Electroosmosis Treatment on Composite Soils

Maher Zuhair Mohammed

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds

School of Civil Engineering

September, 2018

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Acknowledgments

First, all praise to Allah for endowing me with health, knowledge, and strength to overcome all the obstacles to complete this work. Furthermore, I would like to acknowledge my great supervisors, Professor Barry Clarke for suggesting this thesis topic and for encouragement throughout the duration of this thesis. I also wish to thank him for his time during the writing of this thesis and for the long hours of thoughtful discussion. I sincerely feel that without his help and guidance this work would not have been possible. I also wish to thank Dr. Raul Fuentes for his advice, guidance through the four years of my PhD period. I would like to thank them for their great support and precise notes and comments and for keeping faith in me from the first day of my study. It has been both a pleasure and an honour to have worked with them. I am very honoured and blessed for being supervised by them. I am very grateful and thankful to Ministry of Higher Education and Scientific Research (MOHESR) in Iraq for giving me the opportunity to study the PhD and for the fully funded scholarship. I also thankful to the University of Anbar in Iraq which nominate me for the PhD scholarship.

In addition, I would like to acknowledge School of Civil Engineering at the University of Leeds for giving me the opportunity to finish my PhD in this great institution and for providing all the needed support. I would also like to thank all the staff in the School of Civil Engineering at the University of Leeds and all the technical staff for the much appreciated help they gave me throughout this research study. Additionally, I am very grateful for the friendship of my fellow graduate students, their support, advice and assistance gave me great help during the study.

Last but not least, I would like to thank my father and my mother for their support and encouragements for me to keep working hard. Their encouragement provided me with the strength to go on. I wish my father was still alive to see how far I have come as he always wanted me. All the words cannot express my feeling or my appreciation for them. Many thanks to my brother and my sisters for their encouragement. I would like to thank my lovely kids, Aesha, Marya, Osama, and Omar for being beautiful gifts to make my life happier. Special thanks to my wife, for her sacrifices, patience, and support through my study journey to achieve my goals. To my family, may Allah bless you all.

Abstract

As an alternative to stone column in fine grained soils, it is possible to create stiffened columns of soils using electroosmosis (electroosmotic piles). This technique has already been proven. This program of this research is to establish the effectiveness, and the efficiency of the process in different soils. The aim of this study is to assess the capability of electroosmosis treatment in a range of composite soils in terms of the vertical settlement, expelled water, electrical current and power consumption, treatment time and final water content.

The equipment developed by Nizar and Clarke (2013) was used with an octagonal array of anodes surrounding a single cathode in a nominal 250mm diameter 300mm deep cylinder of soil and 80mm anode to cathode distance. The equipment was modified to allow radial and vertical temperature profiles to be monitored during the electroosmotic treatment.

Twenty-four tests were performed on China Clay Grade E kaolin and calcium bentonite (Bentonex CB) mixed with sand fraction C (BS 1881 part 131) at different ratios; (0, 23, 33, 50 and 67%) by weight subjected to different applied voltages (5, 10, 15 and 20). The soil slurry was prepared by mixing the dry soil with water to 1.5 times the liquid limit of the soil mixture. The electroosmotic tests are divided into three phases. In Phases 1 and 2, 15 kPa was applied to simulate a working platform, 50 kPa was used in Phase 3 to simulate a surcharge load. The electroosmotic treatment was only performed during Phase 2. Control tests for each soil mixture were carried out to assess the behaviour of the soil samples subjected to only an increase of vertical pressure, which is 15 kPa in Phase1 and 50kPa in Phase 3

Analysis of the experimental results from this study showed a significant dewatering effect on the soil slurries. The water discharged by the electroosmotic treatment process decreased as the sand content increased. Soil temperature increased significantly when an electrical power was applied and drops when an applied D.C power turned off or when the electrode degraded. The highest increase in temperature was found in pure clays at higher applied voltage after about 8 hours of electroosmosis test.

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A	Cross-Section Area
a	Cross section area of the capillary tube
CEC	Cation Exchange Capacity
c_p	specific heat (kJ/kgºC)
C_v	Coefficient of consolidation (m^2/year)
e	void ratio
e_0	Initial voids ratio
e_1	Voids ratio at the end of Phase 1
e_2	Voids ratio at the end of Phase 2
e_3	Voids ratio at the end of Phase 3
EC	Electrical Conductivity
E	Effective electric field intensity (V/m)
Gs	Specific gravity
h	total hydraulic head (m)
H^+	Hydrogen ion
H_3	Settlement at the end of Phase 3 after electroosmosis treatment (mm)
$H_{3\ control}$	Settlement at the end of Phase 3 in the control test treatment (mm)
i_c	The chemical concentration or gradient $\frac{\Delta c}{L}$
i_e	The electrical gradient which is $\frac{\Delta V}{L}$
i_h	The hydraulic gradient $\frac{\Delta H}{L}$
I	Electrical Current
I_L	Liquid Limit

I_P	Plasticity index
I_h	Hydraulic gradient
Ji	Flow Rate
k_e	coefficient of electroosmotic permeability (m^2/sV)
k_h	coefficient of hydraulic conductivity (m/s)
k_i	electro osmotic transport efficiency (cm^3/Ampere-hours)
k_t	The thermal coefficient
m	Mass of soil (kg)
m_v	coefficient of volume compressibility (m^2/MN)
L	electrode spacing (m)
L_{ii}	Conductivity Coefficient for Flow
n	Porosity
Na	Sodium
NaSiO	Sodium Silicate
OH^-	Hydroxyl ion
PI	Plasticity index
Q	Total volume flow rate (m^3/s)
q_c	Cone resistance
q_h	Hydraulic flow
q_t	The heat flow
r	Radius
R	Electrical resistance (Ω)
SiO_2	Silicon oxide (%)
Si	Silicate
t	Total time (h)

V	Voltage
v	Sample volume
ν_e	The flow velocity due to applied voltage
w	Water content
γ_w	The unit weight of water (kN/m^3)
σ_e	The electrical conductivity
ΔE	Voltage difference
dT	Temperature change
ζ	Zeta potential
η	The viscosity

Chapter 1

Introduction

1.1 Background

Electrokinetic techniques are used in treatment of soft soils to reduce water content by consolidation and drainage, hence increasing the shear strength and stiffness of these soils. In geotechnical engineering, electrokinetics can be defined as the application of electrical current across a saturated soil, this electrical power causes a movement of water from the anode to the cathode (Pugh, 2002) in fine grained soils. The primary concern of electrokinetics in a soil-water system is to force the pore water to flow from the anode toward the cathode. This will produce an increase in density by lowering the water content and thus the void ratio and hence increasing the soil strength and stiffness. This phenomenon is a result of coupling the effect of electrical and hydraulic conductivity of fine grain soils (Acar and Alshawabkeh, 1993).

Electrokinetic treatment also produces electrochemical reactions between soil particles causing cementation between particles (Rittirong et al., 2008b). In addition, the flow of water can remove organic and inorganic components from soil slurries (Acar and Alshawabkeh, 1993).

The mechanism of electroosmosis was first observed in Russia by Ruess in 1809 (Hausmann, 1990) and the first use of electroosmosis techniques in geotechnical engineering was ascribed to Casagrande in 1939 (Micic et al., 2003b). Since then, this method has been used as a soil improvement process, especially for clayey soils. The applications of electroosmosis in consolidation and dewatering have been used widely in laboratories and in-situ tests with different variables (Alshawabkeh et al., 1999b).

1.2 Problem statement

A considerable literature has been developed around the theme of electrokinetic technique and its application in geotechnical engineering, such as electroosmotic consolidation (Casagrande, 1949, Lockhart, 1983b, Lockhart, 1983c, Lockhart, 1983a), friction pile stabilization (Butterfield and Johnston, 1980, Soderman and Milligan, 1961), trenching and excavation of soft soils (Bjerrum et al., 1967, Pugh, 2002), improvement of foundation below buildings and dams (Fetzer, 1967), slope stability (Chappell and Burton, 1975) and remediation of soils (Acar and Alshawabkeh, 1993). The focus of this research is on the electroosmotic piles concept adopted by Nizar and Clarke (2013).

The concept of electroosmotic piles is similar to the soil displacement ground improvement systems such as stone columns in fine grained soils. This technique is used to stiffen the ground by reducing the water content through electrodes in the form of prefabricated vertical drains due to the increase in the mean effective stress around the anodes. However, the stiffness of soils treated by electroosmotic piles increases from the cathode to the anode, while in stone columns there is a step change at the stone column/soil interface (Nizar and Clarke, 2013).

Natural soils normally consist of various sizes of grain particles which contain gravel, sand, silt and clay termed as composite soils (Jalili et al., 2012). The physical properties such as permeability and consolidation of these soils vary with the clay content. Most studies of electroosmotic treatment have been applied to pure clay soils. Research on composite soils is limited.

According to Omine et al. (1989), cited in (Kurata and Fujishita, 1961), composite soils can be classified into three types according to the sand content: sand (contains 80% or over of sand), clay type (under 60%) and the intermediate type (60-80%). The authors also suggested from a practical point of view that soils with sand content less than 80% are treated as a clay soil. According to Skempton (1985), the clay content is the main factor affecting the residual strength in the composite soils.

Most previous research has been carried out on electroosmosis treatment of clay soils. Much uncertainty still exists about the efficiency of this technique with sandy silty clay soils; i.e. composite soils. Lo et al. (1991) reported that the results of the electroosmosis treatment carried out by Caron (1971) on continuous sand and silt soil layers was unsuccessful due to “short circuiting” in the treatment system caused by the relatively high conductivity of the silt soil layers. However, Sumbarda-Ramos et al. (2010) stated that the electrokinetic technique in sandy soils could produce a water flow coupled to the electrical current. Adamson et al. (1966) stated that there is a possibility to use electrochemical method for strengthening sandy soils with a small amount of clay. Therefore, an aim of this study is to determine the amount of clay in a composite soil that would be sufficient for the electroosmotic process to stiffen the treated soil.

Kaolin and bentonite are the most common soils that have been used in laboratory studies in electrokinetic treatment. Other researchers who have looked at composite soils have either used the electrochemical method (Adamson et al., 1966) and (Rittirong et al., 2008b), or they have used electrokinetic remediation (Chung, 2007), (Sumbarda-Ramos et al., 2010) and (Kim et al., 2012). Casagrande (1949) stated that the electroosmosis in sandy soils will be practical when the hydraulic permeability coefficient k_h is equal to or smaller than the electroosmotic permeability k_e. Therefore, this research will study the performance of electroosmotic piles in a range of composite soils by using different mixtures of kaolin and bentonite with sand, then compare the test results with control tests subjected to vertical load only to provide baseline data.

A number of authors have used voltage gradients between (0.5-1 V/cm), for electrokinetic treatment as an optimum voltage gradient for geotechnical purposes (Akram N. Alshawabkeh, et al. 1994, Hamir, et al., 2001, Chung, H. I. 2007,). Lockhart (1983b) concluded that increasing the applied voltage accelerates the electroosmosis process and raises the pH value of kaolin soil (8.5 at 1V to 12.5 at 50V) at the cathode.

Nizar and Clarke (2013) stated that the electroosmotic treatment is a function of voltage and time, the higher the voltage the faster the soil improvement.

Different applied voltages, (5, 10, 15 and 20 Volts) with different electrode arrangements were used in their experimental laboratory work on kaolin soil using a cylinder cell with dimensions (length L= 345 mm, diameter D= 251 mm). They concluded that the final total settlement increases with the increasing applied voltage.

Mohamedelhassan (2009) observed that the increase of settlement and hence the efficiency of electrical field is not linear and may approach a plateau with the increase of applied voltage. Furthermore, a high voltage can lead to unnecessary energy consumption and an increase in soil temperature and desiccation. Morefield et al. (2004) and Kim et al. (2012) noted that the application of electric current causes a rise in soil temperature due to the electrical resistance of soil. They found that the soil temperature increased from 15 to 20, 30, and 65 C°, depending on the electrode arrangement. Increasing soil temperatures may cause an increase in the diffuse layer thickness, which will produce a reduction in surface potential for a constant surface charge (Liaki et al., 2008). Hence electroosmosis reduces the pore pressure and increases the effective stress causing water to flow due to consolidation; creates a hydraulic gradient which limits the efficiency of electroosmosis and uses electrical energy to heat the soil. Villas and Portela (2003) related the rise in temperature to the heat dissipation by Joule effect. Therefore, this study will also explore and measure heat developed at the anodes and the cathodes with different applied voltage and different soil mixtures to observe thermal behaviour of soil during electrokinetic treatment.

The influence of electrode arrangement and spacing play a vital role in the electroosmosis treatment because of its direct effect on the cost. (Alshawabkeh et al., 1999a), (Alshawabkeh et al., 2004), (Rittirong et al., 2008a, Rittirong et al., 2008b), Nizar and Clarke, 2013, Kim et al., 2012, and (Sumbarda-Ramos et al., 2010). Nizar and Clarke (2013) used coiled copper springs as electrodes in six arrangements in their test programme. They concluded that the octagonal arrangements with 8 anodes and one cathode at the centre give the most amount of settlement. Therefore, the above arrangement was adopted in this study to achieve the most efficient electroosmosis treatment.

1.3 Aims and objectives

The purpose of this study is to explore the use of electrokinetic treatment to create electroosmotic piles to increase the stiffness in a range of composite soil. Figure (1.1) shows the aims and objectives presented as a flow chart. The specific aims and objectives of the study are:

1. Review the previous studies of the electrokinetic method in geotechnical engineering. The objectives of this aim are:
    - Provide a context for the electroosmosis treatment.
    - Establish the research criteria from previous studies that govern electroosmotic piles.
    - Determine the range of soils in which the technique can be used and how effective the method is.
2. Investigate the effectiveness of electroosmotic piles to stiffen composite soils. The objectives of this aim are listed below:
    - Create a range of composite soils from kaolin, bentonite and sand with different mixes to study the effects of voltage gradient and time on the process.
    - Implement a control test to establish the properties and behaviour of the soil sample subjected to an increase in pressure. The data for this test will provide a baseline to assess the effectiveness of the electroosmotic piles approach when applied to composite soils.
    - Identify the maximum percentage of sand for electroosmotic piles to stiffen the composite soils by measuring final settlement and expelled water in each soil mix and compare the results with the control test results.
3. Produce guidelines for optimization of the operational electrical energy, overall improvement of the treated soil and the efficiency of the system by achieving the following objectives:
    - Measure the temperature profile between the anode and the cathode to determine how much energy is lost.
    - Observe the thermal behaviour of the electroosmosis treated soil to avoid excessive increases in temperature and energy losses by

comparing the voltage gradient used with the final settlement, then predict the amount of useful energy for each soil mix.

- Evaluate the impact of treatment time on electroosmosis to explore and attain the optimum time required for treatment which achieve maximum relative density with minimum voltage.

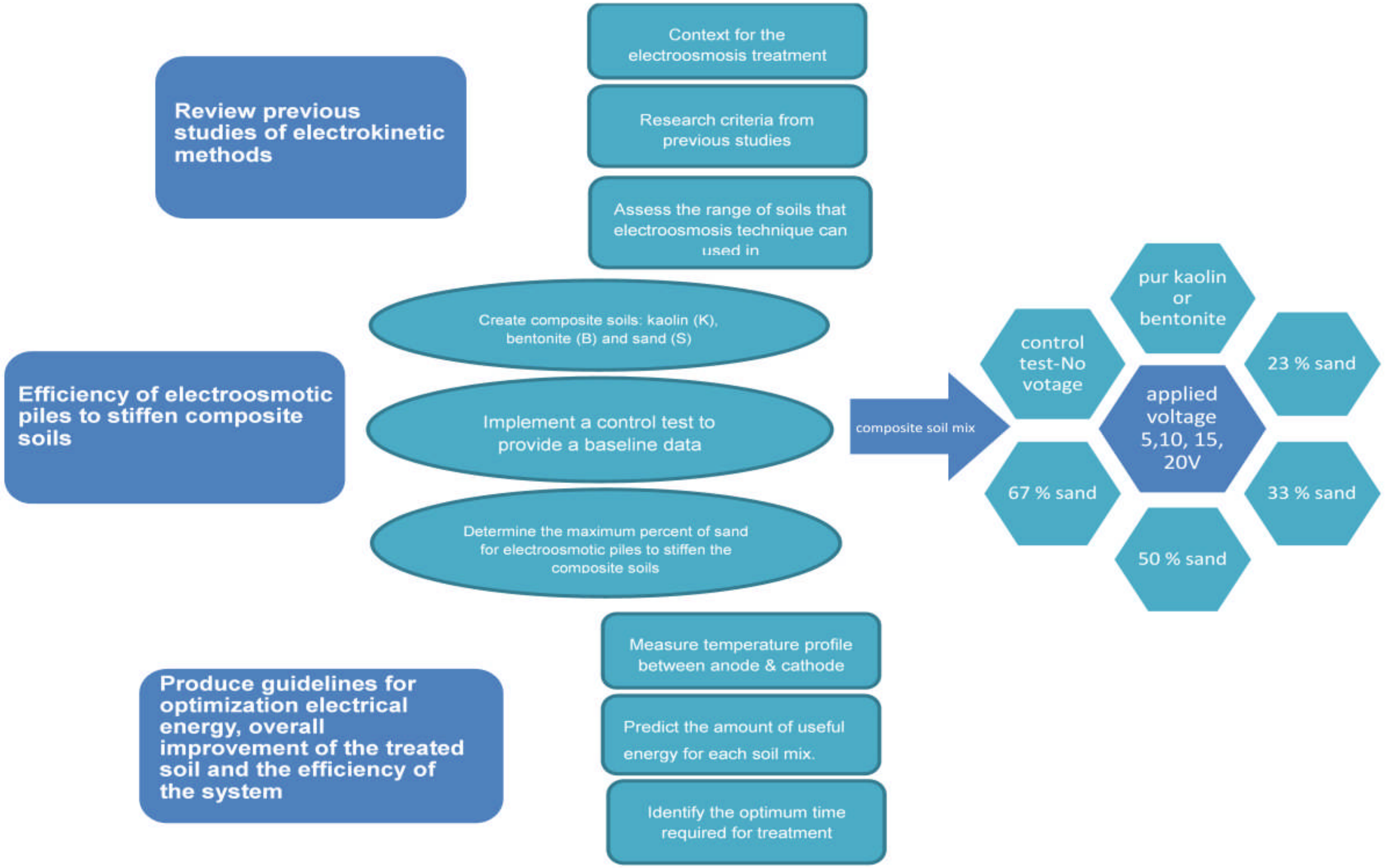


Figure 1.1 Aims and objectives schematic diagram

1.4 Layout of the thesis

This thesis begins with an introductory chapter. It will then go on chapter 2 which presents the literature review of electrokinetic phenomena to understand the theoretical and fundamental background for this phenomenon and identify the research questions. Chapter 2 also describes the clay mineralogy and structure, clay-water system, flow types and theories of electrokinetic in soil. The applications of electrokinetic phenomena in soil treatment in soil treatment fields is mentioned in this chapter.

The third chapter is concerned with the methodology and laboratory process of the experimental program used for this study. It details the materials used, testing equipment, and the testing procedure for this research. An example of the test results is also presented in this chapter.

Chapter 4 presents and discusses the results and analyses of the experimental tests on kaolin and sand soil mixtures. The soil composition and voltage were varied between tests; the settlement of the sample, expelled water, current and temperature were measured during test; and the final water content was measured at the end of a test. The results of settlement and water content of composite soils are compared to the results from the control tests.

In Chapter 5, the results and analyses of the experimental tests on bentonite and sand soil mixtures are described and discussed in same manner as in Chapter 4.

Chapter 6 assesses and compares the effects of electroosmotic treatment on the behaviour of kaolin and bentonite slurry mixed with and without sand under different applied voltages. The comparison between the two soils is in terms of settlement, voids ratio, electrical current, hydraulic and electroosmotic permeability, generated heat, consumed and dissipated energy, and electroosmotic efficiency.

Finally, Chapter 7 discusses the key findings and useful information related to electroosmotic treatments on the behaviour of composite soil when an electric current is applied. The conclusions and recommendation for future works that were drawn from this study are also presented in this chapter.

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the development of electrokinetic phenomena by introducing the relevant literature which cover soil particle mineralogy and structure, chemistry of pore fluid, and double layer theory to provide a better understanding of the soil-water interaction. It then goes on to discuss the flow types in soils, the proposed theories for electrokinetic phenomena, electroosmosis theory and zeta potential.

According to Mitchell (1993), and Acar and Alshawabkeh (1993), electrokinetic phenomena occurs in soil when an electrical potential is applied between two electrodes as a consequence of coupling between electrical potential gradients and hydraulic gradients which causes water movement from the anode towards the cathode. As a results, this technique provides a kind of soil improvement by reducing the water content of the treated soil, thereby increasing its stiffness. Several factors affect this techniques including, soil conductivity, applied voltage, electrode material and electrode arrangement, which are discussed in this chapter.

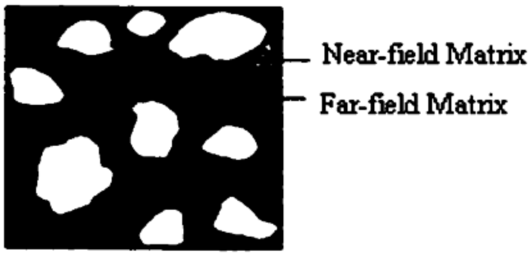
This chapter also discusses some of the geotechnical engineering applications of electrokinetics. Electrokinetics applications have been successfully applied in many laboratory based and some field studies to treat soft clays. This technique has been widely used to improve the stiffness properties of certain soil types, which is known as electroosmosis consolidation. However, research on composite soil consolidation using electroosmosis technology has not been reported in the literature, and the knowledge of the composite soil behaviours under an electric potential is limited. This chapter aims to review the published behaviour of soils treated by electroosmosis in order to provide a better understanding of soil-water interaction due to the application of electrical current before applying this technique to the composite soils used in this study.

2.2 General properties of composite soils

Soils, in nature, normally consist of grain particles of various shapes and sizes. The mechanical and physical properties of these soils, such as, shear strength, compaction characteristics, and permeability, depend on the grain size distribution and have matters of concern because their behaviour is not as those soils of pure clay, silts or sand. According to Omine et al. (1989), cited in Kurata and Fujishita (1961), composite soils can be classified into three types according to the sand content; sand (contains 80% or over of sand), clay type (under 60%) and the intermediate type (60-80%). They also suggested from a practical point of view that soils with sand content less than 80% are treated as a clay soil. According to Skempton (1985), the clay content is the main factor affecting the residual strength in the composite soils.

Jalili et al. (2012) carried out an experimental test to investigate the effect of heterogeneity on excess pore water pressure, stress and strain distribution in composite soils. They concluded that the change of pore pressure in a saturated composite soil depends on the subsequent load and the initial consolidation stress in addition to the plasticity and permeability of clay in the soil mixture.

Omine et al. (1989) divided composite soil mixtures into two types; floating coarse particles (in which grains have no contact) and nonfloating type (in which grains forming skeleton of coarse particles). Fragaszy et al. (1992) suggested that in the floating case, Figure 2.1 (a), the oversized particles percentage is 40% or less and there is a little or no contact among the coarse particles. In the non-floating state, Figure 2.1 (b), the coarse particles are in contact with greater than 65% oversized particles. In this case, the deformation and strength behaviour are controlled by the coarse particles.



Floating Case

Non-floating Case

Figure 2.1 Schematic diagram of soil shows floating and non-floating case with coarse particles (Fragaszy et al. (1992)

To assess electroosmosis treatment on composite soils, it is necessary to review the mineral composition and structure of clay soil since the electroosmosis process depends on the coefficient of electroosmotic conductivity. The electroosmotic flow is induced by an electric field and causes an increase in concentration of cations and the negative charge of clay surface as the cations in negatively charged clay particles are much higher than anions, this results in drawing pore water from the anode to the cathode. Therefore, details about clay mineralogy and structure will presented in the next sections.

2.3 Problems with clay soils

Clay is a fine grained natural soil or rock material that can undergo considerable changes in volume when subjected to load. The water content of clay soils may be greater than their liquid limit. However, clay soils are plastic due to the effect of high moisture content and become non-plastic and hard upon drying (Guggenheim and Martin, 1995). The maximum water content that can be held in soils increases with the increase of clay content and because of the surface activity of clay soils, the presence of water strongly affects their behaviour (Miura, 2001).

Soft clay soils can exhibit an extreme change in their properties, such as high settlement, loss of shear strength, heaving and shrinkage. Atterberg limits are a basic measure of the water contents between states in soil, and include liquid limits, plastic limits and shrinkage limits. Clay soils may appear in four states; liquid, plastic, semi solid and solid, as shown in Figure (2.2), (Das and Sobhan, 1994). The boundary between each state depends on the water content of soil. Liquid limits (I_L) define the water content of clay soil when it changes state from a plastic state to a liquid state. Water content between plastic limit and semi-solid state is called plastic limit (I_P) and the shrinkage limit (S_L) is the state when the losses in water content does not result in any volume change (Seed et al., 1964).

In general, the plasticity of fine clay soils has a significant effect on the behaviour of these soils and their properties, such as compressibility and shear strength. The more compressible a clay soil, the greater the tendency to consolidate over a period of time. These types of soils are difficult to compact when used as a filling material (Das and Sobhan, 1994).

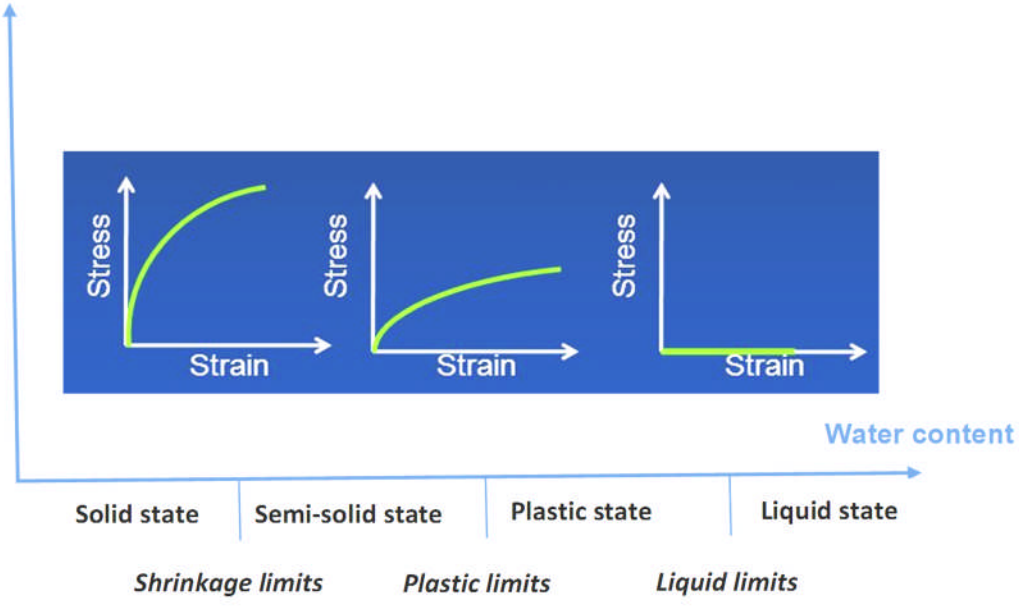


Figure 2.2 Consistency limits of fine soil

2.4 Clay soils; mineralogy and structure

To understand the behaviour of clayey soil particles during the electrokinetic process, it is necessary to survey the characteristics and the compositions of these particles.

2.4.1 Mineralogy

Mineralogy is a fundamental concept in the soil system, and plays a key role in controlling other physical and chemical properties of soil such as shape and size of soil particles. The first stage in formation of minerals in soil particles is weathering of rocks and other residual soils; hence most inorganic soils contains minerals larger than 80% by weight of the derived rocks (Pugh, 2002).The range of particle size, varying from gravel, sand, silt and clay as shown in Figure (2.3).

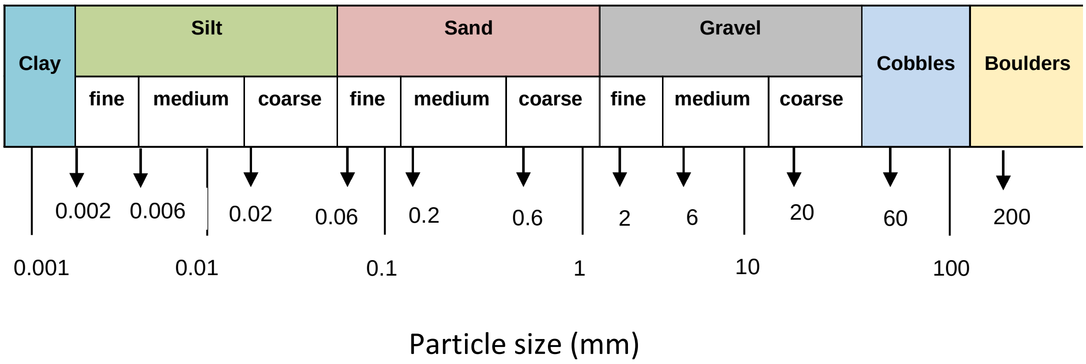


Figure 2.3 Particles size range in soils after (Knappett, 2012)

In geotechnical engineering, the term minerals are used to refer to soil particles smaller than 0.002mm. According to Unified Soil Classification System (USCS), clay soils are fine materials which contain 50% or larger by weight that pass through sieve No.200 (0.075 mm). The word clay also refers to the specific properties stated by (Mitchell, 1993):

- Small particle size
- A net negative electrical charge
- Plasticity when mixed with water
- High weathering resistance

Clay minerals usually have a “platey shape” and high specific surface area (Liaki, 2006). Physically, the plate shape with high specific surface area leads to a strong performance of the electrical forces between soil particles. According to (Terzaghi and Peck, 1956), each soil particle carries a negative charge on its surface. The intensity of these electric charges depends on the chemical and physical manifestation character of the surface charged particle which constitute the high or low “*surface activity*” soils. Based on the chemical combination, the fine soil minerals can be divided in to three main groups; montmorillonite, Illite, and kaolinite. The surface activity of these minerals are quite different; montmorillonite is the most active clay minerals, Illite is less active than montmorillonite. The least surface activity soil minerals is the kaolinite group.

2.4.2 Structure

Mitchell and Soga (2005) stated that the clay minerals in soils are related to the phyllosilicates minerals, which contains many silicate such as pyrophylite, chlorite, serpentine, mica and talc. According to Das and Sobhan (1994) and Mitchell and Soga (2005), the normal shape of the layered silicate in clay minerals consists of two main structural units; silicon tetrahedron and aluminium octahedron, shown in Figure (2.4). The combination of these elements is responsible for different crystal structure arrangements of clay particles. These arrangements vary from poor to nearly perfect depending on the bond direction, electrical neutrality and the close packing of atoms. However, the performance of the layered silicate will vary because of their high surface area and chemical reactivity (McBride, 1994), (Liaki et al., 2008).

Kaolinite minerals consists of successive layers of silica-gibbsite sheets in a 1:1 trioctahedral lattice, as shown in Figures (2.5 a) and (2.6 a). The bonding between repeated layers in kaolinite structure is sufficiently strong, so that there is no swelling in the presence of water.

Illite minerals consist of a gibbsite sheet sandwiched between to two silica sheets, one at the top and another at the bottom as shown in Figure (2.5 b).

The structure of montmorillonite minerals is similar to that of illite, one gibbsite sheet bonded between two silica sheets, there is no potassium ions as in illite, as shown in Figures (2.5 c) and (2.6 b). In montmorillonite, there is a large amount of water attracted into the space between the silica sheets. The bonds between repeated layers are weak and easy to separate by adsorption of water or other polar liquids.

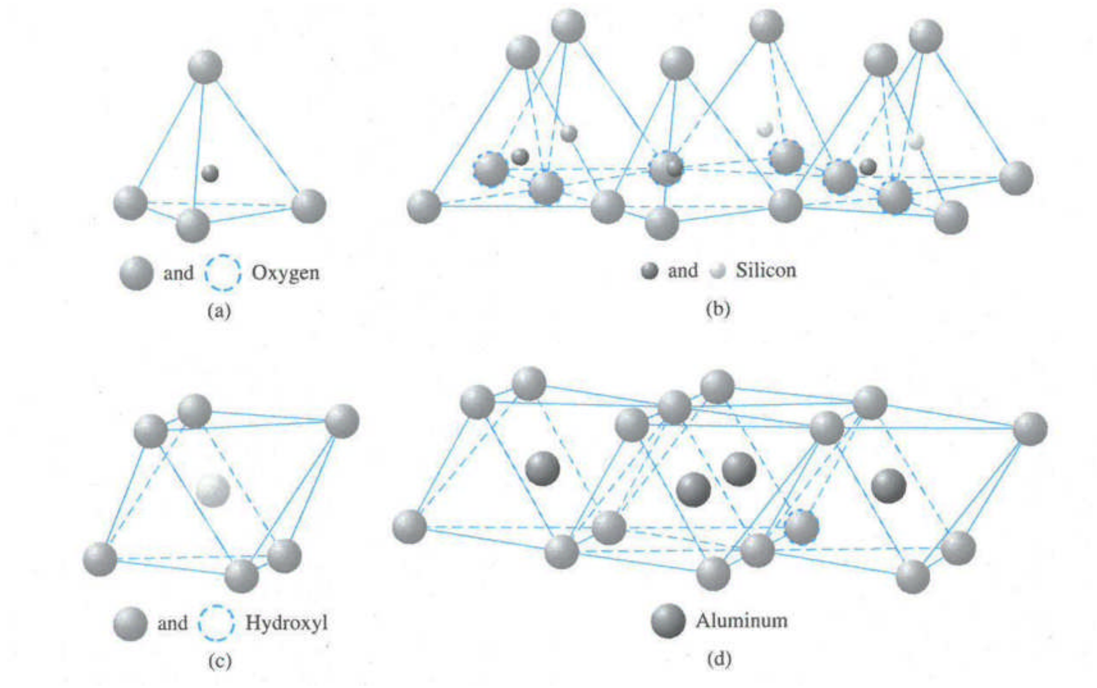


Figure 2.4 (a) Silica tetrahedron; (b) silica sheet; (c) alumina octahedron; (d) octahedral (gibbsite) sheet;(Das and Sobhan, 1994)

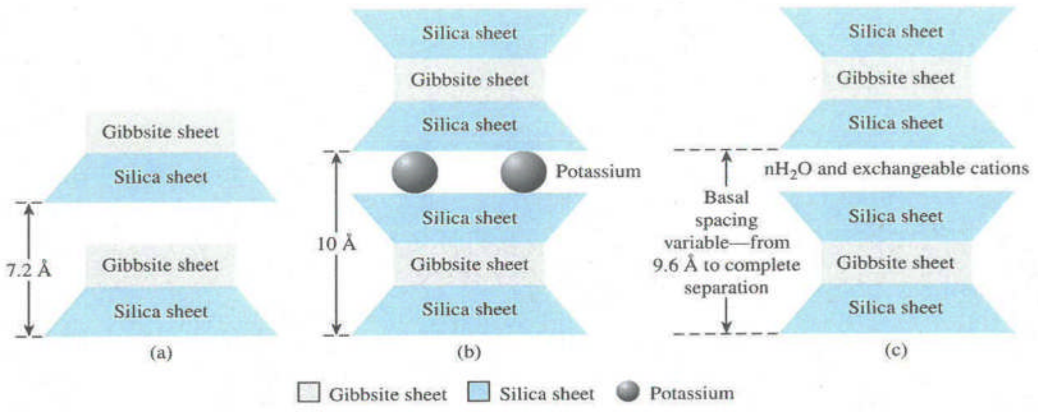
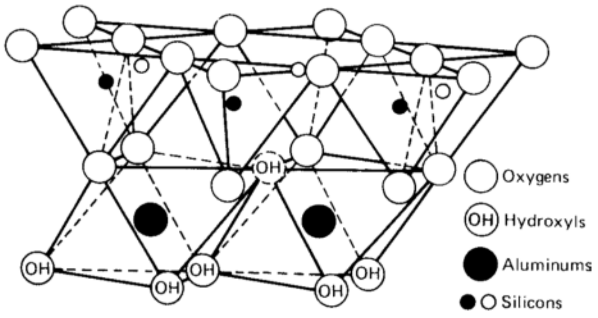
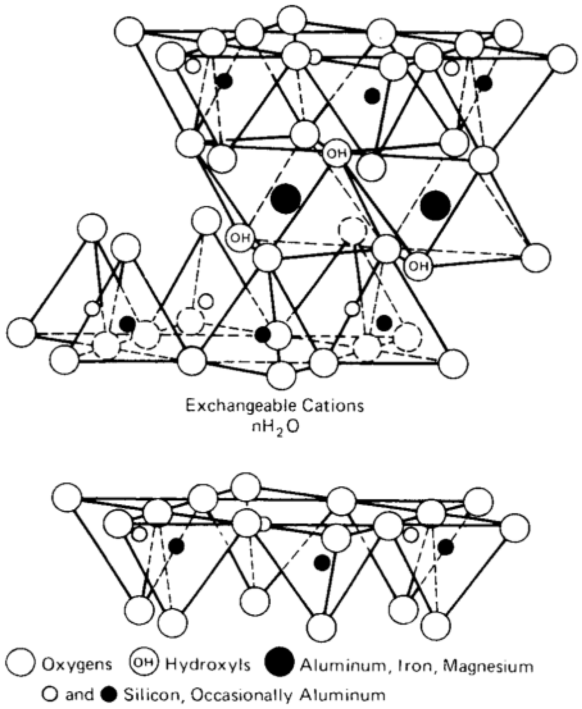


Figure 2.5 Diagram of the structures of (a) kaolinite; (b) illite; (c) montmorillonite (Das and Sobhan, 1994)



(a) kaolinite structure



(b) montmorillonite structure

Figure 2.6 Diagrammatic sketch of the kaolinite and montmorillonite structure (Mitchell and Soga, 2005)

2.5 Diffuse double layer

In dry soils, the surface of the clay mineral particles carries a negative charge which is derived from the large specific surfaces which results from isomorphous substitution. The replacement of silicon atoms in a crystal structure is by a lower valence atom (Al or Mg), or due to a break in continuity of hydroxyl ions (Craig, 1994). In the presence of water, positively charged ions concentrated in the water are attracted by the negative charge on the clay particles to provide an adequate balance in concentration. The negative electrical field in the clay particle surface restricts the diffusion of these cations and their escaping tendency to create the idealized ion distribution. This configuration is termed the diffuse double layer, (Terzaghi and Peck, 1956), (Das and Sobhan, 1994) and (Mitchell and Soga, 2005). This concept consists of two phases: the charged surface of clay particles, shown in Figure (2.7a), and the distributed ionic charge in the adjacent phase. The concentration of the cation decreases with distance from the surface of the clay particle (Figure 2.7b). According to Craig (1994), the thickness of cations layers decreases with the increase in cation concentration and soils temperature.

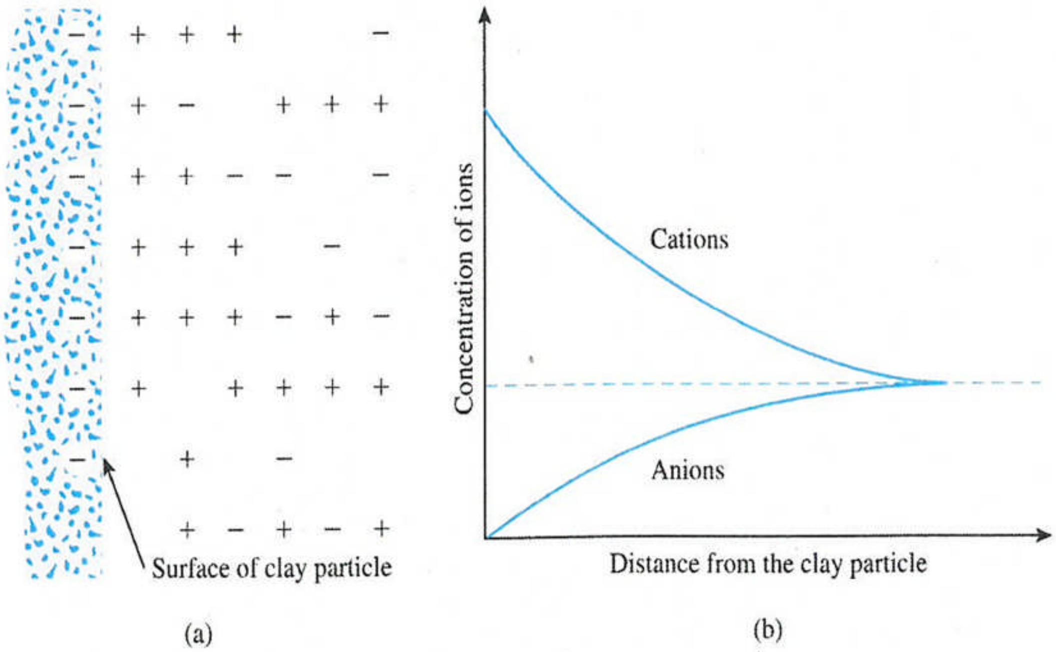


Figure 2.7 Diffuse double layer (Das, 1994)

2.6 Flow types through soils

Flow of water in media, such as clay soil, plays a vital role in the behaviour and properties of these media such as stability, volume change and deformation. Therefore the flow of water in soil is considered an essential problem in geotechnical engineering, especially in consolidation and seepage.

According to Mitchell (1993) and Alshawabkeh et al. (2004), there are four main types of flow through the soil medium: hydraulic, electrical, thermal, and chemical in addition to several types of coupled flow, which means a flow of one type driven by potential gradient of another type. Mitchell (1993) proposed that all the flow rates J_i are linearly proportional to a driving force X_i and conductivity coefficient L_{ii} according to the following equation:

$$J_i = L_{ii}\, X_i \tag{2.1}$$

Figure (2.8) illustrates the four types of direct flow through a soil mass and the governing equation for each type. Table (2.1) explains typical range of flow parameters for fine-grained saturated soil.

2.6.1 Hydraulic flow

Hydraulic flow or hydraulic conduction is the transport of water or fluid due to the effect of head differential through a soil media and described by Darcy's law:

$$q_h = k_h\, i_h\, A \tag{2.2}$$

Where q_h is the hydraulic flow, k_h the hydraulic conductivity, i_h the hydraulic gradient ($\frac{\Delta H}{L}$), and A cross-sectional area normal to the flow direction.

Water flow through soil medium is a function of particle type and size, degree of saturation and temperature (Barker et al., 2004). According to Mitchell and Soga (2005) the hydraulic flow depends on the clay content, soil density, sedimentation procedure and concentration of electrolyte.

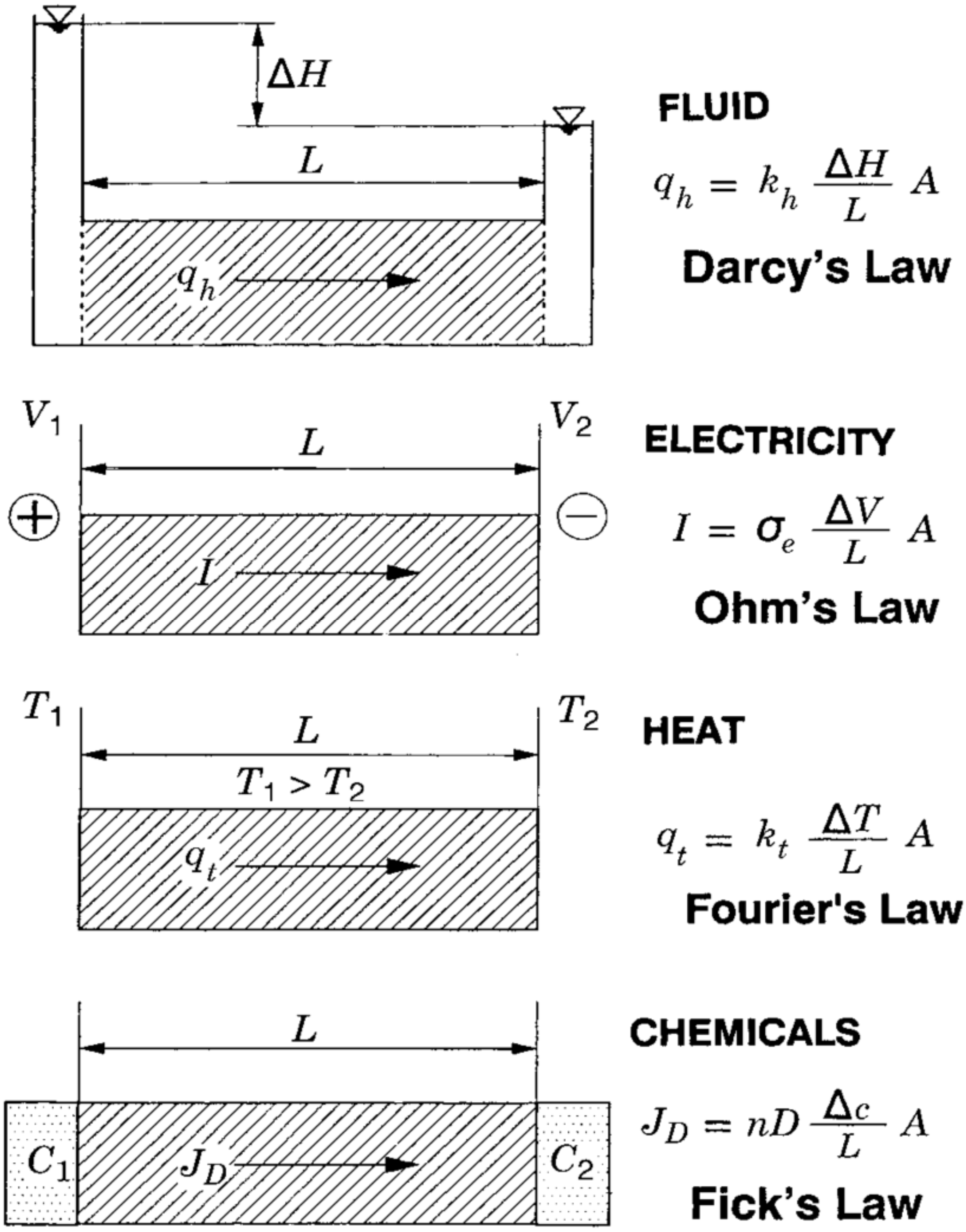


Figure 2.8 Four types of flow through soil mass (Mitchell & Soga, 2005)

Table 2.1 Typical range of flow parameters for fine-grained saturated soils (Mitchell and Soga, 2005)

Parameter	Symbol	Units	Minimum	Maximum
Porosity	n	---	0.1	0.7
Hydraulic Conductivity	k_h	m s^{-1}	1 x 10^{-11}	1 * 10^{-6}
Thermal Conductivity	k_t	W m^{-1} K^{-1}	0.25	2.5
Electrical Conductivity	σ_e	Siemens m^{-1}	0.01	1.0
Electroosmotic Conductivity	k_e	m^2 s^{-1} V^{-1}	1* 10^{-9}	1 * 10^{-8}
Diffusion coefficient	D	m^2 s^{-1}	2 * 10^{-10}	2* 10^{-9}
Osmotic efficiency	ω	---	0	1.0
Ionic mobility	u	m^2 s^{-1} V^{-1}	3* 10^{-9}	1 * 10^{-8}

2.6.2 Electrical flow

The term electrical flow, as used by (Liaki et al., 2008), can be defined as the transport of ions due to the applied electrical potential across a porous medium. These ions will accelerate and gain a kinetic energy when an electrical field is generated as described by Ohm's low (Mitchell, 1993) .

$$I = \sigma_e \, i_e \, A \tag{2.3}$$

Where I is the electrical flow, σ_e the electrical conductivity, i_e the electrical gradient which is $\frac{\Delta V}{L}$, and A the cross-sectional area normal to the flow direction. The electrical conductivity of the soil depends on many factors, such as the mineralogy, porosity, degree of saturation, conductivity of the pore water pressure, temperature and the structure of soil (Mitchell, 1993). The electrical conductivity of the soil-water system is equal to the increase of electrical resistivity:

$$\sigma_e = \frac{1}{R}\frac{L}{A} \qquad \text{Siemens/m} \tag{2.4}$$

Where *R* represents the resistance (Ω), *A* is the cross-sectional area (m^2) and (*L*) is the length of sample (m). The electrical conductivity of saturated soil is usually ranged between 0.01 -1.0 (Siemens/m). According to Barker et al. (2004), there are specific factors affecting the conductivity of the soil treated with electricity including the following:

a) The stability of minerals present, which is a function of pH. The decrease in the pH value from about 8.0 to 7.0 will cause the solubility of the aluminium oxide (a predominated clay mineral) to decrease slightly from 2.8 - 2.4 moll/l.
b) The migration of ions out of the soil. The electrical current applied to the soil-water system would cause a migration of cations and anions towards the cathode and anode respectively.
c) The precipitation of compound as ions mix within the pore fluid. This precipitation results from altering of species of ions within the pore water and forming compounds which may be more sensitive to the variation of observed pH value.

2.6.3 Heat flow

Heat flow or thermal conduction is the transfer of heat through the medium such as a soil due to a temperature gradient. This phenomenon takes place by conduction, convection and radiation (Mitchell and Soga, 2005) as described by Fourier's law:

$$q_t = k_t \, i_t \, A \tag{2.5}$$

Where q_t is the heat flow, k_t the thermal coefficient, i_e the thermal gradient which is $\frac{\Delta V}{L}$, and A cross-sectional area normal to the flow direction. According to Mitchell (1993), the thermal conductivity in soils depends on soil density and the degree of saturation.

2.6.4 Chemical flow:

Chemical flow of diffusion is the flow generated due to the chemical potential gradient and it occurs because of the transport of a chemical species from a high concentration area to a low concentration area (Mitchell, 1993). Chemical flow in a free solution is governed by Fick's law:

$$J_D = D\, i_c\, A \tag{2.6}$$

Where J_D is the chemical flow, D the diffusion coefficient, i_c the chemical concentration or gradient which is equal $\frac{\Delta c}{L}$, and A cross-sectional area normal to the flow direction.

Barker et al (2004) reported that the diffusion coefficient D_{ic} is a variable and it is affected by ions relative to pressure, concentration of solution in porous medium and the electrolyte strength. Liaki (2006) mentioned that the chemical flow through a saturated soil is not like water flow because of the presence of solids and the flow paths is around the particles (tortuosity). He stated that many parameters affect the diffusion through a porous media such as saturated soils and make it complex like ion exchange, double layer distribution of charges, osmotic counter flow, precipitation and organic diffusion. Liaki (2006) also noted that the diffusion coefficient of soil D is time dependant.

2.7 Coupled flow

In practice, a single type of flow doesn't occur in soil independently, usually more than one type of flow operates simultaneously even if only a single driving force exists. An example of this is the transport of chemicals in water under a hydraulic gradient (Pugh, 2002).

Mitchell and Soga (2005) observed that the gradient of one type can cause flows of another types, equation 2.1 can be written as:

$$J_i = L_{ij}\, X_j \tag{2.7}$$

Where L_{ij} is the coupled flow coefficient. The 12 - coupled flow that may occur in soil are presented in Table (2.2). Electroosmosis is of special interest in this study as it is very important during the electrokinetic applications and will be discussed in more details in Sections 2.8.1.

Table 2.2 Direct and coupled flow phenomena (Mitchell and Soga, 2005)

Flow *J*	**Hydraulic Head**	**Temperature**	**Electrical**	**Chemical Concentration**
Fluid	Hydraulic conduction *Darcy's law*	Thermoosmosis	Electroosmosis Chemical	Chemical osmosis
Heat	Isothermal heat transfer or thermal filtration	Thermal conduction *Fourier's law*	Peltier effect	Dufour effect
Current	Streaming current	Thermoelectricity *Seebeck or Thompson effect*	Electric conduction *Ohm's law*	Diffusion and membrane potentials or sedimentation current
Ion	Streaming current Ultrafiltration or (hyperfiltration)	Thermal diffusion of electrolyte or *Soret effect*	Electrophoresis	Diffusion *Fick's law*

2.8 Electrokinetic phenomena in soil

The primary concern of electrokinetics in soil-water system is to force the pore water to flow from the positive terminal (anode) towards the negative terminal (cathode). This will produce an increase in soil strength by lowering moisture content and reduce compressibility. Therefore, the electrokinetic phenomenon is equivalent to the consolidation theory.

Ahmad et al. (2006) proposed that the electrokinetic phenomena concerned with the movements of solids in soil-water system versus the liquid under the effect of electrical field. The electrokinetic flow in porous medium such as soils are based on the relative motion between a charged surface of clay particles due to the creation of electric double layer and the bulk solution at its interface. Hausmann (1990) and Mitchell (1993) stated that the essential electrokinetic phenomena in porous medium involves: electroosmosis, flow potential, electrophoresis, and migration or sedimentation potential.

In this research study, the focus will be on more details of electroosmosis as it is the main governing phenomena in geotechnical engineering. The schematic diagram, Figure (2.9) shows the various electrokinetic processes in soil treatment technique, and Figure (2.10) shows the four electrokinetic phenomena in soil.

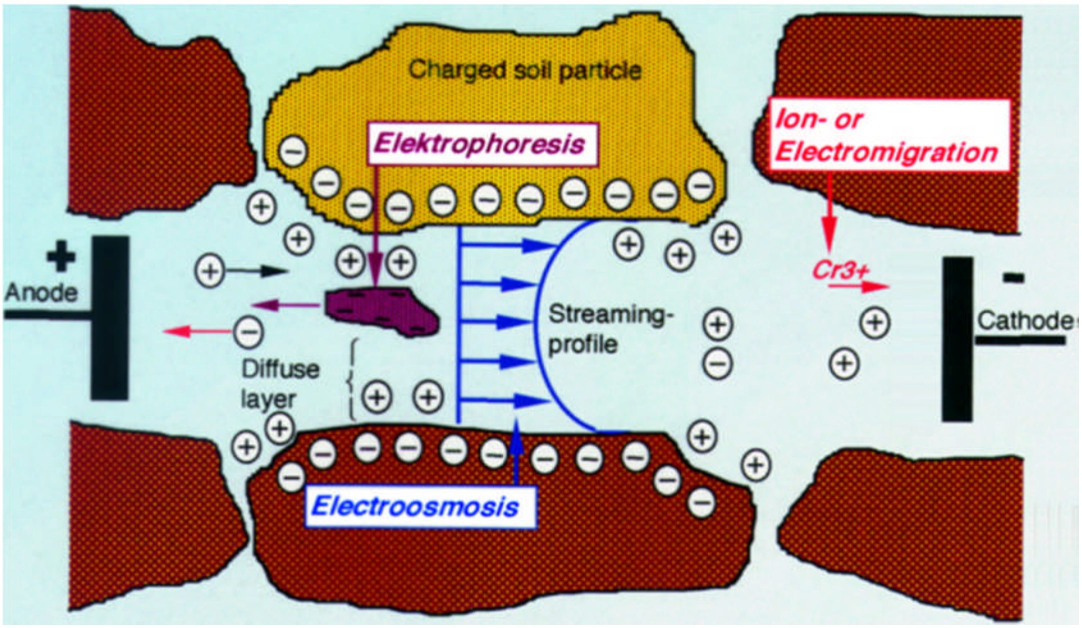
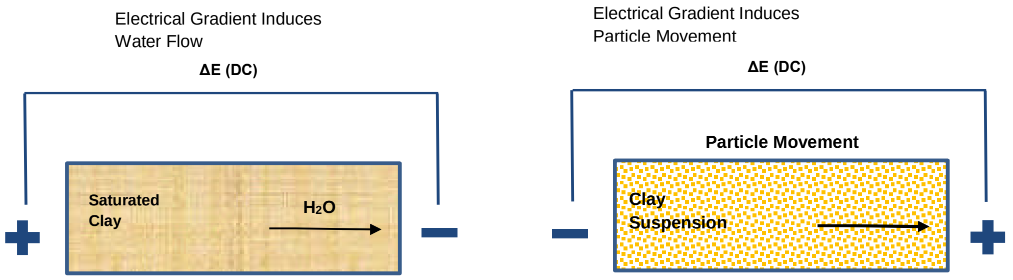


Figure 2.9 Schematic diagram of various electrochemical processes under electrokinetic technique (Mosavat et al., 2012)

2.8.1 Electroosmosis

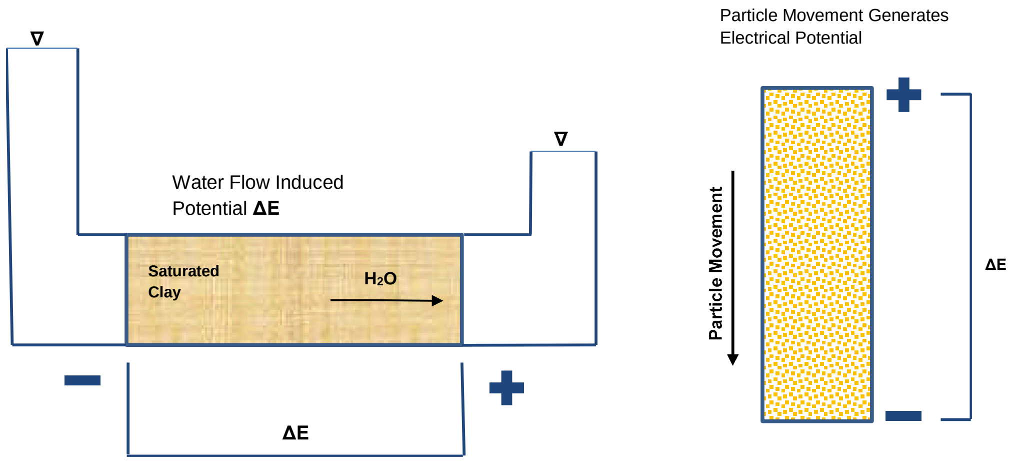
The principle of electroosmosis was first described by Reuss in 1809, who observed that water flows through clay soils when a direct electric current is applied, as shown in Figure (2.11). Hausmann (1990) and (Mitchell, 1993) stated that in a wet soil, water would flow from anode towards cathode under the effect of applied electrical potential as shown in Figure (2.10 a). This flow is caused by attraction of anions to the anode and cations to the cathode and during this migration, moving ions will carry the hydration water around them.

Since the cations in negatively charged clay particles are much higher than anions, as a result, pore water is drawn from the anode to the cathode. Electroosmosis depends on the coefficient of electroosmotic conductivity and the applied voltages. More details about electroosmosis in soils will discussed later.



(a) Electroosmosis

(c) Electrophoresis



(b) Streaming potential

(d) Migration or sedimentation potential

Figure 2.10 Electrokinetic phenomena in soil. (Reproduced from Mitchell and Soga, 2005)

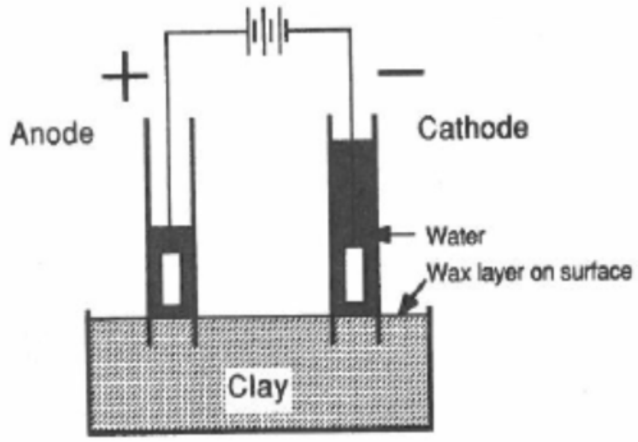


Figure 2.11 Schematic arrangement of Reuss' experiment (Hausmann 1990)

2.8.2 Flow potential (streaming potential)

When water is forced to flow through a soil under a hydraulic or thermal gradient, double layer electrically charged particles are moved with it in the direction of flow. The electrical potential generated between the opposite ends of soil, which is proportional to the hydraulic flow, is termed flow potential or streaming potential as shown in Figure (2.10 b), (Mitchell and Soga, 2005). This method is the reverse of electroosmosis and it was first reported in 1861 by Quinke (Hausmann, 1990).

2.8.3 Electrophoresis

When an electrical field is applied across a colloidal suspension, the negatively charged particles are transported electrostatically to the anode and repelled from cathode as shown in Figure (2.10 c). Hausmann (1990) stated that the negatively charged particles will be attracted toward the anode while the positively charged ions will move towards the cathode under the effect of DC electrical field when the electrode immersed in colloidal soil suspension rather than in coherent soil mass. Mitchell (1993) explained the difference between electroosmosis and electrophoresis where the former involves water transport through a continuous soil particle system while the latter is involved in discrete partial transport through water. Electrophoresis has found application in high water content clay and for concentration of mine waste (Liaki, 2006). Electrophoresis has been used also in supporting bentonite in a slurry wall as shown in Figure (2.12). The bentonite particles creates a “clay boundary film” when attracted to the sand which causes movement of pure water from the sand soils towards the bentonite slurry. According to Acar and Alshawabkeh (1993), electrophoresis is thought to play a role in the electrokinetic remediation techniques in nonpolar organic substances.

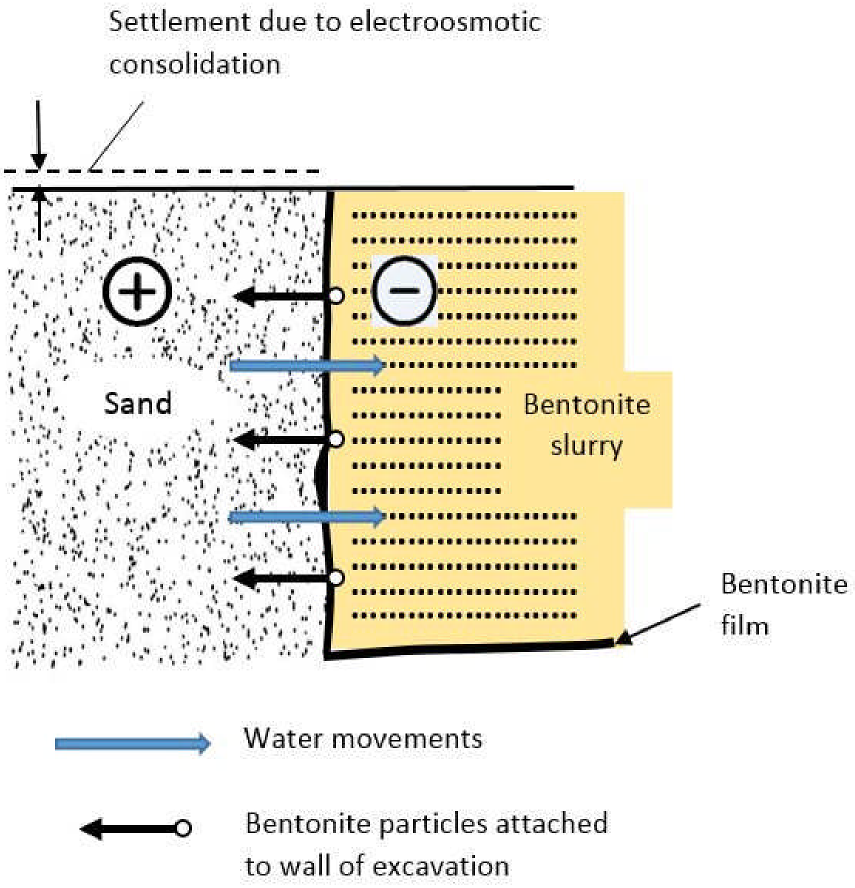


Figure 2.12 Electrophoresis of bentonite slurry wall (Reproduced from Hausmann, 1990)

2.8.4 Sedimentation potential or migration:

Sedimentation potential can be defined as the movements of the charged soil particles in a fluid medium due to the effect of electrical potential difference, as shown in Figure (2.10 d) (Pugh, 2002). The sedimentation potential is observed in clay solutions during gravitational settling, where the movement of negatively charged clay particles and produces a viscous dragging force which retards the movements of the diffuse double layer cations relative to the particles, (Mitchell and Soga, 2005) and (Liaki, 2006).

2.8.5 Electromigration (ion migration)

The movements of ions within the fluid phase of charged soil particles due to the applied electrical potential difference is shown in Figure (2.11 e) (Pugh, 2002). Therefore, ions are attached to the electrodes of the opposite sign and repelled from electrode with the same sign. Electromigration occurs simultaneously with electroosmosis in wet soils and the former take place within the pore fluid in the soil, however, the paths in ion migration in soils are longer and more difficult than in liquid (Liaki, 2006).

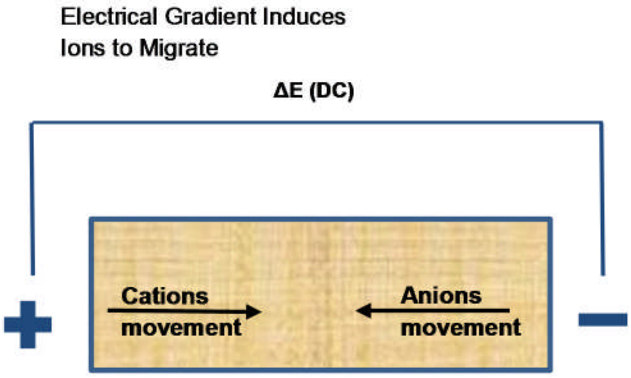


Figure 2.13 Electromigration (ion migration) in soils

From the above electrokinetics phenomena, only electroosmosis, electrophoresis, and electromigration have been given the most attention in geotechnical engineering application because of their practical value for water movements and ions charged in soils treatment.

2.9 Electroosmosis theories and reactions

Electroosmosis phenomenon is an important component in ground modification methods and there is growing research in the literature that recognizes the application and the developments of this technique. Electroosmosis has been used as means of ground improvement such as dewatering and consolidation. The first major studies included lab and field work by Casagrande in 1949. Examples of the development of the application of electroosmosis in soils include stabilizing trenches and cavitation (Bjerrum et al., 1967), slope stability (Casagrande 1952a, 1952b), preventing shrinkage and swelling under foundations (Casagrande, 1949) and (Bjerrum et al., 1967), ground improvement by consolidation (Alfaro et al., 1994), dewatering (Gray and Mitchell, 1967), and assisting pile driven (Esrig, 1978) and (Christenson, 1979).

Many theories of electroosmosis have been developed to explain the mechanism of this phenomenon. One of the earliest and most widely used is Helmholtz theory in 1879 and refined by Smoluchowski in 1914 shown in Figure (2.14).

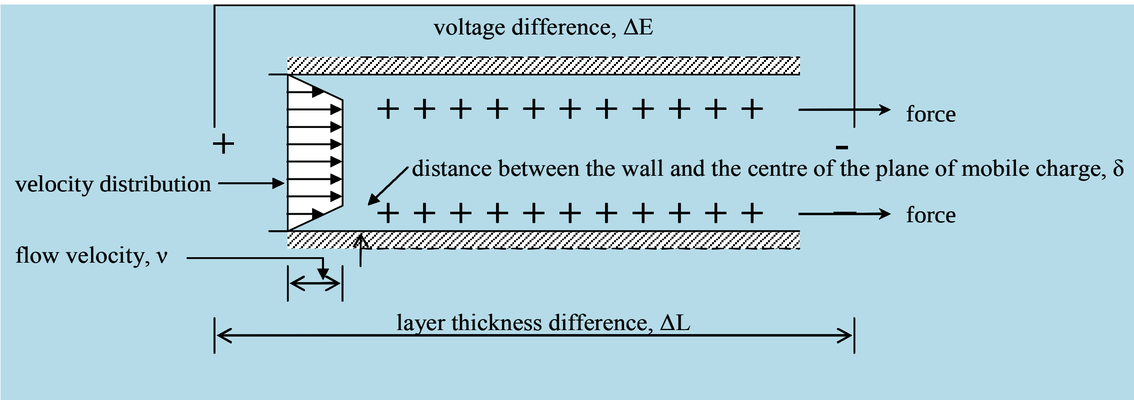


Figure 2.14 Helmholtz-Smoluchowski model for electrokinetic phenomena (Reproduced from Mitchell and Soga, 2005)

As shown in this Figure (2.14), the fluid in the capillary tube formed by clay particles works as an electrical conductor. The surface of the clay particles has negative charges, the cations are concentrated in a layer of the fluid. The concentrated mobile ions are assumed to drag the water in the capillary tube by plug flow. (Mitchell and Soga, 2005), (Das, 2013). The flow velocity due to the applied electrical field can be given by:

$$\nu_e = \frac{D\,\zeta\,E}{4\pi\,\eta\,L} \tag{2.8}$$

Where ν_e is the flow velocity due to applied voltage; D is the dielectric constant; ζ is the zeta potential; η is the viscosity; and L is the electrode spacing.

The Helmholtz-Smoluchowski theory is based on the assumptions that the capillary tube radius is relatively large in comparison to the diffuse double layer thickness around the clay particles, and that all the mobile charge ions are concentrated near the soil-water interface. As shown in Figure (2.14), the high- velocity gradient appears between the two plates of the capillary tube. According to Das (2013), the rate of water flow can be calculated by:

$$q_c = \nu_e\,a \tag{2.9}$$

Where a is the cross section area of the capillary tube.

It is assumed that a soil mass contains a number of capillary tubes due to the interconnection between voids, the cross-sectional area of the voids A_v is:

$$A_v = n\,A \tag{2.10}$$

Where *n* is the porosity, *A* is the gross cross-sectional area of the soil.

The rate of flow *q* through a soil gross cross-sectional area can be given by:

$$q = A_v\,\nu_e = n\,A\,\nu_e = n\frac{D\,\zeta\,E}{4\pi\,\eta\,L}A \tag{2.11}$$

The most widely used electroosmotic flow equation for the soil system is suggested by Casagrande (1949) in according to Darcy’s law, that the relation between the flow rate and the electrical potential gradient for a porous medium in the above equation can be expressed by the relation:

$$q = k_e\,i_e\,A \tag{2.12}$$

Where $k_e = n(D\,\zeta/4\pi\eta)$ is the electroosmotic coefficient of permeability, i_e is the electrical potential gradient.

The coefficient of electroosmotic conductivity(k_e) is independent of pore size, it is depends on the zeta potential (ζ) which is defined by Van Olphen (1977) as the electrical potential at the interface surface between the moving particles in the applied electric field and surrounding fluid.

In addition to electroosmosis, application of direct current causes electrolysis reactions of water at the electrodes; an acid front generates at the anode (O_2 and H^+) and base front generated at the cathode (H_2 and OH^-), (Acar et al., 1990a), (Acar et al., 1990b), (Ahmad et al., 2006) and (Asadi et al., 2013). The primary electrode reactions can be represented by the following equations:

$$2H_2O - 4e \rightarrow O_2\uparrow + 4H^+ \qquad \text{(anode)} \tag{2.13}$$

$$4H_2O - 4e \rightarrow 2H_2\uparrow + 4OH^- \qquad \text{(cathode)} \tag{2.14}$$

Figure (2.15) shows the principle of electroosmosis. According to Alshawabkeh (2009), the electrolysis process depends on the chemistry of soil water, gas production, and the efficiency of electrolysis redox.

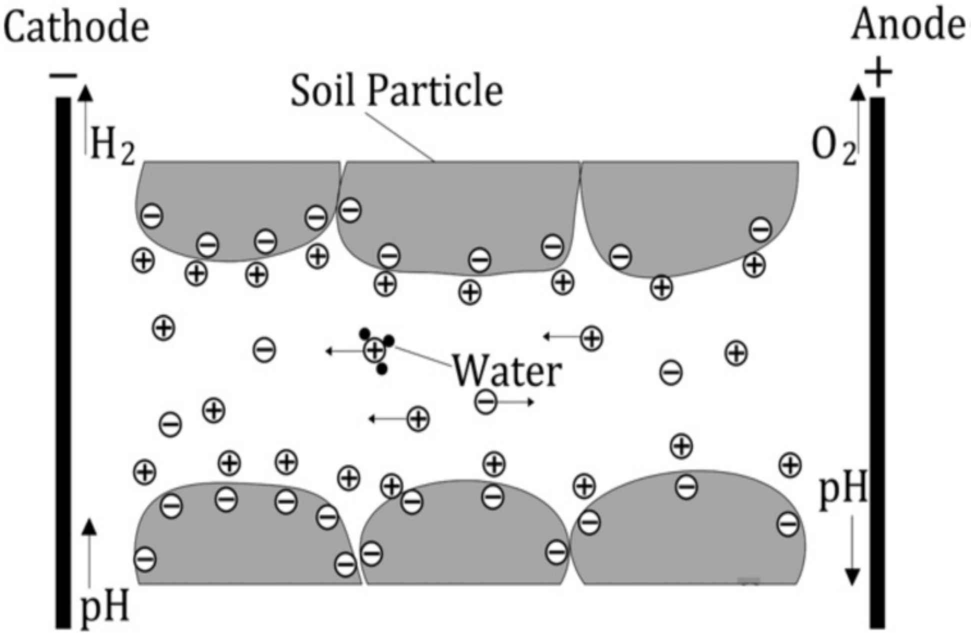


Figure 2.15 Principles of electroosmosis (Peng et al., 2015)

2.10 Zeta potential and its significant

Numerous studies have been carried out about the zeta potential, a classical equation to calculate *ζ-potential* is equation 2.12. Detailed analysis of calculating the zeta potential value in electroosmosis is given by Hunter (1981) who considered that the analysis of forces on the liquid or solid in terms of electrostatic potential is called electrokinetic potential or zeta potential. The interaction energy between particles in the double layer can determine the potential distribution in saturated soil. It can be defined as the slip plane in electrokinetic processes which is allocated at a small and unknown distance from the soil particles surface (Liaki, 2006). Mitchell and Soga (2005) describe the zeta potential as a measure of the double layer potential, with higher zeta potential values related to the thicker double layers and higher sensitivity. Shang (1997) concluded that the zeta potential depends on the electrolyte type, concentration, and valence of water.

Hunter (1981) proposed three features that can affect the surface charge, the double layer and the surface potential as follows:

1. The potential determining which ions that apply a primary control on the charged surface and the potential at the surface of the dispersed phase.
2. The neutral electrolyte ions, which generally control the extension of the double layer out of the solution and not interact within the surface.
3. Other ionic species, which are inside the double layer and interact with the surface especially.

The ζ – potential is usually negative in most soils because of the negative charge at the soil surface. According to Asadi et al. (2013), the zeta potential is an indicator of the double layer thickness. As the zeta potential increases, the thickness of the double layer increases. The result is that electroosmotic flow is generally toward the cathode. However, both pH and ionic strength of the pore fluid, which change continuously during electrokinetic processes, affect the of zeta potential value. (Hunter, 1981) (Tajudin and Azhar, 2012).

2.11 Factors effect on electroosmosis

As the electroosmosis treatment is considered an effective soil strengthening techniques, there are primary factors controlling this process namely, soil type, the applied voltage, electrode materials, and electrode configuration. This section investigates the practical considerations from literature to clarify the effect of these factors and to optimize the electroosmosis treatment.

2.11.1 Effects of boundary conditions

According to Hausmann (1990), there are four possible boundary conditions that may occur depending on the nature of the developed pore pressure, 1) both anode and cathode sealed (no drainage or water access, which is possible in the field; 2) anode sealed and cathode open; 3) cathode sealed and anode open; and 4) both cathode and anode are open. The last two cases are more relevant to laboratory work. Hamir et al (2001) stated that in the fourth case, when both anodes and cathodes are open, there is no excess pore water pressure at the anode because it is open thus creating flow. The most practical boundary conditions used with electroosmotic consolidation are in the second case where maximum dewatering is achieved since no water is allowed to enter at the anode. Therefore, negative pore pressure is generated at the anode thus increasing the effective stress leading to consolidation around the anode. According to Hamir et al. (2001) the pore water pressure developed due to electroosmosis depends on the current density and the soil resistivity.

2.11.2 Effect of soil types

As mentioned before, clay soil minerals possess a “platey shape”, and carry a residual negative charge on their surfaces. Consequently, clay minerals are described as electrically active and have the ability to absorb ions from the surrounding environment; this behaviour is called “cation exchange capacity”.

In general, clay soils have very low hydraulic conductivity and the electroosmotic flow rate in clayey soils is significantly higher than hydraulic flow rates (Jayasekera, 2004a).

Some previous studies have shown that the major clay mineral groups described in section 2.4; kaolinite, illite and montmorillonite (bentonite) possess different electroosmosis abilities depending on their cation exchange capacities and buffering capacity (resistance to pH change).

Acar and Alshawabkeh (1993), Reddy and Saichek (2003), and Mosavat et al. (2013b) mentioned that kaolinite minerals possess a lower cation exchange capacity and buffering capacity compared to other clay minerals. This means that kaolin soil exhibits highest electroosmosis efficiency compared to other soils followed by clayey sand. Mosavat et al. (2014) showed that montmorillonite (bentonite) soils possess a much higher cation exchange capacity and buffering capacity compared to kaolinite. Moreover, these soil minerals exhibit large swelling and shrinkage characteristics upon moisture content change, which make bentonite soils sensitive to the chemical environmental change. According to Wu et al. (2015b), the swelling and shrinkage behaviour of the bentonite were reduced after the electroosmotic treatment, which means this technique may provide a new way to improve the expansive soils stability.

Some previous studies have shown the electroosmotic permeability (k_e) is constant for all soils and it is independent of the soil type, (Casagrande, 1949) and (Jayasekera, 2004a). However, Gray and Mitchell (1967) stated that the electroosmotic permeability varies considerably for different soil types.

The success of electroosmosis depends on the clay content and most studies have focused on clays and silts. There is currently no work carried out on composite soils to establish the percent of clay necessary to ensure electroosmosis works. Some of the electrical energy is used to heat the soil, but there is no research to establish how much and what are the facts that govern increasing temperature.

Therefore in this study, kaolin and bentonite soil in a pure form and mixed with different ratios of sand fraction C were chosen, as they have different mineralogy, permeability and geotechnical properties, to investigate and compare the potential of electroosmotic treatment techniques to improve and stabilise the composite soils. The original properties of the pure kaolin and bentonite soils used in this study are described in details in Chapter 3.

2.11.3 Influence of applied voltage

An experimental demonstration of the effect of voltage on the electrokinetic treatments has been carried out by a number of researchers. Lockhart (1983c) carried out an electroosmosis dewatering test using sodium kaolinite clay suspension with voltages from 1V to 50V. He concluded that increasing the applied voltage produces faster electroosmosis and raises the pH value of the treated soil (8.5 at 1V to 12.5 at 50V) at the cathode.

Nizar and Clarke (2013) stated that the electroosmotic treatment is a function of voltage and time, the higher voltage the faster the consolidation. Different applied voltages with different electrode arrangements were used in their experimental work, (5, 10 and 20V) and they concluded that the final total settlement increases with the increasing applied voltage.

Mohamedelhassan (2009) observed that the increase of settlement with the increase of applied voltage is not linear and may approach a plateau. Furthermore, high voltages can lead to unnecessary energy consumption and increase soil temperature and desiccation. While investigating the effect of the effect of electrokinetic stabilization on soft soils, Mohamedelhassan (2009) found that an increase in temperature within the treated zone (between 5-20 °C) will occur and this generated heat as the applied voltage increased. Morefield et al. (2004) and Kim et al. (2012) noted that the application of electric current caused a rise in soil temperature due to the electrical resistance of soil. Increasing the soil temperature may cause an increase in diffuse layer thickness which will produce a reduction in surface potential for a constant surface charge (Liaki et al., 2008). Hence electroosmosis reduces the pore pressure and increases the effective stress causing water to flow due to consolidation. This effect creates a hydraulic gradient which limits the efficiency of electroosmosis and uses electrical energy to heat the soil.

According to Mosavat et al. (2012), the variation of the applied voltage or current intensity depends on the soil electrochemical properties, and soils with higher electrical conductivity require more current intensity than lower electrical conductivity soils.

Therefore, in the current study, electroosmotic tests were carried out with different applied voltages and compared with control tests without applied voltage to investigate the effect of the voltage gradient changes on the electroosmotic process to attain the optimum power required for treatment.

2.11.4 Effect of electrode material

Electrode material is an important component in the electroosmosis technique, and plays a key role in electroosmotic soil treatment. According to Shang and Lo (1997), the electrode material is one of the crucial factors affecting the influence of the electroosmosis process by the efficiency, corrosion and lifetime. Many electrode material types have been used in previous studies. Table 2.3 shows some electrode types used in other electroosmotic studies with the applied voltages presented by (Hamir et al., 2001).

Lockhart (1983a) investigated the effects of common electrode materials (iron, copper and graphite) on the electroosmosis treatment. He found that for kaolinite, copper electrodes achieved better results than the other electrode types, followed by iron electrodes, and the worst is the graphite electrodes.

Méndez et al. (2012) proposed that some electrodes materials suffer a kind of passivation and oxidation during electrokinitic processes, including silver, stainless steel, titanium, platinum, and gold.

Wu et al. (2015b) and Wu et al. (2015a) investigated the effect of electrode materials on ions transport and exchange behaviour in Na-bentonite soil during electroosmotic consolidation. Four different electrode materials were used in their study; copper and iron as a reactive electrodes and graphite and stainless steel as inert electrodes. They found that for the inert electrodes (graphite and stainless steel) the primary chemical reaction at the anode is the electrolysis of water and only H^+ is produced. In the reactive electrodes (copper and iron), the chemical reaction at the anode is oxidation of the metal electrodes, accompanied with a small amount of water electrolysis. Cu^{2+}, Fe^{2+}/Fe^{3+}, and H^+ are released into the soil during this process, causing a change in soil chemistry and pH. They concluded that the best drainage performance was achieved in the copper electrode, followed by iron, then graphite, and the worst is the stainless steel.

Another type of electrodes that has been used in electroosmotic treatment is electrically conductive geosynthetics (EKG) materials, introduced by Hamir et al. (2001) for use in soil consolidation and the construction of reinforced soil and then used in a range of electrokinetic applications such as; dewatering of fine grained slurries sewage sludge (Kalumba et al., 2009, Glendinning et al., 2010, Zhuang et al., 2014); dewatering and strengthening of mine tailings (Fourie et al., 2007, Fourie and Jones, 2010), and slope stability (Jones et al., 2014). According to Hamir et al. (2001), the EKG material are effective in electroosmosis treatment and provide adequate drainage to increase the shear strength of fill and can provide a noticeable increase in bond strength when used in reinforced soil structures. They have the advantage over metallic electrodes as they do not corrode unlike metal electrodes.

In that sense, no variation was observed in experimental results presented by Zhou et al. (2015). They found that the copper electrode has the best electooosmotic drainage performance for low voltage gradient compared with other electrode materials; iron, graphite and aluminum.

The major challenge in electroosmosis applications is the inevitable corrosion in the anode due to electrochemical reaction when metal electrodes used, which is affects the efficiency of the electroosmotic process and leads to energy dissipation (Zhou et al., 2015) (Lee et al., 2016). However, the copper electrode is still favourable in the electroosmosis soil treatment in many published studies as it is induces better drainage performance compare to other materials.

Table 2.3 Types of electrodes used in other electro-osmotic studies together with the applied voltages, voltage gradients and current densities applied (Hamir et al., 2001)

Author	Electrodes	Applied voltage (V)	Voltage gradient (V/cm)	densities (A/m2)
Casagrande (1949)	Platinum wire gauze as anode. Cotton fabric stretched over wire gauze as cathode	Not mentioned	0.1–12	Not mentioned
Casagrande (1952)	Platinum wire mesh	Not mentioned	1.6	Not mentioned
Nicholls and Herbst (1967)	Steel nail in porcelain filter as cathode. Steel specimen ring as anode	1.5, 3, 6	0.115, 0.572, 1.33	N.A
Evans and Lewis (1970)	Platinum gauze	1.5–2.0	Not mentioned	Not mentioned
Johnston and Butterfield (1977)	Stainless-steel mesh	3	0.3	Not mentioned
Wan and Mitchell (1976)	Silver chloride with porous disc	Not mentioned	1.25	1-1.5
Lo et al. (1991)	Copper electrodes	3–6	0.15–0.3	1.27–3.8
Hamir et al., (2001)	Conductive geosynthetics	5–30	0.4–2.5	0.3–5.9

2.11.5 Influence of electrode configuration

The influence of electrode arrangement and spacing play a vital role in the electroosmosis treatment because of its direct effect on the efficiency and cost. Any electroosmotic application requires optimization of the electrode configuration and spacing. (Kalumba et al., 2009), (Alshawabkeh et al., 1999a), (Rittirong et al., 2008b), (Sumbarda-Ramos et al., 2010), (Nizar and Clarke, 2013), and (Kim et al., 2012).

Alshawabkeh et al. (1999a) stated that the number of anodes should be much higher than the cathodes because of consolidation occurring in the soil surrounding the positive terminal moving toward the negative terminal. They suggested that most effective layout is the hexagonal arrangement with only one central cathode as shown in Figure (2.16). Based on later study, the percentage of the ineffective area for hexagonal arrangement is 29% as presented in Table (2.5). Nizar and Clarke (2013) studied six arrangements of electrodes used in their test program as shown in Figure (2.17). They concluded that the Q4 arrangements with 8 anodes and one cathode at the centre give the most amount of settlement. In this study, the Q4 arrangement adopted by Nizar and Clarke (2013) was used to achieve higher effective area treated by electroosmosis. The detailed spacing and arrangement will describe in Chapter 3.

A field test was carried out by Kim et al. (2012) to study the influence of electrode configuration on electrokinetic remediation. Four different arrangements and spacing of a 1.7 m depth perforated hollow stainless steel pipe were used as a cathode and a steel bar in PVC casing to provide room for the anolyte inlet and outlet, with many holes along was used as an anode as shown in Figure (2.18) . They found that the A4 arrangement (8 m^2 and 1 m spacing between electrodes) shown in figure is the best layout in removing metal from soil compare to the other arrangements. They also found that dense electrode configurations under a constant applied voltage gradient gives rise to current, which leads to raised soil temperature, and this resulted in increases in the electrical energy consumption, as some of the applied energy used to heat up the treated soil.

The reported temperature rose gradually from 15 ºC to 65, 30, and 20 ºC in A2, A3, and A4 respectively, under a constant applied voltage of 100 V, which produced a voltage gradient of 1 V/cm in A2 and A4, but it was 0.5 V/cm in A3, where there was a coverage area of 4 m^2 for A2, and 8 m^2 for A3 and A4. The highest increase in temperature in A2 arrangement is related to the high electrode density within the same area compared to other electrode configurations.

Sumbrada, et al. (2008) studied the effect of electrode arrangement on electrokinetic stabilization of caisson anchors embedded in calcareous sand soil in the lab. The caisson model was 200 mm in diameter and 400 mm high. They concluded that there is a linear relationship between the increase in the required energy and side resistance, so the efficiency of electrokinetic can be increased by optimizing the electric field distribution and the consumption energy through electrodes. According to the experimental investigation of LI and GONG (2012) on the effect of electrode spacing, decreasing spaces between the electrodes with the same voltage gradient leads to effective improvement of the electroosmotic consolidation efficiency.

In addition to the mentioned above factors, there are other parameters that influence treatment time, exchangeable cations, flocculants and acid or salts concentration mentioned in (Lockhart, 1983a) and (Nizar and Clarke, 2013).

Table 2.4 Impact of electrode configuration on electrode requirements and size of ineffective areas (reproduced from Alshawabkeh *et al*., 1999)

Configuration	**Spacing**		**F_1**	**A_{cell}**	**Electrodes/area**		**Ineffective Area**	
	Opp.	**Same**			**N**	**%**	**A_{ineff}**	**% of A_{cell}**
1-D	L_E	L_E	1	L_E^2	$1/L_E^2$	0	$L_E^2/2$	50
1-D	L_E	$L_E/2$	2	L_E^2	$2/L_E^2$	100	$L_E^2/4$	25
1-D	L_E	$L_E/3$	3	L_E^2	$3/L_E^2$	200	$L_E^2/6$	17
Square	R_E	$\sqrt{2}\ R_E$	2	$2R_E^2$	$1/R_E^2$	0	R_E^2	50
Hex.	R_E	R_E	3	$3\sqrt{3}$ $R_E^2/2$	$\frac{\sqrt{4/3}}{R_e^2}$	15.5	$3R_E^2/4$	29

Hex.: hexagonal; Spacing: electrode spacing; Opp.: opposite charge; same: same charge; F_1: number of electrodes per cell; A_{cell}: area of cell; Electrodes/area: number of electrodes per unit area; %: increase percentages; A_{ineff}: ineffective area; % of A_{cell}: percentages of area of cell.

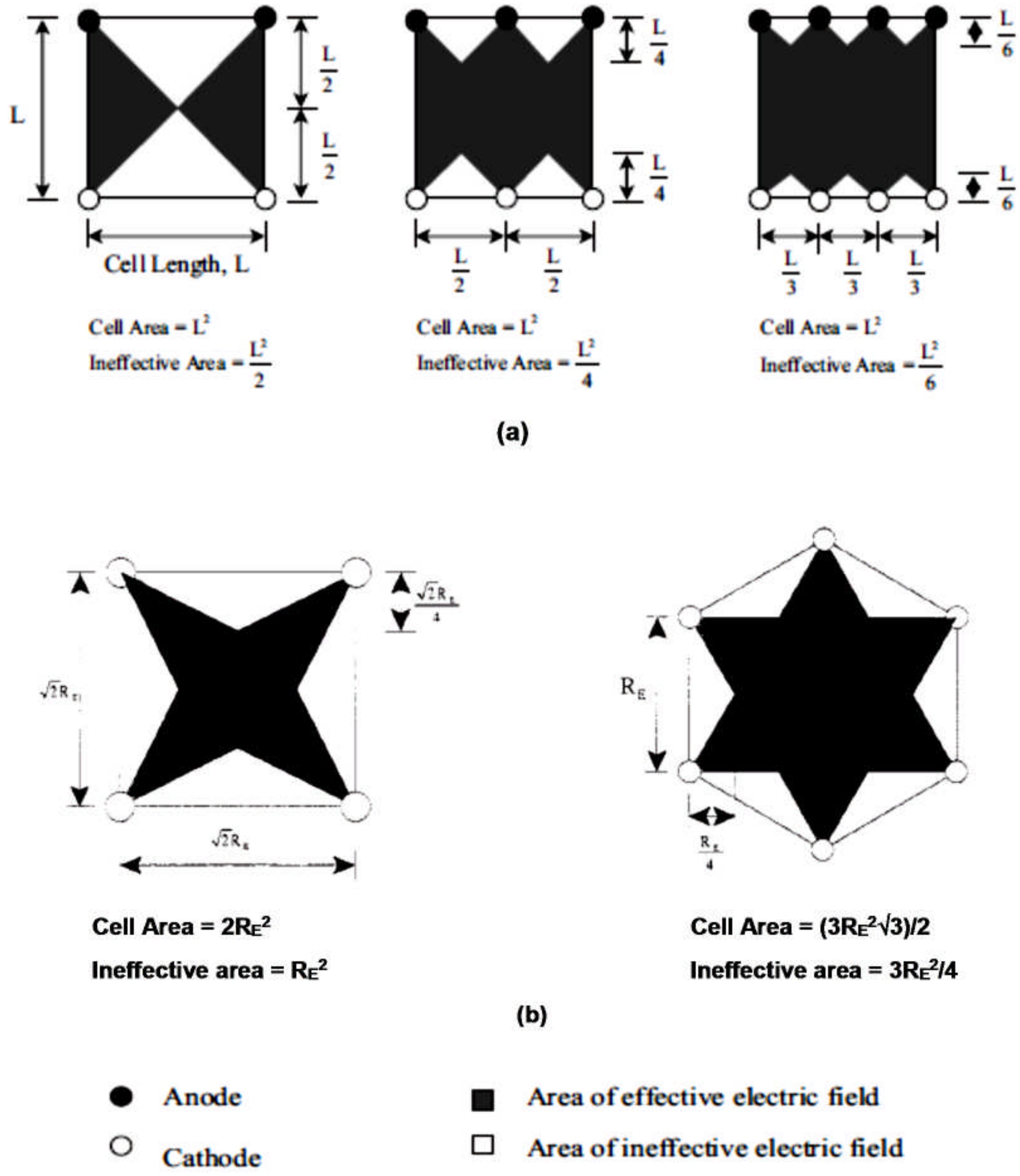
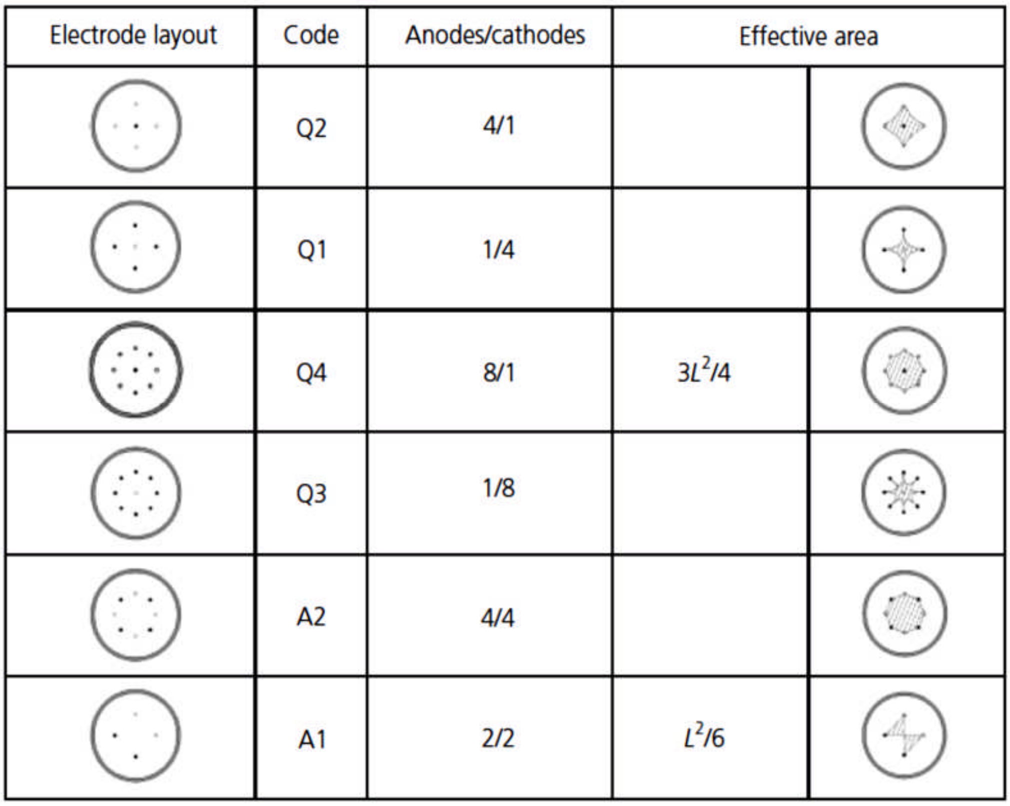


Figure 2.16 Approximate evaluation of ineffective area for (a) 1-D (b) 2-D electrode configaration (Alshawabkeh et al, 1999 a)



Electrode layout	Code	Anodes/cathodes	Effective area	
	Q2	4/1		
	Q1	1/4		
	Q4	8/1	$3L^2/4$	
	Q3	1/8		
	A2	4/4		
	A1	2/2	$L^2/6$	

Figure 2.17 Test electrode layout (Nizar and Clarke, 2013)

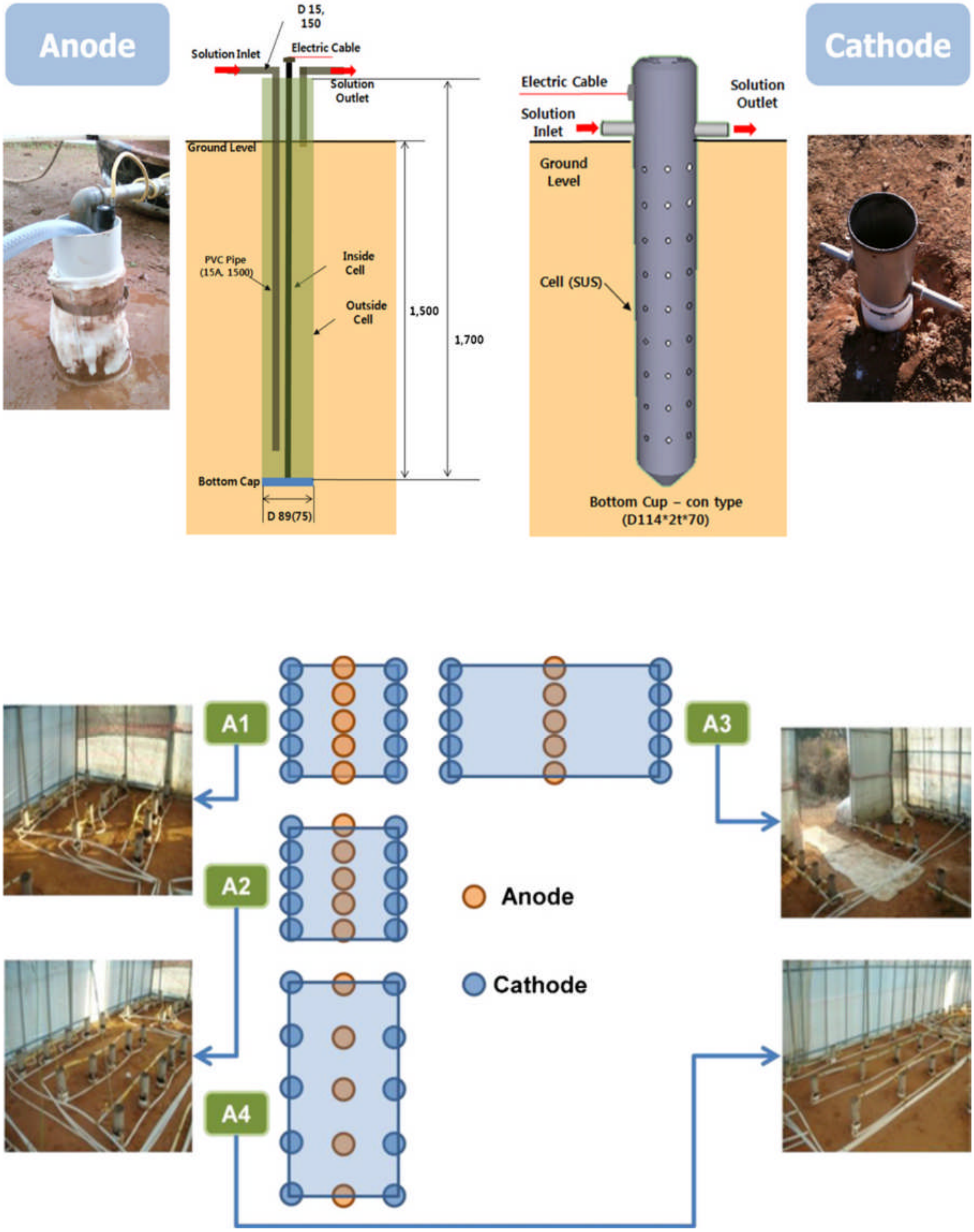


Figure 2.18 Schematic diagram of electrode system and configuration (Kim et al, 2012)

2.12 Typical applications of electroosmosis

Recently, a considerable literature has grown up around the theme of electroosmosis and its application in geotechnical engineering, including: electroosmotic consolidation, friction pile stabilization, trenching and excavation of soft soils, improvement of foundations below buildings and dams, slope stability, and remediation of soils. However, as a purpose of this research, the focus will be on electroosmosis consolidation in geotechnical applications.

2.12.1 Consolidation by electroosmosis

In compressible soil, if a direct current is applied between the electrodes inserted into the soil, an electrical potential will be created between these electrodes forcing water to move from anode to cathode. If the anode is closed, no water is introduced in to the soil. Consolidation in the vicinity of the positive terminal will take place and, because of the total stress of the system, the pore water pressure at the anode decreases due to electroosmosis and the effective stress in the zone surrounding must increase. The cathode is open so the pore water pressure remains the same. This means, a hydraulic gradient will develop between the electrodes forcing water to flow back from the cathode to the anode until the system reaches a balanced state. Hence, electroosmosis will only work in a low permeability soils to produce return flow from the cathode to the anode.

A number of successful field applications have been established in using consolidation by electroosmosis. Table 2.5 summarizes previous investigations on the electroosmosis consolidation.

One of the electroosmosis consolidation applications is the electroosmotic piles concept, mentioned by Nizar and Clarke (2013), which is adopted in this study. This concept based on installation of electrodes vertically and uses them in the form of electrical vertical drains. The influence of this concept can be compared to the displacement achieved using a stone column; as the generated excess pore pressure at the anode due to the voltage gradient is comparable with the radial stress increase resulting from stone columns. This behaviour produces soil consolidation extending from the anodes as a “soft pile”, and the soil stiffness decreases with the increase in distance from the anode.

The principles of using electrical vertical drains in soil consolidation are investigated extensively in the literature as mentioned by Rittirong et al. (2008a) who investigated this techniques by laboratory and field tests. They indicated that the combined of electrical vertical drains with electroosmotic consolidation technique can accelerate soil consolidation.

2.12.2 Increasing friction pile capacity

Electroosmosis can be used in pilling processes to alter the skin friction of steel piles in clay soils when used as an anode due to the development of negative pore water pressure around the pile. This will increase the side resistance and the pile capacity. On the other hand, if the pile is used as a negative electrode, a high pore pressure will develop and this will reduce the skin friction. This behaviour can be used to increase the end bearing capacity in the first case when the steel pile used as an anode, or during pilling in the second case when used as a cathode.

As discussed by Butterfield and Johnston (1980), the penetration resistance can be reduced by a factor of three when the pile works as a cathode during cathodic installation. Conversely, for anodic piles, electroosmosis treatment can be result in doubling the side friction of piles. The bearing capacity of the electroosmosis treated pile is eventually greater than that of the untreated pile even when the electrical potential is disconnected. Also, continued application of electrical potential after installing the pile appears to permanently increase its load capacity. Figure (2.19) illustrate the penetration resistance of piles when used as cathodes and anodes. Soderman and Milligan (1961) concluded that the pile bearing capacity is increased markedly when the steel piles are used as anodes during electroosmotic treatment. However, the effect of electroosmosis treatment appears only within a distance of one diameter from each pile. Later after 33 years, Milligan (1994) carried out load tests to assess the permanence pile capacity increases and the long term effectiveness of electroosmotic treatment. The results demonstrated that pile capacities have not diminished with time.

Table 2.5 Previous research conducted on electrokinetic improvement

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
1.	Casagrande (1949)	Electro-Osmosis in Soils	Sodium-bentonite, London clay, Clayey silt (organic), Clay+ sand (loam), Sandy silt, ground sand, Coarse silt, Fine sand, Mica, powder,	None	0.1- 12 V/cm	platinum, iron, copper	Lab
2.	Lockhart (1983a)	Electroosmotic dewatering of clays, III. Influence of clay type, exchangeable cations, and electrode materials	Sodium Kaolinite, Montmorillonites	NaCl, CaCl2, AlSO4, HCl, CuSO4	1,4,10, and 50V	Carbon-coated stainless steel electrodes	Lab test
3.	Lockhart (1983b)	Electroosmotic dewatering of clays. I. Influence of Voltage	Sodium kaolinite	NaCl, CaCl2	1 , 2 , 4 , 10 and 50 V	Carbon-coated stainless steel electrodes	Lab test,

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
4.	Lockhart (1983c)	Electroosmotic dewatering of clays. II. Influence of salt, acid and flocculants	sodium kaolinite	NaCl, CaCl2	1, 2, 3, 5.5 V, 10, 25, 60 or 72, 150 and 240 V	Carbon-coated stainless steel electrodes	Lab test,
5.	Morris et al. (1985)	Improvement of sensitive silty clay by electroosmosis	silty clay	None	0.40-0.60 V/cm	stainless steel and galvanized mesh	lab test; D=50 & 75mm L=220 &550mm
6.	Lo et al. (1991)	Field test of electroosmotic strengthening of soft sensitive clay	soft sensitive clay	None	25 - 120 V	6.1 m copper electrodes	field test
7.	Hamir et al. (2001)	Electrically conductive geosynthetics for consolidation and reinforced soil	kaolin	None	0.5V/cm , 30V	EKG sheet, copper	Lab; cylinder tank model, D = 150 mm, H = 230 mm

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
8.	Pugh (2002)	The application of electrokinetic geosynthetic materials to uses in the construction industry	clay	None	30V	Electrokinetic geosynthetics (EKG)	Lab and field
9.	Barker et al. (2004)	Electrokinetic stabilisation: an overview and case study	glacial clay	CaCl2 Na2SiO3	8, 20, 50 V	Steel tube; L=14.5m, D=0.3m	Field work
10.	Jayasekera (2004a)	Electroosmotic and hydraulic flow rates through kaolinite and bentonite clays	kaolinite, sodium bentonite	None	0.5, 1.0, 1.5 and 2.0V/cm	carbon anodes, and stainless steel mesh cathodes	Lab
11.	Morefield et al. (2004)	Rapid soil stabilization and strengthening using Electrokinetic techniques	quartz sand, glass bead, kaolinite, montmorillonite	Na3PO4, NaCl , Na2CO3	20V	Zinc metal, Aluminium metal, Iron metal	Lab test; 5x5 cm^2

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
12.	Asavadorndeja and Glawe (2005)	Electrokinetic strengthening of soft clay using the anode depolarization method	soft Bangkok clay	$CaCl_2$	20 V	Titanium electrodes	Lab
13.	Fourie et al (2007)	Dewatering of mine tailings using electrokinetic geosynthetics	mine tailings	None	1.1V/cm for lab, 0.24V/cm for field	Electrokinetic geosynthetics (EKG)	Lab and field
14.	Liaki et al. (2008)	Physicochemical effects on uncontaminated kaolinite due to electrokinetic treatment using inert electrodes	kaolinite	None	0.5 V/cm	stainless steel wires coated in high carbon-dosed polymer	Lab, (370 × 220 × 550) mm
15.	Rittirong et al. (2008a)	Electrokinetic improvement of soft clay using electrical vertical drains	High-plasticity silt with: silt 58%, clay 39% and sand 3%	None	10-30V	conductive polymer with copper foil	Lab & Field work; L=35 cm , W= 10 cm, D=

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
							25cm and (560 m x 4 m)
16.	Rittirong et al. (2008b)	Effects of Electrode Configuration on Electrokinetic Stabilization for Caisson Anchors in Calcareous Sand	Offshore calcareous sand	$CaCl_2$	6 & 13 V	Steel electrode	Lab tests; D=200 mm, L=400 mm
17.	Mohamedelhassan and Shang (2008)	Electrokinetic Cementation of Calcareous Sand for Offshore Foundations.	Calcareous Sand	$CaCl_2$	6V	perforated steel pipes, D=50mm, L=400 mm	Lab test; L=750 mm , D= 575 mm
18.	Mohamedelhassan (2009)	Electrokinetic strengthening of soft clay	Kaolinite and 5% bentonite	None	4, 6, 8, 10, 12 and 14 V	Steel Foundation model , steel mesh	Lab test; 320 mm x125 mm x 250 mm
19.	Ahmad et al. (2010)	Electrokinetic treatment on a tropical residual soil	Silt (MVG)	NaCl, $AlCl_3$, H_3PO_4	30 V	Titanium mesh	Lab test

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
20.	Sumbarda-Ramos et al. (2010)	Electrokinetic treatment for clayed and sandy soils	Sandy clayed loam (CS), sandy (SS)	PbCO3	Current: 1 mA	Ti/RuO2 electrodes	Lab test
21.	Glendinning et al. (2010)	Dewatering sluge using electrokinetic geosenthitcs	sluge	None	1V/cm for lab, 0.33 V/cm for field	Electrokinetic geosynthetics (EKG)	Lab and field
22.	Nizar and Clarke (2013)	Electro-osmotic piles	Kaolinite	None	5, 10, 15 and 20 V	Copper springs	Lab test, D=250, L=350 mm
23.	Mosavat et al. (2013b)	laboratory assessment of kaolinite and bentonite under electrokinetic treatment	Kaolinite, and bentonite	Ca(OH)2, CaCl2, Na2 SiO3	30 V for 15 days	stainless steel electrodes	Lab test; L=38 cm , W= 20 cm, D= 25cm
24.	Tajuddin et al. (2014)	Monitoring Data of Electrokinetic Stabilisation Method for Soft Clay using EKG Electrode	Kaolinite	None	50 V/m	EKG electrode	Lab test, L=450, W= 220 , D= 550 mm

No.	Reference Author	Title	Soil (s)	Additives	Electrical current /Voltage	Electrode materials & application	Field/ Lab test
25.	Hall et al. (2014)	Dewatering of waste slurries using electrokinetic geosynthetic (EKG) filter bags	waste slurries	None	12-36 intermittent voltage (2/3 ratio)	Electrokinetic geosynthetics (EKG)	Lab
26.	Zhuang, Y.F.,(2014)	Case study on hydraulic reclaimed sludge consolidation using Electrokinetic geosynthetics	sludge	None	50-80V	Electrokinetic geosynthetics (EKG)	Field test
27.	Chien et al. (2015)	Soil improvement using electroosmosis with the suitable operation process: field test	Silty clays	CaCl2, Na2O3Si	50 V/m	perforated steel pipes, D=50mm, L=4.5m	Field test

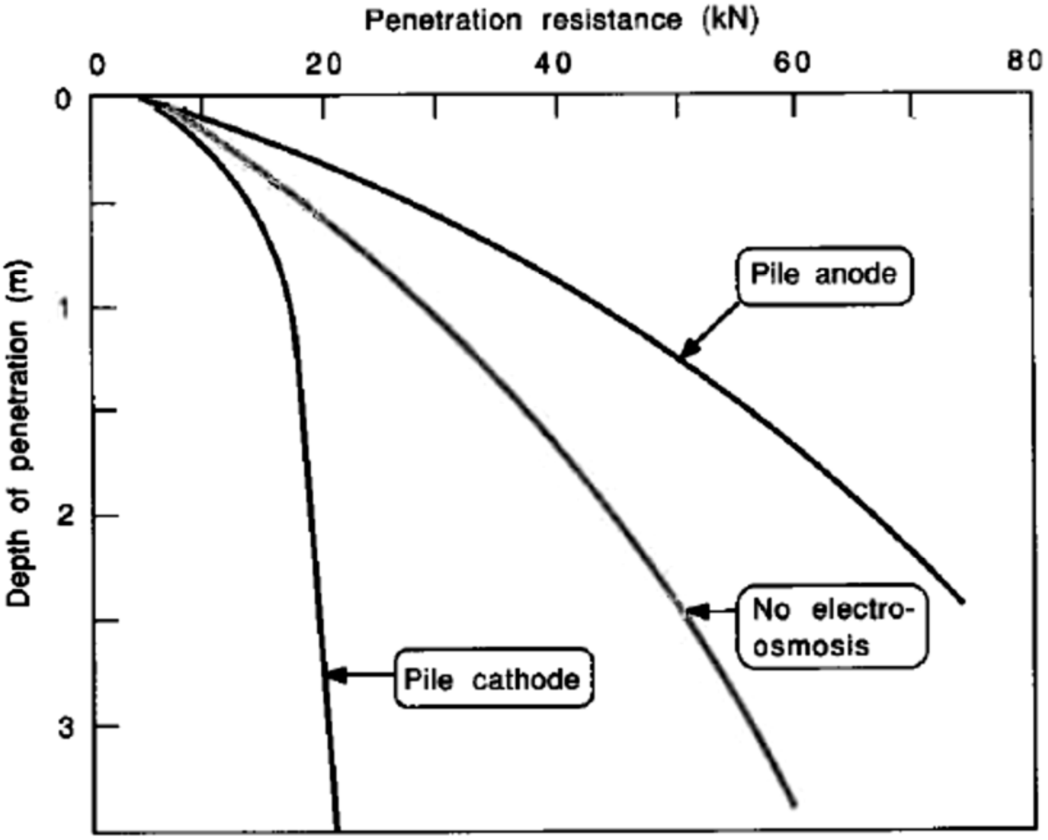


Figure 2.19 Penetration resistance of a model pile tested with and without electroosmosis (After Hausmann 1990)

2.12.3 Assisting pile driveability by electroosmosis

Electroosmosis techniques can assist with piling by increasing pile driveability and decreasing the required energy for driving. This results in softening the soil in the vicinity of the driven pile and an adjacent electrode when an electrical gradient applied. According to Esrig (1978) , it is possible to reduce the energy required for pilling more than 50% when the electroosmosis technique is used.

Figure (2.20) illustrates a method adopted by Abbott (1977), Christenson (1978) and Christenson (1979) for assisting the driveability of a hollow electrically conductive pile. The procedure achieved by insulating the pile from the outside with any suitable electrical non-conductor coating such as polyurethane or epoxy. An electrical D.C power source, is provided in which the cathode is attached to the electrically conductive pile and one or more anodes are placed in the water outside the pile, as shown in Figure (2.20).

Electrical power is applied when the pile is in contact with the soil, resulting in water movement down the outside of the pile through the soil in the vicinity of the pile body from the anodes toward the cathode. This process make the pile easier to drive through the soil by reducing developed friction between the soil and the pile due to the decrease in shear strength of the soil nearby the pile. A further objective of this technique is consolidating the soil and increasing the load bearing capacity by reversing the electrical current flow from the circuit which make the pile works as an anode as mentioned in the above section. However, the figure shows that the anodes are placed at the top of the soil, which in practice treats the surface soil only. Therefore, the anodes should be extended to the same depth as the pile (cathode) required to be installed.

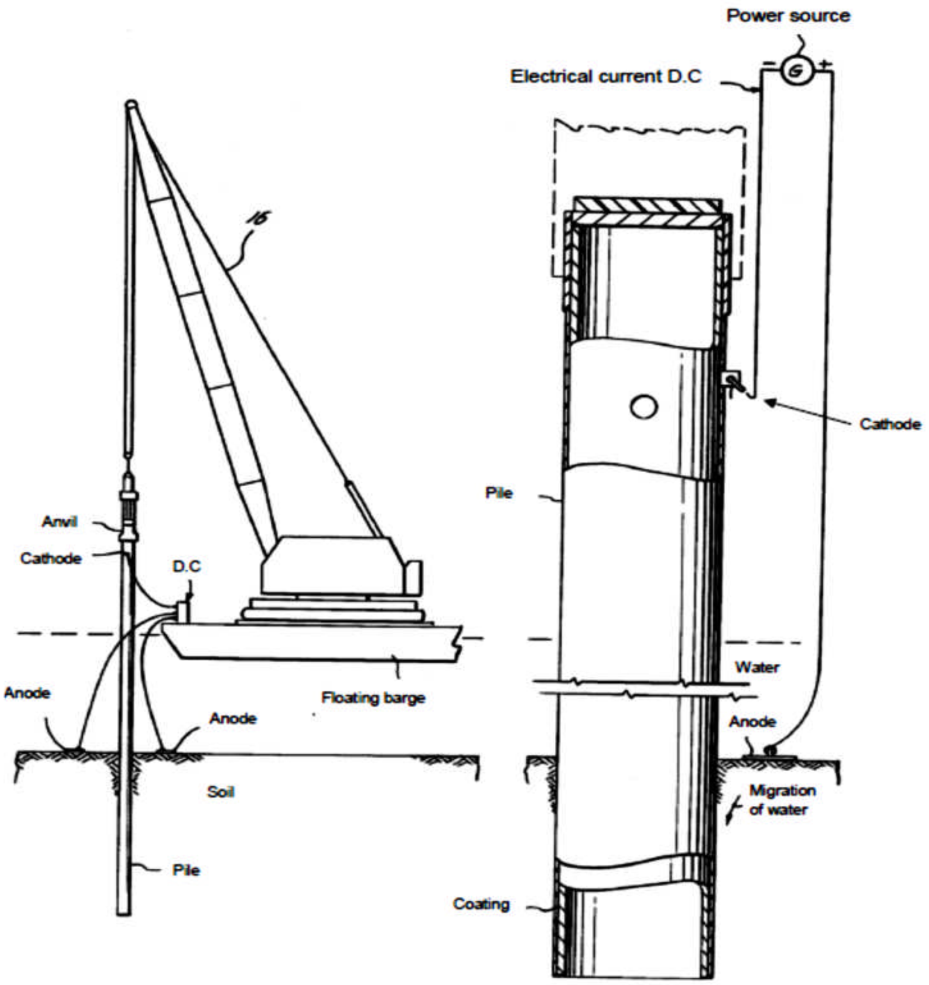
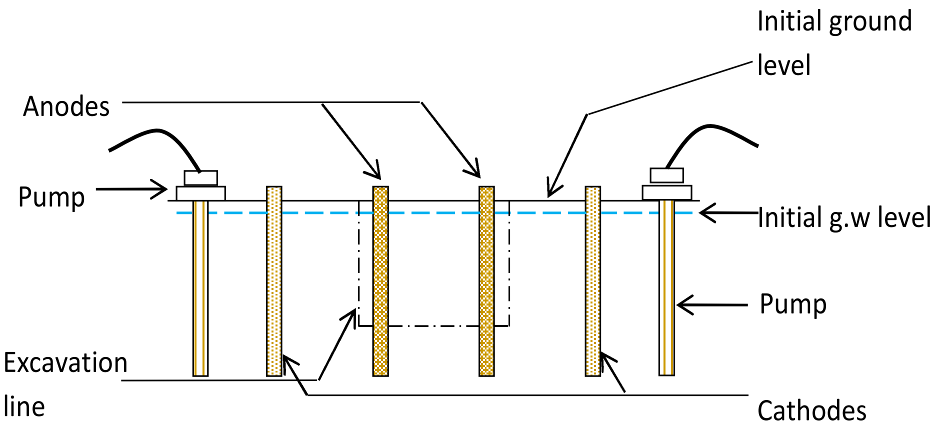


Figure 2.20 Elevational and schematic view of a pile being driven into the soil below water (Christenson, 1979)

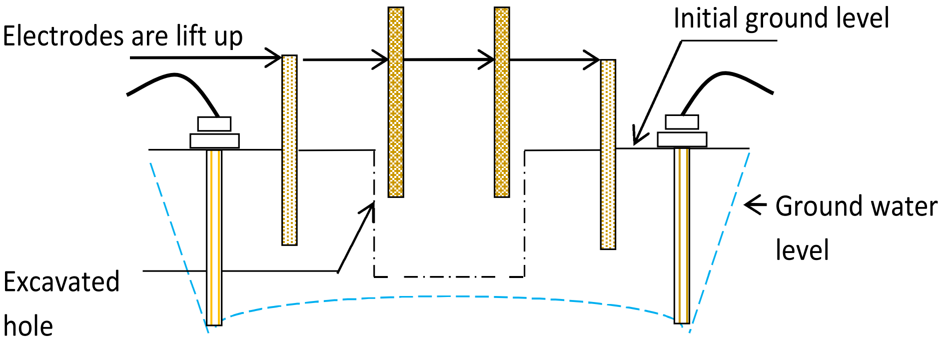
2.12.4 Increasing strength of soil prior to trenching and excavation

In excavation and trenching works, electroosmosis can help in lowering phreatic ground water level by using cathodes as wells in the area to be excavate which allow trenching or other excavation work to take place. Pugh (2002) suggested that the electroosmotic treatments could be use in a single or multi-phase as shown in Figure (2.21). In single phase treatment, there is no need to pump water while in the double phase, pumping out water from cathode will reduce the treatment time.

Bjerrum et al. (1967) carried out an electroosmotic field treatment on a quick clay to achieve permanent increase in shear strength of the treated soil required to enable successful completion of deep excavations during the construction of the sewage treatment plant. The observations of the electroosmotic treatment included measurements of the generated settlement by treatment, and pore water pressures at different depths. Based on observations, an augmentation in shear strength from an initial value of less than 9.8 kPa to 107.9 kPa at the anode after treatment. The average shear strength at halfway down the electrodes was 39.23 kPa. The electrodes used were reinforcing steel bars with 10m long and 19 mm diameter. The total corrosion of the anodes at the end of test (120 days) was 37% of the original weight. They concluded that the electroosmosis can significantly enhance the soil properties, including the increase in the shear strength, and the decreases in the water content. Figure (2.22) shows (a) the undrained shear strength distribution between the row of anodes and the row of cathodes, (b) the initial value of the remoulded shear strength, (c) the water content of the clay at the different positions, and (d) the Atterberg limits of samples taken from the depth of 4.5 m below the ground surface.



(a) before electro osmosis treatment



(b) after electro osmosis treatment

Figure 2.21 Multi- phase treatment (Reproduced from Pugh, 2002)

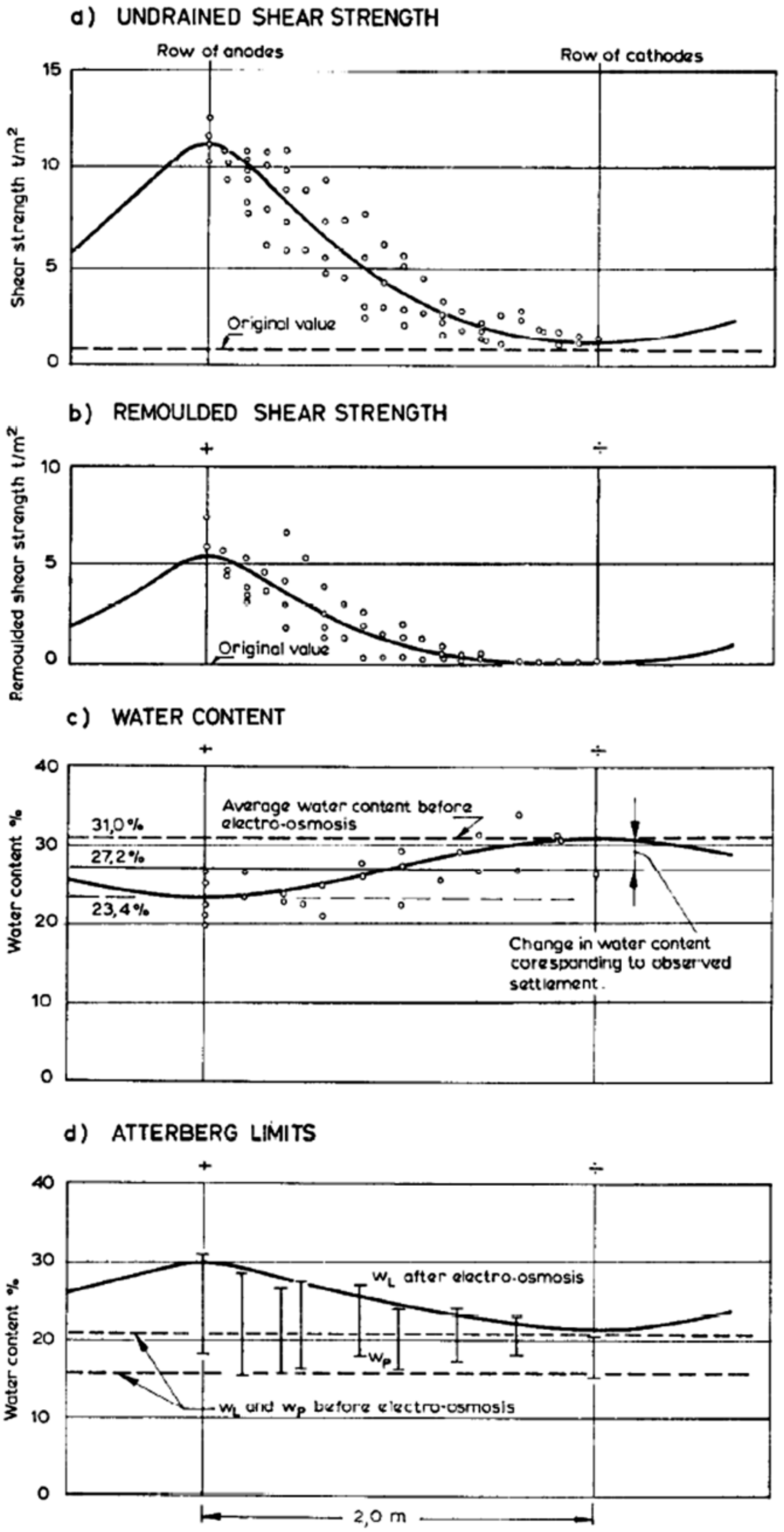


Figure 2.22 The summary of the measured results at a depth of 4.5m below the ground level during excavation period (Bjerrum et al. 1967)

2.12.5 Electrokinetic remediation

Recently, researchers show an increased interest in using electrokinetics in the field of soils remediation. Using electrokinetics in remediation has provided an adequate means to extract contaminates from soils both organic and inorganic, separation of water and solids of waste, and dewatering of mine residues and tunnel slurries (Kalumba et al., 2009).

Acar and Alshawabkeh (1993) demonstrated that when electrokinetic remediation in soil is used, the hydrogen ions moved from anodes to cathodes causing desorption of species from the treated soil surface which assists in dissolution of salts in the soil. Chung (2007) carried out a series of laboratory tests using electrokinetics and ultrasonic technology in treatments for removing heavy metal from contaminated ground water. In his study, he concluded that the coupled effect of electroosmosis and ultrasonic can increase the efficiency of treatment rather than using ultrasonic or electroosmosis separately. Yeung and Datla (1995) noted that the electrokinetic extraction of contaminates from soil will cause a pronounced change of pH value, which has a significant effect on sorption and adsorption degree of chemicals on the treated soil.

In addition to these successful studies and applications of electroosmosis treatment, electroosmosis techniques can be used in other soil improvements applications, such as trenching and excavation of soft soils (Bjerrum et al., 1967, Pugh, 2002), shrinkage and swelling control in shallow foundations and pipe lines Wu et al. (2015b), slope stability (Chappell and Burton, 1975). Electroosmosis may be combined with a wide range of soil improvement applications, such as with conventional surcharging where electroosmosis is used to achieve an additional consolidation pressure (Pugh, 2002).

With the increasing in environmental concerns, “Construction - 2025” aims to provide sustainable construction solutions with considerable growth opportunities. Electroosmotic techniques can be used in the application of slope stability and soil remediation to provide quicker and better effect of consolidation thus contributing to the sustainability agenda.

2.13 Significance of Study

The work presented in this study is a contribution to the application of electroosmosis treatment techniques, for different concentrations kaolin, bentonite and sand subjected to different applied voltage. The results of the research have increased knowledge of the electroosmotic treatment approach to improve the properties of composite soils.

An important knowledge gap found in the literature, which impacts significantly on the aims of this research, is that most of the previous research work on electroosmosis treatment has been carried out on clay soils, doubtfulness still exist to use this technique with composite soils. However, there is useful literature which may provide a wide range background on the behaviour of some clay types treated by electroosmosis, such as kaolin and bentonite.

Potentially the most substantial knowledge gap identified in the literature search is that there is no clay limit in the composite soil to illustrate the use electroosmosis treatment at which this technique work efficiently. To a certain extent this gap can be used to provides details and more evidence on the operation of the electroosmotic process with low fine-grained soil. Therefore, sand-clay mixtures were prepared with the intention of providing a broad range based on the work of Kurata and Fujishita (1961), Vallejo and Zhou (1994) and Al-Moadhen et al. (2017) who suggested that the composite soils could be classified into three types according to the sand content: sand (contains 80% or over of sand), clay type (under 60%) and the intermediate type (60-80%).

In addition, while there has been much discussion in the literature on the calculation of the energy required to achieve the electroosmosis treatment, there is a lack of available work on relating the mount of consumed energy to the dissipated energy due to the temperature developed during the electroosmosis and how this temperature will affect the process. Consequently, it is apparent that inclusion the effect of the applied voltage to the developed temperature is appropriate. This will be addressed through measuring and comparing the temperature for each soil mixture at different applied voltages to reduce the unnecessary energy consumption and optimize the overall cast of the electroosmosis treatment operation.

Therefore, this study will provides insight into which voltage gradient is more effective in electroosmotic treatment for each soil mixture. Also this research can be used as a guide to appropriate composite soil and the amount of sand based at which the electroosmotic technique works efficiently based on soil properties and the sand content.

2.14 Conclusion

This chapter has introduced the necessary background to identify and explore the mechanism of electrokinetic treatment and its application in soil. General properties and description of composite soils was presented to establish the electroosmosis treatment of composite soils. A general description of composite soil was illustrated and its classification also presented.

A review of clay system (mineralogy and structure) was discussed to understand the behaviour of clay soils under electrical current. The four types of flow in soils were introduced briefly.

In this chapter, the electrokinetic phenomena was introduced how it occurs in soils, the concepts of coupled flow and electrokinetic have been discussed with more details and derivations of the theory behind electroosmosis and some figures to explain the importance of these theories. A historical review was also presented in this chapter to highlight how some important parameters effect electroosmosis such as; soil type, applied voltage, electrode materials, and electrode configuration. Also, the effect of temperature developed during electroosmosis and its effect to establish and determine the optimum electrical energy required for electroosmotic consolidation. In the final section, a scope of previous research on electrokinetic phenomena; the relevance and applicability of the technique in geotechnical applications were also discussed.

Most of the previous findings for electrokinetic treatment showed that this techniques can be used as an effective means of soil improvement.

Chapter 3

Electroosmosis Methodology and Laboratory Process

3.1 Introduction

This chapter describes details of the design and implementation of the experimental program to validate the mechanism of electroosmosis treatments in composite soils. The equipment developed by Nizar and Clarke (2013) and shown in Figure (3.1) was used with an octagonal array of anodes surrounding a single cathode in a nominal 250 mm diameter 300 mm deep cylinder of soil with the anodes at a radius of 80mm from the cathode. The equipment was modified to allow radial and vertical temperature profiles to be assessed to determine the efficiency of the system which was defined as the ratio of the useful energy to total applied energy. An increase in temperature indicated a reduction in efficiency since some of the energy was used to heat the sample. Properties of the soils used in research tests were investigated according to British Standards.

Twenty four tests were performed on China Clay Grade E kaolin, with and without sand, and calcium bentonite (Bentonex CB) with and without sand as summarised in Table (3.4). The electroosmotic tests are divided into three phases as described in Section (3.5).

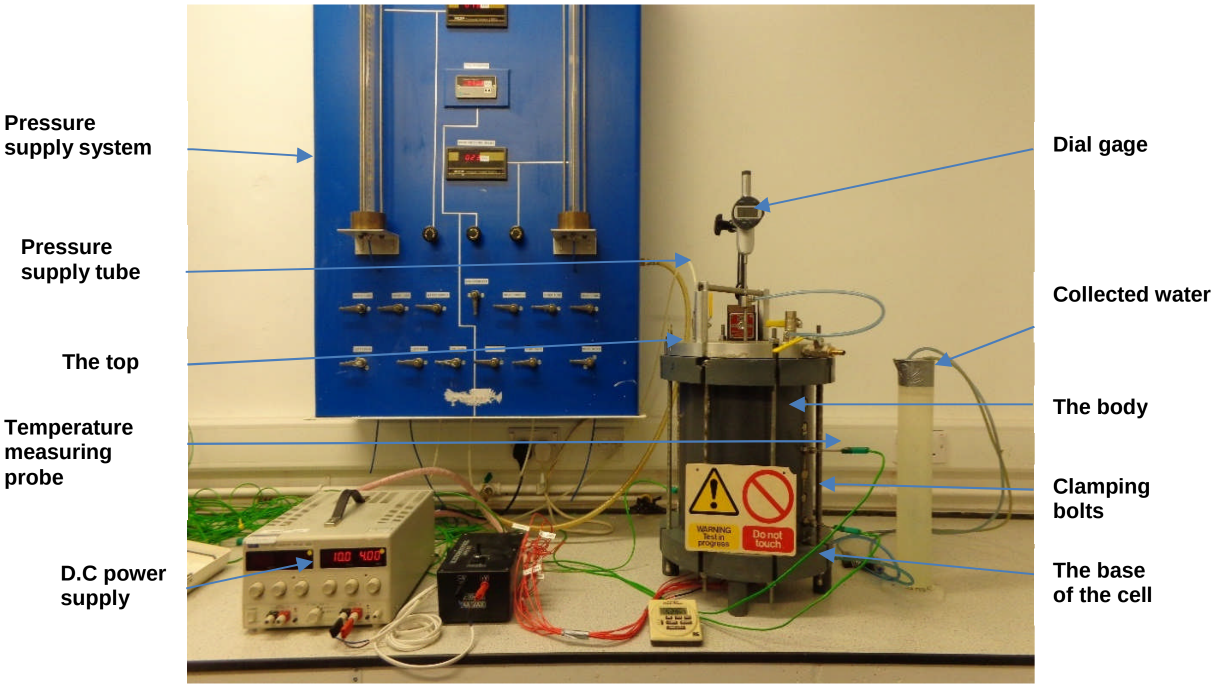


Figure 3.1 General arrangement of the electroosmotic consolidation chamber (Nizar and Clarke,2013)

3.2 Aim of the experimental work

The primary concern of electroosmotic process in a soil- water system is to force the pore water to flow from the positive terminal (anode) towards the negative terminal (cathode). This will increase the strength and stiffness of the soil around the anode as it lowers the water content and, as there is an external pressure, the void ratio reduces and the density increases. There are several important factors that effect the electrokinetic treatment including soil type, voltage difference, time of treatment, and electrode materials and configuration. The aim of this study is to assess the capability of electroosmosis method in a range of sandy silty clay soils; i.e. composite soils by using different mixtures of sand, kaolin and bentonite. This will show the maximum percent of sand possible for the electroosmosis treatment to work and achieve a required consolidation and stabilisation with optimum time of treatment.

3.3 Research process and principles

The principle of electroosmosis consolidation is that the water is forced to move from anode to cathode when an electrical current is applied to a saturated soil. The principles of consolidation theory can be adapted to study electroosmosis consolidation. Therefore, the key principles adopted in this experimental work are:

- The test cell is non-conductive, to ensure there is no effect of losses in the applied current.
- The applied external pressure is vertical and positive in all tests.
- The soil sample is restrained laterally to ensure vertical displacement; i.e. the soil is consolidated one-dimensionally.
- A change in volume is measured by measuring settlement and volume of expelled water to access the accuracy of measurement during the experimental program.
- The current is measured under a constant applied voltage to observe changes in time.
- Copper springs are used as electrodes to reduce degradation due to electroosmosis and allow the electrodes to compress during consolidation due to the electroosmosis or the vertical applied load.
- The temperature at the anodes and cathodes is monitored during a test to determine the energy lost due to soil heating.

3.4 Materials used in the experimental work

3.4.1 Soils

Most research into electroosmotic treatment has been carried out on pure clay soils. Many natural soils are composite soils; that is, they contain a range of particle sizes (Al-Moadhen et al., 2017). Their behaviour depends on the parameter being measured and the particle size distribution.

Artificial soils of known composition have been used in most experimental studies because the variability of natural soils make the intrinsic behaviour difficult to determine. The materials used in the study were two types of clays;

kaolin and bentonite, with fine sand. The reasons for using these types of clay was because they available in powder form and they have different mineralogy, permeability and geotechnical properties, so the results of the electroosmosis treatment on different sample compositions can be compared. The soils were thoroughly mixed so soil structure was not considered. The soils slurry were prepared by mixing the dry soil with tap water at a water content equal to 150% of the liquid limit (I_L) as shown in Figure (3.2), The soil was prepared at this water content to ensure uniform, saturated samples and minimize the air content as it is placed in the test chamber. Note that the liquid limit tests were based on the complete soil sample rather than soil particles smaller than 425μm sieve. The soil was consolidated under an external pressure of 15 kPa to simulate a working platform and ensure saturation. The assessment criteria was the performance of the treated soil mass under an external pressure of 50kPa which simulated a lightly loaded structure. The sand used in the soil mixture was fraction C (BS 1881 part 131) with the sand ratio of: 0, 23, 33, 50 and 67% by weight.

Kurata and Fujishita (1961) proposed that the clay-sand composite soil can be classified into three types depends on the sand content; sandy soil, when sand content > 80%, intermediate, when sand content is between 60-80%, and clay type when sand content <60%. Vallejo and Zhou (1994) concluded from direct shear tests on mixtures of kaolin clay and sand that the sand content had a marked influence on the shear strength of the mixture. It was found that when the sand content is more than 80%, the shear strength was controlled mainly by frictional resistance between the sand. When the sand concentration varied from 50% to 80%, the shear strength of the mixture was provided in part by the shear strength of the kaolinite clay and sand grains, while when the sand content was less than 50%, the shear strength of the mixture was entirely governed by the strength of the clay. Watabe et al. (2011) stated that the hydraulic conductivity of a soil mixture increases significantly when sand is added and if the sand particles form a skeletal structure, but the void ratio of the mixture remains almost constant with the increase in the additive sand. They concluded also that the addition of bentonite soil reduces the hydraulic conductivity of the mixture, even for clayey soils. Al-Moadhen et al. (2017) stated that a composite soil can classified into three types:- clay dominated when clay content between 30% to 40%; sand dominated when clay content less than 20%; and a transition zone with clay content between 20% to 35% depending on clay type and effective stress.

The reason behind using the percent of sand in this study; (0, 23, 33, 50, and 67%) was to examine the effect of electroosmosis treatment on the types of composite soil mentioned by the Kurata and Fujishita (1961), Vallejo and Zhou (1994) and Al-Moadhen et al. (2017). The particle size distribution of kaolin and bentonite soil is shown in Figure (3.3), and plasticity charts for kaolin and bentonite soil and mixtures used are shown in Figures (3.4) and (3.5), respectively.

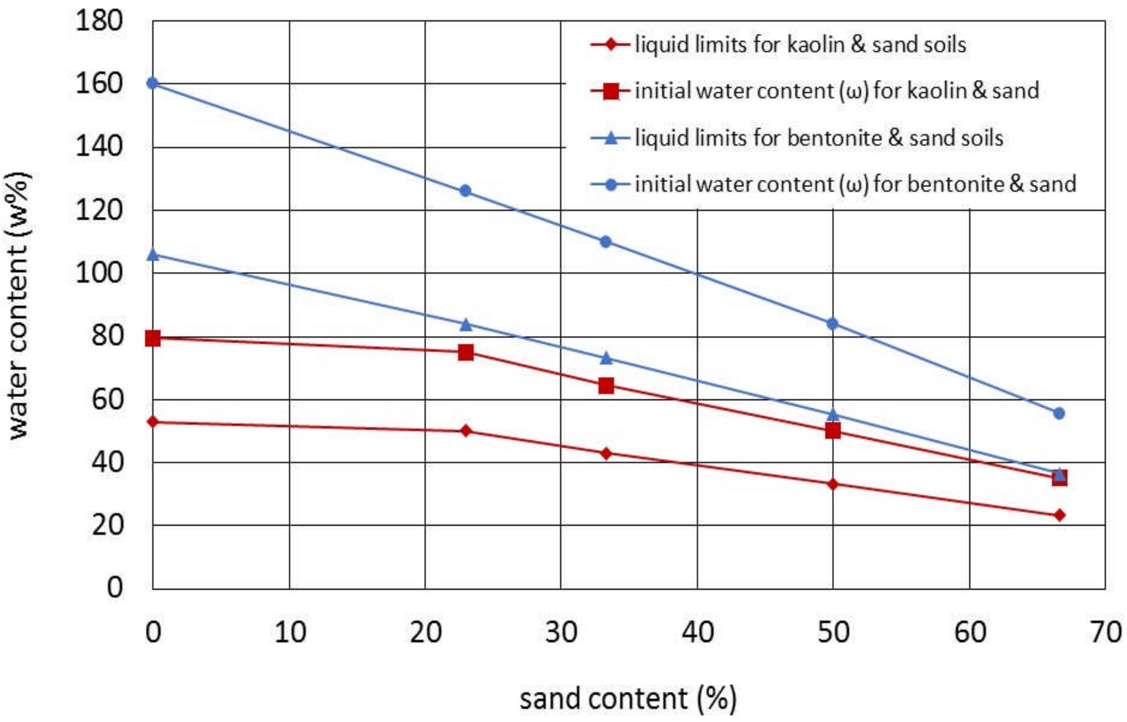


Figure 3.2 The variation in initial water content with sand content in kaolinite and bentonite soil mixtures.

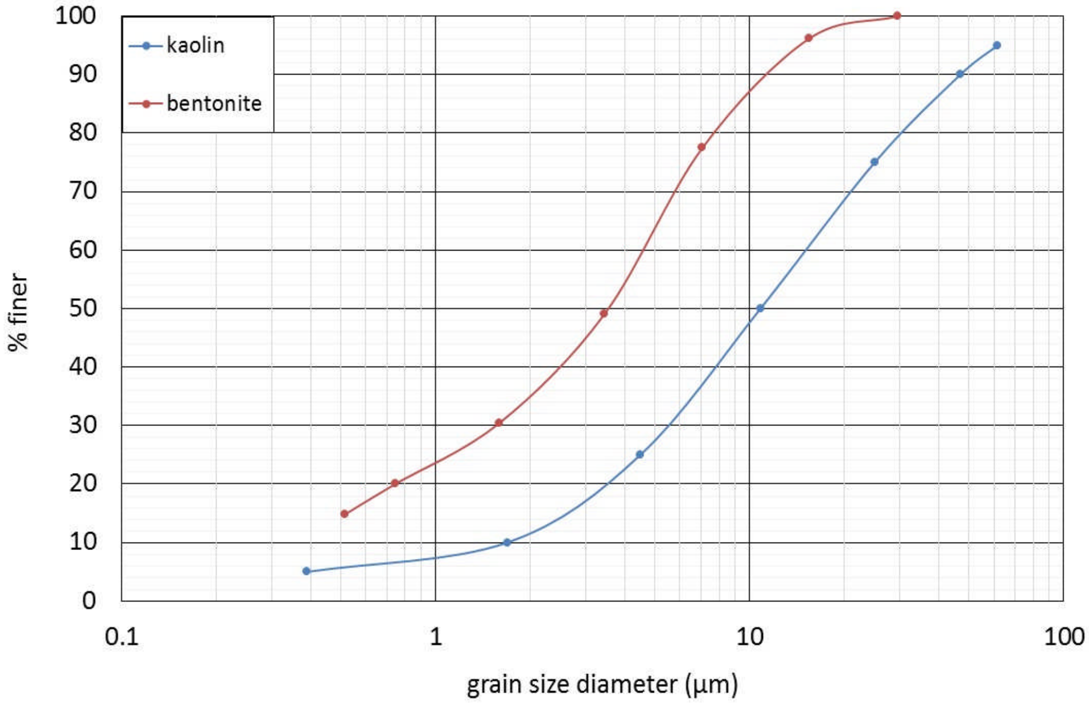


Figure 3.3 Typical particle size distribution graph for kaolin (Polwhite E) and calcium bentonite (Bentonex CB)

3.4.1.1 Kaolin

Kaolin clays have been widely used in electrokinetic applications because of their electroosmotic efficiency, low adsorptive capacity and low activity; and because they are available in powder form, so can be prepared at a given water content. Smith (1998) stated that the kaolinite soil group has very low swelling and shrinkage response to water content and adsorbs little water. Many researchers using kaolin soils in electrokinetic applications reported significant changes of the properties after treatment, increase in shear strength (Asavadorndeja and Glawe, 2005), change in Atterberg's limits, (Barker et al., 2004) (Morefield et al., 2004) and soil compressibility (Lefebvre and Burnotte, 2002, Ahmad et al., 2010).

The first soil used in the experimental work of this study was English China Clay type (polwhite E) supplied by Imerys Minerals. The classification data of this clay are given in Table (3.1) and the chemical properties of this kaolin powder are given in Table (3.2). Kaolin type (E) is a pure medium fine to fine white powder with particle size distribution shown in Figure (3.3) obtained from the manufacturer's specification and the plasticity chart for kaolin and sand mixture is shown in Figure (3.4). The kaolin powder was mixed with a water content of 79.5% which is equal 150% of the liquid limit to create highly viscous clay slurry and ensure uniform soil properties through the test series.

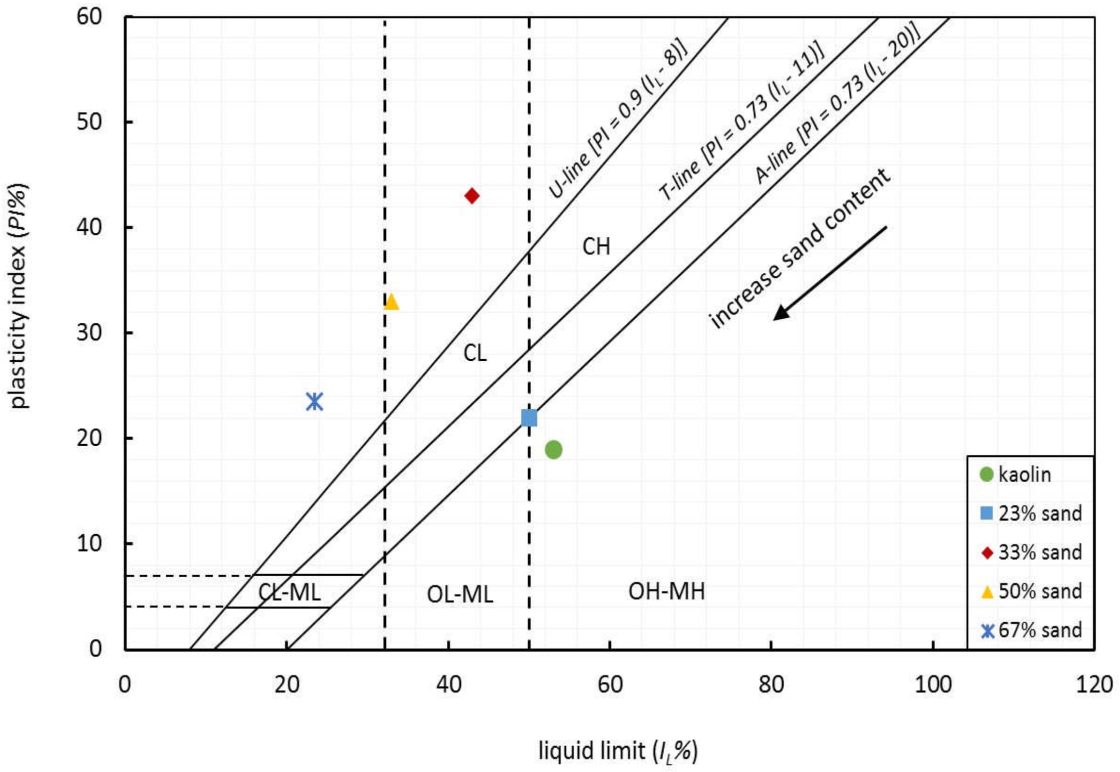


Figure 3.4 Casagrande plasticity chart for kaolinite and sand mixture

Table 3.1 Atterberg's limits, specific gravity and soil classification for kaolin grade E

Soil index	Hamir (1997)	Nizar (2012)	Researcher (2015)
Liquid Limit (I_L)%	54%	53%	53%
Plastic Limit (w_P)%	34%	35%	34%
Plasticity Index (I_P)%	20%	18%	19%
Specific gravity , G_s	2.6^*	2.6^*	2.6^*
Soil Classification	MH	MH	MH

*obtained from manufacturer's documentation

Table 3.2 Chemical features kaolin grade E (manufacturer's documentation)

pH	5
Water soluble salts content (mass %)	0.15
SiO2 (mass %)	50
Al2O3 (mass %)	35
Moisture (mass %)	1.5

3.4.1.2 Bentonite

Bentonite is very high plastic, swelling clay consisting of aluminium sheets inserted between tetrahedral SiO4 units. Bentonite is a widely used clay in geotechnical engineering applications, such as supporting slurry walls, drilling mud, grout material, soil admixture in seepage barriers and back fill during construction (Mitchell and Soga, 2005).

Bentonite has been also used in electrokinetic applications in studies in addition with kaolin, for instance (Jayasekera, 2004b) and (Mosavat et al., 2013a). Jayasekera (2004) stated that the hydraulic conducutivity of kaolinite is two orders of magnitude compared to that of bentonite.

There are many types of bentonite products, such as sodium bentonite, calcium bentonite and potassium bentonite. Calcium bentonite (Bentonex CB) from RS Mineral Ltd was used in this study because of its importance in civil engineering application, and it is relatively low Atterberg’s limit compared to other bentonite types. The particle size distribution for (Bentonex CB) is shown in Figure (3.3) and the plasticity chart for bentonite and sand mixture is shown in Figure (3.5). Chemical properties and mineralogy of this product are presented in Table (3.3).

Table 3.3 Typical mineralogy for bentonite (Bentonex CB)

Montmorillonite	88%
Mica	5%
Feldspars	5%
Quartz	2%
Bulk Density*	800 – 900 Kg/m3
Swelling Volume*	11 ml/2g
Moisture*	Max. 14% by weight
Liquid Limit (I_L)%	106
Plastic Limit (w_P)%	51
Plasticity Index (I_P)%	55
CEC*	76 meq/100g

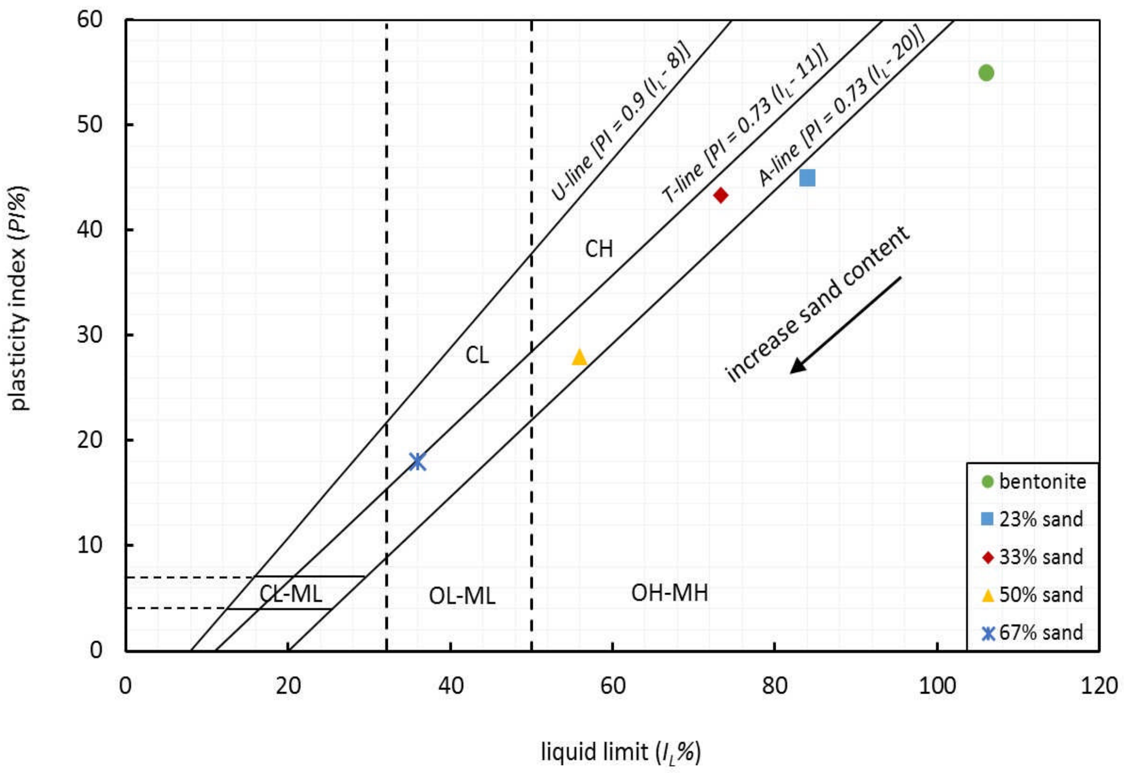


Figure 3.5 Casagrande plasticity chart for bentonite and sand mixture

3.4.1.3 Sand fraction C

Sand used in this study was medium size (fraction C 600um-300um) supplied from David Ball Specialist Sand. The sand is a natural, uncrushed rounded to sub-rounded silica sand washed, dried and graded free from silt, clay or organic matter with the properties shown in Table 3.4.

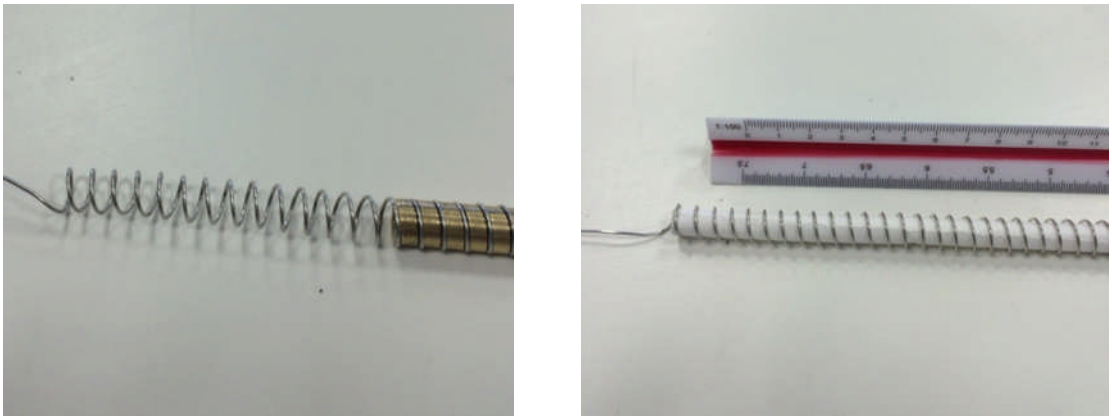
Table 3.4 Properties of sand (C)

Size	600um-300um
Min. within the stated range	80% minimum
Max. larger than	600um is 10%
Max. finer than	300um is 10%
Bulk Density kg/m^3	loose 1560
Moisture content	< 0.1%

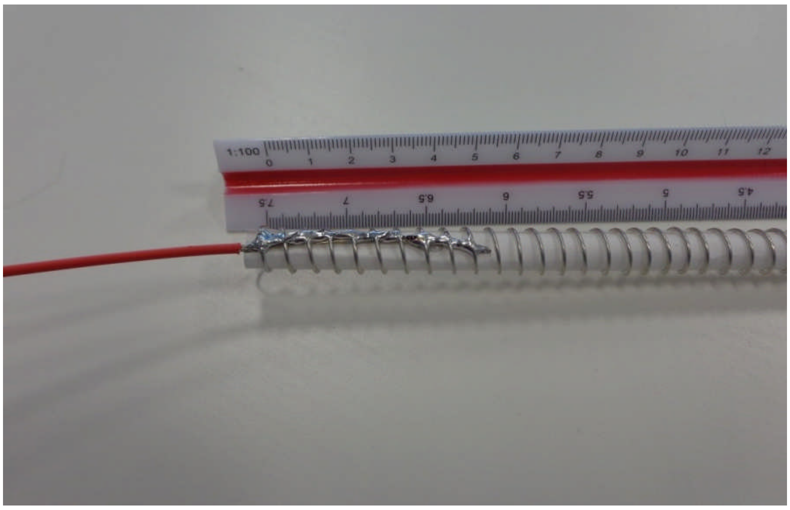
*obtained from manufacturer's documentation

3.4.2 Electrodes

Tinned annealed copper wire was used to form the springs (Nizar and Clarke, 2013) that were used as electrodes in the test program. A spring was made by rolling the selected (0.02 mm) copper wire around an (8 mm) diameter mandrel brass rod shown in Figure (3.6a). Spring electrodes were used to allow the electrodes to compress when the soil consolidated due to electroosmosis or the vertical applied pressure. A cylindrical roll of filter paper was inserted inside the springs to prevent soil entering inside the electrode and allowing an electrode to act as a drain as shown in Figure (3.6b). Copper wires were welded to the springs connecting the electroosmotic cell with a D.C. power supply passing through a glands. Figure (3.6c) shows a coiled spring with filter paper welded with wire cables.



(a) coiled spring electrode (b) copper coiled spring electrode with filter paper



(c): copper coiled spring electrode with filter paper welded to wire

Figure 3.6 Copper coiled spring electrode

3.4.3 Lab DC power supply

A Lab DC power supply obtained by Thurlby Thandar Instruments model (TTi EX752M), shown in Figure (3.7), was used to supply power to the electroosmotic cell. This device with two outputs is capable of supplying a maximum voltage of 150V, 4 amp current and 300W. The voltages used in this research were (5, 10, 15 and 20V).

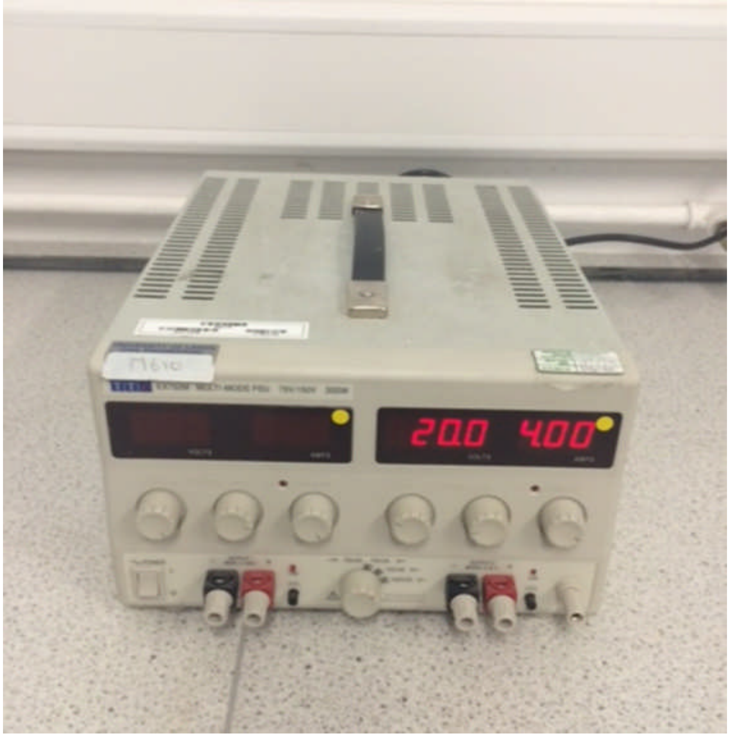


Figure 3.7 Lab DC Power supply (TTIEX752M)

3.5 Testing equipment

Electroosmotic tests took place in an apparatus shown in Figure (3.1) consisting of three parts, the cell body, the cell top and the base. This section will give a brief discerption of each component of the electroosmotic consolidation cell. The general assembly of the electroosmosis consolidation chamber is shown in a schematic diagram, Figure (3.8). The body (7) shown in the Figure (3.8) is made from PVC with a wall thickness (10.9 mm) and an internal dimension (345mm) high and (251mm) inner diameter. A (45mm) flange and collar was fitted at the top of the body to seal the flexible diaphragm (3) as shown in Figure (3.8), the dimensions of the electroosmotic cell was shown in Figure (3.9).

The base of the cell (9) in Figure (3.8) was also made from PVC and used to carry the body and to support the electrodes (6); the drainage outlet was in the base. An O-ring shown in Figure (3.10a) was inserted in a specified groove to prevent leakage between the body and the base. Stainless steel glands in Figure (3.10a) passing through the base were used to hold the electrodes and allow wires to pass through it. O-rings were placed around the anodes glands to prevent anodes from working as a drains and provide a space between the base and the internal bottom plate to allow water to flow through the designed outlet, as shown in Figure (3.10b). The stainless gland, which is fitted in the base, is shown in Figure (3.11). These glands provided with two O-rings, one is outside and the second small one was fitted inside to ensure it's tight around the wire that passed through the gland preventing leakage as can be seen in Figure (3.12). Filter paper was placed on top of the base to prevent flow of soil material through the drainage outlet.

Two types of electrodes plugs were used in the experimental work for the anode and cathode as shown in Figure (3.13). The bottom internal plate was fixed on the top of the base using 5mm diameter bolts. This plate was provided with threaded holes to fit plugs which hold the electrodes as shown in Figure (3.12). These plugs are used to hold the coiled spring electrodes and to allow wires to pass through to the stainless steel glands in the base. The cathode plug was also used as a drain. Figure (3.14) a and b show the cathode and anode plug installations.

The top of the electroosmotic cell can be seen in Figures (3.1) and (3.8), which contains different ports, air bleed, and connected with a semi-flexible rubber membrane marked (3) in Figure (3.1) used to apply pressure to the soil sample in the cell. A dial gauge was attached to the top to measure the movement of the top piston and, therefore, compression of the soil sample.

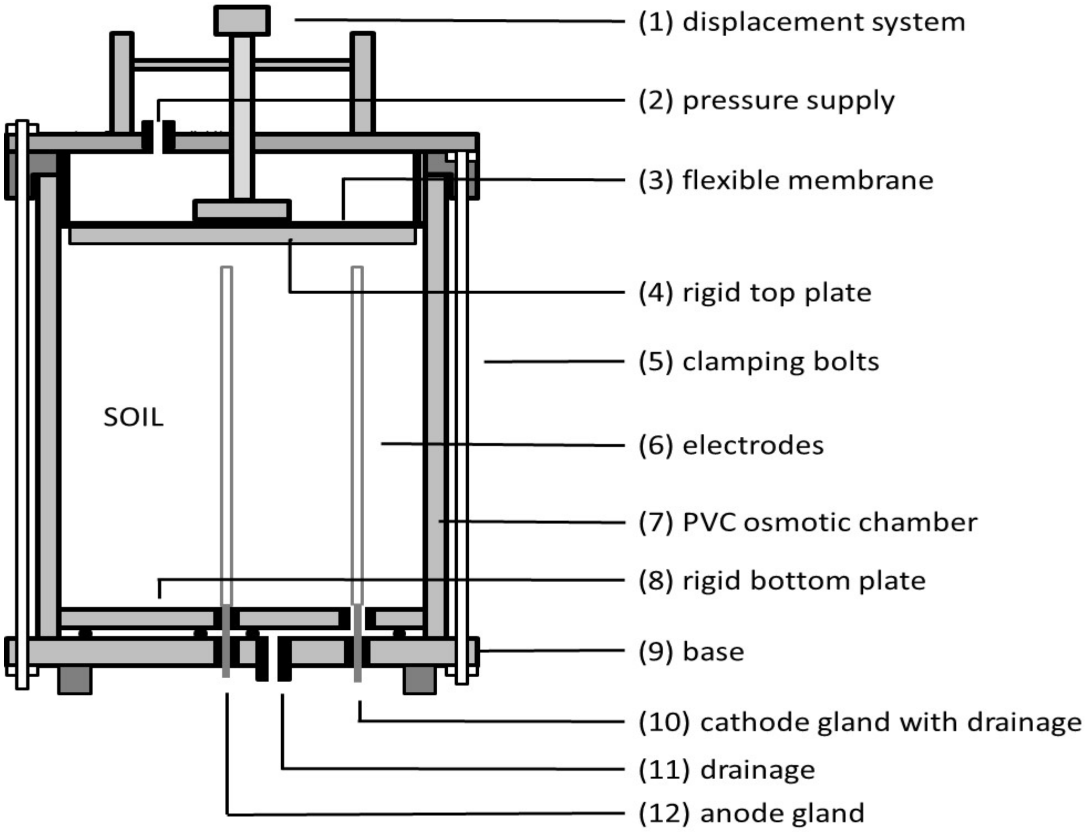


Figure 3.8 Schematic diagram of the test equipment showing the osmotic cell, electrode and pressure system after (Nizar and Clarke, 2013)

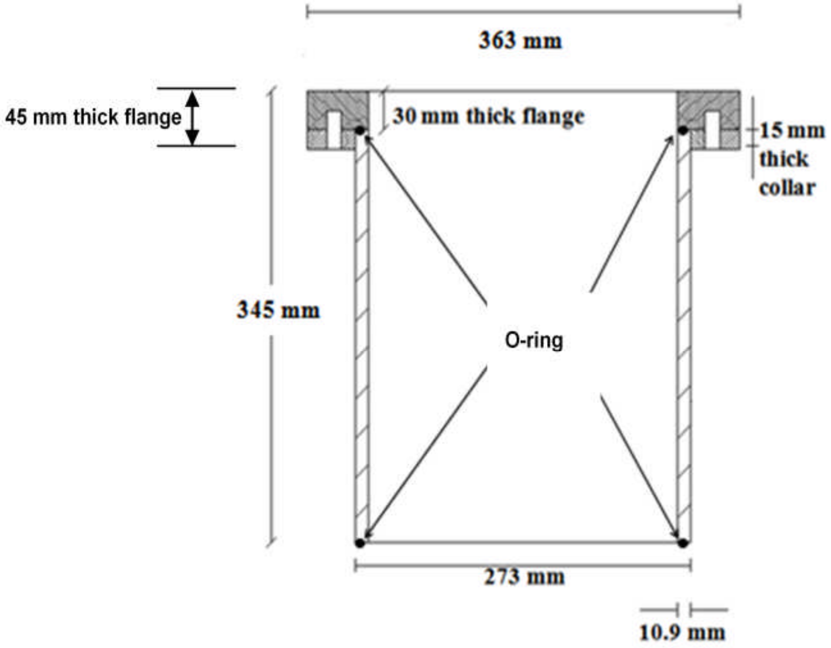


Figure 3.9 Elevation of the osmotic chamber (not to scale)

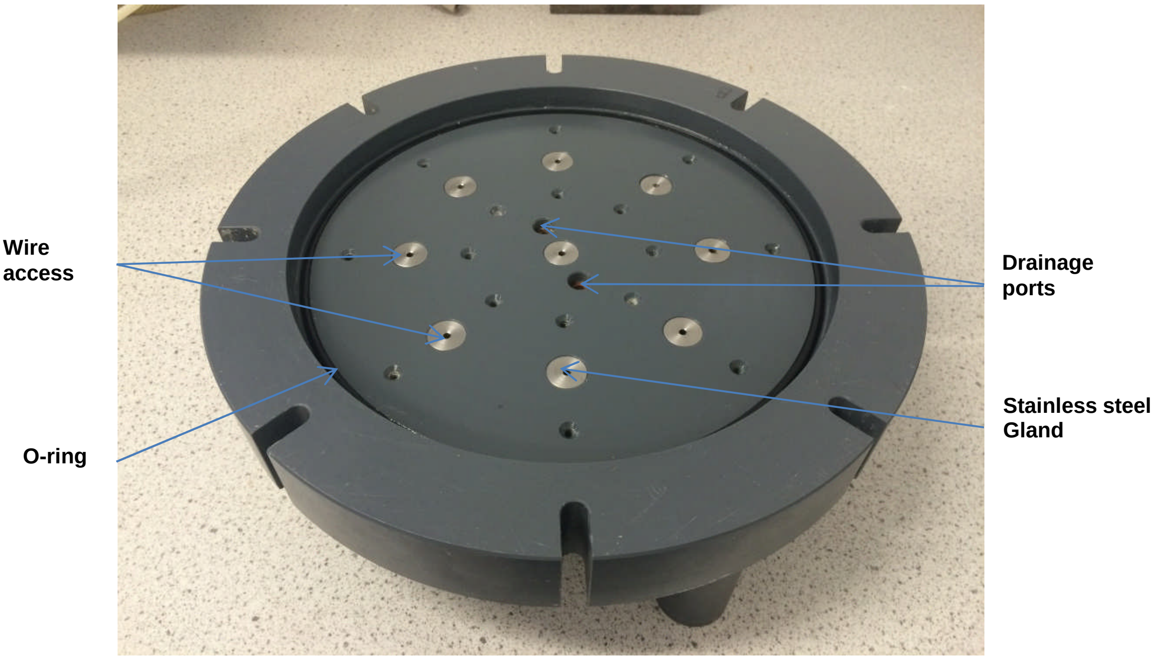


Figure 3.10 (a) The base of the cell and drainage ports

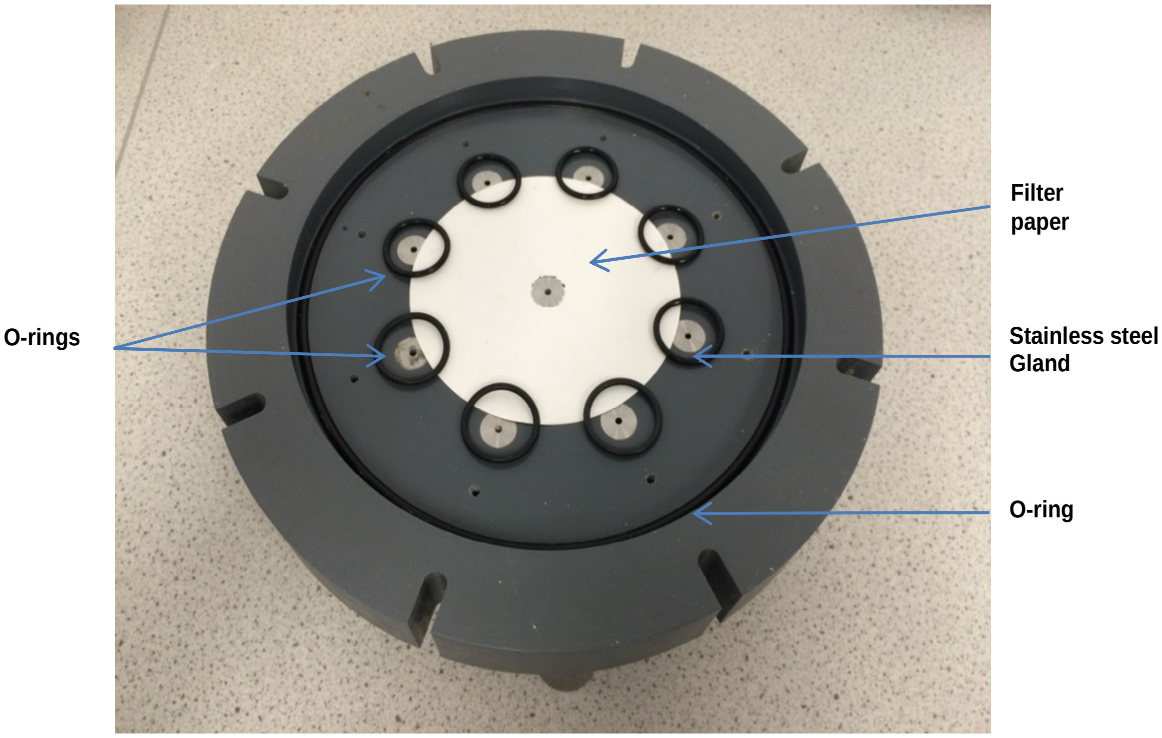


Figure 3.10 (b) The base of the cell showing glands and O-rings

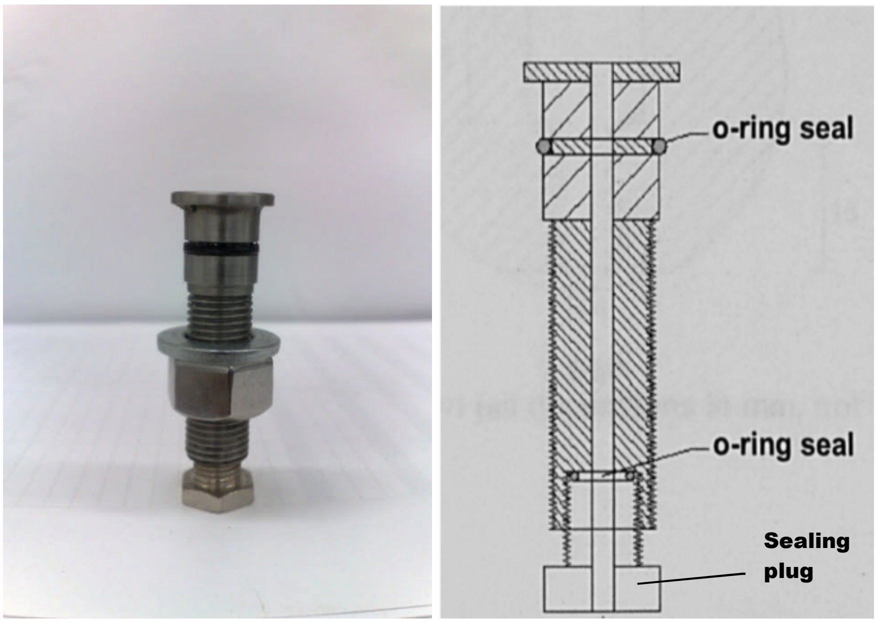


Figure 3.11 Elevation view and schematic diagram of the gland

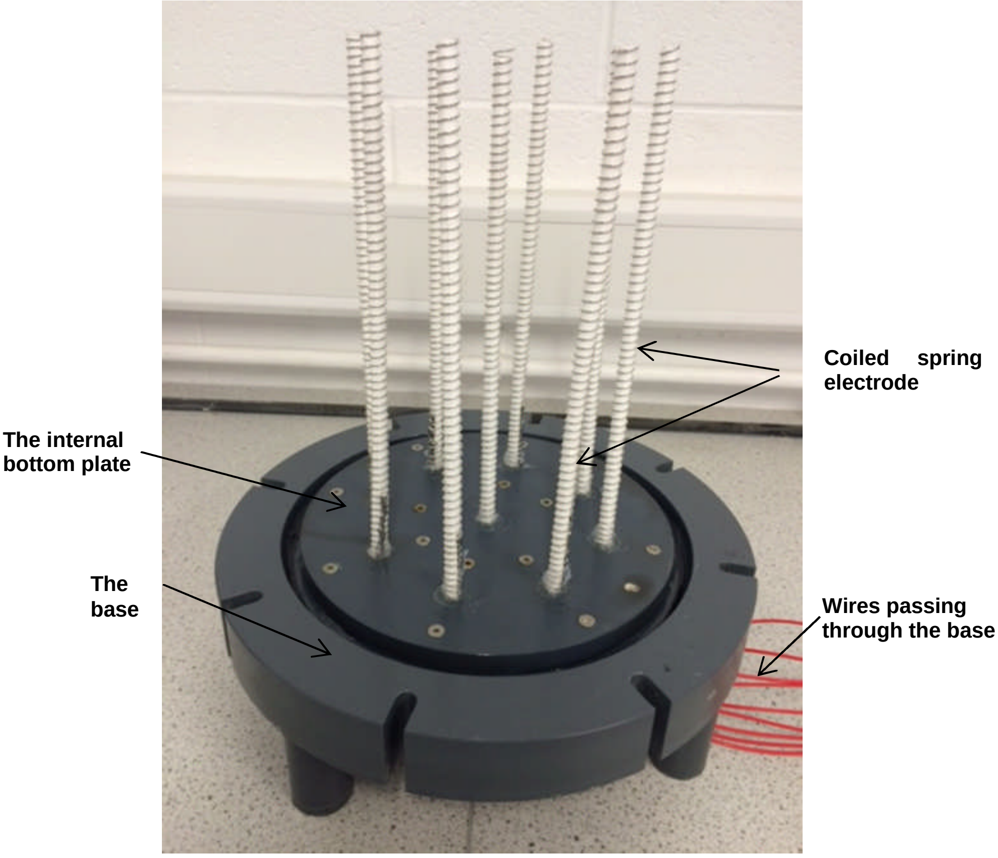


Figure 3.12 The base of the cell with the bottom plate carrying the electrodes

3.6 The test procedure

This section focuses on the procedure of assembling the test cell and conducting the experimental test. The experimental program followed the procedure used by Nizar and Clarke (2013) with some modifications. The test procedure steps were:

1. Assembling the electroosmotic cell.
2. Installing electrodes.
3. Filling the cell with soil slurry.
4. Installing the top of the cell with other parts.
5. Loading the soil in three phases to represent a working platform, electroosmotic consolidation and foundation loading.
6. Dismantle the cell.

3.6.1 Assembling the electroosmotic cell

The base of the cell and all other parts was cleaned and dried before a test. An O-ring was fitted in the groove in the cell base with silicon grease to ensure a seal; the glands were also inserted in their designed location. A filter paper was then placed on the top of the base as can be seen in Figure (3.10 b) to prevent drainage of soil material with water. O-rings were also placed between the base and the internal bottom plate around the anodes plugs to prevent the anodes from working as a drains as shown in Figures (3.10 b) and (3.16).

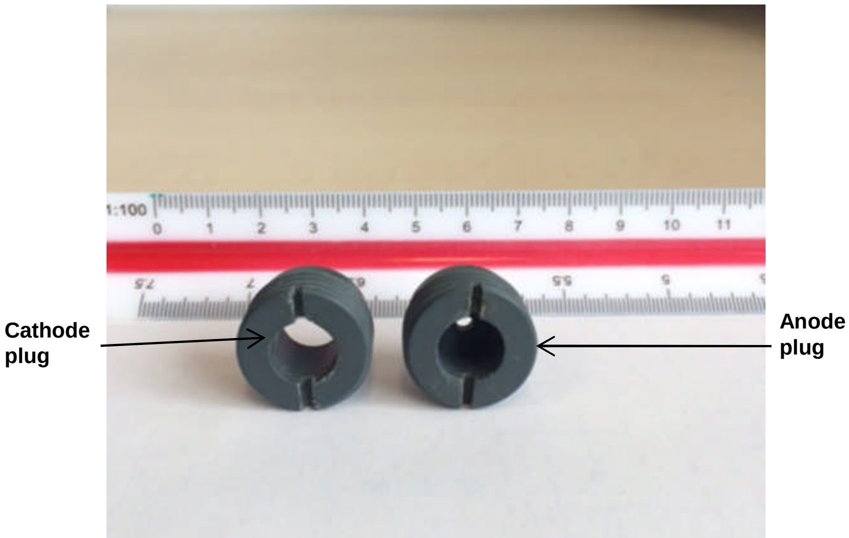
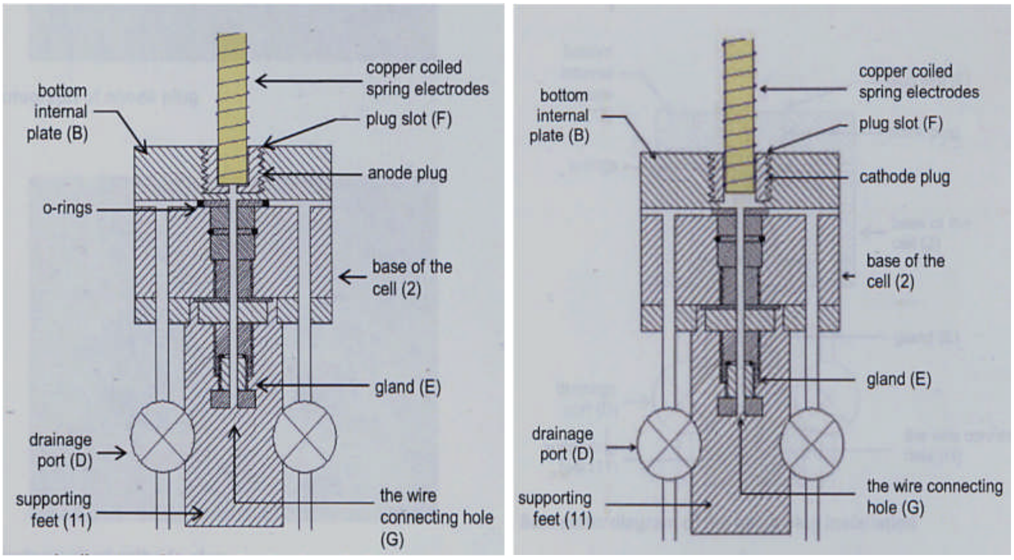


Figure 3.13 Cathode and anode plugs



(a) Anode plug **(b) Cathode plug**

Figure 3.14 Cathode and anode plugs installation

3.6.2 Installing electrodes

After setting up the base of the electroosmosis cell, the electrodes were then placed in the plug slots, wires passed through the plugs and glands as shown in Figures (3.12) and (3.17). The sealing plugs shown in Figure (3.11) were tightened onto the wires to prevent water leaks. The body of the cell was then attached to the base by clamping bolts.

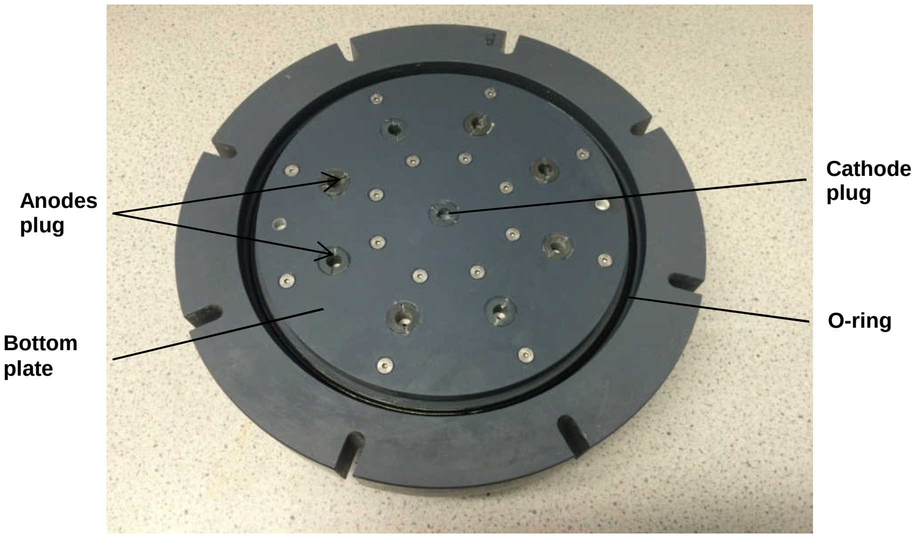


Figure 3.15 The base of the cell showing bottom internal plate and plugs

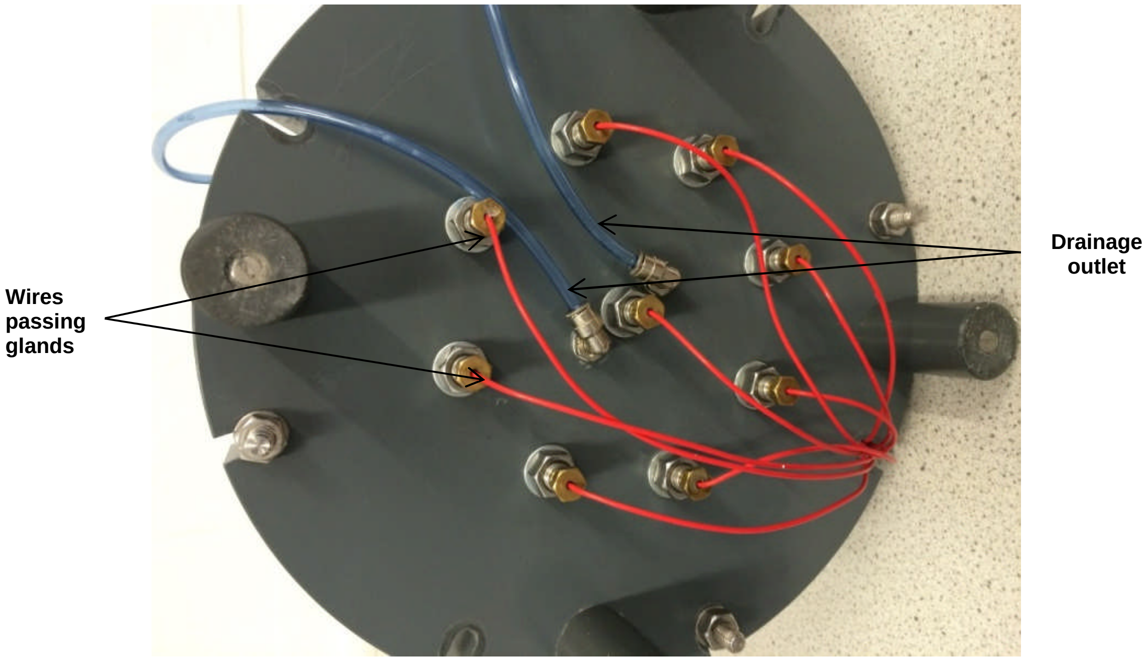
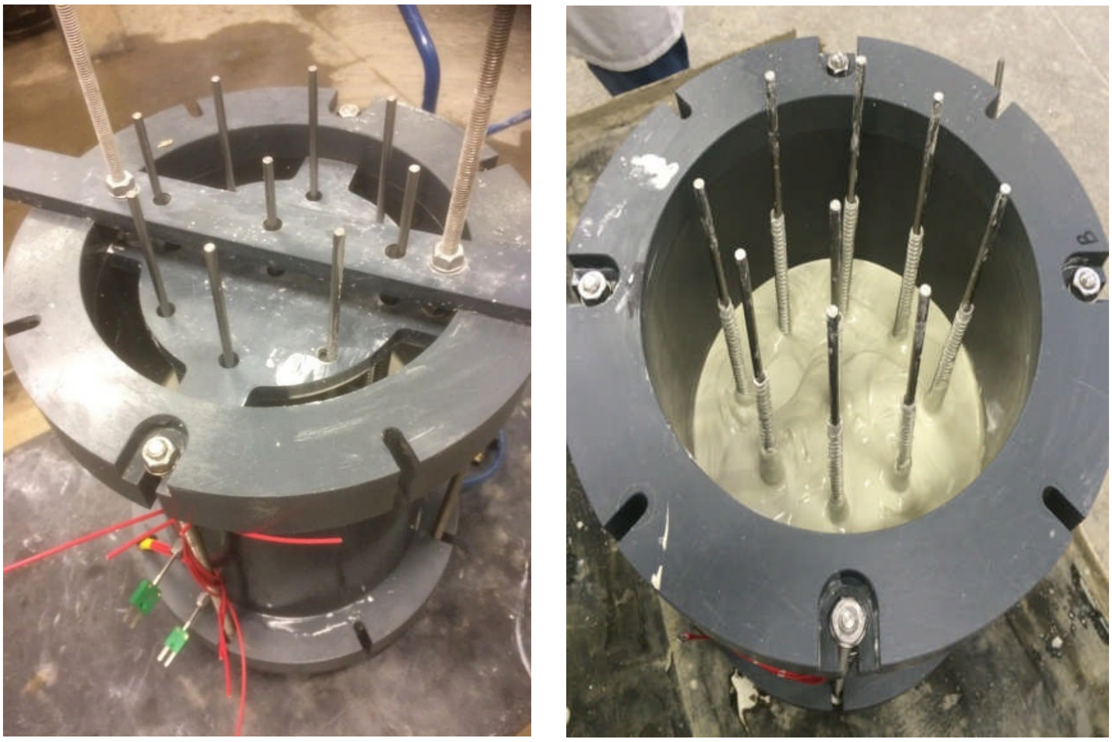


Figure 3.16 The base of the cell showing wires passing the glands and drainage outlet

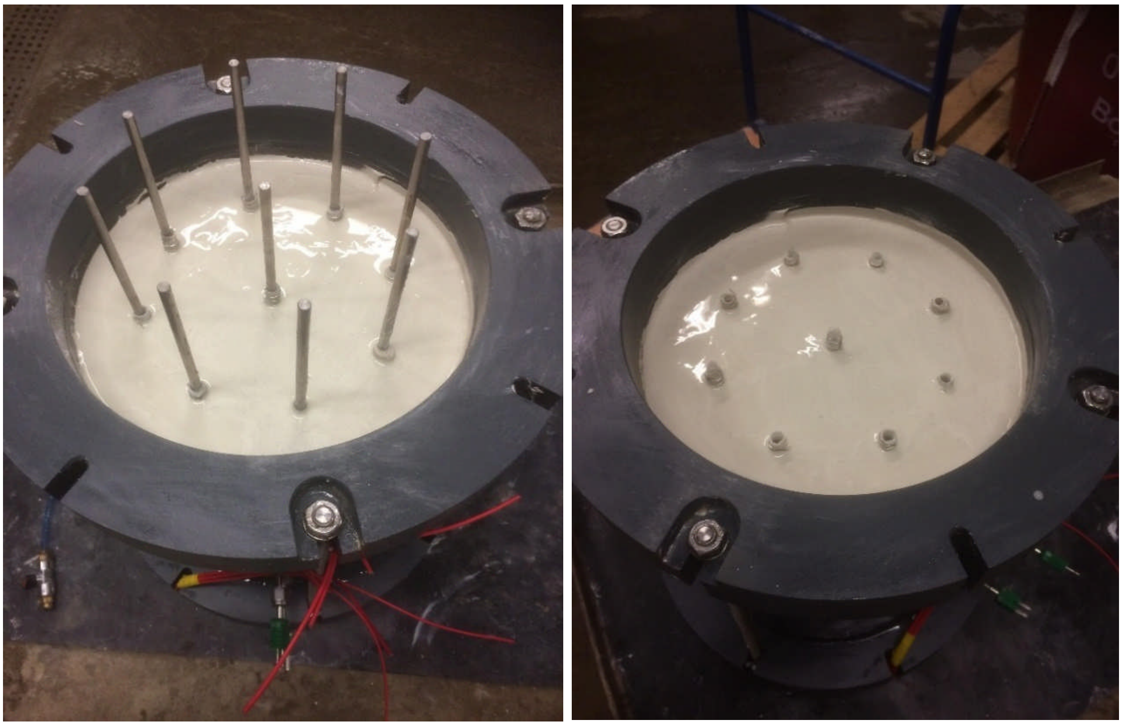
3.6.3 Filling the cell with soil slurry

After the body was fitted to the base, the internal surface of the cell was lubricated with a grease to minimize the side friction that may develop during the consolidation process. Soil slurry was poured into the cell in layers about 50mm depth to ensure uniformity of the sample and, vibrated on a shaking table between each layer to remove any entrapped air as shown in Figure (3.17). A PVC hanger shown in Figure (3.17) was used to hold the electrodes in their designed position when the soil slurry was poured in to the cell. Steel rods were inserted inside the electrodes and held in place to ensure the electrodes were not displaced from their designed location during shaking. The steel bars, and hangar were removed after filling the cell to the final depth. The cell was weighed before and after pouring the soil sample to determine the initial weight of the soil slurry. The final depth of soil mixture was about 300mm.



(a) Holding the springs in place while the first layer was placed

(b) The first prior to vibration with the steel rods inside supporting the electrodes



(c) The final layer after vibration with the steel rods still in place

(d) The complete sample with the steel rods removed

Figure 3.17 Preparing a kaolin soil sample showing (a) the means of holding the springs in place while the first layer was placed, (b) the first layer after vibrating the sample supporting the electrodes, (c) the final layer prior to vibration with the steel rods still in place, and (d) the complete sample with the steel rods removed.

3.6.4 Assembling the cell

Once the cell was filled with soil slurry, a filter paper was placed on top of the soil slurry to avoid direct contact with a top rigid plate to prevent the sample sticking to it. The top rigid plate shown in Figure (3.18) and marked (4) in Figure (3.8) was placed on top of the soil, the diaphragm placed above this plate. The external perimeter surfaces of the top rigid plate was lubricated with a grease to reduce the side friction with the cell walls that may develop during the consolidation process. The top of the cell was attached to the cell body by 4-bolts to clamp the top of the cell with the diaphragm and prevent leakage in the pressure system. The cell was then connected to the air pressure system with all valves closed. A dial gauge was placed to the top of the cell as shown in Figure (3.1).

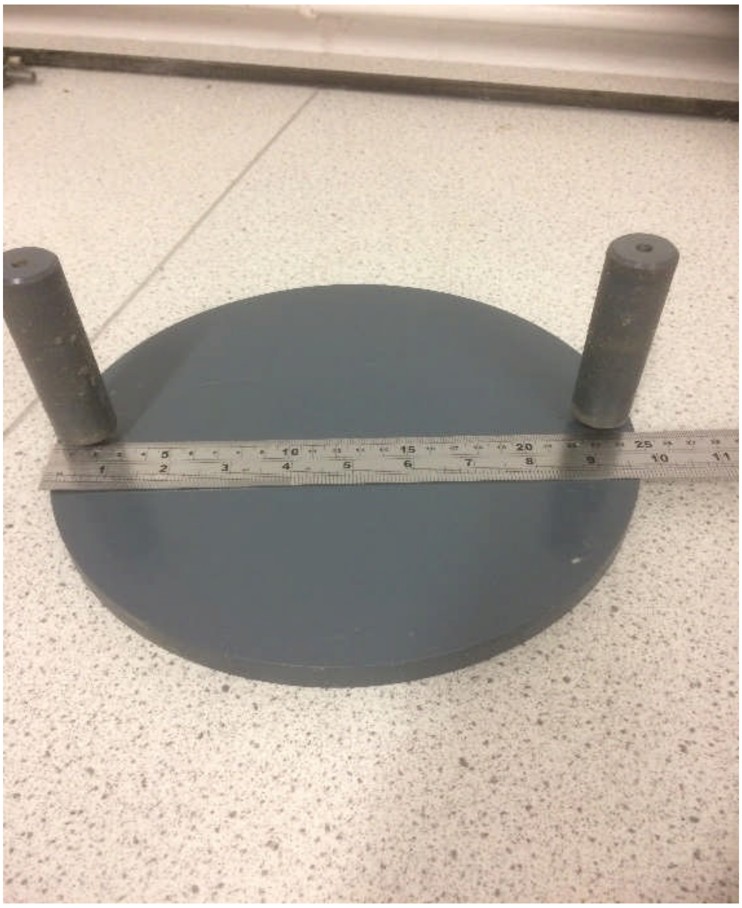


Figure 3.18 The rigid top plate, (4) in the schematic diagram

3.6.5 Loading the system

The soil slurry was left over night to settle and ensure homogeneity. There were three phases to a test:-

- Phase 1: 15kPa was applied to the platen to simulate a working platform, consolidate the soil and ensure that the test chamber was functioning correctly.
- Phase 2: A constant voltage (either 5, 10, 15 or 20V) was applied to the electrodes in addition to the 15kPa pressure. This phase was stopped when there was no further water expelled from the cell indicating the electroosmotic process had stopped due to either the degradation of the anode or the flow due to the hydraulic gradient exactly balancing the electroosmotic flow.
- Phase 3: 50kPa was applied for 24 hours to simulate a surcharge load such as a shallow foundation to assess the performance of the system.

The soil composition and voltage were varied between tests; the vertical settlement of the sample, expelled water, variation of current with time, consumed power, and temperature were measured during a test; and the final water content was measured at the end of a test.

The test started when a load was applied and a drainage valve was opened. In each stage of the test, the settlement of the soil sample and volume of water expelled was reported. Readings were recorded in a log scale as in standard consolidation tests. Phase 1 and Phase 3 each lasted 24 hours for kaolin soil mixtures because the time-settlement curves (Nizar and Clarke, 2013) showed they approached a plateau before 24 hours. Phase 1 in bentonite soil mixtures was kept for 14 days until the rate of settlement was less than 0.01mm/day. Phase 2 started when DC power was applied, treatment time under electroosmosis treatment in Phase 2 depended on the soil type and the applied voltage. The applied voltage was switched off when there was no further water expelled from the cell and when the observed settlement stopped. This was the end of Phase 2. In Phase 3, 50 kPa was used to determine the impact of electroosmosis consolidation on the overall stiffness of the tested soil. Table (3.4) presents a summary of the electroosmosis tests carried out.

Table 3.4 Summary of the carried out electroosmosis tests

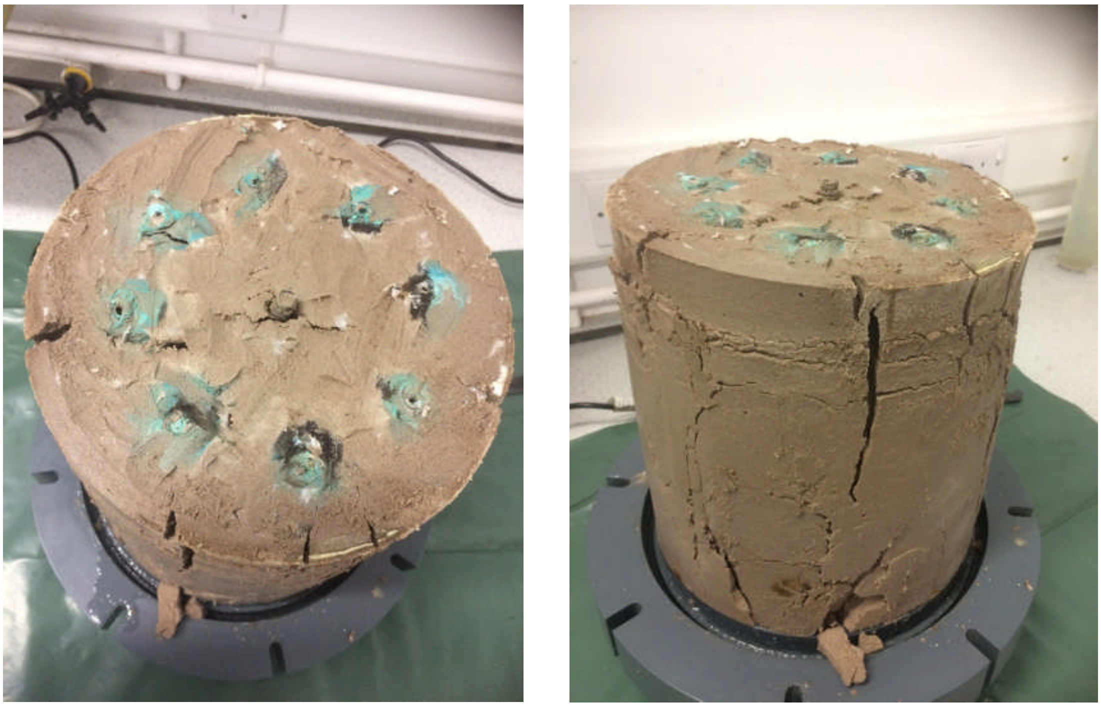
Test No.	Soil type	Water content (w %)	applied voltage (V)	Phase1/ hours	Phas2/ hours	Phas3/ hours	Sett. Phase 1 (mm)	Sett. Phase2 (mm)	Sett. Phase 3 (mm)	Total sett. (mm)	Total expelled water (ml)	Sett. from expelled water (mm)
1	kaolin	79.5	5	24	168	24	30.46	9.92	8.84	49.22	2445	49.41
2	=	79.5	10	24	168	24	31.56	31.83	0.42	63.81	3230	65.27
3	=	79.5	15	24	96	24	31.87	41.43	0.38	73.68	3700	74.77
4	=	79.5	20	24	96	24	30.95	48.48	0.1	79.53	3885	79.14
5	sand & kaolin (23% sand)	75	10	24	120	24	59.79	8.49	2.53	70.81	3510	71.5
6	=	=	15	24	120	24	59.74	16.16	0.71	76.61	3790	77.2
7	sand & kaolin (33% sand)	64.5	10	24	120	24	54.35	6.91	3.61	64.87	3210	64.83
8	=	=	15	24	120	24	53.89	7.68	2.39	63.96	3200	64.67
9	sand & kaolin (50% sand)	50	10	24	96	24	47.42	4.41	5.98	57.81	2845	57.5
10	=	50	15	24	96	24	48.37	6.46	3.15	58.18	2910	58.8
11	=	50	20	24	72	24	48.65	6.75	2.67	58.07	2905	58.6
12	sand & kaolin (67% sand)	35	10	24	96	24	43.66	2.25	4.92	50.83	2470	50.32

Test No.	Soil type	Water content (w %)	applied voltage (V)	Phase1/ hours	Phas2/ hours	Phas3/ hours	Sett. Phase 1 (mm)	Sett. Phase2 (mm)	Sett. Phase 3 (mm)	Total sett. (mm)	Total expelled water (ml)	Sett. from expelled water (mm)
13	sand & kaolin (67% sand)	35	15	24	96	24	43.59	4.16	3.91	51.65	2465	50.11
14	bentonite	160	5	360	192	24	46.68	9.91*	6.67*	63.26*	3130	63.25
15	=	160	10	360	168	144	46.59	14.55	11.72	72.83	3610	72.95
16	=	160	15	360	96	96	46.74	16.06	7.68	70.48	3485	70.43
17	bentonite & sand (23% sand)	126	10	360	168	48	41.22	12.83	5.05	59.10	2925	59.11
18	=	126	15	360	96	96	41.09	14.14	5.46	60.69	3010	60.83
19	bentonite & sand (33% sand)	110	10	360	168	168	35.66	12.12	8.08	55.86	2760	55.78
20	=	110	15	360	168	72	35.53	12.93	4.04	52.50	2600	52.54
21	bentonite & sand (50% sand)	84	10	360	168	168	30.71	11.51	7.57	49.79	2465	49.81
22	=	84	15	360	168	96	30.75	12.53	4.14	47.42	2345	47.39
23	bentonite & sand (67% sand)	55.5	10	360	264	96	30.11	12.33	4.65	47.09	2330	47.1
24	=	55.5	15	360	264	72	30.08	13.33	3.43	46.84	2125	42.95

3.6.6 Dismantle the cell

At the end of Phase 3, the cell was dismantled, the air pressure system was disconnected from the cell, the top of the cell with the diaphragm, the top rigid plate and the body were removed to measure water content at the end of test. The water content was measured at the anodes, cathode, in between electrodes, and at the cell wall at five levels so the variation of water content with depth and distance from the electrodes could be assessed as shown in Figure (3.19).

(a) Dismantle the cell in kaolin soil sample to measure water content



(b) Dismantle the cell in bentonite soil sample to measure water content

Figure 3.19 Location of sampling to determine water content in kaolin and bentonite soil

3.7 Comparison between expelled water in Phase 1 in two tests

An example of the expelled water versus time curve in Phase1 for two tests are presented in this section to assess the repeatability of the tests. Tests for kaolin and sand mixtures (50/50) are shown in Figure (3.20). Expelled water was measured using a measuring cylinder to an accuracy of ± 5 ml. The expelled water curves shows that there was a small difference at the start of the experiment but the percent difference in total water expelled at the end of the tests was 0.004%.

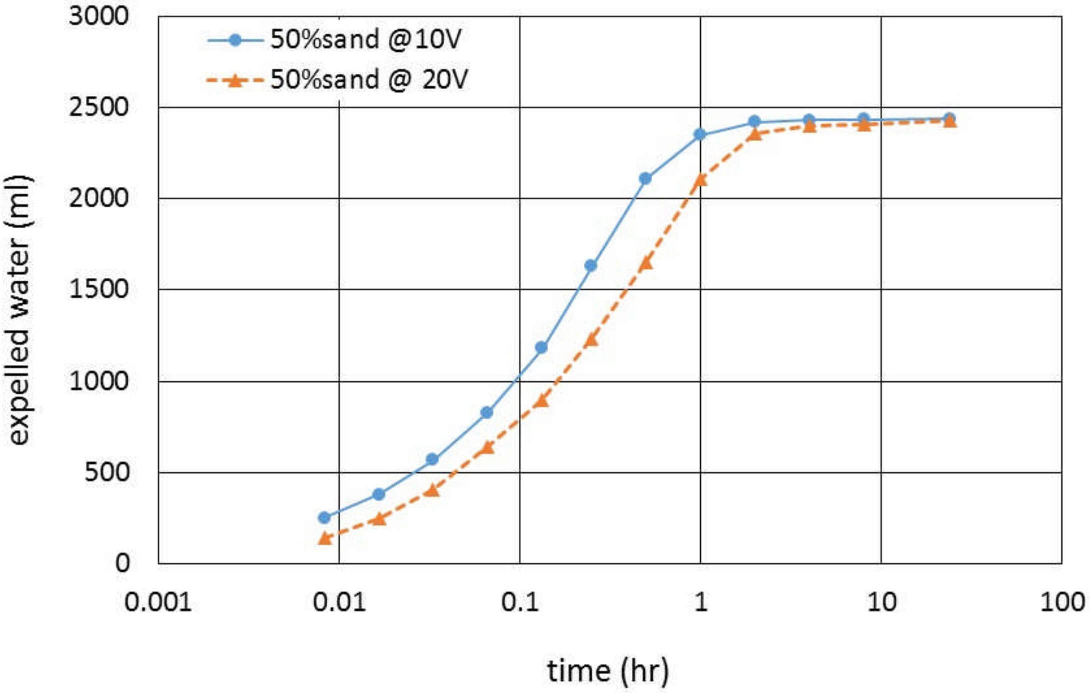


Figure 3.20 Comparison between the expelled water with time in two tests in Phase 1

3.8 Typical test results

An example of the test results is presented in this section. The result for 50% sand with kaolin subjected to 20V in Phase 2 was selected as a typical test of the electroosmosis treatment; the results are shown in Figures (3.21) to (3.31). The results are presented in terms of vertical displacement versus time, water expelled versus time, change in void ratio verse time, electrical current variation and power verse time, water content profile at the end of Phase 3, and the variation of temperature with time during electroosmosis phase.

3.8.1 Vertical settlement, expelled water and void ratio

Figures (3.21) to (3.23) present the variation of vertical displacement and expelled water with time in Phases 1, 2 and 3 respectively. Octagonal electrode configuration with 20V applied for 72 hours osmotic treatment in soil slurry with 50% initial water content was chosen. Octagonal shape with 8-anodes and one central cathode has been used in the experimental tests of this study because of its relatively high effective treated area. Both Phase 1 and Phase 3 ran for 24 hours. Phase 1 was used to ensure a uniform sample and prevent cracking by maintaining a positive effective stress. Phase 3 was used as a measure of the performance of the composite soil. A total of 48.65 mm of vertical settlement occurred and 2430 ml of water was expelled during Phase 1, as shown in Figure (3.21). In Phase 2, where a 20V was applied to treat the sample for 72 hours, it shows 380 ml water was expelled and 6.75 mm of settlement occurred, due to electro osmosis as shown in Figure (3.22). The electrical current stopped when there was no more settlement or expelled water which meant the end of Phase 2 and the start of Phase 3. A total of 95ml water was expelled and 2.67 mm of vertical settlement took place in Phase 3 as shown in Figure (3.23).

The difference in the observed settlement and expelled water converted to settlement shown in Figure (3.21) for Phase 1 shows that the independent measurements give similar results which suggests that the settlement was a function of the change in water content. The direct measurement of settlement in Phase 2 was different from that determined from the volume of expelled water, Figure (3.22). This is attributed to the creation of the electroosmotic piles, stiffened columns around the anodes, which reduced the total settlement even though water was expelled from the cathode. This suggests that the sample is no longer uniform. The difference in Phase 3 shown in Figure (3.23) is attributed to the redistribution of water at the end of electroosmosis treatment phase because the directly measured settlement exceeded that calculated from the volume of expelled water. However, the total vertical displacement in the three phases was 58.07mm compared to 58.6mm due to expelled water as shown in Figure (3.24).

Figures (3.25) to (3.27) show the change in volumetric strain with time in Phase 1, 2 and Phase 3 respectively. The voids ratio during Phase 1 decreased from the initial value of 1.325 to 0.922 which produce 0.304 change in volumetric strain as shown in Figure (3.25). The results of voids ratio after electro osmotic consolidation treatment in Figure (3.26) shows a decrease in the voids ratio of treated samples from 0.922 to 0.858, which is equal to 0.073 volumetric strain. This means that the electroosmotic treatment process increased the average soil density. At the end of Phase 3, the voids ratio shows that the value decreased from 0.858 to 0.843 at the end of 50 kPa which is equivalent to 0.0183 volumetric strain, as shown in Figure (3.27).

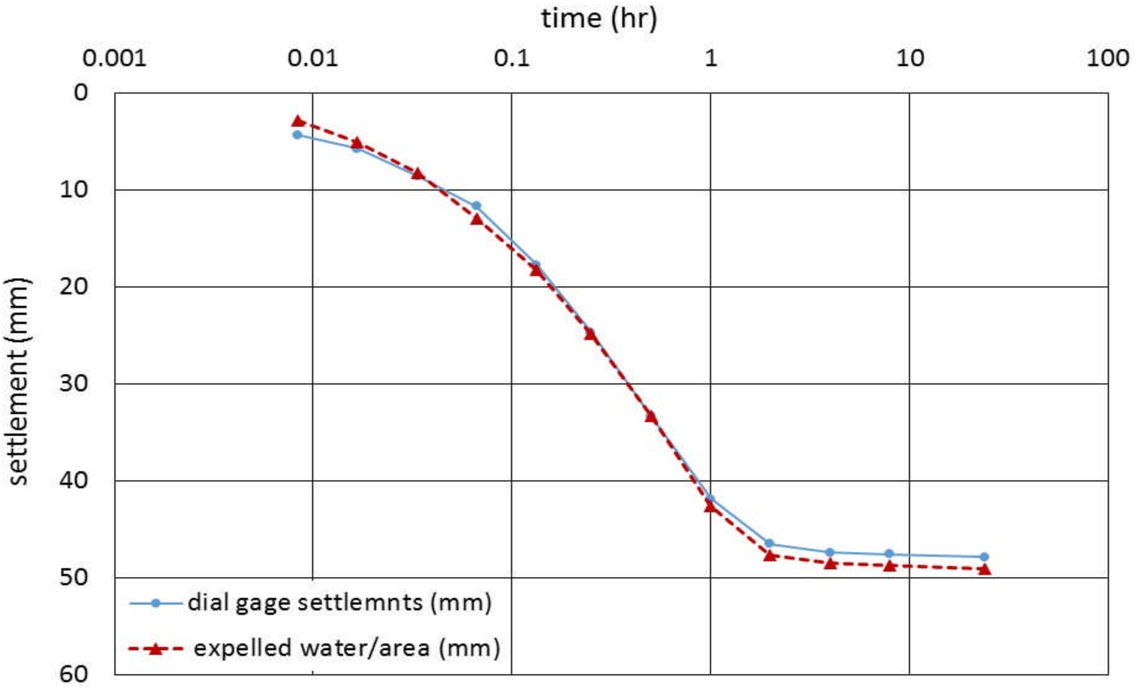


Figure 3.21 Expelled water and vertical displacement verse time in Phase 1 for 50% sand with kaolin soil mix

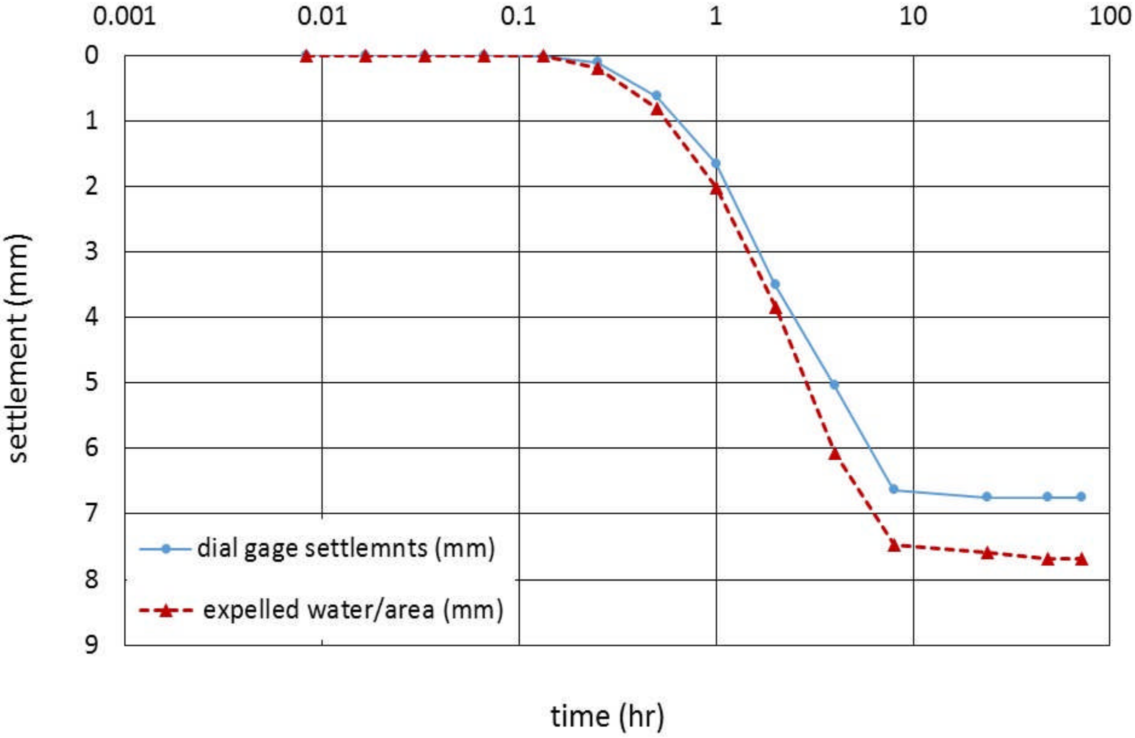


Figure 3.22 Expelled water and vertical displacement verse time for 50% sand with kaolin soil mix in Phase2

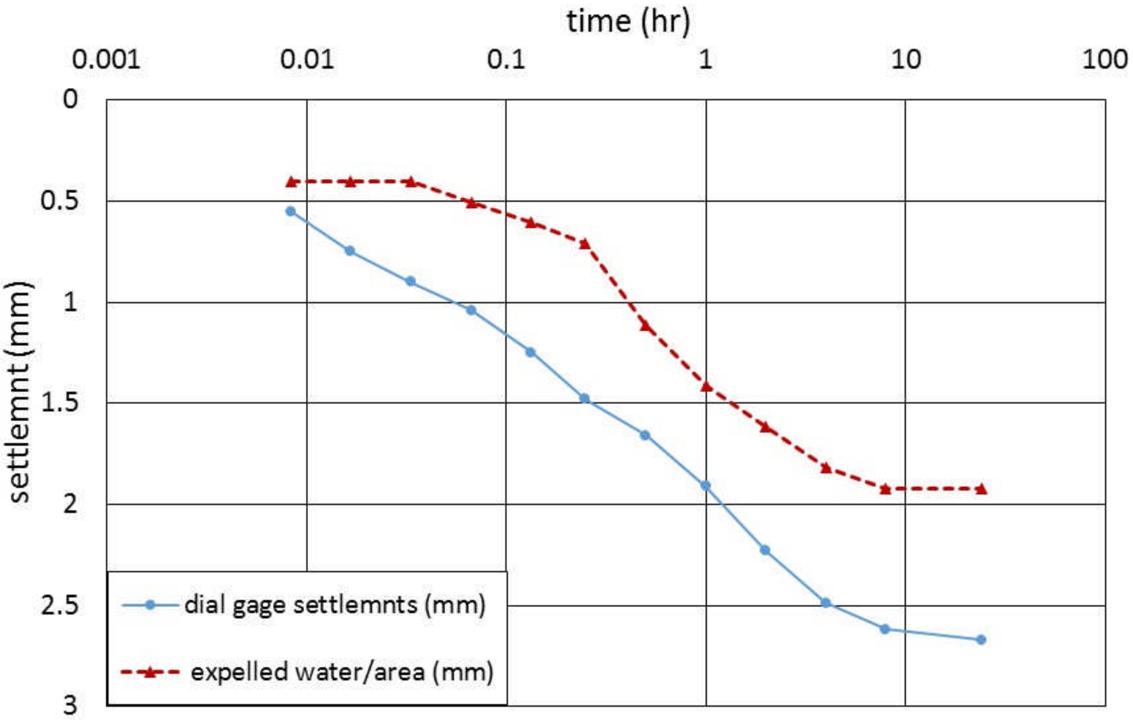


Figure 3.23 Expelled water and vertical displacement verse time for 50% sand with kaolin soil mix in Phase3

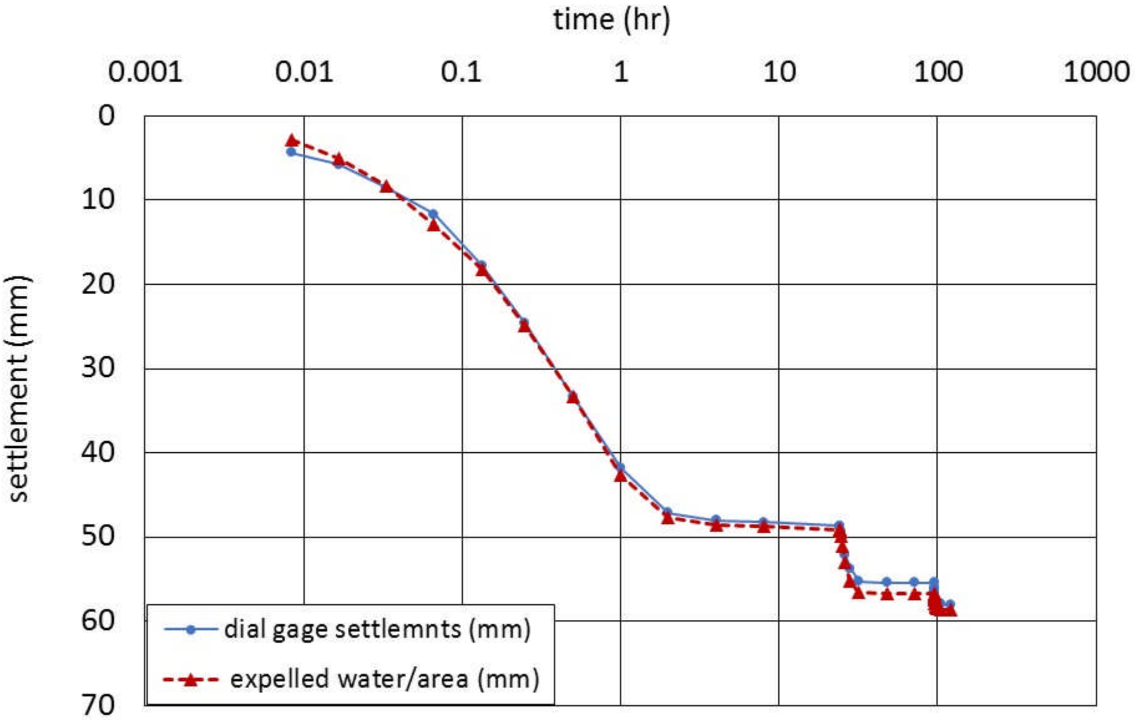


Figure 3.24 Expelled water and vertical displacement verse time for 50% sand with kaolin soil mix in the three phases

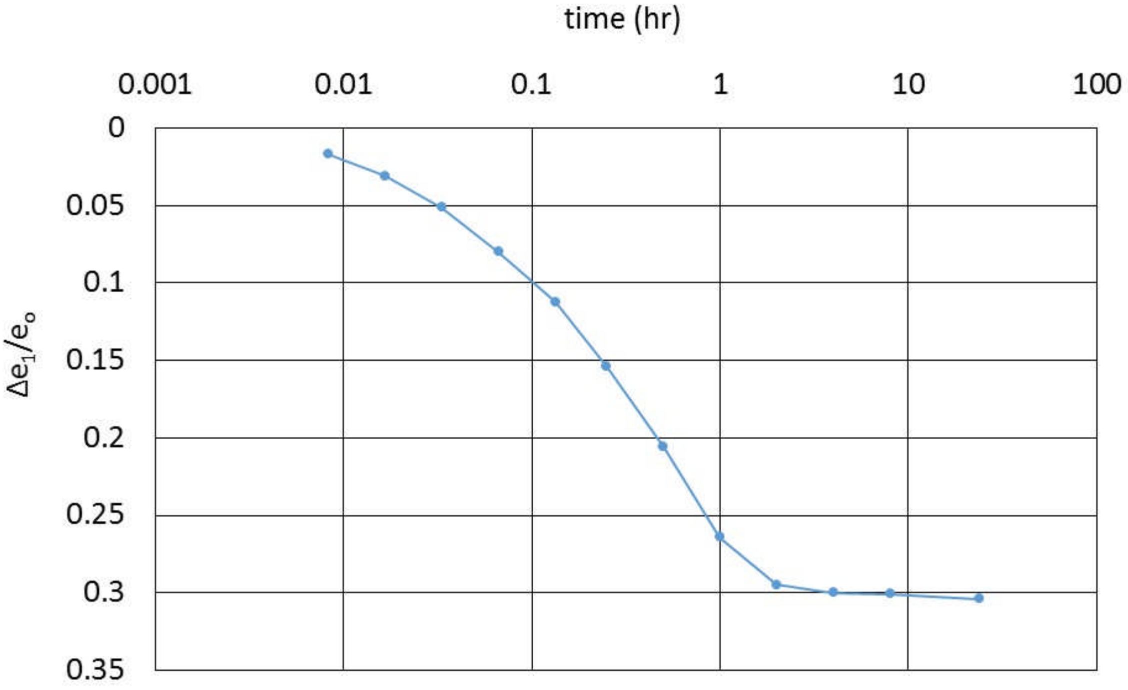


Figure 3.25 The change in void ratio at the end of Phase1, Δe_1 over the initial void ratio e_0

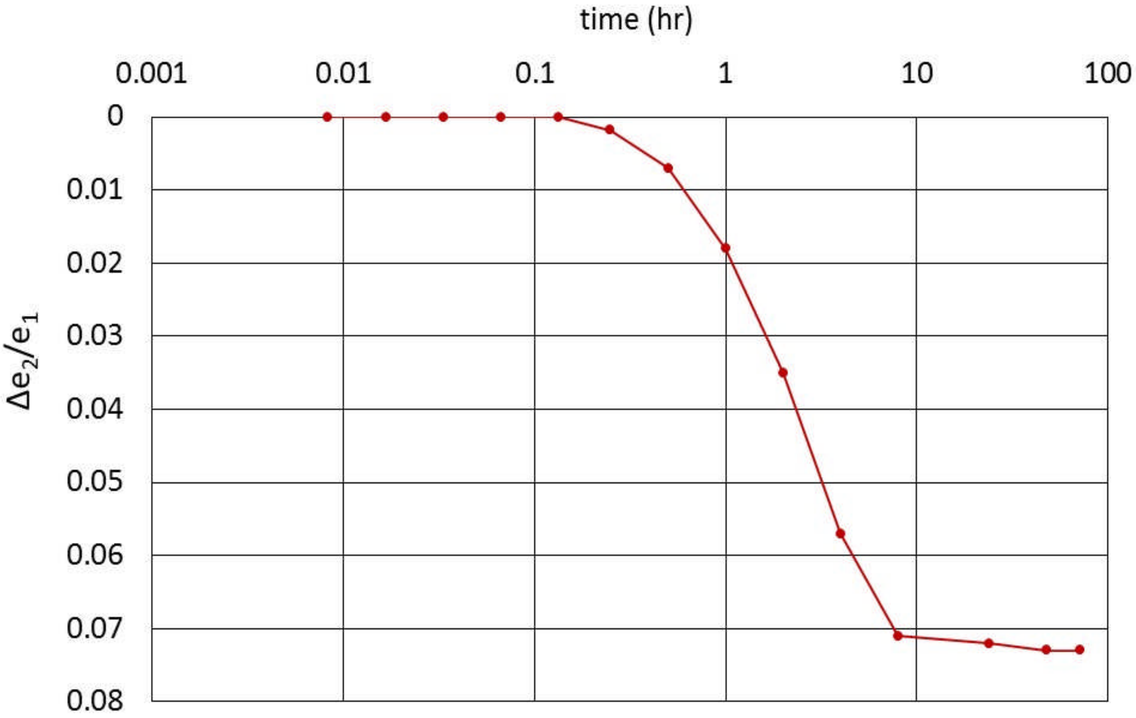


Figure 3.26 The changes in void ratio at the end of Phase2, Δe_2 over the void ratio in Phase1, e_1

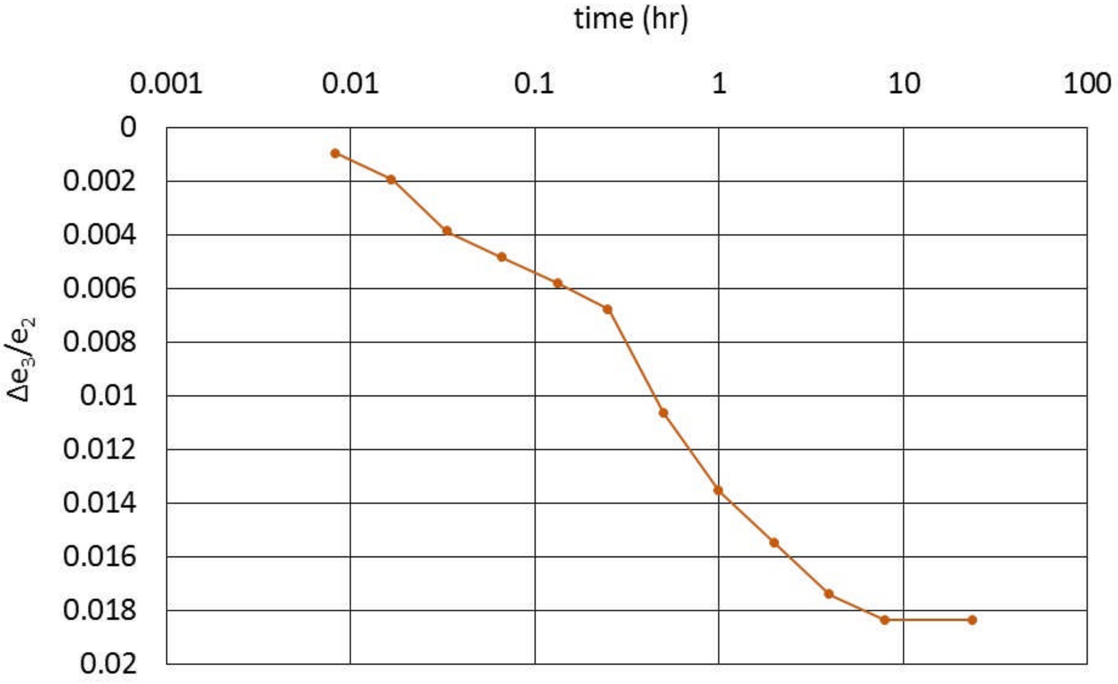


Figure 3.27 Changes in void ratio at the end of Phase 3 over the void ratio in Phase 2, $\Delta e_3 / e_2$

3.8.2 Variation of electrical current and power versus time curves

Figure (3.28) displays the variation of electrical current versus time during the electroosmosis phase. The electrical current decreased gradually with time from (0.14Am) at the start of the Phase 2 to (0.7Am) at 2 hours from when it remained constant until the end of Phase 2. The most interesting aspect of this figure is a clear trend of a decrease in electrical current. The decrease in current with time during electroosmosis consolidation is attributed to the corrosion process in anodes. Nizar Yusof (2012) stated that the decrease in current with time during electroosmosis consolidation under a constant voltage is due to polarisation and conduction behaviour which is dominated by ions. Figure (3.29) presents the variation of power with time during Phase 2. Since the applied voltage is constant, the trend of the current and power curves are the same.

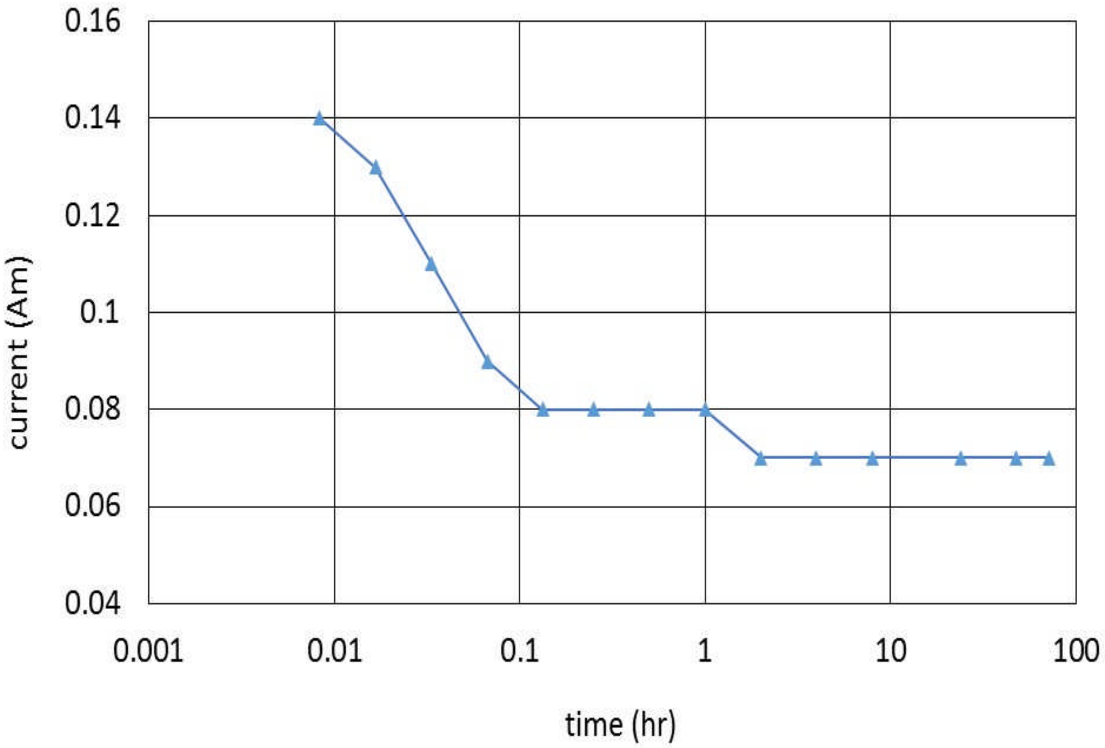


Figure 3.28 Variation of electrical current with time in Phase 2 for 50% sand with kaolin soil mixture

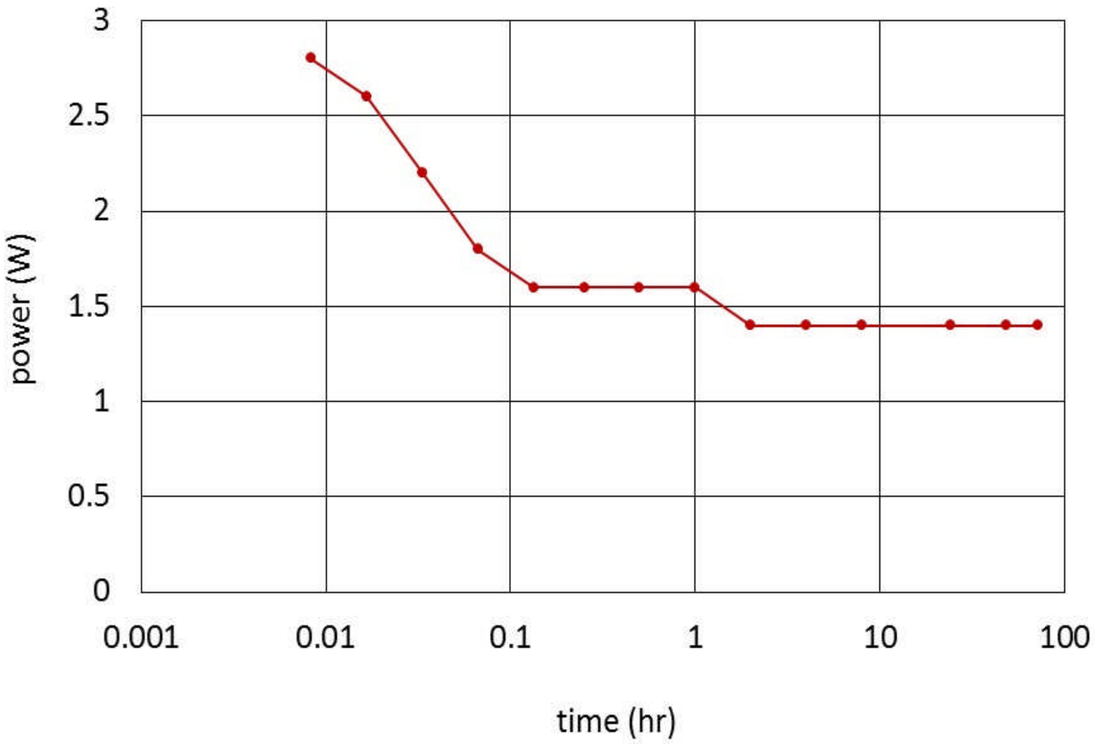


Figure 3.29 Variation of power with time in Phase 2 for 50% sand with kaolin soil mixture

3.8.3 Variation of water content

The final water content profile in the osmotically treated soil at different distances from the cathode (centre) is presented in Figure (3.30). The initial water content was 50%. The process and levels of water content test are described in section 3.6.5 and shown in Figure (3.19). The observed profile on Figure (3.30) shows that the maximum values of water content occur near the wall of the cell and decrease towards the electrodes which is attributed to the movement of water from the anode to cathode due to electroosmosis. The lower values of water contents near the cathode were likely to be related to the high concentration of sand due to drains as explained in Chapter 4.

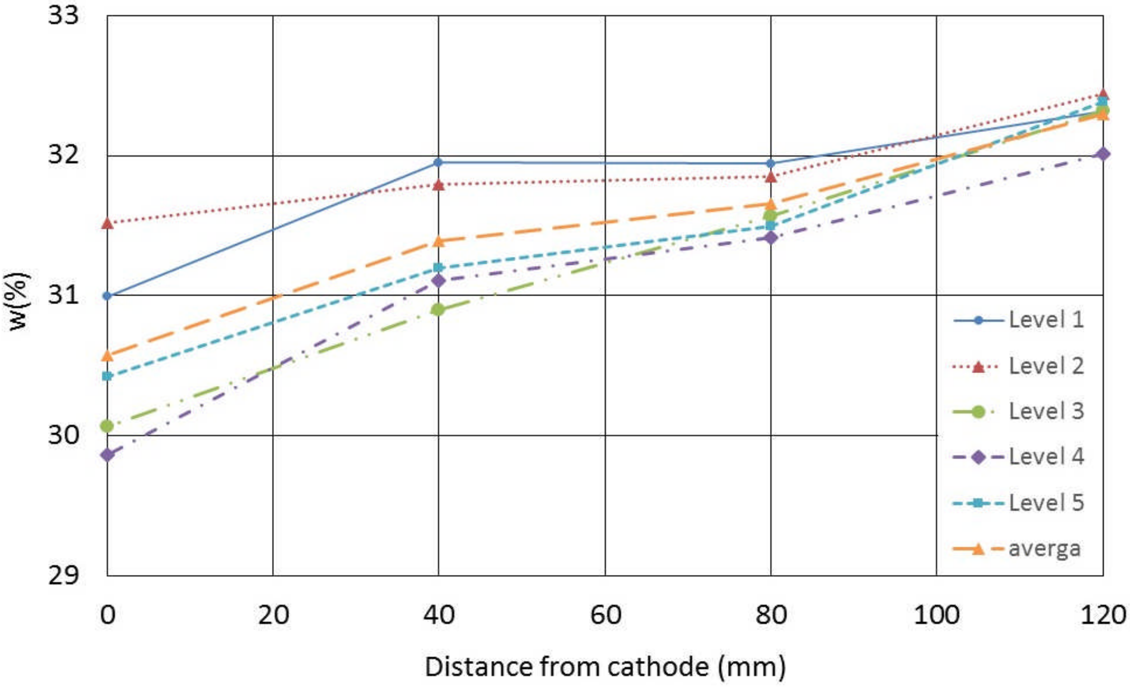


Figure 3.30 Water content profile at the end of Phase 3 shows the variation of water content at different distance from the cathode with at different levels

3.8.4 Variation of temperature

The temperature of the sample was monitored at intervals during Phase 2 by inserting a K type thermocouple temperature probe through glands in the sidewall of the test chamber, at the anode and the cathode near the bottom of the cell (about 50mm above the bottom), and at the cathode at the middle of the cell. Figure (3.31) shows that there was an increase in temperature due to electroosmotic process.

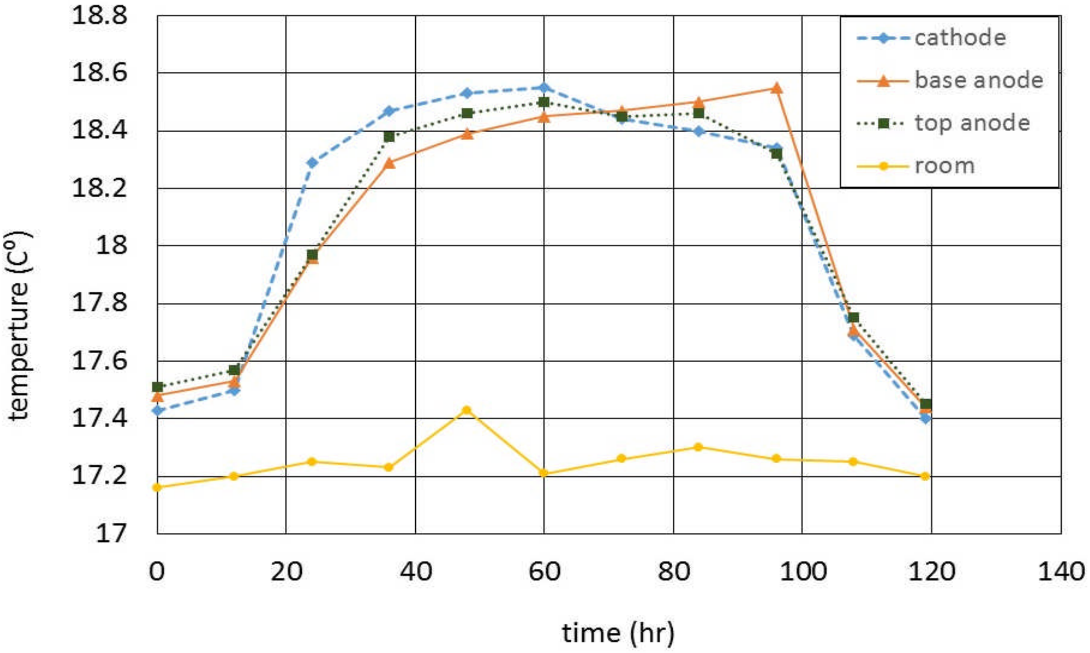


Figure 3.31 Variation of temperature with time during the electroosmotic treatment shows the variation of temperature at the anodes and the cathode

3.9 Summary

In this chapter, the details of laboratory tests, principles, design and procedure are discussed in detail. The choice of soils, electrode materials and electroosmosis cell discussed in this chapter were selected based on the literature study. English China Clay (Kaolin) and Calcium Bentonite (CB) soils were used in this study. The electroosmotic cell was designed to measure the vertical displacement and expelled water. Copper coiled springs were used as electrodes to allow them to deform as the soil consolidated. The initial water content used was 1.5 times the liquid limit of the soil mix, initially, 79.5% for pure kaolinite soil and 160% for pure bentonite soil to ensure a saturated sample that did not segregate during placement. An example of the results of a test is shown in Section 3.8, the full results on the electro osmotic piles series, i.e., different sand content with kaolin and different applied voltage are discussed in Chapter 4, and different sand content with bentonite subjected to different applied voltage are discussed in Chapter 5. The test equipment and procedure for electroosmosis treatments was also discussed in this chapter. From the typical test results showed in Section 3.8, and the results presented by (Nizar and Clarke, 2013) , it can be conclude that electroosmotic procedure used in this study is an effective method to treat soils.

Chapter 4

Experimental Test Results for Kaolin and Sand Soils

4.1 Introduction

In this chapter, the results and analyses of the experimental tests on kaolin based composite soils are presented. The electroosmotic tests were carried out to assess the feasibility of the concepts of ‘soft’ piles in composite soils. The test equipment, test procedure, and properties of the soil mixtures are described in Chapter 3. The soil composition and voltage were varied between tests; the settlement of the sample, expelled water, current and temperature were measured during a test; and the final water content was measured at the end of a test.

The results of fourteen tests are presented in this chapter, performed on the composite soil of China Clay Grade E kaolin mixed with different ratios of fraction C sand (0, 23, 33, 50 and 67%) subjected to 5, 10, 15 and 20V, as summarised in Table 4.1. Electroosmotic treatment was commenced after Phase 1, in which soil slurry was consolidated under 15 kPa vertical pressure. The results of settlement and water content of composite soils are discussed in conjunction with control test results conducted in a small consolidation cell. Based on the experimental data, the efficiency of electroosmotic tests and the consumed energy on the treatment of kaolin based composite soils were analysed.

Table 4.1 Summary of electroosmotic test in kaolin and sand soil mixtures

Test no.	soil	Applied voltage (V)	Phase 1 (hr)	Phase 2 (hr)	Phase 3 (hr)	Total treatment time (hr)
1	kaolin	5	72	120	24	216
2	kaolin	5	24	168	24	216
3	kaolin	10	24	168	24	216
4	kaolin	15	24	96	24	144
5	kaolin	20	24	96	24	144
6	23% sand	10	24	120	24	168
7	23% sand	15	24	120	24	168
8	33% sand	10	24	120	24	168
9	33% sand	15	24	120	24	168
10	50% sand	10	24	96	24	144
11	50% sand	15	24	96	24	144
12	50% sand	20	24	72	24	120
13	67% sand	10	24	96	24	144
14	67% sand	15	24	96	24	144

4.2 Control tests

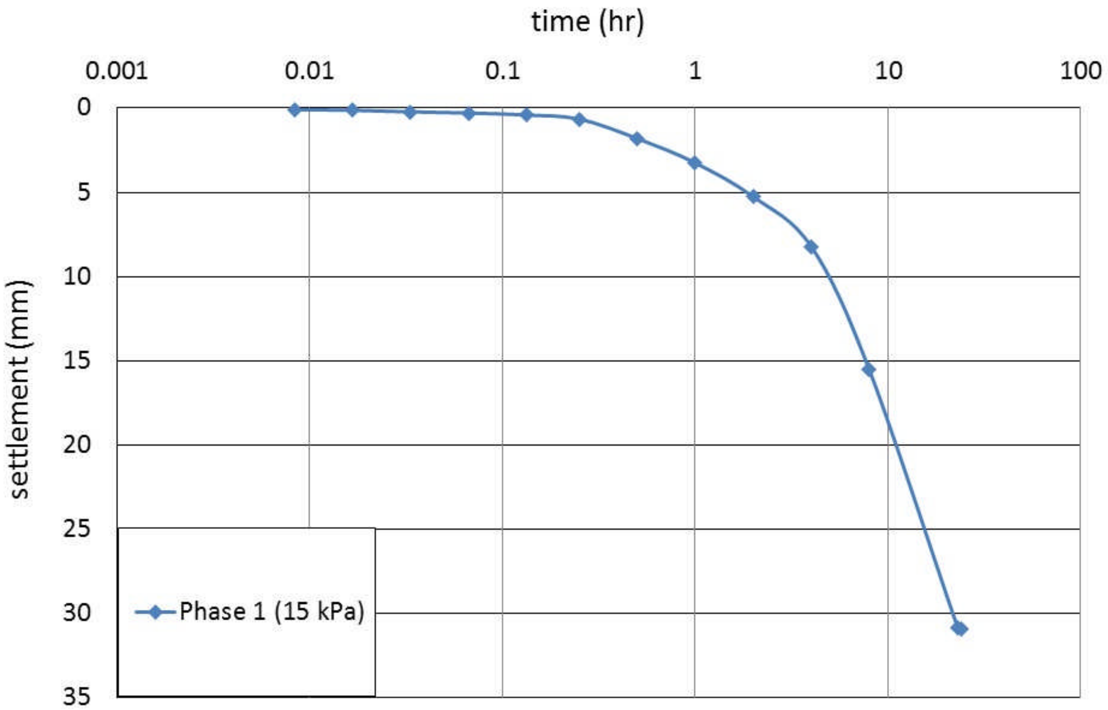
The control tests were carried out to establish the properties and behaviour of the soil samples subjected to only an increase of vertical pressure, which is 15 kPa in Phase1 and 50kPa in Phase 3. A full scale control test was carried out for pure kaolin soils. For kaolin and sand soil mixtures, the control tests carried out using a smaller consolidation cell shown in Figure (4.3).

4.2.1 Results for control tests on kaolin samples

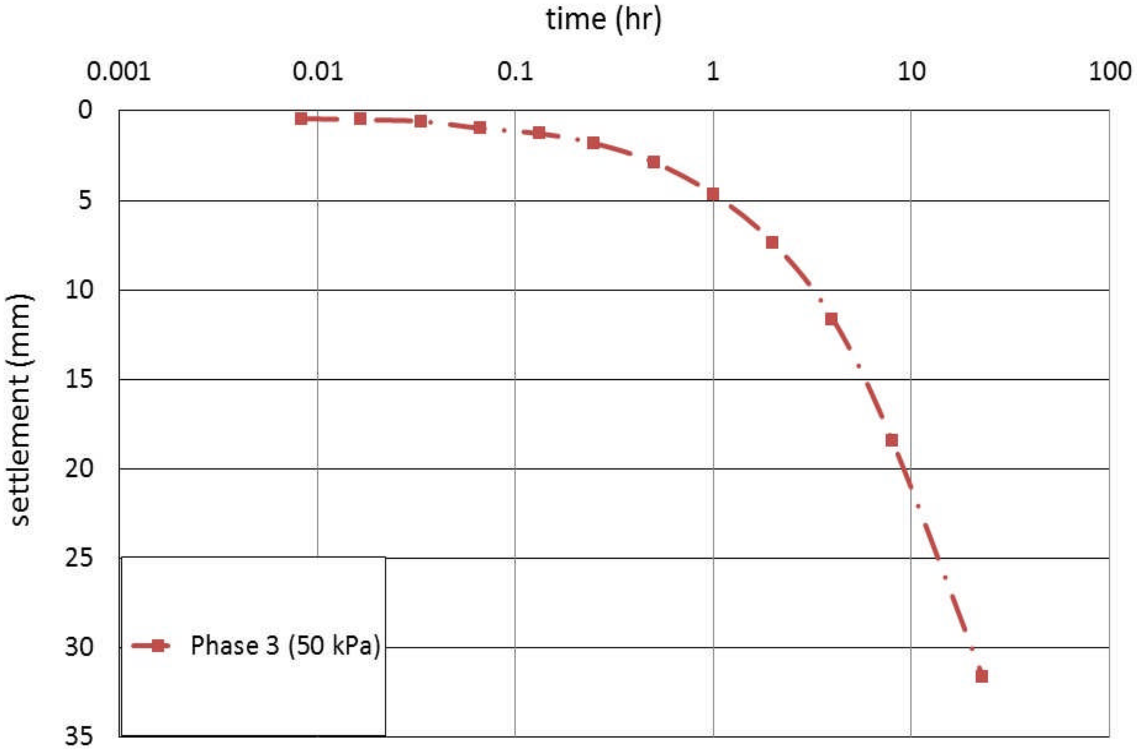
The soil slurry was loaded with 15 kPa for 24 hours in Phase 1 and with 50 kPa in Phase 3 for 24 hours. Table (5.2) compares the water content at the end of Phase 1 based on calculations from the expelled water, and Phase 3 based on calculations from the final water content on both of the control tests cells using the full scale cell and the small consolidation cell, Figure (4.1) shows the time settlement curve on the full scale control cell, both on Phase 1 and Phase 3. The tests were stopped after 24 hrs because the time–settlement curves from Nizar and Clarke (2014) approached a plateau before 24 hours and, from test 1 in Table (4.1), which ran for 72 hours in Phase 1, 98.5% of the total settlement had been taken place by 24 hours of the test time, as shown in Figure (4.2) The difference in the water content values (Table 4.2) between the two cells at the end of Phase 1 and Phase 3 is less than 1.5% and can possibly be attributed to the fact that the test on the full scale cell was ran for 24 hours, while the tests on the small cells was ran for 72 hours as shown in Figure (4.1). However, data from table (4.2) shows a good agreement between the two cells, which allows the use of the small consolidation cell with other soil mixtures.

Table 4.2 comparison between water content for control tests in kaolin soil in the full scale cell and small consolidation cell

Type of cell	Initial water content w_0 (%)	End of Phase 1 w_1(%)	End of Phase 3 w_3(%)
full scale test cell	79.5	65.3	51.5
small consolidation cell	79.5	64.4	50.4



(a) Settlement in Phase 1 full scale control test



(b) Settlement in Phase 3 full scale control test

Figure 4.1 Time – settlement curves for control test in kaolin soil in the large consolidation cell shows the settlement taken place at Phase 1 (a) and Phase 3 (b)

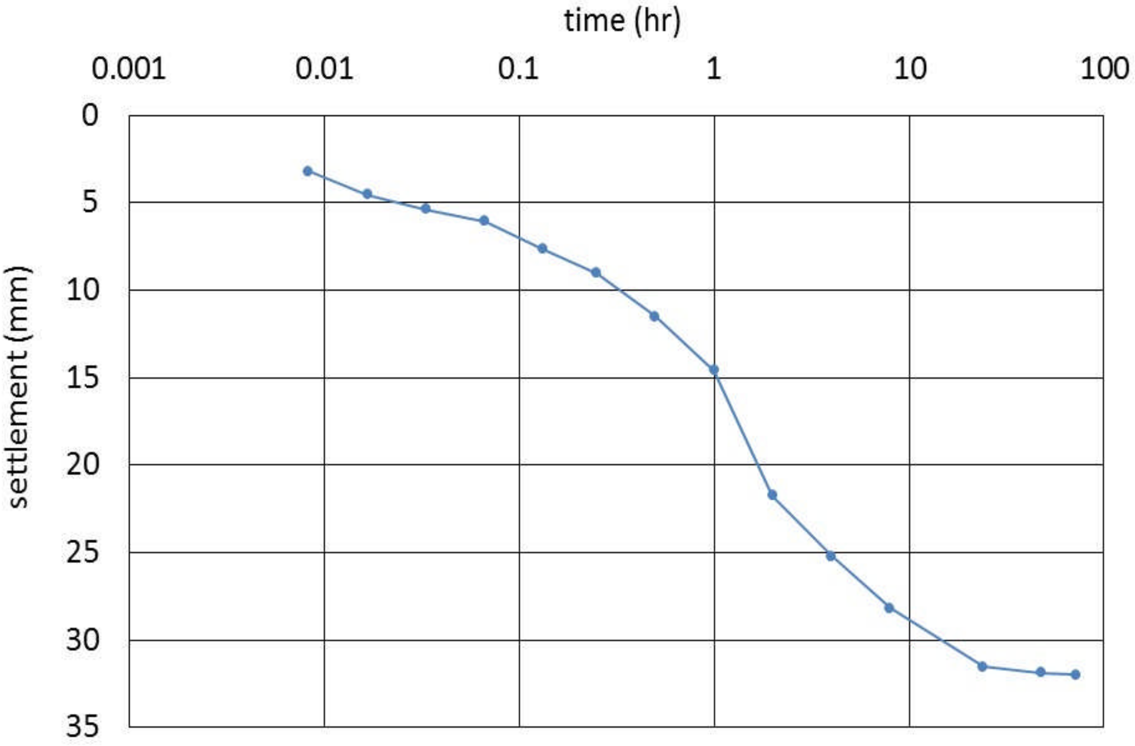


Figure 4.2 Settlement of the kaolin soil in Phase 1 showing that the settlement at 24hr was 98.5% of the primary settlement at 72hr

4.2.2 Results for sand and kaolin control tests

The consolidation cell designed by Al-Moadhen et al. (2017) and shown in Figure (4.3), was used in the control test series for sand and kaolinite soil mixtures. The cell consists of; a loading cap (1); a clear solid acrylic cylindrical cell with 15mm wall thickness (2) to contain and laterally restrain a soil specimen bottom drainage systems (4); porous discs (3) and a stainless steel base (6). An O-ring (5) sits between the cell base and the acrylic tube to ensure a complete seal during consolidation. The cell was designed to sit in a standard oedometer test rig which restricted the outer diameter to 134mm and height 126mm. Drainage was allowed from the bottom of a soil sample through the porous disc (3). The soil slurry mixes were loaded with 15 kPa in Phase 1 for 24 hours and 50kPa in Phase 3 for 24 hours. Figure (4.4) shows the settlement during the two Phases: (1) 15kPa seating load; and (3) 50kPa applied load for the control tests.

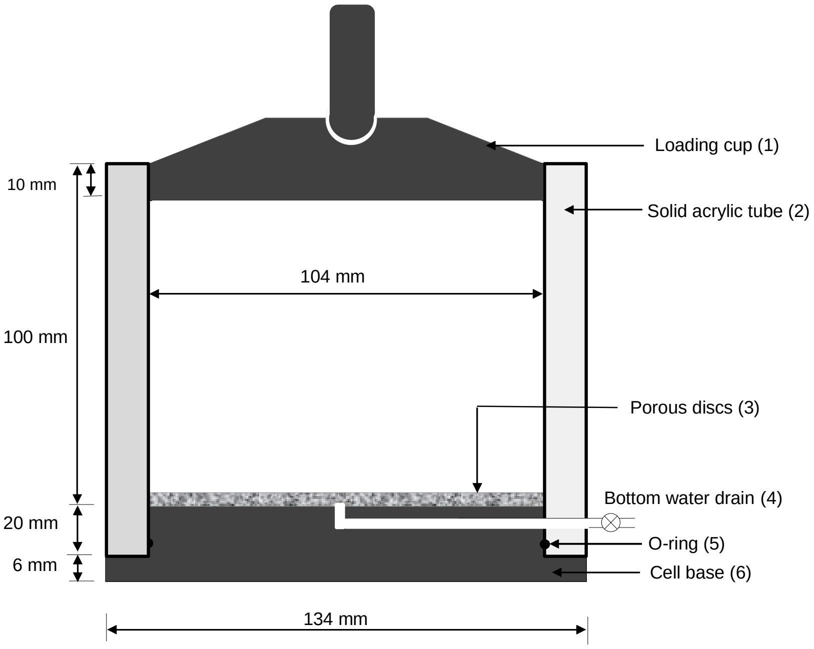


Figure 4.3 (a) Schematic diagram of the consolidation cell used in control tests

Figure 4.3 (b) General arrangement of the consolidation cell used in control tests

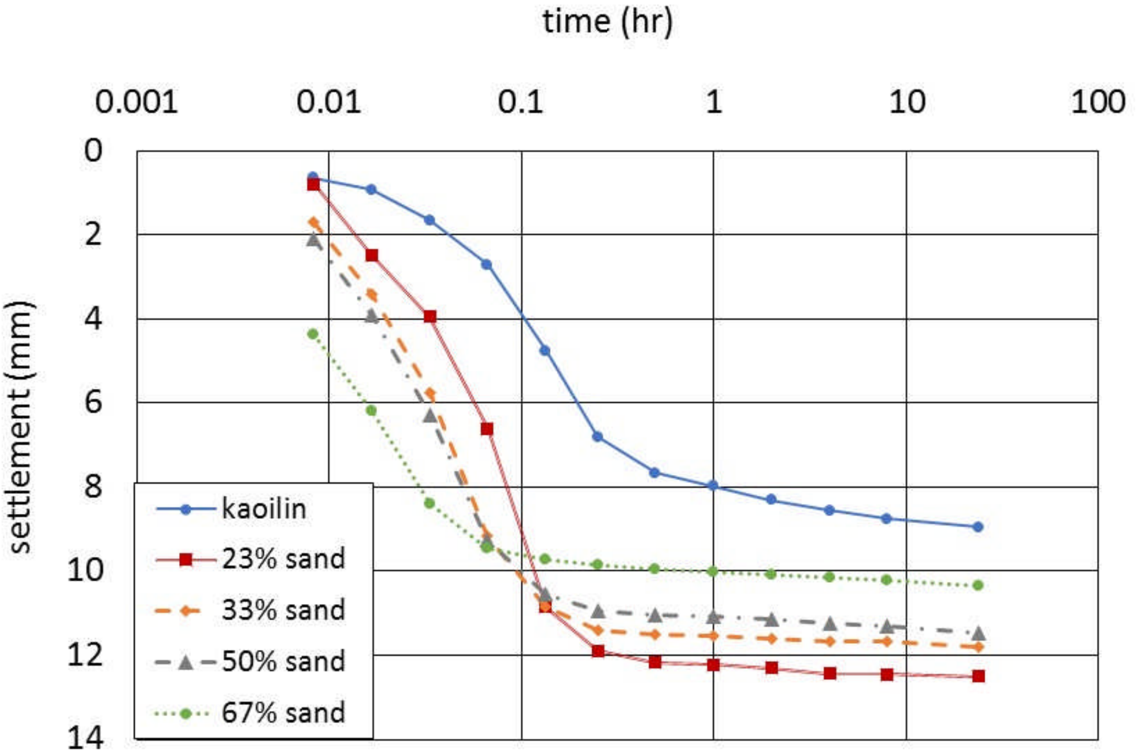


Figure 4.4 Total settlement during Phase 1 15kPa seating load for the control tests

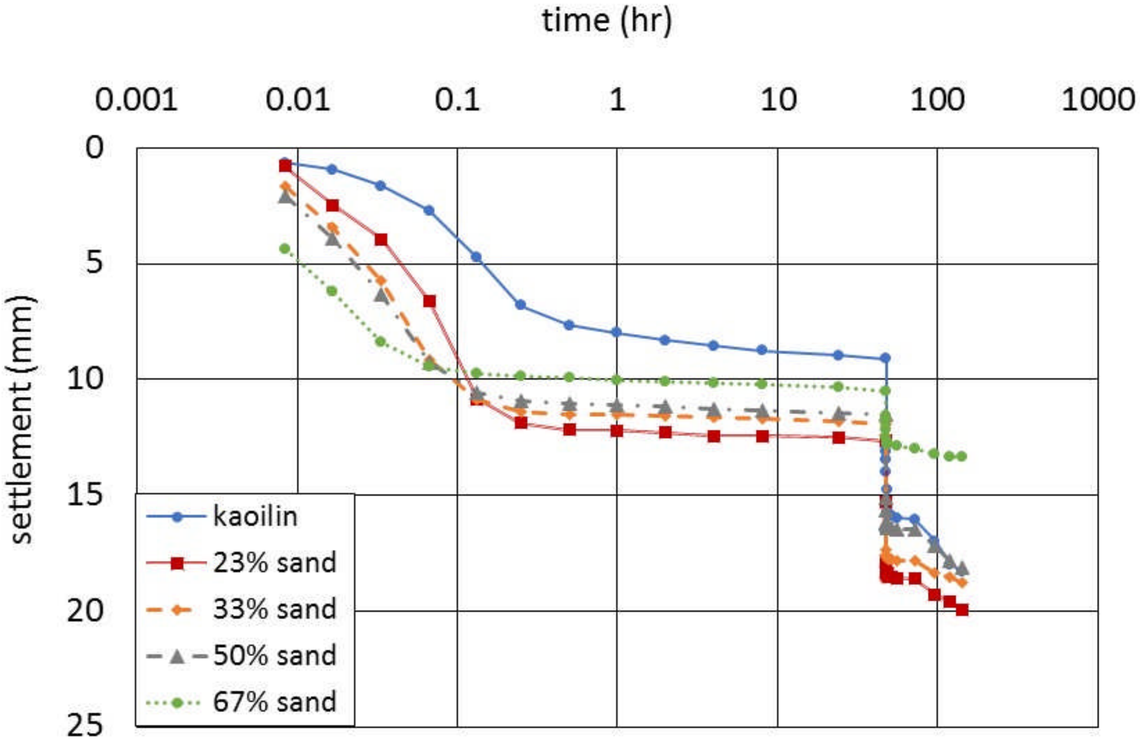


Figure 4.5 Total settlement during the two phases: (1) 15kPa seating load; and (3) 50kPa applied load for the control tests

Figure (4.4) shows the settlement in Phase 1, and the combined settlement in the two phases are set out in Figure (4.5) to compare the primary and final settlement on each soil mixture. An analysis of Figure (4.4) indicates that the settlement of the soil mixtures changed depending upon the sand content. When the sand concentration was 67%, the settlement of the mixtures was small compared to other mixtures, which is similar to the settlement of the pure sand as concluded by Muir Wood and Kumar (2000) who stated that the strain behaviour of the kaolin and sand mixture appears to be dependent on the sand content when the sand content reaches about 70%. For intermediate values of sand concentration (between 23 and 67%), the settlement of the soil mixture was provided in part by the settlement of the sand grains and kaolin clay, depending on sand content in the soil mixture. While, for pure kaolin soil, the settlement was basically that of the pure clay. Kumar and Wood (1997) stated that the stiffness properties and pore pressure response of the composite soil are unaffected by the coarse grains content when the clay content is less than 40%. This behaviour can be clearly seen in 67% sand which shows lower settlement compare to other soil mixtures.

According to Vallejo and Mawby (2000), there is a transition zone in the sand-clay mixtures between the clay and sand controlled structure. In this transition zone, both sand and clay portions controlled the porosity and shear behaviour of fabric in the mixture. When sand concentration by weight is >75%, the behaviour of the mixture is completely controlled by the sand. When the sand content varied between 40-75%, the behaviour of the mixture is controlled in part by the kaolin clay and the sand grains. When the sand content <40%, the behaviour of the mixtures was mainly controlled by the pure kaolin clay.

It has been pointed out from previous studies that the compressibility of fine grained soils depends not only on the mechanical properties of its ingredients, but also on the physico-chemical behaviour. Genevois (1977) concluded from the analysis of the chemical interaction forces of kaolin soil that the compressibility of pure clay under external load depends upon the mechanical and chemical interaction forces. In addition, the variation of the compression index was found to be related to the physico chemical properties.

As Sridharan and Jayadeva (1982) stated that the compressibility of pure clay depends on many factors; including: the negative charge of clay minerals, ion concentration, cation valency, dielectric constant and the temperature of the pore liquid. Horpibulsuk et al. (2011) found that increasing the ion concentration and valence resulted in augmentation of the resistance to consolidation pressure and water holding capacity. Jimenez et al. (1953) deduced that in pure kaolin soil, the coefficient of consolidation c_v, increases as the pressure increases, which is contrary to the behaviour of bentonite soil samples, in which it decreases. This behaviour can explain the slight compressibility of pure kaolin in Figure (4.4) compared to other soil mixtures.

Figure (4.6) shows the liquid limit, initial water content, and water content at the end of Phase1 and at the end of Phase 3. The liquid limit values in this figure were computed using a cone penetrometer, and were found to be inversely proportional to the sand content. The water content values in Phase 1 were calculated based on the expelled water at the end of the phase. These values will later be compared with the water content values resulting from electroosmotic treatment of the composite soil.

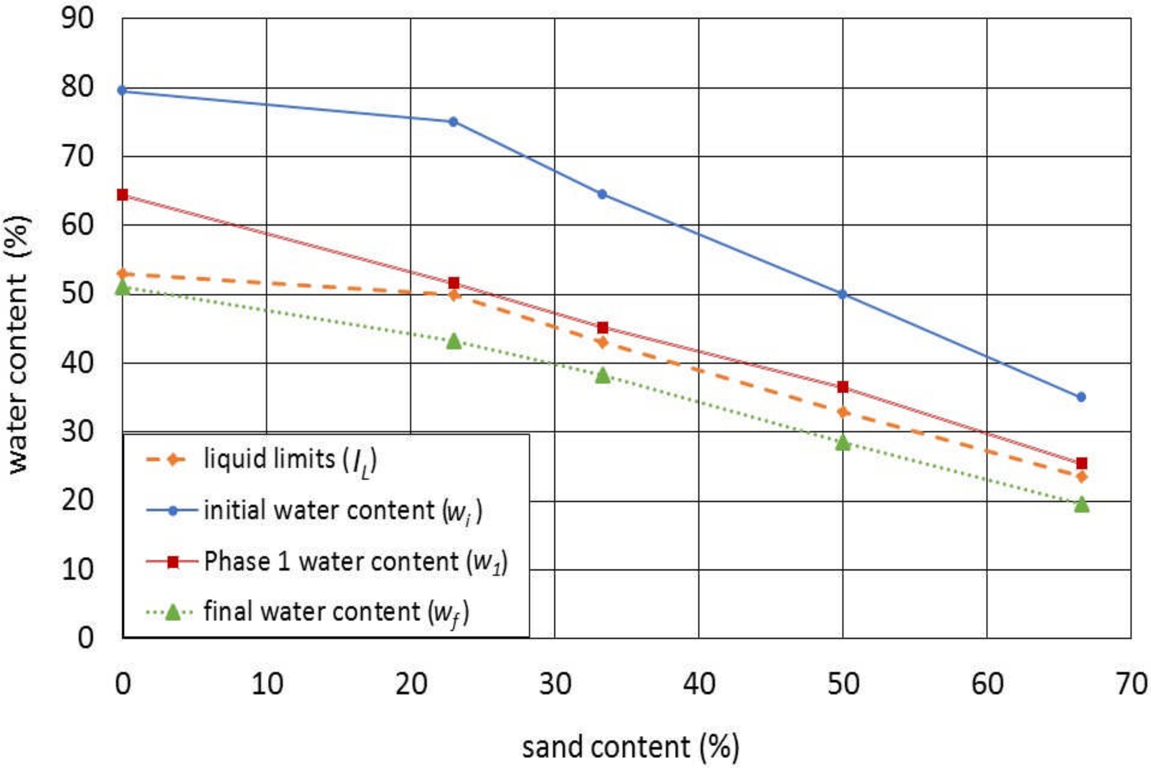


Figure 4.6 Variation of liquid limit, initial water content, Phase 1 water content, and final water content verses sand content in control test

4.3 Results of electroosmotic piles

Electroosmotic pile tests were conducted to evaluate the effects of electroosmosis on the stiffness of a range of composite soils. A pressure of 15 kPa was applied for 24 hours in Phase 1 to create a normally consolidated specimen from the soil slurry and the 15 kPa pressure was maintained during Phase 2 when the voltage was applied. 50 kPa was applied for 24 hours in Phase 3 to simulate a surcharge load to assess the performance of the system by determining the stiffness. The series of electroosmotic tests are summarised in Table 4.1. The results of all the tests in this chapter are presented according to the test series, namely percentage of sand and applied voltage.

4.3.1 Settlement, expelled water and void ratio

The vertical settlement and expelled water during a test were recorded. The voids ratio (e) was calculated for each test, the water content was assessed at the end of Phase 1 and Phase 2 from the amount of expelled water and at the end of Phase 3 at various positions at the end of a test; near the anodes, cathode, in between the electrodes, and at the cell wall.

4.3.1.1 Effect of sand content

The objectives of the tests were to determine the effect of sand content on the stiffness of the soil; the useful energy used in the osmotic process and establish the maximum sand content for the osmotic process to function.

The total settlement for all electroosmotic tests, Figures (4.7) at 10V, and (4.8) for 15V show that the samples were affected by the electroosmotic treatment as the majority of the settlement took place in Phase1 due to the applied 15kPa, and more settlement occurred in Phase 2. While Phase 1 was used to create a uniform sample, it is clear from Figure (4.9a), that the sand content affected the settlement of the samples. Increasing the sand content increased the amount of settlement in Phase1. This trend is counter intuitive since coarse grained soils would be expected to be stiffer. However, these samples were consolidated from a slurry, which means the sand particles within the clay matrix were, effectively, in a loose state. As the sand content increases, there is less resistance from the clay so the sample undergoes more settlement. It is also obvious that the rate of consolidation increased as the sand content increased, but only if the sand content exceeds 23%. It is possible that the sand particles are randomly distributed through the sample and not in contact if the sand content is less than 23% (Al-Moadhen et al, 2017). Therefore, the flow of water will be a function of the permeability of the clay matrix. As the sand content increases, the sand particles start to influence the mass permeability of the sample.

The results in Figure (4.9a) seem to be consistent with those of the control test shown in Figure (4.4) as the time-settlement curves show similar trend. Figure (4.9c) compares the water content from control and electroosmotic tests at the end of Phase 1 based on the expelled water.

The volumetric strain at the end of Phase 1 due to 15 kPa verses the sand content is shown in Figure (4.9b). From this figure, it can be seen that the composite soil reported significantly more change in volumetric strain than the pure kaolin soil, and the rate of consolidation was increasing as the sand content increased. The most interesting aspect of this figure is that the volumetric strain for all composite soils was similar ($\Delta e_1/e_0 = 0.31$), which means that the applied vertical load of 15 kPa as a working platform had achieved 31% changes in voids ratios. Note that the initial void ratio was different, for each soil mixture.

Given that the hydraulic permeability of a soil increases as the sand content increases due to the increase in voids between soil particles, then the impact of applying an electric potential difference to a soil should reduce as the sand content increases because the effect of electroosmosis reduces. This relationship seen in Figures (4.10a) and (4.11a) for 10V and 15V such that, at 67% sand content there is less than 5mm settlement at 10V and 15V, respectively. Increasing the voltage increases the settlement, the amount reducing as the sand content increases.

Figures (4.10 b) and (4.11b) show the volumetric strain at the end of Phase 2 based on the water expelled from applying 10V and 15V during the electroosmotic phase, respectively. As can be seen from these figures, the pure kaolin shows significantly higher reduction in the volumetric strain than other soil mixtures, 0.2 and 0.21 for pure kaolin at 10V and 15V respectively, compared to about 0.02 for 67% sand due to both 10 and 15V, that means the effect of applying an electric potential difference to a soil slurry is inversely proportional to the sand content; as the sand content increases, the electroosmotic treatment effects decrease.

The performance of the system is assessed by the settlement caused by a uniformly distributed pressure of 50kPa Figure (4.12a) for 10V and Figure (4.13a) for 15V after the soil has been treated. This shows that the settlement in Phase 3 increases as the sand content increases, though it is less than 5mm for all cases under 10V and less than 3mm under 15V. The settlement for kaolin and kaolin with 23% sand suggests that the composite soil is a matrix dominated soil with the compression being governed by the clay content (Muataz and Clarke, 2018). Figures (4.12b) and (4.13b) show the volumetric strain at the end of Phase 3, when a 50 kPa load was applied to the soil as a surcharge load after electroosmotic treatment for 10V and 15V respectively. It can be seen in these figures that the lowest change in volumetric strain took place in pure kaolin, less than 0.01 for 10V and 15V, while the greatest change occurred in 67% sand mixture, about 0.05 for both 10V and 15V. As shown in these figures, the results of the volumetric strain after 50 kPa show a decrease in the volumetric strain of the treated samples, the reduction is affected by sand content in the composite soil. Thus, the settlement in Phase 1 increased as the sand content increased because the samples were prepared at 150% of the liquid limit which meant the sandy soils were initially in a loose state; the settlement in Phase 2 decreased as the sand content increased; and the settlement in Phase 3 increased as the sand content increased because the osmotic effect in Phase 2 reduced as the sand content increased.

Note that the volumetric strains for kaolin soils with sand was similar (Figure 4.9b) and different to that from kaolin. While the volumetric strain was similar, the initial void volume recued as the sand content increased. It reduced with sand content (Figure 4.6). Thus the reduction in volume decreased as the sand content increases; that is the soil was stiffer as the sand content increased.

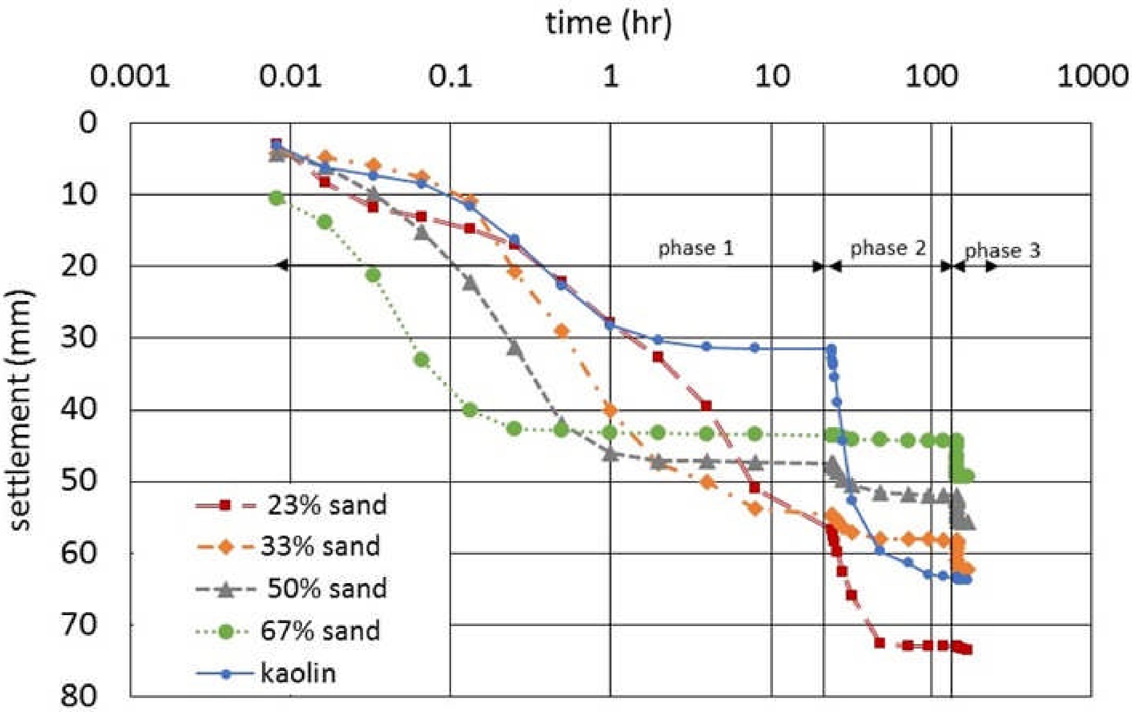


Figure 4.7 The total settlement during the three phases: (1) 15kPa seating load; (2) 15kPa seating load and 10voltage; and (3) 50kPa applied load

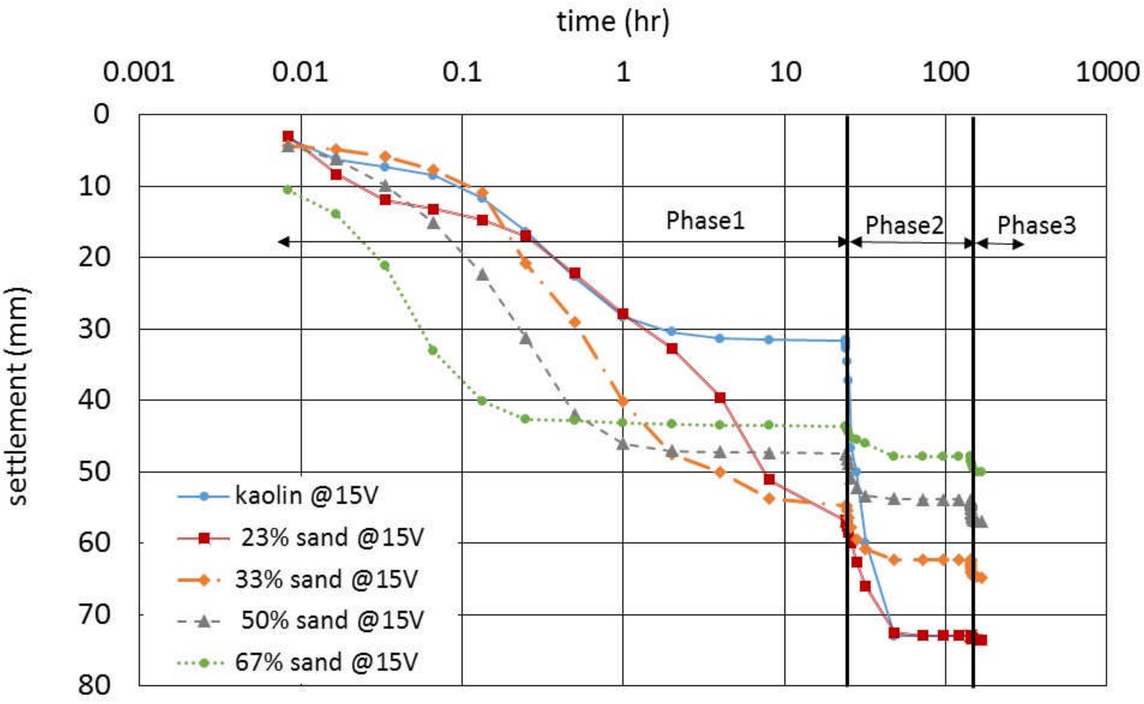


Figure 4.8 The total settlement during the three phases: (1) 15kPa seating load; (2) 15kPa seating load and 15voltage; and (3) 50kPa applied load

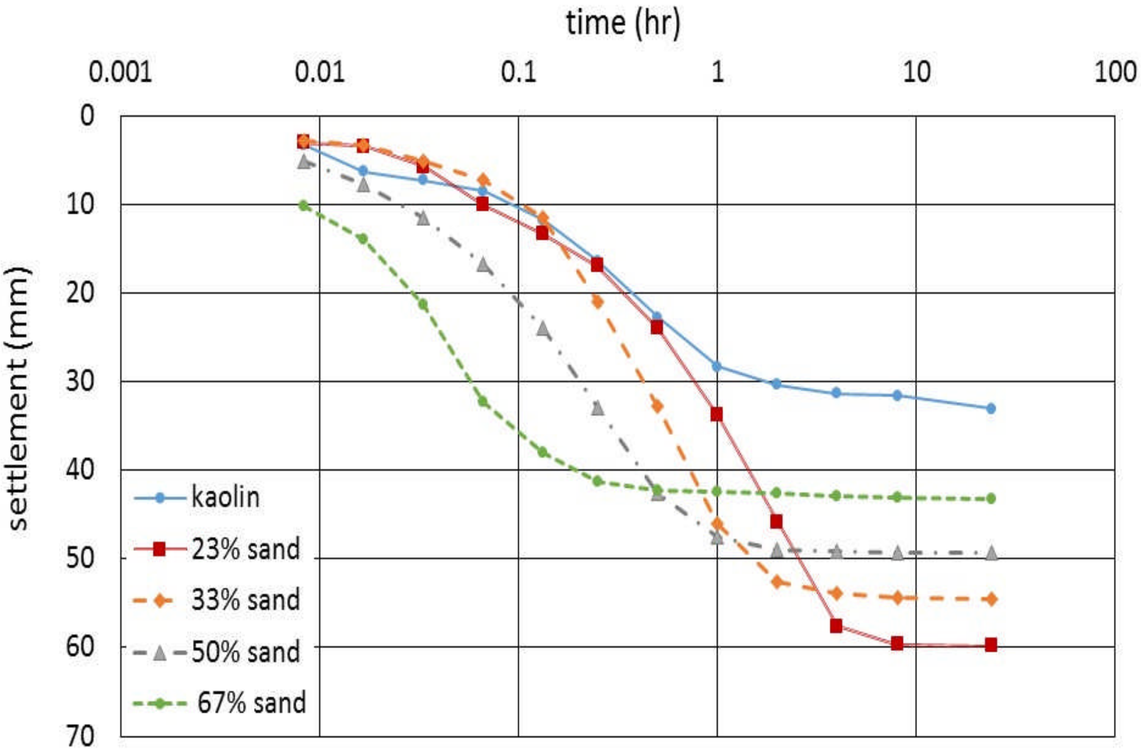


Figure 4.9 (a) Settlement in Phase 1 (15 kPa load applied to the soil as a working platform)

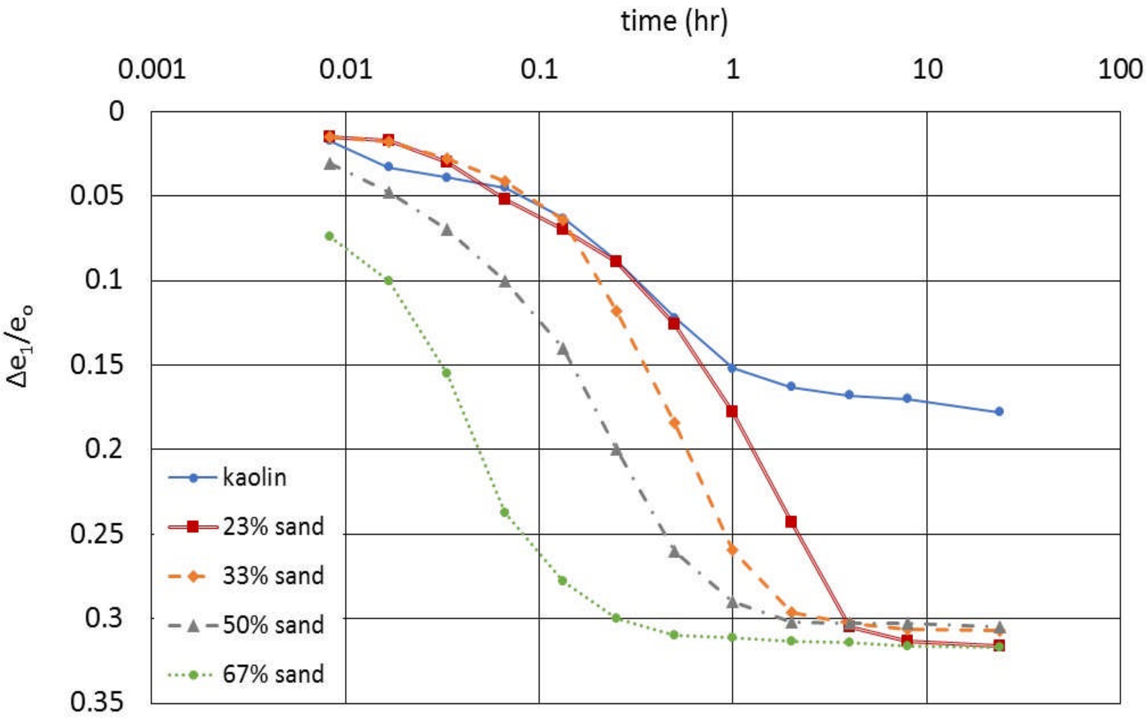


Figure 4.9 (b) Volumetric strain in Phase 1 (15kPa load applied to the soil as a surcharge load)

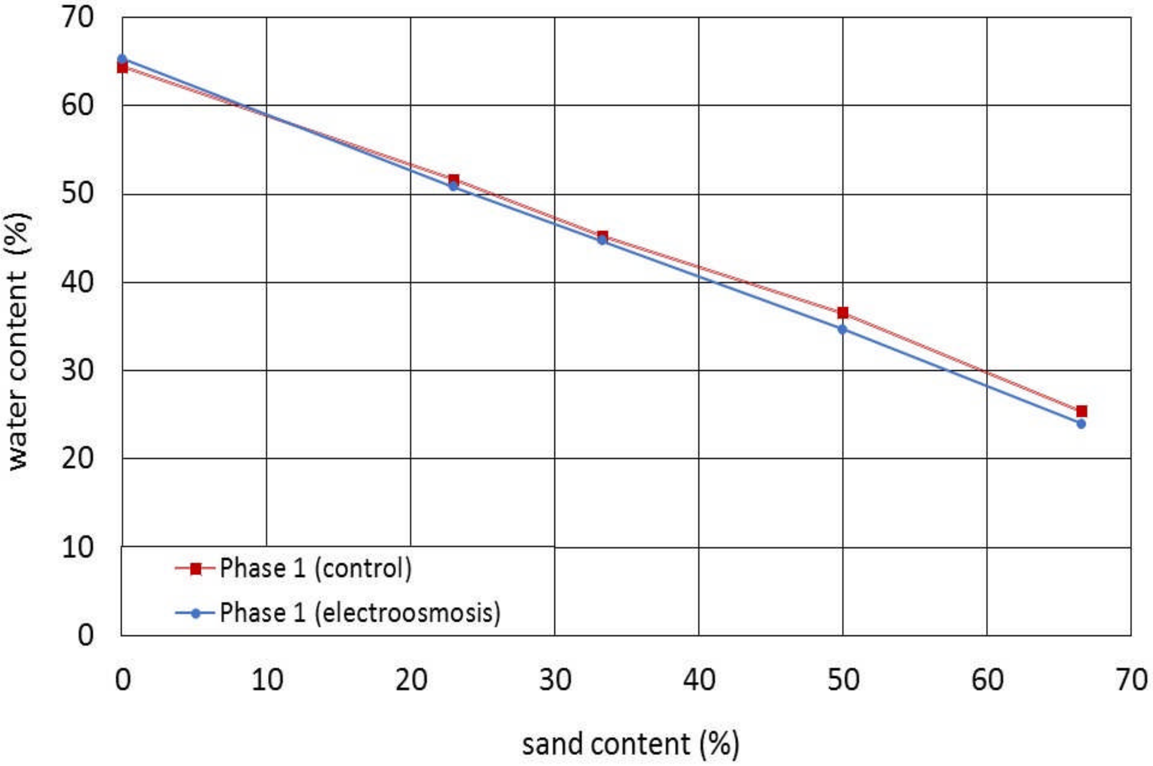


Figure 4.9 (c) Comparison between water content at the end of Phase 1 in control and electroosmotic test

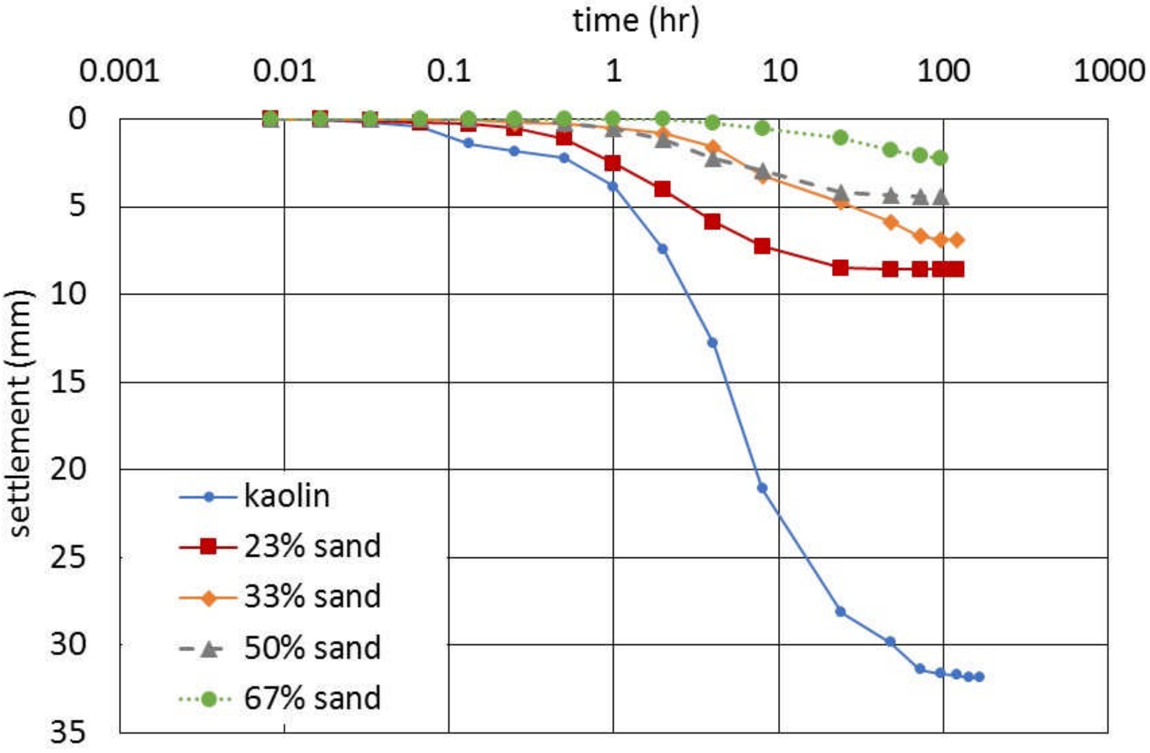


Figure 4.10 (a) Settlement in phase 2 (constant applied voltage10V in addition to the 15kPa load)

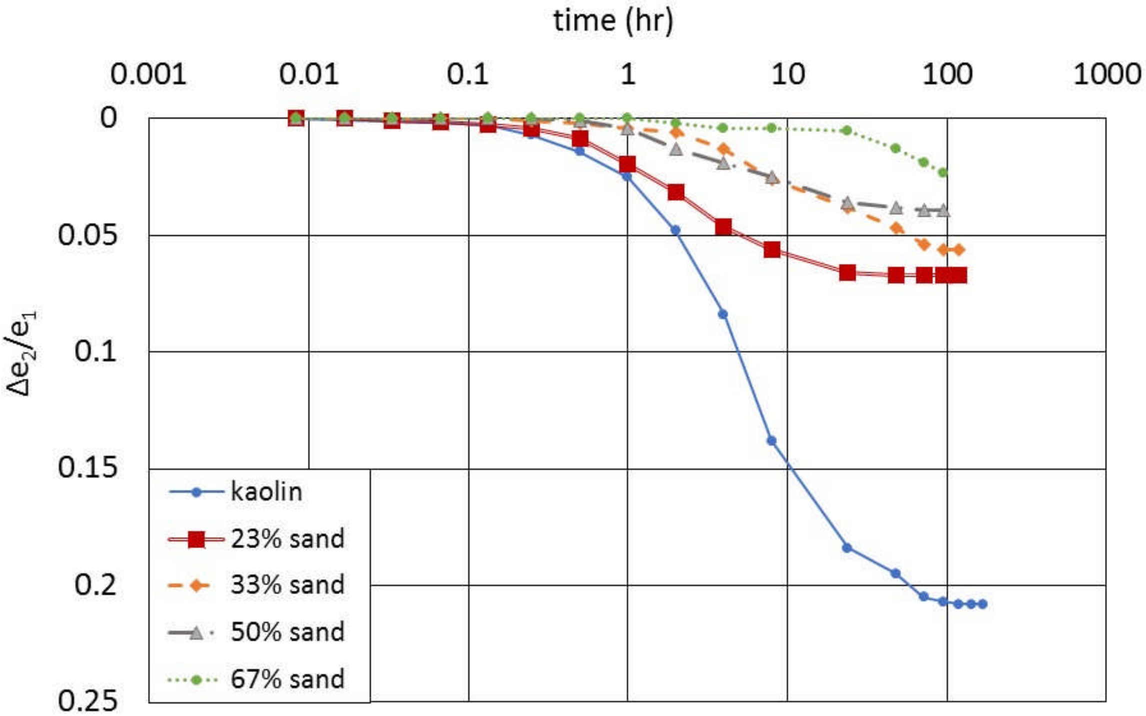


Figure 4.10 (b) Volumetric strain in Phase 2 (constant applied voltage 10V in addition to the 15kPa load)

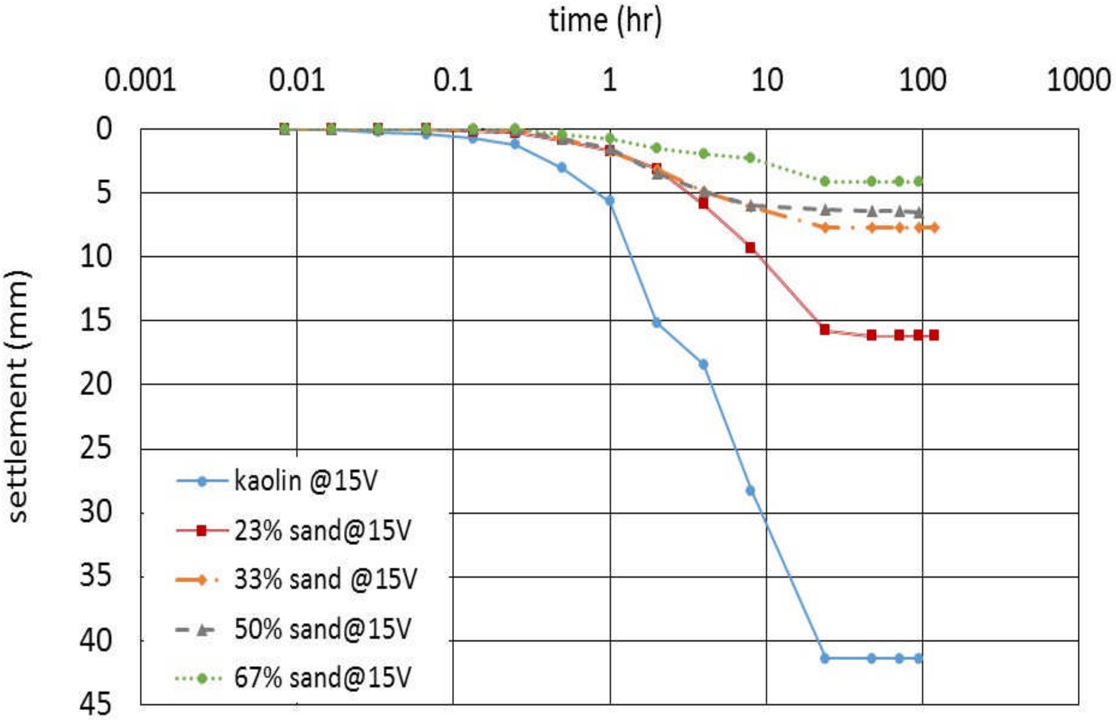


Figure 4.11 (a) Settlement in phase 2 (constant applied voltage15V in addition to the 15kPa load)

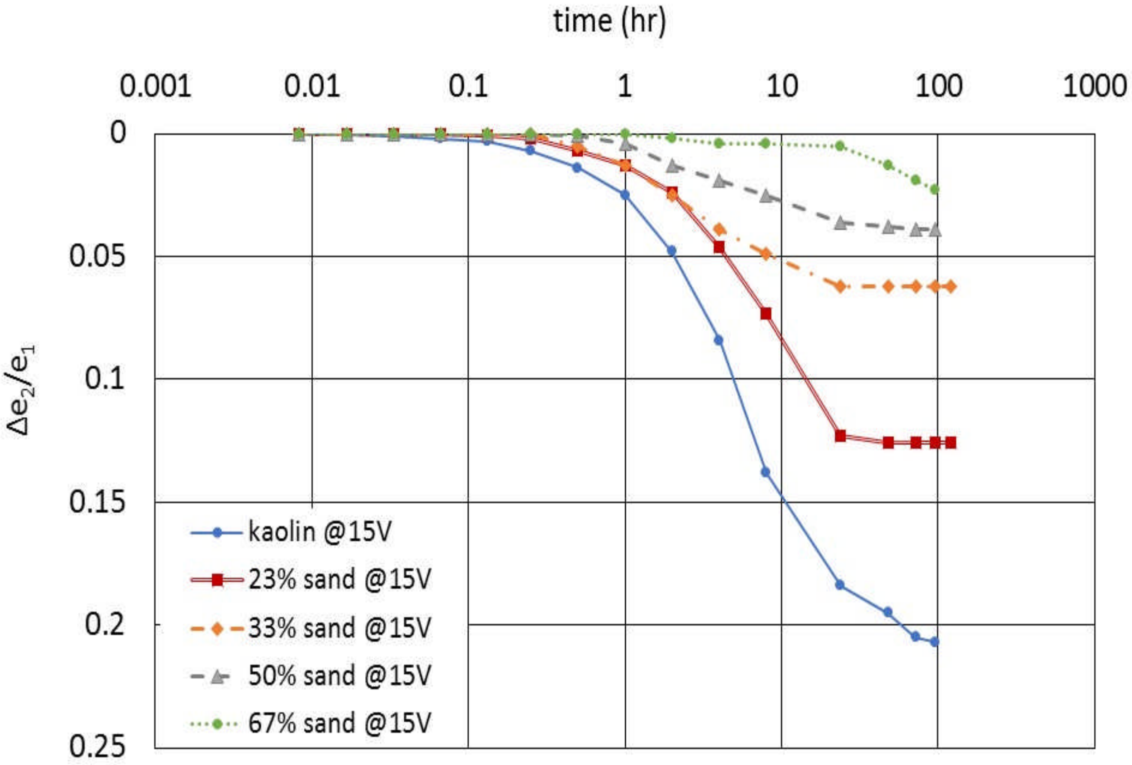


Figure 4.11 (b) Volumetric strain in Phase 2 (constant applied voltage 15V in addition to the 15kPa load)

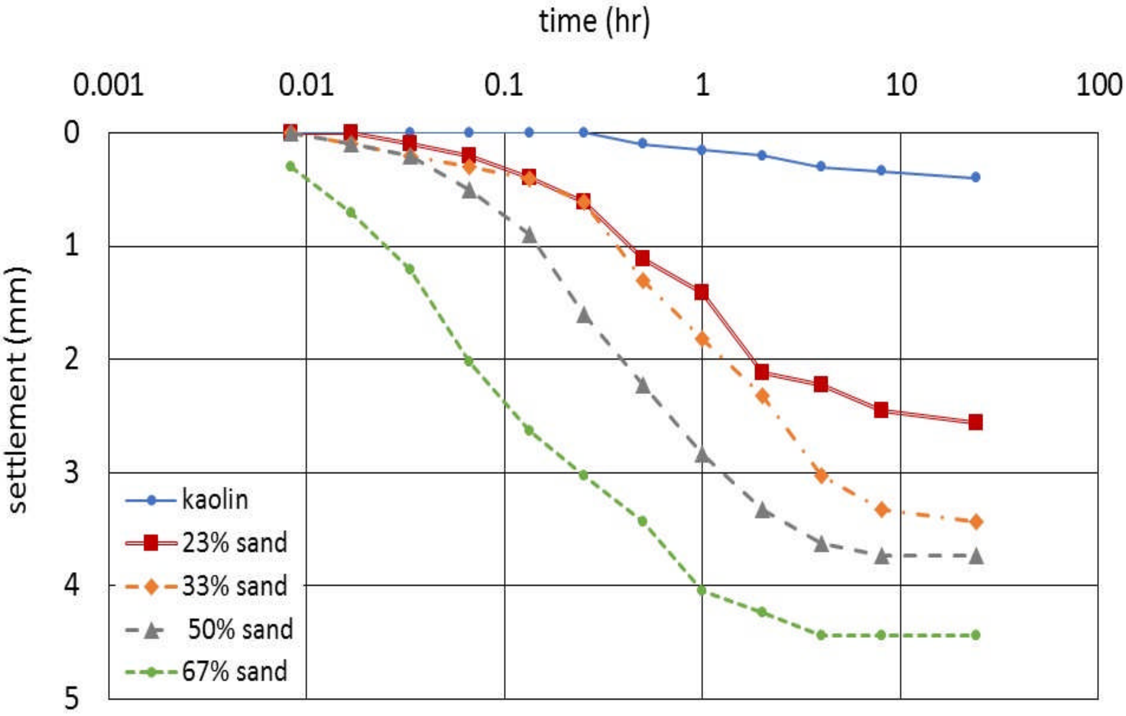


Figure 4.12 (a) Settlement in Phase 3 (50kPa load applied to the soil as a surcharge load after 10V electroosmotic treatment)

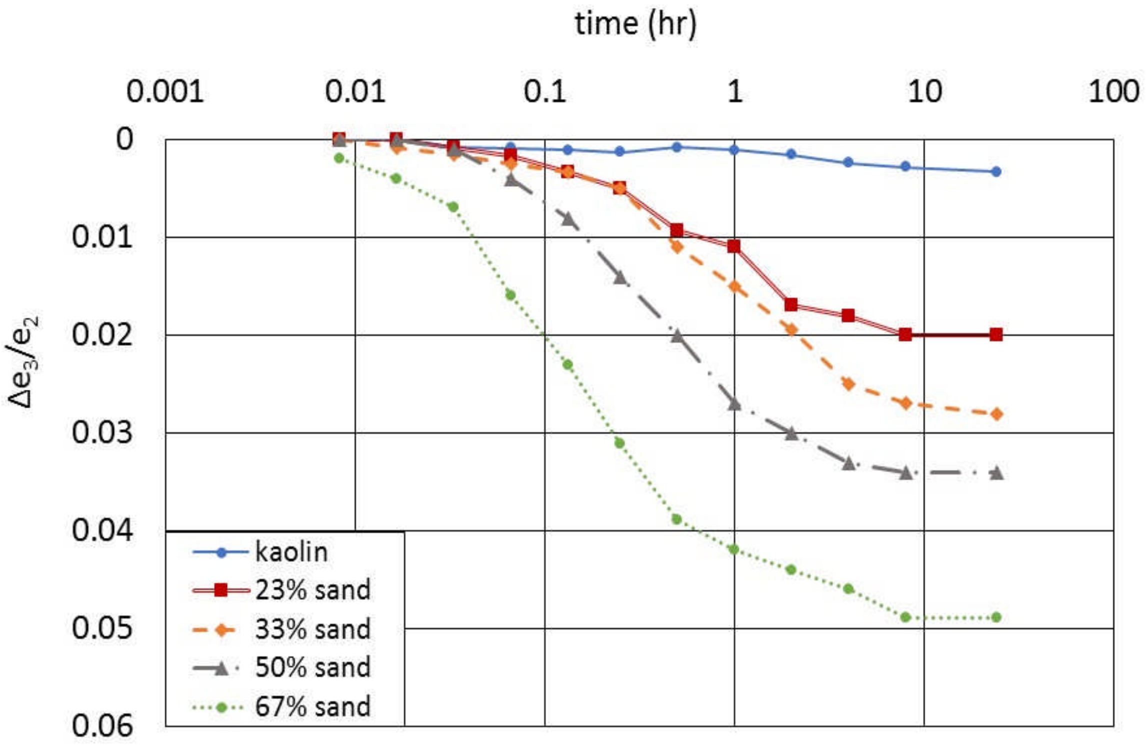


Figure 4.12 (b) Volumetric strain in Phase 3 (50kPa load applied to the soil as a surcharge load after 10V electroosmotic treatment)

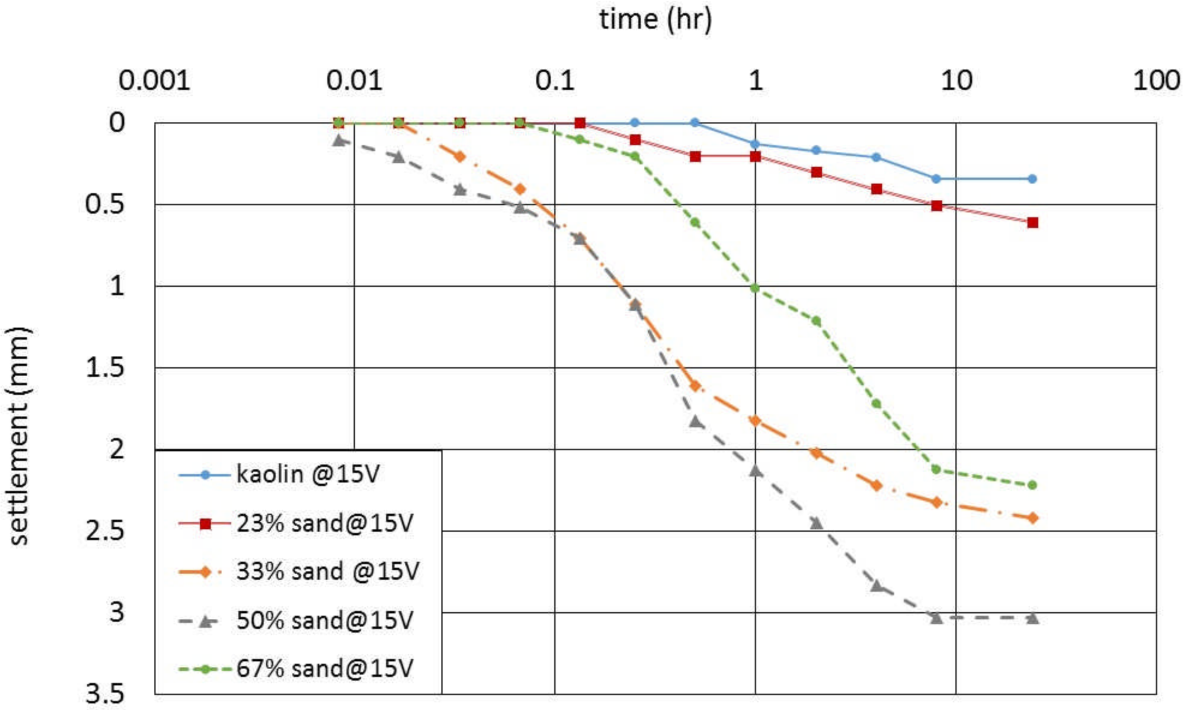


Figure 4.13 (a) Settlement in Phase 3 (50kPa load applied to the soil as a surcharge load after 15V electroosmotic treatment)

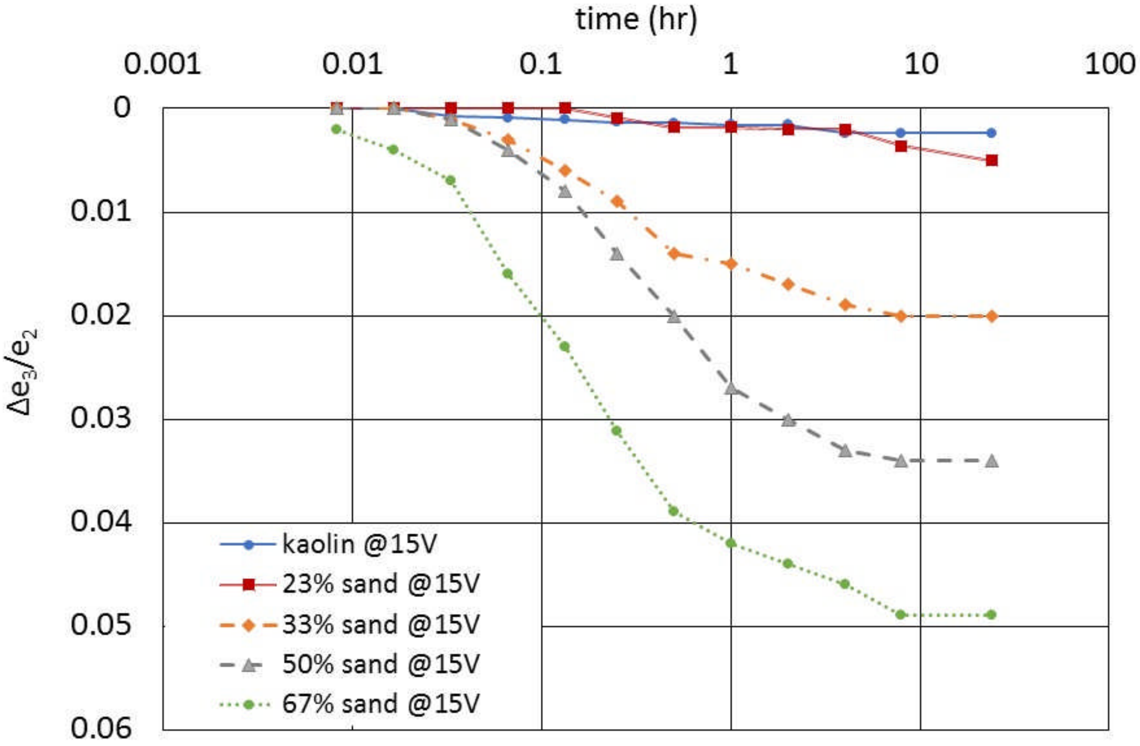


Figure 4.13 (b) Volumetric strain in Phase 3 (50kPa load applied to the soil as a surcharge load after 15V electroosmotic treatment)

Figures (4.14) and (4.15) show that the total settlement (ΔH2 + ΔH3) to compare the settlement in Phase 3 compared to the total settlement resulted from Phase 2 and Phase 3, since the combined settlement gives an indication of the effect of sand content on the compression behaviour when a simulated surcharge loads is applied. The figures show that the combined settlement decreases as the sand content increases. Further, there appears to be a change in behaviour at 23% sand content when 10V was used, and 33% when 15V was used. As the variation in settlement with sand content reduces, the clay dominates the behaviour if the sand content is less than 23% and 33% for 10V and 15V respectively. The percent of settlement in Phase 3 divided by the settlement in Phase 2 and Phase 3, varies from 1% with pure kaolin to about 67% with 67% sand at 10V, and from 0.1% with pure kaolin to about 48% with 67% when 15V applied as shown in Figures (4.14) and (4.15) respectively. While there is very little settlement in Phase 2 with 67% sand, it is possible to predict that there will be no settlement for 10V at 95% in sand Phase 2, assuming the relationship is linear. Therefore, the maximum sand content for electroosmosis to work is 95%.

Electroosmosis produces an over consolidated state. For 10V potential difference the pore pressure generated at the anode is -24.3 kPa according to the formula:-

$$u = \frac{k_e}{k_h} \gamma_w V \tag{4.1}$$

Where k_e is the coefficients of electroosmotic permeability, m^2/sV, k_h is the hydraulic permeability in m/s, γ_w is the unit weight of water, and *V* is the applied voltage. More details about k_h and k_e described in Chapter 6. For pure clay this generates an effective vertical stress of 39.3kPa at the anode (the external pressure is 15kPa). As the sand content increases the hydraulic conductivity increases and the pore pressure decreases. Thus, the effective stress reduces as the sand content increases, thus reducing the settlement in Phase 2. Further, the projected values of settlement in Phase 3 increases as the sand content increases as shown in Figures(4.14) and (4.15), assuming the relationship is linear, until at 100% sand content, 95% of the settlement will takes place in Phase 3 when 10V used and 78% of the settlement when 15V used.

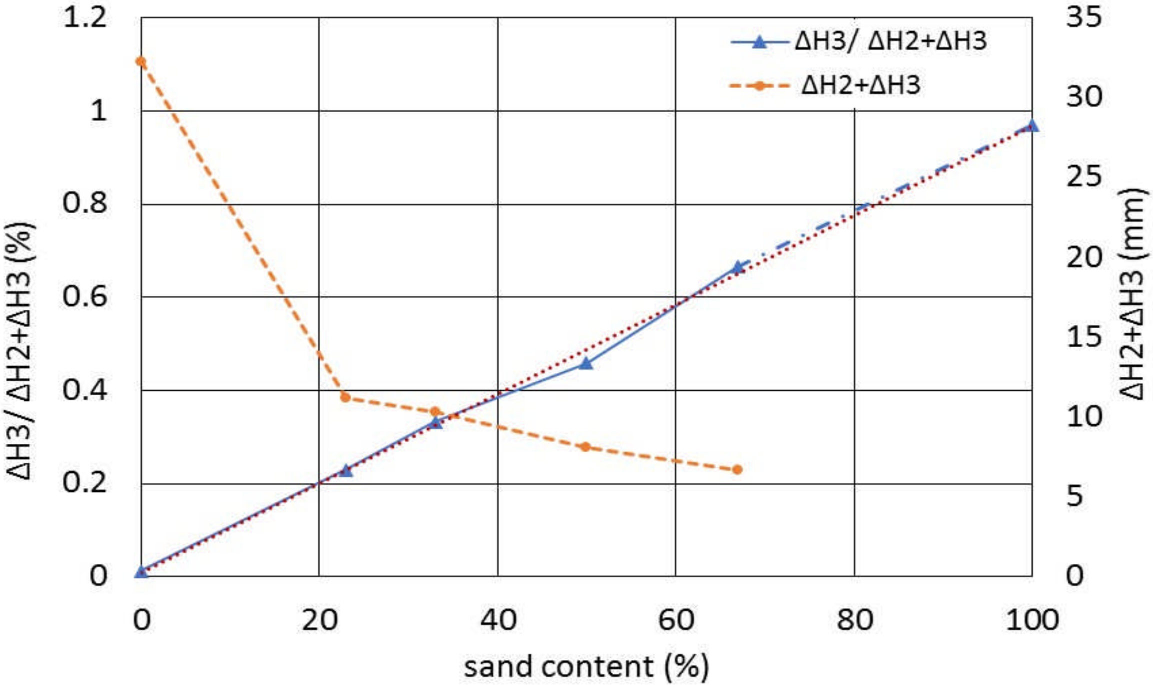


Figure 4.14 Effect of sand content on the compression of the composite soil subjected to 50 kPa (ΔH3) after electroosmotic treatment under 15kPa+10V (ΔH2) showing that the projected settlement in Phase 3 with respect to the settlement in Phase 2 and 3 shows that at 100% sand, 95% of the settlement will occur in Phase 3 with very little effect of electroosmosis in Phase 2

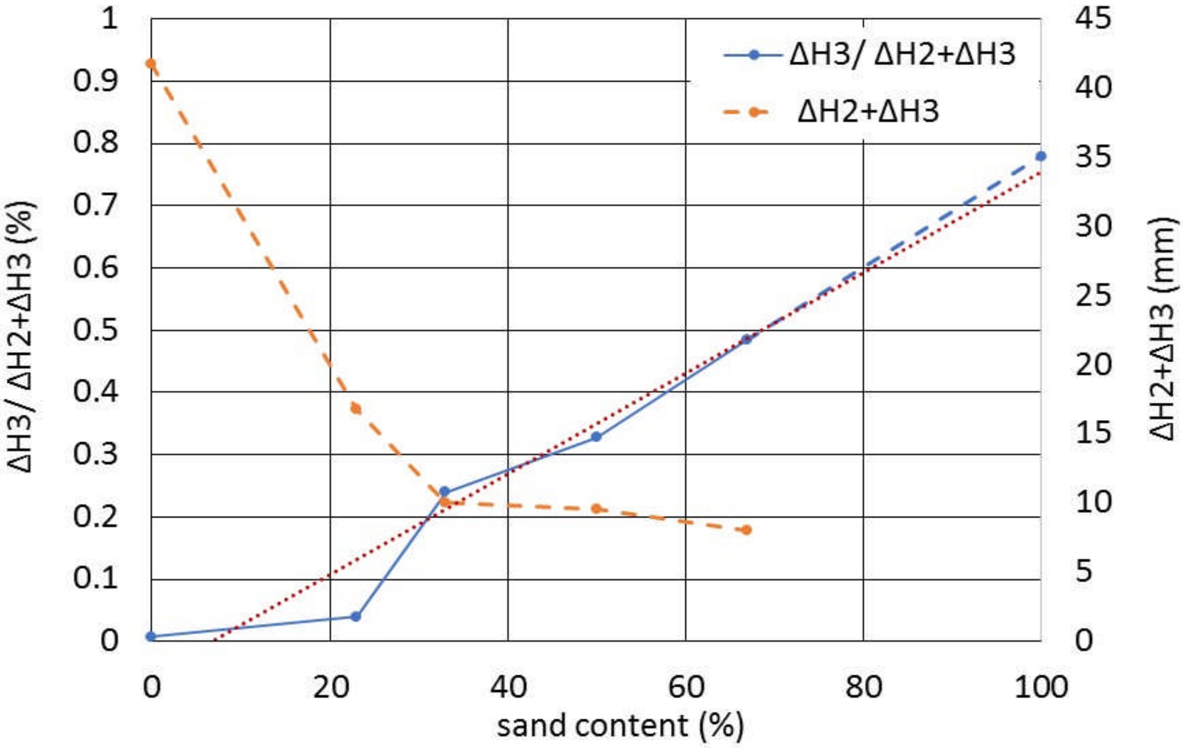


Figure 4.15 Effect of sand content on the compression of the composite soil subjected to 50 kPa (ΔH3) after electroosmotic treatment under 15kPa+15V (ΔH2)

4.3.1.2 Effect of applied voltage

Figures (4.16) to (4.19) show the settlement versus time curves in Phase 2 and Phase 3 obtained from the electroosmotic test for kaolin soils and kaolin mixed with sand at 50% subjected to different applied voltage (5, 10, 15 and 20V). These tests were used to evaluate the effect of applied voltage on the electroosmotic treatment for a number of composite soil mixtures with different types of clay and sand content.

It can be seen from the data in Figure (4.16) that 20V in Phase 2 produced vertical settlements of about 48.5mm, which is significantly more than the other voltages in pure kaolin soils (9.92, 31.83 and 41.43 mm) for 5, 10, and 15V respectively. While from the results in Figure (4.17), 10V resulted in the smallest value of vertical settlements 4.4mm compared to 6.46 and 6.75 for 15V and 20V respectively. This results is in agreement with the finding of Stalin et al. (2011), (LI et al., 2011) and Xue et al. (2017), who concluded that the higher voltage was still found beneficial, as the applied voltage increases, the volume of water expelled also increases and the time for completion of consolidation decreases.

From the figures above, there is a clear trend of increasing settlements as the applied voltage increases. In addition, the time required for treatment is decreased as the applied voltage increased.

The settlements obtained from Phase 3 caused by a uniformly distributed pressure of 50 kPa Figure (4.18) for kaolin soils and Figure (4.19) for kaolin and sand mixed at 50% after the soil has been treated was used to assess the performance of the electroosmotic treatments due to the effect of voltage changes. This shows that the settlement in Phase 3 decreases as the applied voltage increases, though it is less than 1mm for 10, 15, and 20V and 8.82mm under 5V in pure kaolin soils. In Figure (4.19) there is a clear trend of increasing settlement due to 50kPa pressure as the applied voltage used in electroosmosis decreased.

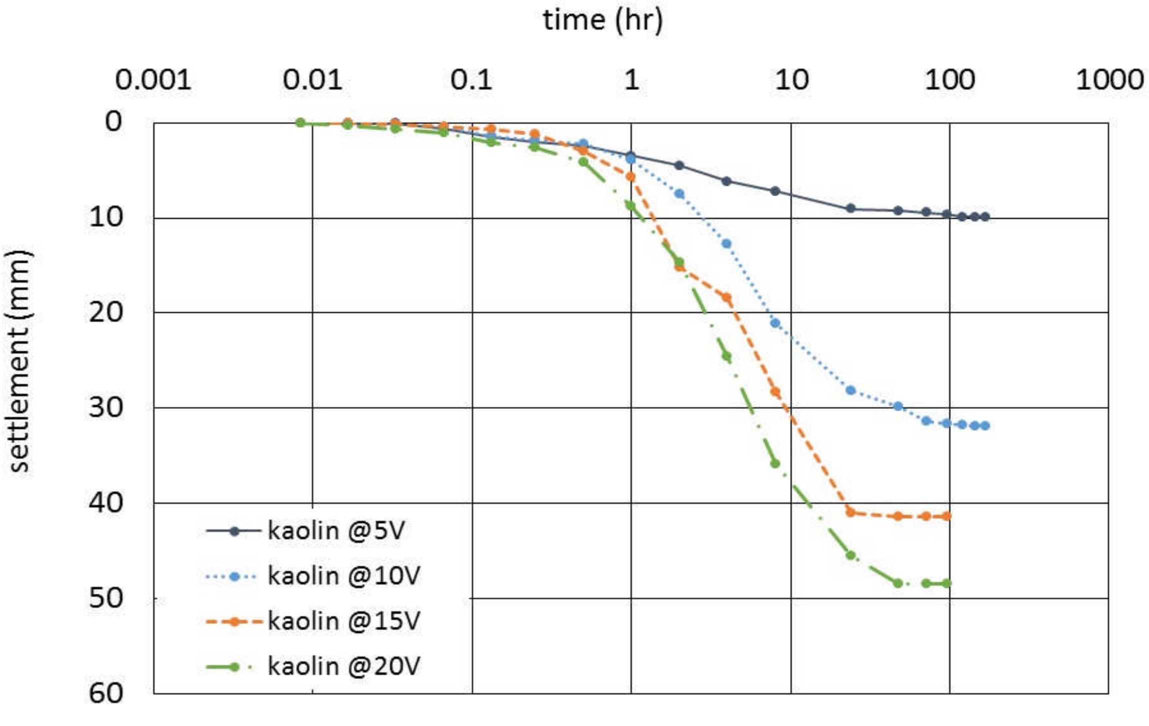


Figure 4.16 Settlement in phase 2 in pure kaolin at different applied voltage in addition to the 15kPa load

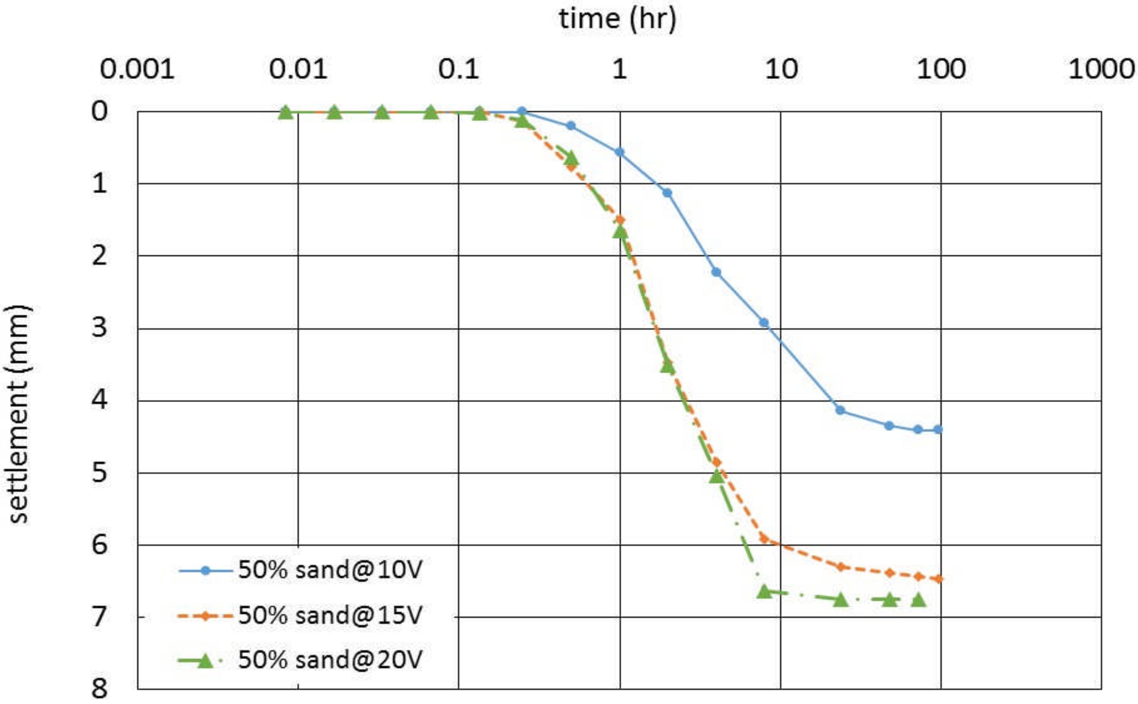


Figure 4.17 Settlement in phase 2 in sand and kaolin mixture (50%) at different applied voltage in addition to the 15kPa load

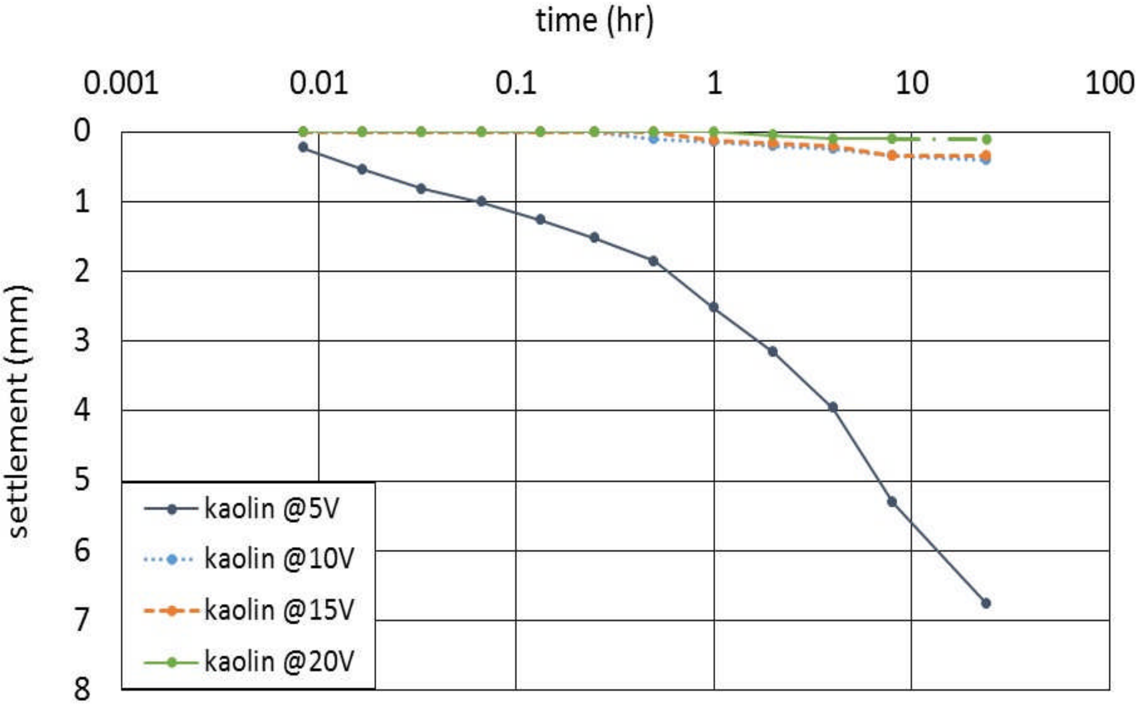


Figure 4.18 Settlements in phase 3 (50kPa load) in pure kaolin subjected to different applied voltage

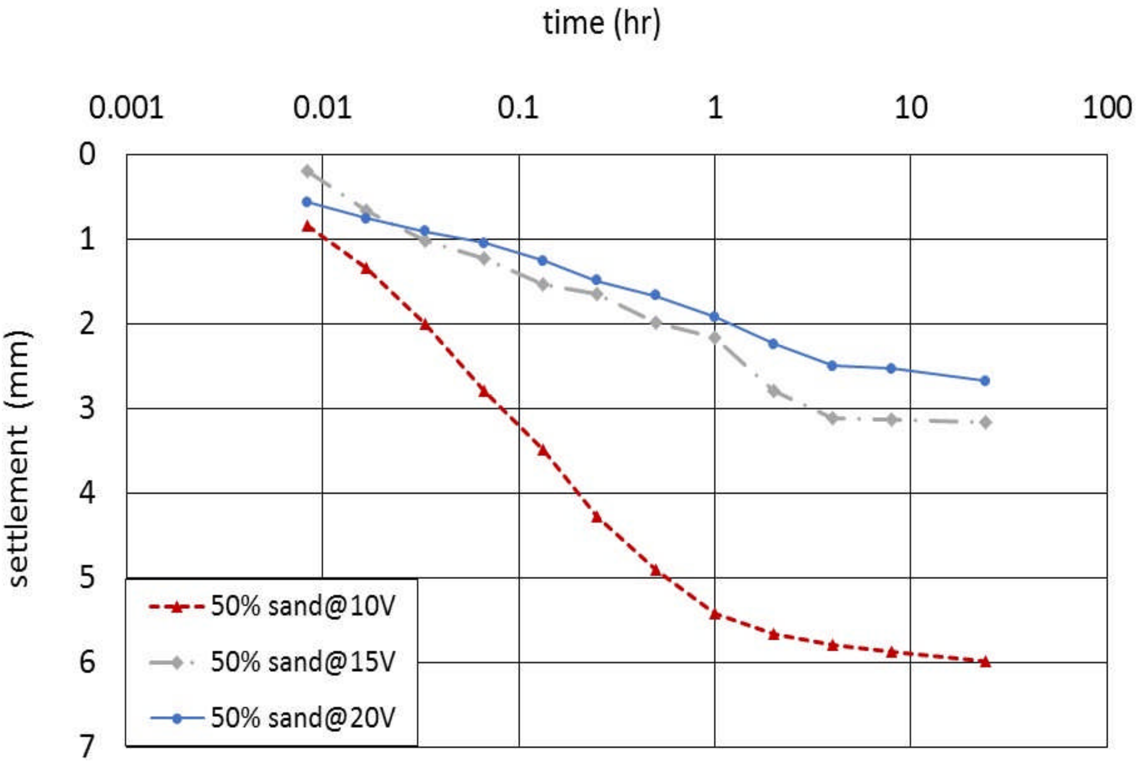


Figure 4.19 Settlements in phase 3 (50kPa load) in sand with kaolin mixture (50%) subjected to different applied voltage

4.3.2 Electrical current and power consumption

The electric current was monitored continuously in the electroosmotic phase until the end of each test. A voltage of 10V and15V was used for all the soil mixtures. 20V was used to study the effect of voltage variation on the electroosmosis treatment in sand and kaolinite soil mixed at 50% each, and 5V was used in pure kaolinite soils only.

4.3.2.1 Variation of electrical current and power with sand contents

Figures (4.20) and (4.21) shows the variation of electric current with time during electroosmosis treatment in Phase 2 for pure kaolin and kaolin with sand soil mixtures subjected to 10V and 15V respectively. It is observed that electric current of these different composite soils show a similar trend of a reduction of current with time. The test on pure kaolin shows that the current reduces for 8 hrs and then increases. A similar behaviour was observed by Chew et al. (2004) when copper electrodes was used; the current initially increased, became stable and then dropped. This behaviour could be related to the beginning of corrosion in electrodes after 8 hours of electroosmosis treatment as mentioned by Yusof (2012). The power required for electroosmosis consolidation is presented in Figures (4.22) and (4.23) for 10 and 15V respectively. Since the applied voltage is constant, the shape of the current and power curves are the same. However, Harbottle et al. (2004) found that, if the applied voltage between the electrodes was kept constant, the potential difference across the soil will vary and be impossible to control due to the effect of ions movement and changes in water content. Mohamedelhassan et al. (2012) related the variation of electrical current with time during the electroosmotic processes to the change in soil electrical conductivity as a result of two opposite mechanisms, a decrease in the bulk soil conductivity due to water drained by electroosmosis, whilst the water in the pores causes an increase in the electrical conductivity during the electroosmosis process due to electrolytic reaction. In Figure (4.24), the maximum power used has dropped from 1.3W in pure kaolinite to 0.6W for sand mixed with kaolin at 67%, while in Figure (4.25), when 15V have been used, the maximum power dropped from 2.85W in pure kaolinite to 1.35W for sand mixed with kaolinite at 67%.

Tajuddin et al. (2014) and Liaki et al. (2008) stated that the electrical current change with time is dependent on the electrical conductivity of soil. The initial reduction of the electrical current is due to the electrical resistance of the soil slurry to the electrical field which results in a reduction in ionic content and the electrical conductivity of soil. According to Rittirong et al. (2008a) the decrease in the electrical current is due to the drop in the applied voltage at the soil-electrode interface. Mohamedelhassan (2009) stated that the decrease in electrical current with time during electrokinetic stabilization is due to the decrease in electrical conductivity of the treated soil which is affected by two components; water in the pore fluid and soil particles. Chien et al. (2015) concluded that the current reduces with time leading to a reduction in the efficiency of the electroosmotic treatment. Zhou et al. (2015) observed that the rapid decreases in current during electroosmosis when copper electrodes are used is considered to be caused by corrosion of electrodes.

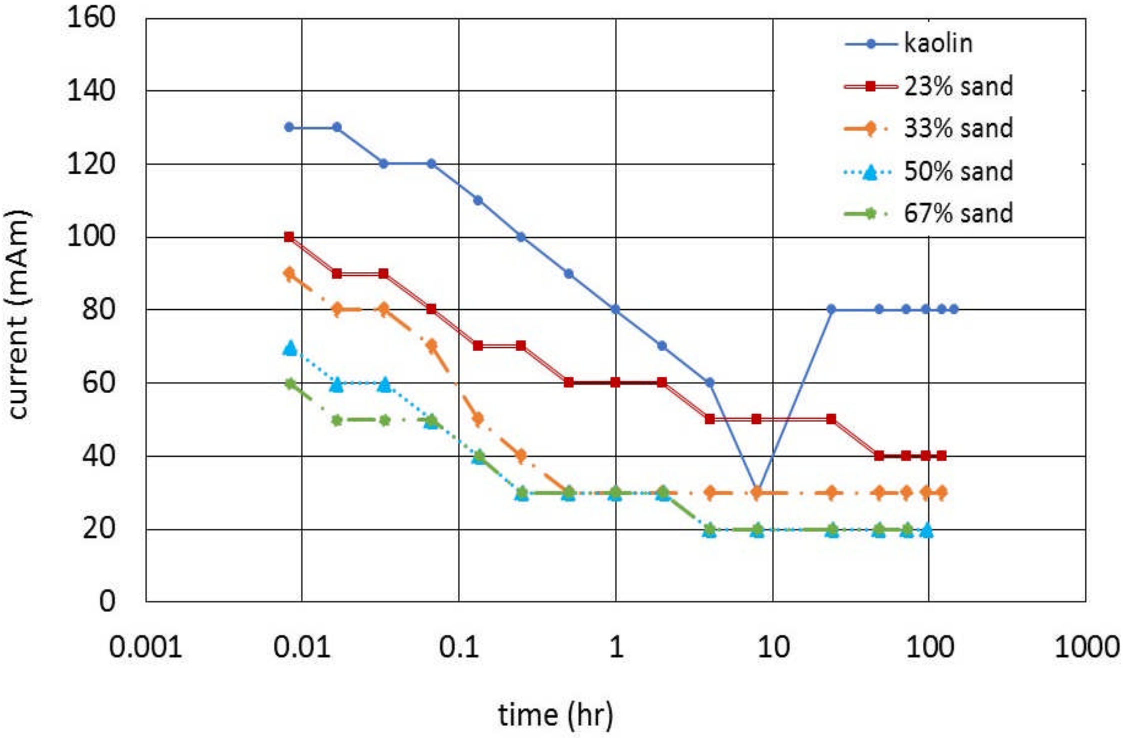


Figure 4.20 Variation of electrical current with time with different sand content at 10V

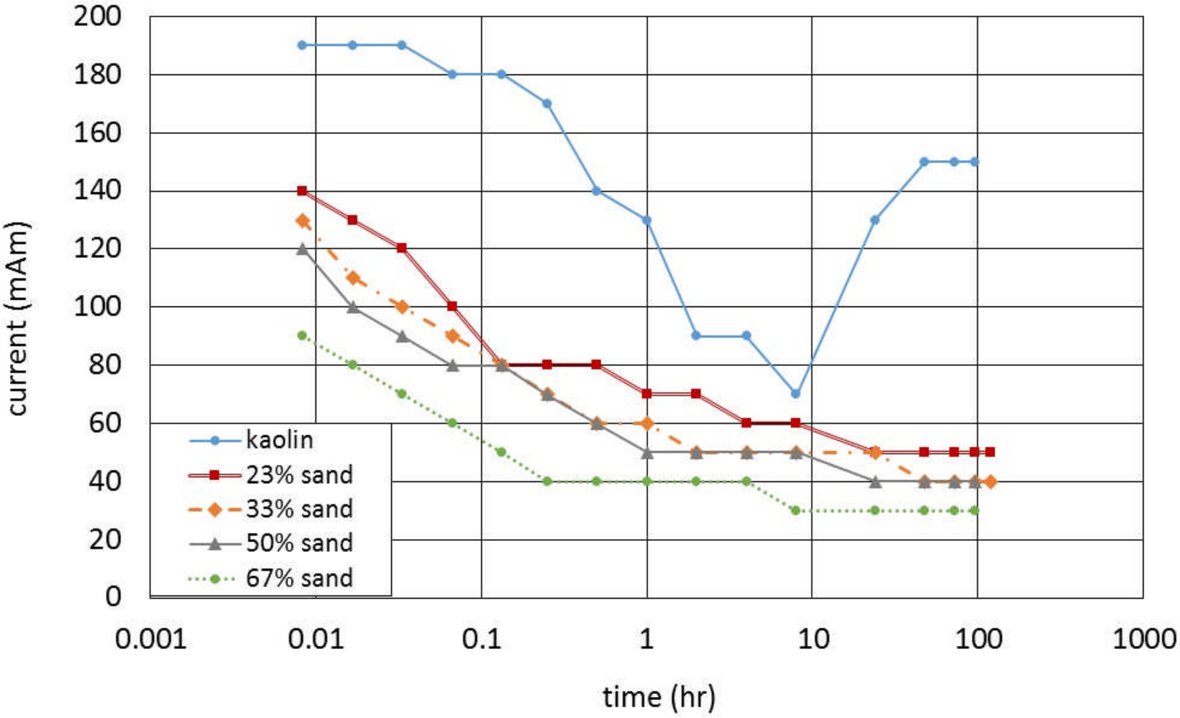


Figure 4.21 Variation of electrical current with time with different sand content at 15V

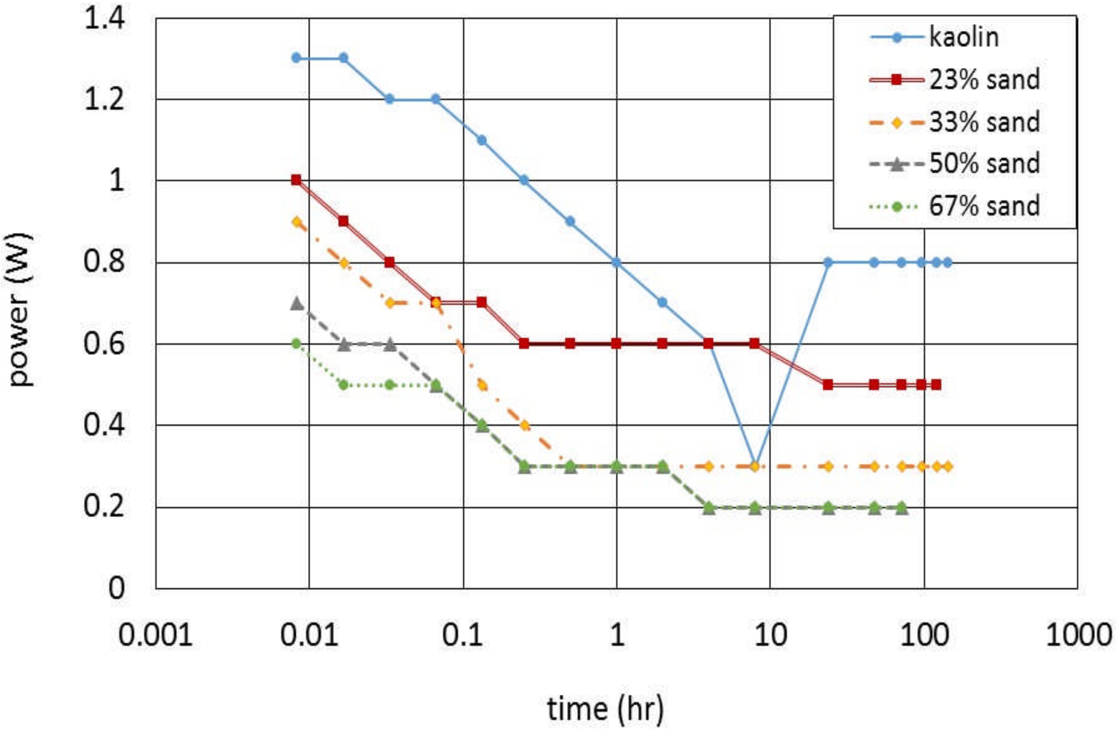


Figure 4.22 Variation of power with time for different sand content at 10V

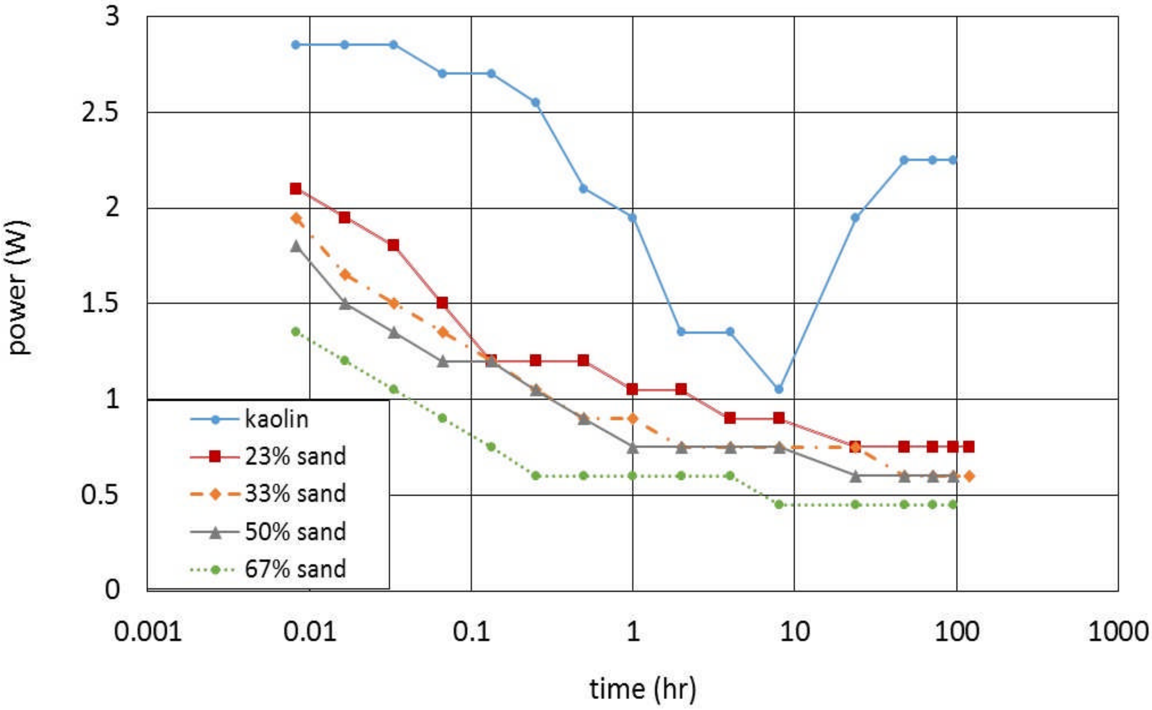


Figure 4.23 Variation of power with time for different sand content at 15V

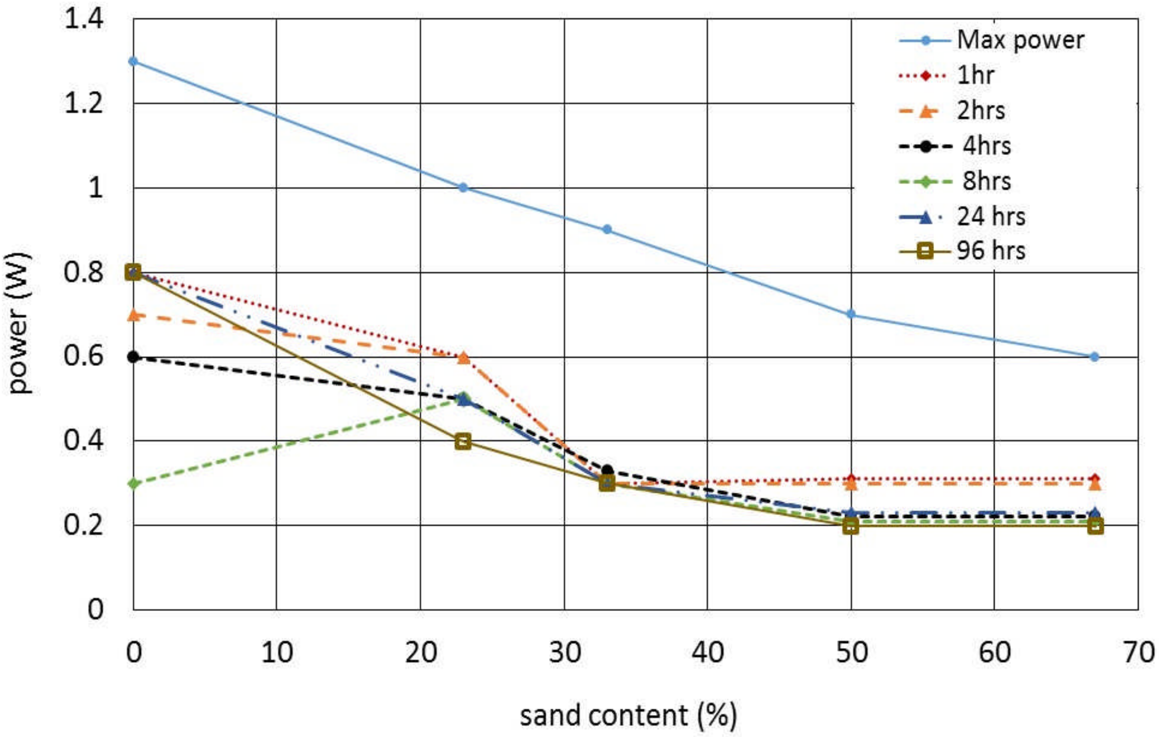


Figure 4.24 Variation in maximum power in Phase 2 with sand content at 10V and the power at 1, 2, 4, 8, 24 and 96hrs

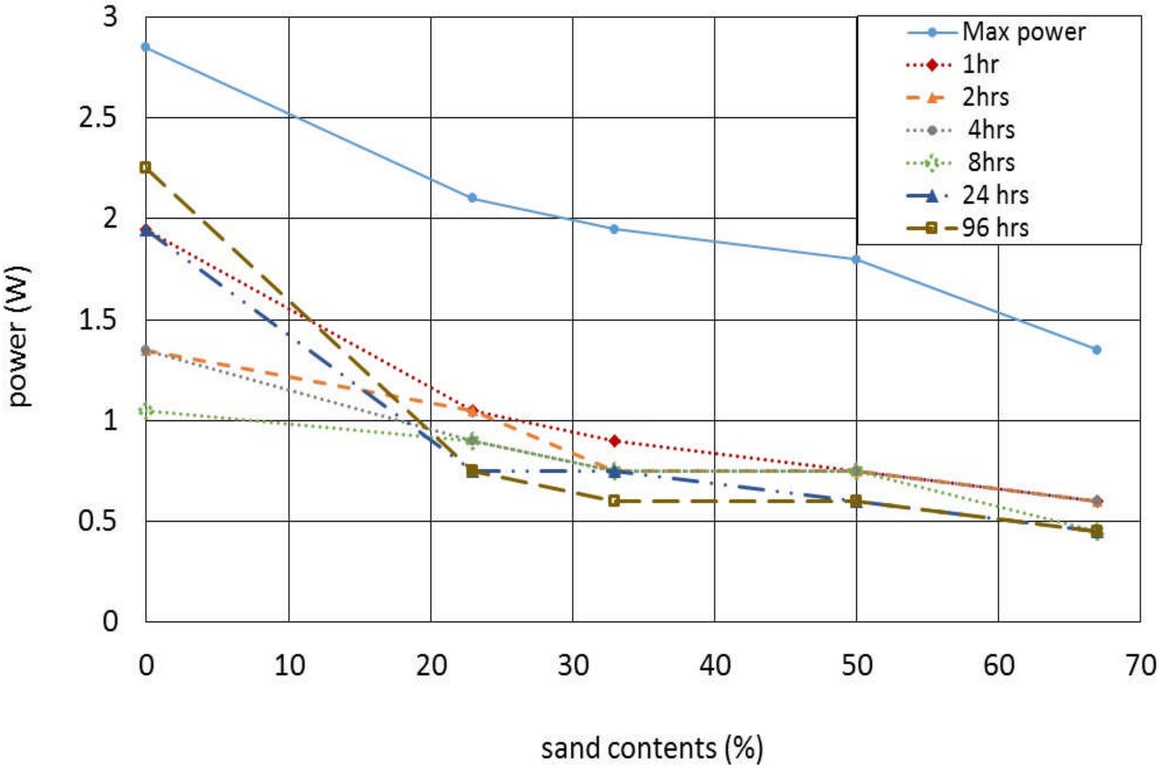


Figure 4.25 Variation in maximum power in Phase 2 with sand content at 15V and the power at 1, 2, 4, 8, 24 and 96hrs

4.3.2.2 Effect of applied voltage on the variation of electrical current

Figure (4.26) shows the variation of electric current with time in Phase 2 for kaolin soils subjected to 5, 10, 15 and 20V. It is observed that the variation in electric current of those four different voltages shows a similar trend which has a lower value at about 8 hours from the beginning of the test except for 5V. After 8 hours of electroosmosis consolidation, the electric current values for 10, 15 and 20V were increased again until they reached a constant value for each applied voltage. The higher the applied voltage, the greater value for the final electrical current. The increase in current after 10hrs in pure kaolinite soils may have been due to changes in the state of saturation in the vicinity of the electrodes with time, and therefore the electrical resistance of the electrode.

Figure (4.27) shows the electric current variations with treatment time for sand and kaolin soil mixed at 50% subjected to 10, 15 and 20V. In this figure, the current tends to decrease monotonically over time, the higher value of electrical current for 20V applied voltage at the beginning of the test was 140mAm compared to 70mAm for 10V, while the final value at the end of electroosmosis phase was 70mAm for 20V compared to 20 mAm for 10V applied voltage.

Figure (4.28) shows the variation in maximum power in Phase 2 with different applied voltages in pure kaolinite and sand with kaolinite mixed at 50%. In this figure, there is a clear trend of increasing consumed power as the applied voltage increased. The most interesting aspect of this figure is that the behaviour for this sand and kaolinite soil mix is linear.

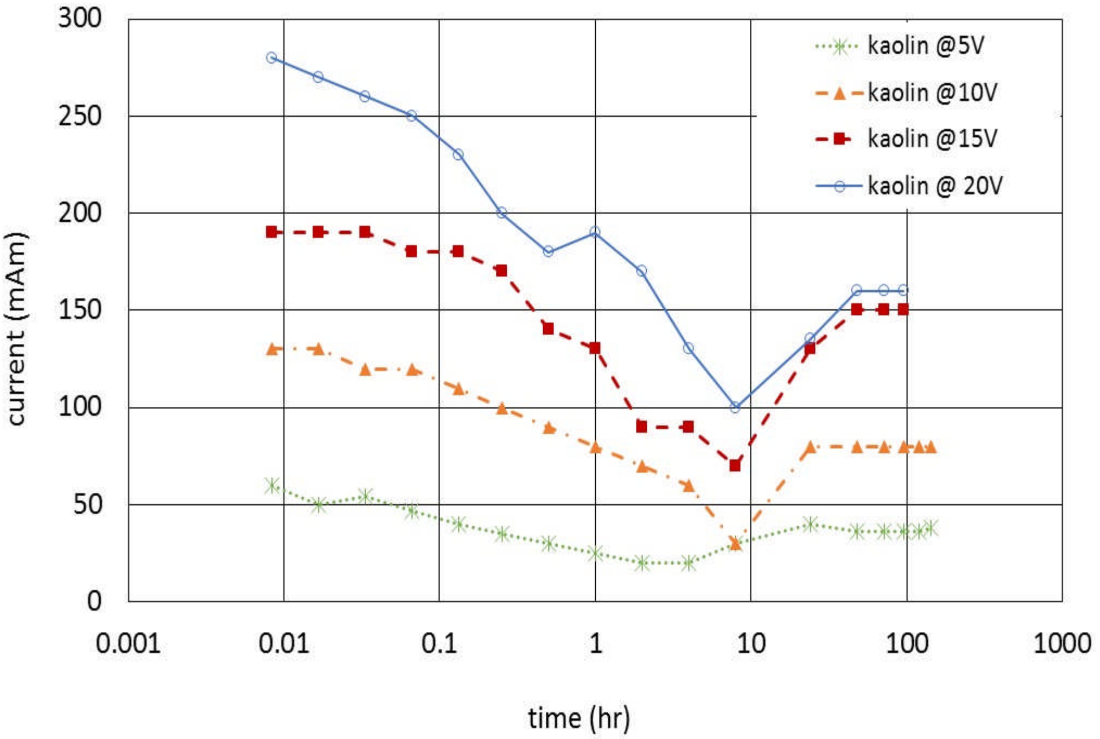


Figure 4.26 Variation of electrical current with time in kaolin soil subjected to different applied voltage

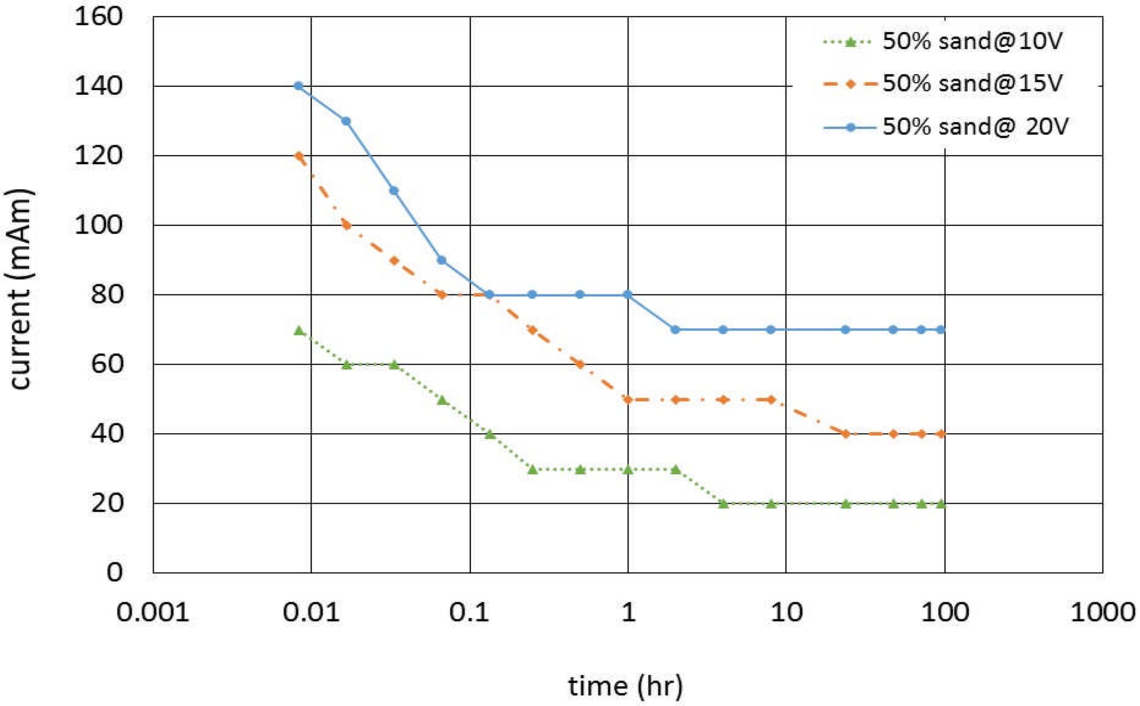


Figure 4.27 Variation of electrical current with time in kaolin and sand soil mix (50%) subjected to different applied voltage

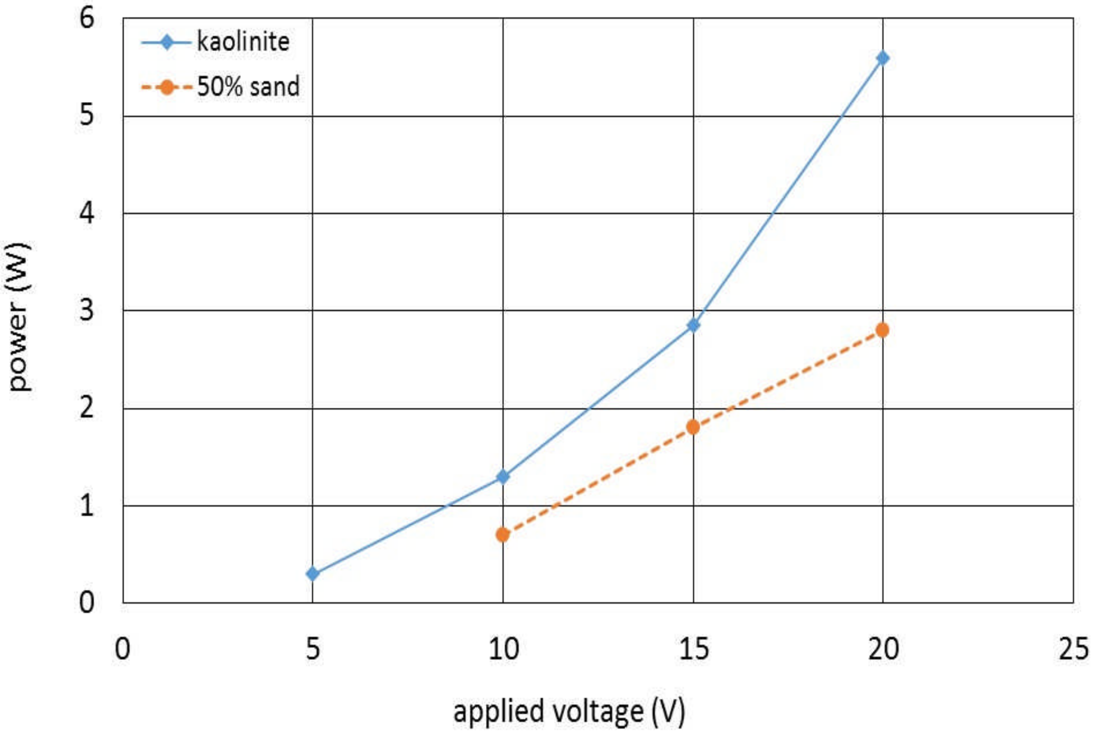


Figure 4.28 Variation in maximum power in Phase 2 with different applied voltage in pure kaolin and sand with kaolin mixed at 50%

4.3.2.3 Degradation of the electrodes

Electroosmosis causes the anode to degrade, with the effect being most significant for a sand content up to 30%. Figures (4.29) and (4.30) show the losses in anode weight after electroosmotic treatment due to the change in soil composition and the applied voltages. From Figure (4.29), it can be seen that a 10V applied voltage resulted in the lower anode corrosion compared to 15V, and the degradation of the anode decreased as the sand content increased in the composite soil.

As Figure (4.30) shows that there is a significant difference for the two groups in the degradation values, 24, 27 and 42% for 10, 15 and 20V respectively in pure kaolin, and 4.5, 9 and 18% for 10, 15, and 20V in 50% sand with kaolin soil.

Zheng et al. (2017) stated that the corrosion of metal electrodes is inescapable during electroosmosis treatment in soil and it is one of the reasons for increasing energy consumption. Li et al. (2012) observed that electrolysis occurs when DC current applied to the saturated soil due to the oxidation of water. As a result, alkaline and acidic environments are generated around the cathode and anode, respectively. Moreover, the authors noticed that the rate of anode corrosion during electroosmosis treatment decreases with elapsed time.

Gronchi et al. (2017) indicated that the critical aspects in the electroosmosis dewatering procedure is the corrosion behaviour of the electrode material, due to the DC application. The oxidation of the anode material causes oxygen evolution, developed heating, and pH decrease which affects the efficiency and increases the operating cost. Citeau et al. (2016) showed that appearance of high DC current density in combination with high developed temperature and low pH may cause dwindling of the anode lifetime.

Mohamedelhassan (2009) found that the loss in the mass of the steel anode by corrosion during the electrokinetic treatment of soft clay subjected to 10V was 4.7%, while Bjerrum et al. (1967) found that the losses was 37% of the original weight of 93 steel bar used as an anodes.

Together these results provide an important conclusion that the degradation of the anode during electroosmosis treatments increases as the voltage increases and decreases with the increase of sand.

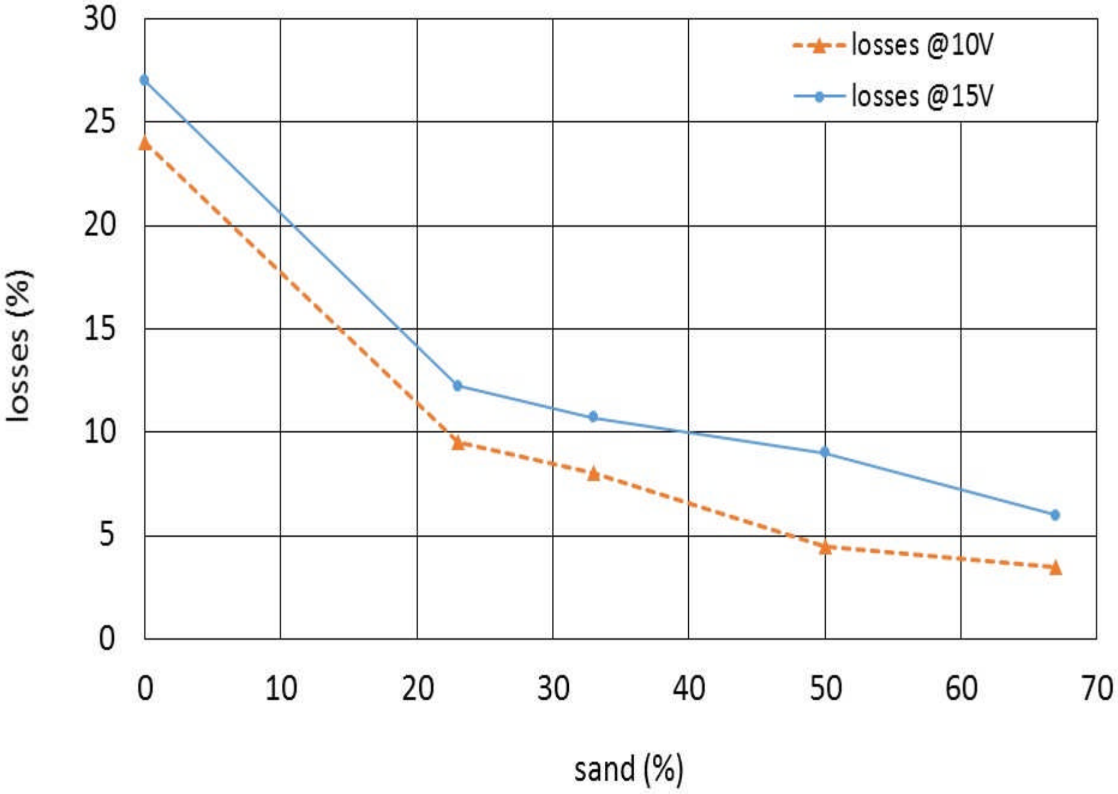


Figure 4.29 Losses in anode weight after electroosmotic treatment for 10V and 15V applied voltage

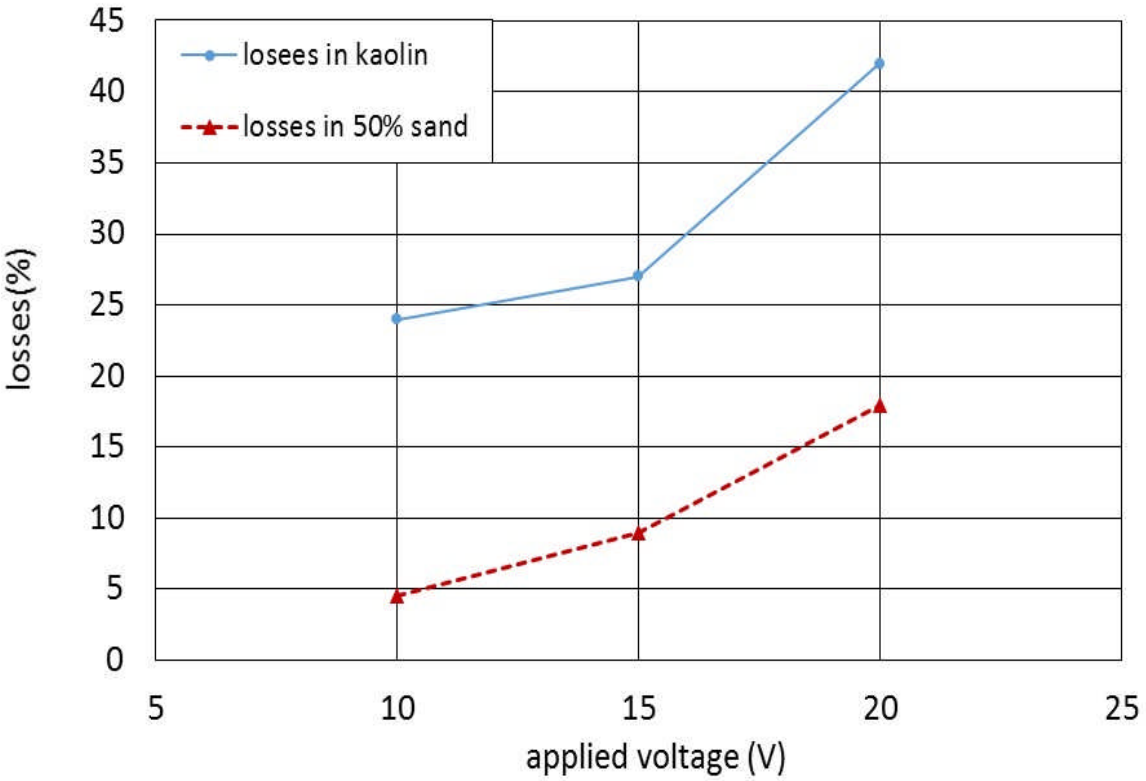


Figure 4.30 Effect of change in voltage on the losses in anode weight (%) after electroosmotic treatment in pure kaolin and kaolin with sand soil mix at 50% each

4.3.3 Water content

The final water content profile was measured at the end of Phase 3 by taking samples as the cell was dismantled from near the anodes and cathode, in between the electrodes, and at the cell wall from five levels so that the variation of water content with depth and distance from the electrodes could be assessed. While the reduction in water content should be the greatest at the anode at the end of Phase 2, the average water content across a sample (the average at each point from the cathode from the five levels as described in section 3.6.6) was more uniform (Figure 4.31) for 10V and Figure (4.32) for 15V with the average reducing with an increase in sand content. At the end of Phase 2 ‘soft’ piles were generated around the anodes but at the end of Phase 3, a more homogeneous deposit is created due to the redistribution of water at the end of Phase 2 when the D.C power turned off.

From the observations, the mean water content of the treated samples after the electroosmotic dewatering tests decreases as the applied voltage increases as shown in Figures (4.33) and (4.34) for 10V and 15V respectively. In addition, the electroosmotically treated soil samples had a higher water content than that in the control test.

It is obvious that that water content in anodic region is lower than that in cathodic region. Significant decreases in the water content of the treated sample were found at the vicinity of the anode and between anode and cathode in pure kaolinite (Figure 4.33), while the minimum water content was recorded at the cathode in Figure (4.34). This inconsistency can be seen in Figure (4.31) and (4.32) for sand content more than 33%, which was by the movements of water through the drain (cathode) which caused movements of fine soil particles (kaolin) and high contents of sand particles at the cathode.

A possible explanation for this results might be related to the electrophoresis which appears through a porous soil system in opposite direction to the electroosmosis flow. (Mitchell and Soga, 2005), (Hausmann, 1990). Li et al. (2014) explained that under a pressure gradient through porous material, the electrically charged soil particles are carried with the electrolyte which induces an electrical potential in a direction against to the fluid flow.

The variation in final water content with sand content (Figure 4.35a decreases with sand content (the soil being prepared at 1.5I_L) both for the control and electro osmotic tests. Figure (4.35b) shows the change in the final water content at the end of Phase 3 for electroosmosis tests (at 10 and 15V) and the control test relative to the initial water content. It can be seen from this figure that when sand was added to kaolin, the general trend of the water content change decreased as the sand content increased. The change in water content was higher in the control test compared to the electroosmotic tests due to the electroosmotic pile created in Phase 2. A smaller change in water content was observed in pure kaolin compared to that in 23% sand due to the physico chemical properties of kaolin clay described in Section 4.2.2. it can be also observed that the increases in the applied voltage results in a greater change in water content.

The average water content of the pure kaolinite samples after the electroosmosis dewatering tests (after phase 2) were 64.2, 51.7, 49.6, and 48.7% for 5, 10, 15 and 20V respectively as shown in Figure (4.36). The results of this figure indicate that increasing the applied voltage caused decreases in the final water content, hence increase the stiffness and shear strength of those soils. This finding is in agreement with the finding of Xue et al. (2017), they concluded that the higher voltage was beneficial in the reduction of the soil water content.

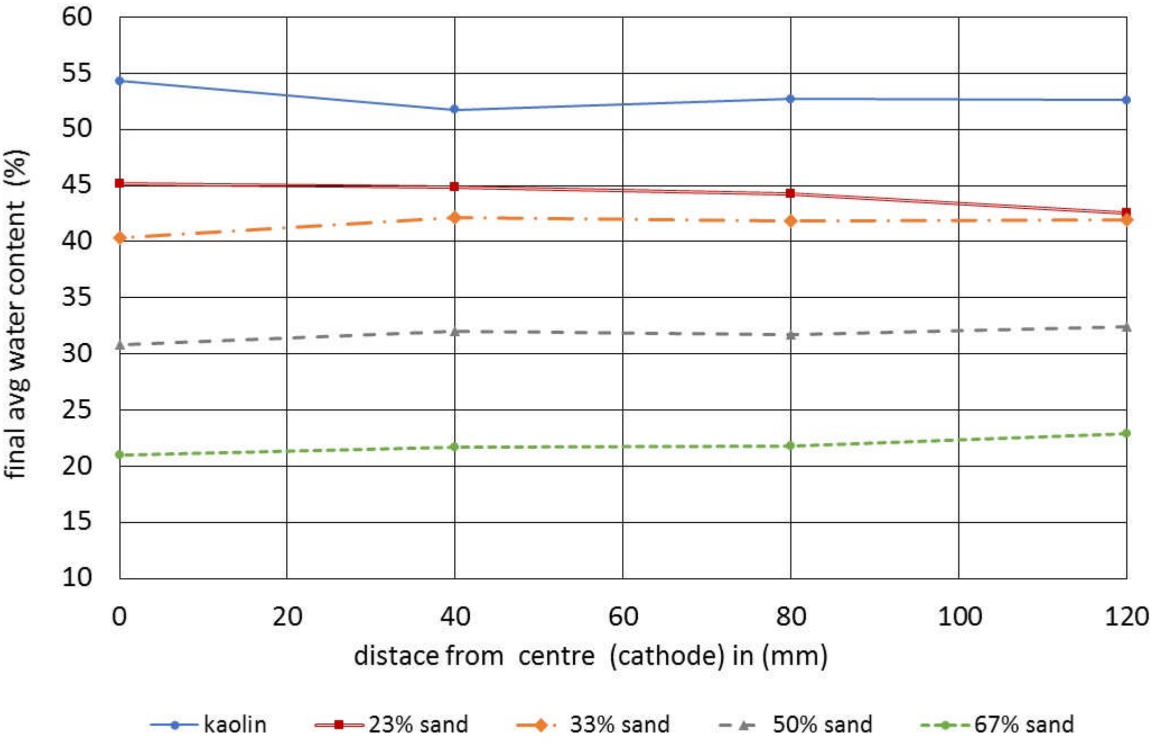


Figure 4.31 Variation in final average water content at each distance from the cathode with sand content at 10V

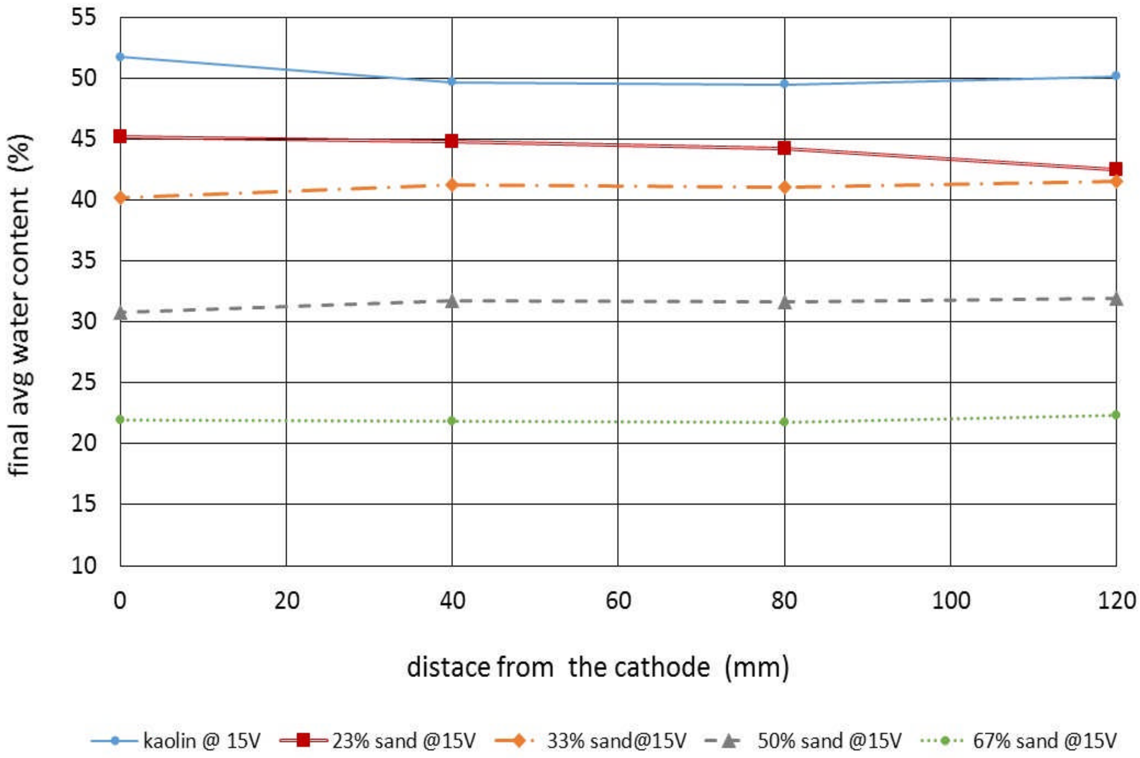


Figure 4.32 Variation in final average water content at each distance from the cathode with sand content at 15V

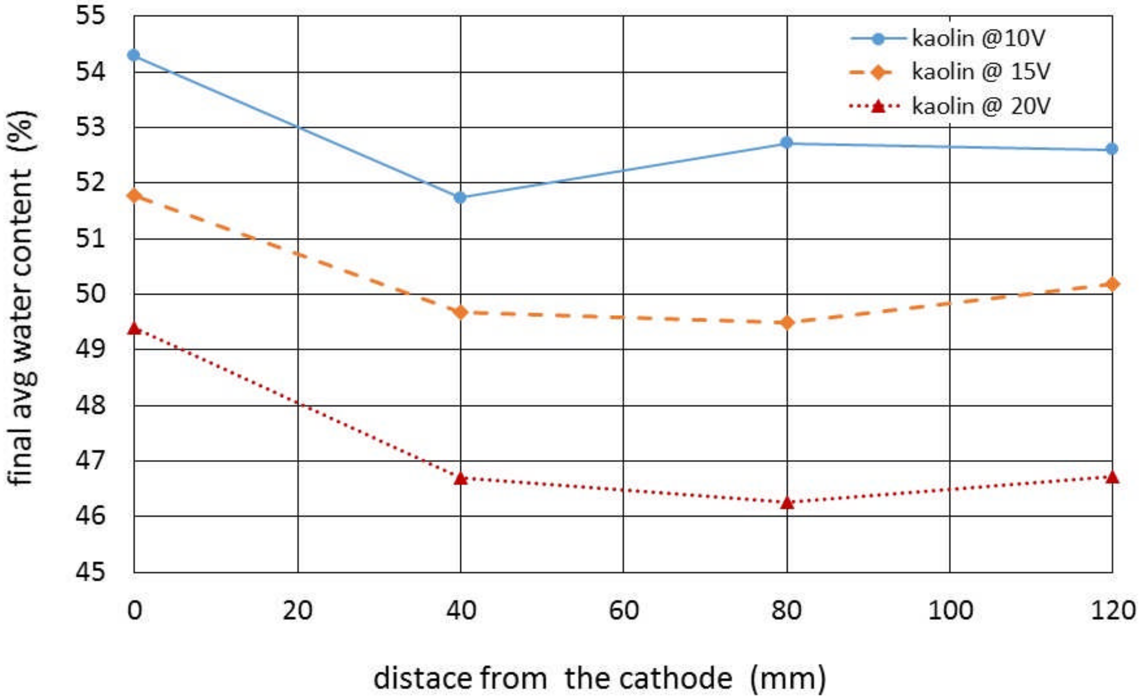


Figure 4.33 Variation in final average water content in pure kaolin subjected to 10, 15, and 20V

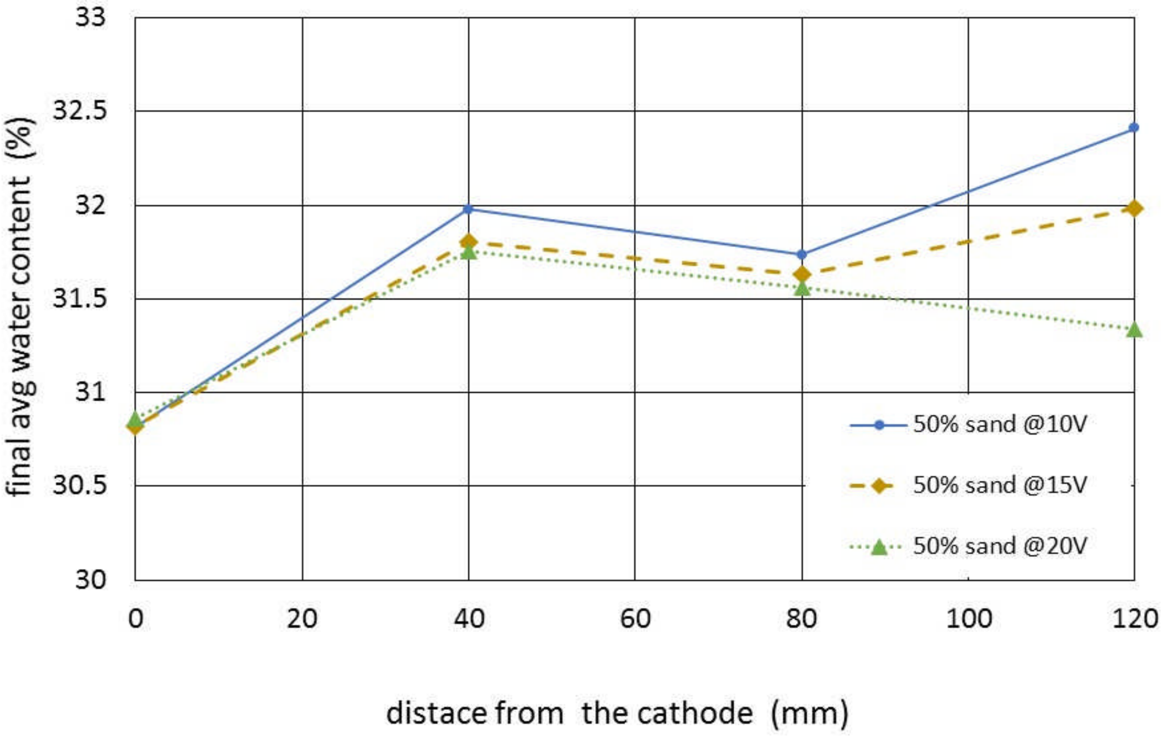


Figure 4.34 Variation in final average water content in sand and kaolinite mixed at 50% subjected to 10, 15, and 20V

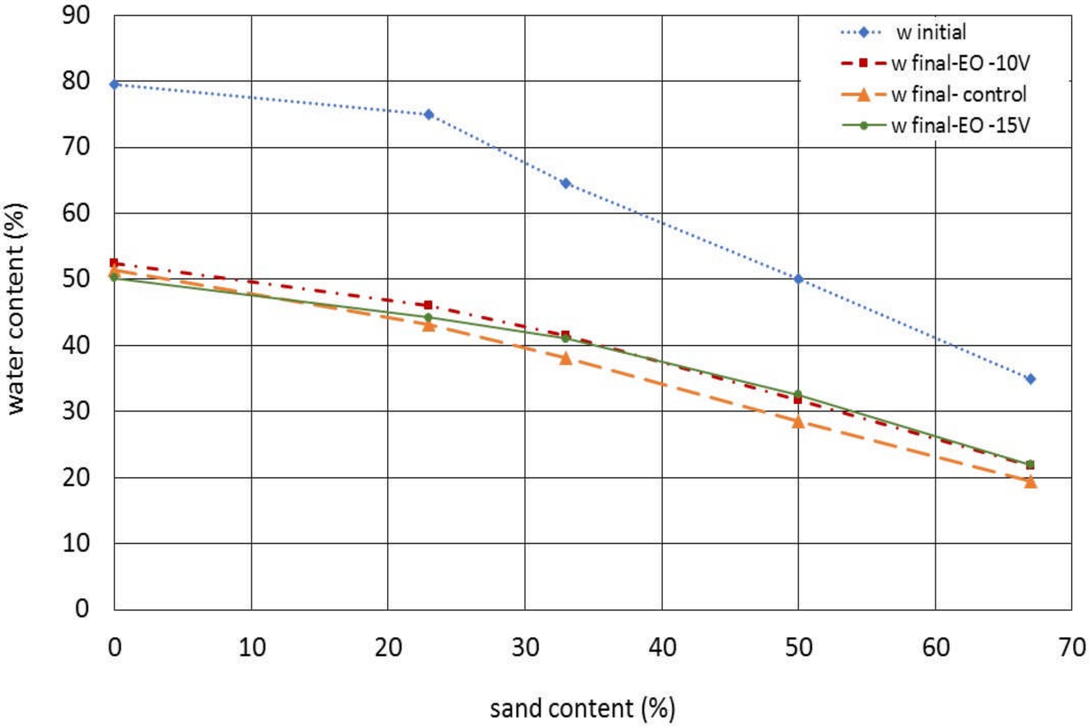


Figure 4.35 a Variation of initial and final water content over the whole sample with sand content and applied voltage in Phase 3

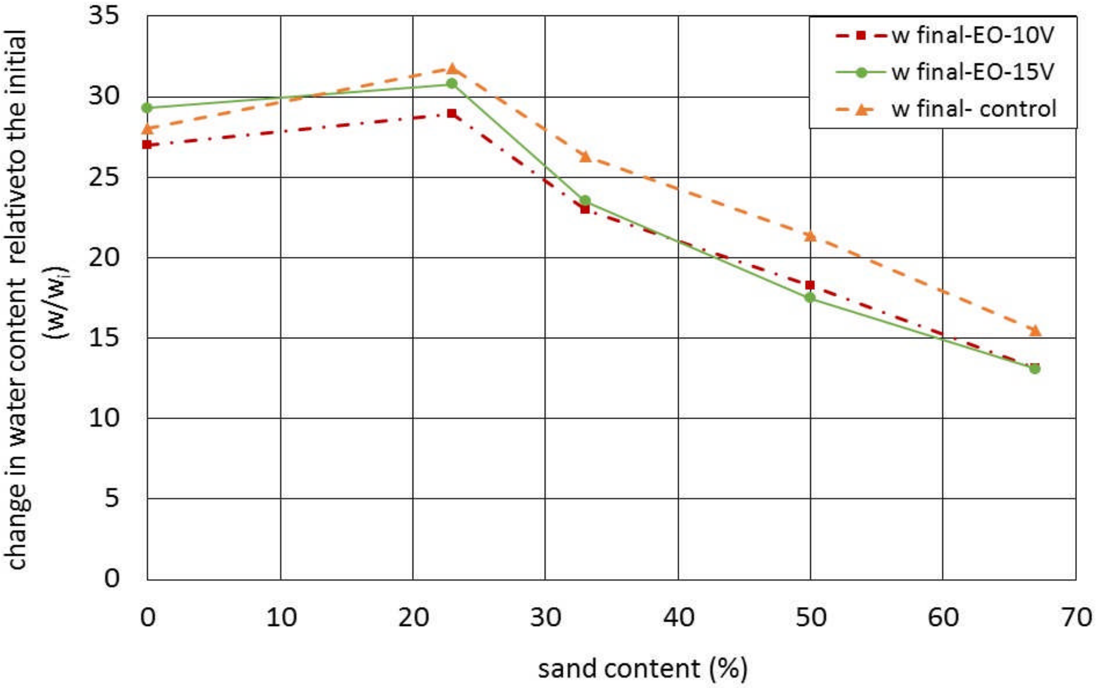


Figure 4.35 b Variation of final water content in electroosmosis and control tests at the end of Phase 3 relative to the initial water content at the start of the test

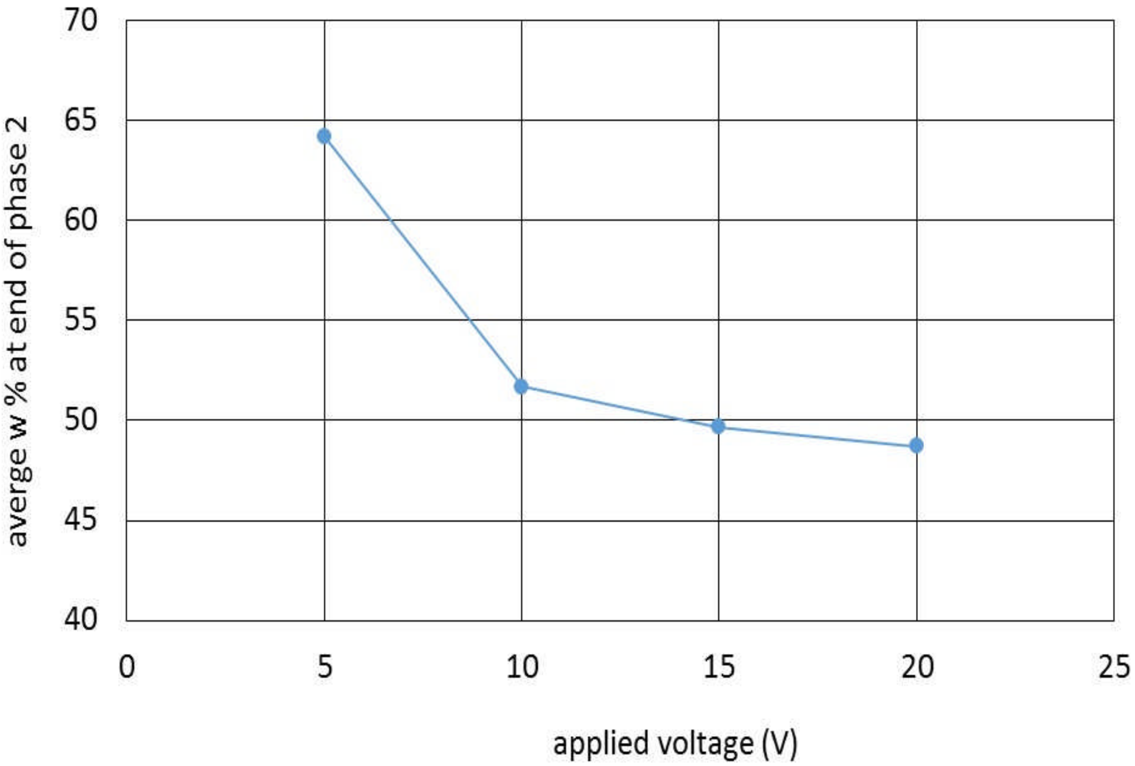


Figure 4.36 Variation of average water content with the applied voltage at the end of Phase 2

4.3.4 Electroosmotic Permeability

Electroosmotic permeability is based on the measurement of discharge water with time, electric intensity, and the area of the sample during electroosmotic tests according to the following equation (Mitchell and Soga, 2005):

$$Q = k_e\, E\, A \tag{4.2}$$

Where Q (m^3/s) is the flow rate, E (V/m) is the effective electric field intensity, and A is the cross section area assumed to be the effective area of an octagon defined by the anodes (Alshawabkeh et al., 1999). It is apparent from the above equation that the coefficient of electroosmotic permeability k_e is empirically related to the total flow of water, Acar et al. (1990a) stated that the electroosmotic permeability of soil decreases with time of treatment. According to Mitchell (2005), the coefficient of electroosmotic permeability is considered to be relatively independent of the pore size, Casagrande (1949), suggested, for a practical basis, that the coefficient of electroosmotic permeability k_e, may be assumed to be a constant for all soils with a value of $5x10^{-9}$ m^2/sV. The experimental results from Acar and Alshawabkeh (1996), Acar et al. (1995) found that the k_e values for Georgia kaolin ranged from $1x10^{-9}$ $m^2/$ sV to $1x10^{-11}$ $m^2/$ sV and these values are change with time due to the effect of pH change.

Mohamedelhassan and Shang (2001) stated that the coefficient of electroosmotic permeability in soil is a function of the effective electric field intensity. Wu et al. (2017) suggested that the electroosmosis conductivity decreases with a decrease in void ratio. Gray and Mitchell (1967) suggested that the electroosmotic permeability is not a constant for soils; it is a function of soil type and water content, and it reduces as the water content reduces until it is zero for dry soils. Figure (4.37) shows the coefficients of electroosmotic permeability, k_e, derived using equation (4.2) were in the range of 0.05×10^{9} m^2/sV for 67% sand content at 35% initial water content and 1.4×10^{-9} m^2/sV for pure kaolinite at 79.5% water contents derived from tests at 10V.

In Figure (4.38), it can be seen that the electroosmotic permeability values reported a significant change in pure kaolin due to the change in the applied voltage, from 1.4×10^{-9} m^2/sV at 10V to 1×10^{-9} m^2/sV at 20V, whilst there was no significant difference in k_e value for sand and kaolin soil mixed at 50% (0.2×10^{-9}

m^2/sV). Table (4.3) shows that the electroosmotic permeability varies with soil type and water content. In this table, it can be seen that the electroosmotic permeability values increased significantly with the increase in water content. These results are in agreement with Smith's (1999) and Gray and Mitchell (1967) research which showed that the electroosmotic permeability is highly affected by the change in water content and to some extent by the electrolyte concentration; the k_e values increased an order of magnitude when the water content ranged between 20-80%. The results in Figure (4.37) and Table (4.3) also confirms that the electroosmosis permeability is associated with the water content of the treated soil, since the initial water content decreases with the increase of sand content as shown in Figure (4.35) and the electrical conductivity of soils depends on the amount of moisture held by their particles as mentioned by (Grisso et al., 2005). In addition, the rate of flow produced by electroosmosis decreases with time which affect the water content and hence the ke value as described by (Mohamedelhassan and Shang, 2001).

Table 4.3 Published coefficients of electroosmotic permeability, k_e

No.	Researcher	Soil type	w_c (%)	k_e in 10^{-9} (m^2/sV)
1.	Mohamedelhassan (2001)	Marine sediment	100-120	8.85 – 9.57
2.	Shang and Lo (1997)	Phosphate clay, Florida	244.8	0.52
3.	Segall and Bruell (1992)	kaolinite	-	3.6
		silt	-	5.4
		sandy clay	-	1.8
		clayey silt	-	4.29 - 4.72
4.	Bjerrum *et al*. (1967)	As Quick clay	31	2 – 2.5
5.	Fetzer (1967)	silty clay, West Branch dam	32	3 - 6
6.	Gray and Mitchell (1967)	kaolinite	73.7	9.4
			61.7	8.1
			52.2	6.7
			42.7	5.4
		silty clay	50.1	3.5
			41.9	2.8
			32.0	2
7.	Mitchell and Soga (2005)	London clay	52.3	5.8
		Boston blue clay	50.8	5.1
		clayey silt	31.7	5.0
		fine sand	26.0	4.1
8.	Guy Lefebvre and Fabien Burnotte (2002)	soft clay	63-79	1.3 – 4
9.	Eykholt and Daniel (1994)	kaolinite	43	2.1 – 6.7
10.	YALCIN B. Acar et al. (1990)	kaolinite	96	0.8 -3
11.	Asadi et al. (2010)	Malaysian peat	-	1 – 0.1
12.	Wang et al. (2016)	dredged marine clay	78.3	57
13.	Lee et al. (2016)	mine tailings	83.4	6.3-53
14.	Punia and Singh () 2017	kaolin	-	5.7
15.	Bader and Heister (2006)	bentonite	-	1.2
16.	Hamed and Bhadra (1997)	kaolin		0.14 – 2.4
17.	Lamont-Black et al.,(2015)	kimberlite tailings	-	7
18.	Glendinning, S. et al., (2010)	sewage sludge	158	1.5
19.	Hall J. et al., (2014)	kaolin (non-flocculated)	20	20
		kaolin (flocculated)	20	10000
		water clarification sludge	16	5-7

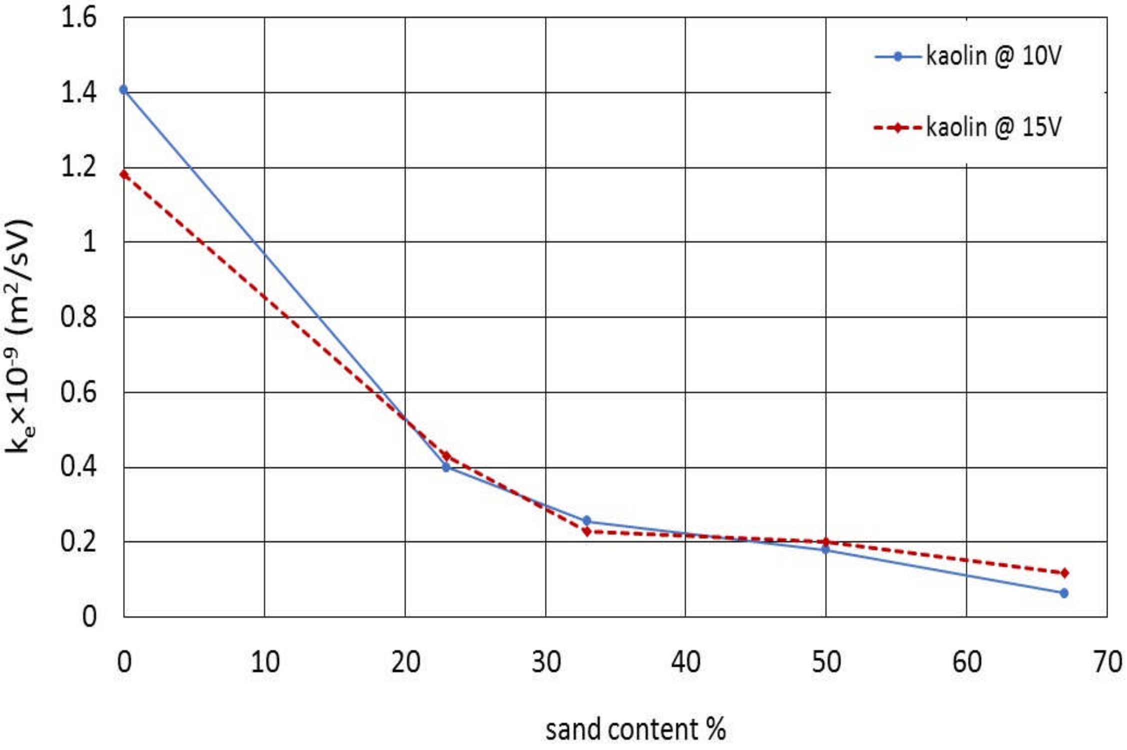


Figure 4.37 Values of electroosmotic permeability *k_e* vs sand contents for 10 and 15V

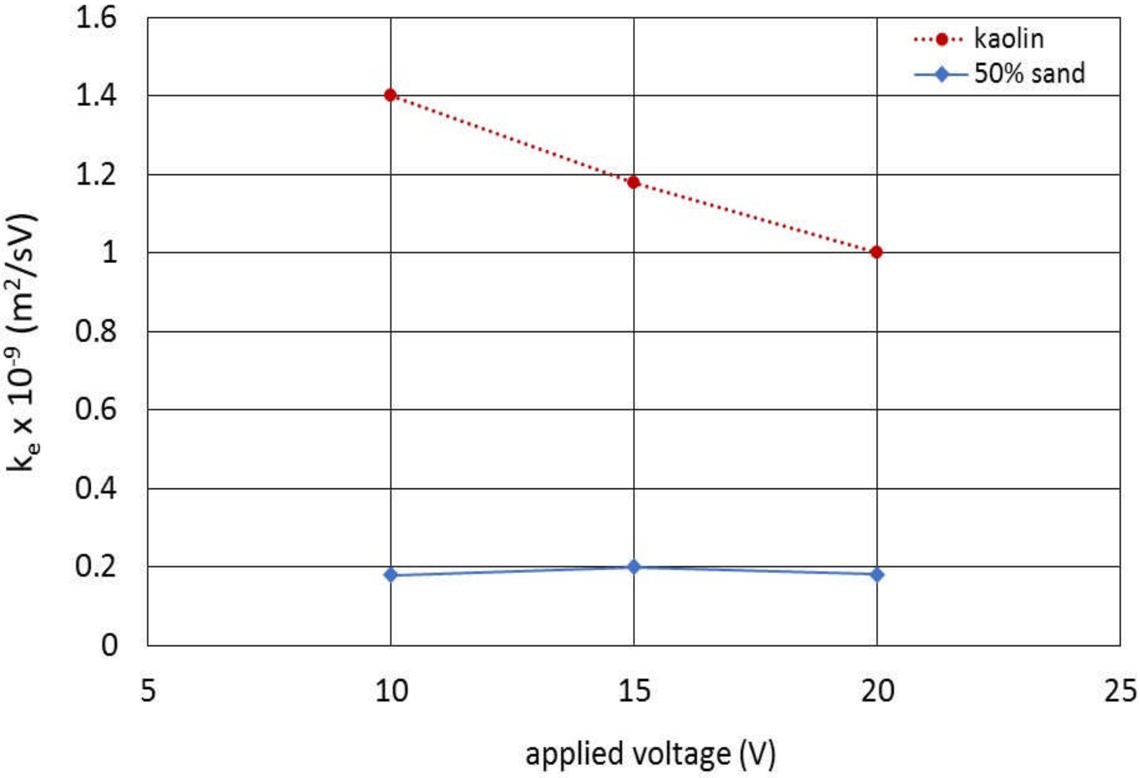


Figure 4.38 Values of Electroosmotic Permeability *ke* vs applied voltage

4.3.5 Variation of temperature developed in soil

The temperature of the soil samples were monitored at intervals during Phase 2 by inserting a K type thermocouple temperature probe through glands in the sidewall of the test chamber. The probes were inserted at the anode and the cathode near the bottom of the cell (about 50mm above the bottom), and at the cathode at the middle of the cell. Insulating varnish was used to prevent the temperature probes acting as electrodes, room temperature was kept constant during the test.

Chen et al. (2002), Morefield et al. (2004), Mohamedelhassan (2009), and Kim et al. (2012) noted that the soil temperature increases if a soil is subject to a voltage difference. Liaki et al (2008) suggested that the increase in soil temperature will increase the diffuse layer thickness and reduce the surface potential.

Figure (4.39) and (4.40) show that there was an increase in temperature during electroosmotic testing phase for 10 and 15V respectively but it was less than 2^{o}C. The initial temperature was the same as the room temperature. The changes in temperature of the soil sample are mainly attributed to the application of electrical current.

Figure (4.41) shows the variation of heat developed during electroosmosis treatment in pure kaolinite under an applied voltage of 20V. It’s clear that the soil temperature increased significantly when an electrical power was applied, and that the soil temperature drops when an applied voltage turned off. The highest increase in temperature was found in pure kaolinite at 20V, from 18.5℃ to 23℃ after about 8 hours of electroosmosis test. The highest temperature value occurred at the cathode, while the lowest occurred at the anode in the base. However, higher applied voltages can cause increased heating, which increased energy consumption and diminish treatment effectiveness. (Mohamedelhassan and Shang, 2001, Lee et al., 2016, Mao et al., 2012)

It can be seen from the results of the above figures that the higher applied voltage resulted in a more significant increase in temperature of electroosmotic treated samples, the heat developed due to applying electrical power is a function of voltage and soil type.

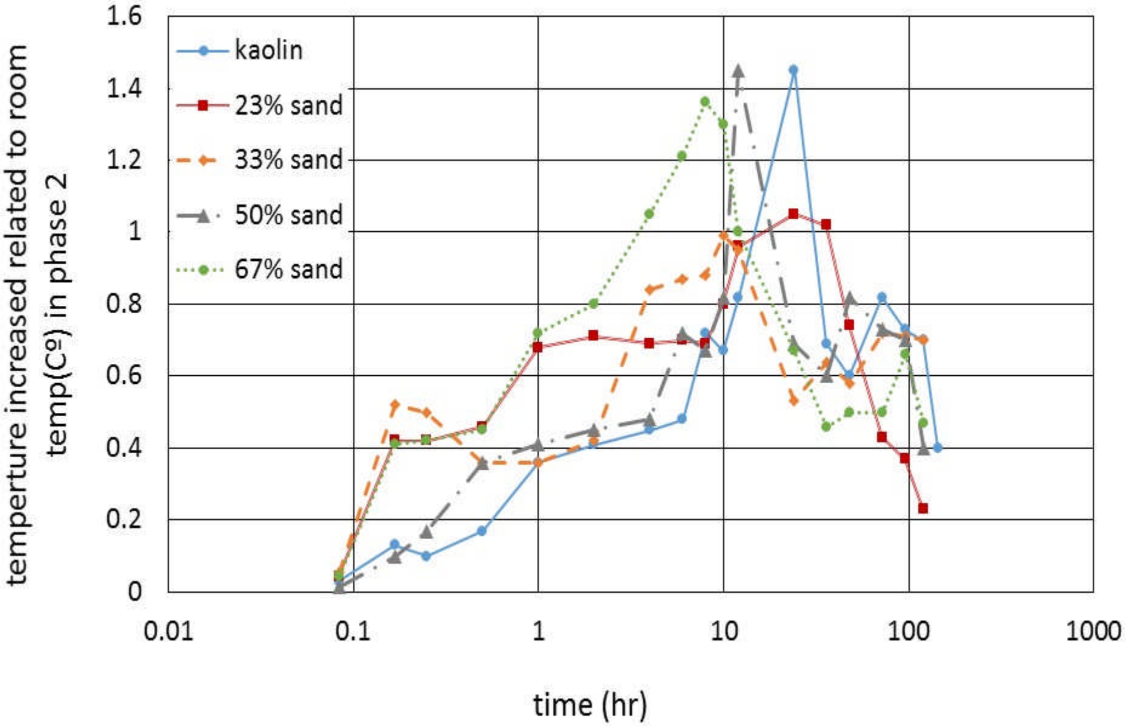


Figure 4.39 Variation of temperature with time during electroosmotic test at 10V

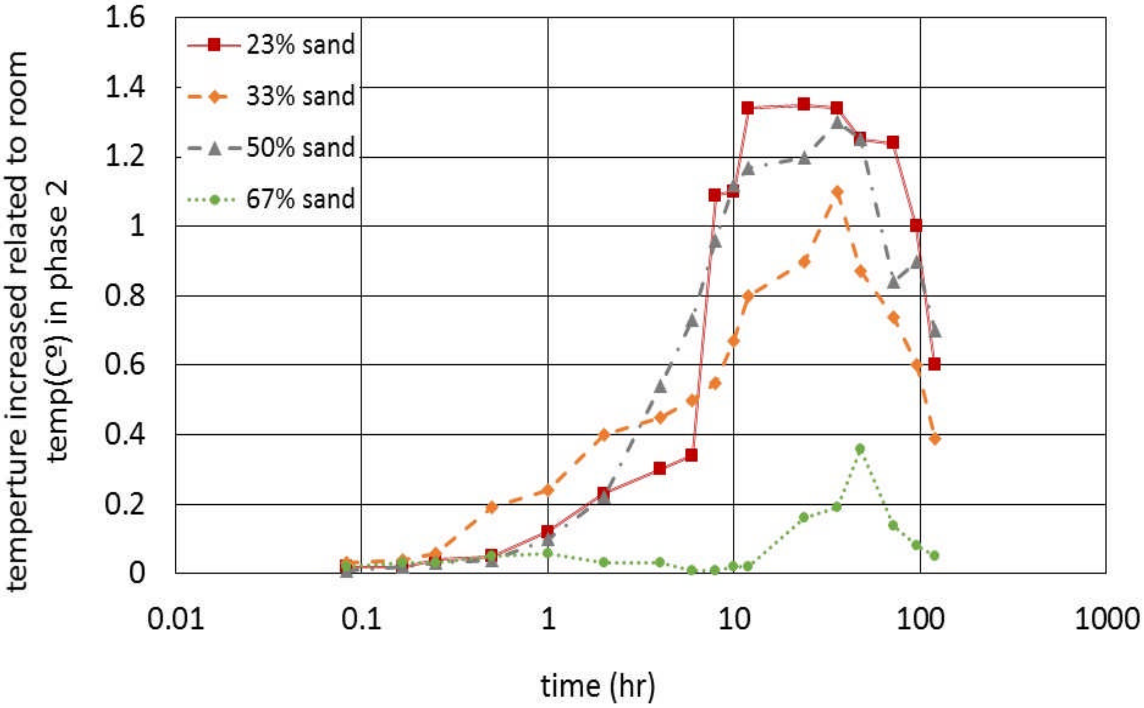


Figure 4.40 Variation of temperature with time during electroosmotic test at 15V

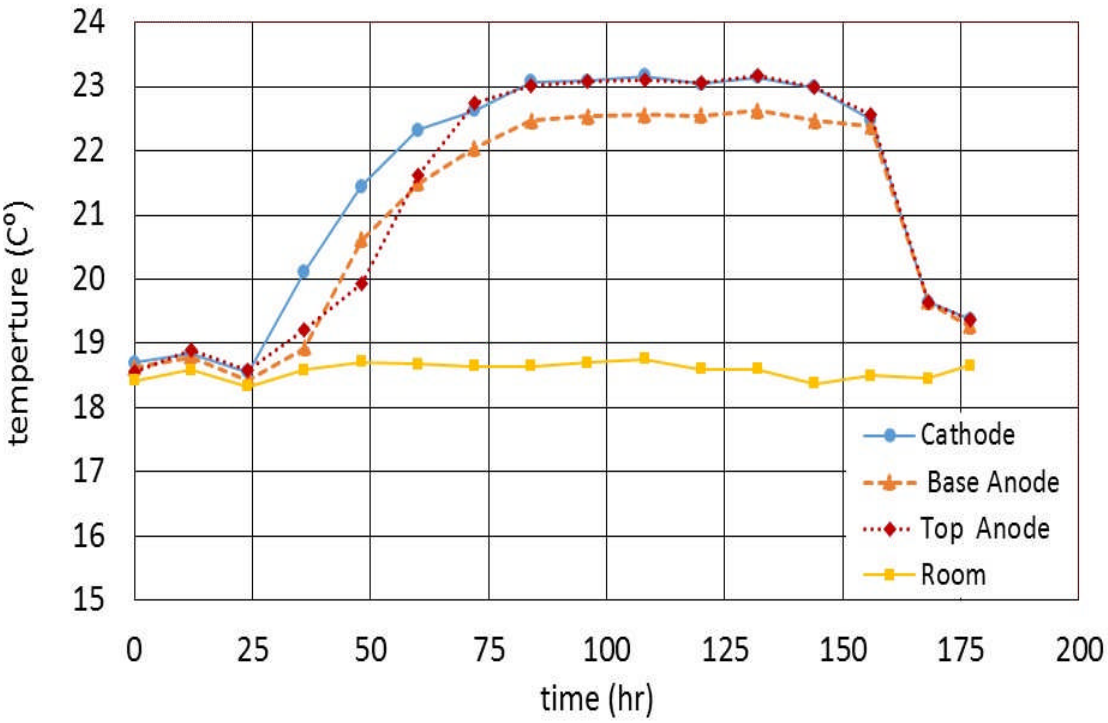


Figure 4.41 Variation of temperature during electroosmosis treatment in pure kaolinite under 20V

4.4 Electroosmotic Efficiency

Recent developments in the field of electroosmotic treatment have led to a renewed interest in the efficiency and cost of this method of soil improvement. Nizar (2012) stated that there are three parameters essential to determine the efficiency of electroosmotic treatment; consumed energy, electroosmotic flow efficiency and electroosmotic transport efficiency.

4.4.1 Energy consumption (E)

Mohamedelhassan (2012) stated that estimating the consumed energy prior to the electroosmosis processing is critical to assess the economic viability of the process. Figure (4.42) presents the results obtained for the consumed energy in electroosmotic treatment (E in kWh/m^3, according to equation below suggested by Lefebvre and Burnotte (2002):

$$E = \frac{VIt}{v} * \mathit{scaling\ factor} \qquad (4.3)$$

Where: V is the mean applied voltage (V); I is the mean current (Am); t is the total time (hour); v is the sample volume (L); scaling factor , to convert electrode spacing in laboratory to field. In these tests, the scaling factor is 1. Figure (4.43) shows the total consumed energy for soil mixtures subjected to 10 and 15V. As the figure shows, there is a significant decrease in the consumed energy as the sand content increases(10.4 kWh/m^3 for pure kaolin to 2.5kWh/m^3 for 67% sand) at 10V and (17 kWh/m^3 for pure kaolin to 5.4 kWh/m^3 for 67% sand) at 15V.

Figure (4.44) shows the results for the consumed energy during electroosmotic treatments in pure kaolin and 50% sand with kaolin subjected to different applied voltage (5, 10 , 15, and 20V). It is intuitive that the consumed energy increases as the applied voltage increases. Figure (4.42) reveals that there has been a steady increase in the consumed energy as the applied voltage increase in pure kaolin (from 2.18 kWh/m^3 at 5V to 29.6 kWh/m^3 at 20V).

Zhuang et al. (2014) and Zhuang (2015) found that the energy consumption required for electroosmotic consolidation of sludge is less than 10kWh/m^3.

Fourie et al. (2007) stated that it is difficult to compare the consumed energy in the electroosmotic treatment discussed in the literature because of different voltage gradients used, different initial and final water contents, and different electrode materials and configuration but it ranged from 0.6 to 880 kWh/dry ton. A lower voltage gradient produces a lower rate of consolidation than a higher voltage gradient, although better energy efficiency. Fourie and Jones (2010) found that the power consumption rates used in field tests is up to 30 times lower than that in laboratory work because of the lower voltage gradient required for the field tests and the greater material volume effected by the electroosmosis treatment compared to the limited volume in the laboratory work.

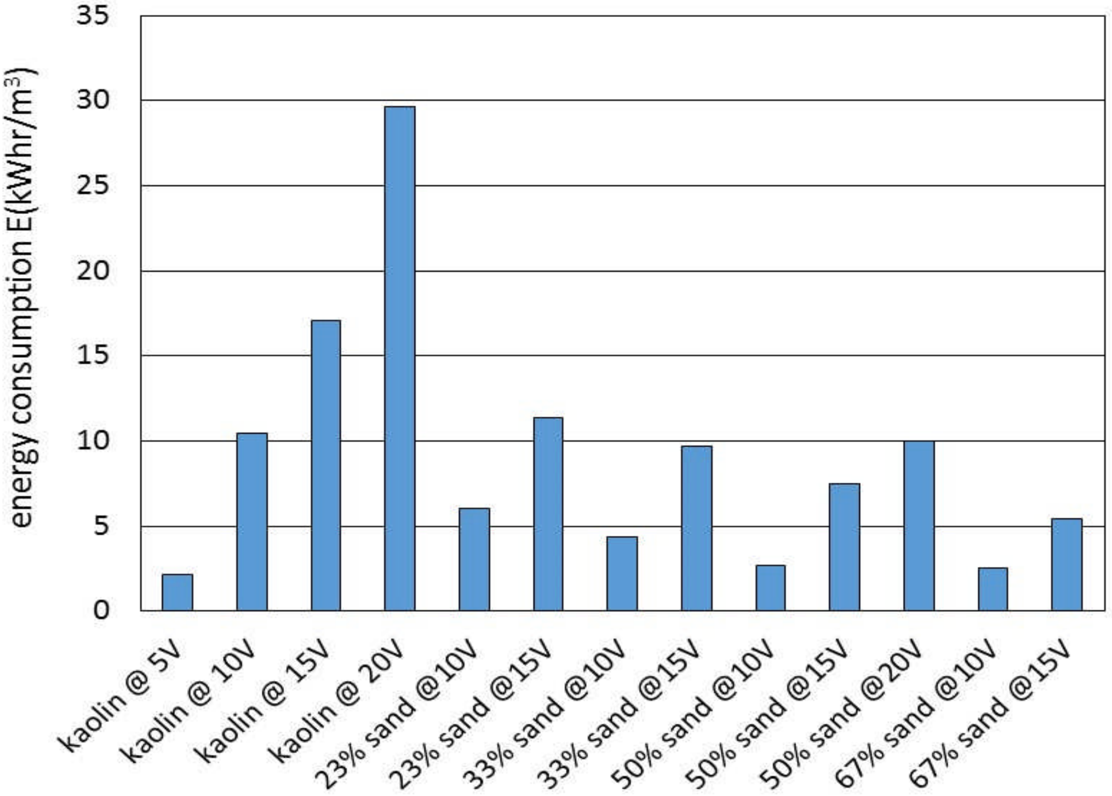


Figure 4.42 Consumed energy in electroosmotic treatment vs applied voltage

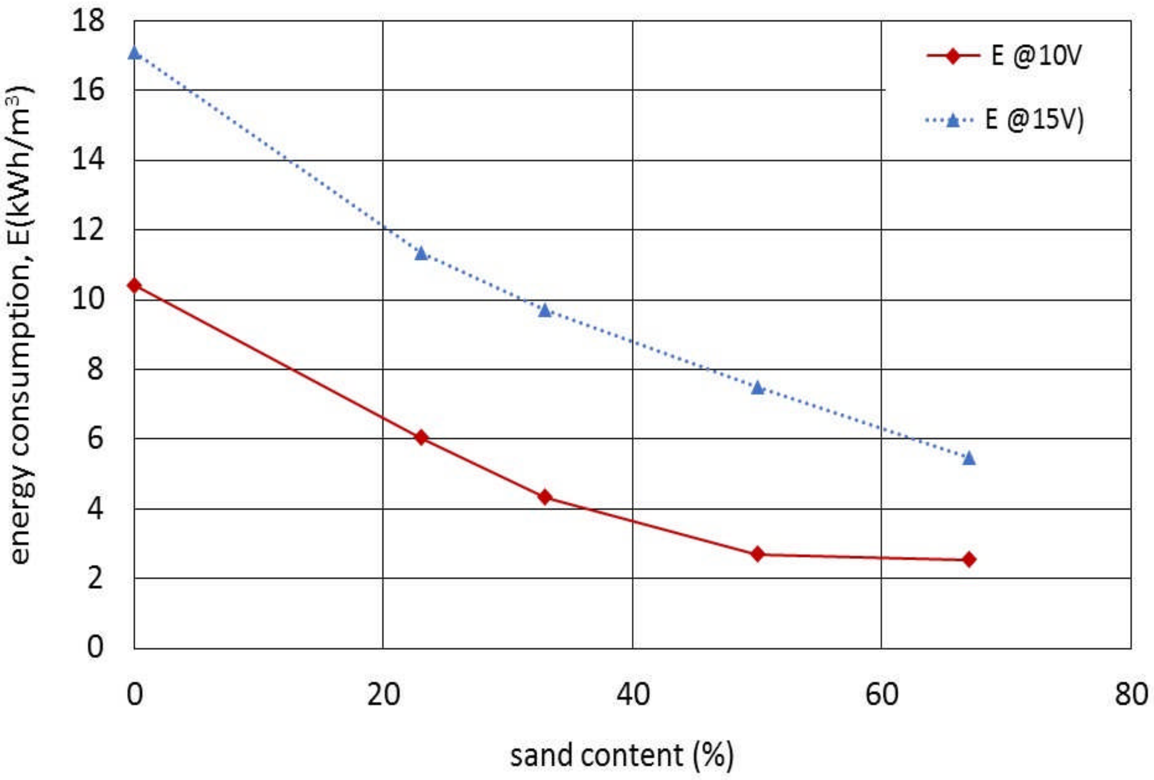


Figure 4.43 Consumed energy in electroosmotic treatment vs sand content for 10 and 15V

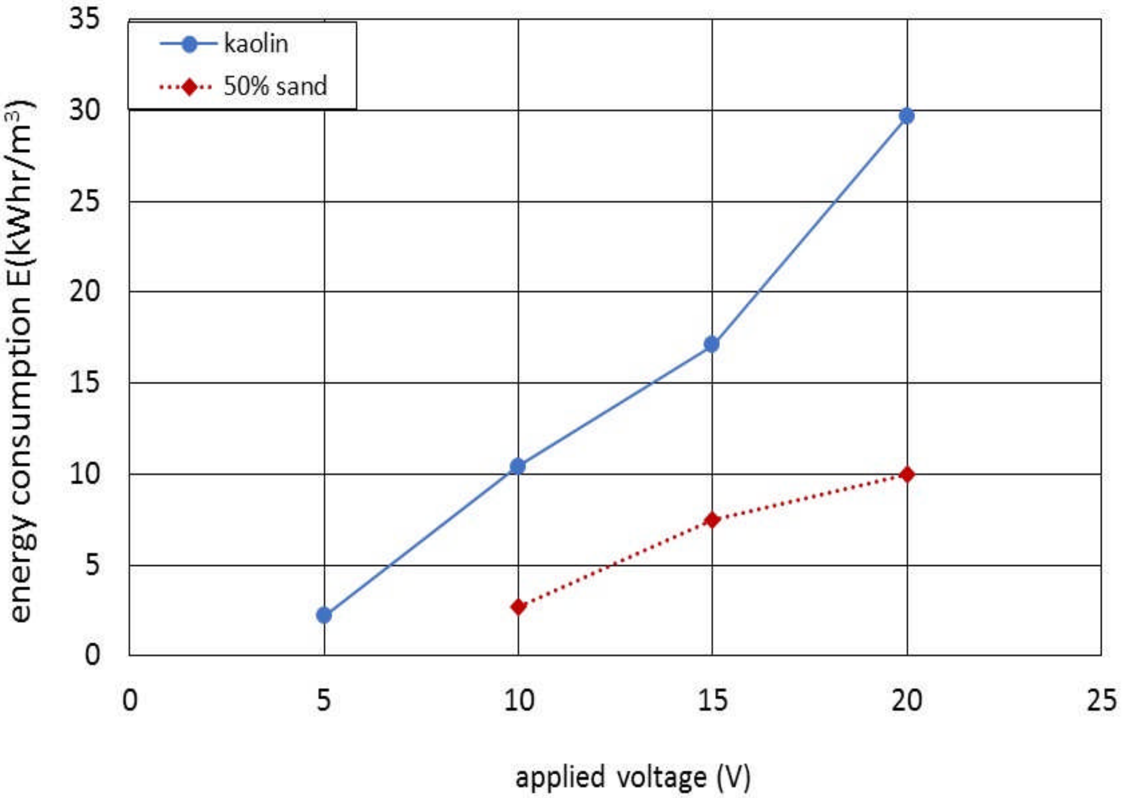


Figure 4.44 Consumed energy in electroosmotic treatment vs applied voltage

4.4.1 Electroosmotic Flow Efficiency

Electroosmotic flow efficiency represents the ratio of total flow divided by total consumed energy in (m3/ [kWh/m3]). The efficiency of electroosmotic treatment total flow per power consumed can be defined as:

$$\frac{Q}{E} = \frac{total\ expelled\ water}{consumed\ energy} \tag{4.4}$$

Where, Q is the total water expelled (cm^3); and *E* is the energy consumption as calculated from equation (4.3). Details of electroosmotic flow efficiency was discussed by Gray and Mitchell (1967) and Eykholt and Daniel (1994). A summary of electroosmotic flow efficiency data for all electrokinetic tests is shown in Figure (4.45).

The flow efficiency vs sand content under 10V and 15V is shown in Figure (4.46). The flow efficiency was greatest in pure kaolin test where no sand was used and it was lowest at 67% sand, (from about 151 for no sand to 43 (m^3/ [kWh/m^3]) for

67% sand at 10V, and from about 120 to 39.3 (m^3/ [kWh/m^3]) for no sand and 67% sand respectively at 15V). Figure (4.47) displays the results obtained for variation of electroosmotic flow efficiency in pure kaolin and 50% sand with kaolin against the applied voltage. What stands out in this figure is the steady decline of the electroosmotic flow efficiency as the applied voltage increase.

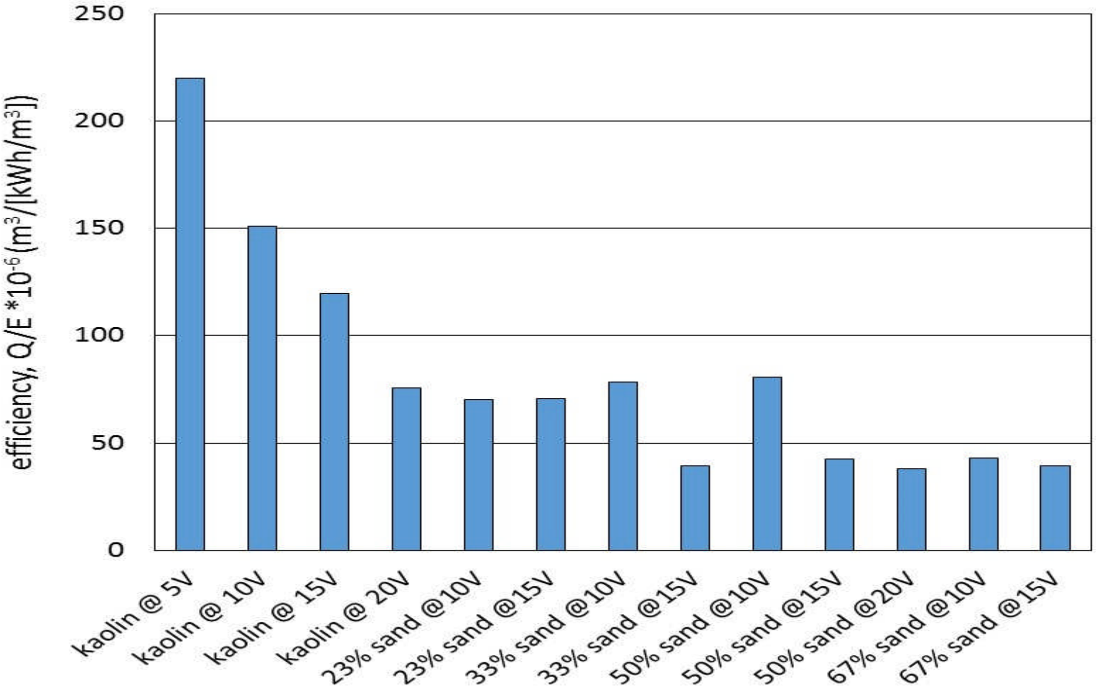


Figure 4.45 Electroosmotic flow efficiency (Q/E)

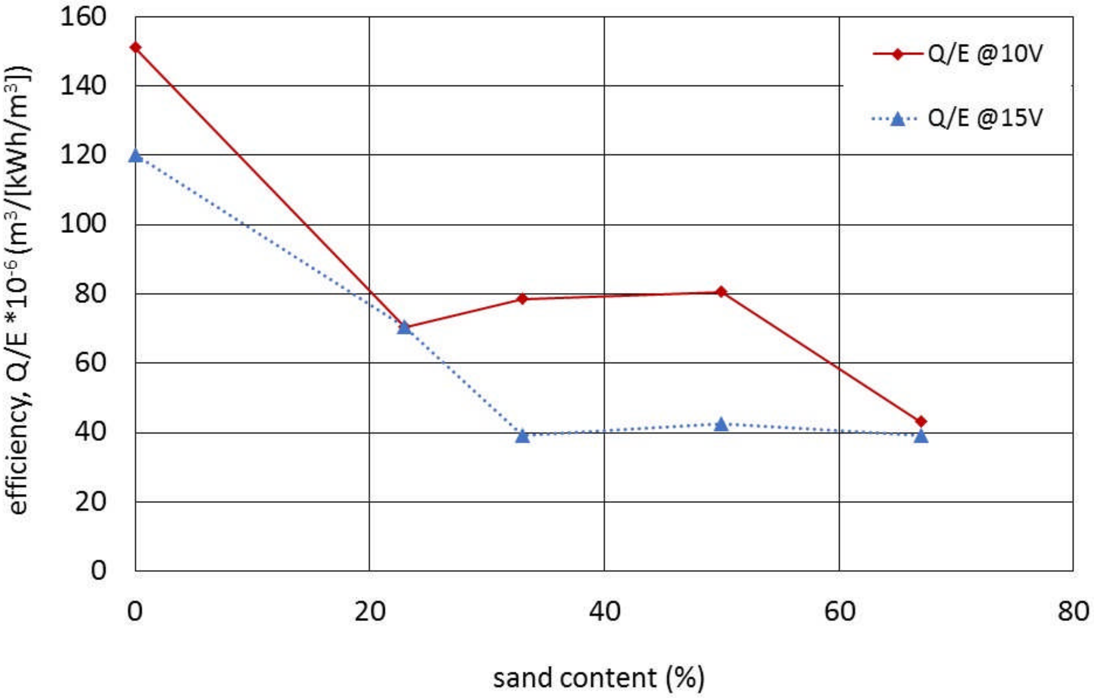


Figure 4.46 Electroosmotic flow efficiency (Q/E) vs sand content for 10 and 15V

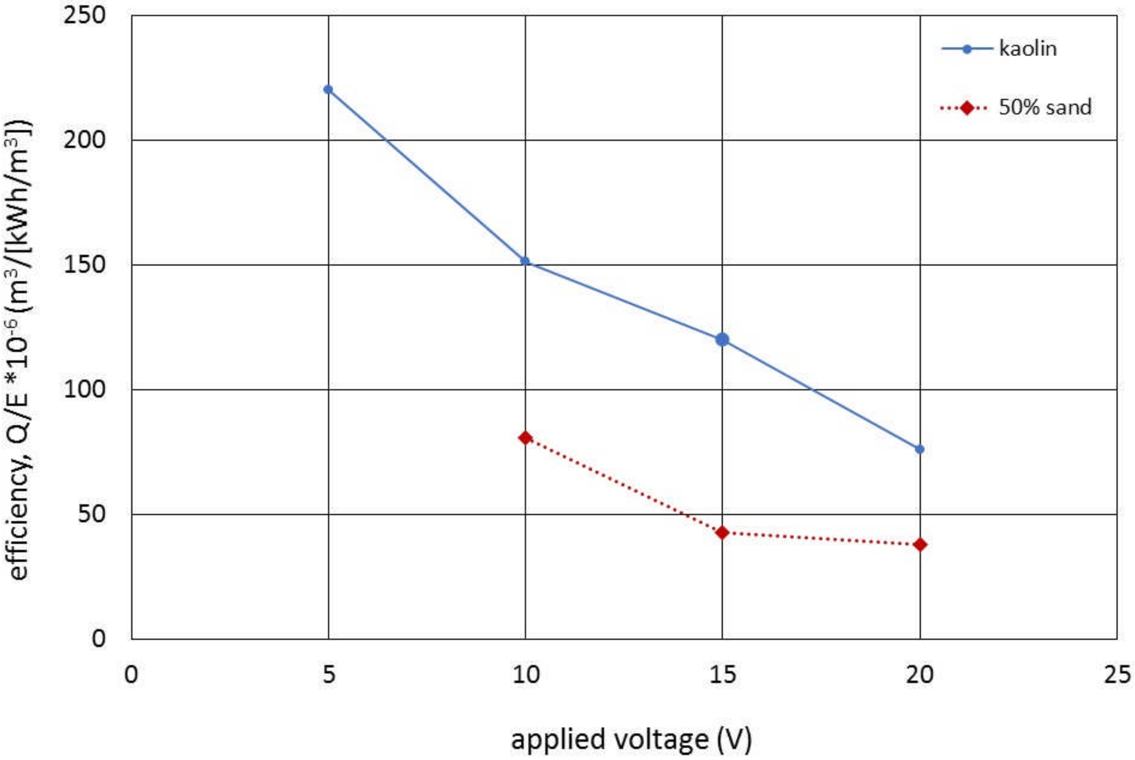


Figure 4.47 Electroosmotic flow efficiency (Q/E) vs applied voltage

4.4.1 Electroosmotic Transport Efficiency, k_i

Gray and Mitchell (1967) defined the electroosmotic transport efficiency as water flow transferred per electric unit charge passed in gal/amp-hour. The electroosmotic transport efficiency can described by equation:

$$ki = \frac{Q}{It} \tag{4.5}$$

Where: Q is the total water expelled (gal); I is the mean current passed through soil sample (Ampere); and t is the total time (hours). Hamir et al. (2001) stated that the economy and efficiency of electroosmosis treatments is governed by k_i. The results for the electroosmotic transport efficiency obtained from electroosmotic tests for all soil are summarized in Figure (4.48).

Figure (4.49) displays transport efficiency vs sand content for 10 and 15V. It can be seen that the values of electroosmotic transport efficiency is likely to decrease as the sand content decrease, (from 0.027 to 0.007 gal/Am.hr for pure kaolin and

67% sand at 10V respectively, and from 0.032 to 0.01 gal/Am.hr for pure kaolin to 67% sand respectively at 15V). However, the fluctuation in k_i value for 33% and 50% sand at 10V could be attributed to the electroosmotic test duration presented in Table (4.1).

Figure (4.50) displays the variation of electroosmotic transport efficiency k_i with the change in applied voltage. It can be seen that the values of k_i in pure kaolin increased as the applied voltage increased and peaked at 15V (0.032 gal/Am.hr), then dropped to (0.027 gal/Am.hr) at 20V. In contrast, the value of electroosmotic transport efficiency in 50% sand and kaolin mix is likely to remain steady during electroosmosis test (0.011 to 0.014 gal/Am.hr).

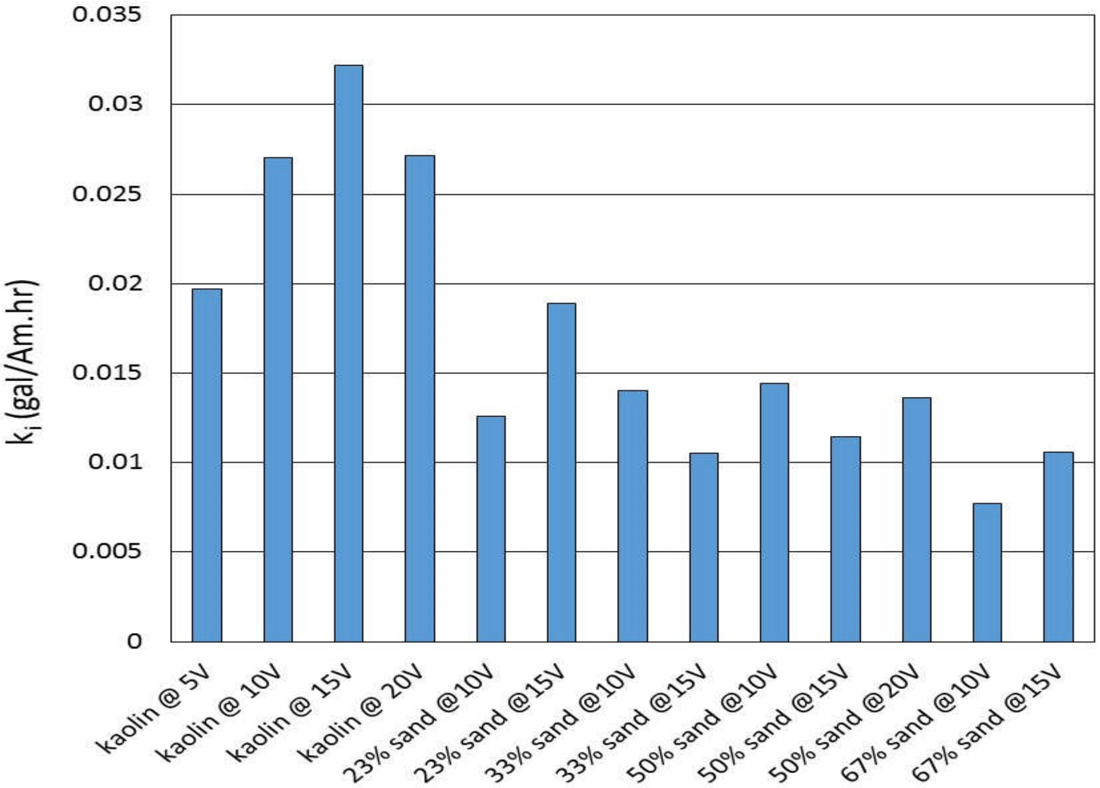


Figure 4.48 Variation of electroosmotic transport efficiency (k_i) vs sand content under different applied voltage

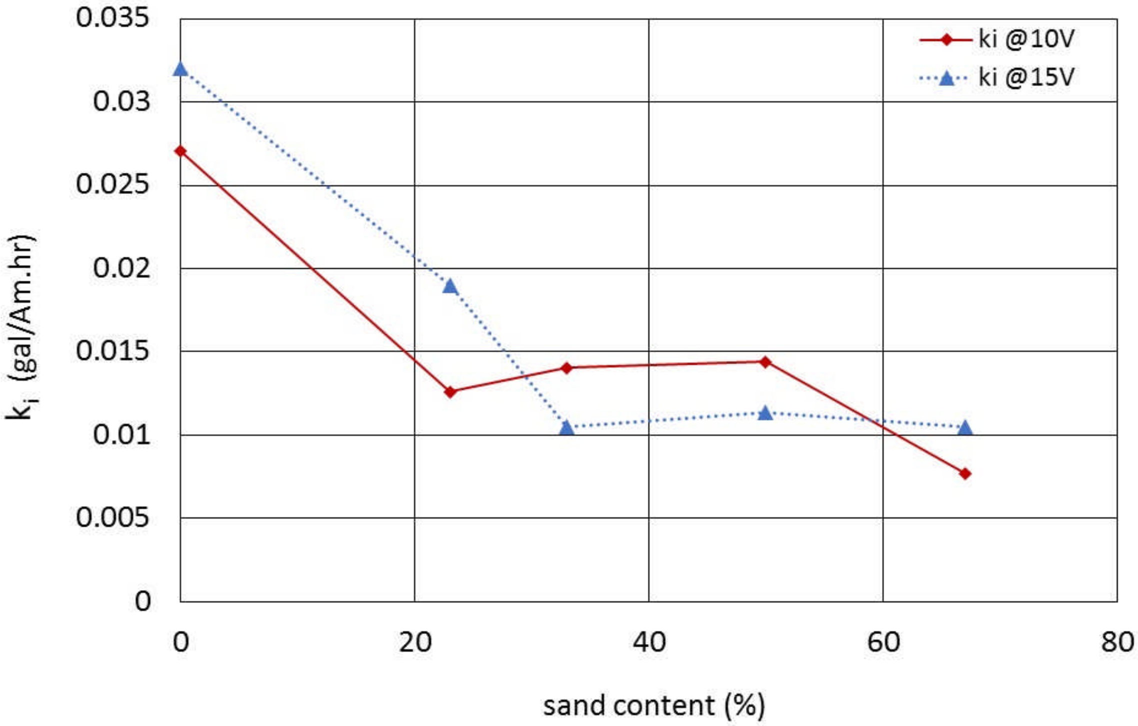


Figure 4.49 Variation of electroosmotic transport efficiency (k_i) vs sand content for 10 and 15V

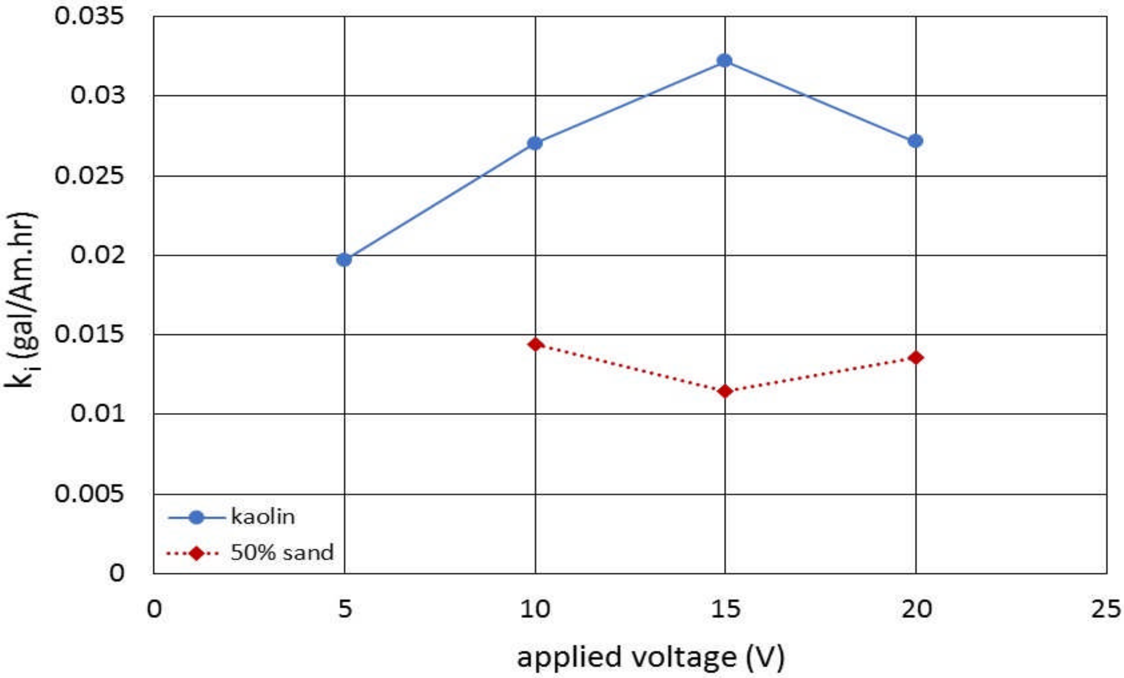


Figure 4.50 Variation of electroosmotic transport efficiency (k_i) vs applied voltage

4.5 Summary

In this chapter, experimental results were outlined and the feasibility of electroosmotic flow through composite soil (kaolin and sand mixes) subjected to various voltages was assessed. From the analysis of the laboratory test data, the following conclusions can be drawn:

- There is a significant increase in settlement as the applied voltage increased for the same soil mix, which means the amount of settlement is a function of the voltage density and the efficiency of treatment increases when the applied voltage is increased.
- As the sand content increased in the soil mix, there is an apparent decrease in the amount of expelled water, which means that the efficiency of electroosmotic treatment decreased as the amount of sand increased.
- The current decreases sharply at the beginning of the test followed by a gradual reduction, maximum current occurs with the maximum applied voltage. The trend of current in each soil mix reduced with time in a similar manner to the rate of settlement under different applied voltages.
- At the same applied voltage, the consumed power decreased as the sand content increased.
- The loss in the mass of the anodes during electroosmotic treatments due to corrosion in kaolinite soil was about (24%) at 10V to about (42%) at 20V, which means the losses increase as the applied voltage increase. Also, the losses in the anodes decrease as the percent of sand increased under the same applied voltage
- The electroosmotic permeability (k_e) reported for soil mixes varied between 0.05×10^{-9} m^2/sV for 67% sand content to 1.4×10^{-9} m^2/sV for pure kaolin subjected to 10V. This finding indicates that the sand content will highly effect the electroosmotic permeability.
- Soil temperature increased when an electrical power was applied and this drops when an applied D.C power turned off. The highest increase in temperature was found in pure kaolin at 20V, from 19C^o to 24 C^o after about 8 hours of the electroosmosis test. It can be concluded from these results that the heat developed due to applying DC power is a function of voltage and soil type.

Chapter 5

Experimental Test Results for Bentonite and Sand Soils

5.1 Introduction

In this chapter, the detailed testing procedures of the electroosmotic piles in a range of composite soils are described. The electroosmotic testing procedure was modified from Nizar and Clarke (2014). The composite soils presented in this chapter consist of calcium bentonite (CB) mixed with different ratios of fraction C sand (0, 23, 33, 50 and 67%) subjected to either 10 or 15V. The results and analyses of electroosmotic pile tests are presented. The electroosmotic pile tests were carried out to assess the feasibility of the electroosmosis treatment on the composite soils in terms of the vertical settlement, expelled water, electrical current and power consumption changes with time during electroosmosis treatment, treatment time and final water content. Heat development in the soil samples during electroosmosis consolidation is also described in this chapter. Table 5.1 summarise the electroosmosis tests carried out for bentonite and sand soil mix.

Table 5.1 Summary of electroosmotic test in bentonite and sand soil mixtures

Test no.	Soil	Applied voltage	Phase 1 (hours)	Phase 2 (hours)	Phase 3 (hours)	Total treatment time (hrs)
1	bentonite	5	360	192	24	576
2	bentonite	10	360	168	144	672
3	bentonite	15	360	96	96	552
4	23% sand	10	360	168	48	576
5	23% sand	15	360	96	96	552
6	33% sand	10	360	168	168	696
7	33% sand	15	360	168	72	600
8	50% sand	10	360	168	168	696
9	50% sand	15	360	168	96	624
10	67% sand	10	360	264	96	720
11	67% sand	15	360	264	72	692

5.2 Control test

The control tests for bentonite and bentonite with sand slurry were carried out using the same consolidation cell, mentioned in section 4.2.2, loaded with 15 kPa in the first phase and 50 kPa in the third phase to provide information on the behaviour of the soil slurry only subject to an increase in the vertical pressure. Note that there was no Phase 2 in the control tests. Phase 1 was run for almost 360 hours until there no appreciable settlement occurred, (equivalent to a rate of settlement less than 0.01mm/day for all soil mixtures) to reach the secondary compression phase, the same as electroosmotic tests. Phase 3 was run for 168 hours for 50% and 67% sand content and for 240 hours in the other control tests. Figure (5.1) shows the liquid limit, initial water content, water content at the end of Phase1 and at the end of Phase 3. Figures (5.2) and (5.3) show the settlement in Phase 1 and Phase 3 respectively. The results obtained from the combined settlement in the two phases are set out in Figure (5.4) to compare the settlement with time of all the bentonite mixes due to the 15kPa and 50kPa applied pressure in Phases 1 and 3.

The results in Figure (5.1) shows that the final water content of all the bentonite mixes after Phase 3 when 50 kPa vertical pressure was applied was close to the liquid limit value. From the above figures, it can be seen that, the settlement for pure bentonite exceeded that of the composite soils and the amount of settlement reduced as the sand content increased.

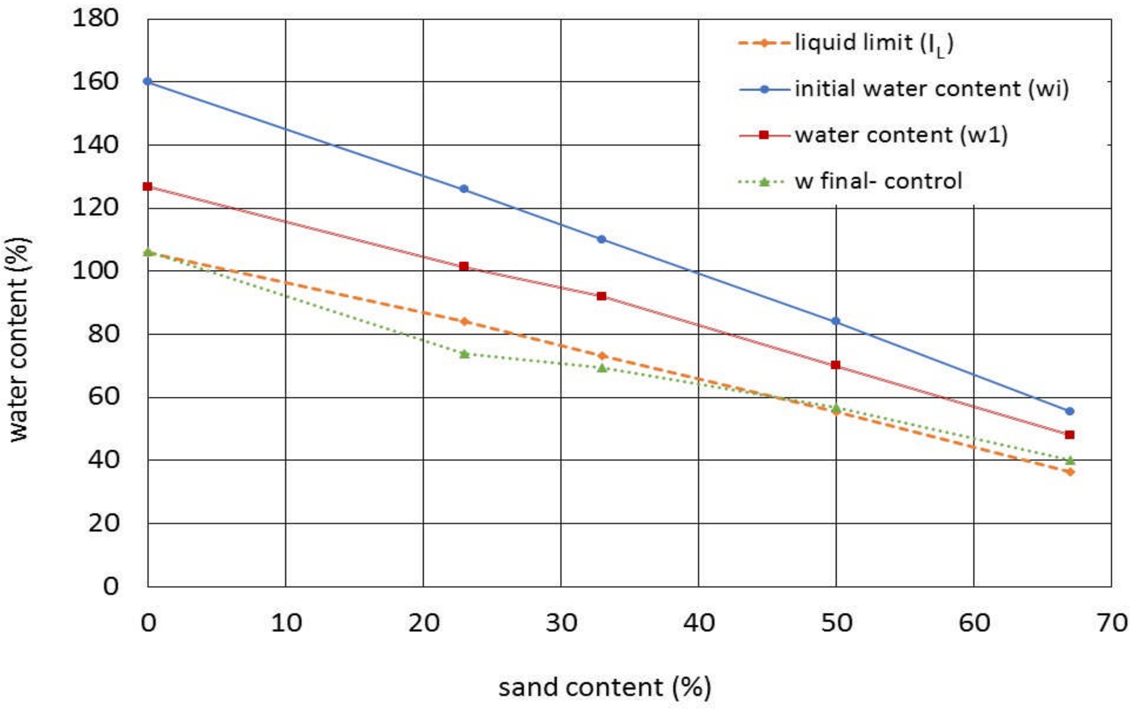


Figure 5.1 Variation of liquid limit, initial water content and final water content verses sand content in control test

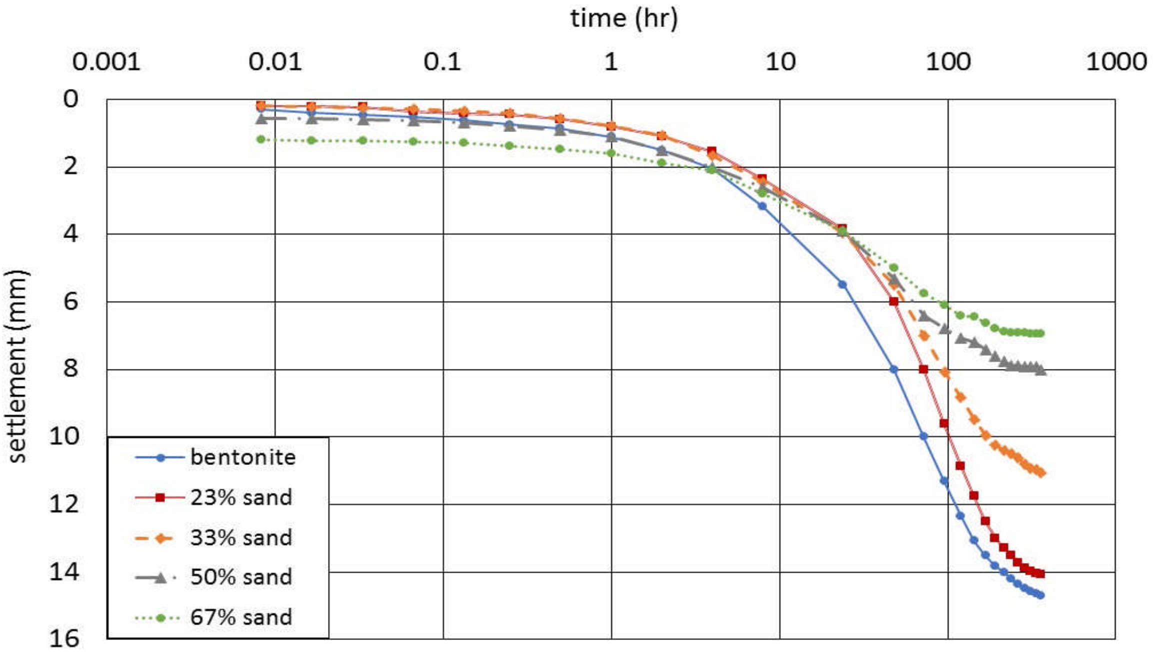


Figure 5.2 The settlement during Phase 1 (15kPa) seating load in the control test

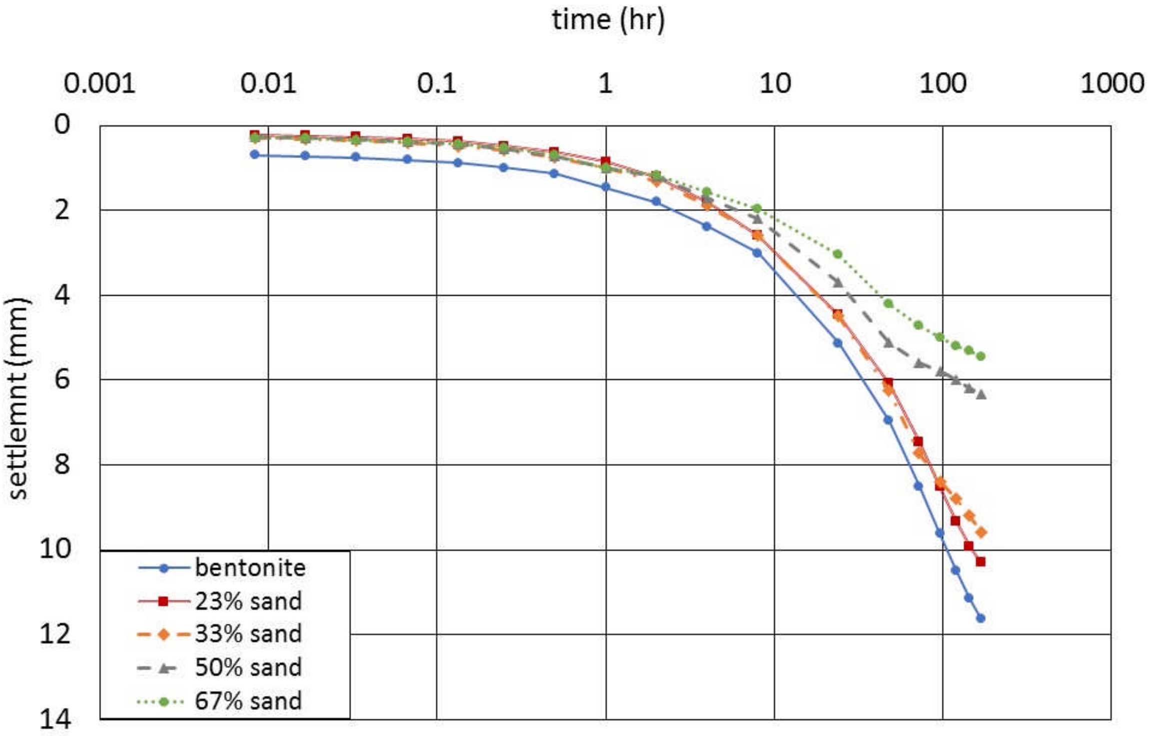


Figure 5.3 The settlement during Phase 3 (50 kPa) applied loading in the control test (note tests were terminated when the rate of settlement was less than 0.01mm/day

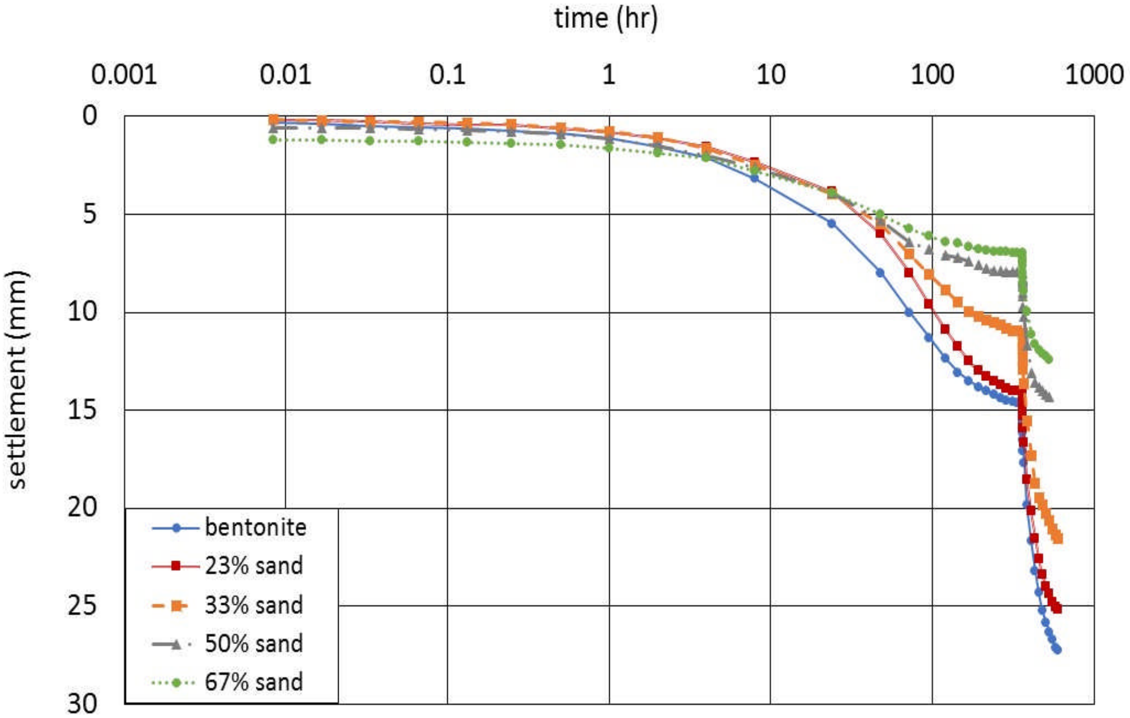


Figure 5.4 The settlement during Phase 1 and 3 for the control tests: (1) 15kPa seating load; and (3) 50kPa applied load

5.3 Results of electroosmotic pile tests

In this chapter, electroosmotic pile tests were conducted to evaluate the effects of electroosmosis on the stiffness of range of composite soils consist of calcium bentonite (CB) mixed with different ratios of fraction C sand (0, 23, 33, 50 and 67%) subjected to 5, 10 and 15V. A pressure of 15 kPa was applied in Phase 1 for 360 hours to create a normally consolidated specimen from the soil slurry and it was maintained during Phase 2 when the voltage was applied. Phase 2 was stopped when there was no further water expelled from the cell indicating the electroosmotic process had stopped due to the degradation of the anode and no current passing through the cell. 50 kPa was applied in Phase 3 to simulate a surcharge load to assess the performance of the system. The series of electroosmotic tests details, time of treatment, and the applied voltage are summarised in Table 5.1. The results of all the tests in this chapter are presented according to the test series, namely; percentage of sand and applied voltage.

5.3.1 Settlement, expelled water and void ratio

This section presents brief details of the tests carried out using bentonite soil mixed with sand at various percent and subjected to a different applied voltages. The effects of these variables were presented in terms of settlement versus time curves, expelled water verse time, and volumetric strain versus time curves for the three phases of the tests.

5.3.1.1 Effect of sand contents

The aims of the tests were to determine the effect of sand content on the stiffness of the soil and the energy used in the osmotic process; and establish the maximum sand content for the osmotic process to function.

Results from the Figure (5.5) plotted for Phase 1 was used to create a uniform sample, it is clear that the sand content affected the settlement of the samples. Increasing the sand content reduced the settlement in Phase 1. This is consistent since coarse grained soils would be expected to be stiffer. However, these samples were consolidated from a slurry which means they were at a higher water content than would occur naturally. As mentioned before, the soil slurries were prepared at different water contents; Figure (5.6) shows the variation of expelled water with time during Phase 1. As can be seen that less water was expelled as the sand content increased. Therefore, the flow of water will be a function of the permeability of the clay matrix. As the sand content increases, the sand particles start to influence the mass permeability of the sample. Figure (5.7) shows the change in voids volume in Phase1 divided by the initial voids volume (e/e_0). It is obvious that the rate of consolidation increases as the sand content increases, but only if the sand content exceeds 23%. It is possible that the sand particles are randomly distributed through the sample and not in contact if the sand content is less than 23% (Al-Moadhen et al., 2017).

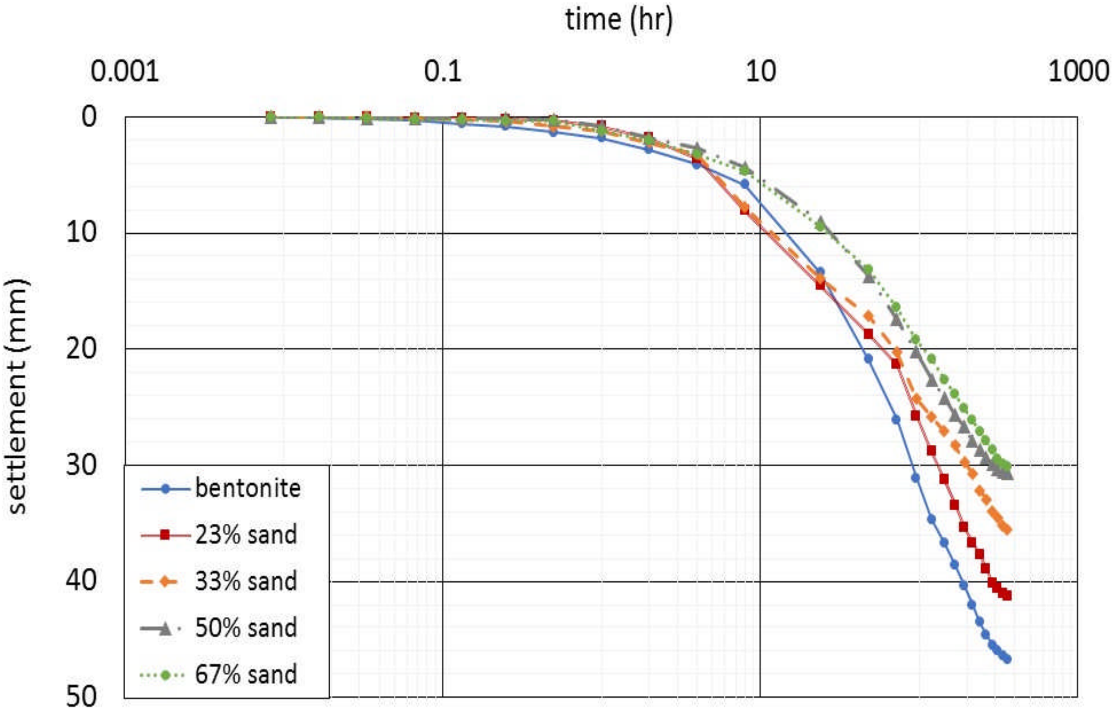


Figure 5.5 Settlement in Phase 1 (15kPa load applied to the soil as a working platform)

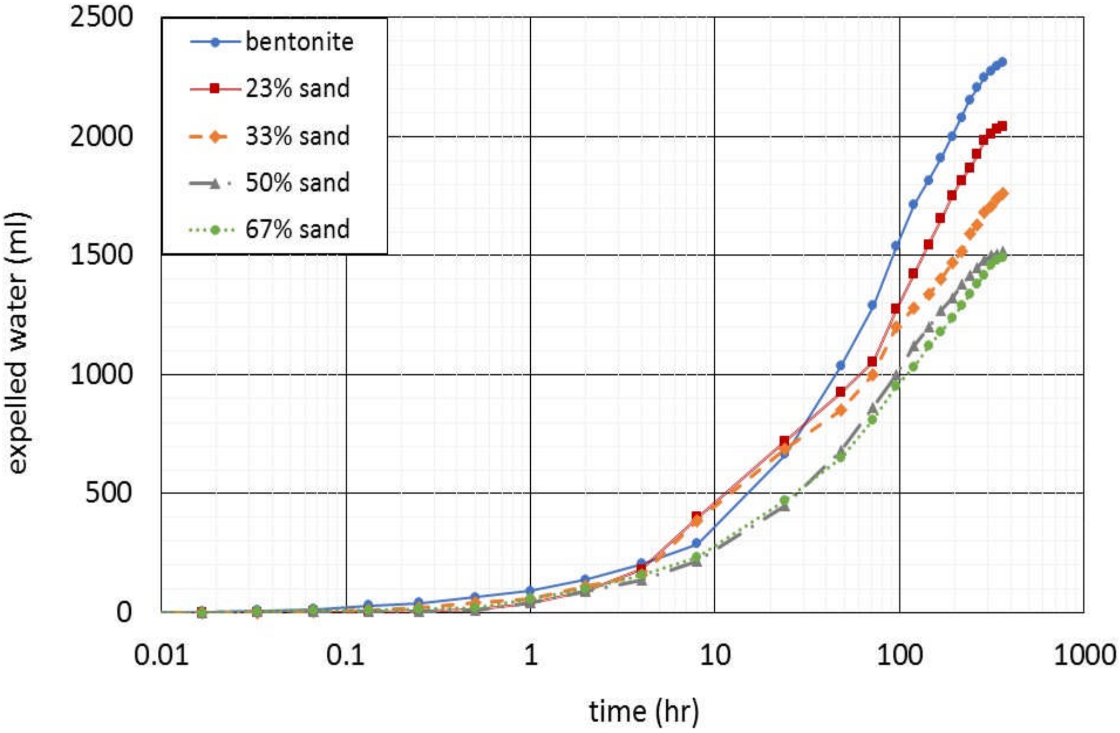


Figure 5.6 Expelled water in Phase 1 (15kPa load applied to the soil as a working platform)

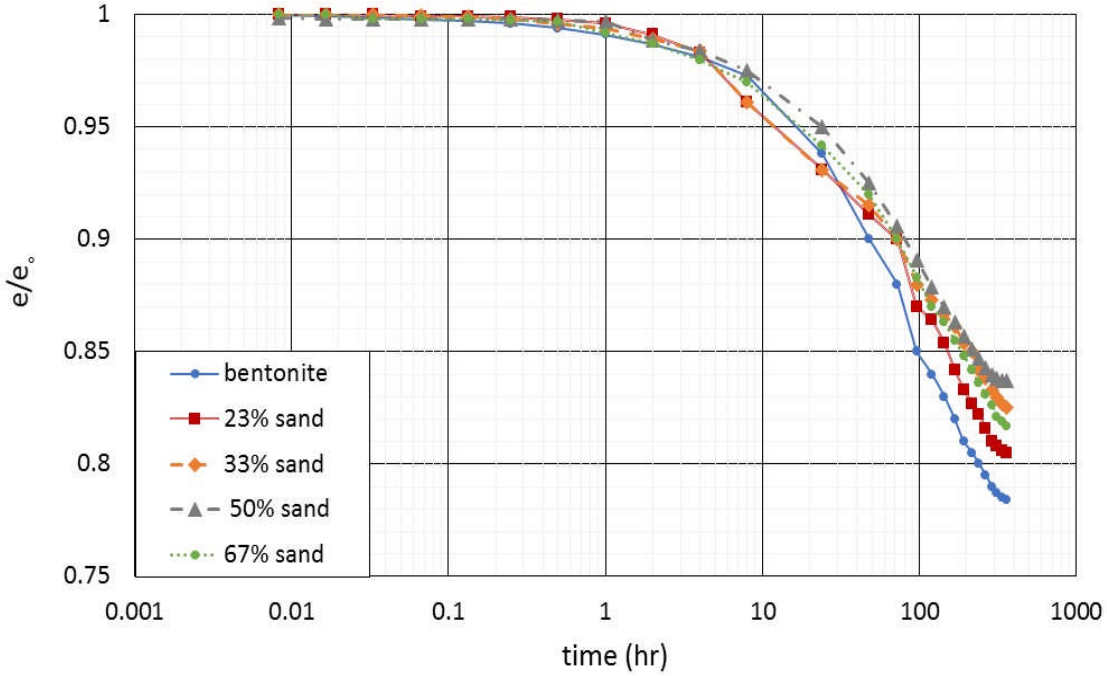


Figure 5.7 Changes in the volume of voids Phase 1/ original volume of voids (15kPa load applied to the soil as a surcharge load)

Figures (5.8) and (5.9) show the expelled water for 10V and 15V during the electroosmotic phase respectively. From these figures, given that the permeability of a soil increases as the sand content increases, the impact of applying an electric potential difference to a soil slurry decreases the rate of expelled water volume as the sand content increases for both applied voltages.

The results shown in the above figures reflect that the sand content in the electroosmotic process can significantly affect the treatment time until the anode degrades completely; assumed to be the point at which there is no current passing through the cell. The consolidation time of electroosmotic treatment ranged from 168hr for pure bentonite to 264 hours for 67% sand at 10V, while it took 96 to 240 hours for pure bentonite and 67% sand respectively at 15V, which means that sand added to the bentonite clay cause decelerate of the consolidation time during the electroosmotic treatment. This behaviour could be related to that the sand added to bentonite leads to decrease in electrical conductivity of the mixture which results in slow down the electroosmosis process.

The consolidation settlement during the electroosmotic treatment in Phase 2 was measured by a dial gauge installed at the top of the cell, as seen in Figure (3.1). Figures (5.10) and (5.11) show the variation in settlement during the electroosmotic phase at 10 and 15V respectively. It can be noticed that the sample swelled when the voltage was applied, and the swelling decreases as the sand content increases. The swelling also increased with the increase in the applied voltage. The effect of the applied voltage on swelling will discussed in the next section.

The swelling that occurred during Phase 2 was likely to be related to gas pressure generated due to the applied electrical current Wu et al. (2015a). More swelling occurred at the beginning of the electroosmotic phase until about 8 hours. Bentonite is characterised as a clay soil with a high montmorillonite content (about 70% of montmorillonite). The interaction between the electric charge of montmorillonite lamellae and the ions is the cause for the swelling and osmotic phenomena. (Dominijanni and Manassero, 2012a) and (Dominijanni and Manassero, 2012b). Most of the soils was subject to gas generation at the electrodes due to the effect of electroosmosis. Wu et al. (2015a) reported that as a result of water movement from the anode, volume shrinkage appeared at the bottom of the soil accompanied by an increasing gas pressure at the soil–anode interface due to water electrolysis and the impervious bottom boundary. Wu et al. (2015b) and (Mosavat et al., 2013b) observed that the behaviour of expansive soil like bentonite during electroosmotic treatment is quite different from other clay soils. Compared to kaolin, the buffering capacity of bentonite is greater; thus the increase in H^+ concentration near the anode and the migration of H^+ ions was less. Wu et al. (2015b) explained that during electroosmotic treatment, electrolysis of water at the anode produces H^+ and O_2 due to oxidation of the metal, and for the same electric current, more H^+ and O_2 gas are generated at the anode for the inert electrodes (graphite and stainless steel) than that for reactive electrodes (copper and iron). The gas generation during electroosmotic treatment should be restrained to improve the effect of electroosmosis on high swelling clay like bentonite, by methods such as a chemical injection or a combination with surcharge preloading. During experimental work of Acar et al. (1990b), gas vents near the electrode were provided to allow the gaseous products to flow out of the electroosmotic cell. As a result, the generated gas pressure and cracking of soil near the anode was more significant in bentonite than for kaolin soil. However, Gingine et al. (2013) stated, for expansive soil, there is a distinct improvement in the swelling properties after electrokinetic treatment.

Jayasekera (2007) concluded that under certain applied voltage and treatment time, a soil may change from an extremely reactive status to a slightly or almost non-reactive condition and optimal voltage gradients and duration depend on clay mineralogy and clay content. Lee et al. (2001) suggested that the swelling pressure of a compacted bentonite increased as the quantity of bentonite and dry density increased, and decreased with an increase in initial water content. Tay et al. (2001) stated that the volumetric shrinkage of the bentonite and sand mixture increased as the bentonite contents increased at any water content. There are an accords between the observations expressed in this study and those described by the above authors, which showed that as the swelling pressure increased with the increases in clay percentage and water content. The observations shown in Figures (5.10) and (5.11) are in agreement with those described by the above authors, which showed that the swelling increased with the increase in clay percentage and water content.

Figures (5.12) and (5.13) show the change of voids ratio in Phase 2 over the void ratio at the end of Phase 1 during the constant voltage applied at 10V and 15V respectively, in addition to the 15 kPa load. As shown in these figures in general, the results of voids ratio after electroosmotic treatment show a decrease in the voids ratio of treated samples, and this decrease in the void ratio is proportional to the decrease in sand content. This decrease indicates that the electroosmotic process is increasing the soil stiffness. In Figure (5.12), it is clear that the volume of voids at the end of Phase 2 was 79% of the volume at the end of Phase 1; whereas, when sand was added the volume of voids at the end of Phase 2 was about 90% of the volume at the end of Phase 1. For 15V, the volume of voids at the end of Phase 2 was between 90% and 92% of the volume at the end of Phase 1. In addition, it is noted that the increase in applied voltage was still beneficial in the reduction of the voids ratio. This can be related to the increase in the hydraulic conductivity of bentonite soil mixtures due to the heat generation accompanying with electroosmosis phenomena which is proportional with the applied voltage as mentioned by Lee et al. (2001)

The performance of the system is assessed by applying a uniformly distributed pressure of 50 kPa. The results are presented in terms of the expelled water versus time, instead of settlement, since the settlement reading was affected by swelling developed in Phase2. The dial gage reading for settlement was different from that calculated based on the expelled water due to the effect of swelling from Phase 2 see Figure (5.14) for 10V and Figure (5.15) for 15V after the soil had been treated. The difference in directly measured settlement and that predicted from the volume of expelled water may be due to redistribution of water within the sample because of the change in effective stress from a non-uniform distribution because of osmosis to a uniform distribution because of the external pressure. As can be seen from these figures, 15V produced more expelled water compared to that for 10V. In Figure (5.15) the expelled water decreased as the sand content increases due to the effect of 15V from Phase 2, while in Figure (5.14) for 10V, it is apparent that there was more expelled water at 33% and 50% sand than 23% sand which means that composite soil behaviour for sand content 23% under electroosmosis treatment behaves as a clay soil. Note that the differences in initial water content and consequently the water content at the end of Phase 1 was different for each soil slurry mixes which effects the electroosmosis process by increasing the electrical conductivity.

Figures (5.16) and (5.17) show that the change of voids ratio in Phase 3 over the void ratio at the end of Phase 2, when a 50 kPa pressure was applied to the soil as a surcharge load after 10 and 15V electroosmotic treatment, respectively. As shown in these figures, the results of the voids ratio after 50 kPa show a decrease in void ratio of treated samples, and the values decrease as the sand content increases.

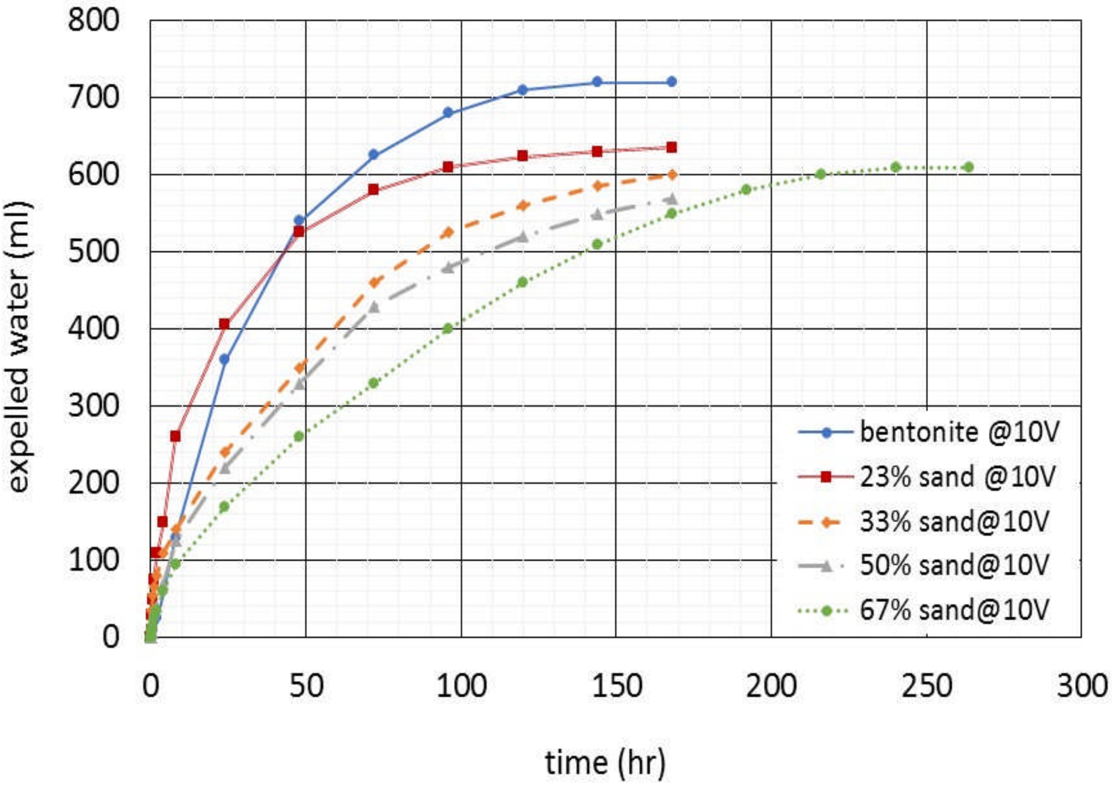


Figure 5.8 Expelled water versus time curves in Phase 2 at 10V

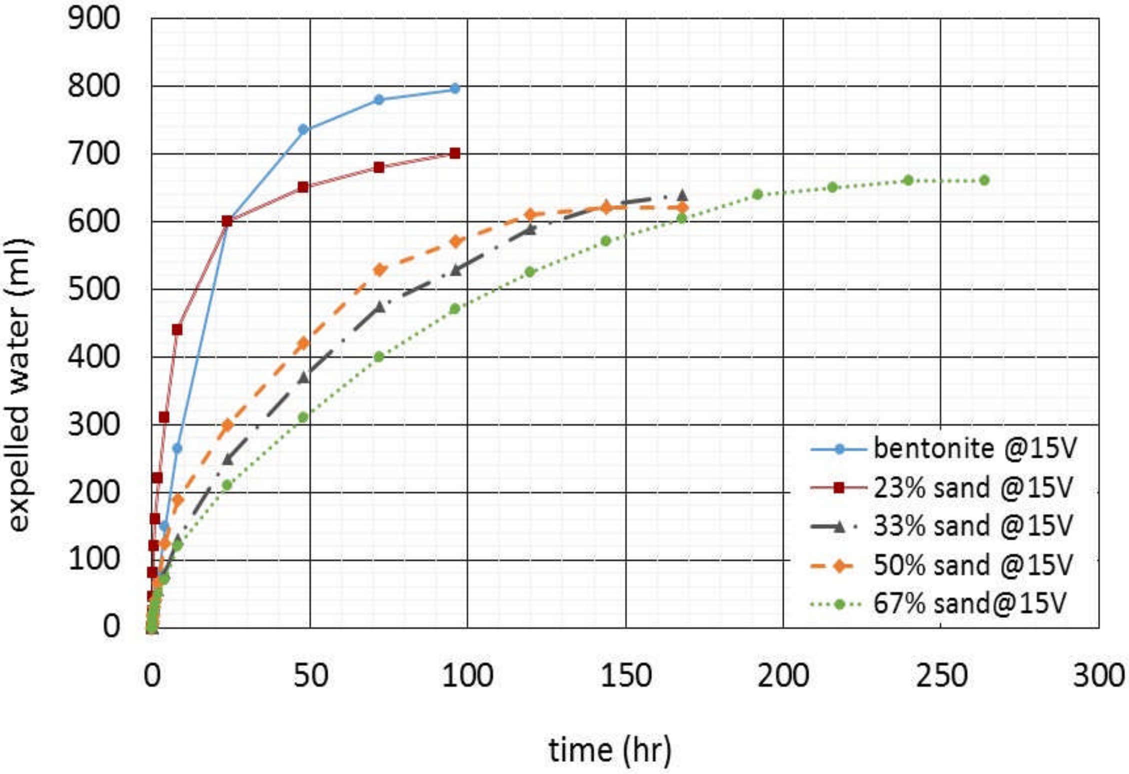


Figure 5.9 Expelled water versus time curves in Phase 2 at 15V

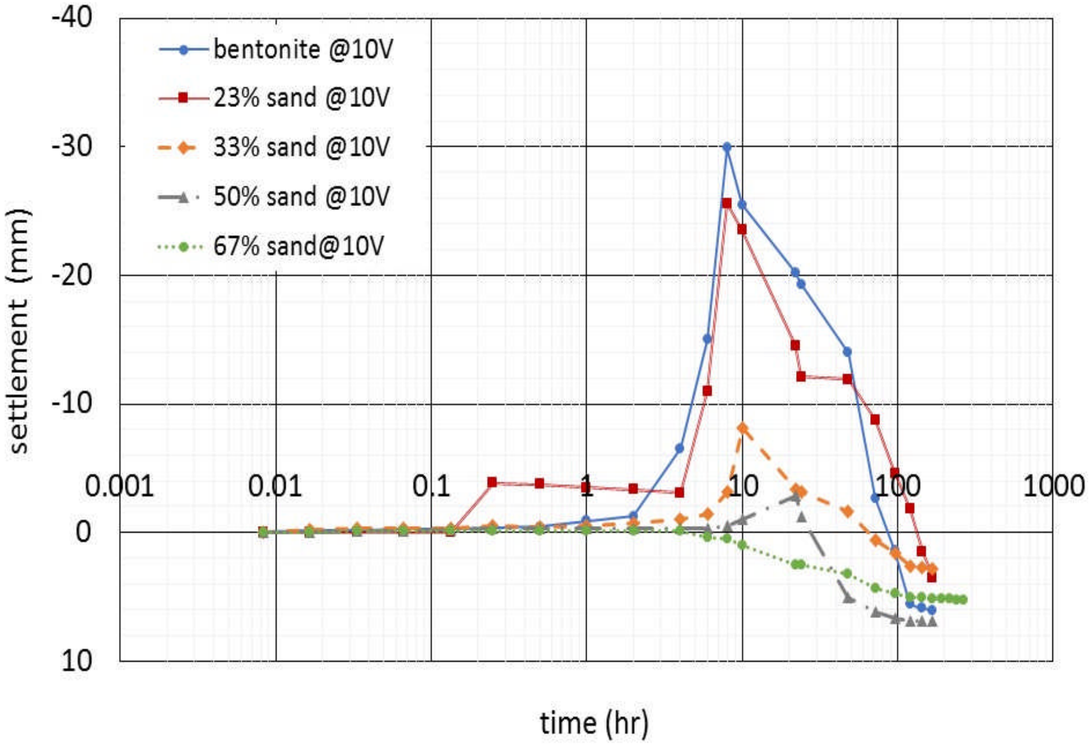


Figure 5.10 Settlement in phase 2 (constant voltage of 10V applied in addition to the 15kPa load, swelling and compression)

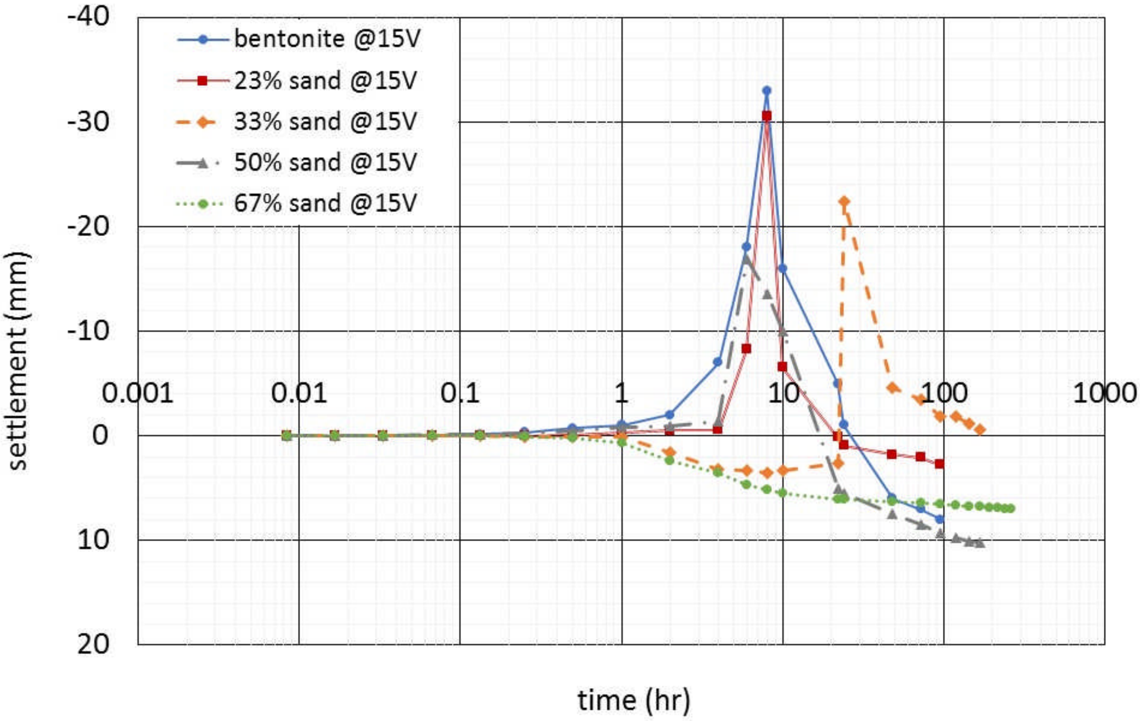


Figure 5.11 Settlement in phase 2 (constant voltage of 15V applied in addition to the 15kPa load, swelling and compression)

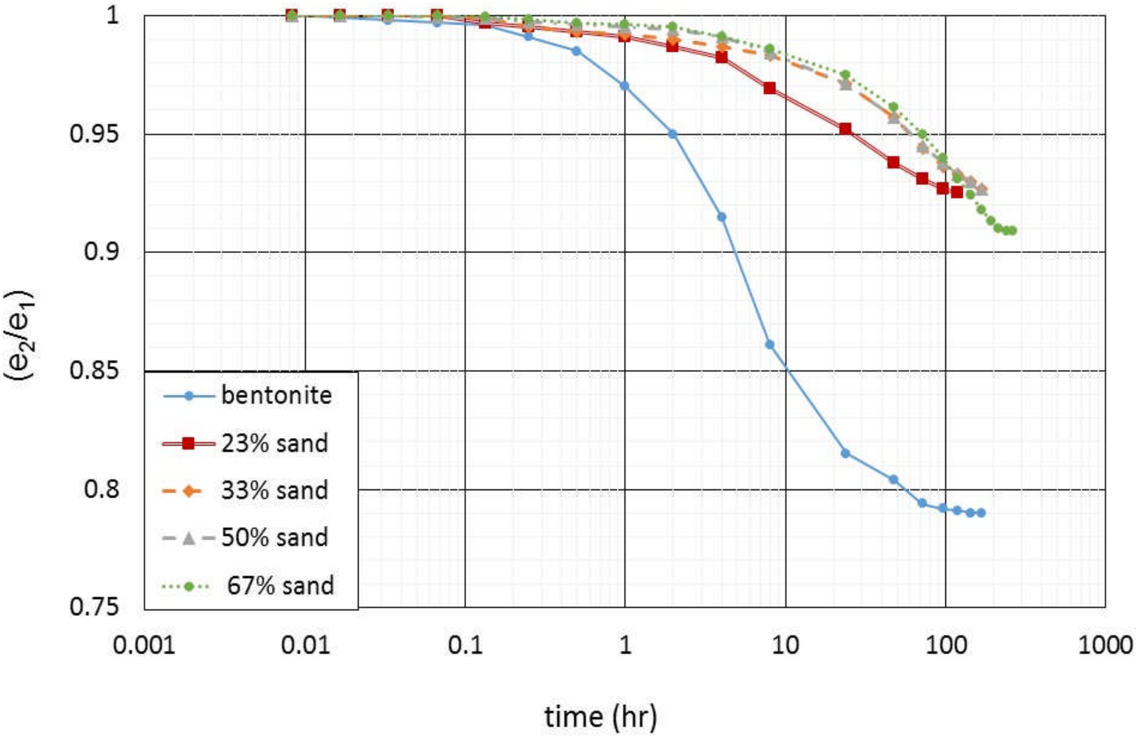


Figure 5.12 Change of voids volume in Phase 2/ void volume at the end of Phase 1 (constant applied voltage 10V in addition to the 15 kPa load)

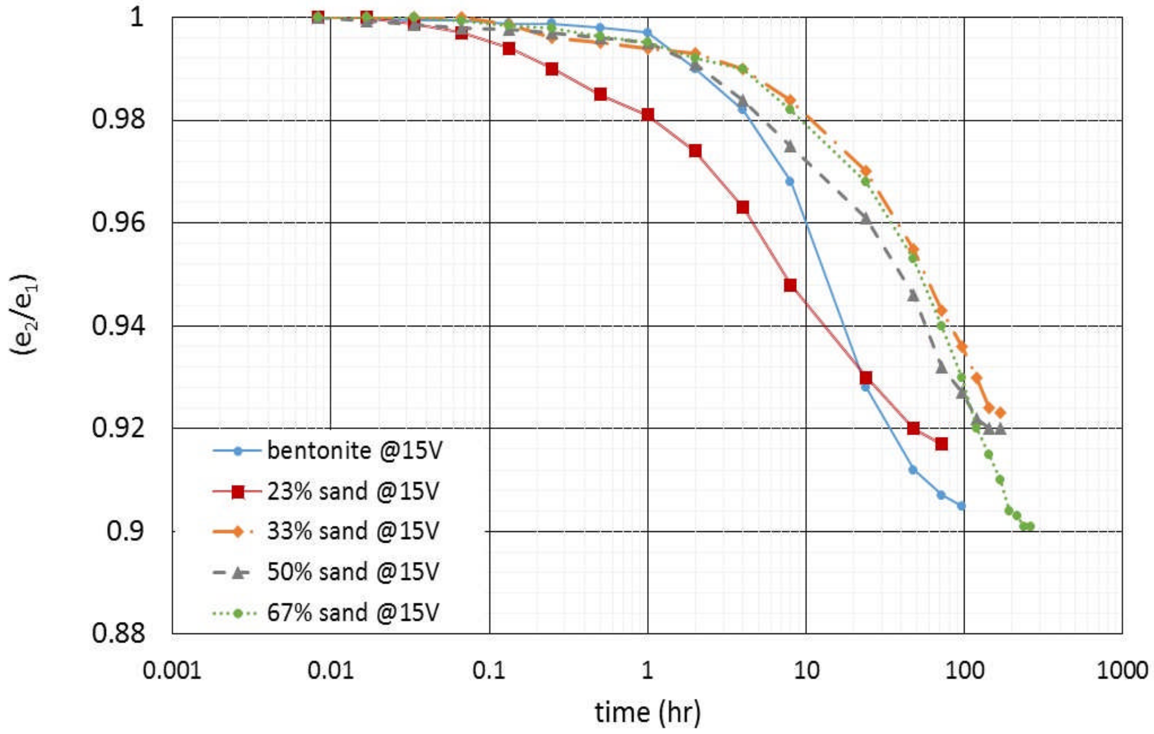


Figure 5.13 Change of voids volume in Phase 2/ void volume at the end of Phase 1 (constant applied voltage 15V in addition to the 15 kPa load)

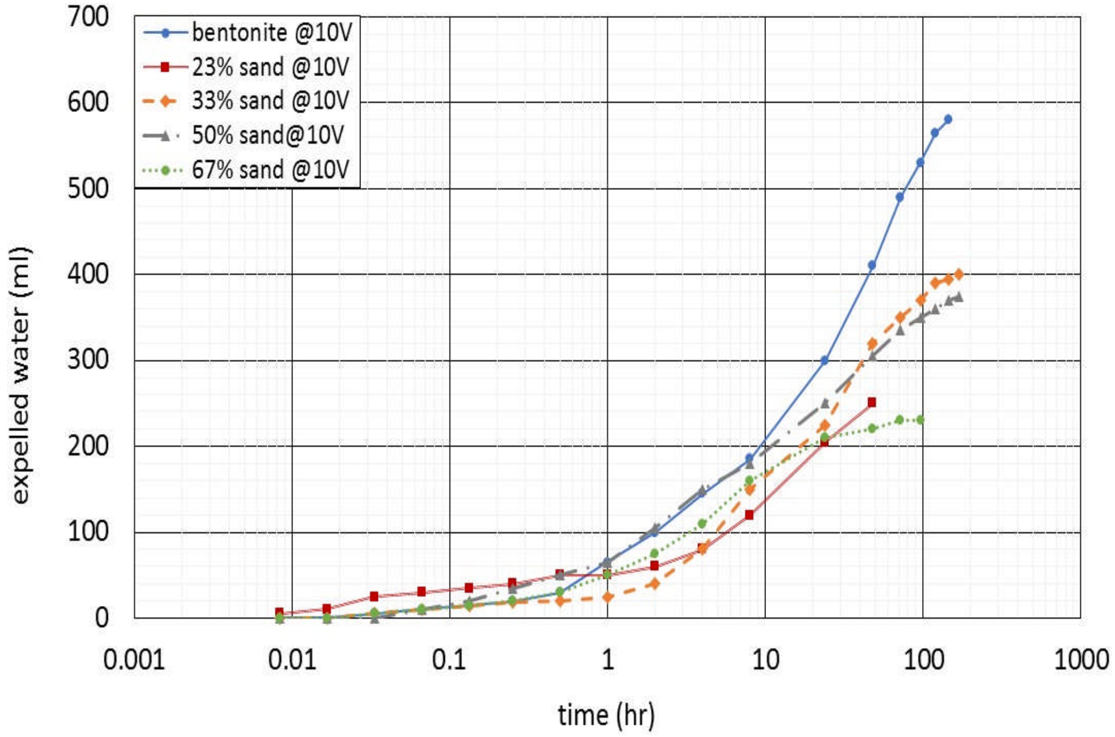


Figure 5.14 Expelled water versus time curves in Phase 3 at 10V

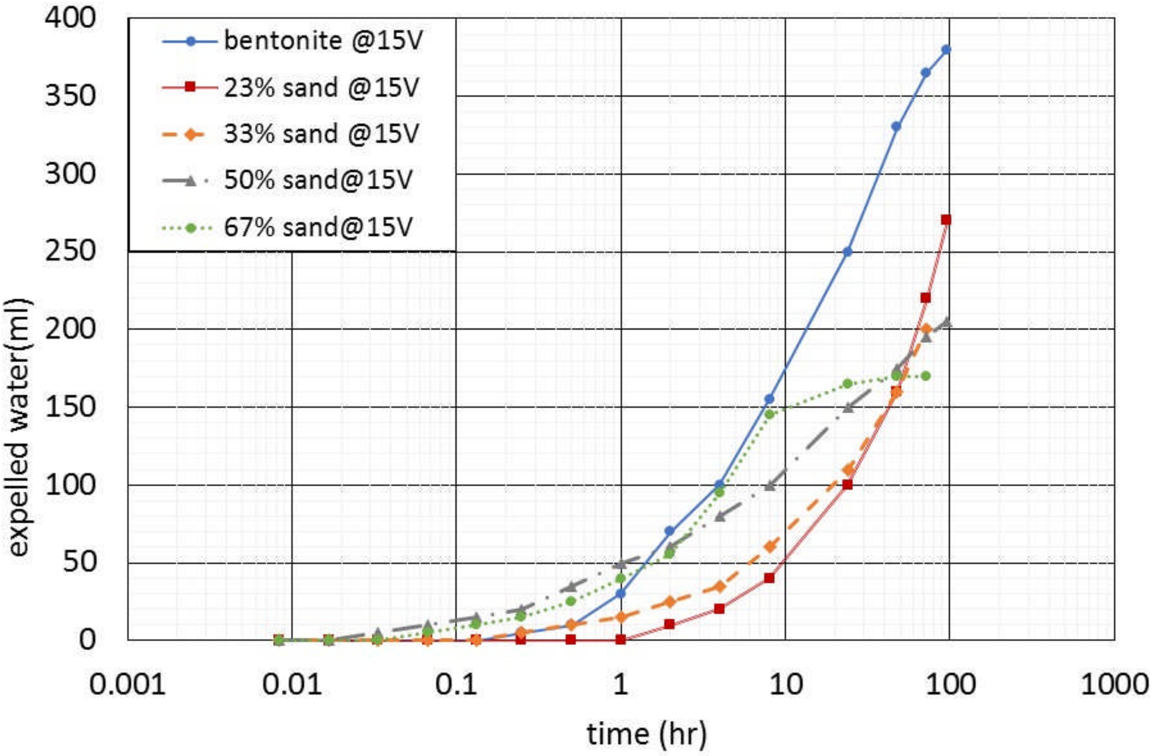


Figure 5.15 Expelled water versus time curves in Phase 3 at 15V

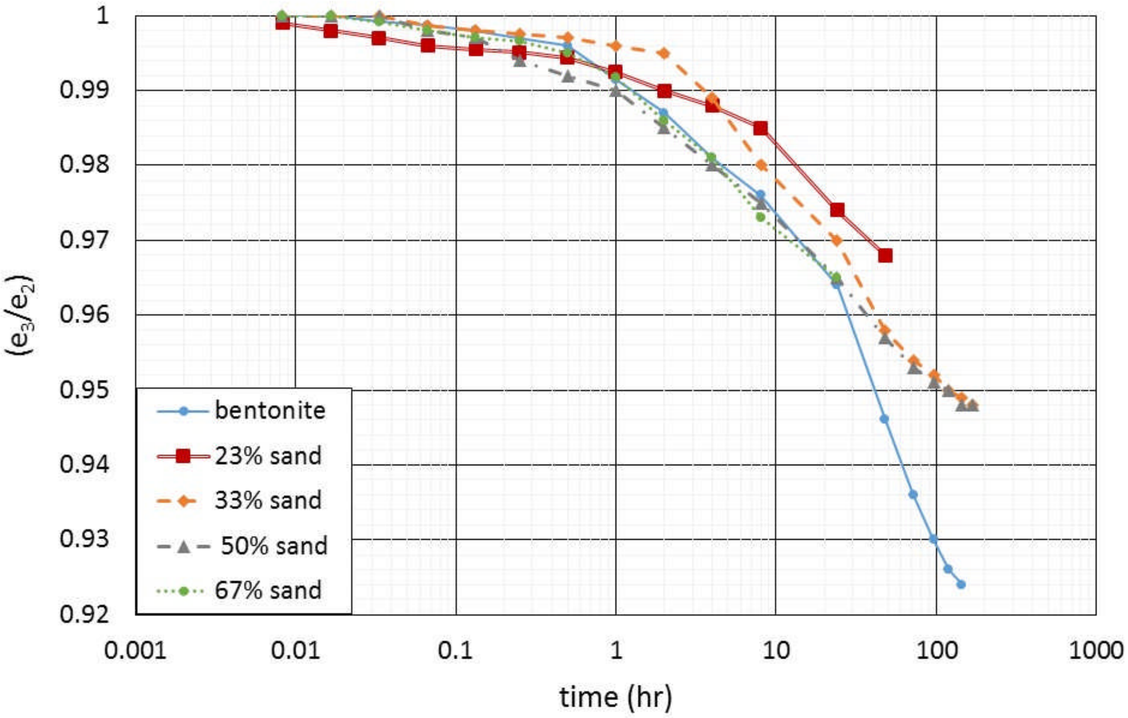


Figure 5.16 Change of voids volume in Phase 3/ void volume in Phase 2 (50kPa pressure was applied to the soil as a surcharge after 10V electroosmotic treatment)

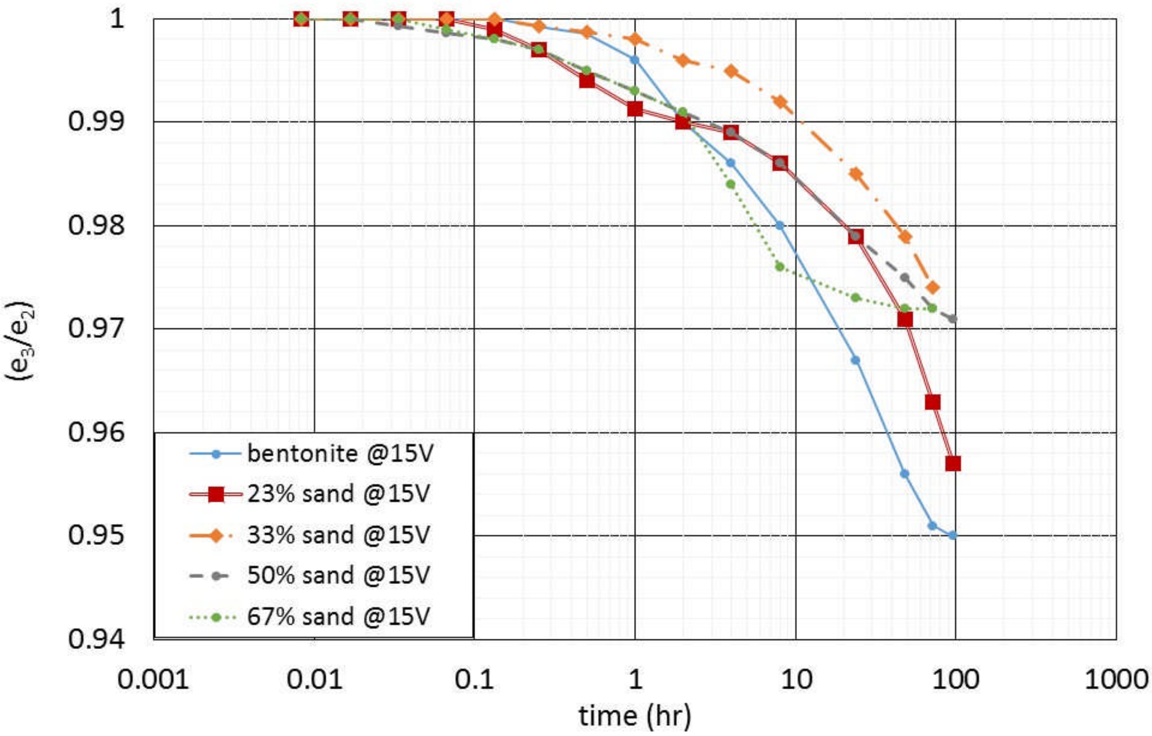


Figure 5.17 Change of voids volume in Phase 3/ void volume in Phase 2 (50kPa pressure was applied to the soil as a surcharge after 15V electroosmotic treatment)

5.3.1.2 Effect of applied voltage

Figures (5.18) to (5.19) show the expelled water and settlement versus time curves in Phase 2 obtained from the electroosmotic test for bentonite soils subjected to different applied voltages (5, 10, and 15V). These tests were used to evaluate the effect of applied voltage on the electroosmotic treatment with different types of clay.

It can be seen from the results in Figure (5.18a) Increasing the voltage increased the amount of water expelled and the rate at which the water was expelled. Figure (5.18b) shows the expected settlement calculated from the expelled water in Phase 2, the higher applied voltage, the greater settlement, about 10, 14.5, and 16mm for 5, 10, and 15V respectively. The results in Figure (5.19) show that the sample swelled for 24hrs after applying the voltage. The amount the swelling increased with the increase in voltage (5V - 27.35 mm after 24hrs; 10V - 29.9mm after 8hrs; and 15V - 33.05 mm after approximately 8 hours). After the initial swelling, the sample consolidated so that the cumulative effect was consolidation. This result agrees with the findings of Xue et al. (2017), who concluded that the cumulative expelled water increases with the increase of applied voltage, and the higher voltage was still found beneficial in the increase of shear strength and the reduction of the soil water content.

From the above figures, it is clear that there is a trend of increased swelling as the applied voltage increased. In addition, the time required to reach the maximum swelling for decreased as the applied voltage increased. Jayasekera (2004b), mentioned that at higher applied voltages, the electroosmotic flow continued for less time than at lower voltages, and the resulting total flow is higher at higher applied voltages.

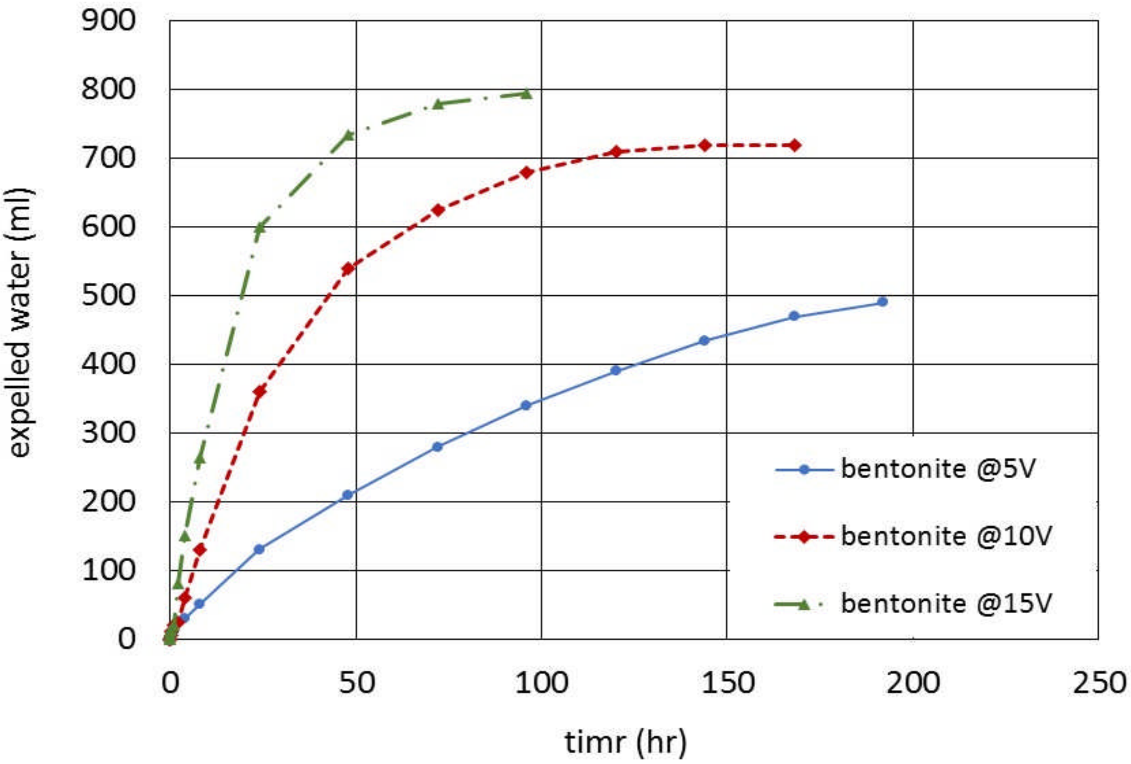


Figure 5.18a Variation in the expelled water verses time during Phase 2 in bentonite at different applied voltages in addition to the 15kPa load

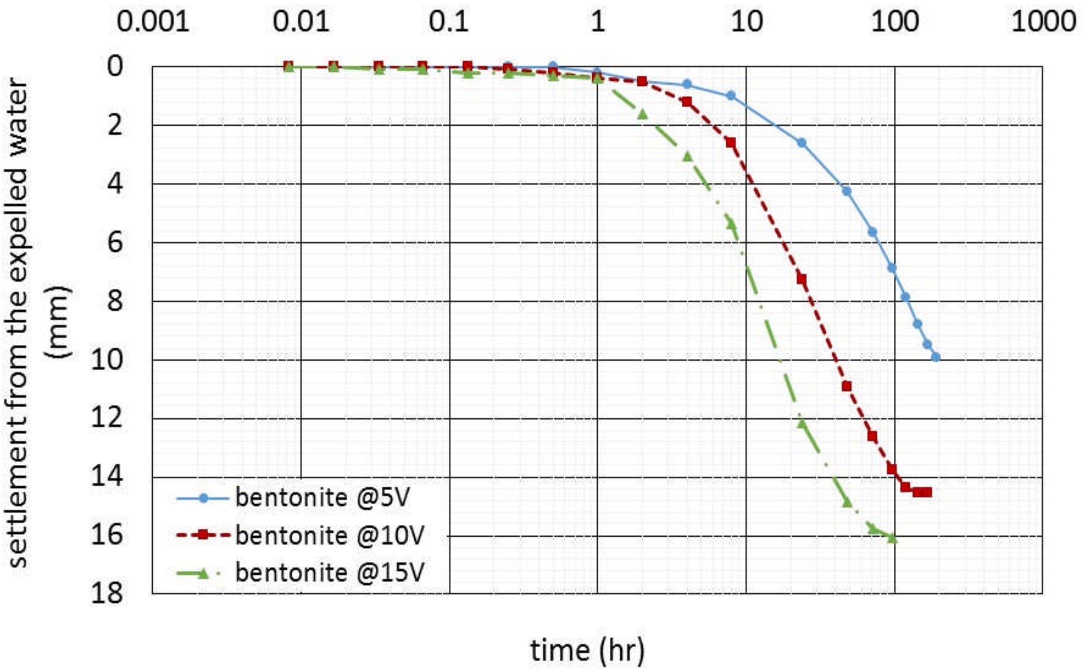


Figure 5.18 b Expected settlement calculated from the expelled water in Phase 2 in pure bentonite soils at different applied voltage

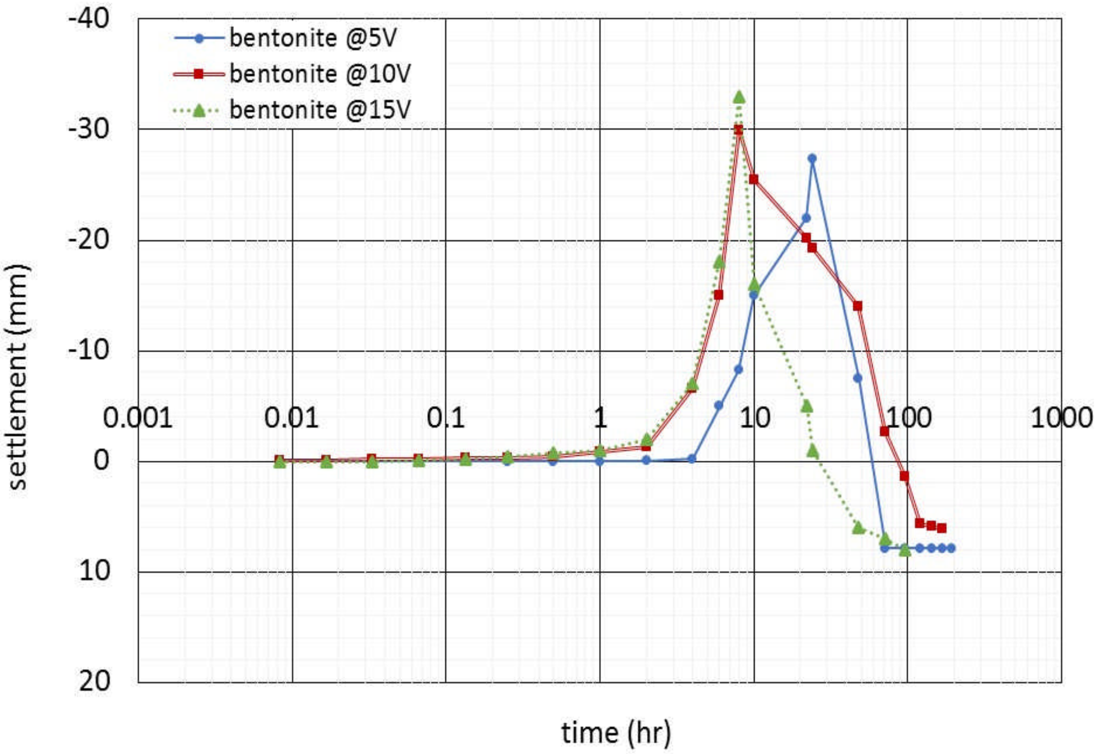


Figure 5.19 Variation in settlement verse time during Phase 2 in bentonite at different applied voltages in addition to the 15kPa load

5.3.2 Electrical current and power consumption

During the experimental programme, the electric current was monitored continuously in the electroosmotic phase until the end of each test. 10V and15 were used for all the soil mixtures. In addition, 5V was used in pure bentonite to study the effect sand content and voltage variation on the electroosmosis treatment in a range of composite soils.

5.3.2.1 Effect of sand content on the variation of electrical current and power

Figures (5.20) and (5.21) show the variation of electric current verse time during electroosmosis treatment in Phase 2 for pure bentonite and bentonite with sand soil mixtures subjected to 10V and 15V respectively.

It was observed that electric current profile for different bentonite soils shows a similar trend; the maximum current reduces as the sand content increases for both 10V and 15V. The current increased to maximum value of 3.61 Amperes after 8hrs for pure bentonite; and 1.82 amperes after about 8hrs for 67% sand at 10V. The maximum current for 15V was 4.0 and 3.04 Amperes respectively though note that the 4.0 Amperes represents the limiting current of the voltage supply. What can be clearly seen in these figures is the rapid decrease in current until it reached zero, possibly the point at which the anodes were totally degraded. A possible explanation for these results might be that the increase in sand content leads to decrease in the electrical conductivity of the soil. These results reflect those of Mosavat et al. (2012), who also found that the variation on the electrical current during electroosmotic treatment depends on electrochemical properties of the soil, such as the electrical conductivity, soils with higher electrical conductivity requiring more charge and higher currents than lower electrical conductivity soils.

Figures, (5.20) and (5.21) also show that the higher applied voltage resulted in a shorter operation time with higher total water flow shown in Figure (5.18), this finding is consistent with that of Jayasekera (2004b),

Figure (5.22) shows the voltage variation during the electroosmotic phase. A voltage drop was observed at electroosmotic tests when 15V was applied. This was because the maximum current capacity of the DC power supply was reached; that is the supply was limited to 4 Amperes. The maximum drop in voltage was recorded on pure bentonite, and there was no change at 67% sand, which is likely due to the maximum capacity of the DC power supplier used.

Prior studies have noted that voltage losses occur during electroosmotic treatment in soils, these studies showed that both electrode material and soil type had an effect on the overall voltage losses (Bjerrum et al., 1967, Mohamedelhassan and Shang, 2001, Lamont-Black et al., 2016). Wu et al. (2015a) concluded that the voltage loss during electroosmotic treatment in sodium bentonite was caused by soil cracking near the anode due to volume shrinkage and gas generation. In addition the four electrodes types used in the study, copper, iron, graphite and stainless steel, exhibited a voltage loss of more than 80% close to the anode. (Mohamedelhassan and Shang, 2001) stated that the voltage drop at the soil-electrode interfaces depends on the soil properties, applied voltage and electrode materials. Zhou et al. (2015) stated that the copper electrode exhibited a rapid decrease in the electrical current and effective potential, the voltage loss during electroosmosis treatment can be attributed to various factors, such as electrode corrosion, gas evolution, electrochemical passivation decomposition and electrochemical potential.

The power required for electroosmosis consolidation was reduced with sand content in a similar trend to the electrical current, and increased as the applied voltages increased (Figures 5.23 and 5.24) for 10 and 15V respectively. In Figure (5.23), the maximum power used has dropped from 36.1W in pure bentonite to 18.2W for sand mixed with bentonite at 67%, while in Figure (5.24), when 15V have been used, the maximum power dropped from 60W in pure bentonite to 45.6W for sand mixed with bentonite at 67%. This drop in power was a result of the limiting current of the power supply, not because of the properties of the soil.

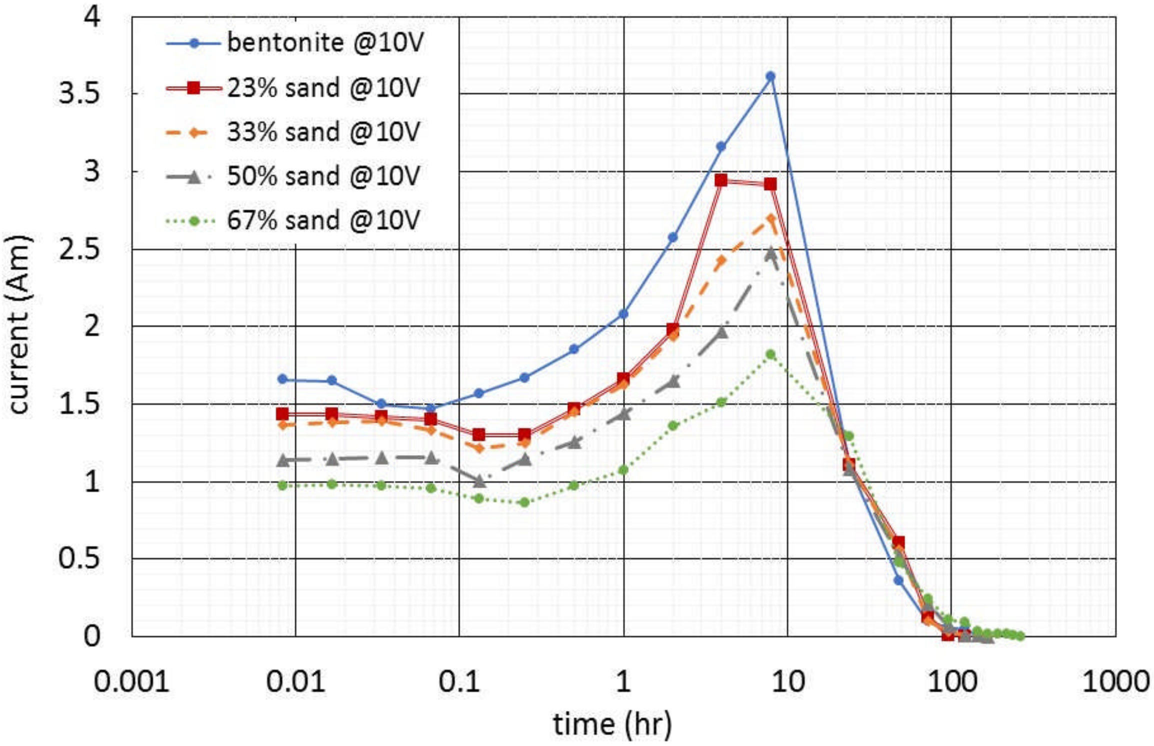


Figure 5.20 Variation of electrical current verse time with different sand content at 10V

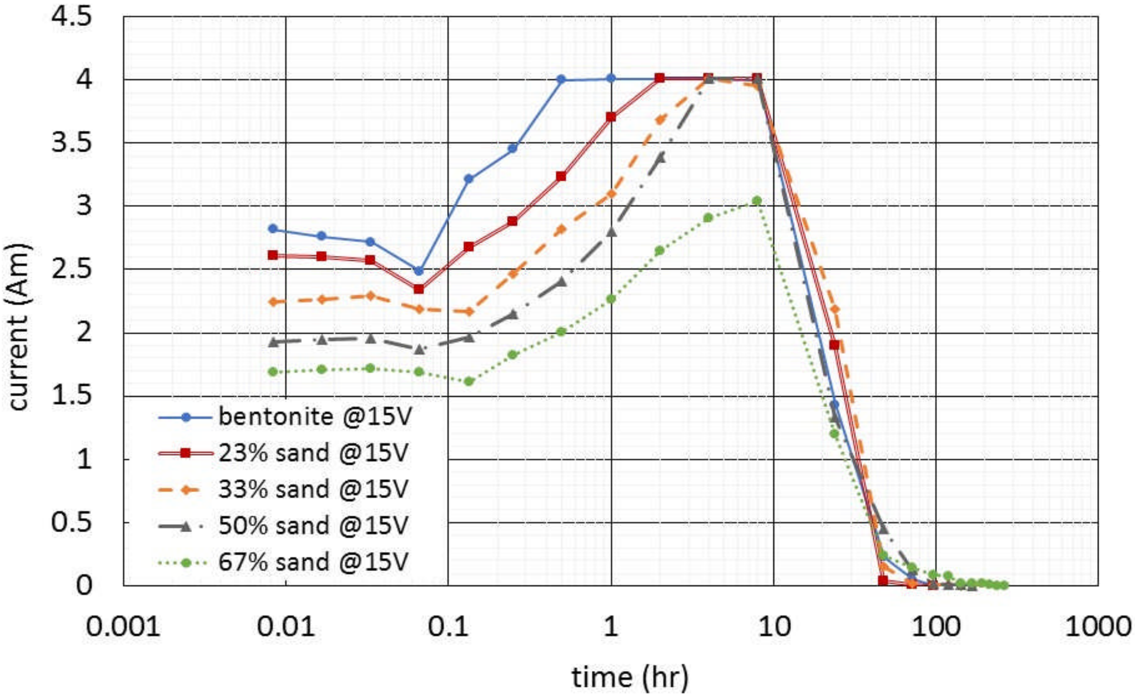


Figure 5.21 Variation of electrical current verse time with different sand content at 15V

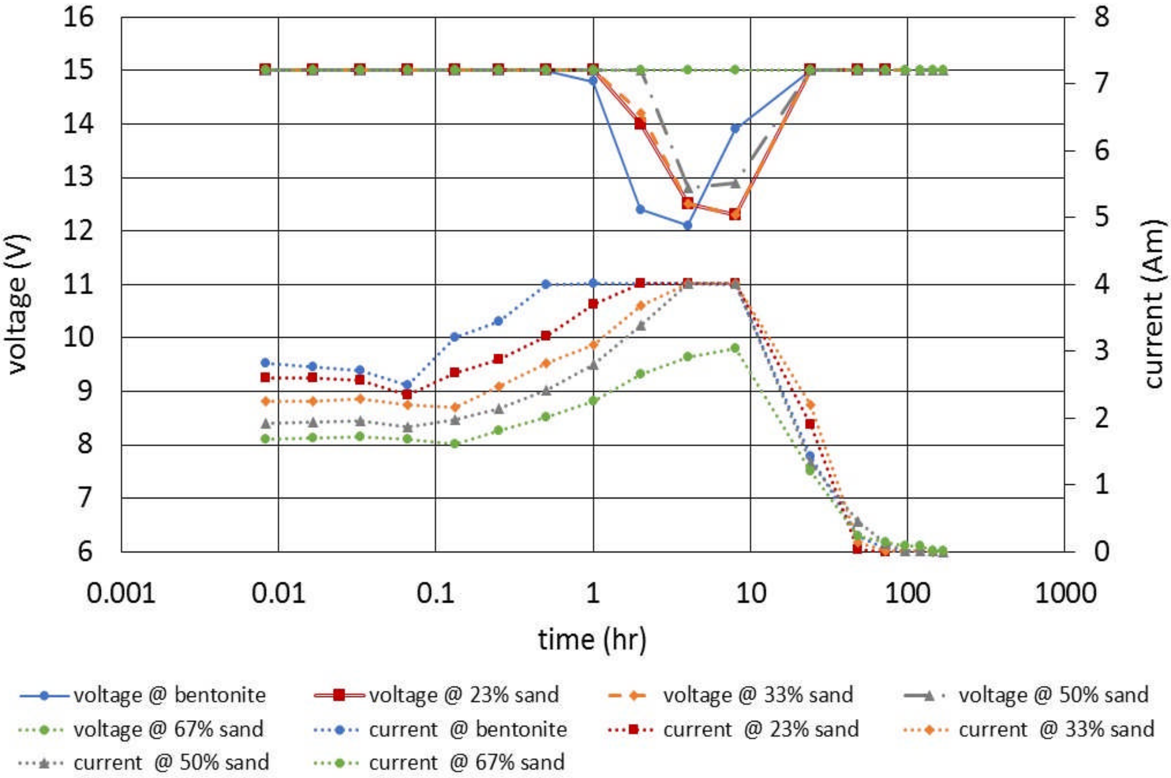


Figure 5.22 Variation of voltage when the current reached the maximum limit of the power supply (4 Amp) when 15V applied

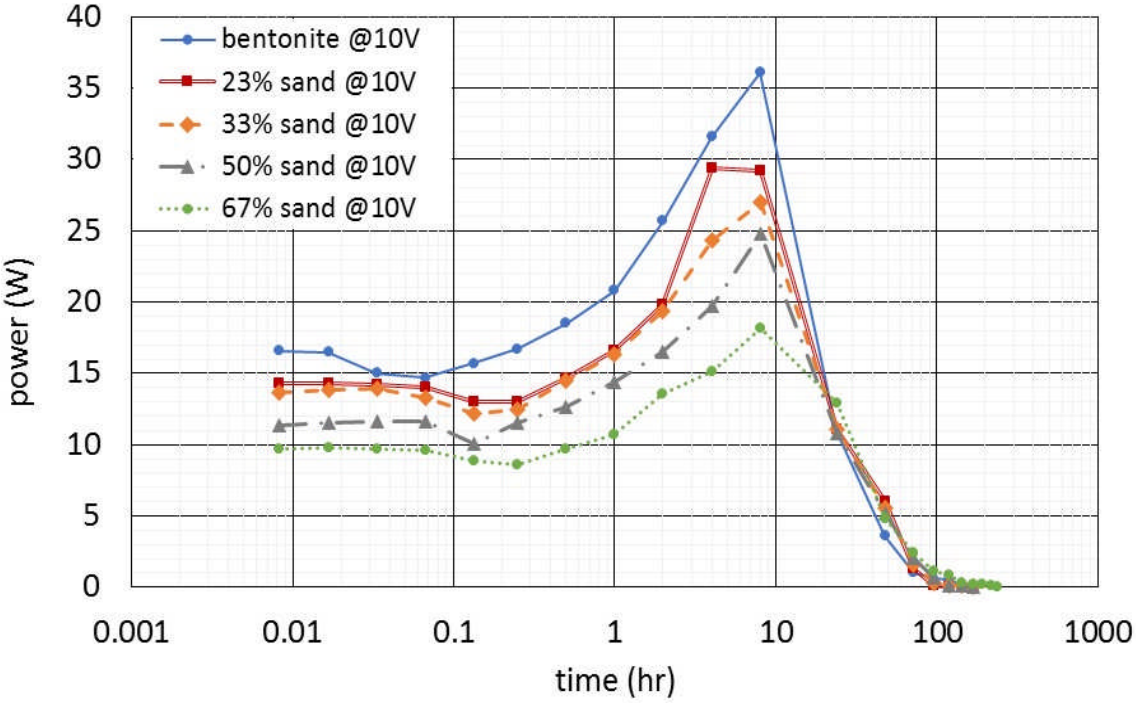


Figure 5.23 Variation of power with time for different sand content at 10V

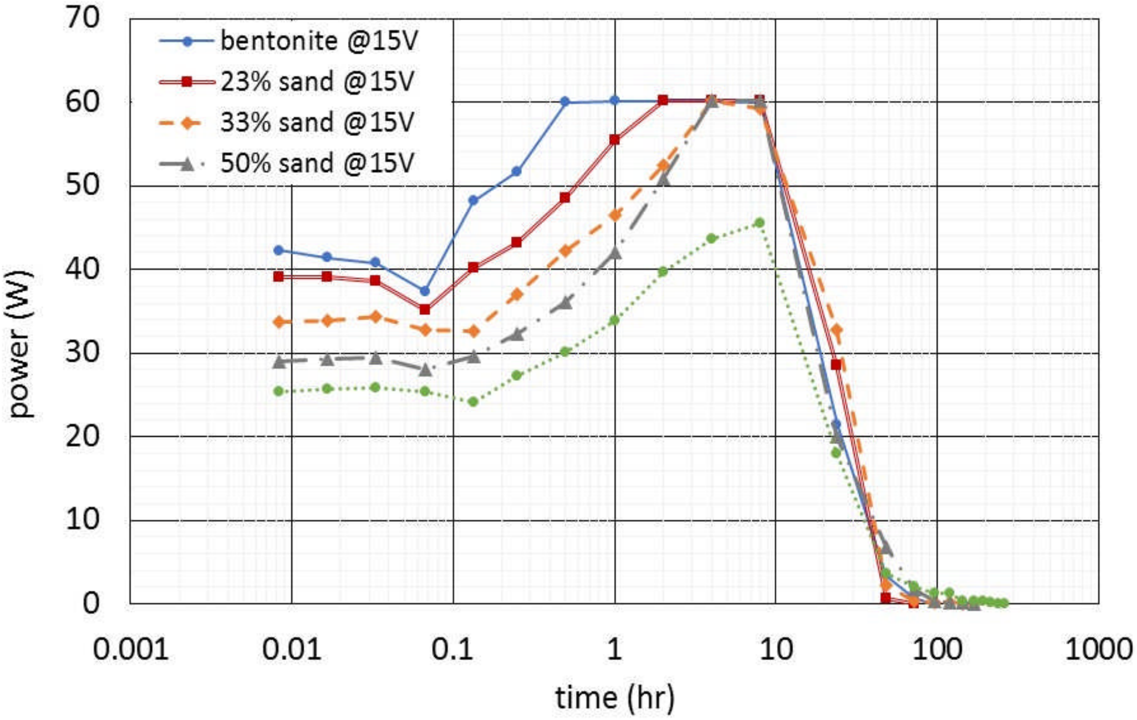


Figure 5.24 Variation of power with time for different sand content at 15V

5.3.2.2 Effect of applied voltage

Figure (5.25) shows the monitoring of electric current in Phase 2 for pure bentonite soils subjected to 5, 10 and 15V. It was observed that electric current of those three different voltages shows similar trend. The figure shows that there has been a marked increase in current with time, and with voltage, the higher applied voltage, the higher electrical current. What can be clearly seen in this figure is the higher current value occurs after about 0.5 hour from the beginning of the test when 15V used, while it is occurred after 24 hours at 5V. However, because of the D.C power supply limits was reached when 15V applied, the actual maximum values was impossible to measure. The path of the current then decreases until reaching zero for all tests, which means complete degradation of the anode. Chew et al. (2004) showed that the electrical current during electroosmotic treatment in marine clay initially rose, became stable and then dropped. Chew et al. (2004) did not provide details of their power supply so it is not certain that the observed maximum current was a soil related phenomenon or a limit of their power supply.

Ou et al. (2015) shows that the electrical current steadily decreased with the increase of electroosmotic treatment time, and this decrease might be related to the cementation created between soil particles, which caused increases in the electrical resistance and therefore reduced the current. Micic et al. (2003a) found that the electro cementation accompanying with electroosmotic process during the application of an electrical power to the soil due to precipitation of amorphous compounds, such as iron oxides and carbonates which is participate as cementing agents that contribute in increasing the shear strength and reduce pore volume of the treated soil.

It is obvious that the consumed power required for electroosmosis consolidations has a similar trend to the electrical current. Since the applied voltage is constant, the shape of the current and power curves are the same, as shown in Figures (5.26).

Figure (5.27) shows the variation in maximum power in Phase 2 with different applied voltages (5, 10, and 15V) in bentonite. In this figure, there is a clear trend of an increase in the consumed power as the applied voltage was increased even allowing for the limit to the current for the test with 15V.

Figures (5.28) and (5.29) compare the results of the maximum consumed power and the power at different time intervals, 1, 2, 4, 8, 24, and 72 hours for both 10 and 15V respectively. In Figure (5.28) when 10V used, the maximum power has dropped from 36.1W in pure bentonite to 18.2W for sand mixed with bentonite at 67%, while in Figure (5.29), when 15V was used, the maximum power dropped from 60W in pure bentonite to 45.6W for sand mixed with bentonite at 67%. What is striking in these figures is the maximum power was occurs at 8 hours. Note that the 60W recorded for most of soil mixed except 67% sand shown in Figure (5.29) was because of the limitation of the current from the power supply. Based on a projection from the curves for 5V and 10V, the maximum power for 15V would be greater than that shown in Figure 5.29.

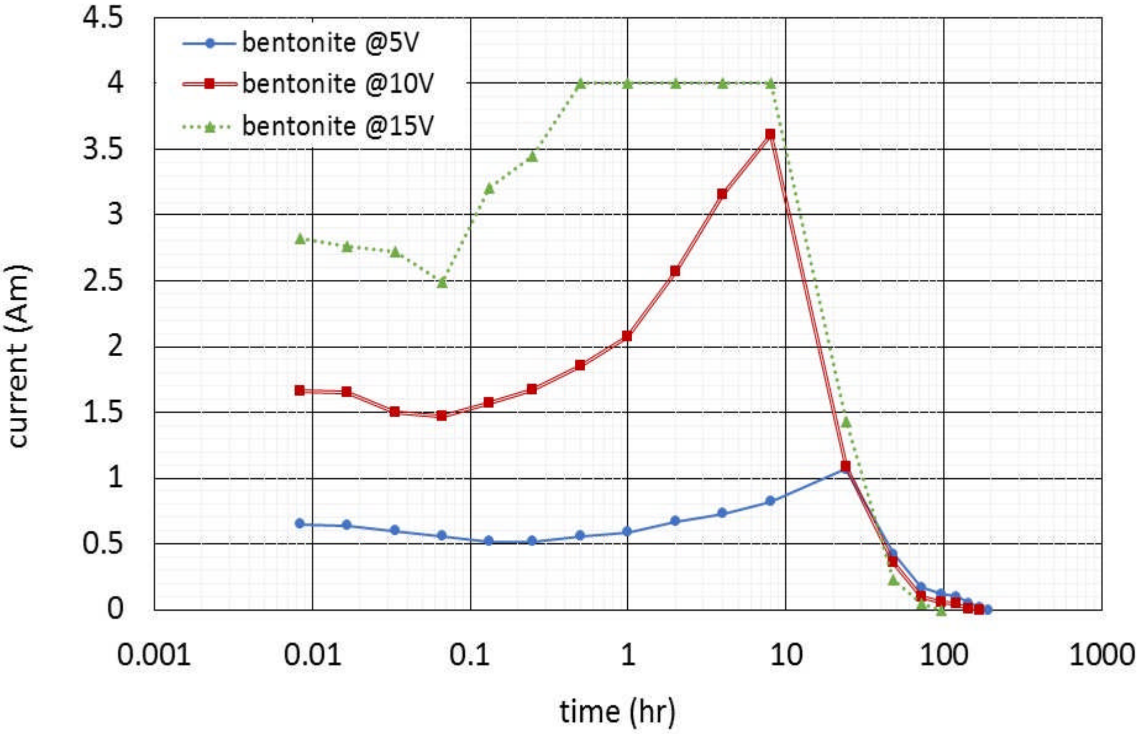


Figure 5.25 Variation of electrical current verse time in kaolin soil subjected to different applied voltage

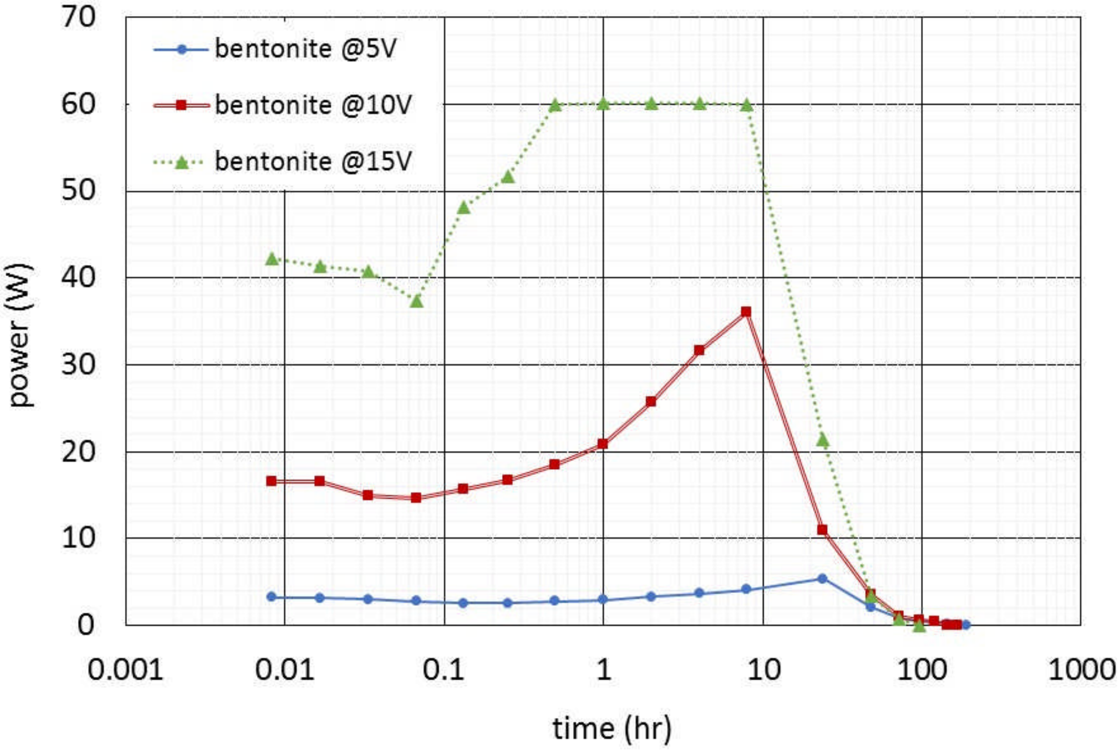


Figure 5.26 Variation of consumed power verse time in bentonite subjected to different applied voltage

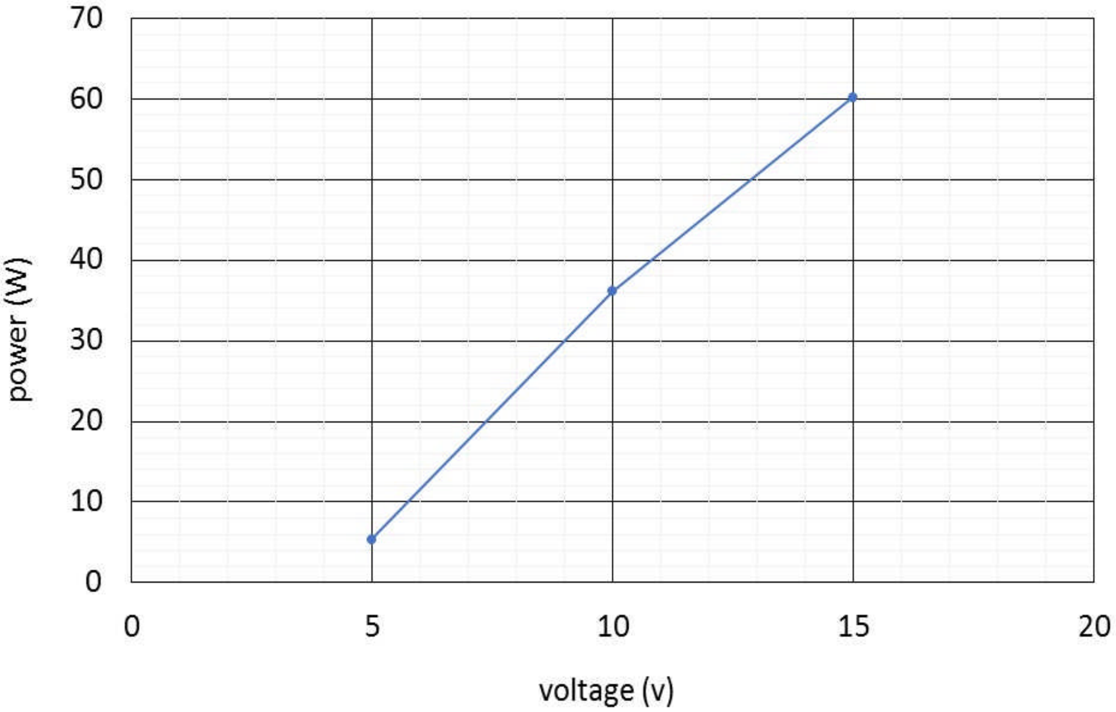


Figure 5.27 Variation in maximum power in Phase 2 with different applied voltage in bentonite (note that at 15V the maximum current supplied by the power supply was reached)

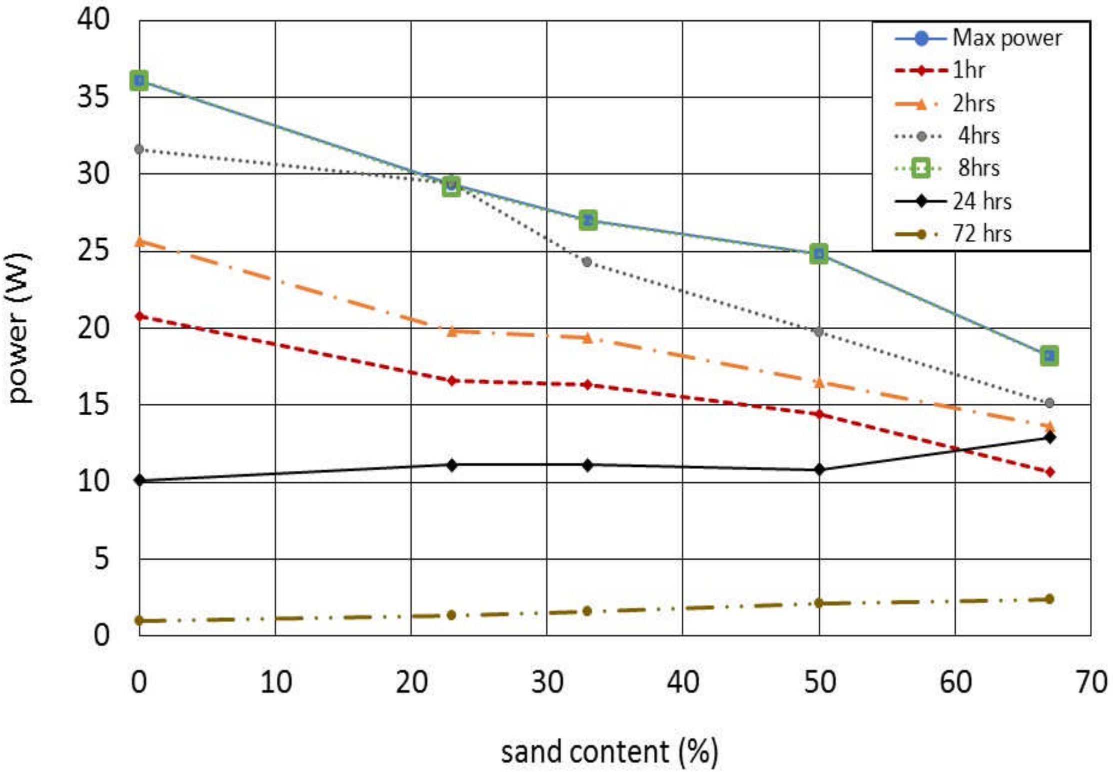


Figure 5.28 Variation in maximum power (at 8hrs) in Phase 2 with sand content at 10V and the power at 1, 2, 4, 24 and 72hrs

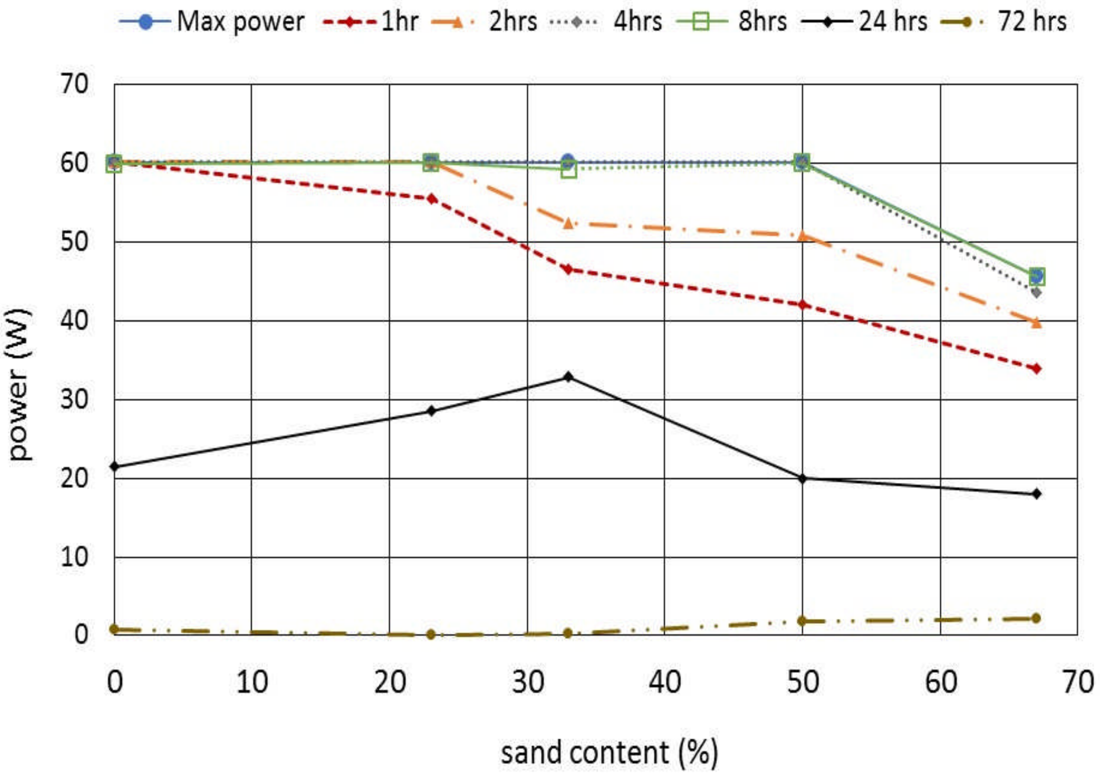


Figure 5.29 Variation in maximum power in Phase 2 with sand content at 15V and the power at 1, 2, 4, 8, 24 and 72hrs. Note that the maximum power of 60W was due to the limit of the power supply and not a soil related phenomenon.

5.3.3 Water content

The final water content was measured at the end of Phase 3 by taking 20 samples from five equal section levels as the cell was dismantled; from the anode, cathode, in between electrodes, and at the cell wall so that the variation of water content with depth and distance from the electrodes could be assessed, as shown in Chapter 3, Figure (3.19). The final average water content profile of the electroosmotic treated samples are presented in Figure (5.30) for 10V and Figure (5.31) for 15V. In general, the final water content was less than the initial water content throughout the whole sample. However, the reduction in water content was not uniform, greater reduction recorded at the anode because of electroosmosis, as the water moves towards the cathode. It can be seen that the water near the anodes is lower than that at the vicinity of the cathode, even after the 50 kPa applied pressure at Phase 3 which cause redistribution of water at the end of electroosmosis treatment phase. The final water content varied across the sample at the end of the tests suggests that the 50kPa pressure applied in Phase 3 does not lead to a redistribution of water content. This suggest that ‘soft’ piles are formed around the anodes, at 80 mm from the centre of the cell (cathode). The most likely reason for the high water content at the vicinity of cathode compares to the anodes area is due to the electroosmosis process. However the final water content of the treated soil was lower than the initial water content throughout the whole sample as shown in Figures (5.30) and (5.31). These results support evidence from previous observations (Jayasekera et al., 2004, Jayasekera and Hall, 2006) which showed that the drier zone generated close to the anode is due to the low hydraulic conductivity of the soil which cause slow movement of water from anode to cathode and the insufficient water migration from the cathode region towards the anode to balance the prevailing electroosmotic flow.

The results, as shown in Figures (5.30) and (5.31) indicate that the final water content decreases with the increase in sand content. It is also noted that the initial water content used is inversely proportional to the sand content and the final water content reduced as the sand content increased.

Figure (5.32) shows the correlation between the final water content and the applied voltage in pure bentonite at the end of Phase 3. As can be seen from the above figure, the water content decreases with increasing applied voltage. Although the mass of water used in the electroosmotic treated soil was similar to that used in the control test since the average water contents were similar. However, the electroosmotically treated soil samples had a higher water content than soils in the control test except in the vicinity of the anodes in 10 and 15V (80 mm from the cathode) due to the generation of electroosmotic piles near the anodes. For 5V, no significant change in water content appeared, which means the soil was unaffected by electroosmotic dewatering compared to other voltages. However, the final average water content calculated based on the expelled water from the whole sample shown in Figure (5.34) were close to that from the control test in pure bentonite.

The average water content calculated from the weight of expelled water of the pure bentonite samples after the electroosmosis dewatering tests and before applying 50kPa (after phase 2) were 118.1, 114.7 and 113.6% in 5, 10 and 15V respectively as shown in Figure (5.33), where the initial water content was 160%. The results of this figure indicate that increasing the applied voltage caused a decrease in the final water content, hence an increase in stiffness and shear strength of those soils.

The variation in final average water content calculated at the end of Phase 3 throughout the whole sample with respect to the sand content was shown in Figure (5.34). It shows that it decreased as the sand content decreased (the soil being prepared at 1.5I_L) for the control, and 10V and 15V electroosmotic tests. From Figure (5.34), it can be also noticed that the change in water content of the electroosmotic treated soil decreased as the sand content increased in a similar trend to the initial water content.

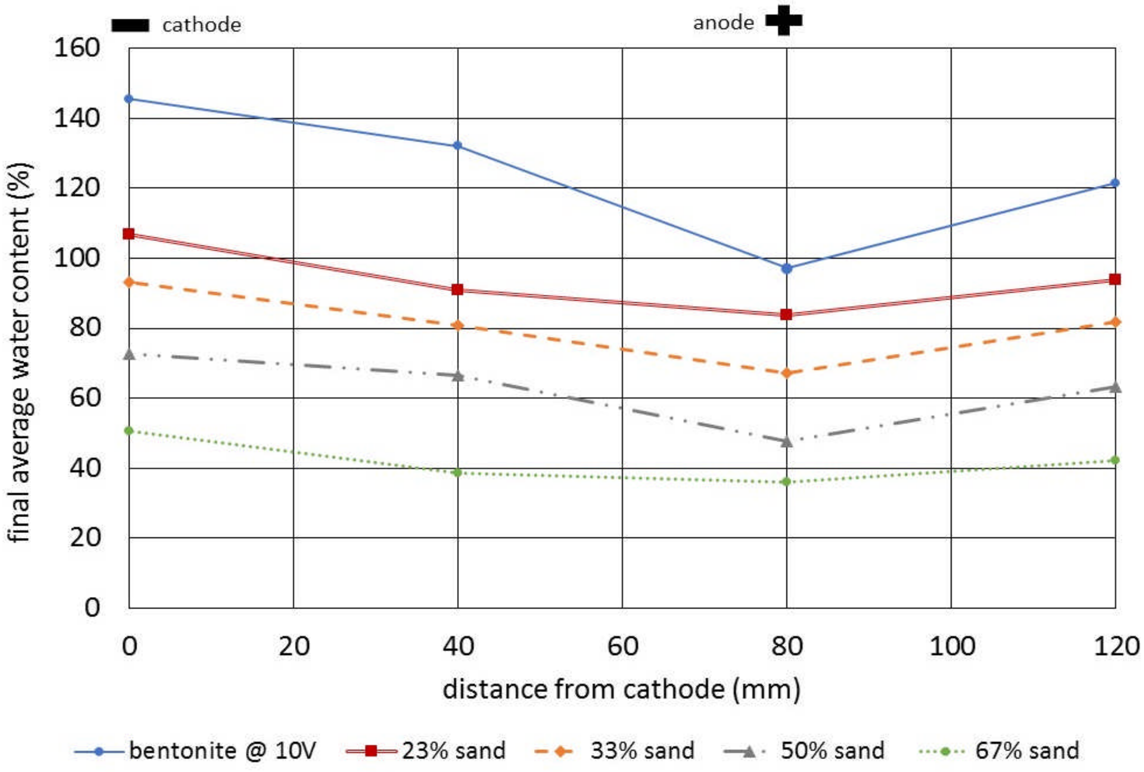


Figure 5.30 Variation in the final average water content at different sand content verse location at 10V

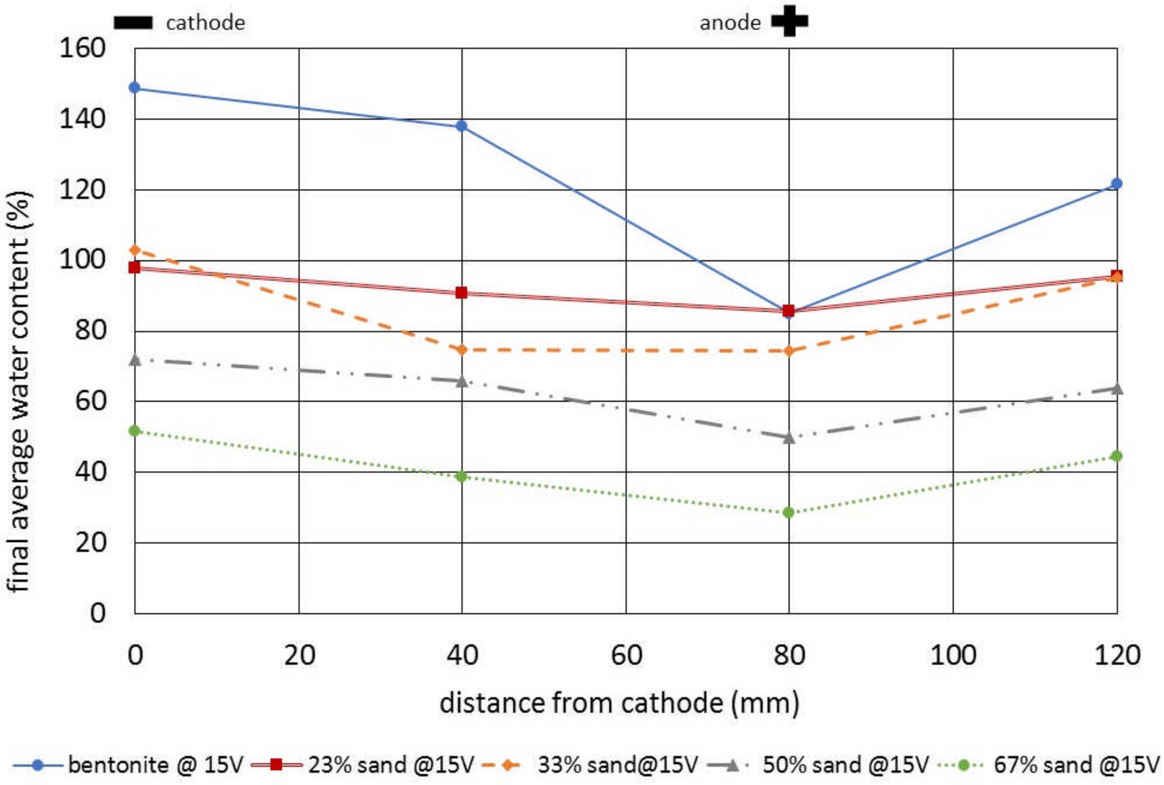


Figure 5.31 Variation in the final average water content at different sand content verse location at 15V

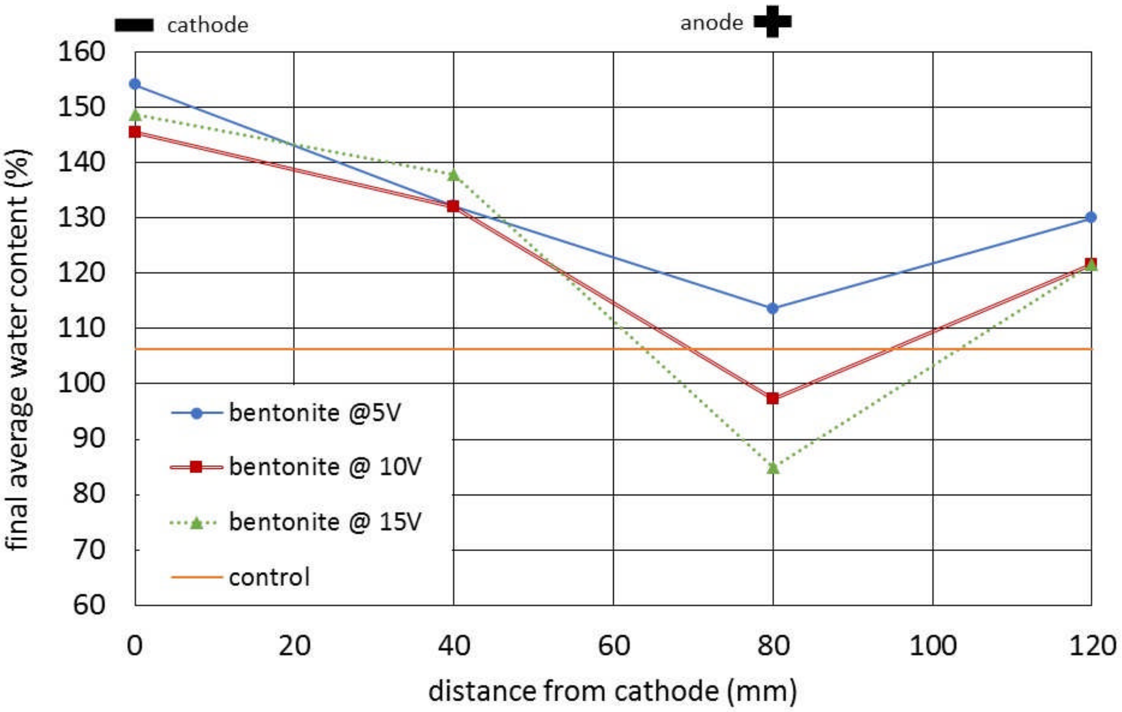


Figure 5.32 Variation in final average water content in pure bentonite subjected to 10, 15, and 20V

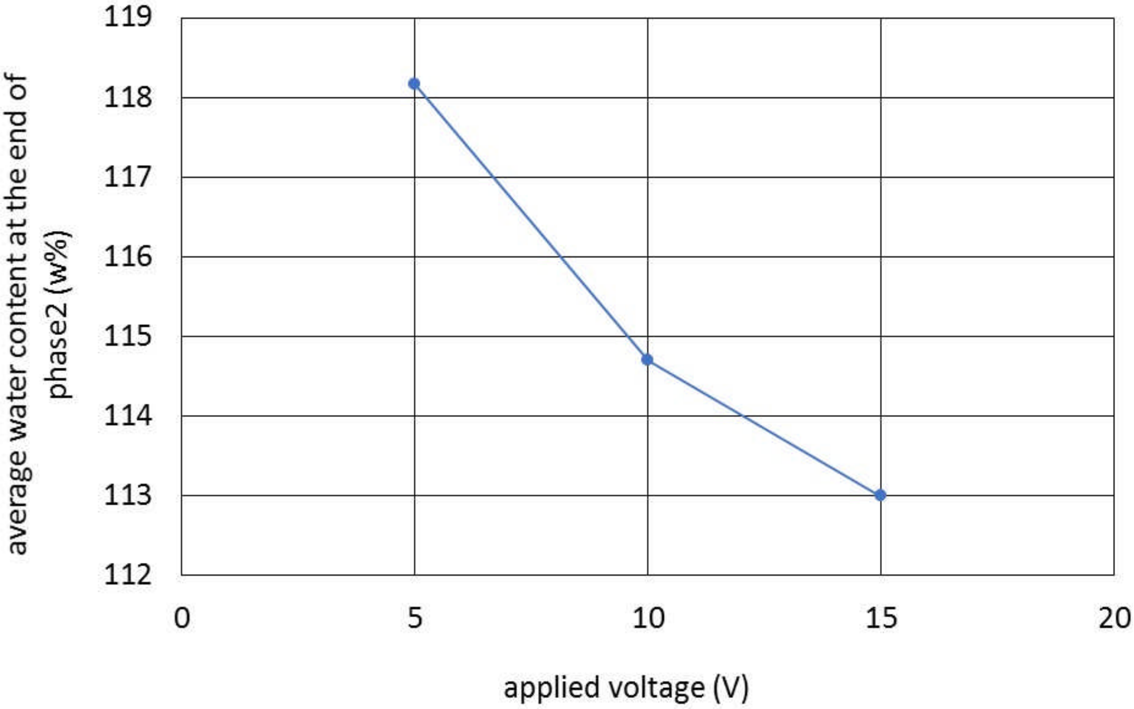


Figure 5.33 Variation of average water content with the applied voltage based on calculations from the expelled water at the end of Phase 2

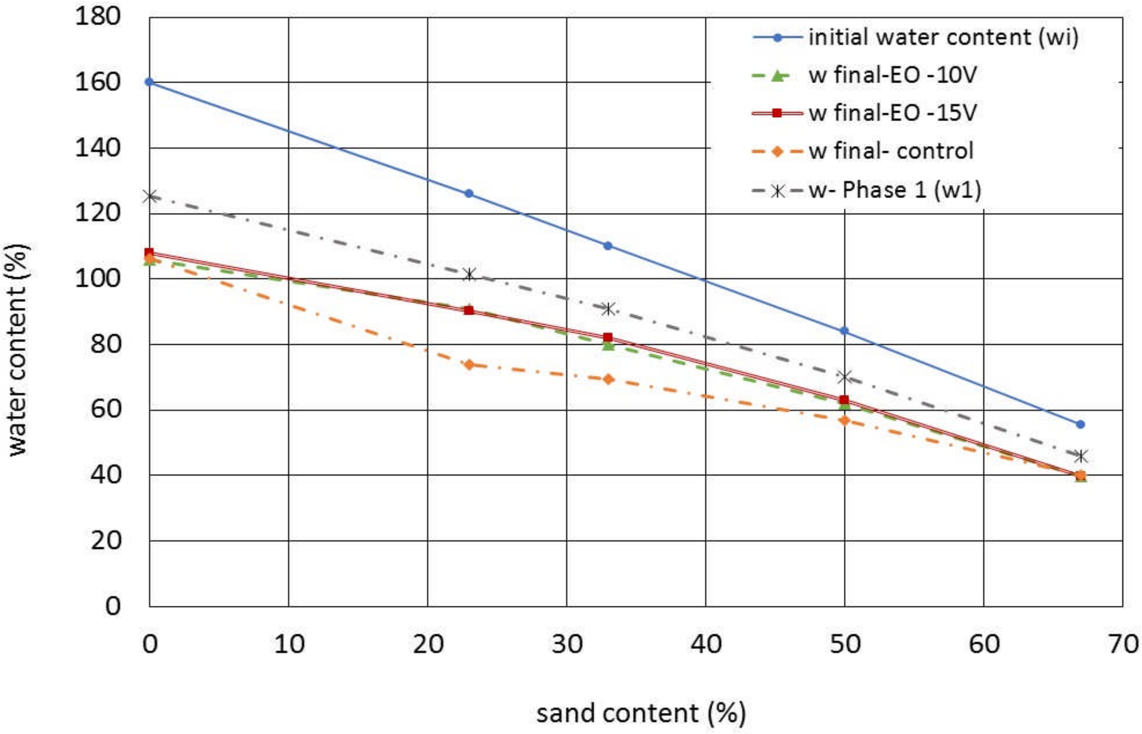


Figure 5.34 Variation of initial and final water content with sand content and applied voltage in Phase 3

5.3.4 Electroosmotic permeability

As mentioned in section 4.3.4, the electroosmotic permeability of soils is based on the measurement of discharge water with time, electric intensity, and the area of the sample during electroosmotic tests according to the following equation (Mitchell and Soga, 2005):

$$Q = k_e \, E \, A \tag{5.1}$$

Where Q (m^3/s) is the flow rate, E (V/m) is the effective electric field intensity, and A is the cross section area perpendicular to water flow assumed to be the effective area of an octagonal prism defined by the anodes (Alshawabkeh et al., 1999).

The coefficient of electroosmotic permeability, k_e, was calculated and is plotted versus sand content in Figure (5.35). The results show that the coefficient of electroosmotic permeability, k_e was in the range from 1.79×10^{-10} m^2/sV to 0.9×10^{10} m^2/sV when 10V was applied and from 1.57×10^{-10} m^2/sV to 0.72×10^{-10} m^2/sV when 15V was applied for pure bentonite and 67% sand with bentonite respectively.

From the results obtained in Figure (5.35), it can be see that the electroosmotic permeability values when 10V used was higher than those at 15V for the same soil mix and initial water content. The difference in these values are likely to be related to the change in flow rate, Q, in addition to the effect of applied voltage based on the equation (5.1). These results are in agreement with those obtained by Estabragh et al. (2014), who also found that that the electroosmotic permeability values ($3.83*10^{-9}$ and $3.79*10^{-9}$ m^2/sV for 15 and 45 V) reduced as the applied voltage increased. These results are consistent with the results reported by Mohamedelhassan and Shang (2001) and Rittirong et al. (2008) that the coefficients of electroosmotic permeability are controlled by the applied electric field intensity in the treated soil.

The results in Figure (5.35) indicated that the values of k_e determined were affected by sand content. An increase in sand content caused a reduction in electroosmotic permeability. Gray and Mitchell, (1967) suggested that the electroosmotic permeability values varied with a change in water content. The initial water content decreases with the increase of sand content, as shown in Figure (5.34). Therefore, the reduction in electroosmotic permeability shown in Figure 5.35 is partly due to the redistribution in water content.

Kaniraj et al. (2011) stated that for effective electroosmotic treatment, the electroosmotic permeability value k_e required is about 10^{-9} m^2/sV. Asadi et al. (2013) concluded that the values of electroosmotic permeability coefficient of soils range from 4.91×10^{-10} to 1.57×10^{-9} m^2/sV.

The electroosmotic permeability values shown on the above figure for bentonite soil mixes differ from the results presented earlier in Table (4.2) for other soil types, but they are broadly consistent with the finding of (Loch et al., 2010) and (Heister et al., 2005), which showed that the coefficient of electroosmotic permeability of Wyoming Na-bentonite is lower than that reported by (Mitchell, 1993), and ranged between 1.16×10^{-10} m^2/sV and 7.94×10^{-11} m^2/sV.

The results obtained from electroosmotic treatment in pure bentonite subjected to 5, 10, and 15V are displayed in Figure (5.36). From this figure, it is clear that the 10V reported significantly more k_e value than the other two applied voltages, 1.79×10^{-10} m^2/sV for 10V compared with $1.53X10^{-10}$ m^2/sV and $1.57X10^{10}$ m^2/sV for 5 and 15V, respectively. The difference in the electroosmotic permeability values is related to the change in osmotic flow caused by these applied voltages and different treatment time (192, 168 and 96 hours for 5, 10, and 15V respectively. This finding is consistent with that of Estabragh et al. (2014) who concluded that the value of electroosmotic permeability k_e decreases with increasing the applied voltage and treatment time. This inconsistency between 10 and 15V might partly be attributed to the drop in voltage mentioned in section 5.3.2.

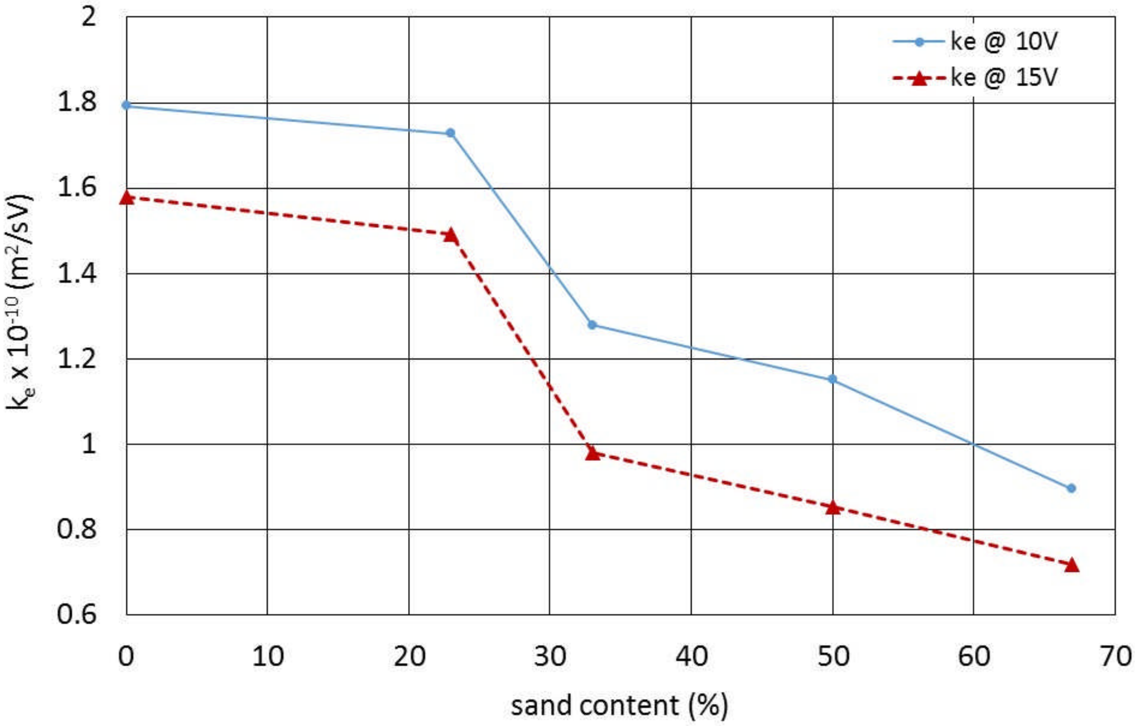


Figure 5.35 Values of electroosmotic permeability k_e versus sand content for 10 and 15V

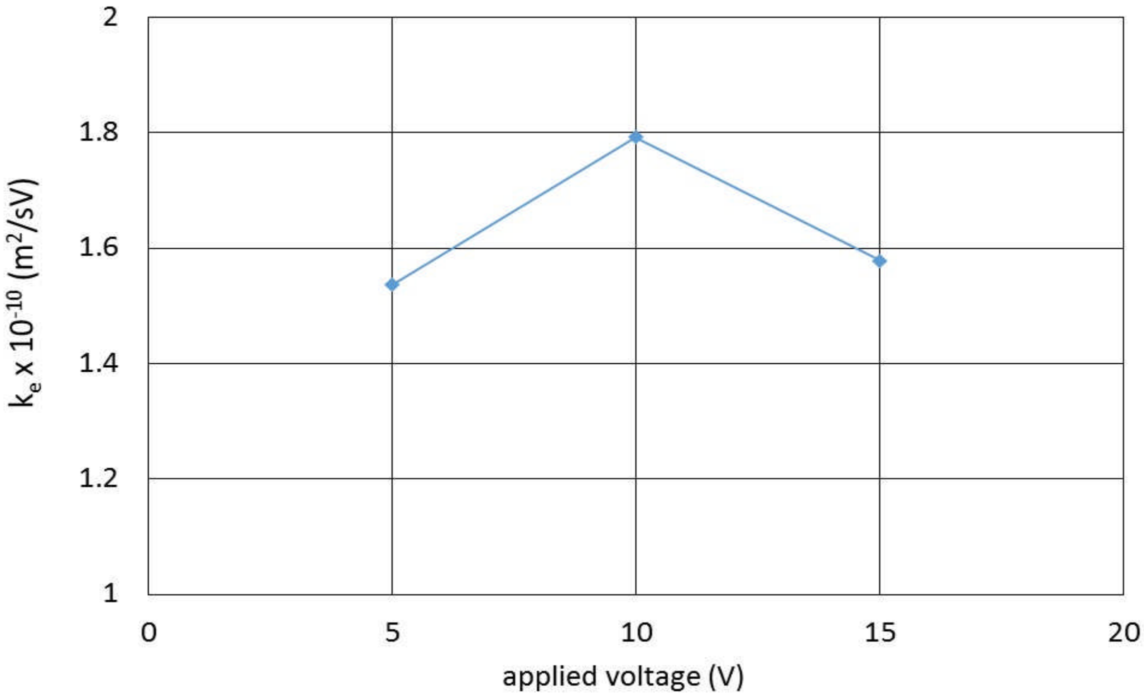


Figure 5.36 Values of electroosmotic permeability k_e versus applied voltage in pure bentonite

5.3.5 Variation of temperature developed during electroosmosis

The temperature changes during electroosmotic treatment were recorded with time, as mentioned in section 4.3.5, by inserting a K-type thermocouple temperature probe through glands in the sidewall of the test chamber, at the anode and the cathode near the bottom of the cell (about 50mm above the bottom), and at the cathode at the middle of the cell as shown in Figure (3.1). Insulating varnish was used to prevent the temperature probes acting as electrodes, and room temperature was kept constant during the test.

Figures (5.37) and (5.38) show the variation of the temperature with time during the electroosmotic treatments in the vicinities of the cathodes under 10 and 15V respectively. The initial temperature for all soil samples were the same as the room temperature (18°C), What can be clearly seen in these figures are the rapid increases in temperature when a DC electrical current applied in Phase 2. The highest increase in temperature was found in pure bentonite soil, from 18℃ to 38℃ after 10 hours when 10V applied, and from 18℃ to 61℃ after 10 hours of electroosmotic treatment for 15V. While, the smallest change was recorded in 67% sand test, from 18℃ to about 29℃ for 10V, and from 18℃ to about 38℃ for

15V. The temperature trends in these electroosmotic tests were attributed to the application of DC current across the samples with time. Looking at the figures, it is apparent that the pure bentonite reported significantly higher generated temperature than the other soil mixes; as the sand content increased the maximum temperature reduced. Prior studies that have noted the importance of heat developed in the vicinities of electrodes during electroosmotic treatment include those by (Gray, 1970); (Shang and Lo, 1997); (Hamed and Bhadra, 1997); (Mohamedelhassan and Shang, 2002); (Mohamedelhassan and Shang, 2008); (Wang and Vu, 2010); (Mosavat et al., 2012); (Mao et al., 2012); and (Lee et al., 2016).

Shang and Lo (1997) suggested that increasing the applied voltage can lead to increased heating which causes energy loss. Mosavat et al. (2012) stated that a side effect of electroosmotic treatment is the excessive heat generated near the electrodes which causes the appearance of cracks in the specimen between the anode and the surrounding soil. As mentioned by (Lee et al., 2016), higher applied voltages will generate heat in the treated soil causing surface desiccation and change in the water content, which may be affect the efficiency of the electroosmotic treatment. Figure (3.19) shows that cracking occurred around the cathode and anode in these tests even though there was a surface load. Thus, the cracks around the anode were probably due to a reduction in volume and the generation of gas (Wu et al, 2015a).

It is apparent from Figures (5.37) and (5.38) that the trend of temperature increase of the treated soil reached a peak at about similar time as the peaked current in Figures (5.20) and (5.21) which is about 10 hours from the test beginning. This finding is consistent with that of Mohamedelhassan and Shang (2008) who found that the increase in temperature verse time of the soil in the followed the trend of the electric current.

Figure (5.39) compares the heat generated due to electroosmotic treatment in pure bentonite under 5, 10, and 15V. It is clear that the soil temperature increased significantly when an electrical power was applied and the maximum temperature recorded for both 10V and 15V was after 10hrs, and it was at about 12hrs when 5V applied. The temperature starts to drops after the peak was reached, . It seems possible that the decrease in temperature starts due to the corrosion of the anodes then drops to room temperature when the anodes degrade completely. The highest increase in temperature was found at 15V, while, the lower generated temperature was due to 5V, from 18℃ to about 22.5˚C.

What stands out in these figures and those for kaolin, Figures (4.39) and (4.40) is that an increase in applied voltage results in a greater increase in temperature for electroosmotic treated samples. The increase in temperature varied with soil composition; for example, more heat was generated in bentonite soils compared to kaolin soils; increasing sand content leads to a reduction in generated heat. That is the heat developed due to applying electrical power is a function of the applied voltage and soil type.

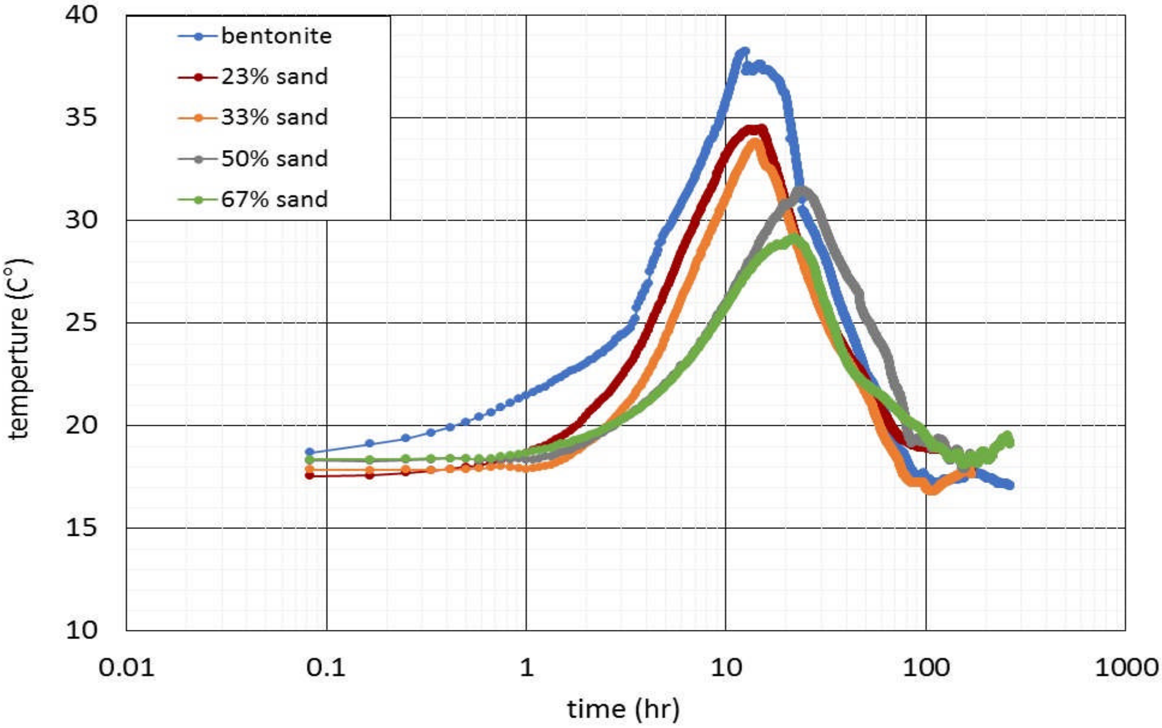


Figure 5.37 Variation of temperature with time during electroosmotic test at 10V

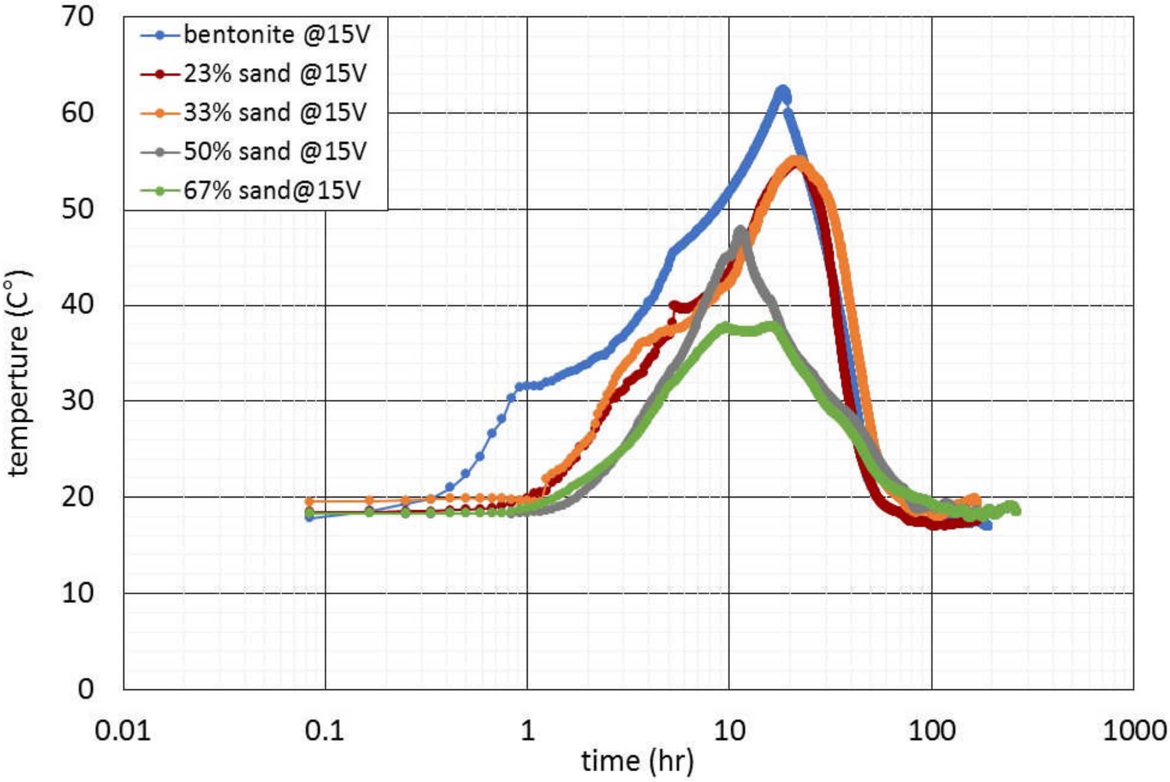


Figure 5.38 Variation of temperature with time during electroosmotic test at 15V

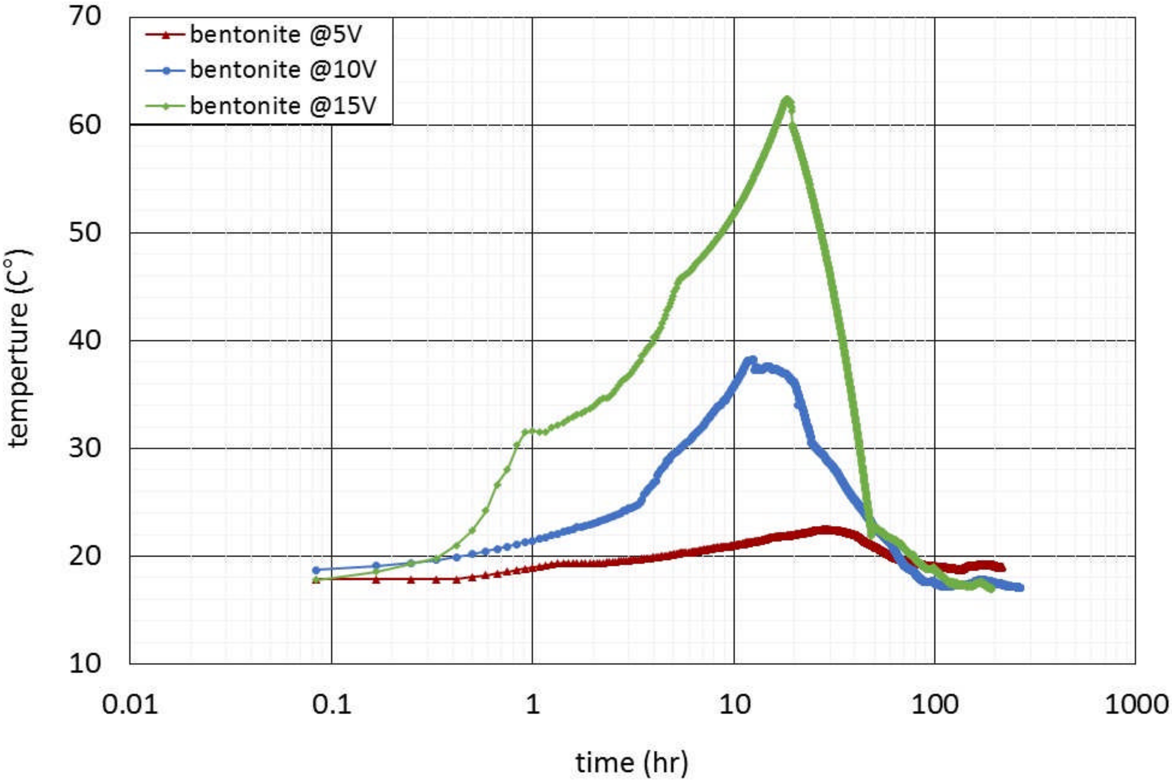


Figure 5.39 Variation of temperature verse time in bentonite at different applied voltages

5.4 Electroosmotic Efficiency

Efficiency is a major area of interest within the field of electroosmosis dewatering application to assess the feasibility of this technique in composite soils in terms of consumed energy, electroosmotic flow efficiency, and electroosmotic transport efficiency as mentioned in section 4.4.

5.4.1 Energy consumption E

The efficiency of an electroosmotic treatment is evaluated by the power consumption, i.e. the energy used to treat a cubic meter of soil for an hour, (Wh/m^3). As mentioned by Mohamedelhassan and Shang (2002), the economic efficiency of an electroosmotic consolidation process is evaluated in terms of the power consumption to treat one cubic metre of soil for an hour. Figure (5.40) presents the results obtained for the consumed energy in electroosmotic treatment E in kWh/m^3, according to equation below suggested by Lefebvre and Burnotte (2002):

$$E = \frac{VIt}{v} * \text{Scaling factor} \tag{5.2}$$

Where: V = mean applied voltage (V); I = mean current (Am); t = total time (hour); v = sample volume (L); scaling factor = to covert electrode spacing in laboratory to field. Since this was a laboratory test a scaling factor of 1 was used.

Because of the variation in time of electroosmosis treatment in Phase 2, as presented in Table (5.1), Figure (5.41) compares the total consumed energy for soil mixtures subjected to 10 and 15V. The figure shows, there has been a gradual decrease in the total consumed energy as the sand content decreased when 10V was applied, 196 kWhr/m^3 for pure bentonite in a net treatment time of 168 hours to 140 kWh/m^3 for 50% sand with bentonite, then increased again at 67% sand to 150 kW/m^3 in a net treatment time of 264 hours. The results show that there has been a gradual increase in consumed energy with the increase in sand content when 15V was applied, 327.8 kWh/m^3 for pure bentonite to about 400 kW/m^3 for 67% sand with bentonite.

This discrepancy in the behaviour between 10V and 15V can be explained by the variation in time of electroosmotic treatment until complete degradation of the anodes, which is ranged from 96 hours for pure bentonite to 264 hours when 67% sand used. Also, when 15v was applied, the maximum current of the D.C power supply was reached, as mentioned in Sec 5.3.2.Table (5.2) shows total time, total energy and average energy per hour for each soil mixture.

Table 5.2 variation of required energy with total time, total energy and average energy per hour

Soil type	Time (hr)	Flow; Q(ml)	Avg. Energy (kWh/m^3)	Total Energy/ hour $x10^3$ ($kWh/m^3/hr$)
bentonite - 10V	168	720	196.4	33
bentonite - 15V	96	795	327.8	31.5
23% sand - 10V	168	635	192	29.8
23% sand - 15V	96	700	304.4	29.8
33% sand - 10V	168	600	159.8	26.8
33% sand - 15V	144	640	351.2	59.2
50% sand - 10V	168	570	140.2	23.5
50% sand - 15V	168	620	364.7	61.5
67% sand - 10V	264	610	150.2	39.6
67% sand - 15V	264	660	399.2	105.9

Figure (5.42) compares the results for the consumed energy during electroosmotic treatments in pure bentonite subjected to different applied voltage (5, 10, and 15). It is obvious that the consumed energy increases as the applied voltage increases as suggested by (Fourie et al., 2007) and Pradeepan et al. (2016). The results of this figure shows the rapid linear increase in the consumed energy due to the increase in the applied voltage; from 38.2 kWh/m^3 for 5V to about 327 kWh/m^3 for 15V.

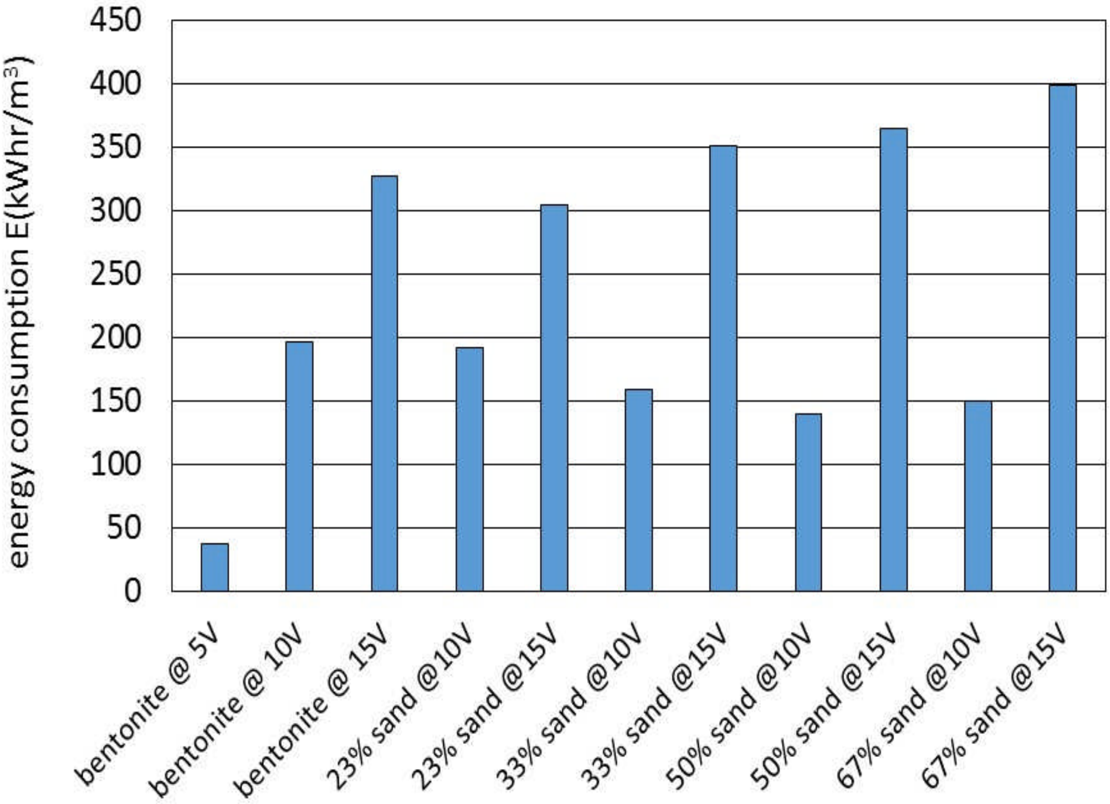


Figure 5.40 Consumed energy in electroosmotic treatment E vs sand content

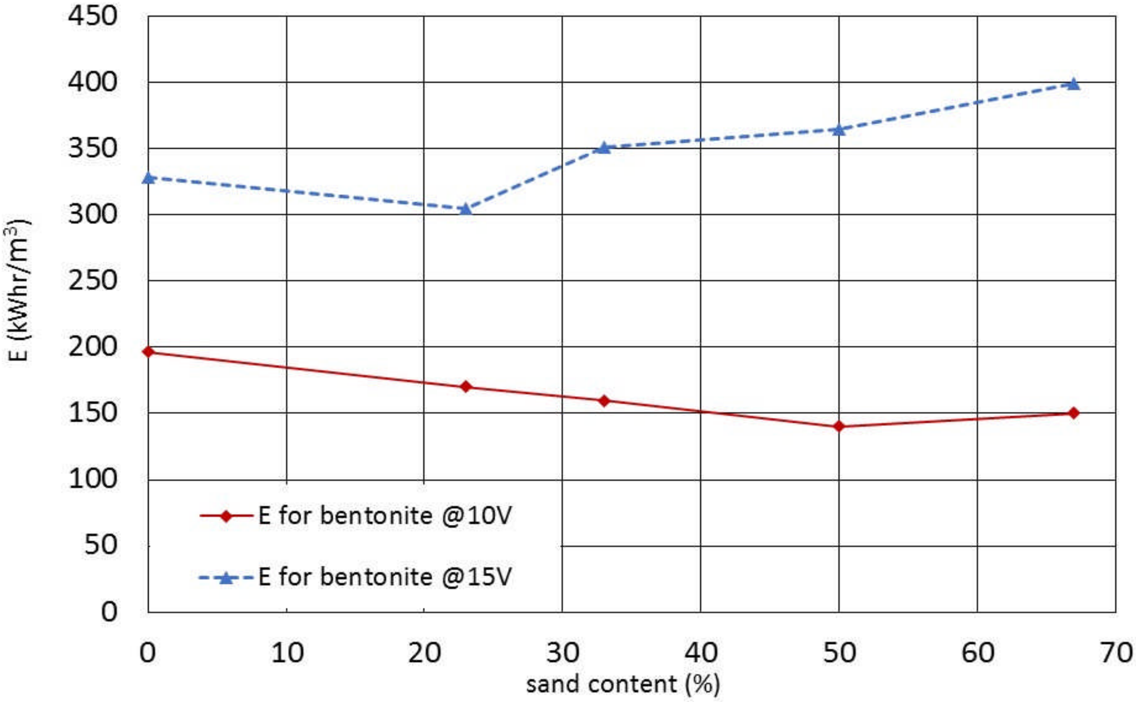


Figure 5.41 Consumed energy in electroosmotic treatment vs sand content for 10V and 15V

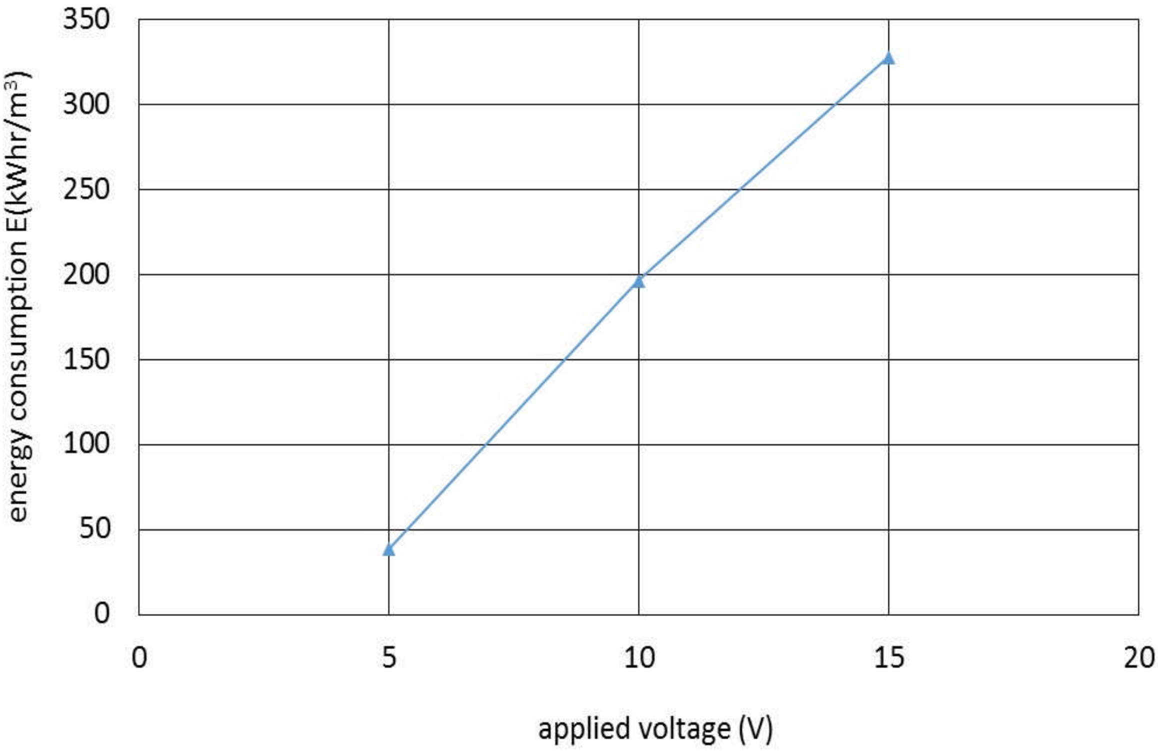


Figure 5.42 Consumed energy in electroosmotic treatment vs applied voltage in pure bentonite

5.4.2 Electroosmotic flow efficiency

Figure (5.43) shows the results obtained for electroosmotic flow efficiency in bentonite and sand soil mixtures subjected to different applied voltages. As mentioned by Gray and Mitchell (1967) and Eykholt and Daniel (1994), the electroosmotic efficiency represents the ratio of total flow divided by total consumed energy in (m^3/ [kWh/m^3]).

The flow efficiency versus sand content under 10 and 15V is shown in Figure (5.44). As can be seen from this figure, there was a gradual increase in the flow efficiency with the increase in sand content; from about 3.6 (m^3/ [kWh/m^3]) for pure bentonite to 4.1 (m^3/ [kWh/m^3]) for 50% sand with bentonite when 10V was applied in a net treatment time of 168 hours and it was approximately the same value with 67% sand in a treatment time of 264 hours. While the figure shows that there has been a gradual decrease in the flow efficiency with the increase in sand content for 15V; from about 2.4 in a treatment time of 96 hours to 1.6 (m^3/ [kWh/m^3]) for 67% sand in a net treatment time of 264 hours.

This inconsistency in the behaviour between 10V and 15V are likely to be related to the variation in the time of electroosmotic process and the consumed energy presented in Table (5.2). In addition to that, when 15V was applied the power supply has reached the maximum designed current capacity (4 Amp) which cause a drop in the power. This leads to reduce in the calculated efficiency factor.

Figure (5.45) shows the results obtained for variation of electroosmotic flow efficiency in pure bentonite verse the applied voltage. From this figure, it can be seen that the greatest value for electroosmotic flow efficiency was when 5V was used; 12.8 m^3/ [kWh/m^3], and the flow efficiency decreases with the increase in the applied voltage, 3.6 and 2.4 m^3/ [kWh/m^3] for 10 and 15V respectively.

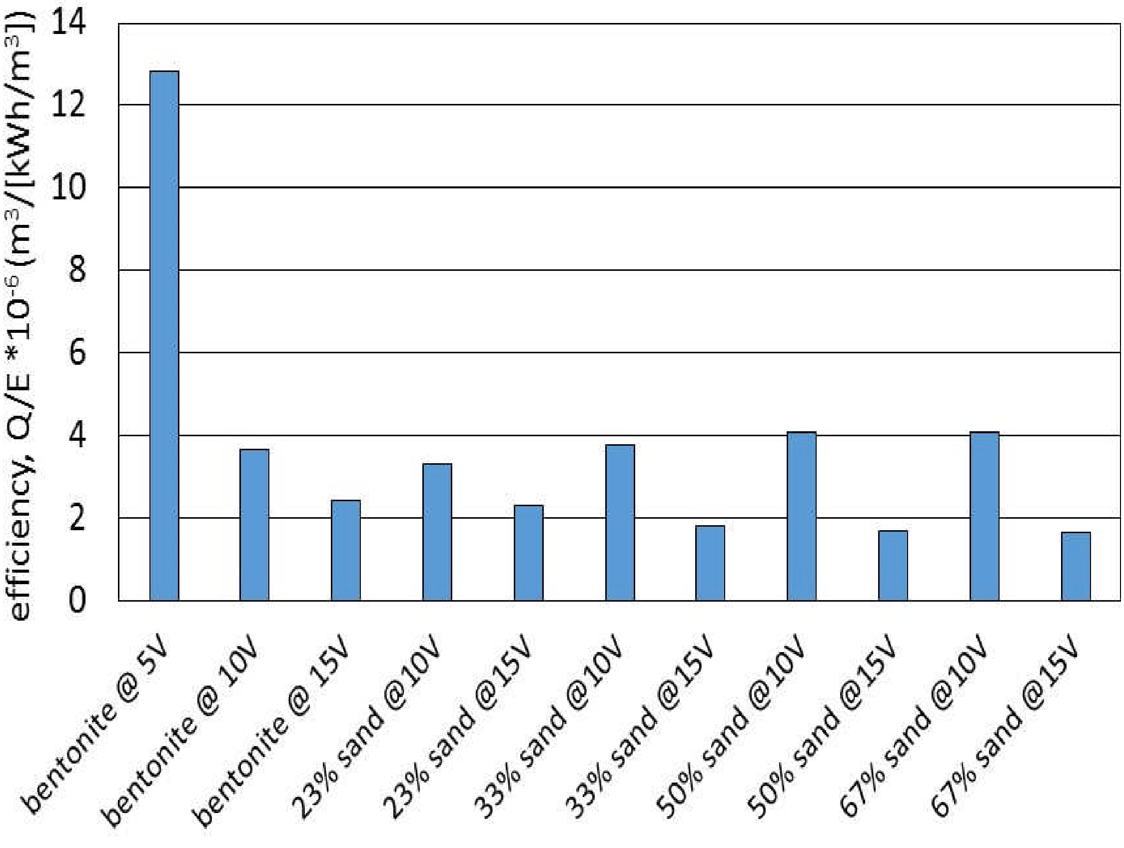


Figure 5.43 Electroosmotic flow efficiency (Q/E)

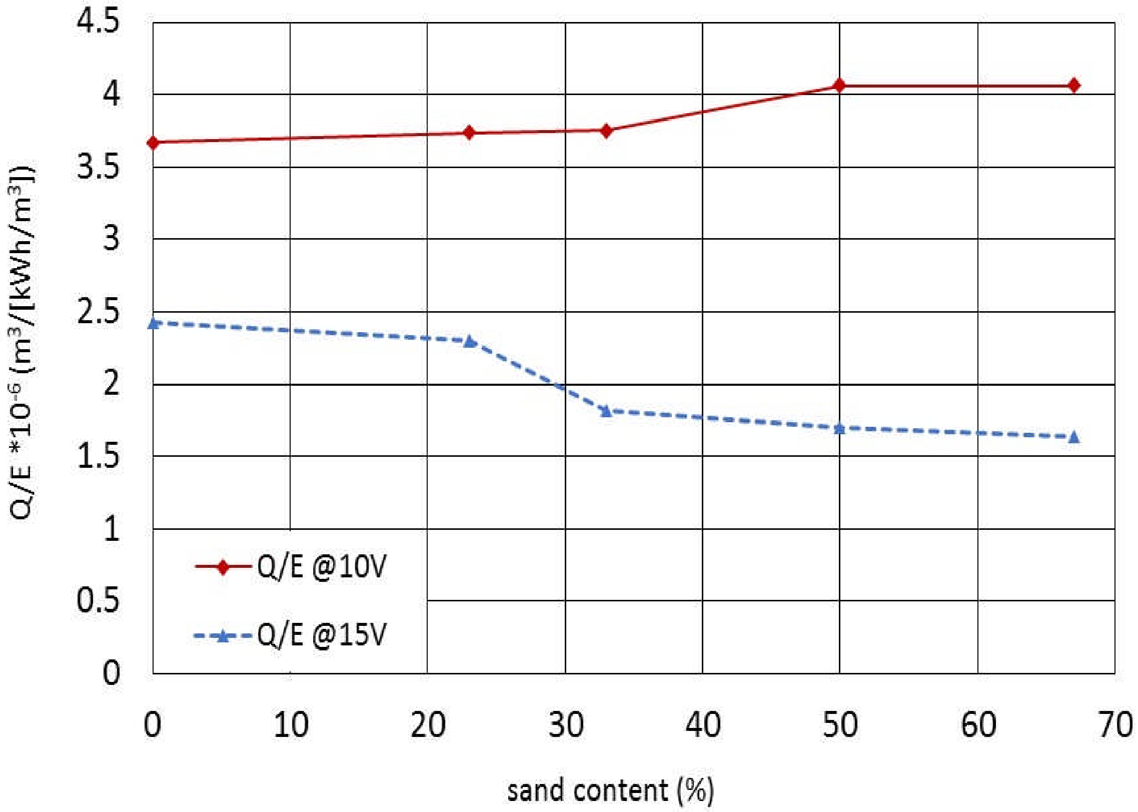


Figure 5.44 Electroosmotic flow efficiency (Q/E) vs sand content for 10 and 15V

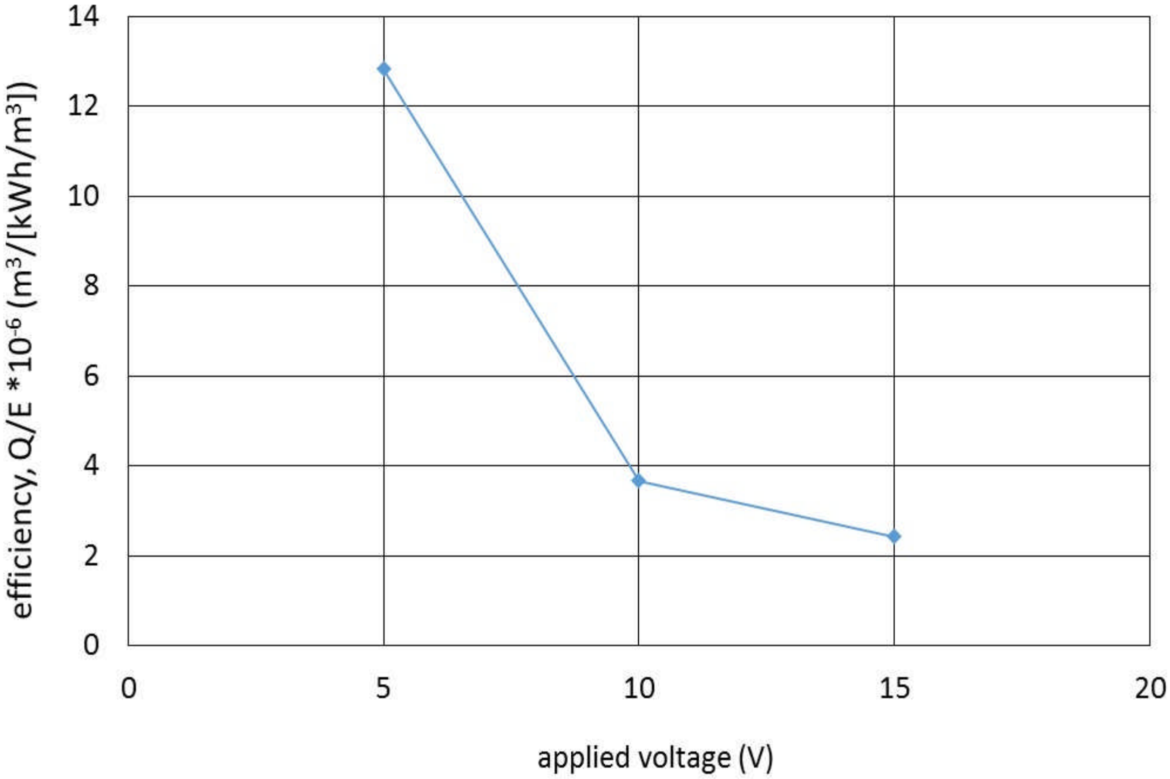


Figure 5.45 Electroosmotic flow efficiency (Q/E) vs applied voltage in pure bentonite

5.4.3 Electroosmotic transport efficiency, k_i

In electroosmotic treatment design, the electroosmotic transport efficiency is defined as water flow transferred per electric unit charge passed in gal/amp-hour, (Gray and Mitchell, 1967). The electroosmotic transport efficiency ki can described by equation as mentioned in section 4.4.3:

$$ki = \frac{Q}{It} \tag{5.3}$$

Where: Q = total water expelled (gal); I = mean current passed through soil sample (Ampere); and t = total time (h).

According to (Mitchell and Soga, 2005), electroosmotic water transport is used to estimate the efficiency of electroosmosis dewatering, and it is as a function of water content, soil type, and electrolyte concentration.

The results for the electroosmotic transport efficiency obtained from electroosmotic tests for all soil was presented in Figure (5.46). Figure (5.47) shows the transport efficiency verse sand content for 10 and 15V.

It is apparent that the values of electroosmotic transport efficiency increased with the increase in sand content when 10V was applied, from 0.65 to 0.72 (gal/Am.hr)*10^{-3} for pure bentonite and 67% sand with bentonite respectively. When 15V was used, the electroosmotic transport efficiency values ranged between 0.65 *10^{-3} gal/Am.hr for pure bentonite during 96 hours treatment time, as the maximum current of the power supply was reached, and 0.72 *10^{-3} gal/Am.hr for 67% sand with bentonite in a treatment time of 264 hours.

Figure (5.48) displays the variation of electroosmotic transport efficiency k_i with the change in applied voltage in pure bentonite. It can be seen that that there has been a sharp drop in the k_i value when the voltage raised from 5 to 10V, (1.14 x10^{-3} gal/Am.hr), then dropped to (0.65x10^{-3} gal/Am.hr) at 10V, and there was no difference between the k_i value when the voltage was raised to 15V.This can be related to the difference in the time of treatment until complete degradation of the electrode (168 hours for 10V and 96 hours for 15V).

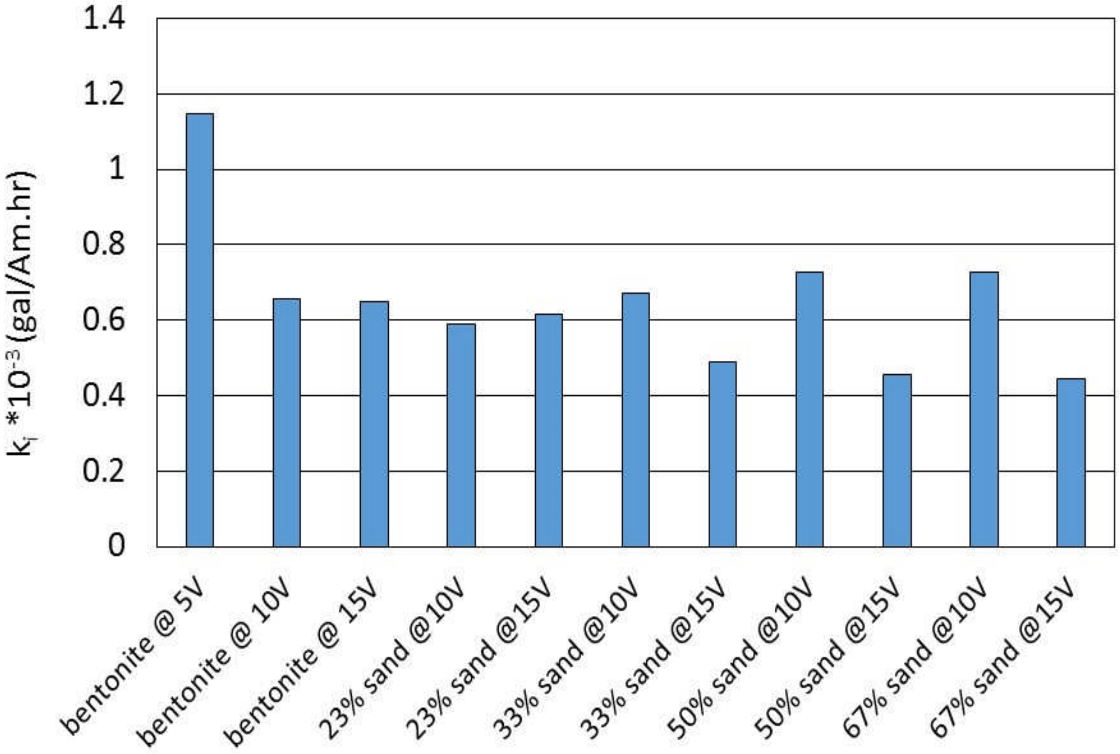


Figure 5.46 Variation of electroosmotic transport efficiency (k_i) vs sand content for different applied voltages

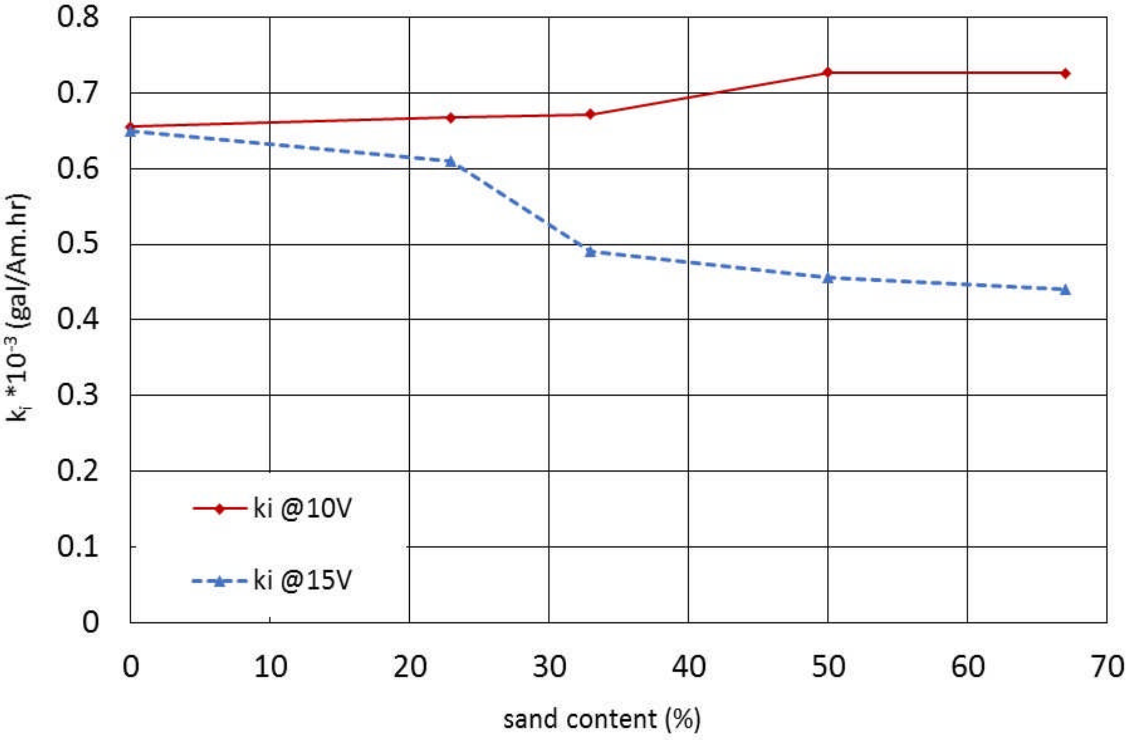


Figure 5.47 Variation of electroosmotic transport efficiency (k_i) vs sand content for 10 and 15V

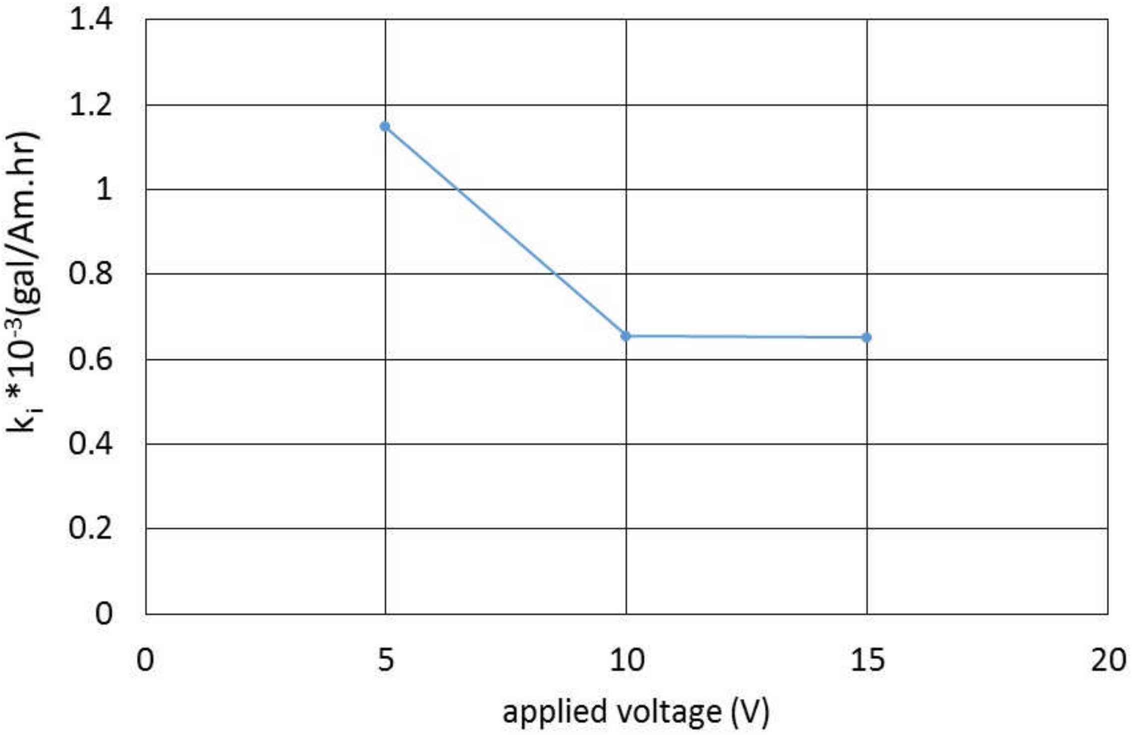


Figure 5.48 Variation of electroosmotic transport efficiency (k_i) vs sand content for 10 and 15V

5.5 Summary

The results of electroosmotic treatment of composite soils (bentonite and sand mixtures) were presented and discussed in this chapter. The electroosmotic treatment tests included two variables; sand content and applied voltage. Vertical displacement, discharge water, electric current, and voltage loss were analysed. The results and conclusions are summarized as follows:

- The electroosmotic treatment generated a significant dewatering effect on the bentonite and sand soil slurry. The water discharged by the electroosmotic treatment process decreased as the sand content increase.
- There is a noticeable increase in settlement due to applying DC power. The settlement increased as the applied voltage increased for the same soil mix, which means the amount of settlement is a function of the voltage density.
- Swelling occurs during the electroosmotic phase due to the applied electrical current, maximum swelling was occurred at about 8 hours from the beginning

of Phase 2, the swelling decreases as the sand content increase, increasing applied voltage cause increase swelling.

- The maximum value of current was about double the value when the voltage was applied regardless of the sand content. After about 10 hours, the current drops until reached zero when the anodes are completely degraded.
- There was a significant decrease in the average water content of the treated samples after the electroosmotic treatment, (28% for pure bentonite and 25% for 67% sand) A clear decrease in the water content was found at the vicinity of the anodes and between anodes and cathode, there was no significant change in the water content at the cathode from the initial water content compares to the anodes area.
- The electroosmotic permeability k_e, as measured under different applied voltages decreases with treatment time and increase with applied voltage. However, the coefficient of electroosmotic permeability in bentonite is lower than reported for other soils. The electroosmotic permeability k_e values varied between 1.8 $\times 10^{-10}$ m^2/sV and 1.57 $\times 10^{-10}$ m^2/sV for pure bentonite to 0.89×10^{-10} m^2/sV 0.72×10^{-10} m^2/sV for 67% sand content subjected to 10 and 15V respectively.
- Soil temperature increased when an electrical power was applied and drops when the anodes are degraded. The highest increase in temperature was found in pure bentonite when 15V was applied, from 18ºC to 62ºC after about 8 hours from the beginning of electroosmotic phase. The generated temperature decreases as the sand content increased. These results show that the heat developed due to applying DC power is a function of voltage and soil type.

Chapter 6

Comparison and Assessment of Kaolin and Bentonite Soil Mixtures Behaviour under Electroosmosis Treatment

6.1 Introduction

This chapter aims to investigate and compare the effects of electroosmotic treatment on properties of two types of clay soils (kaolin and bentonite), mixed with different percent of sand (23, 33, 50, and 67%) as described in chapters 4 and 5. The particle size distribution curves of these composite soils are presented in Figures (6.1) and (6.2) for kaolin and bentonite mixtures respectively. Some physical properties of the clays are given in table (6.1), the liquid limit and the initial water content of the soil mixture are shown in Figure (3.3).

The experimental works were repeated under different applied voltages to study and compare the effects of electroosmosis consolidation on the voids ratio and water contents, electrical current flow, electroosmotic permeability, temperature, consumed and lost energy, and electroosmotic transport efficiency.

Table 6.1 Physical properties of the clays used in the experiments

soil properties	Kaolin	Bentonite
Liquid Limit (I_L) (%)	53	106
Plastic Limit (I_P) (%)	34	51
Plasticity Index (PI) (%)	19	55
Specific gravity , Gs	2.6*	2.65*
Soil Classification	MH	MH

*obtained from manufacturer's documentation

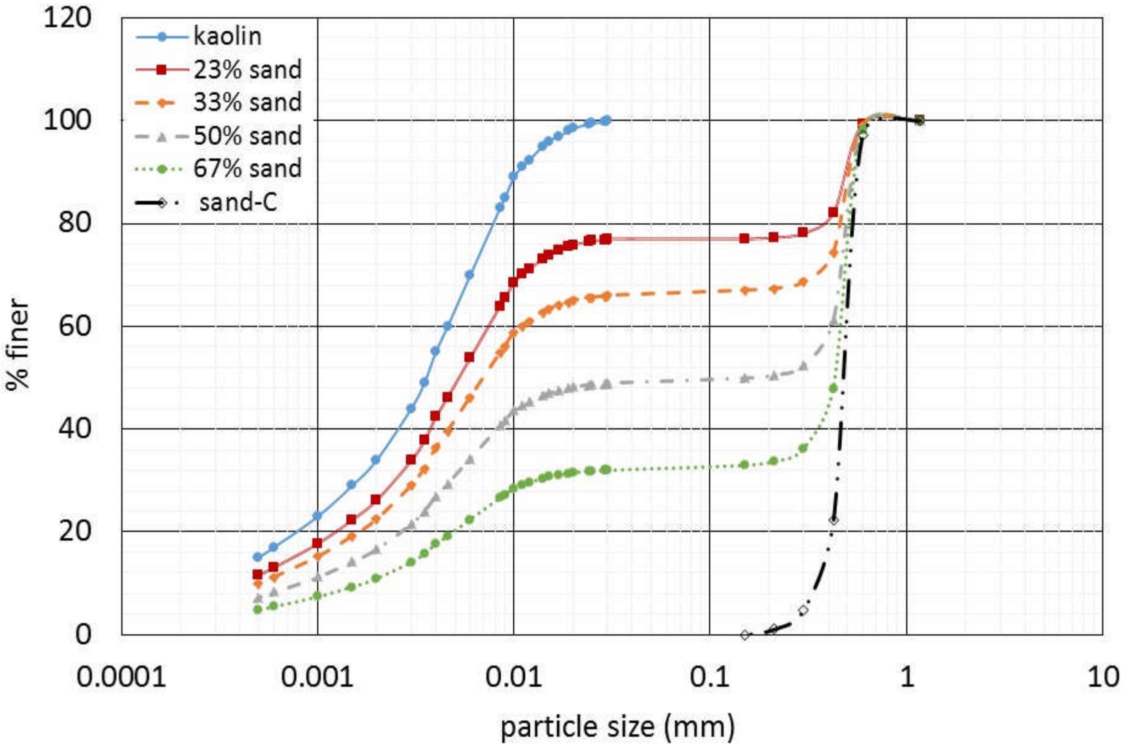


Figure 6.1 Particle size distribution curve for kaolin and sand soil mixture

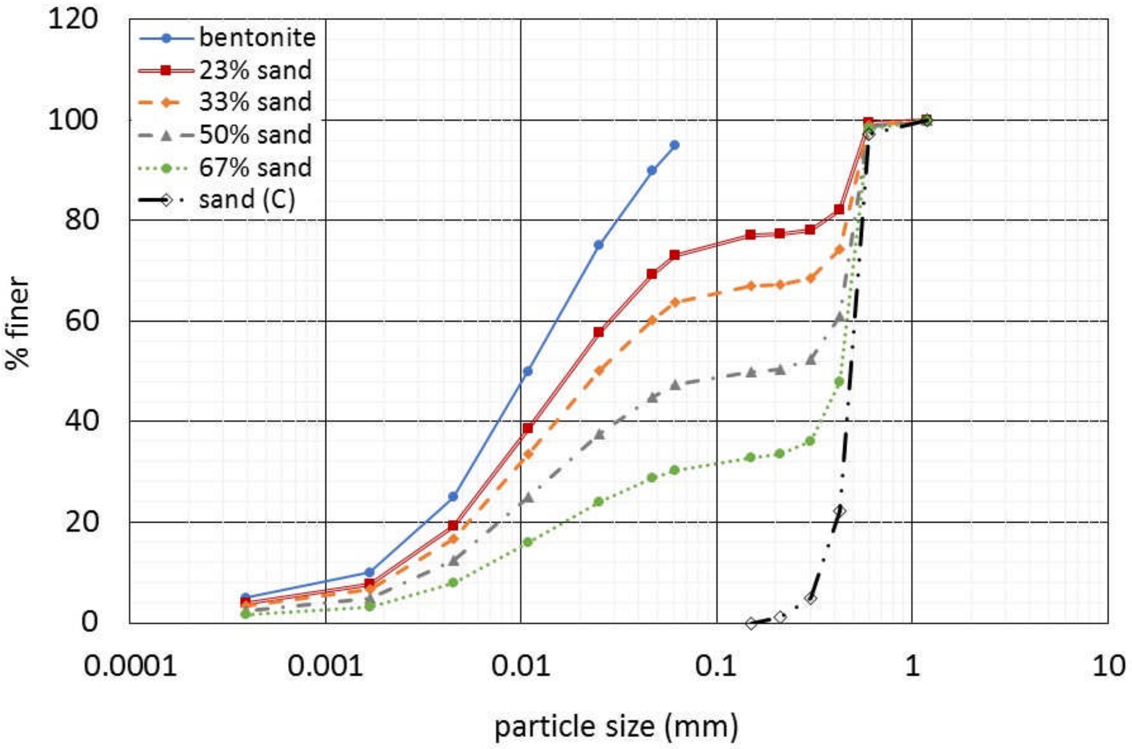


Figure 6.2 Particle size distribution curve for bentonite and sand soil mixture

6.2 Factors affecting the electroosmotic treatment

There have been limited studies investigating the electroosmotic treatment in a range of composite soils, and the variation of sand content with kaolin and bentonite soils, factors that affecting the electroosmotic processing are discussed in this section.

6.2.1 Water content and voids ratio

Variation of water content due to the electroosmotic treatment at the end of Phase 2 compared to the initial water content across the kaolin and bentonite soil mixtures for 10 and 15 applied voltage are presented in Figure (6.3). Note that the water content values was calculated from the expelled water at the end of Phase 2.

The variation of water content with water content at the end of Phase 2 showed similar trends for both kaolin and bentonite mixtures due to the increase in the applied voltages, though the flow through the bentonite specimens was lower. The trend in kaolin soil mixes shows a clear change when the sand content used is >33%. In bentonite mixtures, the change of water content decreases as the sand content increased up to 50% sand, then the trend increase again with 67% sand in both 10V and 15V due to the higher treatment time (264 hours) compared to other mixes, as described in Table (5.2).

It can be seen from Figure (6.4) that the reduction in water content expressed as the change in water content at the end of Phase 2 (w_2) over the water content at the end of Phase1(w_1) for kaolin soil mixtures was greater than that for bentonite for all mixes.

Moreover, the general trend of the change in water content through the composite soils shown in Figure (6.4) seems to be decreasing with the augmentation of the sand content in both soils. The irregularity in the trend recorded at 67% sand with bentonite can be related to the longer time of treatment (264 hours) compare to other bentonite mixture (96 hours for pure bentonite), as mentioned in Chapter 5.

However in both soils, with increasing the applied voltage, the electroosmotic flow through the soil samples increased, the change in water content in Phase 2/ water content at the end of Phase1 was 0.21 and 0.27 for pure kaolin at 10 and 15V respectively, compared to 0.085 and 0.096 for pure bentonite, as shown in Figure (6.4).

Figure (6.5) presents the results of the volumetric strain (change in voids ratio at the end of Phase 2 over the voids ratio at Phase 1) for kaolin and bentonite soil mixtures at 10 and 15 applied voltage. According to Figure (6.5), kaolin soil mixtures showed higher rate of volumetric strain compared to bentonite soil mixtures. Furthermore, the figure shows that there has been a marked decrease in the volumetric strain with the increase in sand content in kaolin soil mixtures, and there was a slight decline in bentonite soil mixtures for both applied voltages (10 and 15V) for the initial water contents used in these experiments. The results showed that the variation of water content and thus the voids ratio of the electroosmotically treated composite soils depends on the properties of the soils, such as, permeability characteristics, clay type, sand content, and time of treatment. Note that the initial water content was different for each soil mix. The initial water content reduced as the sand content increased. The final water content reduced as the sand content increased. The final water content was less than the initial water content throughout the whole sample but the reduction in water content was greater at the anode because of electroosmosis. These results seem to be consistent with those obtained by Mosavat *et al*. (2012), who found that electroosmotic treatment is more effective on clay soils that contains 30% or more particle size less than 2µm (34% for pure kaolin and 18% for pure bentonite). This suggests that electroosmotic treatment is more effective on soils with moderate plasticity like kaolin soils than those with high plasticity like bentonite soils. The effect of electroosmotic flow through kaolin and bentonite clay soil under different applied voltage was also studied by Jayasekera (2004a) who found that, the flow though kaolin soil specimens was higher than that for bentonite specimens under the same applied voltage.

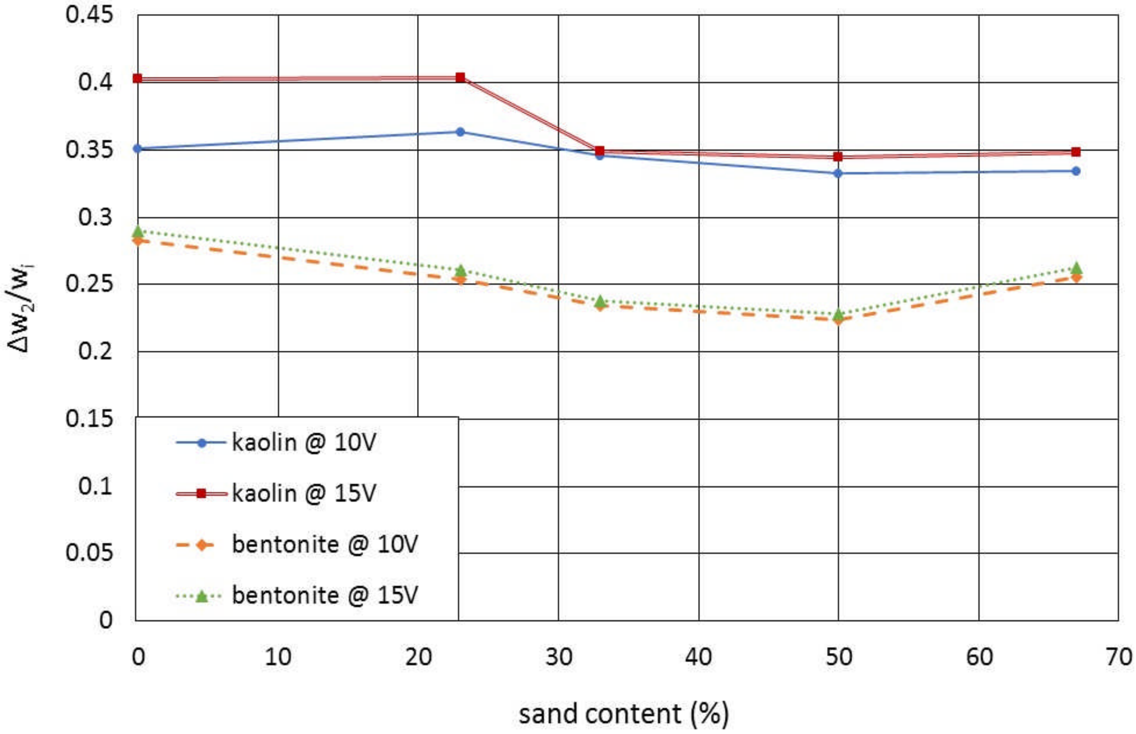


Figure 6.3 Effect of sand content and applied voltage on the variation of water content at the end of Phase 2 (w_2) over the initial water content (w_i)

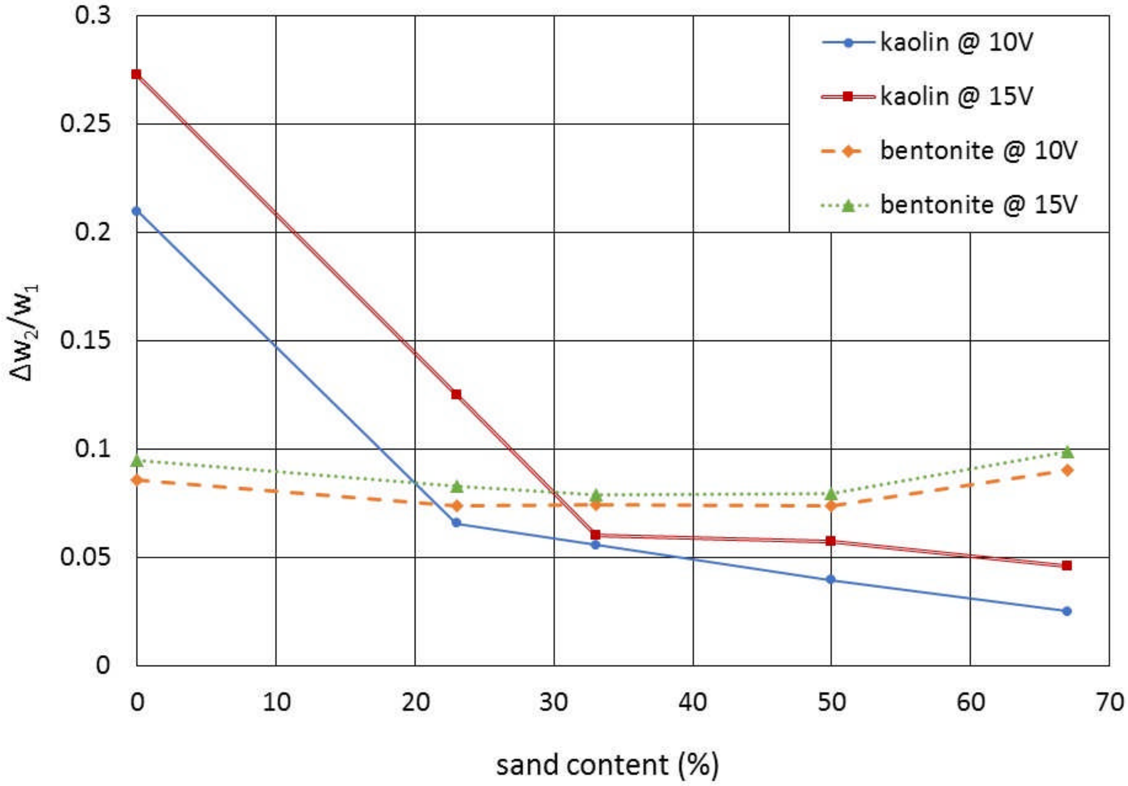


Figure 6.4 Effect of sand content and applied voltage on the variation of water content at the end of Phase 2 (w_2) over the water content at the end of Phase1(w_1)

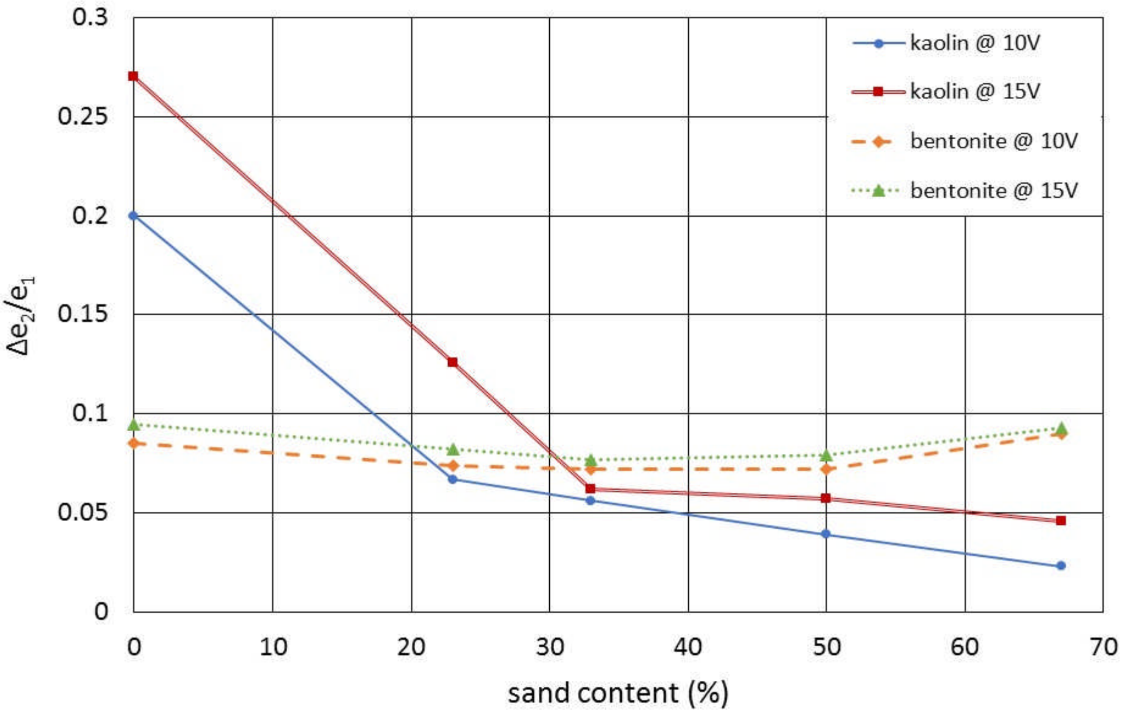


Figure 6.5 Variation of voids ratio at the end of Phase 2 (Δe_2) over the voids ratio at the end of Phase 1 (e_1)

6.2.2 Variation of electrical current

The variation of electric current and power consumption over time across the kaolin and bentonite soil mixtures was presented in Chapter 4 and Chapter 5, sections (4.3.2) and (5.3.2) for kaolin and bentonite mixtures respectively. This section compares the maximum electrical current measured during the electroosmotic phase as shown in Figure (6.6).

From this figure, it is observed that for all soil mixtures and applied voltages, the maximum current value decreases with the increase of sand content, note that the electrical current values for bentonite soil mixed with sand up to 50% showed constant value (4 Amperes) which is the maximum capacity of the DC power supplier used during the experimental test. According to Figure (6.6), kaolin soil mixtures showed lower electric current through the soil sample compared to the bentonite soil mixtures. Moreover, the electric current through the soils is higher for 15V than that at 10V.

Comparison of the above findings with those of other studies confirms that the variation of electrical current during electroosmotic process depends on electrochemical properties of the treated soils; soils with higher electrical conductivity, such as bentonite require higher electrical currents than soils with lower electrical conductivity, such as kaolin (Mosavat et al., 2012).

Acar and Alshawabkeh (1993) and Mosavat et al. (2013b) showed that electroosmotic treatment is preferable in soils that show low adsorption and lower buffering capacity because of lower cation exchange capacity, such as kaolin compared with other clay having high adsorption and high cation exchange capacities, such as bentonite.

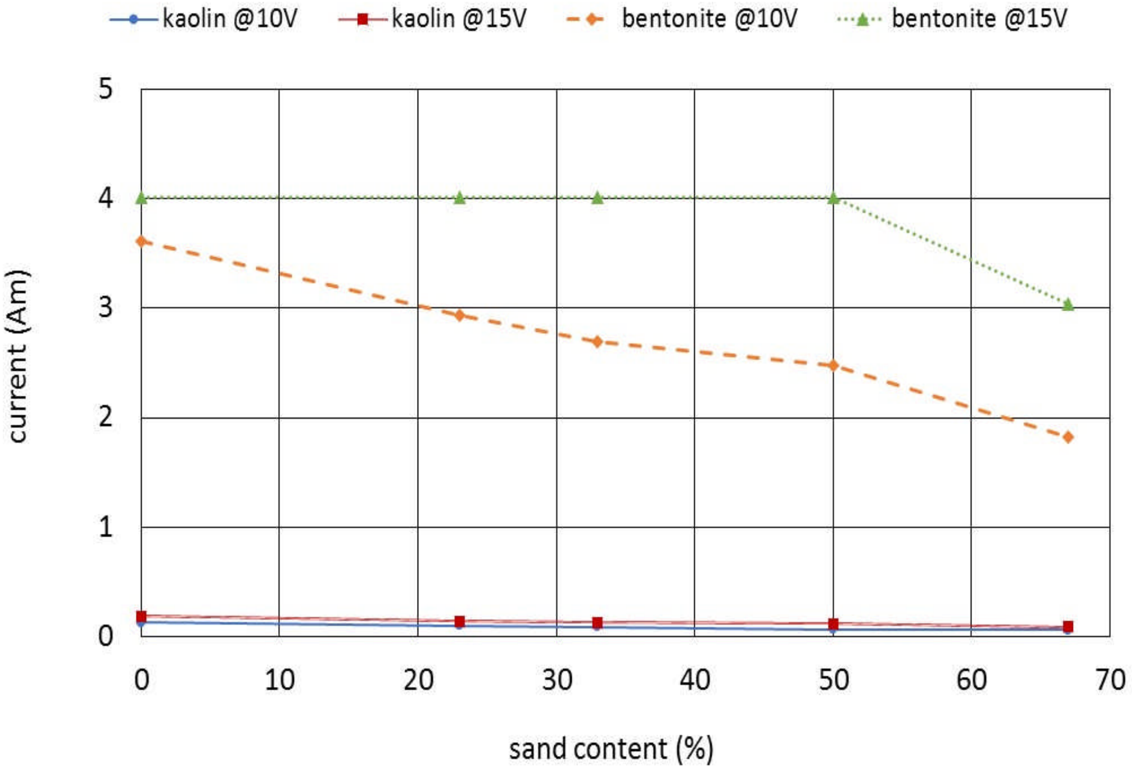


Figure 6.6 Variation of maximum electric current for kaolin and bentonite soil mixtures at 10 and 15V (Note that the maximum current in the power supplier unit was reached, 4 Amperes)

6.2.3 Electroosmotic permeability ratio k_e/k_h

In the application of electroosmotic treatment to engineering practice, the coefficient of electroosmosis permeability k_e, plays an important role in the form of the ratio k_e/k_h, where k_h is the coefficient of hydraulic permeability. The electroosmotic permeability coefficient k_e, controls the flow of water in a soil mass under an electrical gradient, while the flow in soil under a hydraulic gradient is controlled by the hydraulic conductivity k_h.

Mohamedelhassan and Shang (2002) stated that the electroosmosis permeability ratio (k_e/k_h), is an important parameter that controls the effectiveness of the electroosmotic consolidation in terms of determining the generated negative pore water pressure, as shown in equation (6.1).

$$u = \frac{k_e}{k_h} \gamma_w V \qquad (6.1)$$

Where γ_w the unit weight of water, and V is the applied voltage.

Arnold (1973) reported that it is more convenient to measure k_e and k_h values independently, as the direct measurement of the ratio k_e/k_h, involves practical problems caused by electrochemical effects at the electrodes. The determination of k_e has been discussed in Chapter 4 and Chapter 5 for kaolin and bentonite soil mixtures respectively. Figure (6.7) compares the experimental result for k_e values in kaolin and bentonite mixtures with the variation of sand content. It is clear from this figure that there are significantly high k_e values reported for kaolin soil mixtures compared to the bentonite. The figure also shows that there has been a marked decline in the electroosmosis permeability in kaolin and bentonite soil mixtures at 10 and 15V with the increase in sand content.

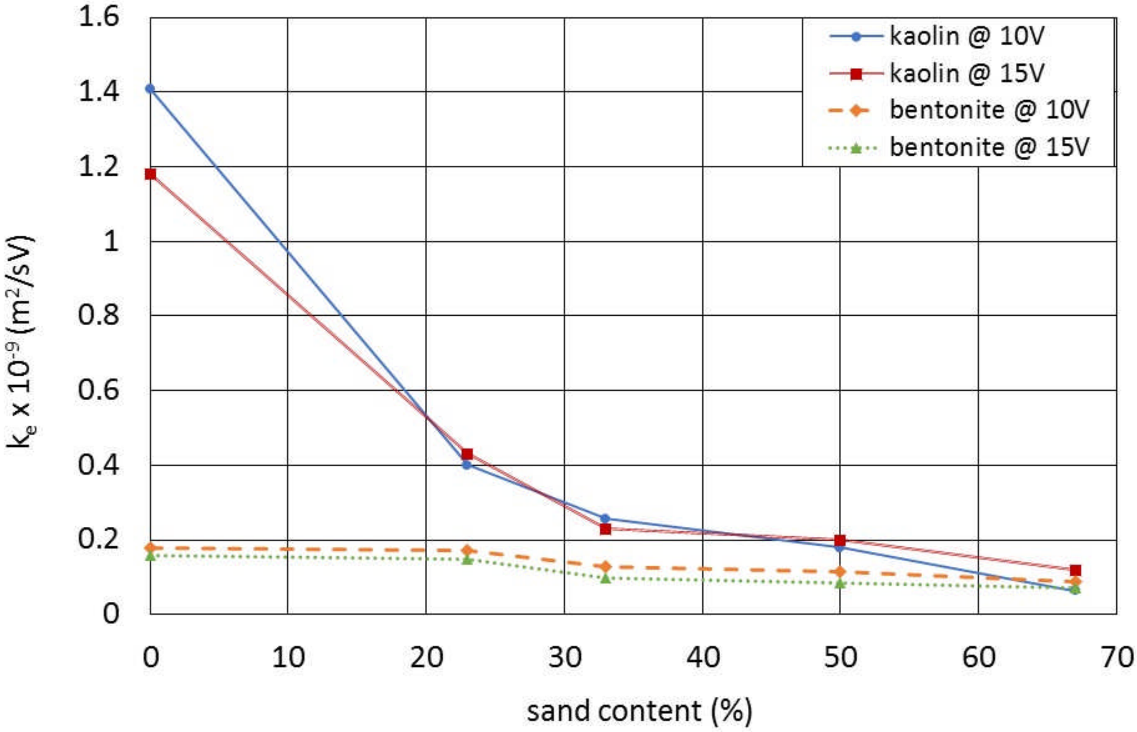


Figure 6.7 Variation of electroosmosis permeability, k_e with sand content in kaolin and bentonite soil mixtures at 10 and 15V

The variation in the electroosmosis permeability values between the type of soil (kaolin and bentonite) at different sand content could be attributed to variation of electrical conductivity of the soils. High electrical conductivity soil, such as bentonite exhibits less electroosmotic behaviour than soils with lower electrical conductivity, such as kaolin. These results seem to be consistent with (Mosavat et al., 2013b) findings, which showed that the electroosmotic permeability of kaolin soil was higher compared to the bentonite soil.

To investigate the electroosmotic permeability ratio parameter, the hydraulic conductivity of each soil mixture should be calculated. The hydraulic conductivity of the composite soil may vary significantly with the change in sand content.

Chapuis (2012) reviewed and assessed 45 predictive methods to study the saturated hydraulic conductivity of soils, who found that there are three reliable methods working fairly well for non-plastic soils; (Methods of Hazen (1892) coupled with Taylor (1948), Method of Kozeny- Carman (Chapuis and Aubertin 2003) and (Chapuis, 2004)). For plastic soils, the most reliable methods suggested by the author are (Methods of Kozeny- Carman (Chapuis and Aubertin, 2003), and of (Mbonimpa et al., 2002).

In this study, the saturated hydraulic conductivity of kaolin soil mixed with sand up to 23% was calculated according to the equation (6.2) below for plastic soils suggested by (Mbonimpa et al., 2002):

$$k_h = Cp \frac{\gamma_\omega \;\; e^{3+x} \;\; 1}{\mu_\omega \; 1 + e \; \rho_s^2 \; w_L^{2x}} \tag{6.2}$$

Where k_h in cm/s, Cp = 5.6 g^2/m^4, γ_ω = 9.8 kN/m^3, μ_ω= 10^{-3} Pa.s, x = 1.5, ρ_s in kg/m^3, w_L in %.

Whereas, the hydraulic conductivity of kaolin soil mixed with sand more than 33% was calculated according to the equation (6.4) below suggested by (Chapuis, 2004) for non- plastic soils (Figure 3.4) Casagrande plasticity chart for kaolin soil mixtures :

$$k_h = 2.4655 \left(\frac{d_{10}^2 \;\; e^3}{1 + e} \right)^{0.7825} \tag{6.3}$$

The hydraulic conductivity values for bentonite and sand soil mixtures also was calculated according to equation (6.3) for plastic soils (Figure 3.5) Casagrande plasticity chart for bentonite soil mixtures:

Table (6.2) shows the calculated hydraulic conductivity values for kaolin and bentonite soil mixtures k_h in (m/s). As can be seen from the table that the hydraulic conductivity values for soil mixes increase with the increase in the sand content. This is obvious since the hydraulic conductivity depends on the pore sizes, and the distribution and interconnections of the pores.

The results obtained for (k_e/k_h) values can be compared in Figure (6.8). The figure shows that there is a reduction in the electroosmotic permeability ratio as the sand content increases in a similar trend to k_e values in Figure (6.7).

It is noticeable from the figure the sharp drop on the electroosmotic permeability ratio when sand was added to kaolin; from (0.7 and 0.6 m/V) for pure kaolin at 10 and 15V respectively, to about 0.26 and 0.28 m/V for both applied voltage when 23% sand used with kaolin, then the values reveals a steady decline until reaches about 0.02 and 0.04 for 67% at 10 and 15V respectively.

On the other hand, the electroosmotic permeability ratio for bentonite mixes shows a steady decrease with the increase in sand content; from 0.12 and 0.1 m/V for pure bentonite at 10 and 15V to about 0.03 when 67% sand was added to bentonite at the both applied voltages.

According to Mohamedelhassan and Shang (2001), the ratio k_e/k_h is the control of the effectiveness of electroosmotic consolidation. The electroosmotic permeability ratio (k_e/k_h) in (m/V) should be higher than 0.1 to generate significant electroosmotic dewatering, which, from Figure 6.8, suggests that any sand added to bentonite will make electroosmosis impractical; whereas, for kaolin, electroosmosis is possible up to 50% sand content. However, Figure 6.8 showed that electroosmosis works in all bentonite sand mixtures even though (k_e/k_h) was less than 0.1.

These results confirmed that the effectiveness of electroosmotic treatment is highly affected by the sand content and the type of soil.

Table 6.2 Summary of the calculated hydraulic conductivity values (k_h) in (m/s) and references

sand (%)	(k_h) for kaolin & sand	reference	(k_h) for bentonite & sand	reference
0	$1.97*10^{-9}$	Mbonimpa et al. (2002)	$1.5*10^{-9}$	Mbonimpa et al.(2002)
23	$1.51*10^{-9}$	Mbonimpa et al. (2002)	$1.79*10^{-9}$	Mbonimpa et al.(2002)
33	$1.76*10^{-7}$	Chuips (2004)	$2.05*10^{-9}$	Mbonimpa et al.(2002)
50	$1.91*10^{-7}$	Chuips (2004)	$2.17*10^{-9}$	Mbonimpa et al.(2002)
67	$3.11*10^{-7}$	Chuips (2004)	$2.31*10^{-9}$	Mbonimpa et al.(2002)

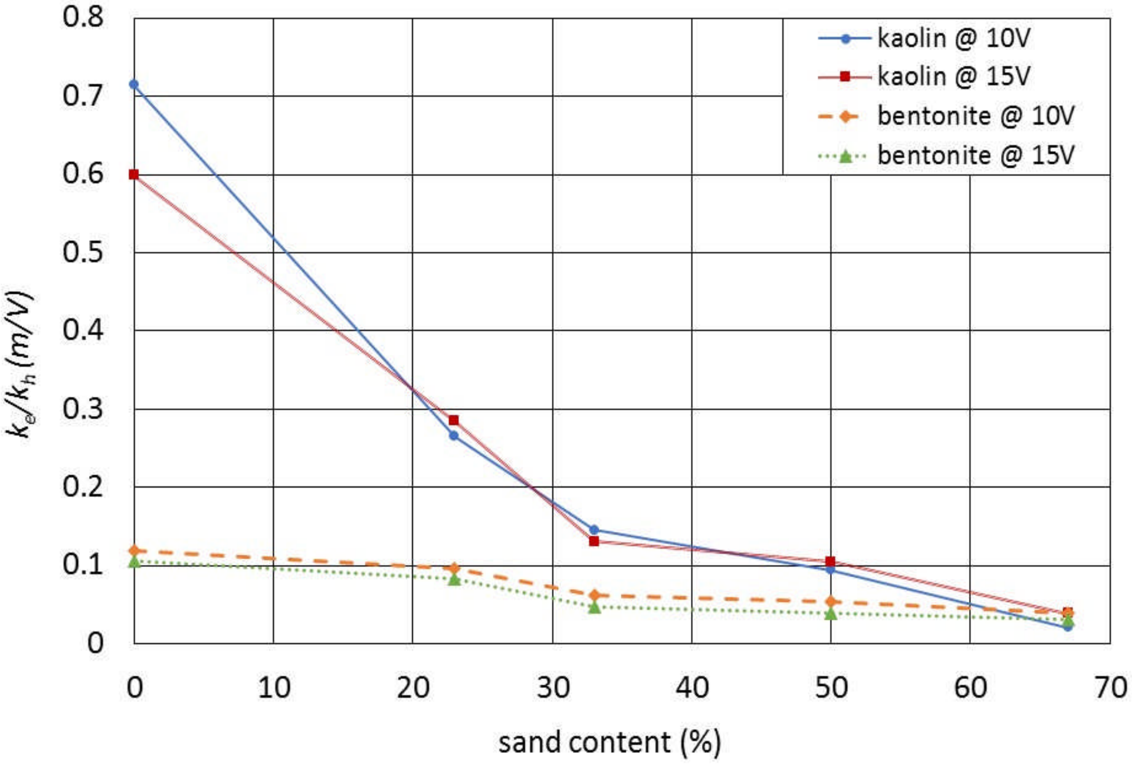


Figure 6.8 Variation of electroosmosis permeability ratio, (k_e / k_h) with sand content in kaolin and bentonite soil mixtures at 10 and 15V

6.2.4 Variation of generated heat

It is known that the application of an electric current to soils during the electroosmotic process causes an increase in soil temperature which has an adverse effect on the electroosmosis treatment, due to the increase in the required energy which leads to increase the treatment cost. The increase in soil temperature during electroosmosis processes has been reported by several researchers.

Hassan et al. (2018) stated that the continuous application of an applied voltage for a long treatment time leads to an increase in temperature of the soil, which enhances the degradation of the anodes. Rittirong and Shang (2014) declared that one of the most predominant effects during electroosmotic process is the generation of heat which increased the power necessary to complete the process. Mosavat et al. (2012) mentioned that one of the limitations during electrokinetic treatment is the excessive heat developed in the vicinities of the electrodes which can cause some adverse effects such as desiccation or cracking of the treated soil specimen.

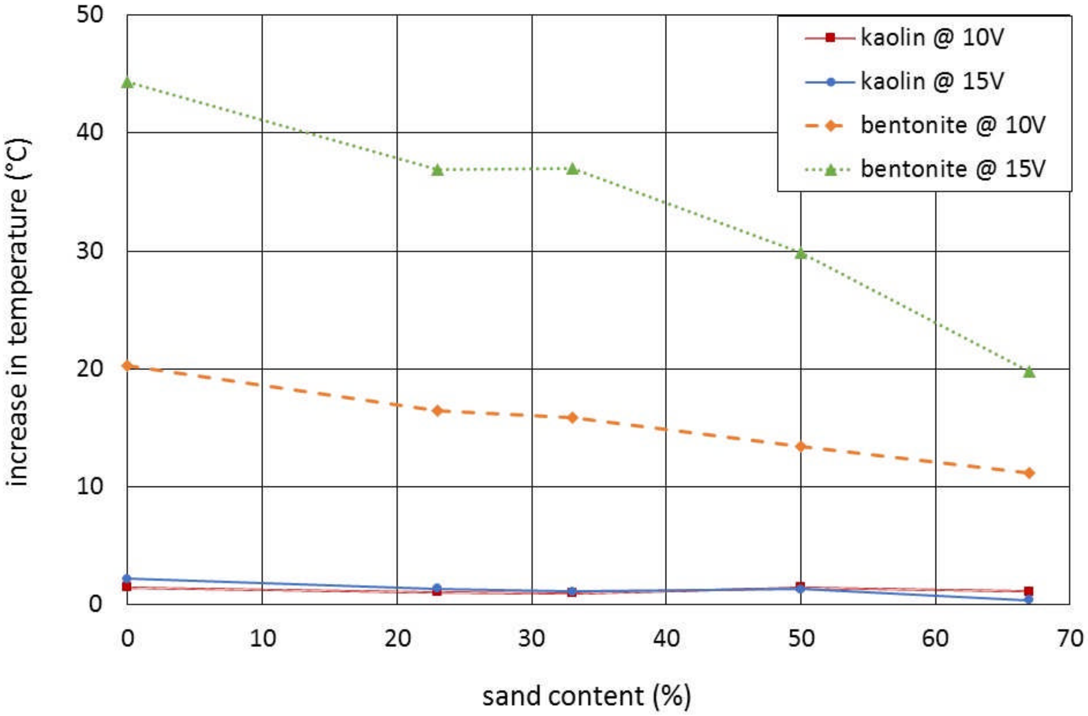


Figure 6.9 Maximum temperature increase for kaolin and bentonite soil mixtures at 10 and 15 applied voltage verses sand content

Figure (6.9) compares the variation of the maximum temperature increase in the kaolin and bentonite soil mixtures at 10 and 15 applied voltage. It can be clearly seen from this figure that the increase in temperature observed in sand and kaolinite soil mixtures during the electroosmosis process when 10 and 15V was applied was less than 2ºC, as mentioned in section (4.3.5). As Figure (6.9) shows, the increase in temperature observed in bentonite soil mixtures was much greater. It can be seen that the increase in the generated temperature is inversely proportional to the sand content, from nearly 20 and 44 ºC for pure bentonite at 10 and 15V respectively, to 11 and 20 for 67% sand. The maximum generated temperature is proportional to the applied voltage, as can be seen from Figure (6.10), the 15V reported significantly more temperature than the other two applied voltage, 5 and 10V in pure bentonite.

The observed variations in temperature of the electroosmotic treated soil mixes might be attributed to variations of the electrical conductivity and the dielectric permittivity of that soils. The variation in soil electrical conductivity also depends on the amount of moisture held by soil particles; for the tap water used in these experiments, the electrical conductivity is 0.0343 S/m. According to Grisso et al.

(2005), clay soils have a high electrical conductivity, silts have a medium electrical conductivity, and sands have lower electrical conductivity as shown in Figure (6.11).

Kaya (2001) mentioned that the dielectric permittivity of the soil slurry is dependent on soil mineral type, bentonite and kaolin soils show different electrical conductivity behaviour. The dielectric permittivity of kaolin of soils is lower than that bentonite, and the electrical conductivity values of kaolin are much lower than those of bentonite.

According to Kibria and Hossain (2017), the application of electrical field to clay soil results in charge separation around the diffuse double layer; as a consequence, the electrical conductivity depends on the specific surface area and surface electrical conductivity. Table (6.2) compares the electrical conductivity values measured by (Kibria and Hossain, 2017). In this study, given that bentonite mixes have higher electrical conductivity compare to kaolin mixes, and the electrical conductivity as mentioned by Grisso et al. (2005) is inversely proportional to the sand content. In addition, the water content held by bentonite soil mixes is much higher than that in kaolin soils; as a result, the increase in temperature recorded in pure bentonite was higher than other soil mixes.

Table 6.3 Electrical conductivity values of some soils after (Kibria and Hossain, 2017)

Clay type	Electrical conductivity: S/m
Sodium bentonite	0·15
Calcium bentonite	0·10
Kaolinite	0·02
Illite	0·07

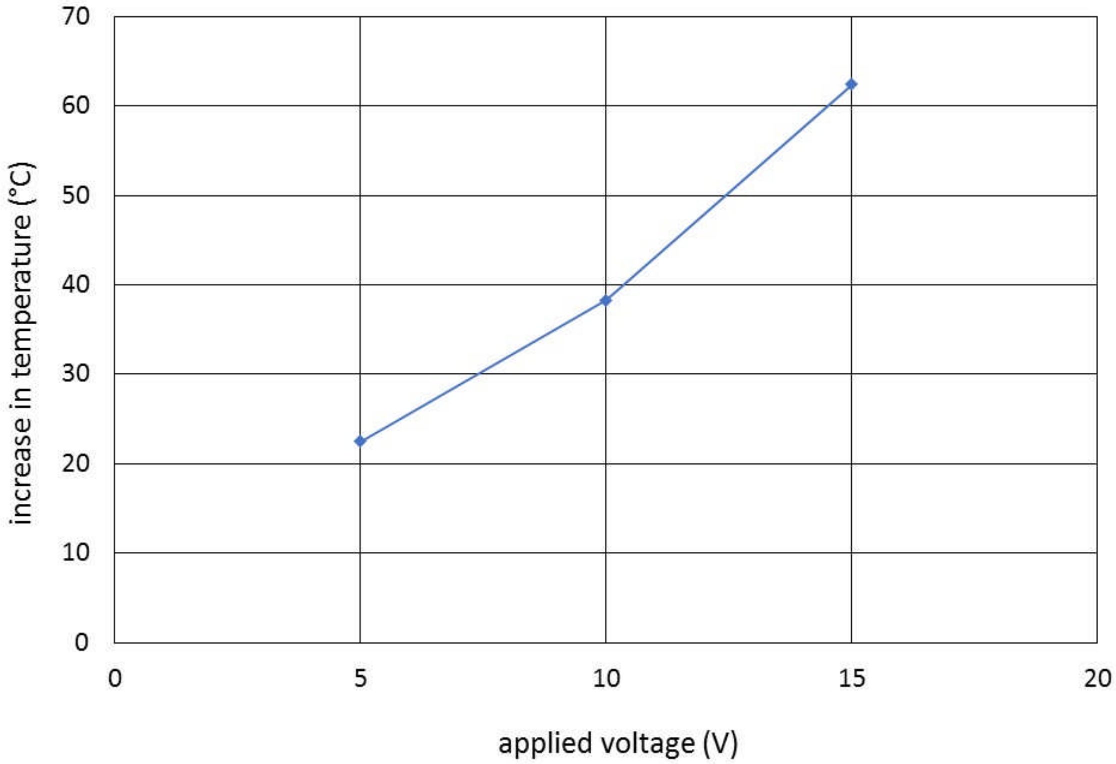


Figure 6.10 Variation of maximum temperature increase in pure bentonite versus the applied voltage

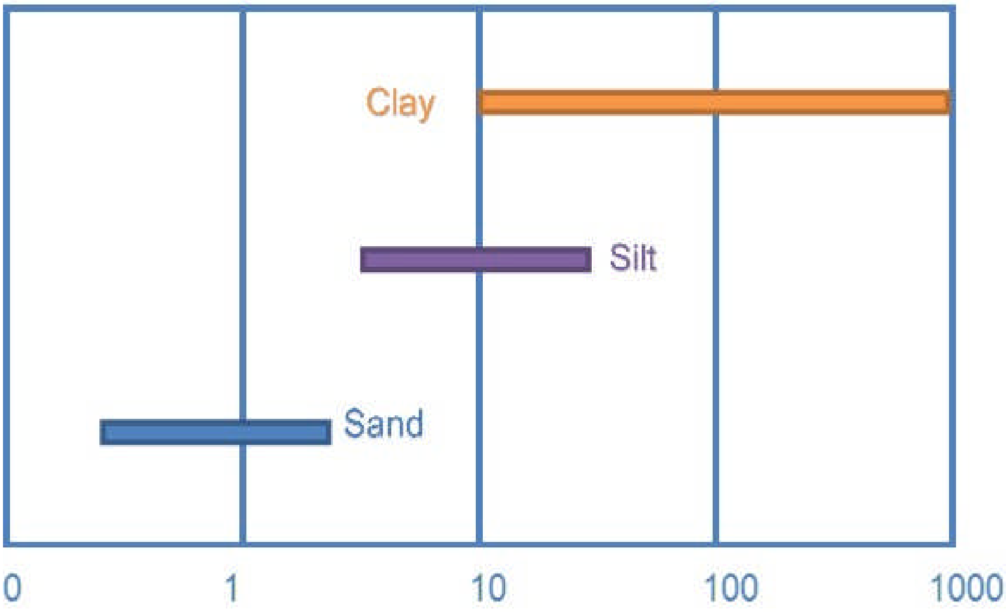


Figure 6.11 Soil electrical conductivity (MilliSiemens/meter) reproduced from (Grisso et al. (2005)

6.2.5 Consumed and dissipated energy

The energy required to complete the electroosmotic process is one of the important factors affecting the efficiency of electroosmotic treatment. Figure (6.12) compares the energy (E), in (kWh) during the electroosmotic process between kaolin and bentonite soil mixtures subjected to 10 and 15V, details of the energy calculation are described in Chapter 4 and Chapter 5. It is apparent that the bentonite soil mixes require more energy than that for kaolin soil mixes shown in more detail in Figure (6.13). The observed increase in consumed energy could be attributed to the dielectric permittivity, which is the ability of soil to store a charge (electrical energy) for an applied electrical field. As mentioned by (Kaya, 2001), the dielectric permittivity of bentonite is much higher than that of kaolin at given applied voltage. Generated heat during the electroosmotic process is another factor that increases the required energy.

Asavadorndeja and Glawe (2005) and Acar et al. (1994) found that the consumed energy in electrokinetic strengthening of soft soil is governed by the electrical conductivity of that soils. As the electrical conductivity of the soils increases, the energy expenditure for the treatment increases proportionally.

A number of authors have considered that some of the energy required during electro kinetic treatment is used to heat up the sample, (Rittirong and Shang, 2014), (Rittirong et al., 2008b), (Baraud et al., 1999), (Shang and Lo, 1997), (Acar and Alshawabkeh, 1996). The energy, Q, in (kJ) used to heat up the soil is given by:

$$Q = c_p \, m \, dT \tag{6.4}$$

Where c_p is the specific heat (kJ/kg°C), *m* is the weight of soil (kg), and dT is the temperature change as described in Section 4.3.5 and Section 5.3.5.

Specific heat capacity of soil (c_p) is one of the properties that controls temperature variations, and it is described as the ability of soil to absorb or release thermal energy. Clarke et al. (2008) defines the specific heat capacity as the amount of heat absorbed by a unit weight of soil due to temperature increase by one degree divided by the amount of heat absorbed by a unit weight of water when its temperature is raised by one degree.

Table (6.4) shows the specific heat capacity of various soils, it can be seen from the data in this table that the specific heat capacity of the dry soil particles is between 800 J/kg K for sandy soil, and 880 J/kg K for clay soil. Also, the saturated soils reported significantly more specific heat capacity values than the dry soils.

According to Bristow (1998), Clarke et al. (2008), and Alnefaie and Abu-Hamdeh (2013), the specific heat capacity (c_p) can be calculated as the sum of the heat capacities of the individual constituents, assuming homogeneous and isotropic medium at a uniform initial temperature. Thus, equation (6.4) can be rewritten as:

$$Q = \left[(c_s\, m)_{soil} + (c_w\, m)_{water}\right]dT \tag{6.5}$$

Note that the water content values and mass of water used to determine the energy lost in heating up the samples were based on the expelled water at the end of Phase 1(start of electroosmotic treatment phase). The volumetric heat capacity used to predict the energy losses due to heat generation was an average value for soil (c_s) 800 J/kg/ ºC, and for water (c_w) 4190 J/kg/ ºC.

The energy losses due to the increase in the generated heat accompanying the electroosmotic treatment for kaolin and bentonite soil mixtures are presented in Figure (6.14), and Figure (6.15) shows the lost energy in kaolin soil mixtures in more detail. It is apparent that the bentonite soil mixtures show significantly more energy loss as a result of the increase in temperature of the samples than the kaolin mixtures, and the losses decrease as the sand content increases. The decrease in the lost energy with sand content can be attributed to the decrease in heat developed with sand content increase described in section (6.2.4). Figure (6.16) presents the energy losses due to the increase in applied voltage in pure bentonite soil subjected to 5, 10, and 15V. The figure reveals that there has been a marked increase in the energy losses due to the increase in the applied voltage. This is an obvious behaviour since the temperature increased as the applied voltage increased.

The actual energy used in electroosmotic treatment which is calculated as the total energy minus the energy lost due to heating are presented in Figure (6.17) for all soil mixtures, and Figure (6.18) for kaolin soil mixtures. Comparing the above figures, the results suggest that there is an average losses of ranged between 5 to 20% in the consumed energy due to the heat generation during the electroosmotic treatments. It can be notice that more energy needed for bentonite soil mixes compared to kaolin due to the higher electrical conductivity of the former soil. These results match those observed by Asavadorndeja and Glawe (2005) and Acar et al. (1994).

Table 6.4 Summary of specific heat capacity values of various soils (after Clarke et al, 2008)

Soil type	Specific heat capacity: (J/kg K)
Kaolin (saturated.)	2362
Kaolin (dry)	800
Sandy CLAY	1696
Sandy CLAY	1459
Soft dark grey sandy gravely CLAY	1764
Soft grey fine sandy CLAY	2646
Soft grey fine sandy CLAY	2200
Stiff dark grey sandy gravely CLAY	1141
Stiff dark grey sandy gravelly CLAY	1125
Stiff grey-brown sandy gravelly CLAY	1104
Very soft grey fine sandy CLAY	2362
Grey slightly silty sandy GRAVEL	1175
Course SAND (dry)	800
Course SAND (saturated)	1483
Dark grey clayey fine sand/silt	1747
Fine SAND (dry)	800
Fine SAND (saturated)	1632
Made ground (silty gravely sand)	1270
Medium SAND (dry)	800
Medium SAND (saturated)	1483

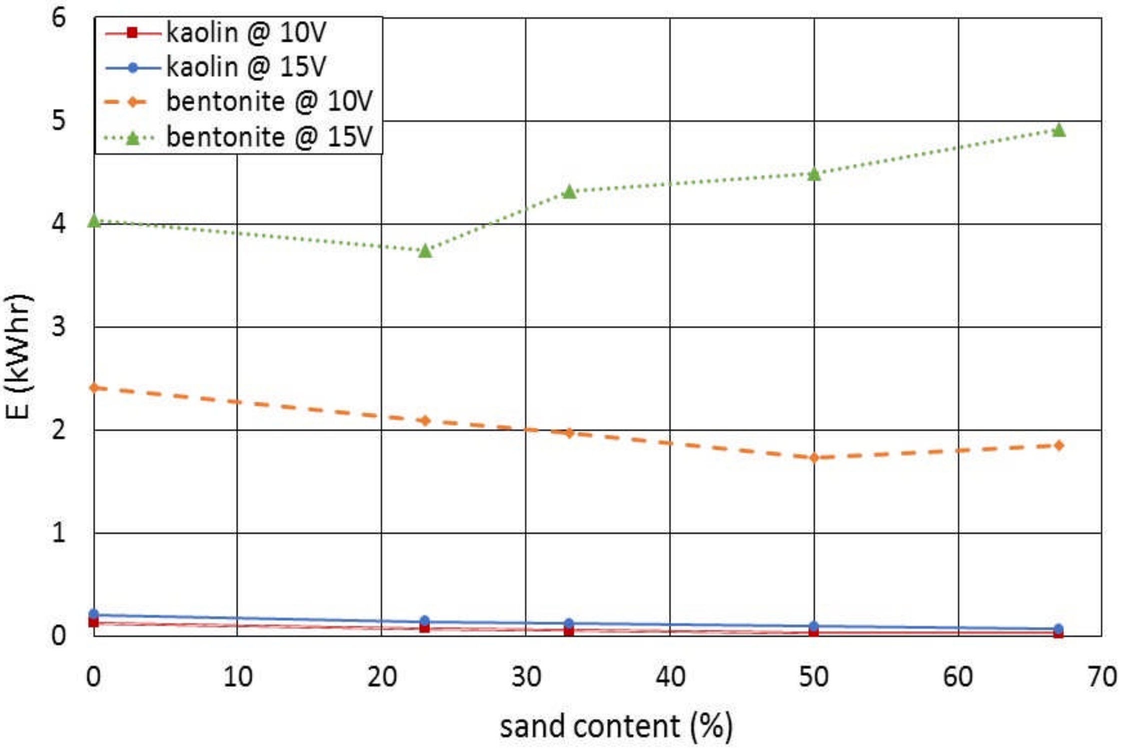


Figure 6.12 Consumed energy E in (kWh) vs sand content for kaolin and bentonite soils

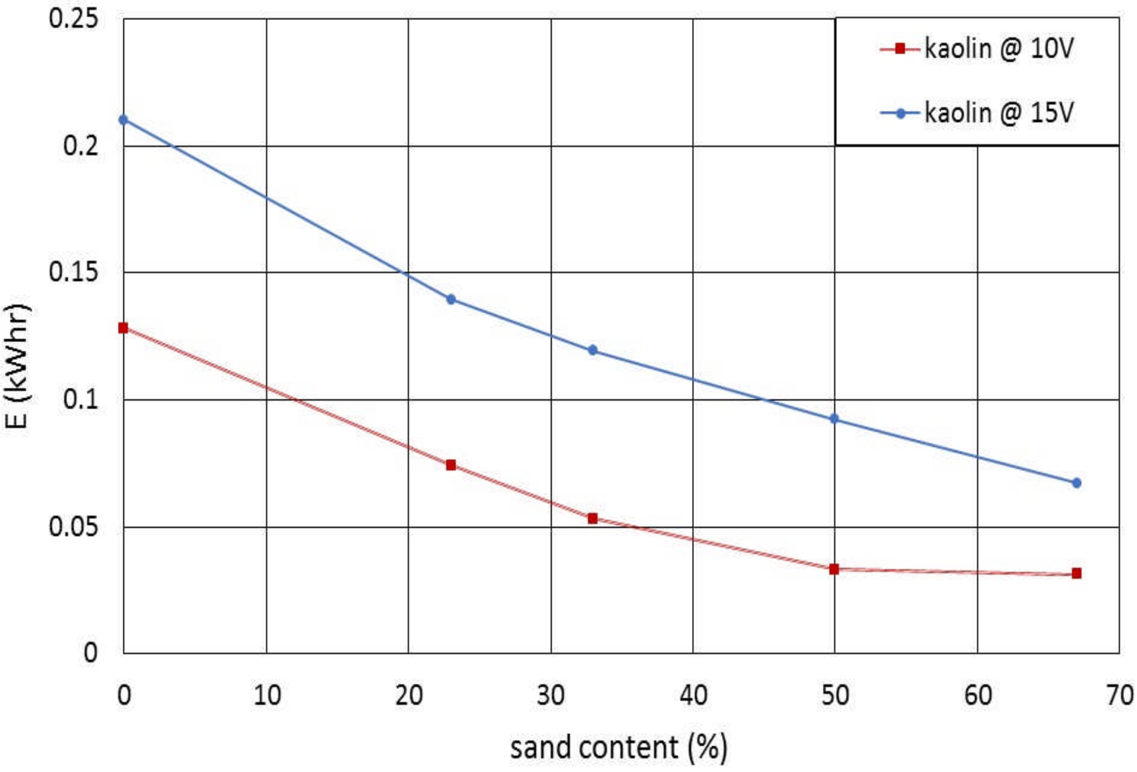


Figure 6.13 Consumed energy E in (kWh) vs sand content for kaolin soils

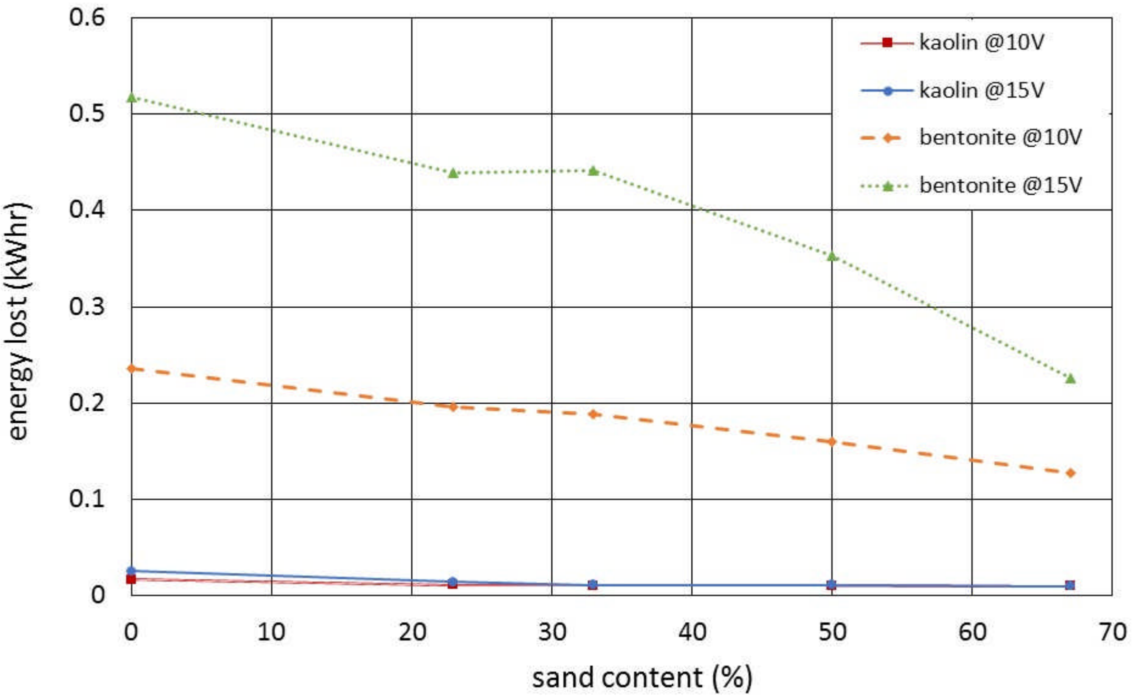


Figure 6.14 Energy lost in bentonite and kaolin soil mixtures due to the increase in temperature

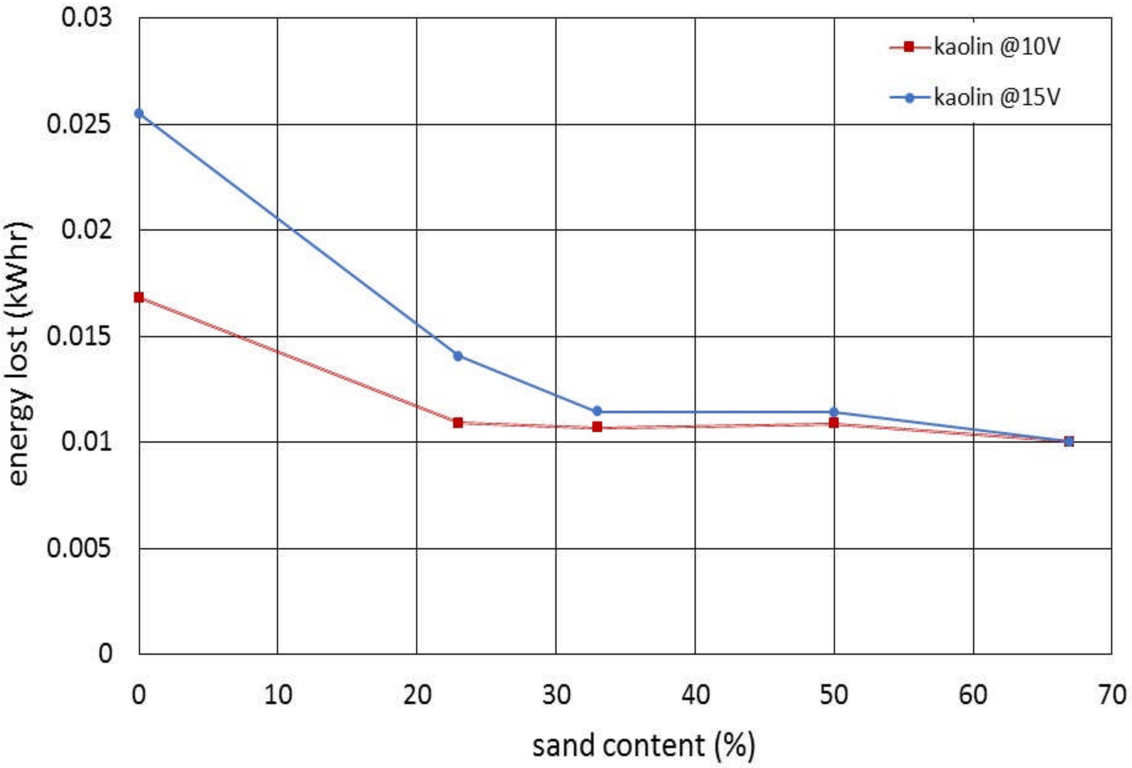


Figure 6.15 Energy lost in kaolin soil mixtures

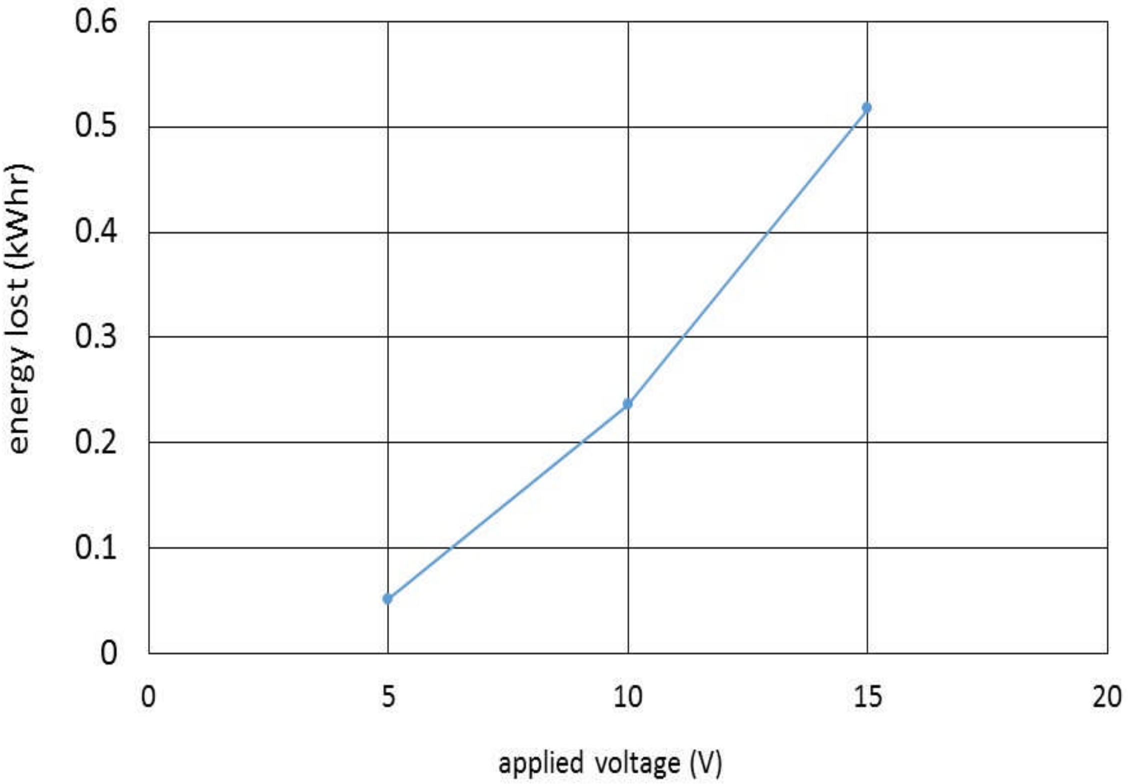


Figure 6.16 Effect of applied voltage on the lost energy in pure bentonite soil due to the increase in temperature

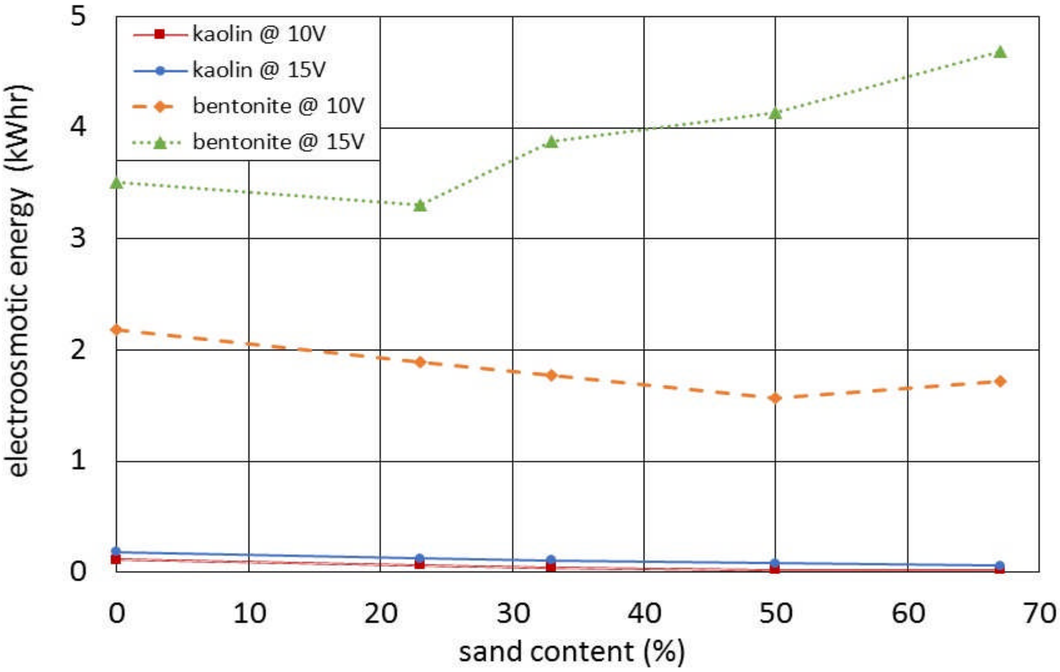


Figure 6.17 Actual energy used in electroosmotic treatment in bentonite and kaolin soil mixtures

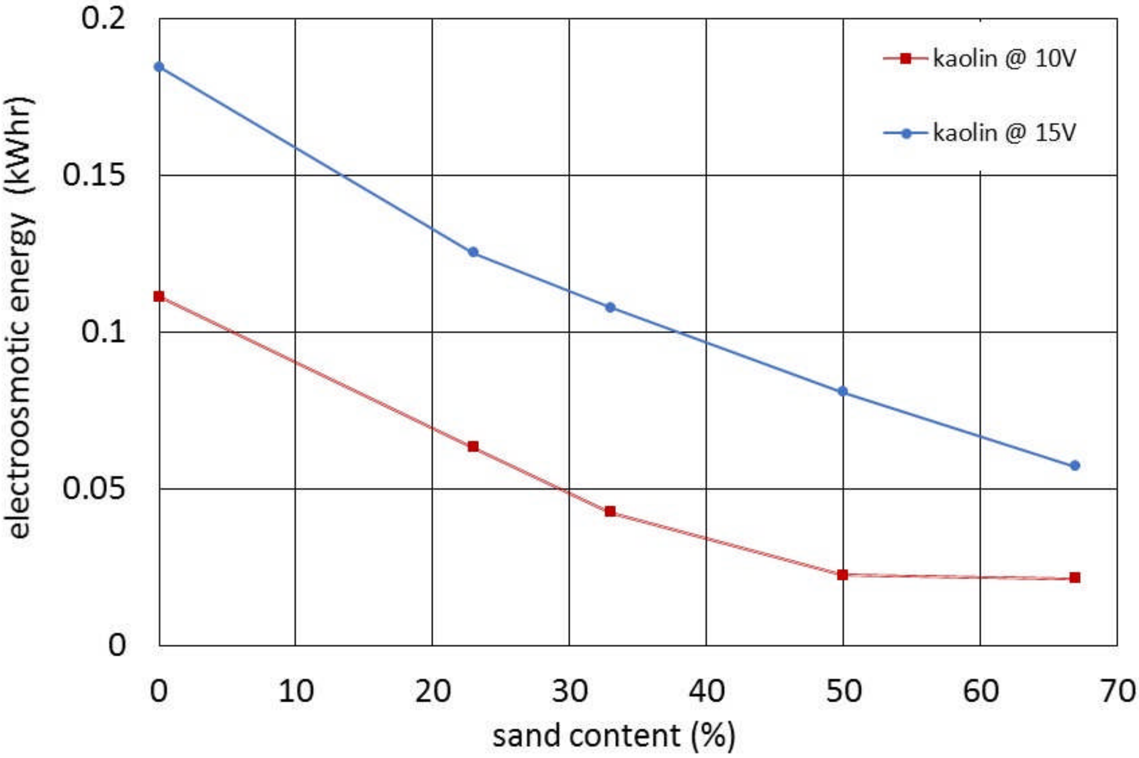


Figure 6.18 Pure energy used in electroosmotic treatment in kaolin soil mixtures

6.2.6 Electroosmotic water transport efficiency ki

The efficiency and economics of electroosmotic flow are controlled by the amount of water transferred per unit current, which can be quantified by the electroosmotic water transport efficiency k_i (cm^3/Amp/s), (Acar et al., 1994), (Hamir et al., 2001), (Jayasekera, 2004a).

The variation of the electroosmotic water transport efficiency (k_i) for kaolin and bentonite soil mixes at 10 and 15V is shown in Figure (6.19).

It is apparent that there are significantly higher transport efficiencies observed for the kaolin soil mixtures than that for bentonite mixes. Also it can be seen that the k_i value for pure kaolin is higher than that mixed with sand (0.027 and 0.032 gal/Amp.hr for pure kaolin at 10 and 15V respectively), then decreases an order of magnitude with the increase of sand, (0.007 and 0.01 gal/Amp.hr when 67% sand used at 10 and 15V).

These results further demonstrate that k_i values are not constant for soils. These results reflect those of Acar et al. (1994), who also found that the k_i values may vary over a wide range from (0 to 0.95 gal/Amp.hr), depending on the electrical conductivity of the porous medium. Gray and Mitchell (1967) indicate that the electrical conductivity of soil changes with water content, cation exchange capacity and electrolyte content. Hamed et al. (1991) stated that electroosmotic transport efficiency k_i decreased with the increase in electrical current density, and may be related to a higher influx of acid front (H^+ ions). Acar and Alshawabkeh (1996) mentioned that the electroosmotic water transport efficiency of kaolinite is higher than that for other clay minerals.

From the results presented on Figure (6.19), and considering the findings of similar studies, it can be concluded that electroosmotic water transport efficiency depends on the applied voltage, sand contents in the composite soil, clay type, time of electroosmosis process electrical conductivity, electrical current gradient, and cation exchange capacity of the electroosmotic treated soil. As shown in Figure (6.19), the pure kaolin subjected to 15V reported more k_i than the other soil mixes. This finding is consistent with that of Acar and Alshawabkeh (1996).

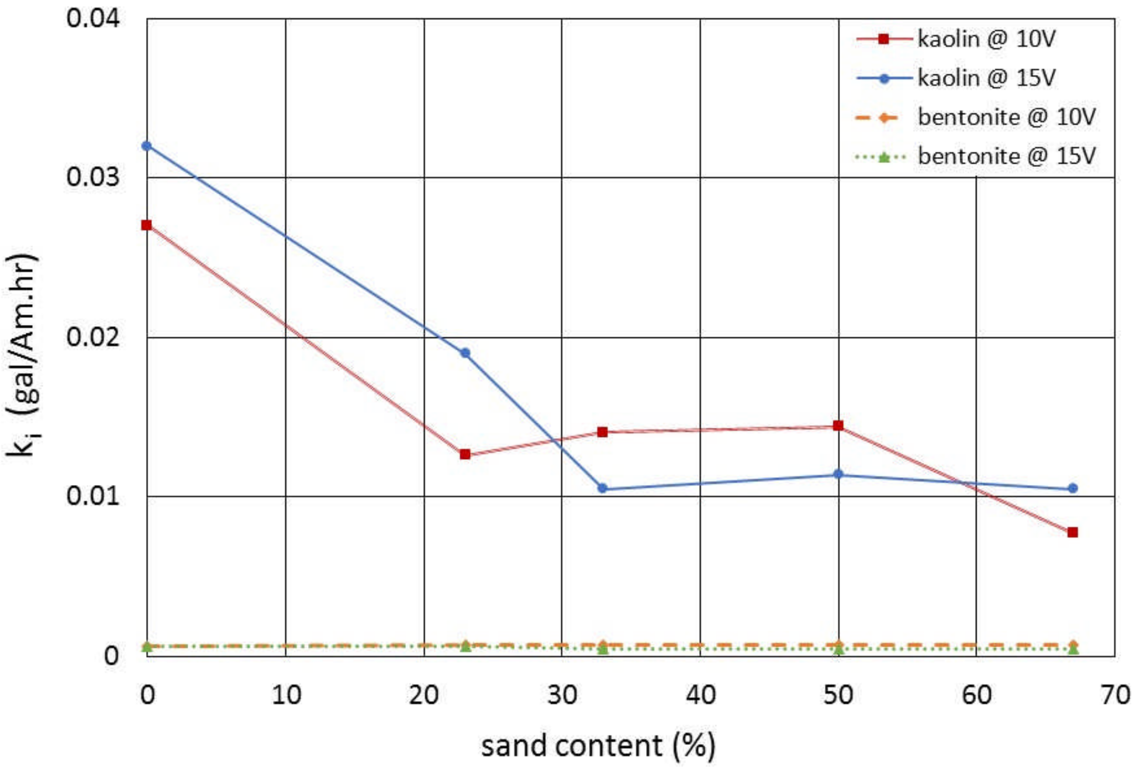


Figure 6.19 Variation of the electroosmotic water transport efficiency (ki) for kaolin and bentonite soil mixes at 10 and 15V with sand content

6.2.7 Electroosmotic effect on settlement

The application of an electric potential through a soil and a surcharge of 15kPa causes a reduction in the volume of the soil due to consolidation. In a one dimensional test, vertical settlement occurs. The amount of settlement depends on the clay type, sand content and the applied voltage. In Phase 1, the sand-kaolin mixture samples took almost 24 hours to observe any outflow from the soil sample, while nearly 14 days was required for sand-bentonite soil mixture to allow any outflow from the cell. Results of these experiments are described in Chapter3.

Figures (6.20) and (6.21) compare the settlement in Phase 3 of electroosmotic treated soil with that of untreated soil (control test) when 50 kPa was applied for kaolin and bentonite soil mixes respectively.

From Figure (6.20) for kaolin and sand mixtures, it can be seen that the ratio of settlement taking place in Phase 3 after electroosmosis treatment with respect to that in Phase 3 in the control test ($H_3/H_{3\ \mathrm{control}}$) varies between 1.2% for pure kaolin to 45% for 67% sand in kaolin-sand mixture when 10V was applied and between 1.08% to 23% for pure kaolin and 67% sand respectively due to the 15V. Figure (6.20) also shows that the settlement ratio ($H_3/H_{3\ \mathrm{control}}$) increases with the increase in sand content. The settlement ratio increases very nearly linearly up to 50% sand when 10V was applied, then there is abrupt change such that the electroosmotic effect at 67% sand content is much reduced. These results confirm what was suggested in Sec 6.2.3 that in a sand-kaolin mixture, electroosmosis is possible up to 50% sand content when electroosmotic permeability ratio (k_e/k_h) in (m/V) is higher than 0.1

The variations of electroosmotic settlement ratio ($H_3/H_{3\ \mathrm{control}}$) across the sand-bentonite soils mixtures are presented in Figure (6.21). As mentioned in Chapter 5, the electroosmosis settlement was based on the amount of expelled water. From this figure it can be observed that the ($H_3/H_{3\ \mathrm{control}}$) ratio fluctuated with the increase in sand content. A possible explanation for this might be related to high different initial water content (160% for pure bentonite to 55% for 67% sand content), and the different time of treatment in Phase 2 until complete degradation of the anodes (168 and 96 hours for pure bentonite at 10 and 15V respectively to 264 hours with 67% sand).

Figure (6.20) and (6.21) also show the relationships between the applied voltage and settlement ratio ($H_3/H_{3\ control}$). It can be observed that in both figures, the ($H_3/H_{3\ control}$) ratio increased with the applied voltage.

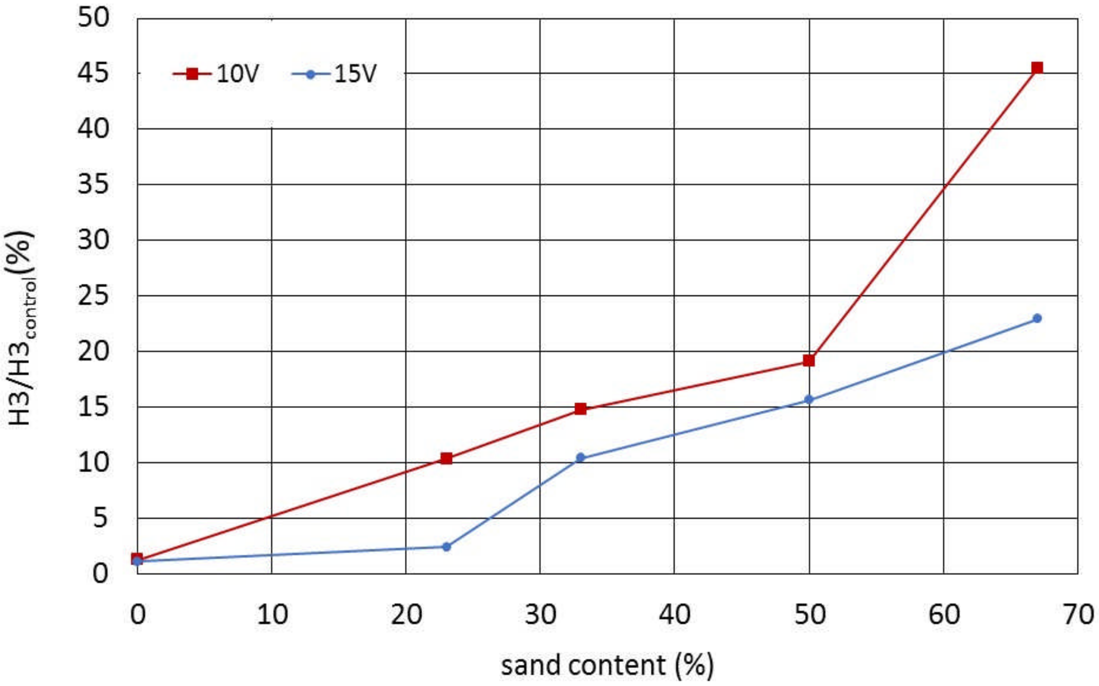


Figure 6.20 Variation of settlement in Phase 3 of the electroosmosis treated soil with respect to Phase 3 in the control test ($H_3/H_{3\ control}$) in kaolin soil mixtures

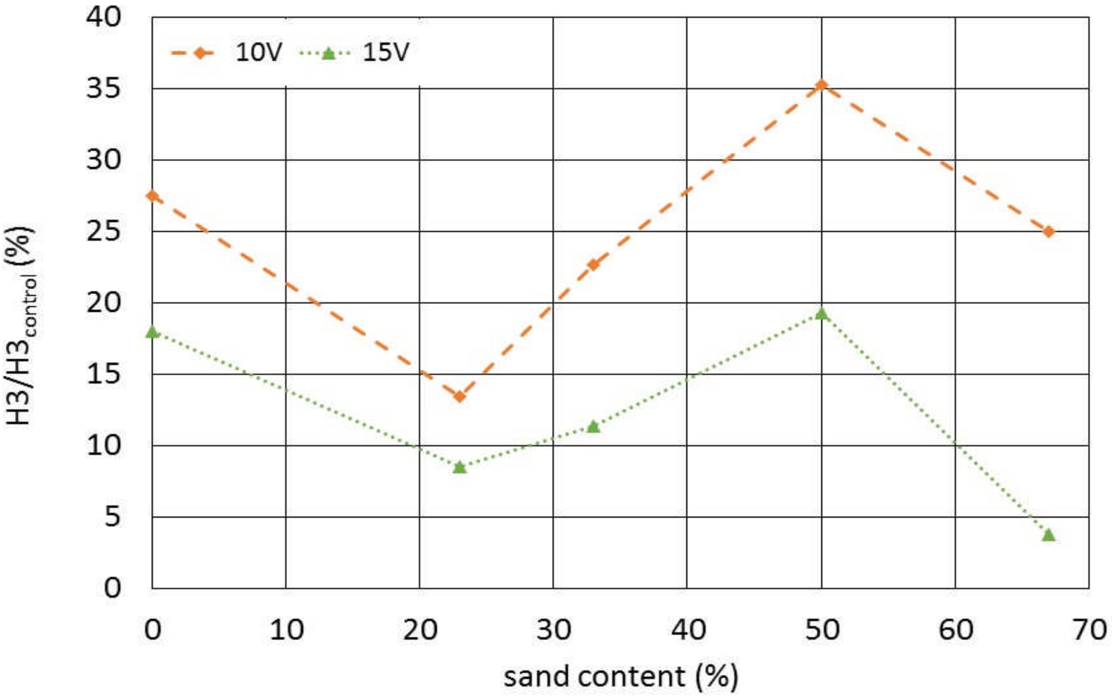


Figure 6.21 Variation of settlement in Phase 3 of the electroosmosis treated soil with respect to Phase 3 in the control test ($H_3/H_{3\ control}$) in bentonite soil mixtures

The variation of the settlement ratio ($H_3/H_{3\ control}$) and the total consumed energy with respect to the sand content of the kaolin and bentonite mixtures are shown in Figures (6.22) and (6.23) respectively.

According to the Figure (6.22), the sand-kaolin mixtures showed a reduction in the required energy as the sand content increased. This is associated with a reduction in the amount of settlement in Phase 2.. Moreover, the consumed energy is greater for pure kaolin compared to sand kaolin mixes, which can be due to the greater electrical conductivity. It can be also seen from this figure that the settlement ratio ($H_3/H_{3\ control}$) and the consumed energy was greater for 15V compared to 10V. From Figure (6.23), it can be observed that while the settlement ratio ($H_3/H_{3\ control}$) fluctuated with change in sand content, the energy required in Phase 2 increased when 15V was applied and decreased when 10V was applied. Further research is needed to fully explain this phenomenon but it could be linked to the length of treatment time, the fact that the maximum current was reached for tests with a low or no sand content, and the effect of the initial water content on the electroosmotic process.

Figure (6.24) shows the variation of total consumed energy with respect to the settlement ratio ($H_3/H_{3\ control}$) against sand content for kaolin soil mixtures. This is a ratio of the work done and the output achieved. It shows that increasing the sand content reduces the benefit of the electroosmotic process to the extent that at 23% sand content for 10V and 33% sand content for 15V, there is very little benefit to be gained even though the electroosmosis is still taking place.

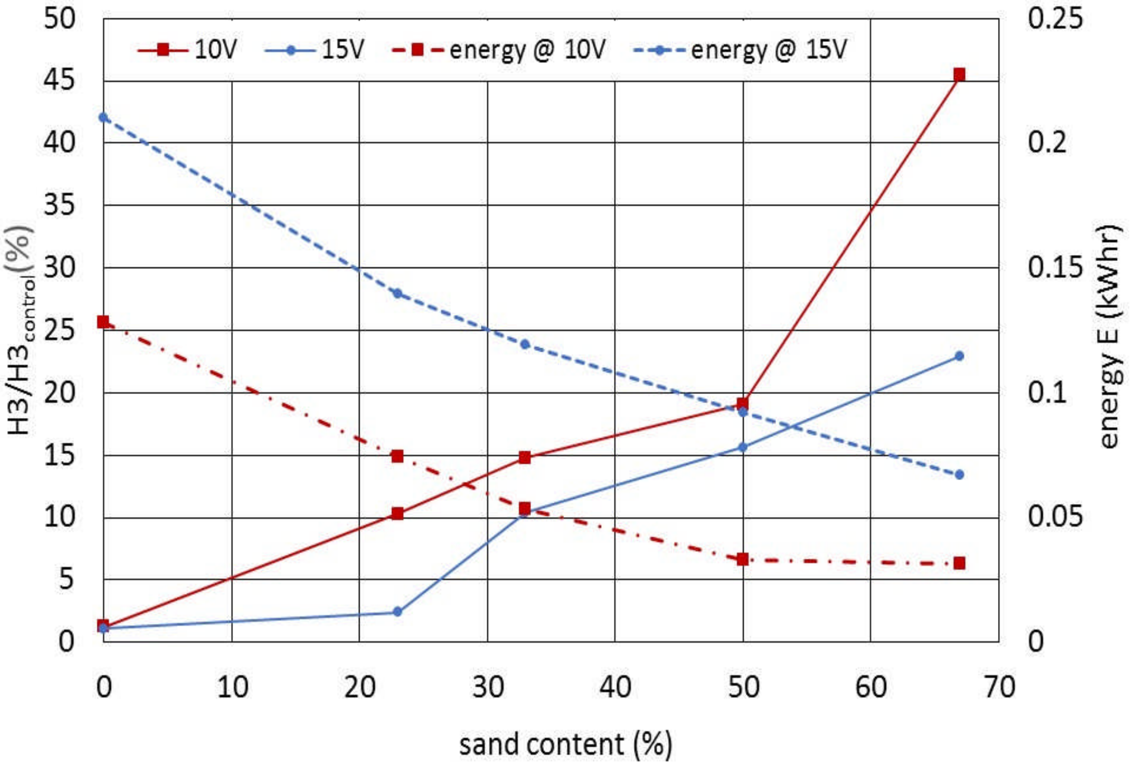


Figure 6.22 Variation of settlement ratio ($H_3/H_{3\ control}$) and consumed energy with sand content in kaolin soil mixtures

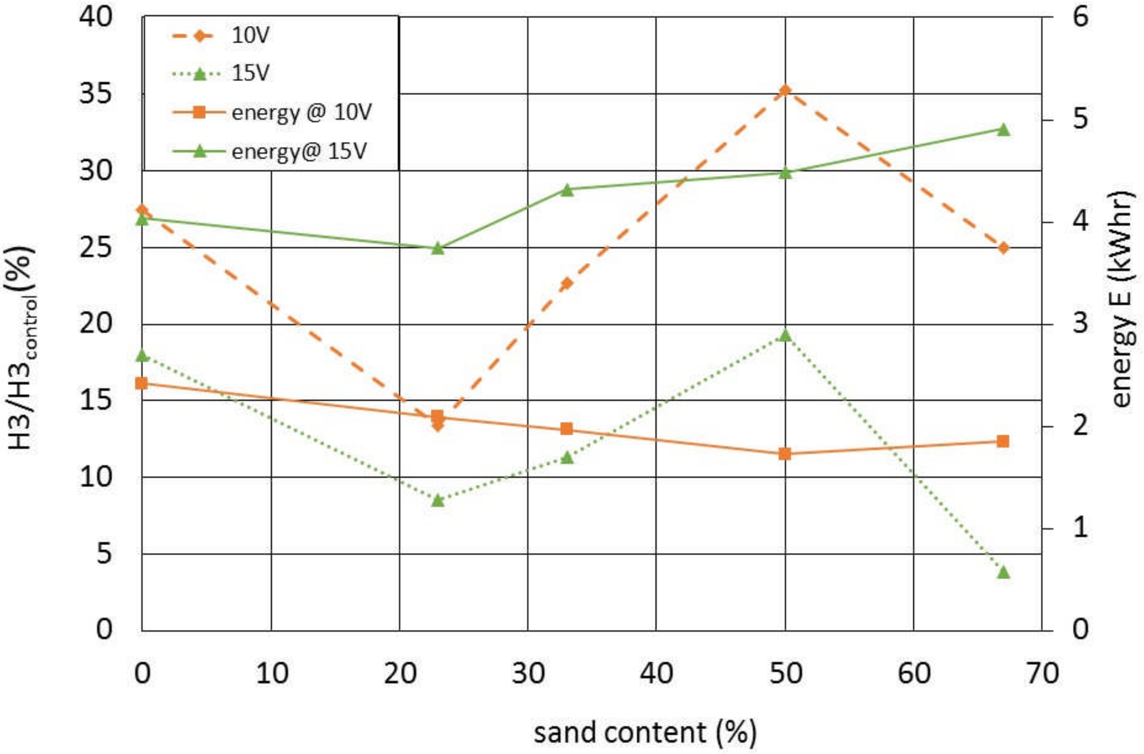


Figure 6.23 Variation of settlement ratio ($H_3/H_{3\ control}$) and consumed energy with sand content in bentonite soil mixtures

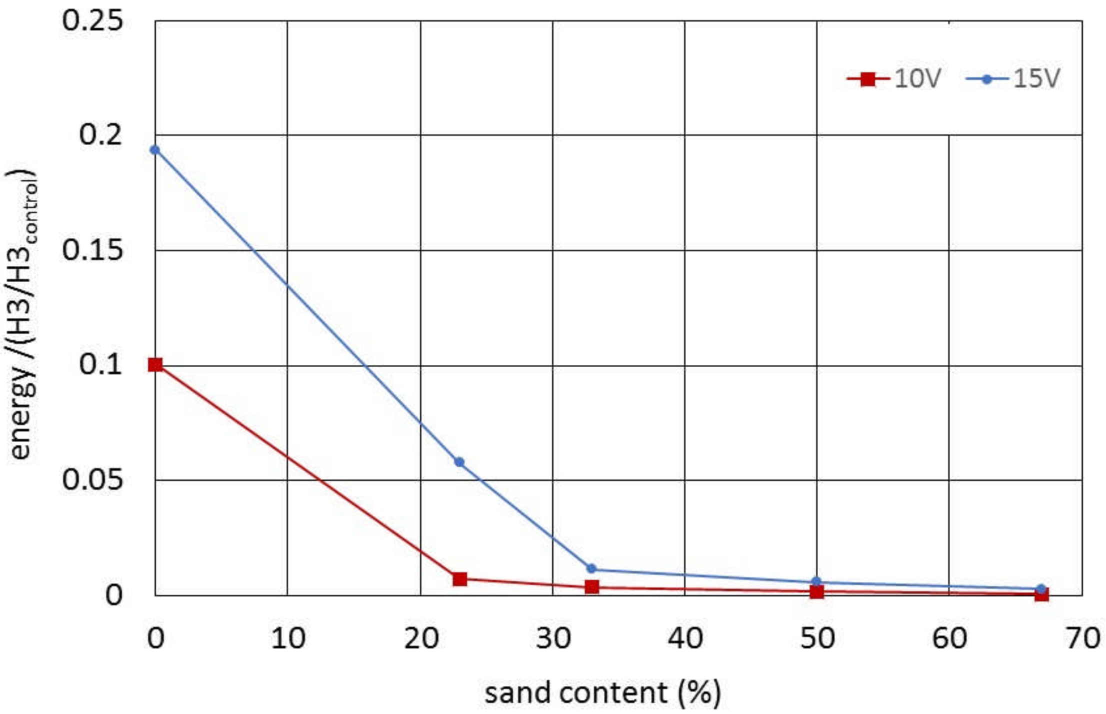


Figure 6.24 Variation of total consumed energy with respect to the settlement ratio (H3/H3 control) in versus sand content in kaolin soil mixtures

6.3 Summary

This chapter has presented and compares some experimental results to investigate electroosmotic treatments effects through a range of composite soils, bentonite and kaolin clay soils mixed with sand and subjected to various voltage gradients. From the analysis of these test results and considering the findings of similar studies, the following conclusions can be made:

- Electroosmosis treatment of saturated soil results in change of water content and thus the voids ratio of the electroosmotically treated composite soils depends on the properties of that soils, such as, permeability characteristics, clay type and sand content.
- Variation of electrical current during electroosmotic process depends on electrochemical properties of the treated soils, soils with higher electrical conductivity, such as bentonite require higher electrical currents than soils with lower electrical conductivity, such as kaolin. Increasing sand content results in a decrease of electrical conductivity of soils.
- The electroosmotic permeability ratio values (k_e/k_h) decrease in a similar trend to the electroosmotic permeability values (k_e), as the sand content

increases in the composite soils. The k_e/k_h ratio for kaolin soil mixes up to 50% sand was >0.1, while the ratio was <0.1 when any sand was added to bentonite. The value 0.1 was suggested by Mohamedelhassan and Shang (2001),as the limit for significance electroosmotic dewatering but these tests showed that significant dewatering took place when k_e/k_h was more than 0.1.

- Temperature variations observed in the vicinities of electrodes during electroosmotic treatment is affects the treatment process, increased the consumed power and desiccation or cracking in the treated soil. No notable temperature increase observed in sand and kaolinite soil mixtures, (<2ºC). There is a significant increase in temperature observed in bentonite soil mixtures, the increase is inversely proportional to the sand content.
- Bentonite soil mixes required more energy than the kaolin soil mixes due to the higher electrical conductivity of the former, some of the consumed energy is used to heat up the treated soil sample.
- The electroosmotic water transport efficiency (k_i) observed at the kaolin soil mixtures much higher than that at bentonite mixes, the ki values for pure kaolin is higher than that mixed with sand.

Chapter 7

Conclusions and Recommendations for Future Research

7.1 Introduction

In this thesis an experimental study into the concept of electroosmotic piles in composite soils was carried out. The main aim of the study was to assess the feasibility of electroosmosis to create a stiffened composite soil formed of either China Clay Grade E Kaolin or Calcium Bentonite (CB) mixed with different ratios of sand Fraction C. There were two subsidiary aims:

1. To determine the effect of soil composition had upon the treated soil.
2. To determine the efficiency of the system.

The mineralogical and geotechnical properties of the tested soils were measured before the electroosmosis treatment began. In the electroosmosis cell tests, the settlement, expelled water, variation of electrical current and applied voltage, and the generated heat was monitored during the test time for 24 osmotic tests. Water content was measured at the end of each test. Electroosmosis conductivity of the treated soils, consumed energy and electroosmosis water transport effectiveness, were calculated to investigate the feasibility of electroosmosis treatment of the composite soil mixes. A control test for each soil mixture was used as a base line for the process. The effectiveness and efficiency of the process were based on the stiffness of the treated soil and the amount of useful energy.

The laboratory investigation in this study demonstrated the combined electroosmotic and preloading technique. It was conducted in three phases; in Phase 1 a15kPa vertical load was applied to simulate a working platform and produce a uniform soil which had been deposited as a slurry. Phase 2, the electroosmosis phase, a constant voltage (either 5, 10, 15 or 20V) was applied to the electrodes in addition to the 15 kPa pressure. This phase was stopped when no further water was expelled from the cell, indicating the electroosmotic process had stopped due to either the degradation of the anode or the flow due to the hydraulic gradient exactly balanced the electroosmotic flow resulting in no flow. Finally, Phase 3, 50 kPa was applied to simulate a surcharge load to determine the stiffness of the treated soil.

The laboratory work was performed on the equipment developed by Nizar and Clarke (2013) with an octagonal array of anodes surrounding a single cathode in a nominal 250 mm diameter 300 mm deep PVC cylinder of soil with the anodes at a radius of 80mm from the cathode. The electrodes used were 10 mm diameter vertical coiled copper springs, which allowed the soil to consolidate either due to an external vertical applied load or electroosmosis. The equipment was modified to measure the generated temperature due to the applied electrical current.

Throughout this thesis, the experimental work has allowed development of the electroosmosis technique by means of use the model used by Nizar and Clarke (2013) allowing a better understanding of how the electroosmotic pile behaves in composite soils. This provides essential details for using the electroosmosis application in field situations.

7.2 Electroosmosis effects on kaolin-sand soil mixtures

The performance of electroosmotic piles in composite soil (kaolin with sand) was investigated in laboratory tests. From the analysis of these laboratory test data, the following conclusions can be drawn:

i. In kaolin and sand soil mixture, there is vertical settlement taking place due to the application of D.C power. The resultant settlement increased as the applied voltage increased for the same soil mix, which means the amount of settlement is a function of the applied voltage density, and the efficiency of treatment increases when the applied voltage is increased.

ii. Different sand ratios were used with kaolin clay (0, 23, 33, 50, and 67% sand by weight). The initial water content was based in the liquid limit of each soil mix which reduced as the sand content increased. The amount of expelled water by electroosmosis decreased when the sand content increased. The volumetric strain change at the end of Phase 2 for pure kaolin was much higher than the kaolin sand mixtures. The volumetric strain is inversely proportional to the sand content, as the sand content increased, the volumetric strain decreased. Note that the initial water content and consequently the water content at the end of Phase 1 was different and decreased as the sand content increased.

iii. The current profile during the electroosmosis test decreased sharply at the beginning of a test followed by a gradual reduction due to the decrease in electrical conductivity with time resulting from the degradation of the anodes. The maximum values occurred with the maximum applied voltage. The consumed power decreased as the sand content increased for the same applied voltage. The trend of current in each soil mix diminished with time, the higher the applied voltage, the greater value for the final electrical current.

iv. Corrosion of the copper anodes used during electroosmosis treatments due to electrochemical reaction was observed. The average losses in the anode's mass due to corrosion in the pure kaolin soil was about 24% at 10V and 42% when 20V used. This means the losses increased as the applied voltage increased. The losses in the anodes decreased as the percentage of sand increased, from 24 and 27% in pure kaolin under 10 and 15V respectively to 3.5 and 6 for 67% sand.

v. The final water content profile was measured at the end of a test (end of Phase 3). From the observations, the average water content of the treated samples after the electroosmotic dewatering tests decreased as the applied voltage increased from 51.5% with no volts in the control test to 47% with 20V for pure kaolin.

vi. The variation of electroosmotic permeability (k_e) due to the change in the applied voltage and sand content was reported. It was found that the k_e values ranged between 0.05×10^{-9} m^2/sV for 67% sand content and 1.4×10^{-9} m^2/sV for pure kaolin subjected to 10V, while k_e was 1×10^{-9} m^2/sV when 20V applied in pure kaolin. This finding indicates that the sand content and the applied voltage affect the electroosmotic permeability.

vii. The temperature of the soil samples was monitored at intervals in Phase 2. Soil temperature started to increase when an electrical power was applied. It was found that an increase in applied voltage resulted in a more significant increase in temperature. The highest increase in temperature was recorded in pure kaolin at 20V, from 19Cº to 24 Cº after about 8 hours of the electroosmosis test. The effect of electroosmosis on increasing the soil temperature decreased when sand was added to kaolin, the temperature decreased as the sand content increased.

viii. Test results show that the electroosmotic transport efficiency ki decreased as the sand content increased and decreased with the increase in the applied voltage; from 0.027 to 0.007 gal/Am.hr for pure kaolin and 67% sand at 10V respectively, and from 0.032 to 0.01 gal/Am.hr for pure kaolin to 67% sand respectively at 15V. The fluctuation in ki value for 33% and 50% sand content at 10V could be attributed to the electroosmotic test duration.

7.3 Electroosmosis effects on bentonite-sand soil mixtures

Regarding the performance of electroosmotic piles in composite soil, a number of conclusions have been drawn from the research into electroosmosis treatment on bentonite and sand mixtures. The following points is to present these conclusions:

i. When electrical D.C power applied to the soil slurry, the water is discharged due to the electroosmosis process. As a results, vertical settlement occurs as an outcome of the dewatering effect on the bentonite-sand soil slurry. The settlement increased when the applied voltage increased for the same soil mix, which means the amount of settlement is a function of the voltage density.

ii. As the sand content with bentonite was varied, (0, 23, 33, 50, and 67% by weight), the amount of water discharged by electroosmosis is seemingly decreased when the sand content was increased in the soil mix, note that the initial water content reduced as the sand content increased. The volumetric strain change at the end of Phase 2 for pure bentonite was higher than other mixture

iii. Swelling occurred during the electroosmotic treatment, which is likely to be related to gas pressure generated due to the applied electrical current. Maximum swelling occurred at about 8 hours from the beginning of Phase

2; the swelling decreased as the sand content increased. Increasing the applied voltage cause increased swelling.

iv. When the D.C power was applied, a noticeable increase in currents occurred at the beginning of the test, regardless of the sand content. After about 10 hours, the current drops to zero when the anodes are completely degraded. The highest current reading associated with the higher applied voltage, and obviously the higher power consumed.

v. The final water content was measured at the end of test (end of Phase 3). From the observations, there was a clear decrease in water content of the treated samples after the electroosmotic treatment. A higher decrease was found at the vicinity of the anodes and between the anodes and cathode. The lower change in the water content was observed at the cathode. The results indicate that increasing the applied voltage caused decreases in the final water content, it is also found that the final water content decreased when the sand content increased.

vi. The electroosmotic permeability, k_e, is calculated during the test. It was concluded that the k_e values decreases with treatment time and increase with applied voltage. The electroosmotic permeability values varied between 1.8×10^{-10} m^2/sV and 1.57×10^{-10} m^2/sV for pure bentonite and 0.89×10^{-10} m^2/sV 0.72×10^{-10} m^2/sV for 67% sand content subjected to 10 and 15V respectively. The increase in sand content caused a reduction in electroosmotic permeability.

vii. The temperature changes during electroosmotic treatment were recorded with time. Soil temperature increased when electrical power was applied and decreased with time until complete degradation of the anodes. The highest increase in temperature was found in pure bentonite when 15V was applied. Increased in applied voltage resulted in a greater increase in temperature of the treated samples. The generated temperature decreased as the sand content increased. The heat developed due to applying electrical power is a function of voltage and soil type.

viii. The values of electroosmotic transport efficiency k_i increased with the increase in sand content when 10V was applied, from 0.65 to 0.72 $(gal/Am.hr)*10^{-3}$ for pure bentonite and 67% sand with bentonite respectively. When 15V was used, the k_i values ranged between 0.65 $*10^{-}$

^{3} gal/Am.hr for pure bentonite during 96 hours treatment time, as the maximum current of the power supply was reached, and 0.72 $*10^{-3}$ gal/Am.hr for 67% sand with bentonite in a treatment time of 264 hours. The variation in behaviour between 10 and 15V may be explained by the difference in the time of treatment until complete degradation of the electrode. In pure bentonite, there was been a descent in the k_i value with the increase in the applied voltage, 1.14 $x10^{-3}$ gal/Am.hr at 5V and $0.65x10^{-3}$ gal/Am.hr at 10V, no difference between the k_i value when the voltage was raised to 15V. This can be related to that the maximum current of the power supply was reached in the 15V test.

7.4 Conclusion regarding to factors effects electroosmosis treatment

In this section, a comparison between electroosmotic flow through bentonite and kaolin clays mixed with different ratios of sand and subjected to various voltage gradients is presented.

i. With the application of voltage gradients, the rate of water flow through the kaolin and bentonite slurry increases by several orders of magnitude due to the effect of electroosmosis flow. This causes changes in water content and voids ratio. The effects of electroosmosis treatment depends on the, clay type, the sand content and the applied voltage.
ii. Generally, the electrical current decreased with time during the electroosmosis process due to the decrease in the electrical conductivity of the soil which can be attributed to various factors, such as electrode corrosion, gas evolution, decreases in water content, electrochemical passivation and electrochemical potential.. The variation of the electrical current depends on electrochemical properties of the treated soils. Bentonite slurries require higher electrical currents than kaolin soils due to the higher electrical conductivity of the former. Increasing the sand content resulted in a decrease of electrical conductivity of soils.
iii. The electroosmotic permeability (k_e) for kaolin soil mixtures was found to be higher than those for bentonite mixtures leading to higher electroosmotic flow in the kaolin mixtures. The electroosmotic permeability

ratio values (k_e/k_h) decreased with sand content due to the increase in hydraulic conductivity of the mix. Therefore, in this instance k_e appears to be almost dependent on the electrical conductivity of the soil.

iv. The heat generation in the vicinities of electrodes was prevalent during the electroosmosis treatment. Soils with comparatively higher electrical conductivities, such as bentonite, as observed from this study exhibited a higher temperature compared to that for kaolin. The temperature increase is inversely proportional to the sand content.

v. Test results showed that the power consumption rates were not uniform for the different soil mixtures of tests carried out. For example, bentonite soil mixes required more energy compared to the kaolin soil mixes. Lower power consumption rates were achieved at higher sand contents. Some of the energy is used to heat up the soil sample. The results from this study suggest that there is an average loss of energy due to heat generation ranging between 5 to 20%.

vi. The electroosmotic water transport efficiency (k_i) reported in kaolin soil mixtures is much higher than that at bentonite mixes. The efficiency of the electroosmosis process could be improved by increasing the voltage.

vii. The vertical settlement at the end of Phase 3 when 50 kPa was applied as a surcharge load decreases as the sand content increases in both soils. The higher the applied voltage, the lower settlement at Phase 3.

viii. In kaolin- sand mixtures, the ratio of settlement in Phase 3 after electroosmosis treatment with respect to that in Phase 3 in the control test ($H_3/H_{3\ control}$), ranged between 78 and 92 for pure kaolin at 10 and 15V respectively to 2.2 and 4.3 for 67% sand in kaolin-sand mixture which means that the settlement ratio ($H_3/H_{3\ control}$) is decrease with increasing of sand content. In bentonite soil mixtures, the ($H_3/H_{3\ control}$) ratio fluctuated with the increase in sand content. A possible explanation for this could be attributed to different initial water content and different time of treatment in Phase2. In both soils, the ($H_3/H_{3\ control}$) ratio increased with the applied voltage.

7.5 Recommendations for future research

The experimental work carried out in this study demonstrated that the electroosmotic piles approach can be used as an effective method for stiffening composite soils. As a result of the findings made during this research, the following recommendations can be made for future research:

i. Large scale tests and field tests on electroosmosis treatment of composite soil should be developed to illustrate the importance of the electroosmotic piles technique for successful insitu electroosmosis applications.

ii. Further investigations, both in the lab and field, on the use of other soil types and sand fraction content on electroosmosis treatment such as gypsum soils, organic soils or other composite soils. This could shed more light on the implications of electroosmotic application in composite soils.

iii. Analytical modelling of the electroosmotic dewatering should be designed from the results obtained in this experimental study and other electroosmotic consolidation test results reported in the literature. This can provide better understanding of interactions and relationships between the selected variables.

iv. Investigation of the effects of polarity reversal or intermittent current during the electroosmosis treatment to optimize power consumption and achieve uniform consolidated soil.

v. Investigation using some types of chemical additives during the electroosmosis processes in terms of the effective strength, overall cost, efficiency and performance of the electroosmosis method.

vi. Further investigation is required in the electrode corrosion to find a proper method and material to treat the electrode and prevent or minimize the electrode degradation.

vii. Further investigation required about the electro-chemical osmosis behaviour and swelling in bentonite soils.

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