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NATIONAL RESEARCH COUNCIL

CANADA

DIVISION OF BUILDING RESEARCH

ELECTRO-KINETIC AND CONDUCTANCE STUDIES OF CLAY

SEDIMENTS IN THE OTTAWA-HULL AREA

by

Edward Penner

ANALYZED

Internal Report No. 305

of the

Division of Building Research

OTTAWA

November 1964

PREFACE

The Leda clay deposits of the St. Lawrence and Ottawa River valleys of Eastern Canada are of great engineering significance because of their relatively high void ratios and sensitive structures. These features result in very large compressions under load and frequent earth flows in natural slopes.

Although these physical properties are easily demonstrated in the laboratory and often observed in nature, the fundamental behaviour of the soil is not well understood. It was with the objective of improving this understanding that Mr. Penner, who is a soil scientist in the DBR Soil Mechanics Section, planned and carried out the research program described in this report.

In addition to describing the test methods and results of electro-kinetic and conductance studies of a variety of Canadian soils the author reviews the technical literature with particular reference to clay-water systems. This leads to several specific conclusions concerning the relationship between sensitivity and some measurable physical and chemical characteristics of the bulk soil. When related to other observations of the performance of the undisturbed soil an improved appreciation of micro-mechanisms during deformation is gained.

It is hoped that this report will stimulate discussion of the fundamental properties of these and similar soils.

Ottawa November 1964 R.F. Legget Director

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Edward Penner

According to the geological studies by Sir William Dawson as summarized by Johnson (1), the fine-grained deposits that are found extensively along the Ottawa - St. Lawrence Rivers and their tributaries were thought to be marine sediments of the Champlain Sea. These deposits were given the name "Leda clay" by Dawson. Although this name has been retained in the literature from time to time, it has been suggested that possibly the whole deposit is not uniquely marine in origin. In particular, geologists have not been in agreement about the sequence of events beginning with the general uplift of the area and the recession of the Champlain Sea.

In the most recent report on the surficial deposits in the Ottawa-Hull area, Gadd (2) stresses the view that "a sudden influx of fresh water produced either by release of meltwater from glacial sources or more likely by the sudden release of large volumes of silt-laden water from the Great Lakes region" was capable of considerable erosion of the old Champlain sediment. This sediment was subsequently deposited in fresh water lacustrine or fluvial environment to which the origin of the upper (and younger) deposits are now assigned.

On the basis of engineering properties, no distinction has been made between these radically different deposits because the clays from the whole St. Lawrence Lowland region have the same unusual engineering problems which are commonly assigned to "leached marine deposits." The dominant property of these fine-grained soils is a characteristic loss of strength when disturbed or remoulded. A combination of structural breakdown and other factors sometimes causes the whole mass to be transformed into a fluid state.

The strength-loss property when remoulded, termed the "sensitivity" of the soil, was described and defined by Terzaghi in 1944 as the ratio of the undisturbed strength to remoulded strength. For Leda clay this ratio is rarely less than ten below the fissured drying crust, and sometimes reaches several thousand. It is not surprising then that this vast deposit is scarred by characteristic flow slides, similar to the flow slides in the Scandinavian countries. Many flow slides occur each year in this region often with disastrous results. Although the prediction and control of potential flow slide sites is the most urgent engineering problem and would have far reaching effects if it could be done successfully, the unique behaviour of this material affects all engineering problems related to settlement and stability.

The research reported in this paper is concerned with elucidating the physico-chemical nature of sensitivity in these deposits, particularly with respect to its relationship to the electrokinetic potential. The soils studied cover the characteristic range of sensitivity encountered in Leda clay and were selected from various locations and depths, mostly from the Ottawa-Hull area.

The author is not aware that measurements of electrokinetic potential have been attempted previously for natural soils in the study of sensitivity, although the concept of interparticle repulsion is frequently invoked when describing the phenomenon. As the structure of the soil, its resultant high moisture content, and the repulsion forces are all important aspects of sensitivity, the nature of the structure has also been given special attention. A method of determining preferred particle orientation by electrical conduction has been evaluated and this adds one further method of evaluating structure to those methods already in use such as volume change due to swelling and shrinking, the thin section technique, heat flow measurements, and the X-ray method.

The results reported in this paper clearly demonstrate that the degree of sensitivity of a soil is not uniquely dependent on any one factor. In fact, sensitivity is an expression of many interrelated soil properties. Soils were selected from various deposits in the Ottawa area which, according to some geologists, have had different sedimentation environments. This affords the special opportunity of evaluating the concept of leaching and speculation on other major contributing causes in the development of highly sensitive soils in the St. Lawrence Lowland deposits of Eastern Canada.

REVIEW OF LITERATURE

1. Sensitivity of Clay Sediments - Definition and Test Methods

Terzaghi (3) defined the sensitivity (S) of clays in terms of the unconfined compression strength at the same water content as

$$S = q_d / q_{dw}$$

where

q_ is the natural (undisturbed) strength

and q_{dw} the remoulded strength.

Because the value for S may vary from 1 (most uncommon) for an insensitive soil to a very large value for highly sensitive soils, Skempton and Northey (4) proposed the following arbitrary sensitivity classification of soils into separate ranges based on shear strength:

| 1. | S | = | 1 | insensitive clays |
|----|---|---|------|-----------------------------|
| 2. | s | = | 12 | clays of low sensitivity |
| 3. | s | в | 2-4 | clays of medium sensitivity |
| 4. | s | Π | 4-8 | sensitive clays |
| 5. | S | = | > 8 | extra-sensitive clays |
| 6. | s | Ŧ | > 16 | quick clays. |

Rosenqvist (5) modified and extended the classification for the more sensitive clays from the fifth category to accommodate "certain Scandinavian soil types" termed "quick clays" as follows:

5. S = 8-16 slightly quick clays
6. S = 16-32 medium quick clays
7. S = 32-64 very quick clays
8. S = >64 extra quick clays.

It is evidently not practicable to determine the sensitivity of all clays by the unconfined compression test used originally by Terzaghi in his definition. Several other methods of determining sensitivity have been reported in the literature but in other respects the definition has been retained.

Eden and Kubota, using Leda clay, found the value of S depended on the test method (6). This means that some or all of the

methods used at present cannot be clearly interpreted. On the basis of their study of various sensitivity test methods, these authors stated that the present methods employed in measuring sensitivity cannot be expected to yield consistent results and that no one method is to be preferred. The factors listed that were thought to be responsible for the "rather poor results" were: insufficient sensitivity in the apparatus for measuring the remoulded strength; the time interval allowed between remoulding and testing for remoulded strength as all clays have thixotropic properties; and whether tests are conducted with increasing or decreasing rates of shear. To this the authors might have added that incomplete breakdown of structure has a strong influence on the remoulded strength and would not be achieved to the same degree in each test method. This is especially true when comparing the remoulding achieved in the vane methods with that achieved in cone tests. The more common methods used are the field vane apparatus, the laboratory vane and the drop cone method.

2. The Nature and Origin of Sensitive Clays

In describing the properties of Norwegian marine clays, Bjerrum (7) mentions that the possibility of explaining flow slides by leaching was indicated in papers in 1929 and 1934 by G. Holmensen (8, 9). Tests made by Rosenqvist (5) and Skempton and Northey (4) did not show that the leaching of laboratory samples with high porewater salt content reduced the natural strength of clays, although it greatly reduced the remoulded strength. Subsequently, comprehensive leaching tests of laboratory-prepared samples by Rosenqvist and Bjerrum did show a reduced undisturbed strength, and such results were used as substantiating evidence regarding the cause of certain slides in marine clays where the salt content was low at the time the slides occurred. Bjerrum states that "where the possibilities of leaching are present (in marine clays) this reduction in shear strength may lead to slides without external causes" (7). Some 35 slides had occurred by that time where no external causes could be found, 28 in quick clays.

The explanation for the development of highly sensitive clays (quick clays) from naturally-deposited marine sediments by the reduction of the electrolyte content in the pore water is attributed to Rosenqvist (5). The results of comprehensive laboratory experiments involving sedimentation, consolidation, and leaching by Skempton and Northey (4) and Bjerrum and Rosenqvist (10) have apparently substantiated the hypothesis. Rosenqvist postulates the formation of a quick clay as follows. When clay minerals are sedimented in water of high salinity the forces of repulsion between particles are low. The particles tend to flocculate when brought close together. The resulting sediment has an open structural arrangement. Because the forces of repulsion are low between particles, their thermal energy can bring them into close proximity. The cations are partly polarized creating Van der Waals forces of attraction. Subsequent consolidation brings the particles still closer together. When the sediment is leached the reduction in electrolyte concentration increases the dissociation of the adsorbed cations which increases the repulsive forces, but the Van der Waals forces remain nearly unchanged. Upon remoulding, the Van der Waals forces are broken down, recombination being prevented because of the high repulsive forces. Although a number of details have been added to the explanation during the last eight or nine years, most researches have accepted this explanation for the development of sensitivity in a marine clay. On the other hand, most researches in this field dating back to Skempton and Northey (4) have been quick to point out that the so-called "leaching theory" does not necessarily explain the formation of all sensitive or extrasensitive clays that are encountered in nature.

Soderbloom (11) stated that the conclusion reached in the literature to the effect that a meta-sensitive product can form only from salt-coagulated material is contradicted by experiments which show that glacial clays become quick when treated with dispersing agents. A further preliminary view expressed by Soderbloom is ... "The quick clays examined are built up of a skeleton of uninfluenced coarse material which is non-cohesive, and this is mixed with a cohesive material in which the cohesive properties are reduced by the influence of dispersing agents. The clay is thus sensitive to mechanical change in the non-cohesive skeleton," ... "Preliminary experiments have shown that even the colloidal fraction of clay contains undispersible constituents." On the other hand, in studies on clay from the Göta River at Alvängen, Soderbloom (11) was unable to develop a highly sensitive condition by leaching alone and has performed experiments which led him to believe that natural oxidation processes plus infiltration of organic dispersing agents from peat beds may well account for the sensitivity developed.

Some fresh-water clays may also be sufficiently sensitive to be classified as quick clays. Eden (12) has reported on the sensitivity of a varved clay from the bottom of Steep Rock Lake after it was dewatered for iron mining purposes. The dark layers were found to have a sensitivity of 12 based on the unconfined compression test, but the light layer was too soft in the remoulded state to form a sample for the compression test. These soils are "slightly quick" according to Rosenquist's revised sensitivity classification. Again in varved clays in Northern Ontario near New Liskeard, Eden and Bozozuk (13) have measured sensitivities as high as 19 with the field vane. The average clay size content (< 0.002 mm) was 93 per cent.

3. Nature and Electrolyte Content of the Pore Water

There is much less information in the literature regarding the nature and electrolyte content of the pore water of sensitive soils than about their engineering properties. Both type and amount of ions in solution appear to influence the mechanical properties of the remoulded soil to a greater extent than the natural soil. For example, Bjerrum (7) has shown that by leaching a marine-deposited clay the natural strength was reduced by 60 per cent but at the same time the remoulded strength was 0.1 per cent of its original strength.

Numerous laboratory studies have been carried out on the strength increase or reduction of remoulded soils by the additions of various electrolytes (14). The most noticeable variations are observed between the effect of adding coagulants and dispersants and are brought about by changing the electro-kinetic behaviour of the clay surfaces.

The natural leaching of a soil originally deposited in sea water will apparently change the relative concentration of the various ions. This observation is reported to have been made by Holmensen before 1930. Rosenquist cites examples of changes in the ratios of the main anions, Cl^- and SO_4^- . The mechanism to explain the differential leaching of anions and cations is apparently based on preferential adsorption although in the case of anions this is not too clear (15). Changes are also brought about in the nature of the electrolyte, most notably in K^+ , by weathering processes. In Norwegian marine clays the most important ions in the pore-water phase have been found to be $Na^+ Mg^{++} K^+ Ca^{++}$, SO_4^- , $C1^-$, and to a lesser extent HCO_3^{-} (15). Although such information about Norwegian soils has been available for many years, this report, to the author's knowledge, presents the first chemical analyses of the pore water carried out on so-called marine clays in Canada in connection with sensitivity measurements.

Although only sparse information exists about the nature of electrolytes in sensitive soil, many total-dissolved-salt measurements have been made on pore water. Skempton and Northey (4) report concentrations ranging from 0 to 30 gm/l. Of

the six marine or estuarine deposited soils, the sensitivity was inversely related to the salt concentration. Bjerrum (7) found the same general relationship for all of the locations studied in Norway.

Although no pore-water chemical analyses have been reported for geologically similar deposits in Canada, there are numerous results of pore-water concentration (gm/l) available for the Ottawa area (16) and some from other locations in the same geological region (17). In the Ottawa area, the salt content has been found to be less than 2 gm/l except for one location. Here the salt increases from the surface with depth and reaches about 15 gm/lat 80 ft. At Nicolet, Que., the site of a flow slide in 1955, salt concentrations were found to range from below 1 to 11 gm/l with no obvious pattern of distribution with depth. All the sensitivities fell in the "slightly quick" range despite the variation in salt concentration. At one level, extra quick clays were encountered. In general, it can be said that no correlation has been found between sensitivity and salt concentration in soils studied by the Division of Building Research, although large variations in sensitivity have been measured. Previous studies of sensitive varved clays (12, 13) have not included the determination of pore-water salt content. For these the assumed glacial origin is generally accepted.

4. Mineral Composition of Sensitive Clays

Attempts have been made in the past by the author and others to establish a definite connection between sensitivity and the mineral composition of the clay-size fraction. Nearly always, in those soils that are suspected to have had a marine origin, at least some chlorite has been reported; whether this has any significance is not known. Such attempts at linking compositional analyses with sensitivity have not been particularly helpful but such a possibility is not ruled out since, in clay mineral analyses, much depends on the analytical techniques used and the interpretations. Furthermore, recent advances in both the science and technology of clay mineral analyses quite naturally render the earlier studies less reliable and leave relatively few studies that are useful. Nevertheless, drawing on the limited information available, it is possible to make the following generalizations about the two main regions of highly sensitive clays -- Fennoscandia (mainly Norway and Sweden) and the St. Lawrence - Ottawa River Valleys of Eastern Canada.

1. Montmorillonite, or other expanding layer silicates, is absent or present in only trace quantities.

- 2. Some chlorites are frequently present.
- 3. Some vermiculite is usually reported.
- 4. Illite, hydrous micas, or micas are the predominant clay mineral.
- 5. Rock-forming minerals consisting of varying proportions of feldspar, quartz and amphibole make up a large part of the claysize fraction with feldspars predominating.
- 6. The same rock-forming minerals found in the clay are represented in the silt- and sand-size fraction.
- 7. The major change accompanying particle size is an increase of clay minerals in the small-size fractions with a consequent dilution of the other minerals.
- 8. Mineral composition is closely related to the source rock but there is some disagreement on the degree of chemical alteration.

The varved clays in the clay belt of Northern Ontario are similar to the above in most respects with the exception that the varved clays are higher in montmorillonite.

The compositional analyses of Finnish clays according to the studies of Soveri (18) are similar to the marine clays in Norway and Sweden with perhaps a lower content of rock - forming minerals in the clay-size range. The strong influence on clay composition of nearby source bed rocks is emphasized by Soveri. No kaolinite or montmorillonite was found in the samples studied.

Soil engineers have found it useful to identify the composite behaviour of a soil on the basis of "activity." The assumption is that the physico-chemical characteristics that determine the mechanical properties of a soil depend on the amount and type of minerals in the clay-size fraction. To this should be added the influence of the concentration and nature of the electrolyte in the pore water. The merit in using such quantities as activity stems from the fact that it has not been possible to predict with any reasonable precision the engineering behaviour of a fine-grained soil from the type and proportions of the clay minerals present. The activity of a soil is determined by plotting the per cent clay-size particles vs the plasticity index. The slope of the line obtained by connecting such a point to the origin is the "activity." The sensitive soils from Fennoscandia and Canada all fall into the groups referred to as "inactive," that is, with a slope less than 0.75. The Canadian soils in the St. Lawrence Lowlands tend to have a somewhat greater slope than the others (15). In general, the clay-size fraction is usually higher although a wide variation exists. As it is not possible to predict the behaviour of a clay soil from its mineral composition except in very general terms, the concept of activity (19) as a measure of composite behaviour will apparently continue to be useful for engineering purposes.

5. <u>Electro-kinetics and Electrical Conductance with Particular</u> Reference to Clay-Water Systems

(a) Electrical conductance of solutions and clay-water systems. - It is self-evident that if electrolytes are partially or completely ionized in solution and a drop in potential exists across two electrodes placed in this solution, a current will flow between the electrodes. In such cases current flow is due to the migration of ions in solution. Positively-charged ions (cations) will move to the negative electrode (cathode) and the negatively-charged ions (anions) will move to the positive electrode (anode). The amount of current carried by an ion will depend on its charge and the rate at which it moves through the solution.

Conductivity of a solution is normally expressed in terms of specific conductivity (λ_s) although it is calculated from resistance measurements. As conductivity (λ) and resistance (R) have a reciprocal relationship it is an easy matter to go from one to the other. Similarly, specific conductivity (λ_s) and specific resistance (R_s) are also reciprocally related for any electrolytic conductor.

$$\lambda_{s} = \frac{\ell}{A} = \frac{\ell}{A} \frac{1}{R} = \frac{K}{R} = \frac{1}{R}$$
(1)

If ℓ , the distance between two electrodes, is exactly 1 cm and A, the area of the electrodes, is exactly 1 cm², $\lambda_s = \lambda$, that is, by definition, specific resistance is the resistance of 1 cm³ of solution. For any particular cell, ℓ and A need not be measured since λ_s is accurately known for many solutions. Also for any given cell ℓ/A is rigidly fixed by the geometry of the electrodes and is called the "cell constant" K. It can be indirectly determined by filling the cell with a solution of known specific conductivity and measuring R. Then from Eq. (1) the cell constant is $K = R \ge \lambda_s$. For any other unknown solution R is measured and hence the specific conductivity, $\lambda_s = K/R$. The units of λ_s are cm/cm² ≥ 1 /ohm = cm⁻¹ ohm⁻¹.

The conductance of a clay slurry is not the sum of the conductance of the clay and the conductance of the pore fluid. As Van Olphen and Waxman (20) have pointed out recently, in the case of rock this is a consequence of the ionic double layer phenomenon which results in surface conductance. The clay being negatively charged attracts positive charges (cations) from the liquid and provides a conductance path along the surface of the clay which is not allowed for in the equation and therefore,

$$\lambda$$
 (pore liquid) + λ (clay) $\neq \lambda$ (clay slurry) (2)

Van Olphen and Waxman point out that for a given pore which is filled with fluid, and where the opposite walls of the pore are approximately parallel, the following equation holds:

 λ (pore liquid) + λ (clay surface) = λ (liquid-filled pore). (3)

Special factors must be taken into account when in situ resistance measurements of clay deposits are used as a basis for estimating the salinity of the pore fluid even though the relative proportions of the various ions remain the same. These factors are: the clay particle concentration, the geometry of the clay structure and the relative magnitude of the surface conductance compared with conductance of the pore liquid. With increasing electrolyte concentration of the pore liquid and decreasing clay particle concentration, the importance of the surface conductivity diminishes.

(b) Electro-kinetic phenomena with particular reference to clay-water systems. - When two phases such as clay particles and water come in contact, there is a spontaneous separation of charges at the interface which gives rise to electro-kinetic phenomena. The negatively-charged surfaces of clay are the result of isomorphous substitution of cations within the crystal structure. Hence, if tetra-valent silica ions have been replaced by tri-valent aluminum ions, the crystal has a resultant excessive negative charge. To counterbalance the excess negative charges, cations are adsorbed on the surface and this neutralizes the clay micelle. Such ions cannot be removed except by replacement. The concept of a fixed negative charge for clays and electro-neutrality by cation adsorption is accepted generally. The spacial distribution of cations, however, is dependent on the properties of the solution. It follows from this that the resultant potential drop exterior to the particle in the solution is a variable. The salient features of one diffuse doublelayer concept is diagrammatically depicted in Figure 1, recognizing that such an illustration may incorporate many oversimplifications partly for the sake of clarity and partly because of the many uncertainties that still exist about the constitution of the clay particle and its environment.

Following the concept of electro-kinetic or zeta potentials and the electrical diffuse double-layer as developed by Alexander and Johnson (20), the negatively-charged particle is surrounded with a shell of strongly-bound water. In this water and next to the particles some cations may be held more or less permanently in position and constitute the so-called immobile Stern layer. These "fixed" cations partly counterbalance the negative charges. The remainder of the cations are considered to be in a mobile layer.

The concentration of cations decreases with distance from the surface of the particle to an average concentration of cations in the bulk solution; conversely, in the mobile layer the concentration of anions is essentially zero at the boundary but increases with distance up to an average concentration of the bulk solution.

The flood of cations in the mobile layer is relatively distant from the particle but, in the sphere of influence of the negatively-charged particle, the cations are in constant motion by virtue of their thermal energy and may be interchanged with cations from the bulk solution. Thus the behaviour of the ion atmosphere is statistically determined and is known as the "diffuse layer." Alexander and Johnson (21) point out that it is sometimes useful to think of a shell of charges equivalent in action to the diffuse layer. The distance between the outside of this shell and the surface of shear (interface between immobile and mobile layers) is known as the thickness of the double layer, d. For water at 25°C.

d =
$$\frac{3.05 \times 10^{-8}}{\sqrt{1}}$$
, cm (4)

where

I is the ionic concentration.

Assuming I = 0.01, d = 30.5 A and when I = 1, d = 3.05 A, this means that the electro-kinetic potential is smaller with increased concentration and drops to zero over a shorter distance, d, from the immobile layer.

When an external electrical potential is applied tangentially to the surface of the particle, the positively-charged diffuse layer will be attracted toward the negative electrode (cathode) and the negatively-charged particle (together with the immobile layer), will be attracted to the positive electrode (anode). This forms the basis for measurement of electro-kinetic potentials. As there are several ways in which this may be done, they have been classified in the literature as follows:

- 1. Electro-osmosis involving the movement of a liquid relative to the solid by the external application of an electrical field.
- 2. Electrophloresis involving the movement of a solid phase with respect to the liquid by the external application of an electrical field.
- 3. Streaming potential involving the movement of the liquid by mechanical means with respect to the solid and measuring the electrical potential induced.
- 4. Sedimentation potential (Dorn effect) involving the movement of the solid by mechanical means (usually gravitational) and measuring the electrical potential induced.

As this paper is concerned with the measurement of the electrokinetic potential by electro-osmosis, further review will be confined to this method.

The electro-osmotic technique has been used to study the electro-kinetic potential of a large variety of pure crystals by Douglas and Walker (22), for other material such as cellulose fibre by Goring and Mason (23), and more recently for the study of bentonite drilling muds by Oakes and Burcik (24).

By this method, a liquid-saturated plug of solid particles is held in a fixed position. An external electrical potential is applied across the plug, and the flow rate of the liquid is measured. Utilizing the flow rate, the applied potential, the dielectric constant and viscosity of the liquid in the diffuse layer, the electro-kinetic potential E_k may be calculated using the Smoluchowski-Helmholtz equation. As with the other methods of measuring electro-kinetic potentials there are limitations with the electro-osmosis technique. The three more important ones are discussed in some detail by Kruyt (25) and may be summarized as follows:

- 1. The conductance determining the conduction current should depend solely on the bulk conductivity of the liquid. This means that surface conductance should not contribute significantly to the total conduction. If it does, it is possible to partly correct for the error.
- 2. The radius of pores of the plug must be much larger than the thickness of the double layer.
- 3. The flow of the liquid must be laminar. Normally this condition is readily fulfilled.

How these limitations have been avoided or how the difficulties introduced have been overcome in the past and in the research described in this paper will be described in the discussion of the technique.

EXPERIMENTAL

1. Apparatus and Methods

An apparatus (Figures 2 and 3) was designed based on the electro-osmotic technique used by others (22, 23 and 24) for the determination of electro-kinetic potentials. Suitable modifications were made to permit a-c resistance measurements of the plug before and after electro-osmotic measurements. The centre section containing the soil plug was designed so that undisturbed samples of clay could be pressed into the holder with a perfect fit between the holder wall and the sample.

The technique was that commonly used for preparing natural soil samples for consolidation tests. Figure 4 shows a clay sample being pressed into the sample holder. For semi-fluid remoulded soils, the sample was contained between two coarse filter papers that were held in place in the sample holder by lucite retaining rings.

The inner electrodes consisted of coarse platinum gauze (covered with platinum black) held tightly on both sides of the sample by porous stones mounted on the end of glass rods. The platinum lead wires were brought to the outside through a hole in the glass rods. These electrodes were used only to measure the resistance of the plug. The whole electrode assembly was more than sufficiently porous so as not to impede liquid flow during the electro-osmosis run.

The external potentials were imposed with the outer electrodes. These electrodes were made of platinum gauze tubes. A layer of silver was deposited on the surfaces by electrolysis and they were then subsequently chloridized in 0.1 N hydrochloric acid solution using an inert cathode.

The entire cell was submerged in a constant temperature bath held at $25^{\circ}C \pm 0.1$. The liquid flow was measured on both the intake and outflow sides with calibrated capillary tubes mounted on a mirror containing an etched millimetre scale. The potential was applied in one direction for 10 min and then reversed for a further 10 min. The values for such runs were averaged to obtain a mean value.

The electrical current through the system was held constant with a manually-operated rheostat, based on continuous measurements of the potential drop across a thermostatted standard resistor in the external current. The current selected for each particular run depended on the resistance of the plug and was arranged to give a 0.5 voltage drop across the plug. The amount of liquid moved through the plug varied between 0.2 and 0.05 cc for a 10-min period, depending on the electro-kinetic potential of the plug material.

The specific conductivity of the solution in both outer cell compartments was based on the predetermined specific conductivity of the pore water in the sample. Although the specific conductivity of the liquid throughout the system was the same (in the clay plug and the outer compartments), it was not practicable to simulate the nature of the electrolyte of the pore water.

The bulk pore-water concentration of the plug was determined from the soil immediately adjacent to the position of the sample plug in the soil profile. A pressure-membrane apparatus with a rubber bellows was used to carry out the extraction (Figure 5). Sufficient pore water was extracted to fill a standard laboratory conductivity cell so that no dilution was normally necessary.

The resistance of the porous plug was measured in the cell between the inner electrodes with a 60 to 1000 cps conductivity bridge, after the apparatus was in thermal equilibrium at the bath temperature of 25° C. The conductivity of the extracted pore water was also measured with this same instrument.

Strength tests for sensitivity calculations were done with the Swedish cone (26). The cone penetration measurement was repeated several times and averaged. The shear strengths were calculated from this average using the equation

$$T = KQ/H^2$$
(5)

where

T is the shear strength H is the penetration depth in the metric system Q is the weight of the cone K is a constant depending on the cone angle.

THEORY

The electro-kinetic potential can be calculated from the well-known Smoluchowski-Helmholtz equations which are applicable independent of the pad dimensions or of the structure within the pad.

$$E_{k} = \frac{4\pi \eta v \lambda_{s}}{\varepsilon i}$$
(6)

where

 E_k is the electro-kinetic potential,

 ε and η are respectively the dielectric constant and viscosity within the double layer, v is the electro-osmotic liquid flow rate,

and λ_s is the specific conductivity of the pore liquid.

Values for λ_s and i must be in cgs electrostatic units. As λ_s is usually in ohm⁻¹ cm⁻¹ it must be multiplied by 9 x 10¹¹, and i, in amperes, must be divided by 0.33 x 10⁻⁹. The electro-kinetic potential will now be in cgs electrostatic units. Further, v is in cm³/sec, η in poises. To convert E_k to practical units (volts) it must be multiplied by 300.

If λ_s is the specific conductivity of the bulk solution the electro-kinetic potential calculated may be too low. It is possible, however, to make at least a partial correction for this by evaluating λ_s for the solution while in the pore; this takes care of the errors caused by surface conductivity of the solids in the plug. It has been suggested in the literature that a part of the error introduced by excessive surface conduction is not allowed for by the method described in this report. In view of the uncertainties of the values for viscosity and dielectric constant in the double layer, no further attempt beyond that employed elsewhere (22) is warranted.

The value for λ_s in Eq. (6) was determined by Briggs' method (27). The resistance of the plug containing the natural pore water was measured in the cell. After the run was completed, sufficient KCl salt was added to the sample to bring the salt concentration of the pore water up to at least 0.1 N, the soil was thoroughly remoulded and the resistance of the plug was measured again. The pore water was then extracted and its specific conductivity (λ_s) determined. The electro-osmotic "cell constant" was calculated from the product of R_{0.1 N KC1} (the resistance of the plug with the high salt concentration) and λ_s 0.1 N KC1. The specific conductivity of the pore fluid at any low salt concentration can then be evaluated as follows:

$$\lambda_{s} = \frac{\begin{bmatrix} R_{0.1 \text{ N KCl}} \text{ (Plug)} \end{bmatrix} \begin{bmatrix} \lambda_{s 0.1 \text{ N KCl}} \text{ (Bulk specific conductivity)} \end{bmatrix}}{R \text{ (Plug at field salt concentration)}}$$

(7)

As may be expected for dilute solutions, λ_s is always higher than the specific conductivity of the pore fluid measured in bulk by an amount equivalent to the conduction added by surface conduction.

In addition to the difficulty of allowing adequately for the surface conductivity effect in applying Eq. (6) a further complication arises with the electro-osmotic method if the pore radii of the porous plug are of the same order as the thickness of the double layer. It is because of this objection that the electro-kinetic properties of clays are normally determined in dilute solutions by electrophoretic means. Some studies have, however, been carried out on plugs made from small particles of the order of 30 microns. Oakes and Burcik (24) have studied bentonite drilling muds by electro-osmosis up to bentonite concentrations of 13 gm/l.

It was of special interest to study the electro-kinetic potentials of these sensitive clays with their natural structure intact and bathed in the natural soil water. Removal of the soil particles from their natural pore-water environment changes the electro-kinetic potential and there is no way of simulating accurately the pore solution of soil. Hence, if the electro-kinetic potentials to be measured are to be meaningful in terms of the in situ potentials, no other method is possible.

Preliminary calculations, although based on a number of assumptions, permit an evaluation of the ratio between the thickness of the double layer and the pore radius in the clay-water systems studied in this report. Assuming that the clay particles are randomly oriented and have a surface area of 72 m/gm, at a water content of 0.652 gm/gm of dry soil, and postulating a uniform distribution of water over the entire surface. the layer of water over the clay surface is 118 Å in thickness. At an ionic strength of 1, the double layer was shown to be 3.05 Å; at 0.1 it is 10 Å; and at 0.01 it is 30.5 Å. The ionic strengths of the pore water in the soil are probably of this order, that is, between 0.1 and 0.01. From this it can be seen that the ratios of pore radius range approximately from 4/1 to 11/1. Bull (28) shows that the electro-kinetic potential is depressed for ratios in capillary tubes of less than 15/1. The two factors taken into account were the overlapping of double layers in small pores and the cylindrical shape of the pores when the radius is small. Equation (6) assumes the surfaces to behave as flat parallel condensers.

It is concluded from this that the measured electro-kinetic potentials may be lower than the real value, in porous diaphragms consisting of finely-divided particles such as those used in this study.

MATERIALS

The majority of the soils studied were from the so-called marine deposits of the Ottawa-Hull area. Some of the undisturbed

samples were taken in blocks from deep excavations; others were sampled with the Norwegian thin wall sampler or with the Swedish foil sampler. Figure 6 is a map of the area showing the sample locations. Other soils included in this study were from Toulnustouc, Quebec (the site of a recent flow slide), Burnaby, British Columbia believed to be a marine clay, and from Seven Sisters, Manitoba - a glacial lacustrine deposit.

RESULTS AND DISCUSSION

1. Preliminary Studies on the Performance of the Electro-osmotic Cell

From the basic equation used to calculate electro-kinetic potentials, it can be seen that the osmotic flow should be proportional to the current. Based on average flow rates (Table I), some preliminary trial runs were carried out to test the apparatus for this relationship for two different soils. Doubling the current also doubled the flow rate. Shown also in Table I are the flow rates for two samples taken from adjacent locations in the same soil block in order to test the reproducibility of the apparatus and technique. Good agreement between runs was not difficult to achieve on soils that were reasonably homogeneous. Repeat runs on the same soils after several months in storage showed small changes in electro-kinetic potential and also in salt concentration. This is believed to result from ageing the soil at a higher temperature than the in situ temperature. Oxidation of the outside layers of blocks is quite common after several months of laboratory storage even when heavily waxed and stored in an atmosphere of high relative humidity.

There was some concern, based on the survey of the literature, that the repression errors on the electro-kinetic potentials would be too severe for the results of the electro-osmosis method to be meaningful due to the smallness of the pores. Such errors would be greatest at low electrolyte concentrations when the diffuse layer thickness is large. The results of the measurements (Table II) show that very large electro-kinetic potentials can be measured by this technique. The potential of the remoulded soil was 19.2 mv. This increased to 23.2 mv when the salts were reduced in the pore water by washing. When finally treated with 1 gm of sodium metaphosphate/ 100 gm of dry soil, the potential increased to 64.5 mv. The measured sensitivity values increased appreciably, as expected, with increasing electro-kinetic potentials. Although such experiments do not permit an evaluation of the amount that the electro-kinetic potential is repressed in an absolute sense, indications are that large values of electro-kinetic potential can be measured in this way by treating the soil particles in ways that are known to influence the diffuse double layer. All these experiments were carried out at a constant soil density.

As a further check on the influence of pore size on the measured potentials, the water content may be increased, thus leading to larger pores in these flocculated systems. The change should be reflected in the measured electro-kinetic potentials as the ratio of the pore radius to double-layer thickness is increased. The results in Table III indicate that when the water content was increased (increasing the over-all porosity), the potentials remained essentially constant within experimental errors. The lowest moisture contents are those encountered in the field. These were increased by nearly four times by adding previously extracted natural pore water of low electrolyte content to which additional electrolyte was added to achieve a high concentration. These experiments were carried out with a very sensitive clay (94-27) and one of lower sensitivity (94-14). The thickness of the double layer was varied (by electrolyte concentration) and the pore size was varied (by changing the water content). As such changes were not reflected in the electro-kinetic potential, it is concluded that the repression of the electro-kinetic potential by the smallness of the pore size in these soils is not a serious drawback to using the electro-osmotic technique under the conditions described. Some repression is to be expected, however, in view of the suggestions presented earlier in this report.

2. Electrical Resistance and Conductance Capacity

Heat conductivity, determined normal and parallel to the direction of sedimentation in clay deposits, is a reasonably sensitive method for establishing the degree of preferred particle orientation. The highest ratio of such coefficients (1.7) was for a lacustrine deposit from Seven Sisters, Manitoba. Electrolytic conduction appears to be an even more sensitive method of determining the anisotropy of clay soils. For the sample previously studied by heat flow methods, the horizontal electrical specific conductivity was 2.65 x 10^{-4} ohm⁻¹ cm⁻¹, and the vertical was 0.710×10^{-3} , giving a ratio of 3.8 or more than twice that given by the heat flow method. The value for the remoulded soil was 1.38×10^{-3} which is a little less than the average of the two extremes. It therefore appears that there is an important contribution by surface conductance to the conductance of the pore water.

One suggested method of comparing the relative contribution by the surface of particles is to compare the conductance capacity ($\lambda_{s}R$) of a clay plug at various salt concentrations (where λ_s is the bulk specific conductivity of the pore water and R is the measured resistance of clay plugs of a given dimension, fully saturated with the electrolyte of λ_{s}). Because R is reduced at low salt concentrations, owing to the relative importance of the surface conduction path at low electrolyte pore-water contents, the values of $\lambda_{c}R$ decrease with decreasing values for λ_{s} . The maximum value of $\lambda_{s}R$ is obtained when the contribution of the surface is reduced to an insignificantly small value compared to the over-all conductivity. It can be seen that the influence of surface conductance also diminishes with a decreasing clay-particle concentration. Figure 7 shows the conductance capacity for two soils at two salt concentrations - at the natural pore-water concentration in the field and at a high salt content of approximately 0.1 N KCl. The lowest point on each curve is for the field moisture content. The difference in conductance capacity is a reflection of the relative importance of surface conductance with the amount of clay and electrolyte present.

It becomes obvious that resistance measurements of the clay-water system do not properly reflect the degree of salinity of the pore water at low salt contents. Such measurements become increasingly dubious with decreasing salt content. Table IV gives the conductance capacity of a marine clay with depth, where the salt content increases with depth. In Table V are listed the natural conductance capacity values for sensitive soils from various locations. The second column from the left gives the conductive capacity values when surface conduction adds only a small amount or nothing to the total conduction. As in Table IV, Table V shows that the lower the natural salinity of the soil, the higher is the proportion of conductance along the particle surfaces.

Comparisons of electrical resistance measurements made at right angles (parallel to the direction of the natural sedimentation and at right angles to this) for a well-oriented lacustrine deposit suggested that such measurements might be used as a sensitive indication of the degree of particle orientation in Leda clay.

Unfortunately, for such comparisons to be a meaningful measure of anisotropy, they would have to be made at the same density and salt content. Although these comparisons cannot indicate the <u>degree</u> of orientation, any difference in vertical and horizontal conductivity indicates the existence of some structural anisotropy. Figure 8 contains the results of all the vertical, horizontal, and remoulded conductivity measurements on sensitive clays from the OttawaHull area, plotted against the bulk pore-water conductivity. Although only a few horizontal determinations were carried out, in every case the conduction in this direction was greater than the vertical value; in all cases the remoulded conductances were intermediate in magnitude.

The experimental results in Figure 8 are further evidence that conductivity values of natural soils do not properly reflect salinity conditions of the pore water, because of the anisotropic conduction of the structure. Cognizance of this must be taken into account when using an electrical sounding probe. Large salinity differences, however, would be expected to show up.

A preferred orientation of clay platelets is in fact the favoured alignment of short electrical conductors, if measured parallel to the long axis of the particles. At the same time, the electrolytic path through the pores of the system may be less tortuous than in a randomly-oriented system of clay particles.

Such measurements in two directions of the natural structure and in a remoulded condition still lead to the possibility that subsequent consolidation has resulted in the sliding of particles into positions that give a preferred alignment of the long axis of clay platelets normal to the direction of loading by the overburden.

3. Detailed Electro-kinetic Studies

The structure of a clay platelet is such that the distribution of charges is not uniform over its entire surface. This is important because these charges are chiefly responsible for the double layer phenomenon in clays. The negative charge along the planar face is probably mainly the result of isomorphous substitution in the clay lattice. The broken bonds around the edges of the platelets can, however, also contribute to the base exchange capacity. Grim (29) points out that in illites the broken bonds make an appreciable contribution to the total cation exchange capacity, and in this connection the effect of pH on edge charge is well recognized.

Although considerable information is now available on the mineralogical nature of the St. Lawrence Lowland clays, no detailed studies have been carried out on the precise origin of the location of the exchange sites.

The non-uniformity of charge distribution around the clay particles, together with some preferential orientation of the long axis in the direction normal to the direction of consolidation, suggests that the electro-kinetic potentials measured in two directions should also show some anisotropy. The measured electro-kinetic potential is a kind of average potential of all the particle surfaces contributing to electro-osmotic flow in any given direction in which the external potentials are applied.

Based on this, if the external potentials are applied parallel to the greatest density of planar surfaces, the flow should be higher than when applied at right angles to this direction. These peculiarities are unique to clay samples because of particle shape, a feature which normally does not arise with plugs made of other fine-grained material.

(a) Influence of mechanical and chemical dispersion. -In earlier studies (14) it was observed that the sensitivity of remoulded Leda clay could be increased by mixing in sodium metaphosphate, a common chemical dispersant. This phenomenon, observed also by others, has been attributed to an increase in interparticle repulsion brought about by high electro-kinetic potentials. These effects were studied on two samples taken from the same profile but at different depths. The sensitivity measurements determined by the falling cone method for two samples, 94-13 and 94-20, were 30 and 75, respectively.

The quantity of dry sodium metaphosphate added to the soil was based on earlier results (14) which showed that the minimum shear strength for the remoulded state was obtained by adding approximately 0.5 gm/100 gm dry soil. Both soils were low in natural pore water salt content -- less than 2 gm/l -- although their sensitivities were entirely different. The results in Table VI bear out the previous hypothesis concerning the increase in electro-kinetic potential brought about by the adsorption of metaphosphate. When such a dispersant is added to a flocculated clay mass and remoulded, the adsorption of the metaphosphate increases the repulsion forces. By mechanically remoulding the soil, the particles that are held together by Van der Waals attraction or other forces are separated. Once separated the repulsion is too high to allow the particles to come close enough together to recombine or flocculate. The fluid in the pore spaces distributes itself evenly between the particles. Instead of particles touching one another to form a cardhouse network, the particles repel each other and behave as separate entities. Water tends to collect on the surface of the sediment if left standing for long periods, as the packing of particles per unit volume that can be achieved is increased. These new conditions occurred although the moisture content was not increased from its natural field moisture content. The remoulded shear strength was 68 lb/ft², and its undisturbed strength was 2080 lb/ft^3 . Changes in strength resulting from metaphosphate additions are plotted in Figure 9 as a function of electro-kinetic potential.

(b) Leaching experiments. - In preliminary studies, naturally-occurring electrolytes were washed out of highly-diluted remoulded clays originally containing pore-water salt contents of approximately 10 gm/l. The electro-kinetic potentials increased but such a treatment is entirely different from the natural leaching process visualized by Rosenqvist (15) that takes place in situ with minimum structural disturbance.

In these experiments, undisturbed samples were cut from these high salt content clays, and electro-kinetic potentials were measured before and after various stages of leaching. The apparatus used for the leaching process is shown in Figure 10. Differential air pressure of less than an atmosphere was applied to the top chamber; no consolidation of the sample occurred during leaching. The effectiveness of leaching was ascertained from measurement of the resistance of the soil plug and of the conductivity of the leachate. The results are shown in Table VII. Leaching was then continued in one sample with a weak solution of sodium metaphosphate which again increased the potentials. This was followed by a further leaching period using only distilled water to remove the excess unreacted metaphosphate which caused yet a further increase in the measured potential. These experiments show that leaching of salts from marine deposits does increase the electro-kinetic potential and hence, the sensitivity. That further increases in sensitivity in the field may result by reaction with naturally-occurring organic dispersants in the leaching fluids seems probable in view of the effect of metaphosphate leaching. It is important to note that such increases in electro-kinetic potential were brought about by leaching without any mechanical disturbance. Unfortunately the full significance of these experiments was not realized at the time and, in consequence, no strength measurements associated with increases in potential were measured in these tests. As the pattern between sensitivity and electro-kinetic potential has already been established for remoulded clays in this paper, this should apply equally well for the leached undisturbed samples.

(c) Electro-kinetic potentials of undisturbed soils of varying salt concentration. - Previous experience with clays from the Ottawa-Hull area failed to show that sensitivity necessarily increases with decreasing natural pore-water salt concentration (14). The results of the sixteen clays included in the present study support the conclusions from the earlier studies. At low pore-water salt concentrations $(4 \times 10^{-3} \text{ ohm}^{-1} \text{ cm}^{-1})$ in terms of specific conductivity), the sensitivity may vary considerably. Soils with salt concentrations in excess of this may still have reasonably high sensitivities but do not exceed 75. The general pattern of the relation between sensitivity and natural pore-water salt concentrations is shown in Figure 11. It is not possible for soils with high salt concentrations to develop very high sensitivities because of the flocculating effect of electrolytes at these concentrations. At low salt contents the sensitivities may be either high or low. The reason for this can be more readily understood in terms of electro-kinetic potentials. These results are given in Figure 12.

Taking into account the range in moisture contents, grain-size distribution and per cent clay which have an influence on sensitivity, the pattern presented in Figure 11 is remarkably consistent with the theory of interparticle repulsion. The two soils that are notable exceptions to the general pattern seem at first glance to have too high a sensitivity for the low potentials measured. Both have a relatively low surface area and therefore slurries of these materials will have different consistencies than for those from soils that are more finely divided. These results show that sensitivity is related to the electro-kinetic potential. It must be recognized that measurements of potentials by the electro-osmosis technique cannot be claimed to give absolute values. Similarly, there are problems in obtaining good sensitivity measurements but it can be said that sensitivity tends to reflect relative differences in electro-kinetic potential between soils from the Ottawa area.

More complete information on these soils, including surface area, natural moisture content, per cent clay-size particles, plasticity indices and depth of sampling is given in Table VIII. Attention is directed to the low surface areas of soils 94-20-5, 94-27-1 and 123-2-3. Figure 13 gives a plot of the relation between clay content and plasticity index. These agree with earlier studies on similar materials (15).

(d) Adsorption of sodium metaphosphate in relation to structure. - Treatment with sodium metaphosphate was carried out on soil 126-5 under two very different conditions. This soil has a relatively high pore-water salt concentration (10 gm/l) and soils with this high a salt content have been found only in one location to date in the Ottawa-Hull area.

In the first case, a small amount of clay (50 gm) was remoulded and diluted with several litres of water. By processes of decantation, filtration and sedimentation the salt was almost completely removed. The original pore-water conductivity was 16.9×10^{-3} ohm⁻¹ cm⁻¹; after washing it was 0.29×10^{-3} . The sample was redispersed and 0.5 gm/100 gm of dry soil of sodium metaphosphate was added. The water content was reduced by air pressure to its original field moisture content. The electro-kinetic potential was increased from 19.7 mv in the remoulded state to 23.2 in the low salt content state, and to 64.6 after treatment with the dispersant.

When the salt from the same soil was removed by leaching the natural structure with distilled water, followed by an extensive leaching period with sodium metaphosphate and another leaching period to remove excess dispersant, the electro-kinetic potential increased only to 30 mv in contrast to 64.6 mv. These results seem to indicate that most of the edge charges are occupied in the natural structure by the edge to face arrangement and not available for exchange. When structural breakdown was effected by mechanical means preceding the metaphosphate treatment, the face-to-face repulsion was kept high and sodium metaphosphate reacted easily with the exposed edges and the micelle as a whole was negatively charged. If this reasoning is correct, it may be assumed that a significant proportion of the adsorption sites for sodium metaphosphate is on the edges of clay platelets, which seems quite probable based on the evidence presented by Van Olphen (30).

(e) Pore-water salt composition. - Conductivity and gravimetric determinations of the pore-water salt concentrations for several of the deposits were compared. Conductivity measurements were carried out at the extracted concentrations without dilution. Gravimetric determinations consisted of weighing the solids after evaporation of a fixed volume of solution at 105°F.

The last column in Table IX gives the specific conductivity of the pore water per gram of solid. Such salts are known to have both organic and inorganic components but no attempt has been made to evaluate accurately the amount of each present.

The changes in the weight conductivity values indicate compositional changes in the solids in the pore water even for one profile but an approximate conversion factor may be calculated to estimate grams of salt per litre from conductivity measurements or vice versa. Table X contains a partial chemical analysis of the extracted pore water in milligrams per litre. Selection of the principal cations and anions was based on earlier studies by Rosenqvist (15). A total pore-water analysis showed that in addition to calcium, sodium, magnesium, potassium, sulphate and chloride, some samples contained moderate amounts of dissolved silica and aluminum. It is interesting to note that the six main inorganic constituents given in Table X comprised as low as one-half of the total solids based on gravimetric studies, indicating that in addition to silica and aluminum, organic constituents are probably also important in terms of the amount present. Other studies at this laboratory suggest that for soils which contain 2 to 4 gm/l of pore water, one-third to one-half of this is lost by treating the evaporated salt with hydrogen peroxide.

Table XI gives the main cations in terms of milliequivalents per litre and the percentages of each ion. At the bottom of the table, the sea water analysis quoted by Rosenqvist (15) is given in the same units.

At the Queensway overpass where the highest known salt content in the Ottawa-Hull area is found, the K^+/Na^+ ratio is essentially the same as in the sea water analysis, but the Mg^{++}/Na^+ ratio in terms of equivalents is about one-third and the Ca⁺⁺ percentage is down, which may indicate selective adsorption of divalent ions by the clay. Conversely, both the Na⁺ and K⁺ contents are above that given in the sea water analysis. In particular, Mg^{++} is much below the sea water analysis in comparison to Ca⁺⁺.

Examination of the $SO_4^{=}$ and Cl^{-} analyses of the Queensway overpass in Table XII shows that the ratio of $Cl^{-}/SO_4^{=}$ decreases with depth. Whether this should be interpreted as selective adsorption or whether the $SO_4^{=}$ has been reduced to relatively insoluble sulphides in increasing amounts with depths is still a matter for speculation. At this location the ratio goes from about 9 at 75 ft to about 13 at 55 ft, as compared with a ratio of 7 in sea water.

On the whole, although differences do exist, the pore-water salts resemble sea water. At other locations where the pore water contained much less salt this similarity diminishes, as has been noted previously by Rosenquist for Norwegian leached marine clays.

Attention is also directed to the constancy of the percentages of the various ions with depth at the Queensway overpass, with the exception of the deviations already noted in the Cl^{-}/SO_{4}^{-} ratios. This fact suggests two things - either this deposit was laid down in increas-

ingly diluted salt water conditions as the sediment was built up, or, if leaching has caused the decreased salt conditions, the mono and divalent ions were leached at the same rate. The former is the more probable answer. Although only the profile from 35 to 75 ft was considered in this study, the increase of salt concentration with depth at this location applies from the present surface to bedrock.

At the Gloucester location the K^+/Na^+ ion ratio is somewhat higher than at the Queensway overpass and higher than that in sea water, as are the absolute percentages of K^+ and Na^+ ions. At this location the sensitivity is much higher for the upper three samples. The deepest sample has more than twice the amount of Ca^+ ions and a lower sodium content. These factors lead to a lower sensitivity and a lower electro-kinetic potential. The soil from the Gloucester profile has a high calcite-dolomite content going as high as 12.5 per cent at the bottom of the profile. This is in contrast to the soil at the Breckenridge site which shows no reaction to HCl and is lower in porewater salt content but despite this has a lower sensitivity.

At the Sewer Plant location the cause of the lower sensitivity and electro-kinetic potential at the 22-ft depth, as compared with samples from 53 ft and 72 ft, appears to be explained on the basis of the kind of ions in the pore water. In the upper part of the profile the Na⁺ content is about half that at depth and the percentages of calcium and magnesium are higher. The sample from Toulnustouc, Quebec, which is also in the St. Lawrence Lowland region, is believed to have the highest sensitivity ever observed at this laboratory. Its silty nature and high sodium content is thought to contribute to the very high sensitivity observed.

(f) Amount of electrolyte required for flocculating sensitive clays from the Sewer Plant location. - Flocculation studies have been carried out with samples from two depths at the Sewer Plant location. The upper soil (94-13) from a depth of 22 ft has a natural pore-water salt concentration of about 1 gm/l and a conductivity of 1.07×10^{-3} ohm⁻¹ cm⁻¹, a low electro-kinetic potential and a sensitivity of 30. Sample 94-27 from a depth of 73 ft has a pore-water salt concentration close to 3 gm/l giving a conductivity of 2. 33 x 10⁻³ ohm⁻¹ cm⁻¹, a high electro-kinetic potential and a sensitivity of 600.

Two types of flocculating solutions were used. One contained only NaCl. In the other, the salt mixture was about the same as that given by Rosenqvist for sea water to simulate marine conditions. In each case one gram of soil (calculated on a dry weight basis) was dispersed mechanically in one litre of water in a 1000 cc graduated cylinder. The results are given in Table XIII. Ten concentrations were used ranging from 0.01 to 5.12 gm/l.

The difference in behaviour to flocculation between the highly sensitive soil (94-29), and the less sensitive soil (94-14) was quite noticeable, despite the fact that the former had a higher porewater salt concentration. From Table XI it can be seen that sample 94-14 had a much higher divalent cation content in the pore water and therefore also on the exchange positions. Rosenqvist (15) observed similar results. The flocculating response in similar solutions appears to depend on the electro-kinetic potential of the soil before it is subjected to the new environment. The electro-kinetic potential in this case may be simply the result of the higher valence ions on the less sensitive soils, which means that the exchange ions do not equilibriate immediately with the ions in the new solution.

In the NaCl solutions the highly sensitive soil (94-29) showed a medium amount of flocculation in the 1.28 gm/l solution after 16 hr. With sample 94-14 the 0.64 gm/l solution caused high flocculation after 16 hr. In the simulated sea water solution, sample 94-29 showed a medium amount of flocculation in the 0.32 gm/l solution after 16 hr. Sample 94-14 showed a medium flocculation in the 0.16 solution for the same time period. Figure 14 is a photograph of soil 94-14 after a flocculation time of 64 hr for a range of salt concentration of simulated sea water.

Attention is directed to the low concentration of ions required to bring about flocculation. Recognizing that particle concentration is important in establishing flocculation times and that those used in the experiment may be quite different than during sedimentation in nature it may be concluded, nevertheless, that sediments were probably formed in the period when nearly fresh water conditions existed.

(g) Shear strength in sensitive clays. - The nature of the undisturbed shear strength of the so-called marine clay sediments that are found extensively in Norway, Sweden and Finland as well as in the St. Lawrence Lowland region in Canada has been the subject of much speculation. Plotted in Figure 15 are the shear strength values versus electro-kinetic potentials for several different conditions at the field moisture content. Point B gives the electrokinetic potential at the strength of the undisturbed Leda clay at the time of sampling. On remoulding, the shear strength was reduced by at least 30 fold as given by point C. Point A was established by adding dry NaCl to the remoulded material to give a pore-water salt concentration of 30 gm/l. Points D and E were determined after adding 0.25 and 0.5 gm of sodium metaphosphate, respectively. If the strength and structural conditions created in the laboratory by adding NaCl in any way represent the marine conditions at the time of sedimentation, the gain in strength during its geological history must have been from 250 to 2080 lb/ft². It seems reasonable to assume that the sediment was laid down at a much higher moisture content and a reduction of moisture content occurred as consolidation proceeded, finally finishing at the present moisture content of about 67 per cent.

All the soils studied show some preferential horizontal alignment of the long axis of the clay platelets. Since the flocculated strength immediately after sedimentation was very low, perhaps even less than 250 lb/ft², and since no further significant increase of particle attraction can be visualized after the initial flocculation is complete, it seems reasonable to assume that much of the strength of a flocculated structure derived from consolidation results from the interlocking of platelets as consolidation proceeds. This is analogous to the strength developed when a clump of randomly-oriented pins are pressed together without bending the individual pins.

Crawford (31) has shown that for this soil at a depth of 52 ft at the Sewer Plant, about a 25 per cent loss of strength occurs when the soil is consolidated slightly in excess of its preconsolidation load, which may be the result of breaking cementation bonds. It is not difficult to visualize for the other 75 per cent that remoulding such a structure breaks down the interlocked structure attained by consolidation. In this way the strength drops back to a freshly remoulded soil, in this case 250 lb/ft². Thus, a sensitive soil has been produced without change in the electrolyte environment after sedimentation.

The degree of softness of the remoulded soil is no doubt a function of the interparticle forces. This has already been shown in this report. All that is required is that the original conditions of sedimentation must result in a flocculated structure. For this the electrolyte content of the water may be quite low, as has already been shown. Such conditions may have existed in the Ottawa-Hull area at the time when land uplift was in progress, the sea was receding, and much fresh water was brought in either from melting glaciers locally or from the Great Lakes region. Under these conditions, the marine deposits were reworked with almost fresh water and redeposited elsewhere in this area. At least one remnant of the original marine deposit exists in the area, and this shows an increase of salt content with depth from the surface downward. Whether the gradual increase of salt content with depth represents the changing salinity of the sea during uplift or whether leaching has taken place cannot be established on the basis of evidence now available. In any case, the remnant is flanked by deposits of similar clay which show essentially very little salt in the pore water from top to bottom. It is difficult to visualize from the bedrock contours that these different conditions side by side, at present, are the result of leaching on either side with the high salt content formation in between. It is suspected that the flanking bodies of clay were laid down following an erosional period in which the present centre portion was left standing.

The locations of borings which revealed these conditions are shown in Figure 6. The salty profile is located at the Queensway overpass. The Sewer Plant location, the soil at which contains less than 3 gm/l from top to bottom, is 6300 ft due north; the salt content is also low at the Sewer Interceptor Shaft 1700 ft due south. The bedrock rises slightly from north to south, about 10 ft/mile. Other probings in the area suggest the remnant containing salt is quite small. To determine this more precisely a program of systematic probings is being planned.

Further arguments in favour of the interlocking theory stem from the fact that these soils increase in strength with depth. If it is argued that cementation bonds are a main cause of soil strength it is difficult to visualize how this would systematically increase with depth. Similarly, if interparticle attraction is the main contributory cause of strength, it is equally difficult to explain why this would increase with depth. No doubt some strength results from packing the flocs. On the other hand, if the interlocking mechanism is acceptable, increased consolidation increases the complexity of interlocking and the increase of shear strength with depth is then easily understood.

Rosenqvist states that "... the distance between the atoms in two neighboring minerals will decrease by increasing normal pressure" (15). The present writer believes that when two particles approach one another during flocculation, the equilibrium position of the two particles is such that the distance between them is established immediately and no amount of overhead pressure will change the distance established by the balance between forces of interparticle repulsion and attraction. This is the condition within one floc. This is visualized as being different for the case between two flocs that have settled one above the other due to sedimentation. Consolidation will obviously bring particles from adjacent flocs into close enough proximity for further points of attraction to be established, but the key to the strength obtained comes from the increased complexity of interlocking.

Viewed in this way the interparticle forces establish the <u>arrangement of particles</u>. Immediately after flocculation, the soil has little strength but nevertheless this is the strength that can be truly assigned to interparticle forces. It is believed that consolidation does not bring the points of contact of particles closer together. The anisotropy that develops is a good indication that the points of closest proximity slide relative to each other and give the observed preferential alignment that is normal to the direction of consolidation. The "arrangement of particles" so necessary for the present concept merely allows strength to be developed as the "tightness" of interlocking proceeds with consolidation.

The type of structure developed conforms exactly to that of Lambe (32) to which Rosenqvist (33) agrees, but there is disagreement as to which feature of the structure one attributes strength.

CONCLUSIONS

The foregoing study permits the following general conclusions for the Leda clays of the Ottawa-Hull area. It is thought that they may also hold for similar clays throughout the St. Lawrence Valley area.

(1) It has been established that the sensitivity of these soils is quite generally a function of the electro-kinetic potential. Any significant deviation can be ascribed to coarseness of the material. Soils with a surface area (despite the clay size content measured by sedimentation) that is low as compared with the average surface area for these soils are more sensitive than predicted from their measured electro-kinetic potentials.

(2) At pore-water conductivities below $4 \ge 10^{-3}$ ohm⁻¹ cm⁻¹, a large variability in sensitivity occurs that is not related to the amount of salt in the pore water. The measured sensitivities are consistent, however, with the measured electro-kinetic potentials.

(3) A low sensitivity for those soils which at present have a low pore-water salt concentration can result from a larger than normal proportion of divalent cations. This results in low interparticle repulsion as reflected by the lower electro-kinetic potentials. (4) Electrical conductivity measurements indicate some anisotropy in particle orientation which results from isotropic consolidation of the deposit after sedimentation and is consistent with earlier heat flow studies.

(5) To date only one deposit has been found at the Queensway overpass which is believed to be a remnant of a marine depositional period. The present pore-water salt analyses from this deposit show great similarity at all concentrations to those of sea water.

(6) In general, the so-called Leda clay in this area is thought to consist of reworked marine deposits (similar, originally, to that noted in the fifth conclusion) which were subsequently resedimented in water of low salt concentration resulting from the dilution of the receding Champlain Sea. This is in reasonable accord with the most recent geological interpretation of this area.

• (7) All of the soils studied were sedimented in a strongly flocculated condition; this is a prerequisite for the development of a highly sensitive soil. Flocculation can be brought about in suspensions of these soils with relatively low salt concentrations of sodium chloride. Flocculation is greatly aided by small amounts of divalent ions, and this is consistent with the double layer theory.

(8) It is postulated that the present sensitivity of Leda clay results from breaking down the interlocking clay platelet structure which greatly reduces the shear strength of the material. In this way, no change in the pore-water concentration need be postulated. Interlocking and the strength of undisturbed clays of this type are achieved by isotropically consolidating flocculated clays. Loss of strength of natural soils caused by loading slightly in excess of the preconsolidation load is interpreted in this report as the breaking down of cementation bonds. According to the limited available information this amounts to about 25 per cent of the undisturbed shear strength. The strength obtained by adding some 30 gm/l of sodium chloride to remoulded soils at their present field moisture contents gives the soil a shear strength far below that of the natural structure. As no increase in the interparticle forces of attraction can be postulated after flocculation is complete, and as the isotropic regain is not sufficiently high to account for the present shear strength of these soils, the interlocking mechanism is believed to be of real significance in the development of strength with consolidation.

(9) It has been shown in this study that by leaching undisturbed soils containing a natural high salt content in the pore water, a more sensitive soil is produced. The theory of leaching is therefore not disputed, if its marine origin can be established.

(10) Changes in the pore water brought about by chemical weathering, by ion diffusion or by leaching, all influence the final sensitivity of the soil. Sufficient studies on the influence of various electrolytes have been carried out here and elsewhere to show the role of electrolytes on the behaviour of clays. Such changes are reflected not only in the sensitivity but also in the electro-kinetic potential.

(11) Measurements of electro-kinetic potential and porewater analyses have been particularly helpful in the discovery of why some soils from this area are not sensitive despite their low porewater salt content.

(12) The degree of sensitivity in Leda clay from various locations in this area is not attributable to any one cause although the loss in strength by the breakdown of the interlocking structure has a dominating influence. The coarseness of the material, the types of ions held on the soil and in the pore water, the amount of cementation and perhaps other factors not yet recognized all play a part in either its undisturbed strength or the strength on remoulding and hence on their ratio which is known as sensitivity.

(13) In situ probe resistance measurements are at best only a guide to pore-water salinity because of anisotropy and surface conduction.

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TABLE I

THE INFLUENCE OF ELECTRICAL CURRENT ON LIQUID FLOW

| i, milliamps | Number of 10-min runs | Flow, cc/10 min, left capillary | Flow, cc/10 min, right capillary | Average | Rate, cc/sec | | | | | |
|-----------------|---|--|---|---------|-------------------------|--|--|--|--|--|
| Sample 94-1 | 3-3 | | | | | | | | | |
| 1.2 | . 2 | 0.0345 | 0.0333 | 0.0339 | 0.57×10^{-4} | | | | | |
| 1.2 | 2 | 0.0362 | 0.0345 | 0.0353 | 0.59×10^{-4} | | | | | |
| 2.4 | 2 | 0.0719 | 0.0705 | 0.0712 | 1.19×10^{-4} | | | | | |
| 2.4 | 2 | 0.0719 | 0.0710 | 0.0714 | 1.19×10^{-4} | | | | | |
| Sample 94-2 | 27-1 | | | | | | | | | |
| 2.4 | 2 | 0.0703 | 0.0704 | 0.0704 | 1.17×10^{-4} | | | | | |
| 2.4 | 2 | 0.0713 | 0.0700 | 0.0706 | 1.18×10^{-4} | | | | | |
| 4.8 | 2 | 0.139 | 0.140 | 0.140 | 2.34 x 10 ⁻⁴ | | | | | |
| Sample 94-2 | Sample 94-27-2 (New sample adjacent to 94-27-1) | | | | | | | | | |
| 2.4 | 3 | 0.0700 | 0.0700 | 0.0700 | 1.17×10^{-4} | | | | | |
| 4. 8 | 2 | 0.139 | 0.140 | 0.140 | 2.34 x 10 ⁻⁴ | | | | | |
| | | | | | | | | | | |

IN THE ELECTRO-OSMOSIS APPARATUS

TABLE II

CHANGING THE ELECTRO-KINETIC POTENTIAL OF A REMOULDED MARINE CLAY (i) BY WASHING OUT SALTS, (ii) BY WASHING OUT

SALTS AND ADDING DISPERSANT

| Treatment | M.C., % | $\lambda_{s}^{(b)}$, ohm ⁻¹ cm ⁻¹ , sample | λ, ohm ⁻¹ -1, pore water | Electro- kinetic potential, mv | S (f) | | | | |
|--|------------|---|--|---|-------|--|--|--|--|
| Sample 126-5 | | | | | | | | | |
| Remoulded sample (a) | 63 | 6.28 x 10^{-3} | 16.9 $\times 10^{-3}$ | 19.7 | 34 | | | | |
| Washed sample (c) | 63.2 | 0.49 x 10^{-3} | 0.29×10^{-3} | 23.2 | 91 | | | | |
| Washed (d) and dispers- ant ad de d | 66.6 | 1.16×10^{-3} | 0.53×10^{-3} | 64.6 | 2150 | | | | |
| Sample 126-4 | | | | | | | | | |
| Remoulded sample (e) | 62.5 | 4.94×10^{-3} | 14.6×10^{-3} | 19.2 | 45 | | | | |
| Washed sample | 62.6 | 1.88×10^{-3} | 1.88×10^{-3} | 25.6 | 120 | | | | |

(a) Natural pore-water salt concentration about 9.6 gm/l.

(b) λ_s = specific conductivity of the sample.

(c) Washed by dispersing mechanically in several gallons of distilled water, solids reclaimed by filtration.

(d) As in (c) and metaphosphate added.

(e) Natural pore-water concentration about 9.1 gm/l.

(f) Sensitivity.

TABLE III

ELECTRO-KINETIC POTENTIALS WITH INCREASING MOISTURE

CONTENTS FOR TWO SOILS OF WIDELY DIFFERENT SENSITIVITIES

| м.с., % | Dry density, gm/cm ³ | λ Sample | λ_{s} Pore Water | Electro-kinetic potential, mv |
|----------------|------------------------------------|-------------------------|-----------------------------|----------------------------------|
| Sample 94-14-A | | NATURAL SA | LT CONCENTRAT | 10N, S = 30 |
| 65.2 | 0.954 | 1.07×10^{-3} | 2.25 x 10-3 | 14.9 |
| 114.6 | 0.652 | 1.26 x 10^{-3} | 11 | 14.3 |
| 160.6 | 0.483 | 1.42 x 10 ⁻³ | 81 | 14.7 |
| 213.3 | 0.379 | 1.52 x 10 ⁻³ | 81 | 14.2 |
| Sample 9 | 4-14-B | ELECTROLY | TE CONCENTRAT | ION \approx 0.1 N |
| 100.6 | 0.708 | 5.40 x 10-3 | 11.3 x 10-3 | 12.1 |
| 153.5 | 0.505 | 6.19 x 10 ⁻³ | 81 | 12.8 |
| 197.0 | 0.407 | 6.72 x 10^{-3} | 81 | 12.8 |
| Sample 9 | 4-27-A | NATURAL SA | LT CONCENTRAT | CION, S = 900 |
| 51.6 | 1.11 | 1.61×10^{-3} | 3.96×10^{-3} | 27.7 |
| 67.5 | 0.942 | 1.75 x 10^{-3} | . 81 | 26.5 |
| 90.0 | 0.740 | 2.13 x 10 ⁻³ | 81 | 26.9 |
| 105.0 | 0.675 | 2.28 x 10 ⁻³ | 81 | 26.9 |
| Sample 9 | 4-27-B | ELECTROLYI | TE CONCENTRAT | ION \approx 0.1 N |
| 66.3 | | 5.24 x 10^{-3} | 13.4×10^{-3} | 19.3 |
| 89.4 | | 6.19 x 10 ⁻³ | 13.2×10^{-3} | 18.6 |
| 115.4 | | 7.08 x 10 ⁻³ | 12.9×10^{-3} | 18.0 |

TABLE IV

CONDUCTANCE CAPACITY OF A REMOULDED MARINE

CLAY WHERE THE SALT CONTENT OF PORE WATER

INCREASES WITH DEPTH IN THE FIELD

| Sample | Depth, ft | (λ _s R) _{nat,} cm ⁻¹ | (λ _s R) _{0.1N KC1} cm ⁻¹ | Δλ _s R cm ⁻¹ | λ _{s.} * ohm ⁻¹ cm ⁻¹ Bulk cond. of pore water | λ_s ohm ⁻¹ cm ⁻¹ In situ cond. of pore water | Surface area, m ² /gm |
|--------|--------------|--|--|---------------------------------------|--|--|--|
| | | | | | | | |
| 126-1 | 35 | 0.606 | 0.748 | 0.142 | 5.61 $\times 10^{-3}$ | 6.93×10^{-3} | 60 |
| 126-2 | 45 | 0.645 | 0.765 | 0.120 | 8.97 x 10 ⁻³ | 10.63×10^{-3} | 71 |
| 126-3 | 55 | 0.665 | 0.755 | 0.090 | 10.9×10^{-3} | 12.4 $\times 10^{-3}$ | 66 |
| 126-4 | 65 | 0.772 | - | - | 14.57 x 10-3 | - | - |
| | | | | | | | |

* Bulk λ_s of 0.1 N KCl \approx 12.7 x 10⁻³ ohm⁻¹ cm⁻¹

TABLE V

CONDUCTIVE CAPACITY OF REMOULDED SENSITIVE SOILS

FROM VARIOUS LOCATIONS

| | | | | λ _s | λ _s |
|------------------------------------|------------------|------------------------------|-------------------|---|--|
| | $(\lambda_{s}R)$ | $(\lambda_{s}R)$ 0.1N KC1 | Δλ _s R | cm ⁻¹ ohm ⁻¹ Bulk cond. of | cm ⁻¹ ohm ⁻¹ In situ cond |
| Location | cm ⁻¹ | cm^{-1} | cm-l | pore water | of pore water |
| | | | | | |
| Toulnustouc, Que. | 0.389 | 0.895 | 0.506 | 0.6×10^{-3} | 1.42 x 10^{-3} |
| Burnaby, B.C. | 0.402, | 0.476 | 0.074 | 1.87 $\times 10^{-3}$ | 2.21 x 10^{-3} |
| Gloucester, Ont. | | | | | |
| Sample 124-3 | 0. 473 | 0.648 | 0.175 | 2. 25×10^{-3} | 3.09×10^{-3} |
| Sample 124-19 | 0.465 | 0.693 | 0.228 | 1.78 x 10 ⁻³ | 2.65 x 10^{-3} |
| Sewer Plant, Ottawa, Ont. | | | | | |
| Sample 94-13 | 0.570 | 0.795 | 0.225 | 0.78 x 10 ⁻³ | 2.37 x 10^{-3} |
| Sample 94-20 | 0.719 | 0.793 | 0.064 | 3.99×10^{-3} | 4.40 x 10^{-3} |
| Breckenridge, Que. | | | | | |
| Sample 129-7 | 0.369 | 0.591 | 0.122 | 1.02×10^{-3} | 1.63×10^{-3} |
| Sample 129-16 | 0.459 | 0.614 | 0.155 | 2.71 x 10 ⁻³ | 3.63×10^{-3} |
| Interceptor Shaft, Ottawa, Ont. | | | | | |
| Sample 136-2 | 0.421 | 0.641 | 0.220 | 0.99×10^{-3} | 1.51×10^{-3} |

TABLE VI

EFFECT OF REMOULDING CLAYS OF TWO DIFFERENT

SENSITIVITIES WITH ADDITIONS OF SODIUM METAPHOSPHATE;

MOISTURE CONTENT WAS HELD CONSTANT

| · | | | Electro-kinetic potential, mv | | | | | | | |
|---|----------------|--|---|-----------|--|---------------------------------------|--|--|--|--|
| Moisture content, Per cent dry wt. | % Clay | Surface area, m ² /gm | Undisturbed sample, vertical section | Remoulded | Remoulded + 0.25 gm/ 100 gm soil | Remoulded + 0.5 gm/ 100 gm soil | | | | |
| Sample 94-13 (a) | | | | | | | | | | |
| 66.9 | 82 | 72 | 16.2 | - | - | - | | | | |
| 65.6 | 11 | ** | - | 16.6 | - | - | | | | |
| 65.0 | 11 | *1 | - | 84 | 23.9 | - | | | | |
| 65.0 | 11 | \$ 1 | - | - | - | 30.3 | | | | |
| Sample 94 | <u>-20</u> (b) | | | | | | | | | |
| 52 | 72 | 47 | 23, 5 | - | - | - | | | | |
| 52.1 | 11 | 11 | - | 26.2 | - | - | | | | |
| 52.2 | 11 | | - | - | 30.1 | - | | | | |
| 52.5 | 11 | 11 | - | - | - | 36.9 | | | | |

(a) Sensitivity 30, λ_s natural pore water, 0.76 x 10⁻³ ohm⁻¹ cm⁻¹

(b) Sensitivity 575, λ_s natural pore water, 1.19 x 10⁻³ ohm⁻¹ cm⁻¹

TABLE VII

ELECTRO-KINETIC POTENTIALS OF LEACHED UNDISTURBED

SPECIMENS AT NATURAL FIELD MOISTURE CONTENT

| | | | _ | | |
|--|------------|--|---|----------------------------------|------------|
| | M.C., % | λ _s , ohm ⁻¹ cm ⁻¹ , of sample | λ _s , ohm ⁻¹ cm ⁻¹ , pore water | Electro-kinetic potential, mv | S |
| Sample 126-5 | | | | | |
| Before leaching | | 4.98 x 10^{-3} | 15.3×10^{-3} | 15.2 | 34 |
| After 6 day s' leaching | | 0.33 x 10^{-3} | 0.46 $\times 10^{-3}$ (leachate) | 22.1 | |
| Sample 126-4-1 | 66.5 | | | | |
| Before leaching | | 4.19 x 10 ⁻³ | 14.6 x 10^{-3} | 16.9 | 45 |
| After leaching | | 0.29×10^{-3} | - | 22.8 | |
| Sample 126-4-2 | | | | | |
| Before leaching | | 4.50 x 10 ⁻³ | 14.6 x 10^{-3} | 16.8 | 4 5 |
| After leaching | | 0.34×10^{-3} | - | 21.6 | |
| Sample 126-4-1 | | | | | |
| Salts leached out followed by leaching with sodium meta- phosphate solution | | 0.65×10^{-3} | 1.25 \times 10 ⁻³ (leachate) | 26.2 | |
| After further leaching with distilled water | | 0.56 x 10 ⁻³ | 0.82×10^{-3} (leachate) | 30.0 | |

TABLE VIII

ELECTRO-KINETIC POTENTIALS FOR SOILS LISTED

IN ORDER OF SENSITIVITY

| • | | | | | | | | | |
|----------|--------------|------|--------------------------------|----------------------------------|-------|------------|------------|------------------------------|---|
| Sample | Depth, ft | P.I. | Natural E _k , mv | Remoulded E _k , mv | S | M.C., % | Clay, % | Area, m ² /gm_ | $\lambda_s \times 10^3$, pore water conductivity |
| | | | | | | | | | |
| 136-2 | 32 | 44 | 12.6 | 16.4 | 11 | 75.3 | 85 | 77.8 | 1 |
| 94-13-3 | 22 | -38 | 16.2 | 16.9 | 30 | 66.9 | 82 | 72 | 1.07 |
| 124-19-5 | 60 | 17 | 20.2 | 20.8 | 33 | 62.9 | 77 | 62 | 1.78 |
| 126-5-4 | 75 | 45 | 16.1 | 19.2 | 34 | 62.4 | 85 | 72 | 15.4 |
| 126-4-4 | 65 | 45 | 16.4 | 19.2 | 45 | 65.3 | 89 | - | 14.6 |
| 126-1-4 | 35 | 44 | 19.3 | 22.3 | 53 | 66.1 | 78 | 60 | 5.61 |
| 126-3-4 | 55 | 40 | 17.4 | 20.6 | 60 | 63.9 | 79 | 66 | 11.4 |
| 126-2-4 | 45 | 46 | 21.0 | 23.7 | 74 | 63.8 | 78 | 60 | 8.97 |
| 129-16-4 | 57 | | 22.2 | 25.2 | 118 | 80.1 | 85 | 85 | 2.71 |
| 124-3-5 | 12 | 28 | 24.9 | 26.9 | 126 | 86.6 | 71 | 79 | 2.25 |
| 129-7-5 | 30 | | 19.9 | 24.5 | 183 | 89.7 | 79 | 76 | 1.02 |
| 124-12-5 | 39 | 27 | 28.8 | 28.7 | 453 | 83.5 | 76 | 79 | 2.19 |
| 94-20-5 | 53 | 7 | 23.5 | 26.2 | 575 | 52.5 | 72 | 47 | 2.94 |
| 124-9-6 | 30 | 24 | 29.7 | 29.7 | 600 | 94.0 | 86 | 80 | 2.33 |
| 94-27-1 | 72 | 15 | 21.4 | 24.3 | 900 | 50.6 | 67 | 54 | 3.54 |
| 123-2-3 | | 5 | 33.8 | 32.8 | 1000+ | 41.0 | 54 | 29 | 0.6 |

TABLE IX

Resume of specific conductance vs. salt concentration *

| | Specific | Salt co | ontent, gm/ | /1 | Batio | |
|------------------|--|----------|-------------|--------|----------------------------------|--|
| Sample | $\lambda_{\rm s}$, ohm ⁻¹ cm ⁻¹ | Sample 1 | Sample 2 | Ave. | $\lambda_{\rm s}/{\rm wt.}$ (gm) | |
| Gloucester, Ont. | | | | | | |
| 124-7-10 | 2.35 x 10^{-3} | 1.508 | 1.516 | 1.512 | 1.55×10^{-3} | |
| 124-11-10 | 2.09 x 10^{-3} | 1.508 | 1.524 | 1.516 | 1.39×10^{-3} | |
| 124-16-6 | 1.93×10^{-3} | 1.276 | 1.268 | 1.272 | 1.51×10^{-3} | |
| 124-18-10 | 2. 43 x 10^{-3} | 1.650 | 1.605 | 1.627 | 1.49 x 10 ⁻³ | |
| Breckenridge, Qu | 1e. | | | | | |
| 129-2 | 0.61×10^{-3} | 0.350 | 0.350 | 0.350 | 1.75×10^{-3} | |
| 129-6 | 1.04×10^{-3} | 0.580 | 0.5930 | 0.587 | 1.77×10^{-3} | |
| 129-10-7 | 1.69×10^{-3} | 1.112 | 1.184 | 1.148 | 1.48 x 10 ⁻³ | |
| 129-18-1 | 4.17 $\times 10^{-3}$ | 2.605 | 2.630 | 2.618 | 1.59×10^{-3} | |
| Sewer Plant, Ott | awa, Ont. | | | | | |
| 94-14 | 2.17 x 10^{-3} | 1.7920 | 1.756 | 1.774 | 1.22×10^{-3} | |
| 94-29 | 3.89 x 10^{-3} | 3.120 | 3.185 | 3.153 | 1.24×10^{-3} | |
| Queensway Overr | pass, Ottawa, Ont. | | | | | |
| 132-1-6 | 8.19 x 10^{-3} | 4.904 | 4.890 | 4.895 | 1.68×10^{-3} | |
| 132-3-5 | 13.84×10^{-3} | 8.650 | 8.630 | 8.640 | 1.60×10^{-3} | |
| 132-5-8 | 17.68 x 10^{-3} | 11.720 | 11.710 | 11.715 | 1.51×10^{-3} | |

* Measured by evaporating pore water at 105°F.

TABLE X

PORE-WATER COMPOSITION, MG/L; SOILS ARE ARRANGED

| | | | | | | | _ | | | | |
|------------------|------------------|-----------------|------------------|------|-------------|-----------------|-------------|--------------|----------------------------|-------|-----------------------|
| Sample | Ca ⁺⁺ | Na ⁺ | Mg ⁺⁺ | к+ | so4= | C1 ⁻ | A* Total | B** Total | $\lambda_{s} \cdot 10^{3}$ | S | *** E _k |
| 136-2 | - | - | - | - | _ | - | _ | _ | 1 | 11 | 12.6 |
| 94-13-3 | 62.0 | 201 | 64.0 | 32.6 | 293 | 3.5 | 656.1 | 1140 | 1.07 | 30 | 16.2 |
| 124-19-5 | 20.8 | 305 | 12.0 | 17.4 | 119 | 396 | 870.2 | 1200 | 1.78 | 33 | 20.2 |
| 126-5-4 | 86 | 3370 | 178 | 124 | 567 | 4997 | 9322 | 9600 | 15.4 | 34 | 16.1 |
| 126-4-4 | 74 | 2910 | 132 | 111 | 441 | 4317 | 7985 | 9100 | 14.6 | 45 | 16.4 |
| 126-1-4 | 36 | 1250 | 46.8 | 56.6 | 132 | 1682 | 3203.4 | 3500 | 5,61 | 53 | 19.3 |
| 126-3-4 | 62 | 2220 | 92 | 85.4 | 2 86 | 3167 | 5922.4 | 7100 | 11.4 | 60 | 17.4 |
| 126-2-4 | 43 | 1653 | 59 | 71 | 1'76 | 2214 | 4216 | 5600 | 8.97 | 74 | 21.0 |
| 129-16-4 | - | - | - | - | - | - | - | - | 2.71 | 118 | 22.2 |
| 124-3-5 | 12.0 | 420 | 10.5 | 18.8 | 7.3 | 445 | 913.6 | 1500 | 2.25 | 126 | 24.9 |
| 129-7-5 | 6.7 | 209 | 6.3 | 15.3 | 10.9 | 35.5 | 283.7 | 570 | 1.02 | 183 | 19.9 |
| 124-12-5 | 8.3 | 405 | 6.3 | 21.6 | 52.1 | 482 | 975.3 | 1450 | 2.19 | 453 | 28.8 |
| 94-20-5 | 17.6 | 851 | 27.5 | 54.1 | 687 | 7.1 | 1644.3 | 2400 | 2.94 | 575 | 23.5 |
| 124-9-6 | 8.8 | 419 | 7.8 | 27.6 | 131.1 | 507 | 1101.3 | 1550 | 2.33 | 600 | 29.7 |
| 94-27-1 | 14.4 | 851 | 21.0 | 47.6 | 424 | 10.6 | 1368.6 | 2900 | 3.54 | 900 | 21.4 |
| 123 - 2-3 | 2.4 | 131 | 0.3 | 7.4 | 58.7 | 7.1 | 206.9 | 400 | 0.6 | 1000+ | 33.8 |
| 94-14 | 36.0 | 224 | 108 | 46.5 | 287 | 7.1 | 708.6 | | | 30 | |
| 130-1 | 32.0 | 295 | 0.3 | 61.4 | 796 | - | 1184.6 | | | 55+ | |
| - | | | | | | | | | | | |

IN ORDER OF INCREASING SENSITIVITY

Sea Water 400.0 10556 1272 380 2649 18980 34482 (Rosenqvist)

* A Total is the summation of the six constituents.

- ** B Total is the approximate total weight of solids based on conductivity measurements.
- *** Ek is the electro-kinetic potential.

TABLE XI

CATION CONTENT OF PORE WATER IN MILLI-EQUIVALENTS/LITRE

AND PER CENT AT VARIOUS DEPTHS

| | | | | | | | | | | Total | | | | | Natural |
|---------------------------|-----------|------------|------|--------|--------------|-----------------|------|--------|------|----------|--------|----------------------------|---------------------|-----------------|---------------------|
| | Depth, | Ca^+ | ++ | Na | + | Mg ⁺ | + | K+ | | Cations, | | <u>1/2 Mg⁺⁺</u> | Remoulded | <u>K+</u> | Undisturbed |
| Sample | ft | mqts*/l | % | mqts/1 | % | mqts/l | % | mqts/l | % | mqts/l | S | Na ⁺ | E _k , mv | Na ⁺ | E _k , mv |
| Queensway | Overpass | , Ottawa, | Ont. | | | | | | | | | | | | |
| 126-1-4 | 35 | 1.8 | 2.9 | 54.3 | 88.6 | 3.8 | 6.2 | 1.4 | 2.3 | 61.3 | 53 | . 07 | 22.3 | 0.026 | 19.3 |
| 126-2-4 | 45 | 2.2 | 2.7 | 72.0 | 89.0 | 4.9 | 6.1 | 1.8 | 2.2 | 80.9 | 74 | . 07 | 23.7 | 0.025 | 21.0 |
| 126-3-4 | 55 | 3.1 | 2.8 | 96.5 | 88.0 | 7.5 | 6.9 | 2.2 | 2.7 | 109.8 | 60 | .08 | 20.6 | 0.022 | 17,4 |
| 126-4-4 | 65 | 3.7 | 2.6 | 126.5 | 88.0 | 10.9 | 7.6 | 2.8 | 1.95 | 143.9 | 34 | . 09 | 19.2 | 0.022 | 16.4 |
| 126-5-4 | 75 | 4.3 | 2.6 | 146.5 | 86.9 | 14.6 | 8.7 | 3.2 | 1.9 | 168.6 | 33 | .10 | 19.2 | 0.022 | 16.1 |
| Gloucester, | Ont. | | | | | | | | | | | | | | |
| 124-3-5 | 12 | 0.6 | 2.9 | 18.3 | 90.0 | 0.9 | 4.4 | 0.5 | 2.5 | 20.3 | 126 | 0.050 | 26.9 | 0.027 | 24.9 |
| 124-9-6 | 30 | 0.4 | 2.0 | 18.3 | 91.5 | 0.6 | 3.0 | 0.7 | 3.5 | 20.0 | 600 | 0.037 | 29.7 | 0.039 | 29.7 |
| 124-12-5 | 39 | 0.4 | 2.1 | 17.7 | 91.6 | 0.6 | 3.1 | 0.6 | 3.1 | 19.3 | 453 | 0.031 | 28.7 | 0.031 | 28.8 |
| 124-19-5 | 60 | 1.0 | 6.3 | 13.3 | 84.2 | 1.0 | 6.3 | 0.5 | 3.2 | 15.8 | 33 | 0.079 | 20.8 | 0.033 | 20,2 |
| Breckenridg | ge, Que. | | | | | | | | | | | | | | |
| 129-7-5 | 30 | 0.3 | 2.9 | 9.1 | 88.4 | 0.5 | 4.9 | 0.4 | 3.9 | 10.3 | 183 | 0.06 | 24.5 | 0.043 | 19.9 |
| 129-16-4 | 57 | | | | | | | | | | 118 | | 25.2 | | 22.2 |
| Sewer Plant | , Ottawa, | Ont. | | | | | | | | | | | | | |
| 94-13 | 22 | 3.1 | 17.3 | 8.7 | 4 8.6 | 5,3 | 29.6 | 0.8 | 4.5 | 17.9 | 30 | 0.64 | 16.9 | 0.09 | 16.2 |
| 94-14 | 22 | 1.8 | 8.4 | 9.7 | 45.5 | 8.6 | 40.4 | 1.2 | 5.6 | 21.3 | - | 0.88 | | 0.12 | |
| 94-20 | 53 | 0.9 | 2.2 | 37.0 | 89.0 | 2.3 | 5.5 | 1.4 | 3.4 | 41.6 | 575 | 0.065 | 26.2 | 0,038 | 23, 5 |
| 94-27 | 72 | 0.7 | 1.7 | 37.0 | 91.0 | 1.7 | 4. 2 | 1.2 | 2.9 | 40.6 | 900 | 0.049 | 24.3 | 0.033 | 21,4 |
| Toulnustouc | , Que. | | | | | | | | | | | | | | |
| 123-2 | - | 0.1 | 1.7 | 5.7 | 95.0 | . 025 | | 0.2 | 3.4 | 6.0 | 1000++ | 0,005 | 32.8 | 0.033 | 33.8 |
| Interceptor | Shaft, Ot | tawa, Ont. | | · | | | | | | | | | | | |
| 136-2 | 32 | | | | | | | | | | 11 | | | | |
| Burnaby, B. | .C. | | | | | | | | | | | | | | |
| 130-1 | 38 | 1.6 | 10.0 | 12.8 | 79.6 | 0.02 | 0.1 | 1.6 | 10 | 16.02 | 55+ | 0.005 | 16.4 | 0.123 | 12.6 |
| Sea Water (Rosenqvist) |) | 20 | 3.4 | 460 | 77 | 106 | 17.8 | 10 | 1.7 | 596 | | 0.23 | | 0.022 | |

* milli-equivalents

TABLE XII

SULPHATE -CHLORIDE RATIOS AT VARIOUS LOCATIONS

| | | | <u> </u> | | |
|-----------------------------------|--------------|----------------------------|----------------|---------------------------|-------------------|
| Sample | Depth, ft | SO ₄ = mgm/l | C1- mgm/1 | Ratio $C1^{-}/SO_{4}^{=}$ | % C1 ⁻ |
| Queensway O | verpass, O | ttawa, Ont. | | | |
| 126-1-4 | 35 | 132 | 1682 | 12.8 | 93.0 |
| 126-2-4 | 45 | 176 | 2214 | 12.5 | 93.0 |
| 126-3-4 | 55 | 286 | 3167 | 11.0 | 92.0 |
| 126-4-4 | 65 | 441 | 4317 | 9 . 8 | 90.0 |
| 126-5-4 | 75 | 567 | 4997 | 8.8 | 89.0 |
| Gloucester, C | Ont. | | | | |
| 124-3-5 | 12 | 7.3 | 445 | 61 ?? | |
| 124-9-6 | 30 | 131.1 | 507 | 3.9 | 80 |
| 124-12-5 | 39 | 115.1 | 433 | 3.8 | 79 |
| 124-19-5 | 60 | 119 | 396 | 3.3 | 77 |
| Breckenridge | Que. | | | | |
| 129-7-5 | 30 | 10.9 | 35.5 | 3.2 | 76 |
| 129-16-4 | 57 | | | | |
| Toulnustouc, | Que. | | | | |
| 123-2-3 | | 58.7 | 7.1 | 0.12 | 11 |
| Sewer Plant, | Ottawa, Or | ıt. | | | |
| 94-13 | 22 | 293 | 3.5 | 0.012 | 1.2 |
| 94-14 | 22 ± | 287 | 7.1 | 0.025 | 2.4 |
| 94-20 | 53 | 687 | 7.1 | 0.01 | 1.0 |
| 94-27 | 72 | 424 | 10.6 | 0.025 | 2.4 |
| S ea Water (Rosenqvist) | - | 2649 | 1 898 0 | 7.15 | |

TABLE XIII

FLOCCULATION CHARACTERISTICS FOR TWO SOILS OF DIFFERENT SENSITIVITY

SAMPLE 94-29, SENSITIVITY 600

| | | (| Grams/litr | e NaClon | ly | | | | | | | |
|---|--------------------------------|-------------|---|--|--|--|---|--|---|--|--|--|
| | 0.01 | 0.02 | 0.04 | 0.08 | 0.16 | 0.32 | 0,64 | 1.28 | 2.56 | 5.12 | | |
| 20 min | _ | _ | - | - | | | - | _ | slight | medium | | |
| 30 min | 1 - 1 | 1 _ 1 | - | - | - | - ! | _ | - | medium | high | | |
| 60 min | _ | - | - | _ | - 1 | - ! | - 1 | - | medium | high | | |
| 16 hr | - | - | - | | | | | medium | complete | complete | | |
| | Grams/litre of sea water* salt | | | | | | | | | | | |
| 10 min | - | - | - | - | - | - | - | - | slight | slight | | |
| 20 min | - | _ | - | - | - | _ | - | medium | high | high | | |
| 60 min | - | - 1 | - | - | | - | medium | high | high | high | | |
| 16 hr | | | - 1 | | - 1 | medium | high | complete | complete | complete | | |
| | | | Grams/litr | e NaClon | ly | , | | · | · | | | |
| 10 min | - 1 | 1 | 1 | | · · · · · · · · · · · · · · · · · · · | (I | 1 | | 1 | | | |
| | • | 1 - i | - | - | 1 - 1 | - | - | • · | - | slight | | |
| 20 min | - | - | - | - | - | - | - | - | - slight | slight high | | |
| 20 min 60 min | - | | - - - | | - - - | | - | - - slight | - slight high | slight high high | | |
| 20 min 60 min 120 min | - - - | - - - | - - - | - - - | - - - - | | - - slight | - slight high | - slight high high | slight high high high | | |
| 20 min 60 min 120 min 16 hr | - - - - | | - - - - | - - - - | - - - - - | | - - slight high | - slight high complete | - slight high high complete | slight high high high complete | | |
| 20 min 60 min 120 min 16 hr | - - - | | - - - Grams/litr | - - - - e of sea wa | - - - - - ter* salt | - - - - | - slight high | - slight high complete | - slight high high complete | slight high high high complete | | |
| 20 min 60 min 120 min 16 hr 5 min | - - - - | | - - - Grams/litr | - - - - e of sea wa | - - - - ter* salt | - | - slight high | - slight high complete | - slight high complete slight | slight high high complete slight | | |
| 20 min 60 min 120 min 16 hr 5 min 10 min | - - - - - | | - - - - - - - - - - - - | - - - - - e of sea wa - - | - - - - ter* salt | - - - - - | - slight high - - | - slight high complete - slight | - slight high complete slight medium | slight high high complete slight medium | | |
| 20 min 60 min 120 min 16 hr 5 min 10 min 20 min | | | - - - Grams/litr - - - | - - - - - e of sea wa - - - | - - - - ter* salt | - - - - - - - - - - - - | - slight high - slight | - slight high complete - slight medium | - slight high complete slight medium high | slight high high complete slight medium high | | |
| 20 min 60 min 120 min 16 hr 5 min 10 min 20 min 60 min | - - - - - | | - - - Grams/litr - - - - | - - - - - e of sea wa - - - - | - - - - - - ter* salt | - - - - - - - - - - | - slight high - slight high | - slight high complete - slight medium high | - slight high complete slight medium high high | slight high high complete slight medium high high | | |
| 20 min 60 min 120 min 16 hr 5 min 10 min 20 min 60 min 120 min | | | - - - - - - - - - - - - - - - - - - - | - - - - - e of sea wa - - - - - - - - | - - - - - - ter* salt | - - - - - slight medium | - slight high - slight high high | - slight high complete - slight medium high high | - slight high complete slight medium high high high | slight high high complete slight medium high high high | | |
| 20 min 60 min 120 min 16 hr 5 min 10 min 20 min 60 min 120 min 16 hr | | - (| - - - - - - - - - - - - - - - - - - - | - - - - - e of sea wa - - - - - - - - - - - - - - | - - - - ter* salt - - - - - - - - - - - - - - - - - - - | - - - - - slight medium high | - slight high - - slight high high high | - slight high complete - slight medium high high complete | - slight high complete slight medium high high high complete | slight high high complete slight medium high high high complete | | |

* the various salts were mixed in the approximate ratio that exists in sea water to simulate marine conditions.



THE ELECTROKINETIC POTENTIAL EK AND THE ELECTRICAL DOUBLE LAYER

BR 3113.1



Figure 2 Assembled electro-osmosis apparatus
(1) etched mirror scale



Figure 3 Main components of the electro-osmosis apparatus (2) inner electrode; (3) outer electrode;

(4) calibrated capillary tube; (5) solution compartment; (6) sample holder; (7) filling tube.



Figure 4 Pressing undisturbed soil sample into sample holder



Figure 5 Pore-water extraction apparatus



LOCATION OF SAMPLING SITES IN THE OTTAWA-HULL AREA



CONDUCTANCE CAPACITY OF REMOULDED CLAY GEL AT DIFFERENT ELECTROLYTE CONCENTRATIONS



HORIZONTAL, VERTICAL AND REMOULDED CONDUCTIVITIES OF NATURAL CLAY SOILS FROM THE OTTAWA HULL AREA



BR 3113-4



Sample Holder

Figure 10 Apparatus used for leaching undisturbed specimens of clay



FIGURE 11

SALT CONCENTRATION OF THE PORE WATER IN TERMS OF SPECIFIC CONDUCTIVITY, AS A FUNCTION OF SENSITIVITY



FIGURE 12 ELECTROKINETIC POTENTIALS OF UNDISTURBED LEDA CLAY AS A FUNCTION OF SENSITIVITY

13A 3170



FIGURE 13 ACTIVITY CHART OF SOILS STUDIED

BR 3113-8



Figure 14 Effect of NaCl concentration on flocculation after 64 hr