through turnbuckles during use.

The tank is provided with manholes on one side into which cross-drains discharge. This will permit accurate measurement of drainage and also serve to feed water into the soil where saturation is desired. Sleeves are provided through the tank wall in the manholes to permit the installation of various measuring



Figure 47. Experimental Tank at University of Maryland

terns and types. Both flow patterns and gas formation at the electrodes can be observed directly in the small transparent model.

A building is presently being constructed at the University of Maryland by the Washington District, Corps of Engineers for large scale studies. These studies will be carried on cooperatively with the University. The building, Figure 47, will provide a tank 50 ft. long, 12 ft. wide and a soil depth of 9 ft. An airplane wheel which can be loaded to 25,000 lb. will be tracked back and forth by a low, cranelike motorized device running on the tank walls, Figure 48. A heavy I-beam carried on wheels will be available to serve as a reaction



Figure 48. Dynamic Loading Apparatus for Experimental Tank

devices. The building is heavily insulated and sufficient refrigerating capacity will be provided to hold the temperature as low as 0 F. for long periods. Two continuously variable direct current generators will be available, one of which will deliver a maximum 250 volts and the other a maximum 1000 volts.

The studies which can be carried out with these facilities appear to be without limit. Effect of ground water elevations, electrokinetic reactivities, mass ionic exchange, freezing and thawing, trafficability, and distribution of pressure are but a few.

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DISCUSSION

E. S. BARBER, University of Maryland. Mr. Preece's excellent paper presents many instances of the application of electrokinetics to soil stabilization, and outlines a comprehensive investigation, including full scale tests at Maryland University, to extend and improve its usefulness.

It is pointed out that past applications may not have been carried out by the most economical method, and the efficiency of electroosmosis varies markedly between different soils, even between different homoionic modifications of the same soil, as shown by Dr. Winterkorn's tests. Keeping in mind that the power consumption of the early experiments may be proven quite excessive as progress is made in the work, it is of interest to note the current consumption that has been used in the early applications.

Table A shows the continuous current required to control groundwater around several excavations during construction. An optimum of 30 kilowatt hours (25 amperes at 110 volts) was used to increase the bearing capacity of two piles, 20 feet long spaced six feet, center to center. In stabilizing masses of soil, the Russians used from one to six kilowatt hours per cubic foot (100 volts between electrodes three feet apart).

TABLE A							
DRAINAGE	WITH	ELECTRO-OSMOSIS					

	Wells ^a		Flow pe					
	Depth	Spacing in Line	Gravity Alone	Gravity Alone Electro- osmosis plus Gravity		Supply of Electricity per Well		
	Ft.	Ft.	Cu. fl per day	Cu. ft. per day	Volts.	Amp.	Kw	
Railroad cut. U-Boat Pen.	25 66	33 33	0.7 av., 0.8-34	105 av., 7.7-320	90 40	25 20-30	$2.2 \\ 1.0$	
approach	40	33	negligible	3.3 av.	30	15	0.5	

* In double lines with anodes in parallel lines.

While the cost per unit volume is higher, it is possible to stabilize soil by direct heating, in which case alternating current can be used as well as direct current.^{1, 2}

¹ "Arc Melted Pavement," Business Week, September 23, 1933, p. 22.

³ "Abutments for Small Highway Bridges," by J. Feld, Highway Research Board Proceedings, 1945, p. 412.