

The Application of Electroosmosis in Clay Improvement

A Laboratory Investigation of Electrokinetics Use on Clay

Master's thesis in Infrastructure and Environmental Engineering

Khaled Alaydi

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Department of Civil and Environmental Engineering
Division of GeoEngineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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Cover: Induced water and ions flow after the application of electric current in clay.

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Abstract

Electroosmosis is one of the processes that occurs when an electric current is applied through saturated fine grained soil. The process can be used for different purposes. A modification has been made to permeameter for applying electroosmosis. By adding graphite electrodes to the inlet and outlet of the cells, it was possible to conduct electric current through the sample. The carried out tests were permeability tests, followed by electroosmotic treatment of the samples without applying any axial loading. Backpressure and cell pressures were used throughout the experiment.

Two cells having the same samples were used. In the tests before the application of a current, the permeability was in the range of sensitive clay, almost quick, which is the type of samples provided. The electrical resistance of the soft clay proved to be too large for the used current source. Therefore, saline water was used instead of fresh water to reduce resistance. The first cell was connected to 13V power supply (i.e non-constant current) and provided with saline water while the second cell was only provided with saline water without any electric current.

The results were confirmed to the expectations, where the electric current increased the flow in the first cell and resistance were reduced in both cells due to the addition of saline water. Electroosmosis contributed to almost 90% of the volume discharge in the first cell. Some challenges reduced the efficiency of the experiment such as gasses production, leakage, and loss of electric current in the system.

Important recommendations from the experiment such as the importance of using a non-conducting fluid, oil for example, as a surrounding liquid for detection of any leakage and eliminating the possibility of current loss. Graphite electrodes performed well, but gasses production should be treated in early stages and further investigations on the effect of alternating polarity in reducing the process need to be explored.

Keywords: Electroosmosis, permeability, clay, laboratory investigation, resistance, flow, electric current.

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Contents

List of Figures	xi
List of Tables	xi
List of Symbols and Abbreviations	xiv
1 Introduction	1
1.1 Overview	1
1.2 Goals and methods	2
2 Theory	3
2.1 Clay chemistry	3
2.1.1 Exchangeable cations	3
2.1.2 Diffuse double layer	4
2.1.3 Adhesion forces and interaction	5
2.2 Quick clay	6
2.3 Electrokinetic applications in Soil	7
2.3.1 Electroosmosis	8
2.3.2 Electromigration	10
2.4 Governing parameters	11
2.4.1 Zeta potential, ζ	11
2.4.2 Permeability coefficient of electroosmotic flow, K_e	12
2.5 Electroosmosis side effects	13
2.5.1 Electrolysis of water	13
2.5.2 Reactions at electrodes	14
2.5.3 pH change	14
3 Previous Investigations and Applications	15
3.1 Previous investigations	15
3.2 Field implementation	18
4 Test Design	19
4.1 Equipment	19
4.1.1 Permeability equipments	19
4.1.2 Electric equipments	20
4.2 Samples	22
4.3 Procedure	23

4.3.1	Experiment execution	23
5	Results	27
5.1	Permeability measurements	27
5.2	Electroosmotic permeability	29
5.3	Resistance measurements	31
5.4	Current measurements	31
6	Conclusion	34
6.1	Summary	34
6.2	Challenges and recommendations	34
6.3	Further investigations	35
	Bibliography	36
A	Appendix	I
B	Appendix	II
C	Appendix	III

List of Figures

1.1	North east of Montreal landslide (Carpenter, 2010)	1
2.1	Clay particles arrangement (Van Olphen et al., 1977))	4
2.2	Ion concentration and the distance from the particle surface (Yeung, 1994)	5
2.3	Proximity of diffuse double layer and electrokinetic potential (Rankka, 2004)	5
2.4	Principles of quick clay formation (Brand & Brenner, 1981)	7
2.5	Elektrokinetic induced flow in soil	8
2.6	Clay surface and water interface (Jones et al., 2011)	12
2.7	(a) Electrode processes during electroosmosis,(b) pH distribution,(c) ζ potential (d) intraporous pressures	14
3.1	Morris et al test equipment, 1985	16
3.2	Micic et al test equipment, 2001	17
3.3	Jeyakanthan et al, 2011	17
3.4	Field investigation, Burnotte	18
4.1	Flexible wall permeameters diagram	20
4.2	Cell A with water	20
4.3	Cell B with oil	20
4.4	Electrodes position	21
4.5	Output module	22
4.6	Input module	22
4.7	Experiment procedure	24
4.8	New procedure	25
5.1	(a) Coefficient of permeability in cell A, (b) Coefficient of permeability in cell B	28
5.2	(a) Electroosmotic coefficient of permeability, with saline water, in cell A (b) coefficient of permeability, with saline water, in cell B . . .	30
5.3	Current measurements for cell A	32
5.4	Final resistance for cell A	33

List of Tables

2.1	Classification of clay based on sensitivity (Rankka, 2004)	6
2.2	Coefficients of electroosmotic permeability	13
4.1	Soil properties	23
5.1	Test information	27
5.2	Measured coefficient of permeability	29
5.3	Average daily flow	29
5.4	Measured resistance for cell B	31

List of Symbols and Abbreviations

Symbols

Notation	Unit	Description
Δ	-	Difference
ε_o	$m^{-3}kg^{-1}s^4A^2$	Dielectric constant
ζ	mV	Zeta potential
η	-	Viscosity of pore fluid
μ_{eff}	$m^2/V.s$	Effective mobility of ion
σ	kPa	Stress
σ_s	N/m	Surface tension of water
A	m^2	Cross-sectional area
C	mol/l	Ionic concentration
C_m	g/l	Mass concentration
D	F/m	Permittivity of soil
I	A	Electric current
i_e	V/m	Electrical gradient
J_m	$mol/m^2.s$	Ion migration flux
k^*	m/s	Coefficient of permeability
K_e	$m^2/s.V$	Electroosmotic coefficient of permeability
q	m^3/s	Flow rate
R	J/K.mol	Universal gas constant (8.314J/K.mol)
T	K	Absolute temperature
Z	-	Charge number

* Coefficient of permeability, also known as hydraulic conductivity which is dependent on the soil parameters with m/s as a unit. Usually it is mixed with the absolute permeability, K, which is dependant on the liquid as well and a unit of m^2 .

Abbreviations

Acronym	Description
CEC	Cation exchange capacity
DC	Direct current
f_{vdW}	Van der Waals forces
f_{es}	Electrostatic forces
f_{lb}	Capillary forces
FWP	Flexible wall permeameters
pH	Potential of hydrogen

Chemical elements

Symbol	Elements
+	Positive valency (Cation)
-	Negative valency (Anion)
Cl	Chlorine
Ca	Calcium
H ₂ O	Water molecule
K	Potassium
KCl	Calcium chloride
M _e	Metal electrode
Mg	Magnesium
Na	Sodium
NaCl	Sodium chloride

1

Introduction

In this chapter, an overview of the importance of investigating the use of electrokinetics in improving sensitive clay will be discussed. In addition, the aims of the research and the methodology are presented.

1.1 Overview

Sensitive clays are linked to risks in geotechnical field especially in slope stability related problems. The presence of sensitive clays, such as quick clays, might be the main reason of enormous landslides and slope failures. Almost all slopes failures in Sweden, Norway and Canada were caused by quick clays (Rankka et al., 2004). An example is the famous Rissa landslide, where seven farms and five homes were taken by the slide and one person was killed (Gregersen, 1981).

In addition, sensitive clays present many difficulties in different design problems such as designing of walls, foundations and other underground structures. For these reasons, many methods had been discovered to map, detect, and improve sensitive clays.



Figure 1.1: North east of Montreal landslide (Carpenter, 2010)

This project will test the validity of electroosmosis and its applications on clay. Electroosmosis could be used in many geotechnical problems such as dewatering,

remediation and improvement of clays. The solution requires the use of electricity but without the need of chemicals, which is considered as an environmental solution but not necessary the most economic.

1.2 Goals and methods

The main aim of the thesis is to test the effect of electroosmosis on the hydraulic conductivity of clay. Focusing on the following details:

1. The effect of the gradual increase of the applied current on the coefficient of permeability
2. The effect of sudden increase of electric current on the coefficient of permeability of the sample
3. The endurance of the new coefficient of permeability after the removal of the induced current

The work on the project was divided into two main parts.

1. The theory part which has to do with reviewing literature to have an understanding of the clay chemistry, interactions and forces, and electokinetics properties.
2. Experimental program, which aims to apply the reviewed theories and to test different alternatives in applying electroosmosis.

2

Theory

For promoting the use of Electrokinetics in quick clay improvement, and selecting the most applicable experimental methods to apply it, a summary of the available literature on the topic is presented. In this chapter quick clay chemistry, adhesion forces, the history of Electrokinetics and its applications will be given based on theories and articles review.

2.1 Clay chemistry

Clay, fine or cohesive soils, has three main minerals groups which are: Kaolinite, Illite, and Montmorillonite. Minerals of clay are mainly made of phyllosilicates (silicates and oxygen) layers which are tetrahedral and octahedral layers condensed in a ratio of 1:1 or 2:1 (Jones et al., 2011). Clay surface properties depend on several factors such as the chemical composition, layer charge and the type of exchangeable cations. The composite of different layers leads to the particle state which in its turn coagulate to form aggregates. Clays are also considered to be hydroxides of silicon, aluminum or magnesium due to the presence of oxygen in higher share than the other elements.

The majority of clay minerals have negatively charged sheets, with the exception of LDH (layered double hydroxides), positively charged minerals and neutral talc and pyrophyllite. The negatively charged surface of clay requires a positively charged ions, exchangeable cations, which is found in the fluid zone surrounding the clay particle forming the diffuse double layer (Remediation Engineering of contaminated Soils, p.96). Because of its negatively charged surfaces, clay tends to develop cation exchange capacity (CEC) which differ between different types of clay compositions. CEC is measured in milliequivalents per 100 grams of soil (meq/100g), where a meq represents the number of ions (Fundamentals of Soil Cation Exchange Capacity (CEC), David B. Mengel).

2.1.1 Exchangeable cations

Exchangeable cations such as Na^+ , K^+ , Ca^{2+} and Mg^{2+} , are attracted by the negative charged surface of the interlayer in Clay particles (Formation and Properties of Clay-Polymer Complexes, The Clay Minerals). Cations will also attracts and traps water molecules in the interlayer depending on the type of the cation whether it is a hydrated or non-hydrated one. Different cations have different effect when they added. The addition of cation of double charge such as Ca^{2+} or Mg^{2+} act as

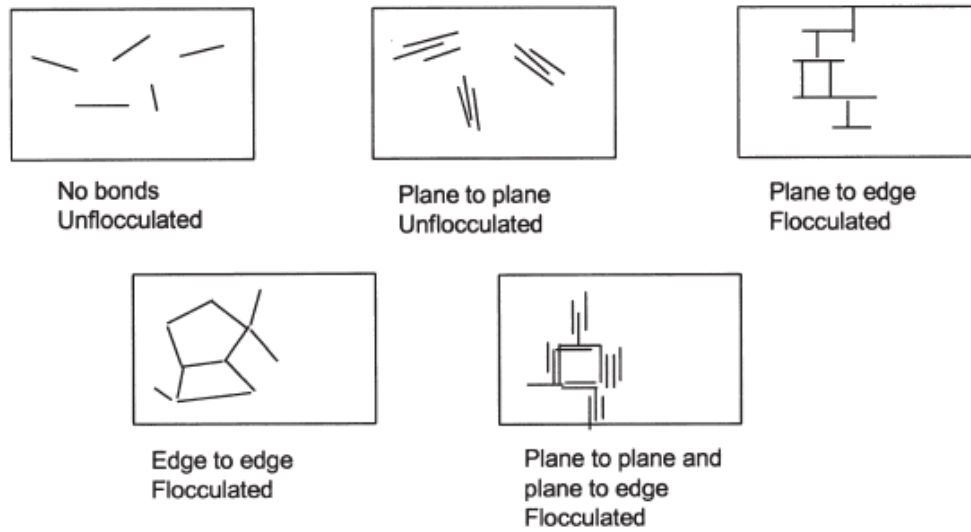


Figure 2.1: Clay particles arrangement (Van Olphen et al., 1977))

a better flocculators than other cations. For instance Ca^{2+} and Mg^{2+} have relative flocculating power of 43 and 27 respectively (Sumner & Naidu, 1998). Consequently, flocculated clay particles will dewater faster, letting consolidation to occur faster. In addition, flocculated soil has higher strength than dispersed soil with the same empty space ratio (Lambe & Whitman, 1979). Particles can be assembled in different arrangements. Figure 2.1 shows the arrangements from dispersed to flocculated.

2.1.2 Diffuse double layer

Being negatively charged, clay particles tend to attract cations towards their surface (Soga & Mitchell, 2005). Free ions found on the pore water, such as the exchangeable cations, will get closer to the surface of the clay particles and therefore the concentrations of cations will be higher close to the surface, see Figure 2.2.

Cations attracted to the surface of the particle will form a layer which is the diffuse double layer. The distance between the diffuse layer and the particles is dependant on many factors but most important is the concentration of the ions attracted and their surface charge (Fällman et al, 2001). In case of high concentrations of ions, the spread of the diffuse layer will be smaller. The diffuse layer proximity to the surface represents the electrokinetic potential of the system, Figure 2.3 (Rankka et al., 2004).

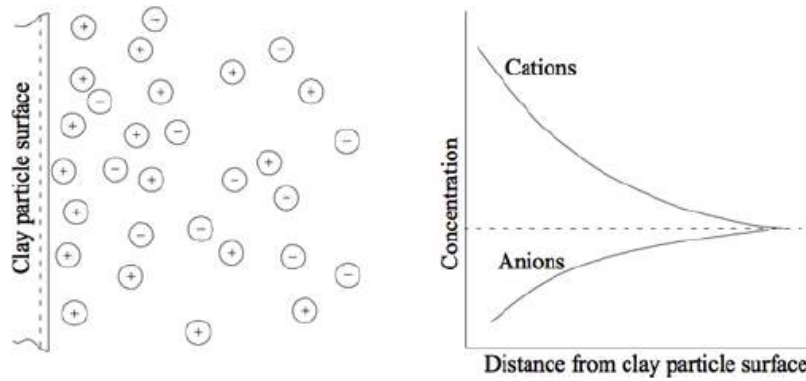


Figure 2.2: Ion concentration and the distance from the particle surface (Yeung, 1994)

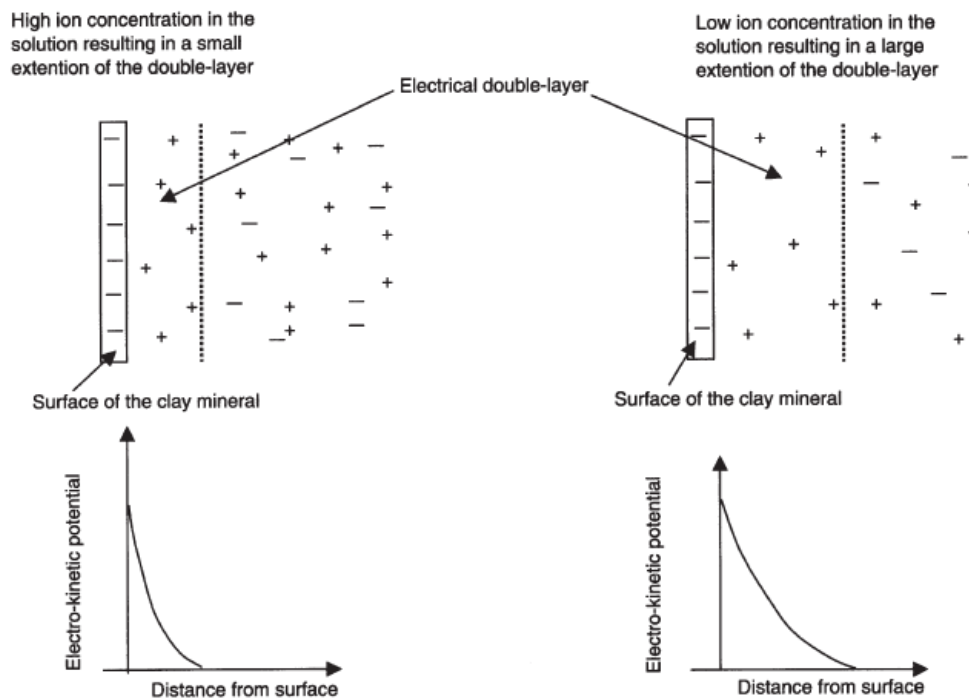


Figure 2.3: Proximity of diffuse double layer and electrokinetic potential (Rankka, 2004)

2.1.3 Adhesion forces and interaction

Since clay particles are charged molecules, many forces are active between two particles (Santamarina, 2003). These forces are including but not limited to the following:

1. Van der Waals forces, which are forces of attraction between two masses. Can

be calculated using the following equation:

$$f_{vdW} = -\frac{AR}{12h^2} \quad (2.1)$$

A: Hamaker constant (for mica with air, $10 \times 10^{20} J$)

2. Electrostatic forces, which are repulsive forces developed in the diffuse layer of two particles:

$$f_{ES} = -\frac{Q^2}{16\pi\epsilon_o R^2} \left(1 - \frac{h}{\sqrt{R^2 + h^2}}\right) \quad (2.2)$$

Q: particle surface charge, ϵ_o : dielectric constant ($8.85 \times 10^{-12} m^{-3} kg^{-1} s^4 A^2$)

3. Capillary forces (Liquid Bridge), which is caused by the presence of water in the pores between two clay particles. Estimated using the following:

$$f_{LB} = -\left(1 - \sqrt[4]{\frac{v}{8\pi R^3}}\right) 2\pi R \sigma_s \quad (2.3)$$

v : liquid bridge volume, σ_s : surface tension of water (0.074 N/m)

Van der Waals forces, representing the forces of attraction, dominate in close particles with small separation between their surfaces, and they have low sensitivity to the electrolytes concentrations. On the contrary, electrostatic forces are repulsive forces which are dominant where the separation between the surfaces is wide and that show high sensitivity to the concentration of the electrolytes available (Ghosh, n.d.). The combination of the electrostatic and Van der Waals forces gives the basis of the DLVO theory (Deyaguin-Landau-Verwey-Overbeek), which deals with the stability of colloids.

2.2 Quick clay

Quick clay is referred to clay with structure that collapses completely when being remoulded where the shear strength is thus reduced zero. In some countries such as Sweden, clay is considered to be quick clay when it has a sensitivity of 50 or more. Sensitivity is defined as the relation of of the undisturbed undrained shear strength to the remoulded one (Rankka et al., 2004). Table 2.1 shows the classification of Clay based on sensitivity.

Table 2.1: Classification of clay based on sensitivity (Rankka, 2004)

Designation	Sensitivity
Low sensitivity	<8
Medium sensitivity	8 - 30
High sensitivity	>30

Quick clay is recognized to be of glacial origin, and is found in former glaciated areas such as Scandinavia. Many research have been done to specify the reason behind the

formation of quick clay. Rosenqvist (1946) suggests in his theory that salts leaching of marine clays is the reason behind the change of clay to quick clay. Despite the fact the further research showed that low salt concentration is indispensable for high sensitivity, but it's not enough cause for switching clay to quick. Other reasons for the form of quick clay are summarized the ion composition of pore water, pH, dispersing agents, and particle shape (Rankka et al., 2004). Brenner has illustrated more on the formation of quick clay which can be see in Figure 2.4.

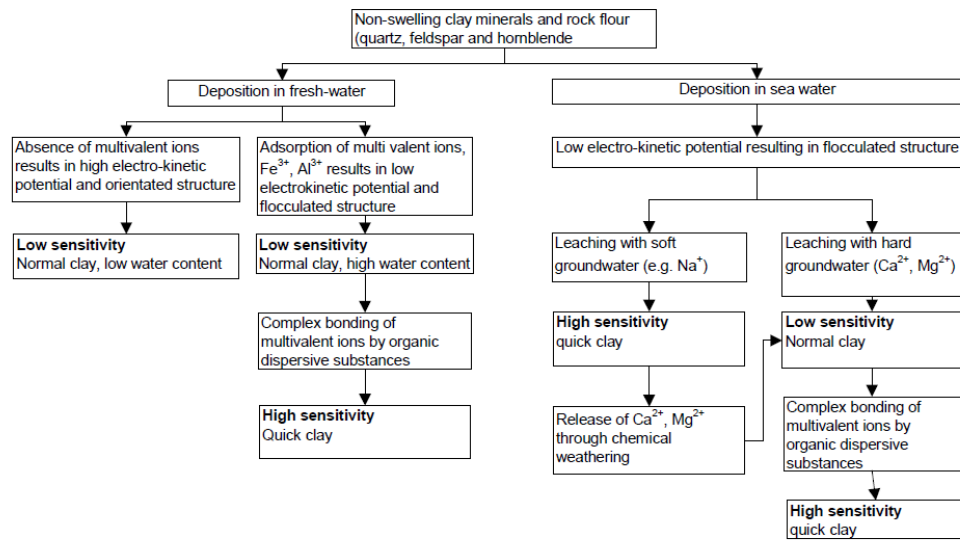


Figure 2.4: Principles of quick clay formation (Brand & Brenner, 1981)

2.3 Electrokinetic applications in Soil

Elektrokinetic phenomena occur when electric field is applied through electrodes in saturated clayey soil (Micic et al., 2001). The induced electric field creates a flow of water and ions in the soil which can be seen in Figure 2.5. The phenomena occurring are:

- Electroosmosis: flow of water between the pores towards the cathode
- Electromigration:
 - (a) Electro-phoresis: flow of charged particles due to the application of electric current
 - (b) Ionic migration: flow of dissolved ions in the pore fluid towards both electrodes

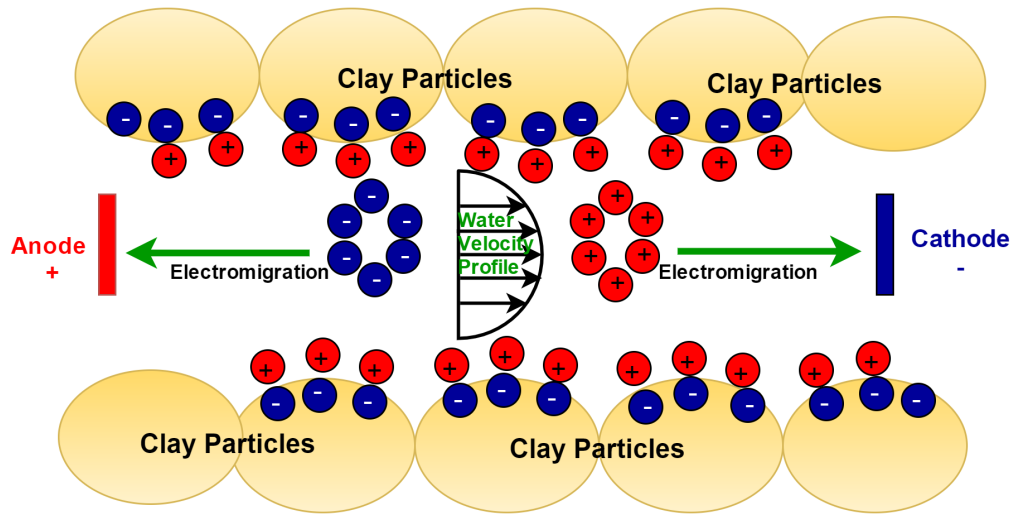


Figure 2.5: Elektrokinetic induced flow in soil

2.3.1 Electroosmosis

First discovered by the German scientist Ferdinand Friedrich Reuss in 1807, electroosmosis occurs when a direct current is applied to saturated soil. When electroosmosis occurs, water in the soil will flow from anode to cathode, inducing a negative pore pressure which will result in faster consolidation and increase in the shear strength of the soil (Micic et al., 2001). The phenomenon is developed for the fact that clay particles have negative surfaces which attracts the cations that are surrounded by water molecules. Once a current applied to the system, the cations start moving towards the cathode with the surrounded water molecules (Asadi et al., 2013).

History

L. Casagrande was one of the first to apply electroosmosis in field in the 1930's, who eventually used the technique in different projects later (Gray & Mitchell, 1967). The strength increase in the soil had been proven to be permanent. Miligan (1995) concluded that the bearing capacity of steel piles, installed in clay in one of the projects, was still the same after 33 years of the project. In addition, Lo et al (1991) demonstrated that the soil strength improvement was a result of the expansion of the effective strength envelope and increase of the preconsolidation properties (LO KY & HO, 1991). This concludes that the soil improvement is set to be permanent. The technique of electroosmosis has been used in different fields: soil improvement, stabilization of slopes, dams, embankments, dewatering, and remediation (Micic et al., 2001). All the successful electrokinetics applications were done to soils of low salinity, i.e., salt concentrations less than 2g NaCl/l in the pore water, however, for higher concentrations such as in marine sediments, limited data suggests that high concentrations of salt decreases or stop the flow induced by electrokinetics (I. L. Casagrande, 1949; Gray & Mitchell, 1967).

Theories

Since the 1800's many theories have been developed about electroosmosis and how to model the flow induced by it. Helmholtz-Smoluchowski is one of the most common theories about the topic the theory is useful for the calculation of the electroosmotic flow after inducing an electric current through the sample. Moreover, the Casagrande's electroosmotic flow equation is also used for the calculation of the flow relating the new permeability parameters and the electrical gradient (Soga & Mitchell, 2005).

1. Helmholtz-Smoluchowski

This theory is most common simplification of the electroosmotic flow. The theory assumes that thickness of the diffuse double layer is small compared to the size of the pores. The main parameter in this theory is the Zeta potential, ζ (Asadi et al., 2013). To calculate the flow the equation is as follow:

$$q = \frac{\zeta D}{\eta} n \frac{\Delta E}{\Delta L} A \quad (2.4)$$

where:

- q = flow rate (m^3/s)
- ζ = zeta potential (V)
- η = viscosity of pore fluid (Ns/m^2)
- D = permittivity of soil (F/m)
- n = porosity of soil
- $\frac{\Delta E}{\Delta L}$ = electrical potential gradient (V/m)
- A = cross-sectional area (m^2)

K_e , the electroosmotic coefficient of permeability which can be determined in the lab during the electroosmosis experiment. According to Helmholtz-Smoluchowski theory, electromosmotic coefficient of permeability should not be affected by the pore size. Hence, the type of soil whether it's fine or coarse grained shouldn't effect the flow induced by electroosmosis according to this theory, K_e calculation is done using Figure 5.1 which is determined by comparing Equation 2.4 to Darcy's law (Soga & Mitchell, 2005).

$$K_e = \frac{\zeta D}{\eta} n \quad (2.5)$$

Other theories such as Schmid theory, which is considered to be small-pore theory, can be used to calculate the electroosmotic flow.

2. Casagrande's flow equation

This flow equation is similar to Darcy's, which is commonly used in the geotechnic field (L. Casagrande, 1957). The limitation of the equation is that is is valid when there are open boundaries from the anode and cathode sides. The equation is as follows:

$$q = K_e i_e A \quad (2.6)$$

q = flow rate (m^3/s)
 k_e = electroosmotic coefficient of permeability (m^2/sV)
 i_e = electrical gradient (V/m)
 A = Cross-sectional area (m^2)

2.3.2 Electromigration

Electromigration is the flow of ions in a media due to the presence of induced electric current. In this process, the negatively charged ions will migrate towards the anode while the positively charged ions will migrate towards the cathode. The rate of electromigration depends on the mobility of involved ions. In addition, the migration of ions toward the electrodes is proportional to the concentration of ions in water and to the electric field intensity (Kim et al., 2005). Most common applications of electromigration is to remediate soil from chemical contamination.

History

In 1994, Lindgren et al. tested insitu remediation using electromigration process. The experiment was done by using dye ions and measuring its concentrations in unsaturated sand with the application of constant current with gravimetric water content between 4% and 27% and the results showed that migration of ions was highest in a water content between 14% and 18%. In the following year, Lindgren and Mattson applied a system of electrodes to soluble chromium found in unsaturated soil. The result of the experiment showed that 88% of the chromate was remediated by applying 10mA constant current for eight days (Huweg, 2013).

Theories

Electromigration is represented as the ionic mobility which is the average velocity of ions due to the application of a force. In general, the rate of transport of ions by electromigration is faster than that done occurring due to the flow of fluid under the electroosmosis effect, for instance, the anions will still migrate towards the anode although electroosmotic flow is carrying ions to the opposite direction (Denisov et al., 1996). The ratio of the ion transport compared to the electroosmotic flow is reported to be between 10-100 (Sullivan, 2008).

The migration flux of ions is, as shown in Equation 2.7, dependant on the effective ionic mobility which in its turn takes soil porosity into consideration (Jia, 2006).

$$J_m = \mu_{eff} C \Delta V \quad (2.7)$$

J_m = ion migration flux ($mol/m^2.s$)
 μ_{eff} = effective mobility of ion ($m^2/V.s$)
 C = ionic concentration (mol/l)
 ΔV = applied voltage (V)

The effective ionic mobility, μ_{eff} is determined theoretically using Nernst-Townsend-Einstein relation. Equation 2.8 shows that the mobility is dependant on the soil porosity, tortuosity factor and the molecular diffusion of the ion.

$$\mu_{eff} = \frac{D^*ZF}{RT} \quad (2.8)$$

- D^* = diffusion coefficient (m^2/s)
- Z = charge number
- F = Faraday's constant ($96.487 C/mol$)
- R = universal gas constant ($8.314 J/K.mol$)
- T = absolute temperature (K)

2.4 Governing parameters

Electrokinetics, especially electroosmosis, is controlled by several parameters including soil properties and experiment method factors. These parameters are important for recognizing the efficiency of electrokinetics application in different sets of conditions.

2.4.1 Zeta potential, ζ

The water in the pores, which contains negatively and positively charged ions, form a boundary layer which in its turn consists of an inner fixed zone, known as stern layer, and an outer mobile zone. Zeta potential is defined as the potential between these two layers (Jones et al., 2011). The values of ζ for clay are negative due to the negatively charged surface, which vary between 0 mV to -50 mV (Soga & Mitchell, 2005). Equation 2.4 of Helmholtz-Smoluchowski theory shows that the value of ζ is proportional to the electroosmotic flow, which means the more negative the value of ζ , the more efficient is the electroosmosis process. Figure 2.6 shows the different interactions between the clay surface and the surrounding water including the zeta potential definition.

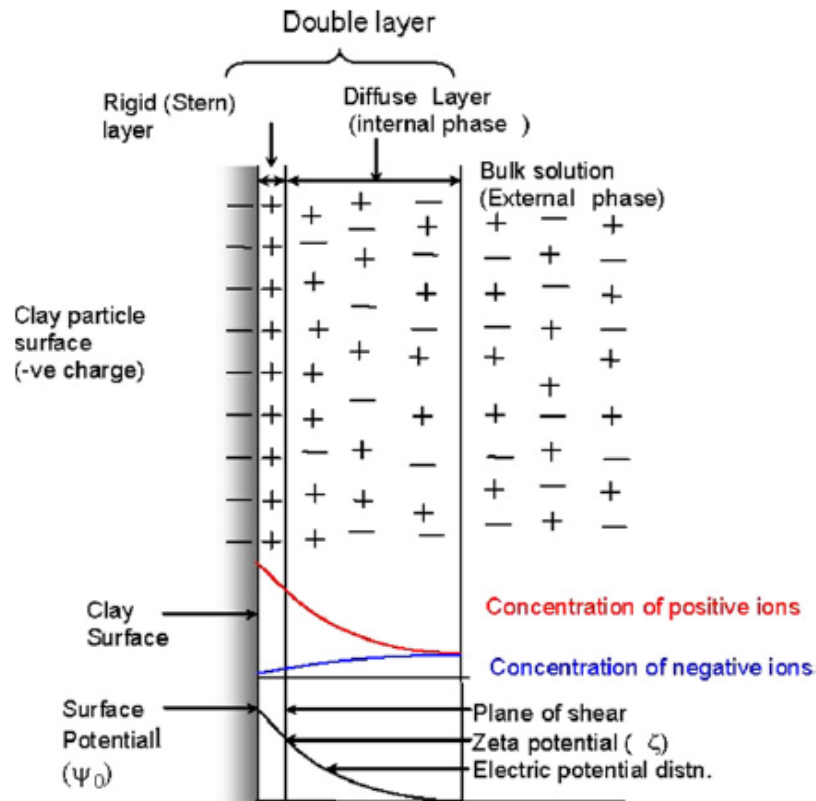


Figure 2.6: Clay surface and water interface (Jones et al., 2011)

2.4.2 Permeability coefficient of electroosmotic flow, K_e

Such as the common coefficient of permeability, the electroosmotic coefficient is the new coefficient after the application of electric current to the sample. The coefficient can be calculated as in equation Figure 5.1. The equation shows that the coefficient is dependent on different factors such as the porosity of the soil and the zeta potential. On the contrary, Casgrande noted from the results of lab experiments, that the coefficient is a constant for all soils in case it is expressed as a flow velocity induced per unit of the electric potential applied (Gray & Mitchell, 1967). Mitchell and Soga (2005) stated that K_e ranges between 1×10^{-6} and 1×10^{-8} (m/s per V/m).

Table 2.2: Coefficients of electroosmotic permeability

No.	Material	Water Content (%)	$k_e 10^{-5}$ ($cm^2/s - V$)	k_h (cm/s)
1.	London clay	52.3	5.8	10^{-8}
2.	Boston blue clay	50.8	5.1	10^{-8}
3.	Kaolin	67.7	5.7	10^{-7}
4.	Clayey silt	31.7	5.0	10^{-6}
5.	Rock flour	27.2	4.5	10^{-7}
6.	Na-Montmorillonite	170	2.0	10^{-9}
7.	Na-Montmorillonite	2000	12.0	10^{-8}
8.	Mica powder	49.7	6.9	10^{-5}
9.	Fine sand	26	4.1	10^{-4}
10.	Quartz powder	23.5	4.3	10^{-4}
11.	Ås quick clay	31	20 – 2.5	2.0×10^{-8}
12.	bootlegger Cove clay	30	2.4 – 5.0	2.0×10^{-8}
13.	Silty clay, West Branch Dam	32	3.0 – 6.0	$1.2 \times 10^{-8} - 6.5 \times 10^{-8}$
14.	Clayey silt, little Pic River, Ontario	26	1.5	2.0×10^{-5}

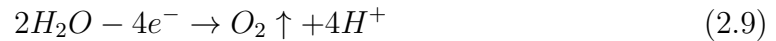
K_e and water content values are from Casagrande (1952) (no.1 to no.10). K_h are estimated by (Soga & Mitchell, 2005) authors.

2.5 Electroosmosis side effects

In addition to the water flow, there are other effects that are caused by the application of electric current through a clay sample. These effects are of great interest since they will effect the selection of materials and the expected reaction of the system after the application of electric current.

2.5.1 Electrolysis of water

One of the important side effects of electric current flow with water is the electrolysis process. Electrolysis of water occurs when a high voltage is applied to the system. At the level of anode, oxygen gas is produced according to the following reaction:



The products of the reaction on top include Hydrogen ions which reacts with the anions in the water to form acids which decreases the pH of water solution.

At the cathode, water molecule will gain electrons to form hydrogen gas according to the following reaction:



Another gas is produced here as well which will effect the permeability of the sample. In addition, the production of hydroxide ions may increase the pH of the water (Soga & Mitchell, 2005).

2.5.2 Reactions at electrodes

Another effect at the level of the electrodes is the oxidation and reduction reactions that might occur. Oxidation occurs at the anode while reduction at the cathode. Nevertheless, for the reactions are present if the used electrodes are made out of metals (Jeyakanthan et al., 2011). These reactions are described in electrodes part of section 4.4.

2.5.3 pH change

The previously described reactions induce the decrease of pH at the level of anode and increase of pH at the cathode. Figure 2.7 shows the change of pH, ζ potential and the intraporous pressures between the anode and cathode. A decrease in pH will result in the reduction of ζ potential which reduce the efficiency of the process by decreasing the electroosmotic flow rate (“Nanoscience: colloidal and interfacial aspects”, 2010). Another effect of pH is on the flocculation of clay. An increase in pH induces the decrease off exchangeable Al^{3+} which results in the dispersion of clay (“Handbook of soil conditioners: substances that enhance the physical properties of soi”, 1998).

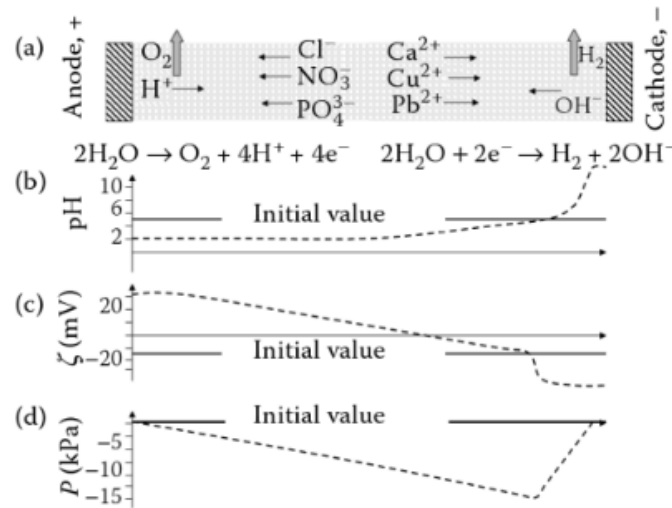


Figure 2.7: (a) Electrode processes during electroosmosis, (b) pH distribution, (c) ζ potential (d) intraporous pressures

3

Previous Investigations and Applications

This chapter will present the previous laboratory experiments and practical applications that have been done using the electrokinetics approach including electroosmosis and electromigration. Using of electroosmosis started with Casagrande's field applications in Germany. After the first applications, the technique attracted the interest of many researchers and engineers since the method is considered environmental friendly and cost efficient compared to conventional methods of dewatering or remediation soils.

3.1 Previous investigations

After Casagrande, many researchers showed interest in evaluating the efficiency of the electroosmosis treatment. Different tests had been done with different sets and tested samples. Some tests had loading while other were only using electric field. A brief description of different laboratory investigations is presented below.

Morris et al, 1985

Morris et al performed an electroosmotic test to evaluate the effectiveness of the treatment on silty clay samples. The test were done in a tube apparatus, where the samples were also loaded with an increasing axial loading to a maximum of 30 kPa. Electric current was provided by a power supply of voltage ranging between 0.4-0.6 V/cm. Samples were 250 mm in height and 77mm in diameter. Moreover, the electrodes used were stainless steel wool since it is considered to be noncorrosive. Figure 3.1 shows the test equipment used. After performing different tests such as cyclic triaxial, consolidation, and oedometer tests, the results showed that there is a significant increase in strength of the tested samples (Morris et al., 1985).

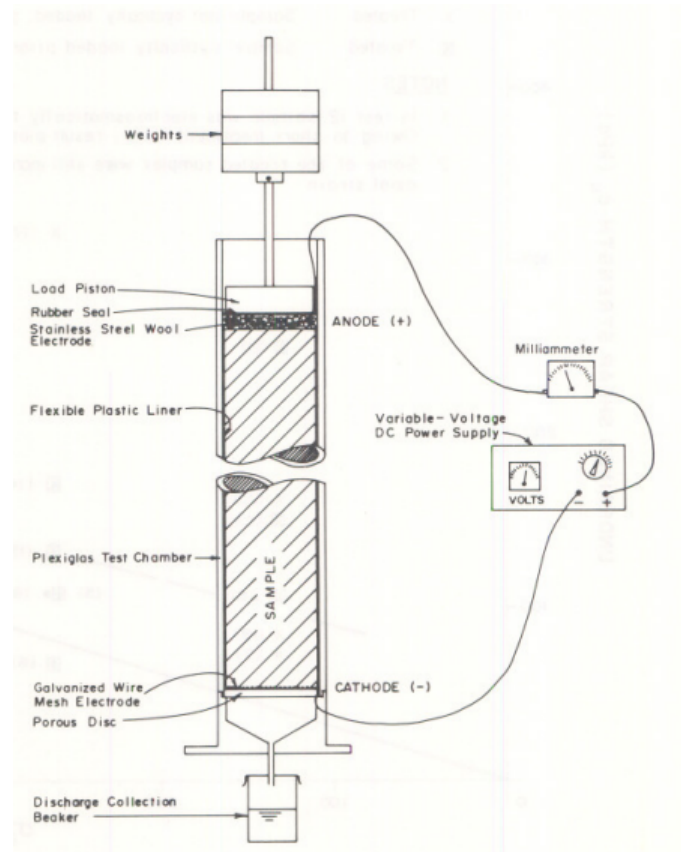


Figure 3.1: Morris et al test equipment, 1985

Micic et al, 2001

This experiment was performed on samples from marine sediments to check the possibility of using electrokinetics for enhancing the surcharge preloading in consolidation which tends to improve both the mechanical and physical properties of the tested samples. Consolidation pressure was applied gradually until it reached 15 kPa and then the samples were conducted with electric field for 6 days of voltage gradient 12.8 or 25.6 V/m. The test cell has a rectangular box shape with the dimensions of 255mm x 100mm x 200mm as shown in Figure 3.2. The electrodes were 1.2mm steel mesh with 5mm nominal openings. The results show an increase in shear strength closer to the anode, and proved the effect of electroosmosis on the pH change (Micic et al., 2001).

Jeyakanthan et al, 2011

Jeyakanthan et al proposed a design for applying electroosmosis during a triaxial test. The apparatus was aimed to measure permeability, pore pressures and to evaluate the electro-chemical effect on improving the strength of soil. Clay slurry samples were used of 60 mm diameter and 120mm height. The samples were reconsolidated by a 35 kPa. Electroosmotic treatment was applied using a different voltage gradient for each test such as 4.4 V for the triaxial test. Perforated copper discs are used as

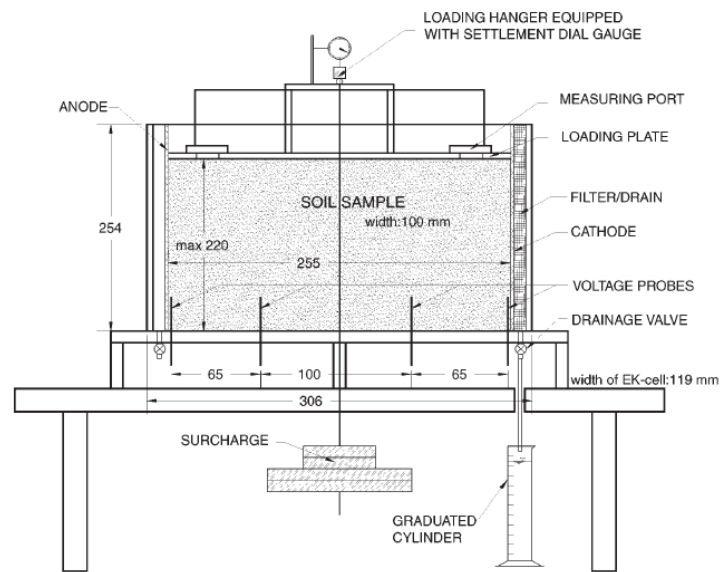


Figure 3.2: Micic et al test equipment, 2001

electrodes which are fixed to the upper and lower caps. The apparatus can be seen in Figure 3.3

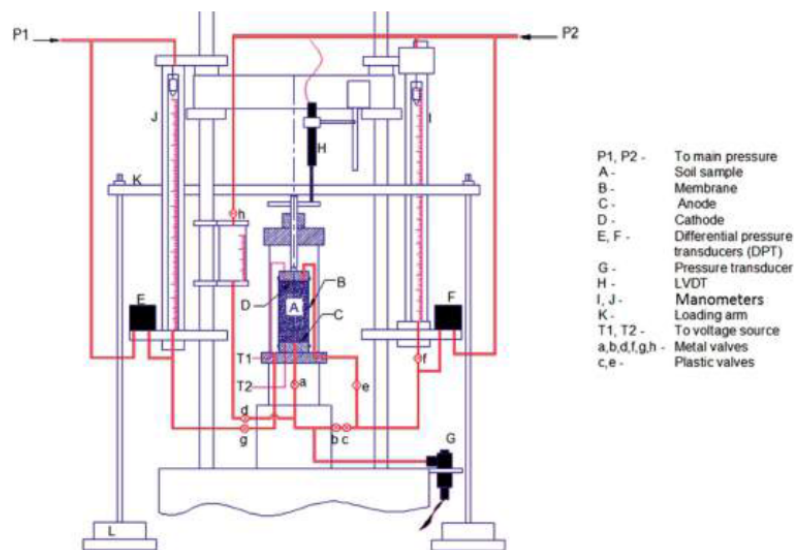


Figure 2.15: Setup used by Jeyakanthan et al, 2011.

Figure 3.3: Jeyakanthan et al, 2011

3.2 Field implementation

Electroosmosis has been used in many fields for different reasons. Some projects included the process for improving the soil other for dewatering or stabilizing a slope. Below are some projects that included electroosmosis.

Electroosmotic consolidation: Mont St-Hilaire, Canada

Electroosmotic treatment of 48 days was applied to the soil of the field near Mont St-Hilaire in the ST. Lawrence valley. The field tests were done to evaluate the efficiency of chemical treatment during electroosmosis. The field has clay which is normally consolidated with c_u lower than 35 kPa. Steel pipes with outside diameter of 17 cm are used as electrodes.

At the end of the 48 days, the settlement reached 0.46m. An increase of 50 kPa at 10m depth to 72 kPa at 13m depth occurred after the treatment at the mid-distance between the electrodes. In addition, after 28 days of the treatment, 9% of compression occurred and 12% after the end of the treatment (Burnotte et al., 2004).

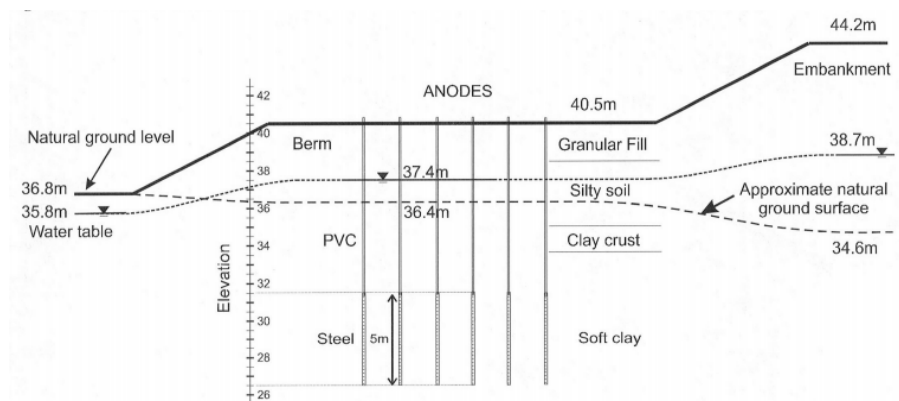


Figure 3.4: Field investigation, Burnotte

Soil improvement using electroosmosis: Taipei, Taiwan

In this project, the application of calcium chloride solution followed by sodium silicate while applying electroosmosis treatment is done. Perforated steel pipes of 50mm diameter are used as electrodes. The results showed that the soil surrounding the anode became very stiff. Moreover, the experiment included reversing of polarity which didn't enhance any improvement regarding strength or treatment, and therefore as a conclusion was that the polarity reversal is not applicable when having ECT, electroosmotic chemical treatment (Ou et al., 2009).

4

Test Design

The chapter will describe the used materials with the appropriate reasoning of each. Moreover the chapter will include the procedure followed to construct the experiment will be discussed. The experiment will test the validity of the theories reviewed earlier starting from the effect of electrokinetics on the coefficient of permeability of clay.

The testing of the theories can be done by different ways, however, in this project, the most feasible, time efficient and easy adjusted techniques will be used. The materials part includes the electrodes, which have different alternatives to choose from, where each alternative will be discussed and compared to the others. The samples used are also described in this part of the report.

4.1 Equipment

In this section the main equipments and materials used in the experiment are described. The equipments include the coefficient of permeability measuring apparatuses and electric current controlling hardware and software.

4.1.1 Permeability equipments

The permeability equipments are the common apparatus used to measure the coefficient of permeability of a sample. In the laboratory, flexible wall permeameters (FWP) are used to execute the constant head method for determining coefficient of permeability of the samples. The method is described in (D 2434-68, 2006) where the equation to calculate the coefficient of permeability is as follows:

$$k = QL/Ath \quad (4.1)$$

k = coefficient of permeability,
 Q = quantity of water discharged,
 L = distance between manometers,
 A = cross-sectional area of specimen,
 t = total time of discharge,
 h = difference in head on manometers

FWP, shown in Figure 4.1, enables the ability to control the pressures at both burettes and inside the cell. The pressure control makes it feasible to re-consolidate the samples, obtain desired cell pressures and head gradients.

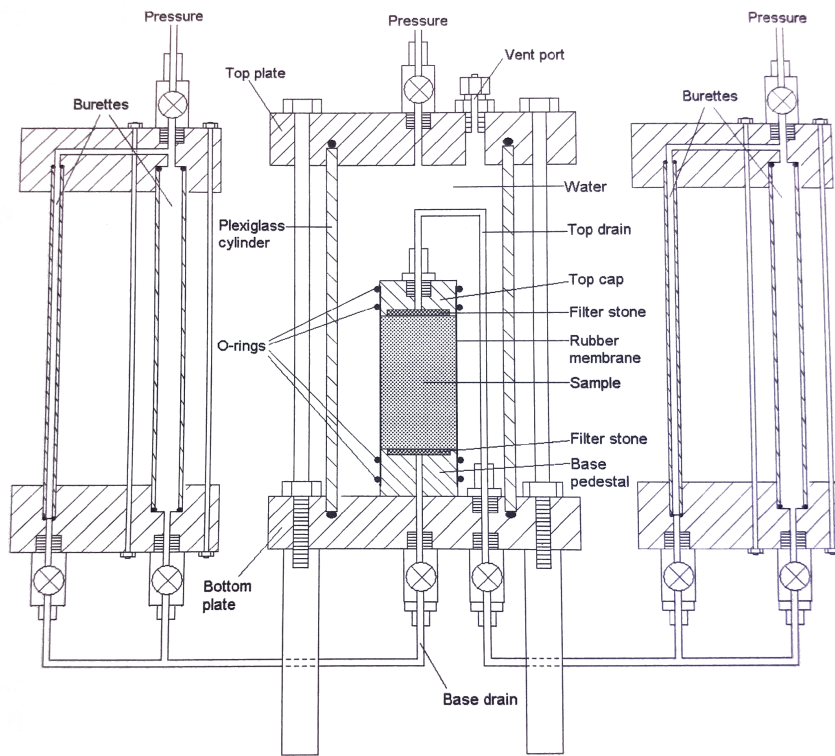


Figure 4.1: Flexible wall permeameters diagram

For eliminating the trapped air in the pipes and in the sample, the inlet was placed to pump water from the bottom of the sample while the outlet is taking water out of the sample from the top part, which makes it easy to take air out. The electrodes are placed in the plastic inlet and outlet of the permeameter for the reasons mentioned in the the electrodes section below.

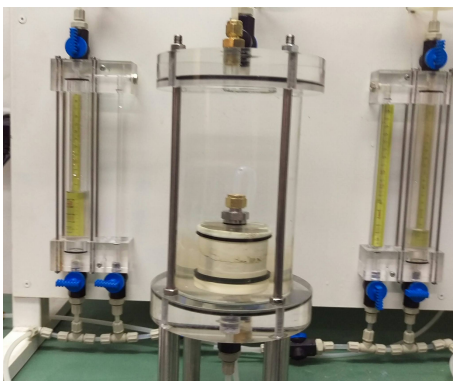


Figure 4.2: Cell A with water

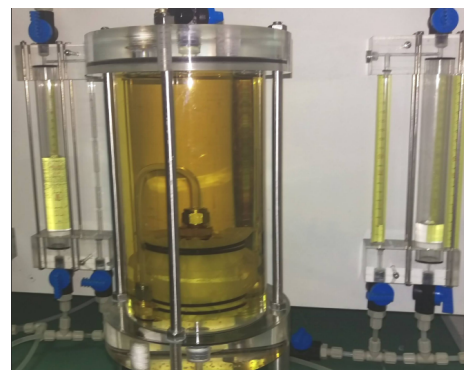


Figure 4.3: Cell B with oil

4.1.2 Electric equipments

This part will describe the electric equipments used to send and measure the electric current through the sample. The electric system includes hardware instruments that

are used in addition to the software required. The equipments needed also include wires, resistors, crocodile clips and a 12V-30V power supply.

Electrodes

In electroosmosis, electrodes are needed for the transfer of electricity. The selection of material, shape and location of electrodes to use are of great influence on the efficiency of the process. In previous experiments, a number of electrodes were investigated for the electroosmosis application (LO KY & HO, 1991). Many considerations should be taken when deciding on the material and dimension of the electrodes. For instance, the resistivity to heat and corrosion, chemical reactivity and cost are important factors to consider when comparing different alternatives for electrodes (Jeyakanthan et al., 2011).

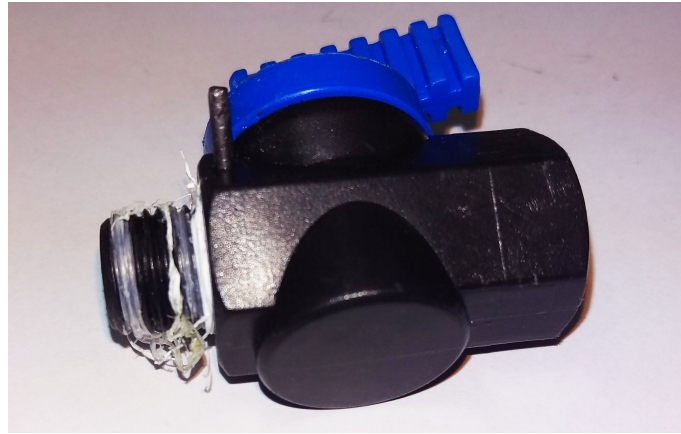


Figure 4.4: Electrodes position

Electroosmosis induce the presence of gases at the level of electrodes due to hydrolysis. At the anode, Oxygen gas will be found which will react with electrode, if it was made of metal, and causing the oxidation of it (Jeyakanthan et al., 2011). The reactions at the electrodes can be described as follows:

Oxidation at the anode:



Reduction at the cathode:



Where M_e is the metal, and n is the valency of it. M_j^{n+} is the dissolved cation in the solution. The oxidation of the metallic electrodes was discovered to be a reason behind the reduction of the electric passage efficiency (Bjerrum et al., 1967).

For gold or silver electrodes the cost is the main purpose for excluding them. Using nonmetallic electrodes induced the loss of current at the interface between soil and electrodes by significant values (Mohamedelhassan* & Shang*, 2001).

For the aforementioned reasons, the selection was made on using graphite as a conductor. However, for excluding the possibility of electricity loss at the interface of electrode-soil, the electrodes will be placed outside the sample. For simplicity, the electrodes will be conducting the current through the water flow instead of being directly connected to the sample. A 2mm pencil lead was used as an electrode which is selected based on the space available for their placement. The electrodes should also be stiff enough not to break when they are inserted in the apparatus or when they are connected to the wires.

Power supply

The application of the current should be controlled. The experiment requires the precision in the applied current and the control over switching it on/off easily. For these reasons, the battery supplying the current can't be connected directly, and the use of a computer controlled system is essential. National Instruments offers the ability to control constant current signals through LabVIEW SignalExpress software, which will be described in the following section. Connecting a 12V-30V power supply to the NI 9265 module, enabled the ability to send and control current signals up to 20 mA, Figure 4.5. In order to make sure that the electrodes are transferring electric current through the sample another module from national instrument, NI 9219, is used to measure the electric current between the two electrodes, Figure 4.6.



Figure 4.5: Output module



Figure 4.6: Input module

Measuring tools

NI instruments provide the software Labview package that includes SignalExpress. SignalExpress can generate, create and acquire from different data acquisition instruments including electric instruments. A multimeter is used to measure resistance of clay and to make sure that the connections are working fine. From simple electric background, it is known that to measure current or resistance, the multimeter should be connected in series. On the other hand, for measuring voltage, the connections of the multimeter should be in parallel with targeted voltage measurement.

4.2 Samples

The tested samples are of clay with known strength parameters. The reason behind having them of known parameters is to be able to detect any change in the strength

after the application of the electric current. The samples will be cylindrical of 50 mm diameter and 20 mm in height. The samples are made to be small compared to other tests, so that the process of water flow won't consume a lot of time. Moreover, the smaller the height of the sample, the closer the measured coefficient of permeability to be one-dimensional. Nevertheless, the sample had to be stable and the dimensions shouldn't effect the results of the experiment. Some properties of the soil samples are given from the laboratory and they are tabulated below:

Table 4.1: Soil properties

Parameter	Value	Unit
Depth	3	m
Density	1.71	t/m ³
Water content	47	%
Coefficient of permeability	1×10^{-10} - 1×10^{-9}	m/s
Coefficient of consolidation	2×10^{-8} - 2×10^{-7}	m ² /s

Samples of the same depth were used in the project for consistency. Regarding the given coefficient of permeability, it would be a reference to make sure that the measured one is in the range. In addition, water content will be compared with the one after finishing the experiment. The given tests results and image of the sample can be found in Appendix A and Appendix B respectively.

4.3 Procedure

The steps of the experiment were selected to be easily repeated and representative of a field treatment applications. Before the start of the experiment some preparation needed to take place. The preparation includes the mounting of samples and saturating them. Eliminating any trapped air in the connecting pipes is also a major step to do before starting the experiment. In addition, the filter stones should be cleaned using microwaves and by placing them in vacuum bell jars afterwards. Besides the mechanical preparation, software and laptop preparation was done as well that includes the understanding of how the software works and how to measure electric parameters.

4.3.1 Experiment execution

The experiment is done by using two cells for reaching the aims of the thesis. The first cell is to evaluate the effect of gradual increase electric current while the second is for the direct increase of electric current. The coefficient of permeability of both cells will be evaluated after the removal of the electric current. For both cells, the first two steps are the same which are to undergoing reconsolidation and one week of coefficient of permeability measurements while the steps that follows are different for each cell. The surrounding liquid of the first cell is water while oil was used for the second one. The use of oil makes it easy to detect and leakage which wasn't present when the first cell was mounted. A rubber membrane was also used to seal

the samples and prevent any exchange of water with the surrounding. The planned procedure can be seen in Figure 4.7.

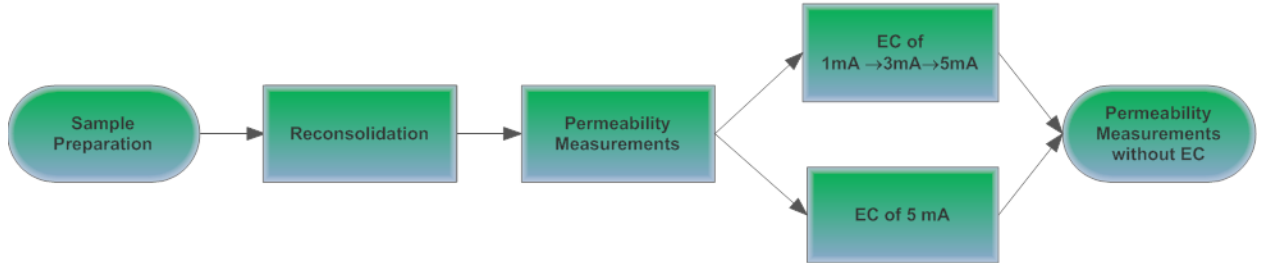


Figure 4.7: Experiment procedure

Reconsolidation

After mounting the saturated samples in the cells, they were set to undergo isotropic consolidation by using cell pressure of 100 kPa. During the consolidation process, the inlet flow is set off, where the water is draining from the outlet only. The application of the pressure was gradual from 0 to 40, 70 and then to 100 kPa with an hour in between. The applied cell pressure has also the role of ensuring that the membrane is in contact with the sample, leaving no voids in between the sample and the membrane. The sample was then left to consolidate for two days. The calculation of time needed for consolidation was done using Terzaghi (1943). Nevertheless, the sample was left to consolidate for more time than the calculated to ensure that end of consolidation.

Coefficient of permeability measurements

After two days of consolidating the samples, the measurement of coefficient of permeability started. The measurements were done daily, where each day the discharge flow is measured and the coefficient of permeability is calculated based on equation Equation 4.1. A backpressure of 20 kPa was applied in the first burette which is 2 meters of water head pressure.

Electric current application

The application of electric field is to be done by controlling the electric current subjected to the sample. For the first sample an 1 mA then 3 mA followed by 5mA was to be done. For the second sample application of direct 5 mA of current was to be done. At this stage the voltage parallel to the sample was to be measured using SignalExpress and consequently the resistance of the sample would be calculated using ohm's law. When the application of small current for the first sample was done, the measured voltage was 13V which is the maximum of what the battery can supply with. Changing the current to a higher value also didn't effect the measured voltage.

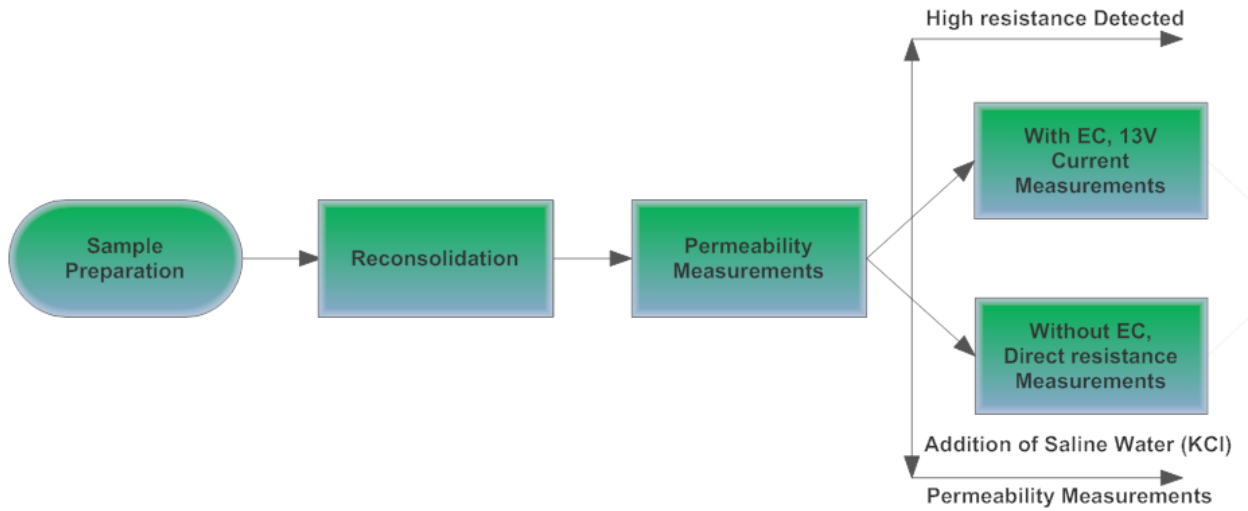


Figure 4.8: New procedure

Measuring resistance

After having unreasonable results when connecting electric current through the system, measuring resistance directly from the electrodes was done using the multimeter. In addition, resistance was measured directly for the clay tube which the sample was taken from. The measured resistance of the system showed that it was very high for a battery that we have to be enough to conduct enough current. Therefore, the task changed to reduce resistance of clay to enable electroosmotic treatment. For the first sample, since the measured resistance was higher than what can be detected by the multimeter, SignalExpress was used to measure the current going through the sample after the application of 13V DC. On the other hand, resistance was measured directly for the second sample since the multimeter could detect it.

Addition of saline water

For improving the conductivity of the sample, which is the same as decreasing resistance, water in the inflow was replaced with saline water with a controlled salt concentrations. The salt added is potassium chloride (KCl) which has a molar mass of 74.56 g/mol. The water to be added was chosen to have similar salt concentration of seawater. Sea water has approximately 35 g/l of sodium chloride (NaCl) of 58.55 g/mol as a molar mass.

Using stoichiometry, concentration of KCl needed to reach a salinity similar to that of seawater can be calculated as shown in Equation 4.5. Deionized water was used in dissolving the salt.

To reach a similar concentration of salinity, KCl should be added with the same molar concentration of that of NaCl:

$$c = c_{m,NaCl}/M_{NaCl} = 35/58.44 = 0.5989 \text{ mol/l} \quad (4.4)$$

4. Test Design

Therefore, the mass concentration of KCl is:

$$c_{m,KCl} = c \times M_{KCl} = 0.5989 \times 74.56 = 44.65g/l \quad (4.5)$$

Afterwards, current was measured continuously for the first sample which had a DC of 13V, whereas the resistance was measured daily for the second sample using the multimeter which didn't have any electric field connected to. This will enable to measure resistance decrease due to the addition of saline water. In addition to see the effect of electric current on the speed of flow which will enable the possibility of measuring the electrosmotic effect on the hydraulic conductivity.

5

Results

In this chapter, results of the experiment will be presented and discussed. The main results follow the sequence of experimental procedure and they are follow:

- Permeability measurements: The daily measured coefficient of permeability for both cells.
- Electroosmotic coefficient of permeability: The electroosmotic permeability of the first cell.
- Resistance measurements: The Resistance measurements for the second cell using multimeter.
- Current measurements: The measurements of current in the first cell using SignalExpress after the application of 13 V DC.

Some general information about the experiment are shown below in Table 5.1.

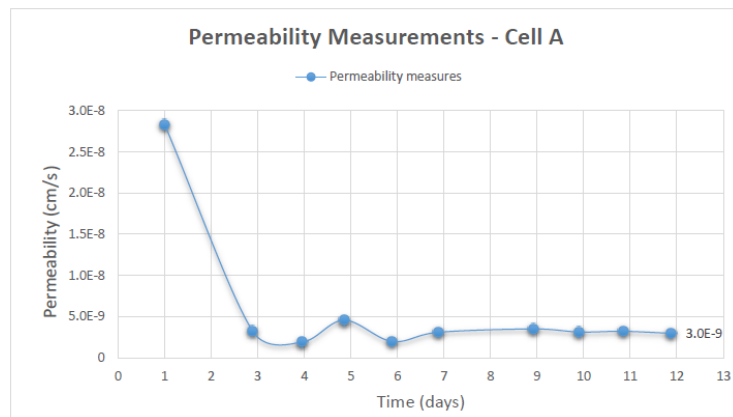
Table 5.1: Test information

Parameter	Value	Unit
Cell pressure	70	kPa
Back pressure	20	kPa
Sample cross-sectional area	19.6	cm ²
Sample height	2	cm
Burette diameter	2.1	cm

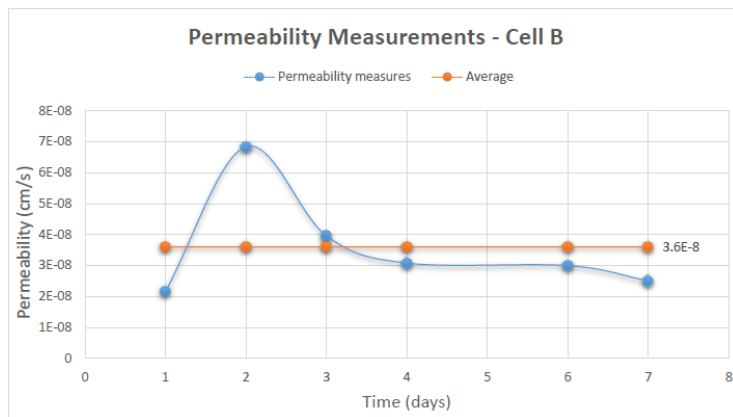
5.1 Permeability measurements

The permeability measurements were done for the two samples with tap water. Afterwards, saline water replaced the fresh water.

Coefficient of permeability is calculated based on equation Equation 4.1. In this first scenario, the gradient is only pressure difference between the inflow and outflow. The results of permeability of each sample is shown below:



(a)



(b)

Figure 5.1: (a) Coefficient of permeability in cell A, (b) Coefficient of permeability in cell B

Figure 5.1 shows the permeability measurements of both cell A and B which is supposed to be of the same soil sample. coefficient of permeability of cell A turned out to be less than that of cell B by 10 times. Nevertheless, both values are in the common coefficient of permeability range for clay, which is also presented in Table 2.2. For cell A, the average is not taken since the first point is considered an outlier; hence, the average is to be of the rest of the points.

The samples are considered to be of high sensitivity close to be quick and the coefficient of permeability is in the range of 10^{-8} to 2×10^{-8} cm/s. Another value that can be calculated is the bulk permeability which is the total amount of outflow water over the entire experiment time, and using the same formula of the daily permeability. The table below summarize the average coefficient of permeability for both cells and the bulk ones as well.

Table 5.2: Measured coefficient of permeability

Coefficient of permeability (cm/s)	Cell A	Cell B
Average	3.0×10^{-9}	3.6×10^{-8}
Bulk	3.2×10^{-9}	3.5×10^{-8}

Discussion

The results shown for both cells, which are from the same soil samples, are close to the values provided in the literature as well as for the ones provided by the laboratory. It is also clear that there is a difference by a factor of 10 between that of cell A and B.

A simple reasoning for that could be that soil has different coefficient of permeability since permeability depends on porosity, grain size and soil texture. Another reason is that there is a doubt in the first cell to have a leakage. No detection of leakage could be observed since the surrounding liquid used is also water unlike the second cell where oil was used. The results of cell A shows that the permeability started with a value close to that one of cell B, but then decreased tremendously afterwards which increase the chance of having a leakage in the system.

5.2 Electroosmotic permeability

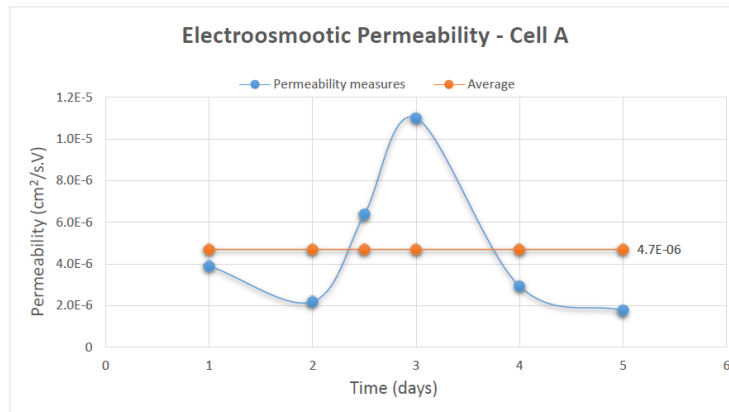
For the first cell, cell A, a 13 V power supply was connected to the sample, with saline water in the burette. However, the second cell has only saline water as a change from the initial conditions without any power applied. Since both gradients, electric and head, were applied for cell A, electroosmotic permeability couldn't be calculated directly. A split in the flow between head flow and electric flow should be made. To do so, the plateau value of flow of cell A of the initial test is used to estimate the new head flow. By using the results of adding saline water to the second sample, it is showing that an increase in permeability by a factor of 1.2 occurred. An assumption can be made that the same factor will increase the head flow of the first sample is made. Consequently, flow induced by electricity can be calculated and then electroosmotic coefficient permeability as well based on Equation 2. Table 5.3 shows the average flows distribution between head and electric and total.

Table 5.3: Average daily flow

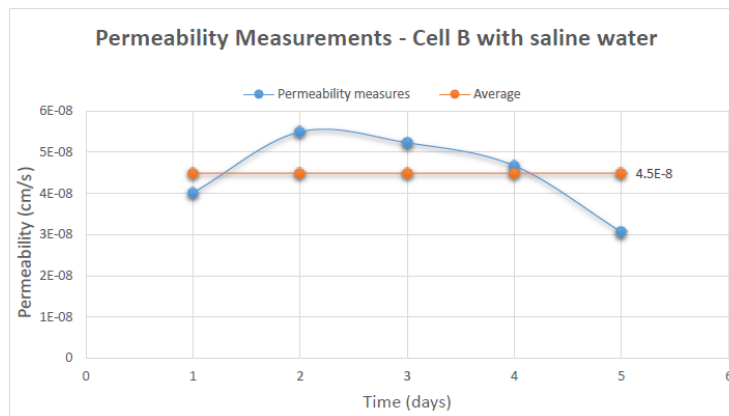
Average daily flow (cm ³ /day)	Cell A
Total	5.68
Head flow	0.60
Electric flow	5.08

The graphs below shows the electroosmotic coefficient of permeability which will be discussed afterwards.

5. Results



(a)



(b)

Figure 5.2: (a) Electroosmotic coefficient of permeability, with saline water, in cell A (b) coefficient of permeability, with saline water, in cell B

Discussion

The average daily flow shows that the electroosmotic flow contributed the most to the occurring flow with a 90%. It's clear from the second cell that saline water had an effect on increasing the flow by a factor of 1.2 without having a current connected. An increase in $0.9 \times 10^{-8} \text{ cm}^2/\text{s}$ occurred when saline water was added. This assures that the increase in flow in the first cell is mainly because of the electric current and a small contribution might be because of the saline water.

The electroosmotic coefficient of permeability is less than that in Table 2.2 for a quick clay by a factor of 10. The high resistance of the samples can be a reason for the low flow of water due to electroosmosis since the flow of water is linked to that of current as well.

5.3 Resistance measurements

As mentioned in the test design, this wasn't considered initially as a part of the project. Current couldn't flow as it was supposed to in the presence of a 13 V power supply. The initial resistance, which is the one measured directly from the sample's tube, was about 11 M Ω . For cell B, the resistance was measured without the application of any current. Daily resistance was measured using the multimeter to evaluate the effect of addition of saline water.

Table 5.4: Measured resistance for cell B

Day	Resistance (k Ω)
1	2300
2	574
3	475
4	274

Discussion

The addition of saline water with the calculated concentrations resulted in the decrease of the measured resistivity in cell B as shows in Table 5.4. The decrease of resistivity will enable the electroosmotic treatment and will increase the water flow through the sample. After dismounting the sample, the resistivity was measured directly from the sample and it was around 300 k Ω which is close to the value recorded at the last day when the sample was mounted.

5.4 Current measurements

For the first cell, the current was measured using the modules after connecting the sample with a 13 V DC power supply. According to Ohm's law, for a constant voltage, the decrease in resistance will result in an increase in current flow. Therefore, it is expected that the measured current to increase while adding saline water instead of fresh water. The results shown below in the graphs confirms the expectations. Graphs are plotted after extracting the acquired current data from SignalExpress. The resistance was also measured using the multimeter directly from the sample after being dismounted Figure 5.4

5. Results

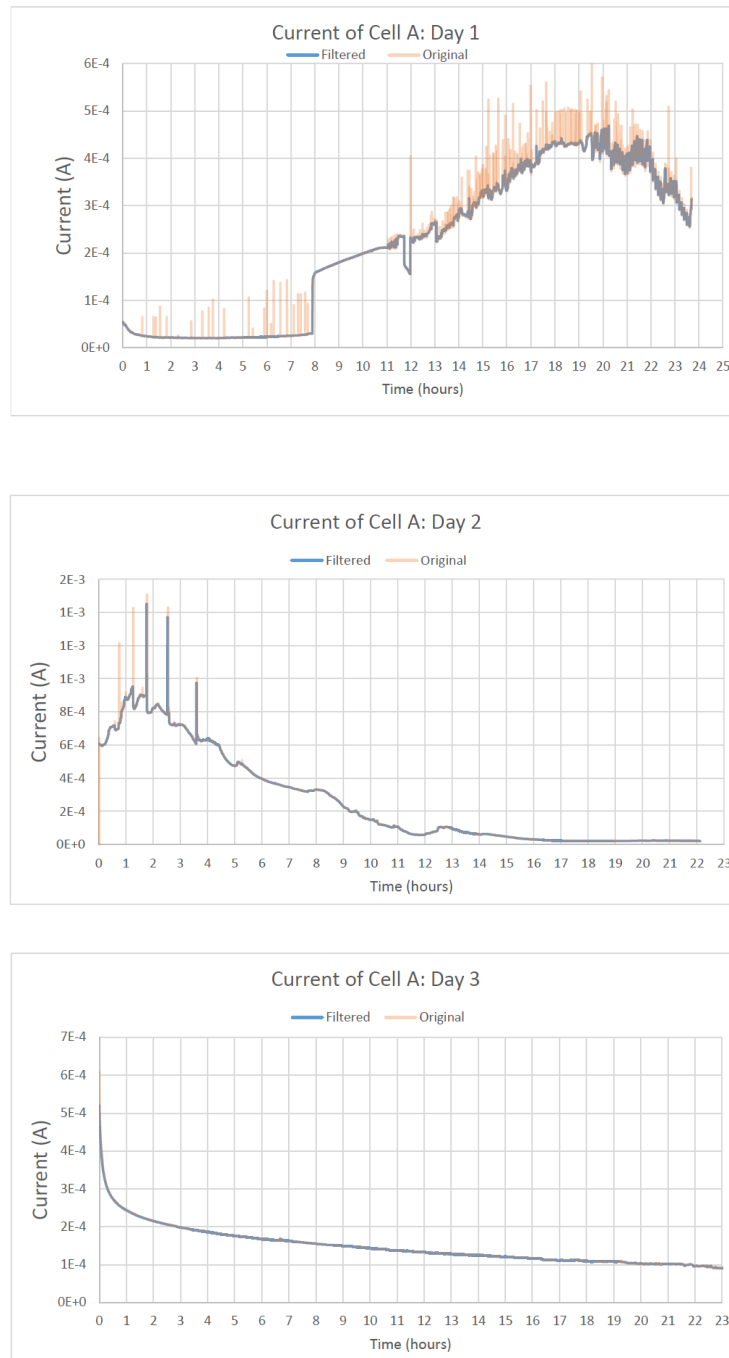


Figure 5.3: Current measurements for cell A



Figure 5.4: Final resistance for cell A

Discussion

The results of current measurements show that the current was increasing and reaching a limit and then decrease back. The first day shows that the current started increasing from 50 nA to reach 500 nA in less than 24 hours. However, the discharge tube had air bubbles trapped in the second day morning. The bubbles were taken out by inserting a water-filled tiny tube into the discharge tube and filling the bubbles with water. This process made the air move out of the tube and was filled instead. After clearing the air bubbles, the current measurements resumed. The second graph shows that the current started from the maximum of the first one which implies that the reason of the decrease of current is the trapped air. Repeating the same steps as before and applying current for the third day resulted in more production of gases which stopped the water and current flow.

After dismounting the sample, resistance was measured directly from the sample as shown in Figure 5.4. The multimeter shows a value about 760 kΩ. A reduction in resistance occurred from 11 MΩ to the previous mentioned value due to the addition of saline water. This improvement in conductivity will for sure influence the electroosmotic treatment and improve the permeability of clay. Nevertheless, this measured value wasn't the same when the multimeter was connected to the cell through the electrodes. The reason is that the electric current was flowing to the water in the cell as well.

6

Conclusion

In this chapter a summary of the discussed results will be presented. Challenges during the experiment and recommendations on how to do the test in a better way will be included. Further investigations and the plan of the next steps in the experiment extension are to follow as well.

6.1 Summary

The results can be divided into three parts. First is the permeability coefficient measurements which resulted in acceptable values within those provided by the literature and the ones provided by CRS tests. The second part is the evaluation of the electroosmotic permeability, where the value of the measured coefficient was less than the one provided in the literature. The electric current in the first sample was lost in the water surrounding the cell as explained in the last part of the discussion. Nevertheless, the results show the great influence of electroosmosis in the flow of water, where the flow of water after the application of the electric current was 90% due to electroosmotic flow. The last part is about the conductivity of the samples which is a great factor controlling the efficiency of the treatment. In this project saline water was used to increase the conductivity of the samples which was accomplished in few days.

6.2 Challenges and recommendations

The project was a challenging one for the presence of different subjects such as chemistry, electricity and learning new software. The time limit was less than what the first goals needed, and some delays occurred for different reasons such as malfunction in the software.

For next similar projects, it would be better to use oil for it won't conduct electricity and increase resistance. Another advantage of oil that one can detect any water leakage going out from the sample. Checking the resistance of the samples and the need of any conductivity improvements are a major steps that should be done before starting the electroosmotic treatment. Electrolysis is a major drawback in the project, where trapped gases had a great influence on the results.

6.3 Further investigations

For better results, the side effects of electroosmosis should be taken into consideration. Eliminating the electrolysis of water which has a large influence in the process is essential. The gasses produced by the electrolysis should be reduced and to do so alternating current could be the solution. Another solution could be the use of degassing valves.

The injection of minerals and checking its effect on the strength of the material was one of the goals of this project, however, there was not enough time to do so. Finally, the application of electroosmosis directly on a triaxial cell can be tested.

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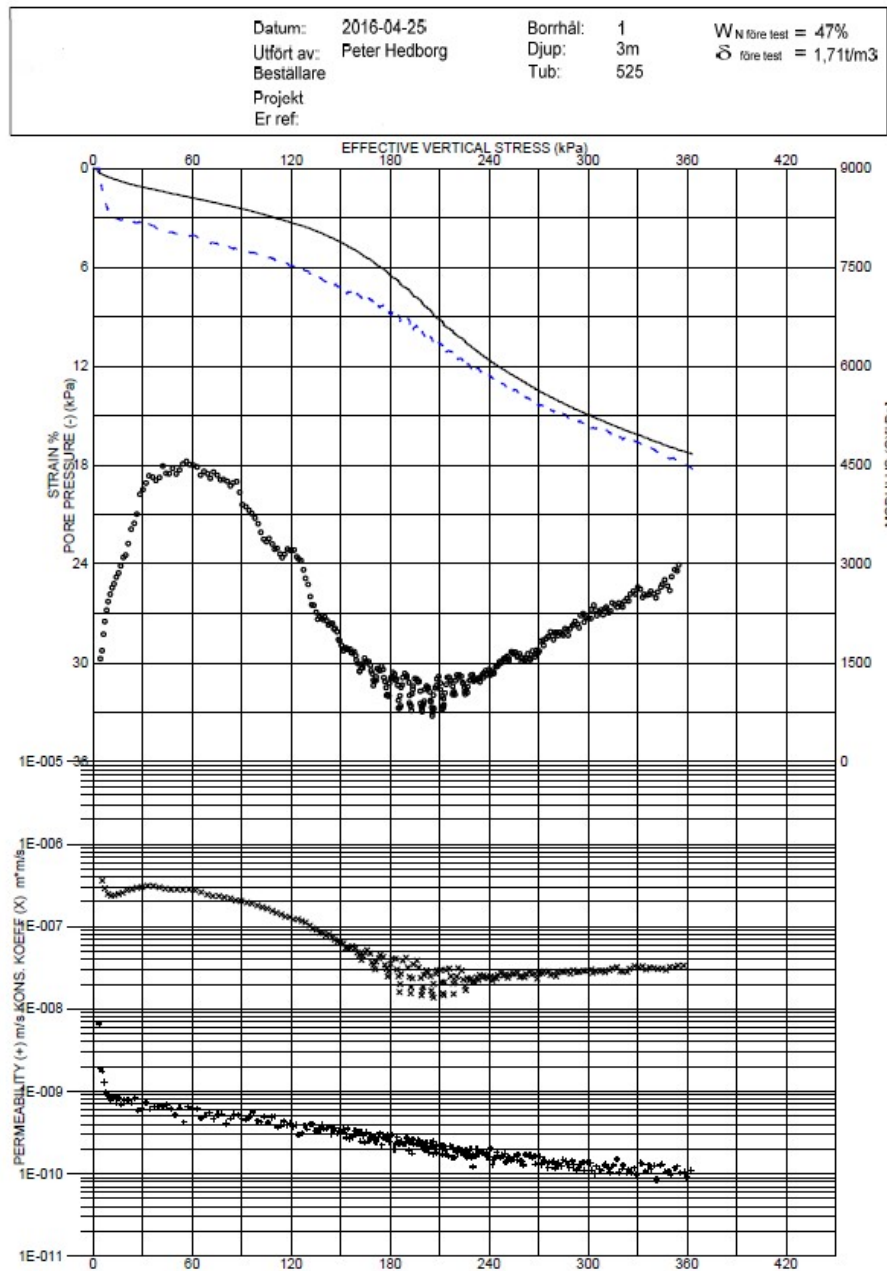
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A

Appendix

CRS Test Results



B

Appendix

Sample

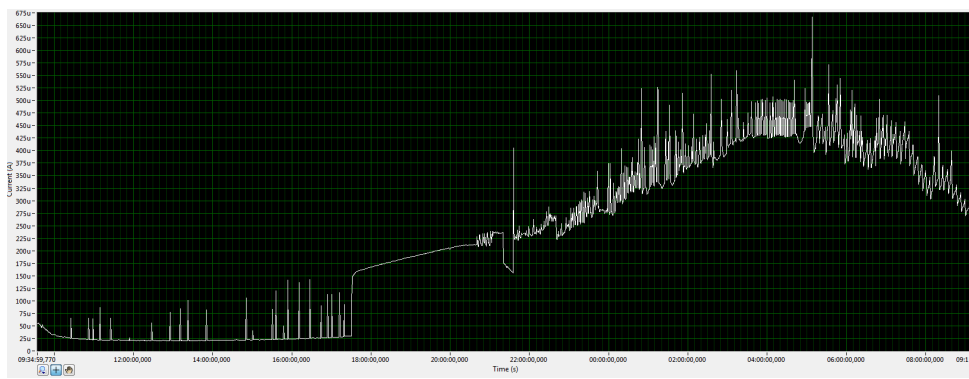


C

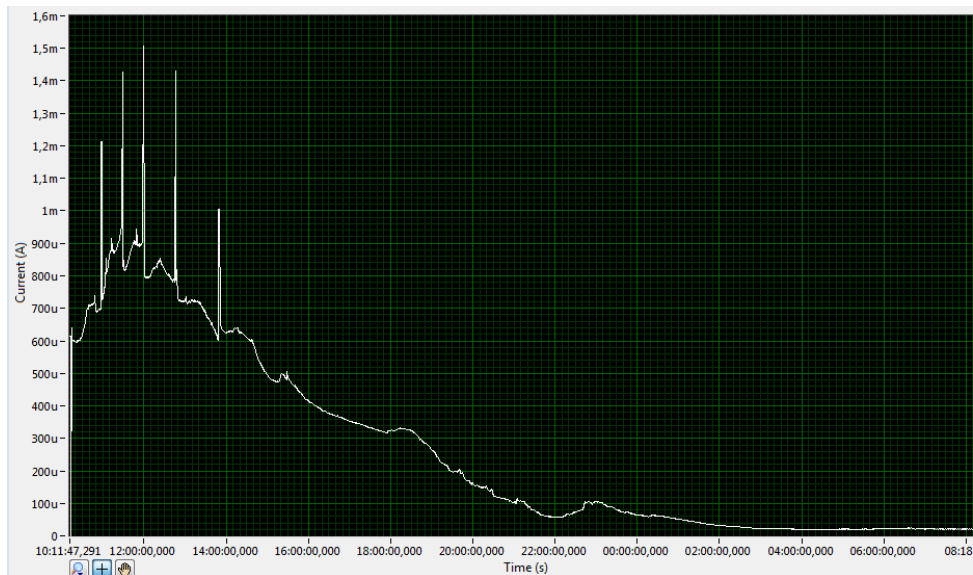
Appendix

SignalExpress Extracted Graphs

First Day



Second Day



Third Day

