UNIVERSITY OF
BIRMINGHAM

ELECTROKINETIC STABILISATION OF SOFT CLAY

by

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A thesis submitted to
The University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Civil Engineering
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The University of Birmingham
July 2012

ABSTRACT

The application of chemical ground improvement using the electrokinetic stabilisation (EKS) method has the potential to overcome problems soft highly compressibility soil. This technique has the potential to enhance the strength and reduce compressibility of a wide range of soils. The aim of this study was to evaluate the use of EKS as an effective method to strengthen soft clay soils. A detailed laboratory programme of work was conducted using the initial base model developed by Liaki (2006). This study was conducted in two stages using laboratory scale models, using an inactive kaolinite clay. The test model using reusable Electrokinetic Geosythentics (EKG) developed at the Newcastle University to apply a constant voltage gradient of 50 V/m across a soil sample approximately 400 mm. The first stage involved testing of a 'pure' system with distilled water as the main pore electrolyte fluid supplied under zero hydraulic gradient conditions for periods of 3, 7 and 14 days. The second stage repeated test using calcium chloride and distilled water (CaCl-DW), DW and sodium silicate (DW-NaSiO) and CaCl-NaSiO, at the anode and cathode, respectively. Throughout both physical and chemical characteristics were measured. This enabled assessment of the design and configuration that could be used in the field together with a number of key limitations.

The data presented herein enables a fuller understanding of the mechanisms contributing to the improvements achieved and how effective monitoring through the use of relatively simple test, e.g. pH and Atterberg Limits, can be achieved. Specifically cation exchange was considered to be the main mechanism causing a significant increase in shear strength observed for the CaCl-DW system with the increase seen to be more uniform across the soil sample for a period up to 14 days. This was supported by results of Atterberg limits,

pH, electrical conductivity and chemical concentrations. Precipitation and cation exchange are the main contributors to the increase of shear strength for the CaCl-NaSiO system after 7 and 14 days treatment. However, precipitation of CSH gels has greater influence on the shear strength at the near proximity of cathode followed by cation exchange at the near proximity of anode and at the remainder of the soil sample.

DEDICATION

For my loving Mak and Abah, beloved wife, lovely daughters and siblings

ACKNOWLEDGMENTS

I would like to acknowledge gratefully for the assistance received from the following:

Dr Ian Jefferson for his constant supervision, guidance and encouragement. Professor Christopher Rogers and Dr David Ian Boardman for sharing their knowledge, expertise and experience which contributed to the success of the study.

Dr Gurmel Ghataora and Dr Alex Royal for sharing his knowledge and experience on the laboratory testing.

My colleagues in the geotechnical department and other departments include Mr Aziman Madun, Mr Saiful Wahab, Mr John Uniyme, Mr Saifaldin, Mr Samuel, Mr Samir, Mr Farhad, Mr Gulio and list goes on.......to share their opinion, knowledge and experience during my study.

Ministry of Higher Education Malaysia for granting the scholarship.

Employer's University Tun Hussein Onn Malaysia for permission of study leave and sponsoring family allowances.

Lab technicians', Mr Jim White, Mr John Erdington, Mr Michael Vanderstam, Mr David Cope, Mr Nathan and Mr Bruce Reed for their support.

Finally, friends in Birmingham and post graduate members' in room F59A and F59B for their help and support.

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A	Cross-Section Area
Al	Aluminium
Ca	Calcium
CaCl	Calcium Chloride
CEC	Cation Exchange Capacity
c_u	Undrained shear strength
D	Diffusion Coefficiency
DDL	Diffuse Double Layer
DW	Distilled Water
e	Void ratio
EC	Electrical Conductivity
EE	Edge to Edge
EF	Edge to Face
EK	Electrokinetic
EKG	Electrokinetic Geosynthetic
EKS	Electrokinetic Stabilisation
EO	Electroosmosis
f	Frequency
Fe	Iron
FF	Face to Face
G_s	Specific gravity
H^+	Hydrogen ion
I	Current
i_c	Chemical Potential gradient
i_h	Hydraulic gradient
J_i	Flow Rate
K	Potassium
K_e	Electroosmotic Conductivity
K_h	Hydraulic Conductivity
L_{ii}	Conductivity Coefficient for Flow
LL	Liquid Limit

n	Porosity
Na	Sodium
NaSiO	Sodium Silicate
OH	Hydroxyl
OH^-	Hydroxyl ion
PI	Plasticity index
PL	Plastic limit
q_c	Cone resistance
q_h	Hydraulic Flow
q_u	Unconfined compressive strength
r	Radius
R	Resistance
Si	Silicate
u	Ionic Mobility
V	Voltage
w	Water content
X_i	Driving Force

Chapter 1

INTRODUCTION

1.1 Background and Problem Statement

An increasing proportion of building development takes place in areas of poor ground and this poses challenges for the geotechnical engineers to provide satisfactory foundation performance at low cost. Construction, buildings and infrastructure founded on soft clays are often affected by stability and settlement problems. A proportion of the final settlement can be achieved prior to construction by preloading the soil but this often takes 6 - 9 months or more to achieve (Charles & Watts, 2002). The larger the preload, the less time it will take to achieve the final settlement, however great care is needed not to cause premature failure of the ground. Preconsolidation may be a cost-effective way of reducing the settlement due to lightly distributed loads from roads or residential buildings provided that material for providing load is readily available and accessible for treatment. Where neither material nor time are available, there are many other methods of ground improvement that have been implemented in the field including preloading with installation of vertical drains, and chemical stabilisation as surface and deep soil treatment techniques. Chemical stabilisation of clay soils using calcium-based stabilisers, such as lime and cement has been practiced routinely over the many decades. Its overall benefits include an increase in soil strength, stiffness and durability, and a reduction in soil plasticity and swelling or shrinkage potential. However, frequently these methods are not suitable to stabilise a soil under an existing structure which may be settling. There are a few options for stabilisation of fine grained soils under these circumstances such as soil freezing, hydrofracture grouting and electroosmotic consolidation (Alshawabkeh & Sheahan, 2003). All these methods have been shown to result in measurable ground movements that are potentially damaging to adjacent and overlying structures. Previous studies (Rogers *et al.*, 2003, Alshawabkeh & Sheahan, 2003, Barker *et al.*, 2004) suggested that chemical treatment under an electrical gradient to transport chemical ions between bespoke electrodes can overcome such problems, whilst achieving desired results. This method is known as Electrokinetic Stabilisation (EKS).

EKS is the application of electrokinetics to draw stabilising chemicals through soil. The technique consists of applying direct current (DC) under a voltage gradient in the range from 20 to 60 V/m typically, to provide an electric field across a wet soil mass via a pair of electrodes to promote the migration of stabilising agents into the soils. This technique is particularly well suited to soils of low permeability for which the addition of the stabilising agents by hydraulic means is impracticable. In addition, the technique treats soils without excavation, an advantage over traditional mix-in-place chemical stabilisation (Rogers *et al.*, 2003). However, EKS has not yet become widely used as a common practice in geotechnical engineering due to the lack of understanding on the electrochemical effects and physicochemical phenomena taking place when chemical stabilisers are introduced concurrently with a passage of the current through a soil-porewater-electrode system.

1.2 Rationale and Scope of study

This study is part of the ongoing research development in University of Birmingham to prove the concepts and establish the practical possibilities of improving the in-situ weak soil condition by using EKS method. It is has shown from previous research by Rogers *et al.* (2003, 2004) and Liaki (2006) that with further development this technique may provide potential solutions for the improvement of soft clays and in due course it could be applied in the field. Before this method could be used successfully in the field without much doubt over its capability to increase the shear strength and bearing capacity of problematic soils, a rigorous controlled laboratory setup is designed in order to replicate the field condition.

Much research has been conducted in electrokinetic stabilisation application by using metal electrodes but none was performed using EKG electrode. Therefore, the first stage of this study examines the performance of EKG electrode under an electric gradient to establish the basic characteristic of EKS method which ions from an external source were not introduced at both electrodes. This stage was called “pure system’ and initiated for repetitive tests with similar test setups as Liaki (2006), so as to confirm the results and also to ascertain the repeatability of experimental results. The pure system test results were discussed and compared with Liaki (2006) in Chapter 6 to improve clarity and conciseness of the thesis.

Second stage of this study was focused on the design, implementation and analysis of EKS with chemical stabilisers. This was conducted in two phases. The first phase was performed to investigate the effect of calcium chloride and sodium silicate alone in the system. Calcium chloride was introduced at the anode while distilled water was introduced at the cathode. In other test, the distilled water was introduced at the anode and sodium silicate was introduced at the cathode. Those tests will provide the underlying mechanism through the process when those selected ions were introduced before it was applied simultaneously in the second phase. Through these tests, it was confirmed the amount of chemical stabilisers and time needed to achieve the effective EKS process in the actual soft soil ground (discussed in Chapter 7).

The second phase of this study of EKS with chemical stabilisers involves detailed laboratory investigation that would assess the efficiency of EKS technique when both calcium chloride and sodium silicate were simultaneously introduced at the anode and cathode, respectively. This phase was designed to facilitate the transport of desired ions at both electrode through the soil, enhancing the ability of EK to promote precipitation of CSH and CAH, thus resulting of soil cementation along the soil profile. This second phase is discussed together with first phase in Chapter 7 of EKS system with chemical stabilisers.

1.3 Research Aim and Objectives

The aim of this study is to evaluate the use of EKS as an effective method to strengthen soft clay soils. In order to achieve this goal, the following objectives have been devised:

1. To develop a new approach and procedures using electrokinetic stabilisation of soft clay soil.
2. To examine the effectiveness of strengthening soft clay soils by addition of appropriate chemical stabilisers under an electrical gradient.
3. To investigate various electrochemical effects such as electroosmosis, electromigration and electrochemical effects on physical, chemical and physicochemical behaviour of soft clay soil.

1.4 Contribution to Knowledge

The results of the research presented herein have increased knowledge of the EKS approach, when used to improve the properties of soils. In addition, greater understanding of the physico-chemical effects occurring with this technique has been made. The findings show that the EKS technique has the potential to be implemented successfully in the field application, not only to treat soil for new development projects but to improve soils under existing foundations or structures.

Rigorous and intensive study of this technique which initiated by Rogers *et al.* (2003) in the bench studies and followed by Liaki (2006), who focused on pure system using different electrodes in the laboratory. Therefore, the findings of this current study which is using suitable chemical stabilisers in the laboratory have shown a great potential to be adopted in the field application in the near future. This study also provides details and more evidence on the operation of the electrokinetic process in more complex situations where a number of potentially mobile ions are present. At the same time, disadvantages such as low efficiency under low unsaturated condition, corrosion problems, generation of undesired by-products and others are part of the field test shortcomings can be overcome with the good knowledge of this electrokinetic process by using proper setup and design configurations, drawing from lesson learnt from the research presented herein. The analysis of simulated data helped to recognise further delineate a systematic approach for a more accurate description of the electrokinetic process. The knowledge obtained during the theoretical stage promoted a deeper understanding and lead to important guidelines for soil improvement by electrokinetics. Consequently, this research provides a framework from which field test results may be better understood or related as to propose new hypotheses on how to improve the operation. Specifically the types of testing and monitoring that can be used, to assess the improvements made using standard test methods, combining tests such as Atterberg Limits with pH monitoring to gain a good overall picture of the nature of the changes achieved. Significantly this research has shown how using different stabilising solutions at either anode/cathode or both can be controlled to achieve improvement in soil properties. Importantly, this work has developed previous studies on the ‘pure’ system to help elucidate the mechanisms controlling these improvements both spatially and temporally.

1.5 Outline of thesis

Chapter 2 of this thesis presents the literature reviews of electrokinetic phenomena to understand the theoretical and fundamental background required for this thesis. The understanding of electrokinetics requires a comprehension of the clay mineralogy, clay-water-electrolyte system, flow theories and electrokinetic phenomena. Further in **Chapter 3**, a comprehensive review of electrokinetic applications in geotechnical and geoenvironmental engineering is discussed to provide the key mechanisms and the underlying problems faced by many researchers in laboratory scale and suggestions for field applications.

To ensure a more complete understanding of EKS was achieved, consistent with the aim and objectives (see Section 1.2), the laboratory work was divided into two stages. Stage one consisted of preliminary laboratory work conducted including assessment of physical and chemical properties of clay soil used in this study before being treated using EKS method, called in this thesis for convenience the 'pure' system. These were compared with results from a previous study (e.g. Rogers *et al.,* 2003, Barker *et al.,* 2004, Liaki, 2006) using the same type of soil (**Chapter 4**) During this further modifications were made to improve the overall test methodology before starting Stage 2. During Stage 2 the procedures, setup and design configuration of main laboratory experiment to investigate the effectiveness of EKS using different stabiliser combinations as a ground improvement technique were undertaken (see **Chapter 5**).

Chapter 6 presents and discusses the results of EKS testing using distilled water only (pure system) as the electrolytes at both electrodes to provide a baseline study. **Chapter 7** presents and discusses the main findings of EKS method using chemical stabilisers with different configurations. This chapter is divided into three main sections including monitoring data during EKS testing until end of the test, physical properties and chemical analysis of clay soil after EKS testing for certain period of time.

Chapter 8 discusses details of key findings and useful information related to electrochemical effects on soil behaviour when an electric current is applied and when selected cations and anions were introduced into the soil system. Finally, **Chapter 9** outlines the conclusions that were drawn from this study and recommendation for future works in the laboratory study and field applications.

Chapter 2

ELECTROKINETIC PHENOMENA

2.1 Introduction

This chapter provides details of fundamental study with respect to the development of this thesis through presenting the relevant literature which cover physical and chemical behaviours of clays, clay-water electrolytes system, the types of flow, electrokinetic phenomena and electrochemical effects.

Electroosmosis is the movement of water resulting from the application of a direct current through porous medium. When an electric current is applied through saturated fine-grained soil between two electrodes, water contained in the soil migrates from positive charged electrode (anode) to the negative charged electrode (cathode). This results in dewatering and consolidation of the soil mass if the drainage is available at the cathode. The method can reduce the water content of the soil, thereby increasing its strength (temporarily).

Electroosmosis is a specialised technique and commonly used in very low permeability soils where groundwater movement under the influence of pumping would be excessively slow with permeability of 10^{-9} m/s or less. Electroosmosis causes groundwater movements in such soils using electrical potential gradients, rather than hydraulic gradients (Cashman & Preene, 2001). The mechanism of water movement by electroosmosis was studied as early as 1809 by Reuss and 1879 by Helmholtz (Mitchell & Soga, 2005). The first analyses and application of electroosmosis dewatering technique of clay soils in geotechnical engineering were attributed to Casagrande in 1939 (Mohamedelhassan & Shang 2001, 1997; Micic *et al.*, 2003). Since then the technique has been used to improve strength and settlement properties of certain types of soft clay and is widely known as electroosmosis consolidation. In addition, ion migration, electrolysis and chemical reactions occur leading to the formation of new irreversible compounds. Electroosmosis dewatering and electroosmosis consolidation techniques have been used across a range of laboratories and sites scale with varying success (Alshawabkeh & Sheahan, 2003).

Where electroosmosis has proved successful, it usually has been as a result of using the process to introduce a chemical into the soil, either through anode solution or by direct electrolyte replacement. Indeed, Bell (1993) stated that chemicals such as calcium chloride and sodium silicate are sometimes added to ensure the growth of cementitious material in the pore space. This improves the stability of the soil either by cation exchange occurring in the clay mineral content, or by cementitious material being deposited in the pore space. This adaption of electroosmosis is known as electrokinetic stabilisation (EKS).

EKS is a technique that can be used to improve the volume stability of the soil around and beneath foundations. In addition, EKS is the technique of applying an electrical current through a soil mass to promote the migration of chemicals from injection points, which are usually the electrode themselves (Barker *et al.,* 2004). This technique aims to improve the physical characteristic by altering the chemical composition of the treated soil. Liaki (2006) reported the properties of most interest herein are those related to volume stability, and hence the sensitivity of the clay to water content changes. EKS technique is particularly well suited to clayey soil (low permeability soil) for which the injection of the stabilising agents by hydraulic means is impracticable. Therefore, the technique does not require significant excavation or soil disturbance, an advantage over traditional mix-in-place chemical stabilisation. Alshawabkeh & Sheahan (2003) reported that laboratory experiments showed that shear strength increases significantly across the soil sample. They also concluded that the method has the potential to be implemented in the field, and produce improved geotechnical properties with minimal volume change.

The utilisation of electrokinetic in geotechnical engineering for dewatering, consolidation and stabilisation of low permeability and to transport certain chemical species in an electrolyte system had opened new opportunities for application in geoenvironmental engineering. Recently the electrical treatment technique has been applied to in-situ remediation, which was used to clean up contaminated sites containing heavy metals and hydrocarbons. The idea of electrokinetic remediation started in the 1980s after it was noticed that water transported by electroosmosis contained high amounts of heavy metals and other chemical species (Azzam & Oey, 2001). Even though this application of electrokinetic remediation is not the main purpose of this study, the subject has benefited from research carried out in relation to the chemical stabilisation of soils in situ by Rogers *et al*. (2003).

This chapter aims to review the fundamentals of soil behaviour improved by electrokinetic stabilisation and the phenomenon of electrokinetic in soil including the associated chemical, physicochemical and electrochemical phenomena. In addition, the effects of the electrokinetic stabilisation on the index, physical and mechanical properties of soil also will be reviewed. In order to better the understanding of the soil-water-interaction, it is fundamental to study the behaviour of clay controlled by its mineralogy, composition and fabric, and how these influence properties of clays. However, the application of electrokinetic technique in geotechnical and geoenvironmental engineering will be discussed later in Chapter 3.

2.2 Clay Mineralogy

Mineralogy is the primary factor controlling the size, shape and properties of soil particles. The mineralogy structure of clays is of great interest. This is because the clay fraction can significantly influence the overall behaviour of (composite) material. The distinct behaviour of clay particles with respect to other constituent is strictly dependent on the different ratio existing between the solid surface and their mass which is defined as specific surface (Musso, 2000). Mechanically, specific surface leads to a strong influence of the electrical forces and of the liquid solid interface phenomena. That result in the bonding (cohesive) properties of clays and, in association with a particular chemical structure, in their swelling characteristics. Hydraulically, the smaller size of the particles determines a smaller dimension of the pores. The averaged velocity of fluid flow through a soil depends on the capillary size and the permeability of the soil, which decreases quickly with smaller grain size under natural water content conditions (Musso, 2000).

It is well known that at least two definitions of clay exist. According to Mitchell & Soga (2005), clay can refer both to a size and to a class of mineral. As a size term, it refers to all constituents of a soil smaller than 0.002 mm. The mineral term refers to specific clay minerals that are distinguished by small particle size, a net negative electrical charge, plasticity when mixed with water and high weathering resistance. Mostly, particles of clay minerals are platy and in a few cases they are needle shaped or tubular.

Clay minerals in soils belong to the phyllosilicates, which also contains other layer silicates such as serpentine, pyrophyllite, talc, mica and chlorite. The principal structures of clay minerals are made up of combinations of two simple structural units, the *silicon tetrahedron* (Figure 2.1) and the *aluminium* or *magnesium octahedron* (Figure 2.2). Different clay mineral groups are characterized by the stacking arrangement of sheets (sometimes chains) of these units and the manner in which two successive two-sheet or three-sheet layers are held together (Mitchell & Soga, 2005).

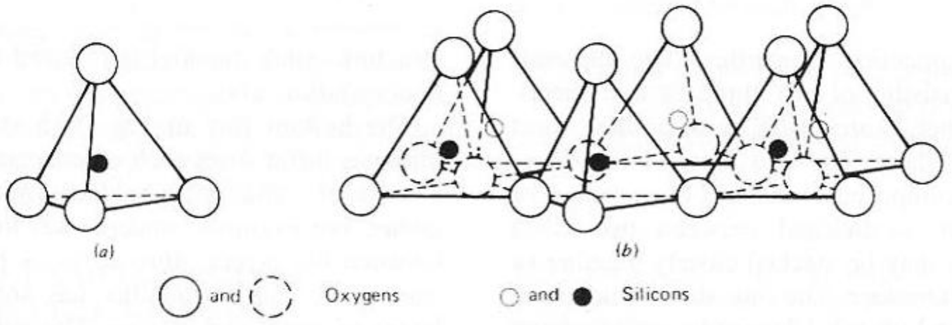


Figure 2.1: (a) Silicon tetrahedron and (b) silica tetrahedral arranged in a hexagonal network (after Mitchell & Soga, 2005).

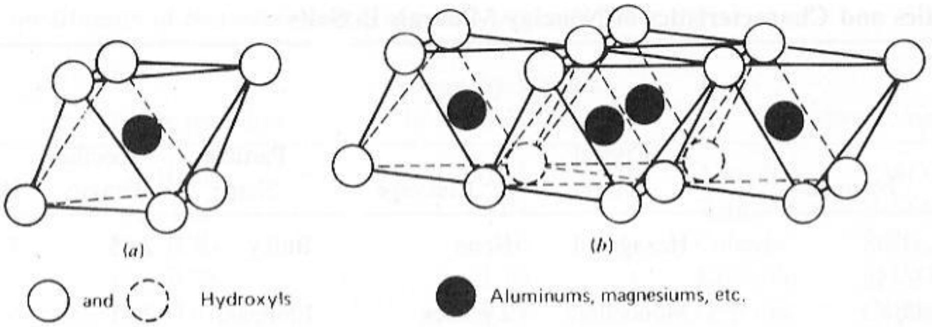


Figure 2.2: (a) Octahedral unit and (b) sheet structure of octahedral units (after Mitchell & Soga, 2005).

In the silicon-oxygen sheets, the silicon atoms are coordinated with four oxygen atoms. The oxygen atoms are located on the four corners of a regular tetrahedron with silicon atom in the centre. In the sheet, three of the four oxygen atoms of each tetrahedron are shared by three neighbouring tetrahedrals. The silicon-oxygen sheet is called the *tetrahedral sheet* or the *silica sheet* (Mitchell & Soga, 2005). Octahedral sheet is composed of magnesium or aluminium in octahedral coordination with oxygen or hydroxyls. The aluminium or magnesium atoms are coordinated with six oxygen atoms or OH groups. The oxygen atoms are located on the six corners of a regular octahedron with aluminium or magnesium atom in the centre

The analogous symmetry and the almost identical dimensions in the tetrahedral and the octahedral sheets allow the sharing of oxygen atoms between these sheets. The fourth oxygen atom protruding from the tetrahedral sheet is shared by the octahedral sheet. In the 1:1 layer minerals, this sharing of atoms may occur between one silica and one alumina sheet. In the 2:1 layer minerals, one alumina or magnesium sheet shares oxygen atoms with two silica sheets, one on each side. The combination of an octahedral sheet and one or two tetrahedral sheet is called a layer. Most clay minerals consist of such layers, which are stacked parallel to each other (van Olphen, 1977).

2.3 Physical Chemistry of Clays

Clays have unusual physicochemical properties chiefly because of the combined influenced of two factors. These are the high surface area and the electrical charge in the silicate structure of the clay mineral. The high surface area results from the small particle size and platy or elongate morphology of the minerals and the negative charge from ionic substitutions in the crystal structure. The charge is now thought to occur as discrete charge rather than as a uniform distribution over the surface (Gillot, 1987).

Particles exhibit properties characteristic of the colloidal state when they have sizes within range of about 50 to 2000 Å (Gillot, 1987). The surfaces of materials have distinctive physico-chemical properties. In the interior of a solid, liquid or gas there is no imbalance in the forces acting on the atoms which are surrounded on all sides by a similar configuration of other atoms. The surface atoms of a solid or liquid however are pulled by attractive forces most strongly on the side facing inward (Gillot, 1987).

A colloidal suspension has properties which are different from those of either a true solution or a suspension of coarser particles as described as Gillot (1987):

1. A colloidal suspension will pass through filter paper.
2. It shows electrical effects such as electrophoresis and electroosmosis.
3. The particles are observable in the ultra-microscope.
4. The particles may often be caused to precipitate of “flocculate” by the addition of small amounts of electrolytes.
5. The whole system may set forming gel, the process being known as gelation.

2.4 Clay-Water-Electrolyte System

Water usually defines as a liquid composed of water molecules, H_2O. However, some of the molecules disassociate themselves from the compound into hydrogen ions (H^+) and hydroxyl ions (OH^-). Water and soil particles interact with each other because, under ordinary circumstances, water molecules are strongly attracted to and absorbed on the soil particles surface. The negative electrical charge of the mineral attracts the cations, including the hydrogen ions disassociated from the water, to the surface of the mineral. The absorbed water molecules are more intense near the clay particles; with the intensity decreasing with an increase in distance from the clay particles (see Figure 2.3).

Mitchell & Soga (2005) stated that unbalanced force fields at the interfaces between soil and water cause interactions between small soil particles, dissolved ions and water. If two particles are in close proximity, their respective force fields overlap and influence the behaviour of the system, especially when the magnitudes of these forces are large relative to the weights of the particles themselves. Clay particles, because of their very small size, unique crystal structure, and platy shapes, have very large specific surface areas and are especially influenced by these forces (Mitchell & Soga, 2005). Several types of interparticle attractive and repulsive forces determine the flocculation-deflocculation behaviour of clays in suspension and the volume change and strength properties of the soils at void ratios common in natural deposits. Therefore, principles of surface, colloidal and soil chemistry provide understanding many of the interactions and their consequences in clay-water-electrolyte system.

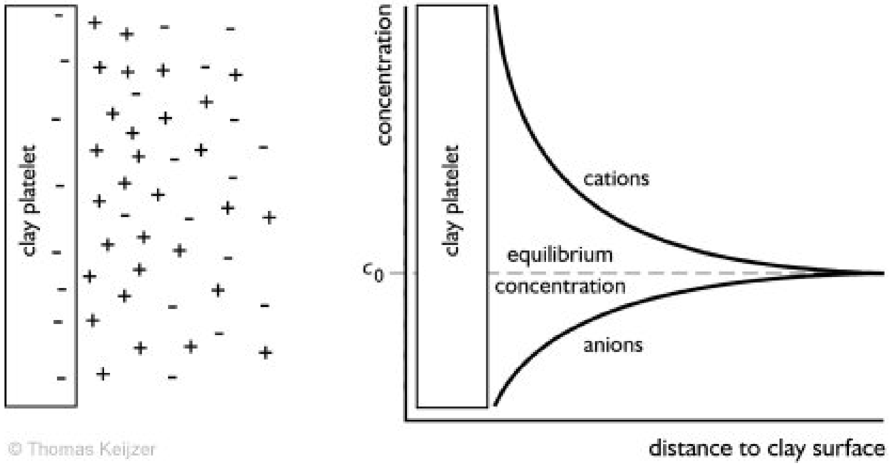


Figure 2.3: Distribution of cations and anions adjacent to a clay platelet according to the diffuse double layer theory (after Mitchell & Soga, 2005).

Adsorbed cations are tightly held on surfaces of negatively charged dry particles. Cations in excess of those needed to neutralize the electro-negativity of the clay particles and associated anions are present as salt precipitates. When water is present, the precipitates can go into solution. The absorbed cations, because of their high concentrations near the surfaces of particles, try to diffuse away in order to equalise concentrations throughout the pore fluid. Their freedom to do so, however, is restricted by both the negative electrical field originating in the particle surfaces and ion-surface interaction that are unique to specific cations. The escaping tendency due to diffusion and the opposing electrostatic attraction lead to ions distribution adjacent to a single particle in suspension that are often idealized as shown in Figure 2.3.

2.5 Diffuse Double Layer

The charged surface and distributed charge in the adjacent phase are together termed the diffuse double layer. The diffuse double layer consists of two phases; the charged surface of the particle and the distributed ionic charge, which is accumulated in the liquid near the particle surface (van Olphen, 1977). Several theories have been proposed for the ion distributions adjacent to the charged surfaces, which the Gouy-Chapman is the simplest and perhaps the most important one (Mitchell & Soga, 2005).

The Gouy-Chapman theory was improved by a more realistic double layer model which is the Stern model. The theory of the model assumes that some ions are tightly retained immediately next to the particle surfaces in a layer of specifically adsorbed water, the stern layer, and the double layer is diffuse beyond this layer as shown in Figure 2.4. The double layer consists of two layers, Stern layer and Gouy layer (also called diffuse double layer), and the two layers are separated by the Helmholtz plane.

Hiemenz (1977) pointed out that generally, the thicker the diffuse layer the less the tendency for particles in suspension to flocculate and the higher the swelling pressure in expensive soils. The diffuse layer become thinner when an increase in electrolyte concentration reduces the surface potential for the condition of constant surface charge and the decay of potential with distance is much more rapid. The consequence of this phenomena cause the flocculation of particle in suspension when facilitated by an increase in electrolyte concentration. Hence swelling behaviour of clay depends on electrolyte concentration.

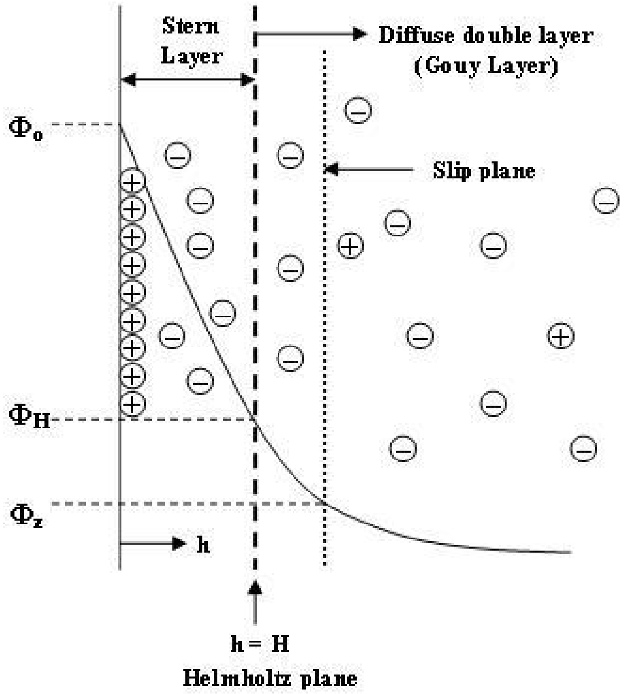


Figure 2.4: Stern's model and ions distribution in the electric double layer (after Hiemenz, 1977).

Mitchell & Soga (2005) also mentioned that an increase in cation valence will suppress the mid-plane concentrations and potential between interacting plates, thus leading to a decrease in interplate repulsion. Adsorbed multivalent ions usually restrict the separation distances between clay platelets, consequently resulting in a limited applicability of the double layer equations.

The dielectric constant of the medium is a measure of both surface potential and the thickness of the diffuse layer, since for a constant surface charge, the surface potential function increases as the dielectric constant decreases while thickness of the double layer decreases when the dielectric constant decreases (Hiemenz, 1977). As a result, suspended particles have greater tendency to flocculate. Temperature increases can cause an increase in the thickness of the diffuse layer and a decrease in surface potential for a constant surface charge (Mitchell & Soga, 2005).

The theory of the diffuse double layer provides useful insight into ionic distribution adjacent to clay particles. This theory allows for reasonable prediction of flocculation-deflocculation, swelling and the effect of pore fluid compositional changes. However, there is serious disagreement in many cases that consider some factors such as pH, ion size, particle interference and forces (Mitchell & Soga, 2005).

2.6 Cation Exchange

Clay absorbs cations of specific types and amounts under various environmental conditions such as temperature, pressure, pH, chemical and biological composition of the water. The total amount adsorbed balances the charge deficiency of the solid particles. Exchange reactions involved replacement of a part or all of the adsorbed ions of one type by ions of another type. The types of adsorbed cations depend on the depositional environment. For example, sodium and magnesium are dominant cations in marine clays since they are common in sea water. These exchange reactions may change the physical and physicochemical properties of the soil (Mitchell & Soga, 2005). Different samples of the same clay mineral give different values for cation exchange capacity so a range of values exists for the same mineral due to the differences in structure and composition between samples. In addition, particle size also has an important effect (Gillot, 1987).

There are three sources of clay exchange capacity. Isomorphous substitution is the major source of clay exchange capacity, except for kaolin mineral. In clay minerals, however, some of the tetrahedral and octahedral spaces are occupied by cations other than those in the ideal structure. Common examples are aluminium in place of silicon, magnesium instead of aluminium, ferrous ion (Fe^{2+}) for magnesium. This presence in an octahedral or tetrahedral position of a cation rather than that normally found, without change in crystal structure, is isomorphous substitution. In clay minerals, isomorphous substitution causes the clay minerals to obtain a net negative charge. Cations are attracted and held between the layers and on the surfaces and edges of the particles to preserve electrical neutrality. Many of these cations are exchangeable cations because they may be replacing by cations of another type. The quantity of exchangeable cations is called the cation exchange capacity (CEC) and is usually expressed as miliequivalents (meq)[3] per 100 g of dry clay (Mitchell & Soga, 2005).

The second major source of clay exchangeable capacity is broken bond due to unsatisfied valencies at edges and corners to which exchange ions become attached. The number of exchange sites increases as particle size decreases and fine fractions of many minerals show an increase in exchange capacity. This effect is shown by kaolinite and contributes up to 20 percent of the total in smectite (Mitchell & Soga, 2005). Another source is replacement of the hydrogen of an exposed hydroxyl by another type of cation. Under certain conditions actions from within the structure may become exchangeable. For example, in an acid environment the aluminium ions move from within the silicate structure of clay minerals into exchange positions (Gillot, 1987). Therefore, the contributions of each of these sources depends on various environmental and compositional factors, so a given clay minerals does not have a fixed, single value of exchange capacity. The capacity is directly related to the specific surface and surface charge density.

2.6.1 Ion Selectivity

The ease of cation replacement depends on the valence, ion size and relative abundance of different ion types. The lyotropic series generally states that higher valence cations can replace cations of lower valence and larger cations replace smaller cations of the same valence. The lyotropic series is written as (Mitchell & Soga, 2005):

$$Na^+ < Li^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$$

This series shows that the cations to the right will preferentially replace those to the left. Thus cation such as Ca^{2+} and Al^{3+} will replace those cations commonly found in clays. The cation commonly found in the diffuse double layer and the pore water are variously sodium, potassium, calcium, magnesium and lithium, and in some cases higher order ions are also present. When cations of a higher valency and/or a larger ionic radius, such as calcium, silicon or aluminium, are introduced in significant concentrations, they saturate the solution and become absorbed at clay surface in preference to those ions originally present (Barker *et al.,* 2004). Valence is the most important factor controlling ion selectivity, divalent ions being more strongly retained than monovalent ions and trivalent ions more strongly retained than divalent ions. Cations with larger non-hydrated radius or small hydrated radius have greater replacement power. However, it is possible to displace a cation of high replacing power such as Al^{3+}, by one of low replacing power, such as Na^{+}, by mass action, if the concentration in solution of the ion of low replacing power is high relative to that of the ion of higher replacing power (Mitchell & Soga, 2005).

The rate of exchange depends on a number of aspects, including clay type, solution concentrations, and temperature. In general, exchange reactions in the kaolin minerals are almost instantaneous. In illite, a few hours may be needed for completion because a small part of the exchange sites may be between unit layers. A longer time is required in smectite because the major part of the exchange capacity is located in the interlayer regions (Mitchell & Soga, 2005).

2.7 Flow Theories

Flow of water play a vital role in the deformation, volume change, and stability behaviour of clays themselves, and they may control the rates at which the processes occur. Therefore, flow of water through soil and rock has been extensively studied because of its essential role in geotechnical problem of seepage, consolidation, and stability, which form a major part of engineering analysis and design. A part from that, chemical, thermal, and electrical flows in soil are also important (Alshawabkeh *et al.,* 2004; Mitchell & Soga, 2005).

The four types of flow mentioned above, are each driven by their own potential gradient, several types of coupled flow are important under variety of circumstances (see Figure 2.5). A coupled flow is a flow of one type, such as hydraulic, driven by a potential gradient of another type, such as electrical (Alshawabkeh *et al.,* 2004). Ion migration through any medium due to any gradient such as chemical, electrical, hydraulic or thermal, is a function of both the driving force (magnitude of the gradient across the medium) and the coefficient of flow (the inverse of the resistance possessed by the medium to the flow). It is known that, provided that the flow process does not change the state of the soil, each flow rate or flux, J_i is linearly related to its corresponding driving forces, X_i and the conductivity coefficient for flow, L_{ii} according to equation below (Mitchell & Soga, 2005):

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

The terms in Figure 2.5 are identified in Table 2.1(a) which also shows more details on the laws governing each type of these direct flows. Typical ranges for the values of direct flow conductivities for hydraulic, thermal, electrical, and diffusive chemical are shown in Table 2.1(b). These ranges are for full saturation and fine grained soils, that is, silts, silty clays, clayey silts, and clays. The values for partly saturated soils can be much lower. Also listed in Table 2.1(b) are values for electroosmotic efficiency, and ionic mobility. These parameters are needed for analysis of coupling of hydraulic, electrical, and chemical flow.

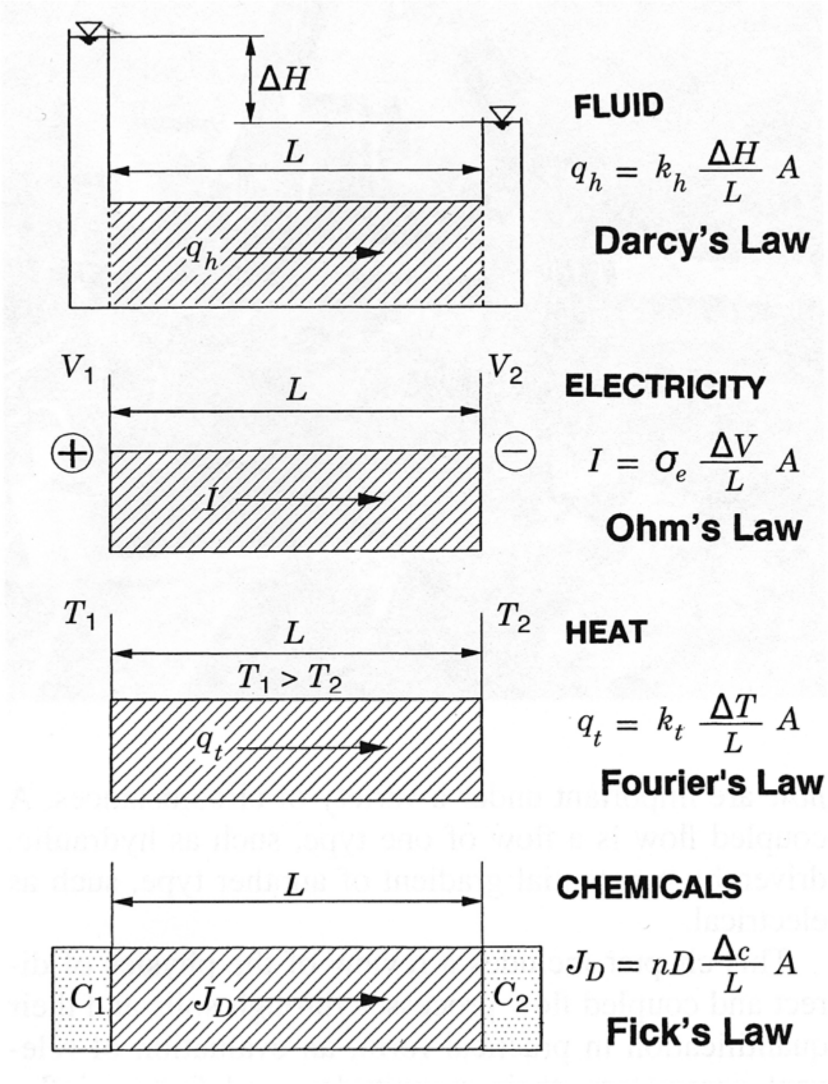
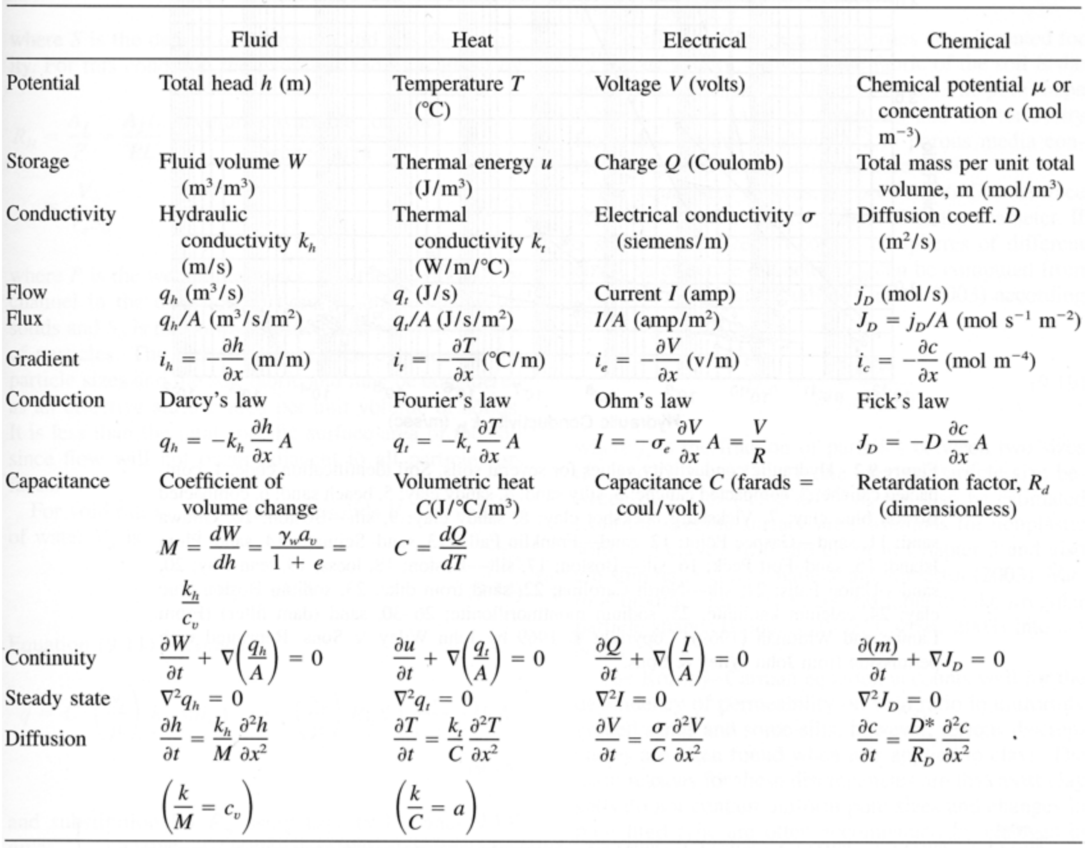


Figure 2.5: Four types of direct flow through a soil porous mass. A is a total cross-section area normal to flow; *n* is porosity (after Mitchell & Soga, 2005).

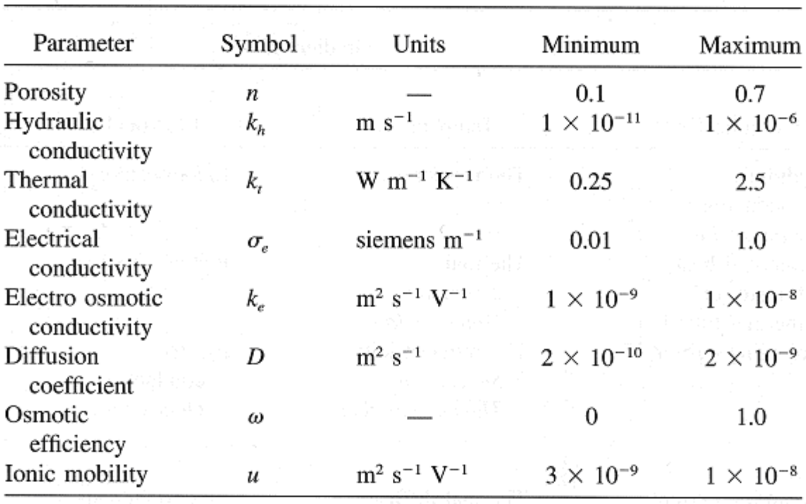
Table 2.1: (a) Conduction analogies in porous media and (b) Typical Range of Flow parameters for fine-grained soils (after Mitchell & Soga, 2005).

(a)



	Fluid	Heat	Electrical	Chemical
Potential	Total head h (m)	Temperature T (°C)	Voltage V (volts)	Chemical potential μ or concentration c (mol m^{-3})
Storage	Fluid volume W (m^3/m^3)	Thermal energy u (J/m^3)	Charge Q (Coulomb)	Total mass per unit total volume, m (mol/m^3)
Conductivity	Hydraulic conductivity k_h (m/s)	Thermal conductivity k_t (W/m/°C)	Electrical conductivity σ (siemens/m)	Diffusion coeff. D (m^2/s)
Flow	q_h (m^3/s)	q_t (J/s)	Current I (amp)	j_D (mol/s)
Flux	q_h/A ($m^3/s/m^2$)	q_t/A ($J/s/m^2$)	I/A (amp/m^2)	$J_D = j_D/A$ (mol s^{-1} m^{-2})
Gradient	$i_h = -\frac{\partial h}{\partial x}$ (m/m)	$i_t = -\frac{\partial T}{\partial x}$ (°C/m)	$i_e = -\frac{\partial V}{\partial x}$ (v/m)	$i_c = -\frac{\partial c}{\partial x}$ (mol m^{-4})
Conduction	Darcy's law $q_h = -k_h \frac{\partial h}{\partial x} A$	Fourier's law $q_t = -k_t \frac{\partial T}{\partial x} A$	Ohm's law $I = -\sigma_e \frac{\partial V}{\partial x} A = \frac{V}{R}$	Fick's law $J_D = -D \frac{\partial c}{\partial x} A$
Capacitance	Coefficient of volume change $M = \frac{dW}{dh} = \frac{\gamma_w a_v}{1 + e} = \frac{k_h}{c_v}$	Volumetric heat C(J/°C/m^3) $C = \frac{dQ}{dT}$	Capacitance C (farads = coul/volt)	Retardation factor, R_d (dimensionless)
Continuity	$\frac{\partial W}{\partial t} + \nabla\left(\frac{q_h}{A}\right) = 0$	$\frac{\partial u}{\partial t} + \nabla\left(\frac{q_t}{A}\right) = 0$	$\frac{\partial Q}{\partial t} + \nabla\left(\frac{I}{A}\right) = 0$	$\frac{\partial (m)}{\partial t} + \nabla J_D = 0$
Steady state	$\nabla^2 q_h = 0$	$\nabla^2 q_t = 0$	$\nabla^2 I = 0$	$\nabla^2 J_D = 0$
Diffusion	$\frac{\partial h}{\partial t} = \frac{k_h}{M} \frac{\partial^2 h}{\partial x^2}$ $\left(\frac{k}{M} = c_v\right)$	$\frac{\partial T}{\partial t} = \frac{k_t}{C} \frac{\partial^2 T}{\partial x^2}$ $\left(\frac{k}{C} = a\right)$	$\frac{\partial V}{\partial t} = \frac{\sigma}{C} \frac{\partial^2 V}{\partial x^2}$	$\frac{\partial c}{\partial t} = \frac{D^*}{R_D} \frac{\partial^2 c}{\partial x^2}$

(b)



Parameter	Symbol	Units	Minimum	Maximum
Porosity	n	—	0.1	0.7
Hydraulic conductivity	k_h	m s^{-1}	1×10^{-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
Electro osmotic 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}

2.7.1 Hydraulic Flow

Hydraulic flow, or hydraulic conduction, is the transport of fluid due to a hydraulic gradient, or head differential, as described by Darcy’s Law:

$$q_h = v_h A \tag{2.2}$$

$$q_h = k_h i_h A \tag{2.3}$$

Where q_h is the hydraulic flow, v_h is the water flow velocity, k_h is the hydraulic conductivity, i_h is the hydraulic gradient, ΔH/L, and A is the cross-section area normal to the direction of flow. According to Darcy’s Law, the resistance to flow of liquids and gases dependent on the viscosity, that is, the resistance of the molecules within the liquid or gas to move relative to each other when subjected to an externally applied shear force. Fluid flow within soil is a function of the degree of saturation, particle size and packing arrangement, and temperature (Barker *et al.,* 2004). The hydraulic conductivity for soils depends on the clay content, the sedimentation procedure, the compression rate and the electrolyte concentration (Mitchell & Soga, 2005).

2.7.2 Electrical Flow

Electrical flow, or electrical conductance, is the transport of ions due to an electrical potential applied across a medium. When an electric field is created in a medium, electrons will accelerate and gain kinetic energy. These electrons then collide with atoms and transfer kinetic energy, as described by Ohm's Law (Mitchell & Soga, 2005):

$$I = \sigma_e \, i_e \, A \qquad (2.4)$$

Where, I is the electrical flow, σ_e is the electrical conductivity, i_e is the electrical gradient, $\Delta V/L$ and A is the cross-section area normal to the direction of flow. σ_e is applies to soil-water systems and equals the inverse of the electrical resistivity:

$$\sigma_e = \frac{1}{R}\frac{L}{A} \text{ (siemens/metre; S/m)} \qquad (2.5)$$

Where R is the resistance (Ω), l is length of sample (m), and A is its cross-sectional area (m^2). The value of electrical conductivity for a saturated soil is usually in the approximate range of 0.01 to 1.0 S/m as seen Table 2.1(b). The electrical conductivity value depends on several properties of the soil, including porosity, degree of saturation, composition (conductivity) of the pore water, mineralogy (as it affects particle size, shape, and surface conductance), soil structure (fabric and cementation) and temperature (Mitchell & Soga, 2005). According to Barker *et al.* (2004), the specific factors affecting the conductivity of the soil undergoing treatment include the following:

(a) *The solubility of the minerals present, which is a function of pH.* The reduction in pH from around pH 8.0 to 7.0 causes the solubility of aluminium oxide (a predominantly clay mineral) to reduce slightly from approximately 2.8 to 2.4 mmol/l.

(b) *The migration of ions into and out of the soil*. The applied electrical current would cause anions and cations within the pore fluid to migrate towards the anode and cathode, respectively. Ions are also introduced through addition of chemical solution at the electrodes and corrosion of the anode.

(c) *The precipitation of compounds as ions mix within the pore fluid*. As the species of ions alter within the pore fluid, compound are formed that may be more sensitive to changes in pH over the ranges observed, thus resulting in precipitation.

2.7.3 Chemical Flow

Chemical flow, or diffusion, is the transport of a chemical species due to a gradient in its concentration. This net transport of chemicals from an area of high concentration to an area of low concentration is a result of random molecular motions (Mitchell, 1991). Chemical flow in a free solution is described by Fick's law:

$$J_D = D\, i_c\, A \qquad (2.6)$$

Where is the diffusion, D is the diffusion coefficient, i_c is the concentration or chemical potential gradient, $\Delta c/L$ and A is the cross-section area normal to the direction of flow. Diffusion coefficient is affected by the valency of the flowing ions relative to each other, solution concentration, pressure, and electrolyte strength. Diffusion through soil is somewhat reduced owing to a reduced cross-sectional area of flow, increased tortuosity of flow path, and interactions between differing chemical species and pore water (Barker *et al.,* 2004).

2.7.4 Thermal Flow

Thermal flow, or thermal conduction, is the transfer of internal energy, due to a temperature gradient, by conduction, convection or radiation as described by Fourier's law:

$$Q_t = k_t \, i_t \, A \qquad (2.7)$$

Where Qt is the thermal flow, k_t is the thermal conductivity, i_t is the thermal gradient, $\Delta T/L$ and A is the cross-section area normal to the direction of flow. Internal energy describes the energy that atoms possess as they vibrate around their equilibrium positions. The resistance to thermal conduction is dependent on the freedom that atoms and electrons possess when vibrating around their equilibrium positions (Barker *et al.,* 2007). The thermal conductivity in a soil depends on the density and the degree of saturation of the soil because soil has a greater thermal conductivity than stationary water. However, where pore water is allowed to flow, much thermal flow occurs because of convection through pore water (Mitchell & Soga, 2005).

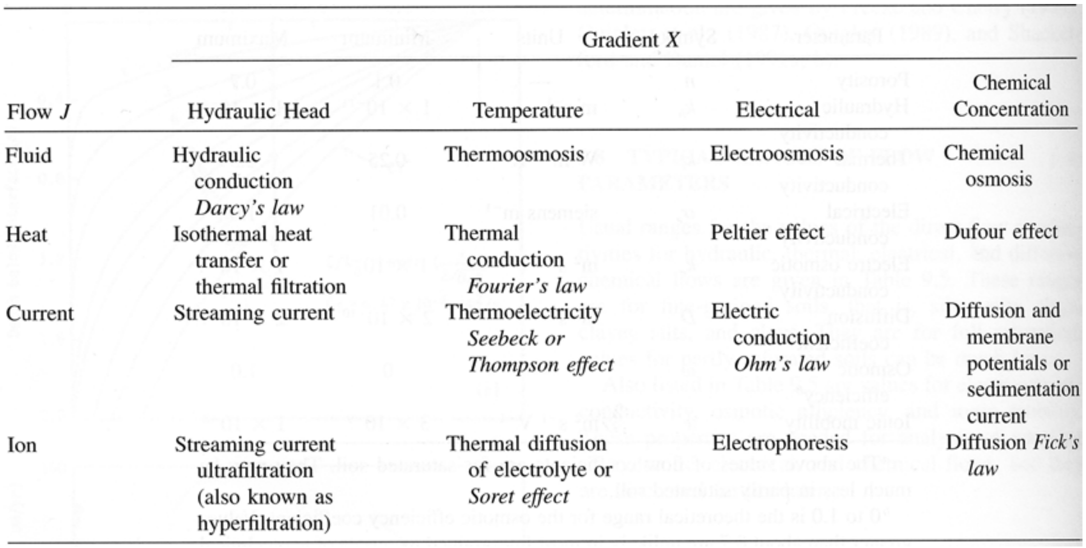
2.7.5 Coupled Flow

There are more than one type of flow that can operate through soils and rock. These act simultaneously, even when the driving force acting is the same. For example, when chemicals are transported under hydraulic gradient, there is a concurrent chemical flows through the soil (Mitchell & Soga, 2005). A gradient of one type X_j can cause a flow of another type Ji, according to:

$$J_i = L_{ij} X_j \tag{2.8}$$

Where L_{ij} is called coupling coefficient. All types of coupled flow are listed in Table 2.2. Measurement of coefficient of flow of the ions through the soil is complicated owing to the heterogeneity of soil and the creation of coupled flows. The creation of so many flow types through a soil system results in the need for complex methods of analysis. The processes of coupled flow generally use Direct Observational Approach and Irreversible Thermodynamics. Both theories assume that the soil properties remain constant throughout the investigation, although any variation in properties may be taken into account during the analysis (Barker *et al.,* 2007).

Table 2.2: Direct and Coupled Flow Phenomena (after Mitchell & Soga, 2005)



	Gradient *X*			
Flow *J*	Hydraulic Head	Temperature	Electrical	Chemical Concentration
Fluid	Hydraulic conduction *Darcy's law*	Thermoosmosis	Electroosmosis	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 (also known as hyperfiltration)	Thermal diffusion of electrolyte or *Soret effect*	Electrophoresis	Diffusion *Fick's law*

2.7.6 Direct Observational Approach

This method involves the use of various coefficients to describe both direct and coupled flows. These coefficients are placed in a matrix format in which, initially, there are many coefficients, although several may be eliminated because they are already known, some gradient may not exist, and some may be so small as to be assumed negligible (Barker *et al.,* 2007).

Thus the number of unknowns will be reduced from the matrix of flows and forces in which the determination of coefficient can be simplified. The various coefficients may be obtained through simple laboratory experiment in which the type and number of gradients and flows may be controlled and measured. For example, the effect of hydraulic gradient that caused flow can be eliminated by controlling hydraulic heads using Marriott bottle method which maintain the same level of water at both electrolytes This method is simple, and the most appropriate when couplings are significant and/or some degree of uncertainty of the measured coefficient is acceptable (Barker *et al.,* 2007).

2.7.7 Irreversible Thermodynamics

When several flows are of interest, each resulting from several gradients, a more formal methodology is necessary so that all relevant factors are accounted for properly. Therefore, irreversible thermodynamics may be used as a more comprehensive system of analysis when the simplifications employed in the direct observational approach are unacceptable. This method is a phenomenological, macroscopic theory that provides a basis for description of systems that are out of equilibrium in order to produce quantitative prediction model.

2.8 Electrokinetic Phenomena in Soils

Electrokinetics is defined as the physicochemical transport of charge, action of charged particles and effects of applied electric potentials on formation and fluid transport in porous media. Coupling between electrical and hydraulic flows can be responsible for different types of electrokinetic phenomena in soil. The electrokinetic phenomena include electroosmosis, streaming potential, electrophoresis and sedimentation potential (Mitchell & Soga, 2005). Further major phenomena reported by Acar & Alshawabkeh (1993) and Yeung (2006) that occur when an electric field is applied to any soil sample were electromigration. However, for the purposes of this research study, only electroosmosis, electromigration and electrophoresis will be discussed in the following sections, since they have been given the most attention in geotechnical engineering because of their practical value for transporting water and charged ions in fine grained soils.

2.8.1 Electroosmosis

Electroosmosis is defined as fluid movement with respect to a solid wall as a result of an applied electric potential gradient. In other words, if the soil is placed between electrodes in a fluid, the fluid will move from one side to other when an electromotive force is applied. When an electrical potential is applied across a wet soil mass, cations are attracted to the cathode and anions to the anode. As ions migrate, they carry their water of hydration and exert a viscous drag on the water around them (Mitchell & Soga, 2005). A net positive mobile charge exists in the electrical double layer because the net charge on the soil particle is commonly negative. As a result, a net flow of pore water takes place in the double layer toward the cathode relative to the stationary soil particles. This motion of double layer water applies a viscous force to the free pore water. The result is that the whole pore water moves towards the cathode in response to the applied electrical gradient (Figure 2.6(a)).

According to Azzam & Oey (2001), the electoosmosis flow velocity in soils can be measured in the laboratory according to Figure 2.7 and described by equation below:

$$V_e = k_e \, i_e \tag{2.9}$$

Where, V_e is the electroosmotic flow velocity, k_e is the electroosmotic permeability coefficient, i_e is the electrical potential gradient $\Delta U / l$, U is the electrical potential, l is the length of soil specimen.

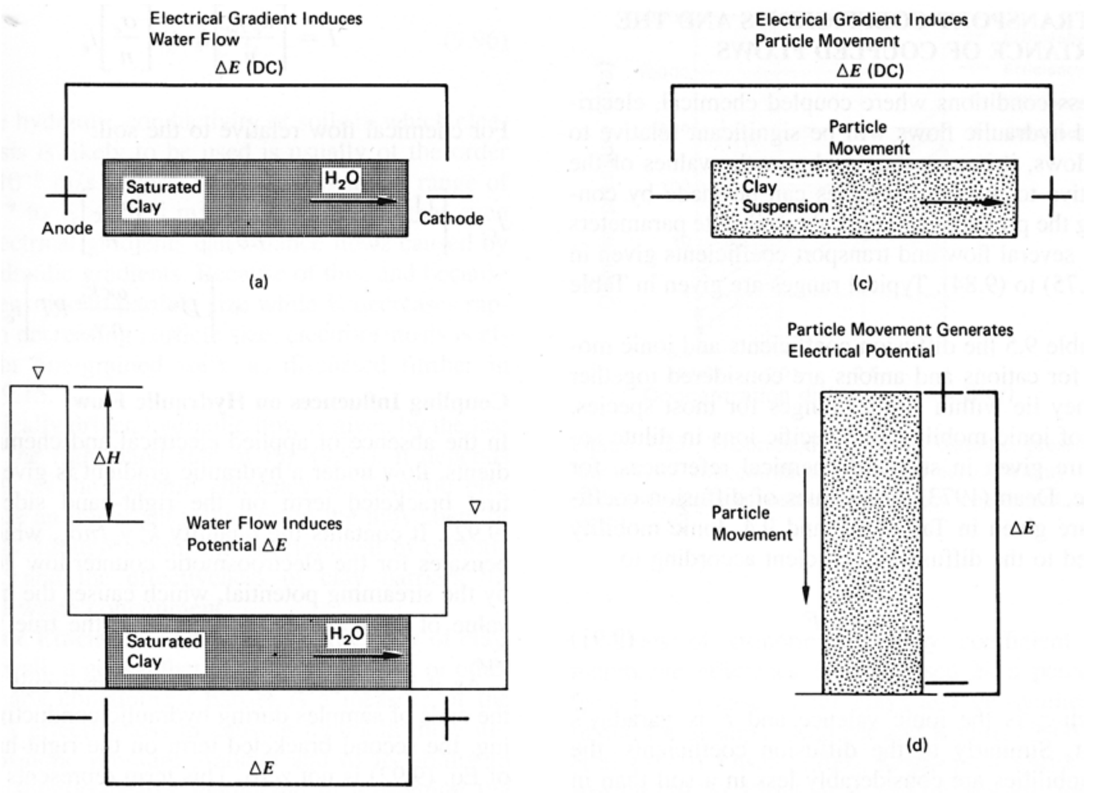


Figure 2.6: Electrokinetic phenomena: (a) electroosmosis, (b) streaming potential, (c) electrophoresis, and (d) migration or sedimentation potential (Mitchell & Soga, 2005).

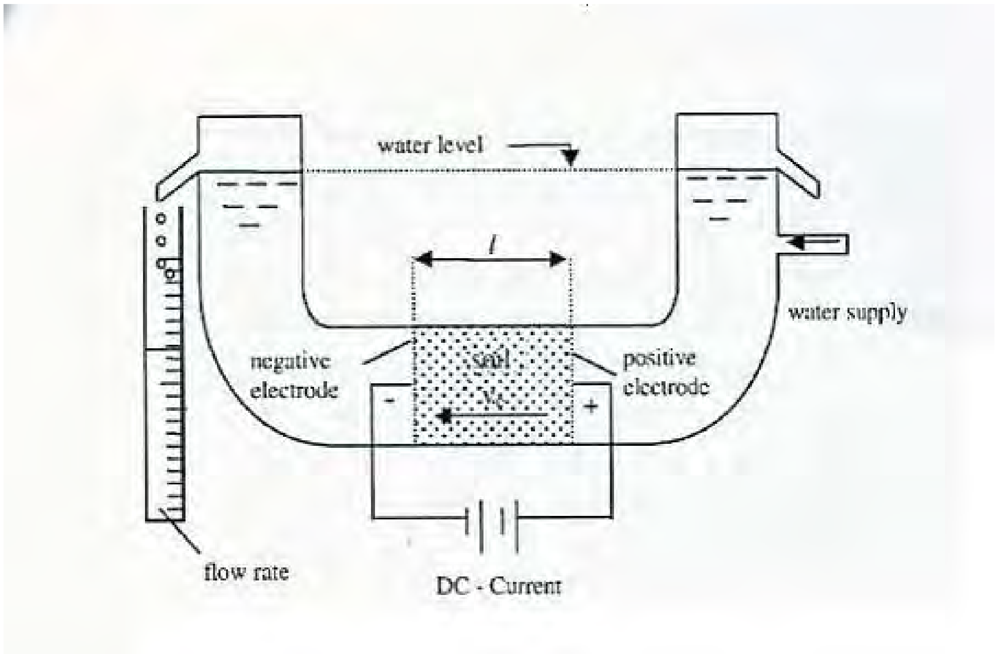


Figure 2.7: Test set up for the evaluation of the EO flow rate (Azzam & Oey, 2001).

The magnitude of electroosmosis depends on the coefficient of electroosmotic hydraulic conductivity (k_e) and the voltage gradient. The value of k_e is assumed to be a function of the zeta potential of the soil-pore fluid interface, the viscosity of the pore fluid, soil porosity, and soil electrical permittivity. When the soil pores are treated as capillary tubes, the coefficient of electroosmotic permeability is given by,

$$k_e = \frac{\zeta D}{\eta} n \tag{2.10}$$

Where, ζ is the zeta potential, D is the relative permittivity, n is the porosity, and η is the viscosity (FT/L^2). According to Helmholtz-Smoluchowski theory, k_e is dependent mainly on porosity and zeta potential. The value of has been assumed to be constant during electrokinetic process as long as there is no change in the concentration of ions or pH of the pore fluid (Mitchell & Soga, 2005).

Electroosmosis is a phenomenon that occurs only in soils containing these particles with charged surface. It is a function of the excess of positively charged ions over negatively charged ones, or vice versa. It therefore does not occur in sands, silts or gravels unless an appreciable amount of clay particles is present (Harbottle, 2003).

Several theories have been proposed to describe the electroosmosis phenomena and to provide a basis for quantitative prediction of the volume rate of liquid through a soil mass generated by a direct current electric field. The widely accepted theory is the Helmholtz-Smoluchowski model.

One of the earliest and most widely used theoretical models of electroosmosis process is based on a model introduced by Helmholtz in 1879 and refined by Smoluchowski in 1914 (Mitchell & Soga, 2005). The profile of this theory for the flow induced by electroosmosis in a capillary is shown in Figure 2.8. In this model, the saturated capillary is treated as an electrical condenser with ions of one sign on the wall surface and mobile ions of opposite sign in the liquid near the wall surface.

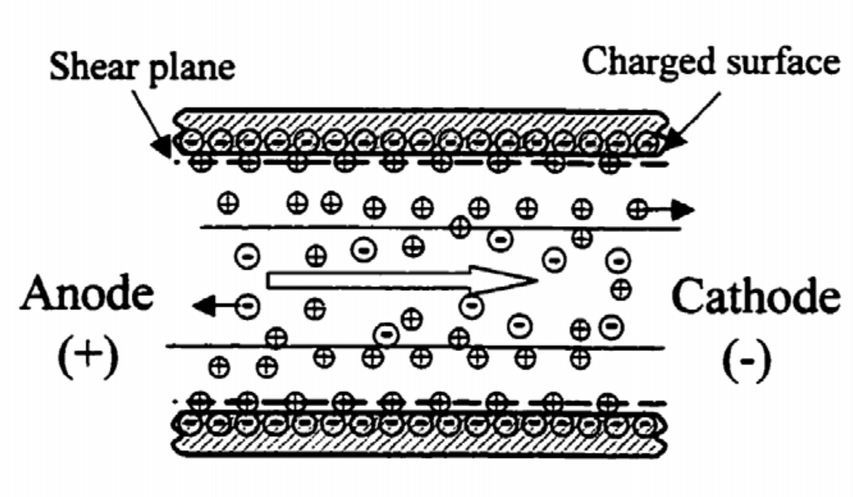


Figure 2.8: Schematic of electroosmotic flow between two charged surfaces (Duckhin, 1974).

2.8.2 Zeta Potential of Clay Minerals

The electrical potential in the shear plane is defined as zeta potential. van Olphen (1977) stated that special mention should be given at this point to the zeta potential in the double layer at the interface between a particle that moves in an electric field and surrounding liquid. The shear plane is found at a small distance which is between charge surface and electrolyte solution and unknown distance from the surface of the particles. It should be noted that the location of the zeta potential cannot be measured by existing theories. This is one of the limitations of zeta potential concept as reported by van Olphen (1977). However, Shang (1997) has assumed the computed zeta potential located at 0.6 nm from the clay surface. The sign and magnitude of the zeta potential directly relate to the strength and direction of the electroosmosis flow.

The zeta potential is considered as an indicator of the surface charge properties of the soil solids suspended in a water-electrolyte system as shown in Figure 2.9. A schematic of the electrical potential distribution in the Stern-Gouy double layer as related to distance to clay particle surface (see Figure 2.10).

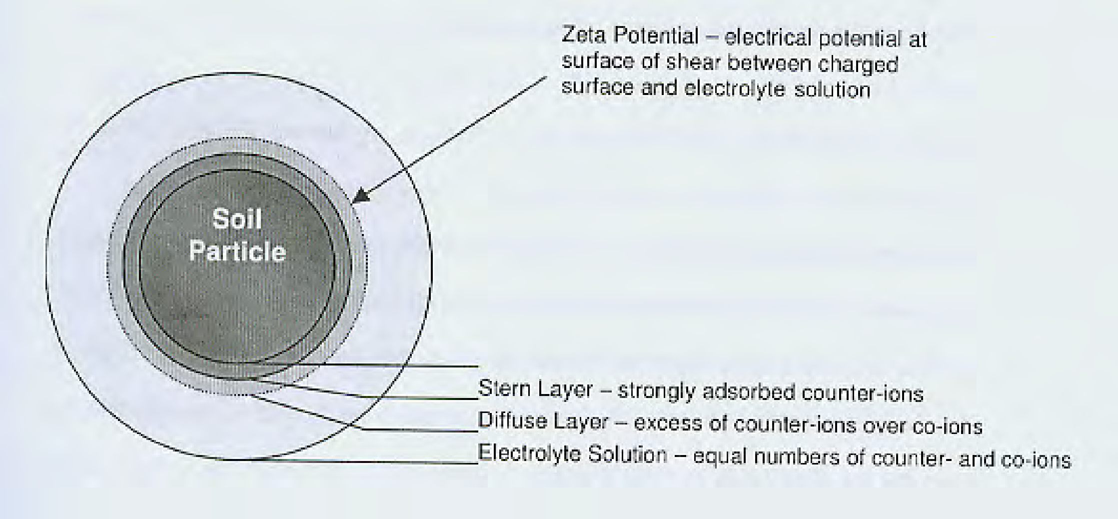


Figure 2.9: Idealised representation of water around clay particles (after Harbottle, 2003).

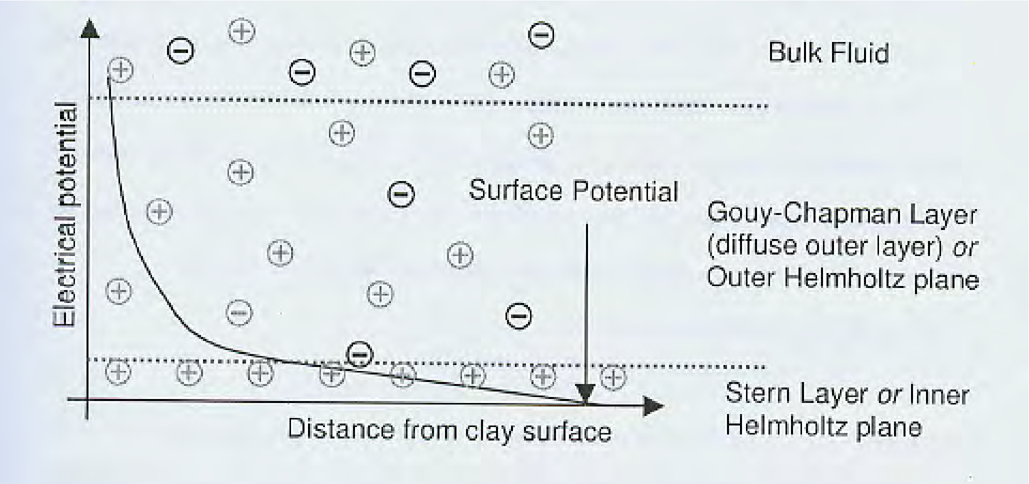


Figure 2.10: Typical variation of electrical potential with distance from clay surface (after Harbottle, 2003).

The zeta potential of most soil is negative because soil surfaces usually carry a negative charge. 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 electroremediation, affect the value of zeta potential (Hunter, 1981). Yeung (2006) reported that values of the zeta potential in most clay types are generally in the range of 0 to -50 mV. The polarity and magnitude of the zeta potential depends on a number of factors including: mineral surface, pore electrolyte concentration, and pore pH. Therefore, the point of zero charge (PZC) is defined as the pH at which the electrical potential at the edge of the compact electrical double layer is 0 mV (Hunter, 1981).

Vane & Zang (1997) reported that relationship between zeta potential and pH are significantly varied for different clay minerals. The zeta potential of kaolinite seems to be a strong function of pH, ranging from +0.7 mV at pH = 2 to -54 mV at pH = 10. However, behaviour of bentonite in response to pH changes was markedly different than that of kaolinite. The zeta potential of bentonite did not change by more 20% over a pH range of

2-10 (-31 to -36 mV). The relationship between the zeta potential and pH for kaolinite has been empirically determined (Eykholt & Daniel, 1994):

$$\zeta\ (\mathrm{mV}) = -38.6 + 281e^{-0.48\ \mathrm{pH}} \qquad (2.11)$$

In particular, low pH values are usually measured at the anodes and high value at the cathode. Whether, the electroosmotic flow is toward the anode or the cathode, the effect of electrode reaction on low pH.

Increasing acidity and ionic strength cause the zeta potential to become less negative and even to attain positive values at low pH. Flow rates have been observed to decrease if the pH of the electrolyte is depressed below neutral and to increase at alkaline pH values (Eykholt & Daniel, 1994).

2.8.3 Electromigration

Electromigration is the term that describes the transport of ions in the pore fluid due to electrostatic attraction. When the direct current electric field is applied across the soil, positive ions will be attracted to the cathode and negative ions to the anode. Experiments demonstrate by Acar & Alshawabkeh (1993) show that when the initial ionic conductivity of the pore fluid is high and when the initial soil pH is between 2 and 3, the electroosmotic process is not efficient while the ionic species are transported efficiently by electromigration. Electromigration is the major transport mechanism for ionic species under electric field in soils. Consequently, in a porous medium with conductive water, it seems that electromigration is the major cause of charge transport relative to electroosmosis. Furthermore, the mechanism depends mainly on the ion mobility (Paillat *et. al,* 2000). Hamnett (1980) confirmed that large ions such as potassium, copper or nickel were less mobile than small ones such as sodium which has a higher mobility. More, electrical migration will increase when species ionic concentration increases.

The mass flux due to electromigration in an electrolyte depends on the electric potential gradient, on the ionic mobility and concentration of a particular ion in the electrolyte. In the pore fluid of the soil, the tortuosity and porosity affect the mass transport rate further. Considering the effective ionic mobility in the soil to be (u_i*), ie is the electrical potential gradient ΔU/l, c_i is the concentration of ions. The mass flux per unit cross section can be given by (Azzam & Oey, 2001).

$$J_{ems} = u_i^* \, i_e \, c_i \qquad (2.12)$$

The effective ionic mobility, u_i*, is a measure of how fast ions will migrate toward the opposite charged electrode. According to Acar & Alshawabkeh (1993) it can be represented by following equation.

$$u_i^* = D_i^* \, z_i \, \frac{F_o}{RT} \qquad (2.13)$$

Where D_i^* = effective diffusion coefficient (m^2/s)

z_i = charge of ion i

F_o = Faraday's constant

R = Universal gas constant

T = Absolute temperature (˚K)

The effective diffusion coefficient, D_i^*, is defined by

$$D_i^* = D_i \quad n \qquad (2.14)$$

Where D_i = diffusion coefficient of ion i in a free solution at infinite dilution (m^2/s)

= tortuosity factor; and

n = porosity

2.8.4 Electrophoresis

Electrophoresis describes the transport of the larger colloidal or other charged material through soil mass. A charged colloidal particle suspended in a liquid is surrounded by an electric double layer, which plays a fundamental role in various interfacial electrical phenomena. Thus, electrophoresis is defined as the phenomenon that occurs when the direct current electric field is applied across a clay suspension; the negatively charged particles are attracted electrostatically to the anode, while they are repelled from the cathode as shown in Figure 2.6(c). Electrophoresis involves discrete particle transport through water, while electroosmosis involves water transport through a continuous soil particle network (Mitchell & Soga, 2005).

According to Acar & Alshawabkeh (1993), electrophoresis becomes significant in electrokinetic remediation only when surfactants are introduced in the processing fluid to form charged particles with other species or when the technique is employed in remediating slurries. The charged particles would be transported across the soil under the electrical field. The efficiency of this technique in remediating nonpolar organic substances is currently under investigation. Electrophoresis transport of negatively charged clay particles is significant only when slurry is processed. Therefore, electrophoresis has been used for concentration of mine waste and in high water content clays. Bentonite clay (commercial name of Wyoming smectite from Fort Benton, USA) is the most suitable material for electrophoresis because of its stability in suspension. Moreover, electrophoresis may be used when contaminant are charged particles (Acar & Alshawabkeh, 1993).

2.9 Electrochemical Effects

Along with the main effects of electrokinetic technique, there are other mechanisms affecting the electrokinetic process. These include the electrolysis of pore water molecules and the reaction of electrode to the application of electric current.

2.9.1 Electrolysis

Application of direct current through electrodes immersed in water induces electrolysis reactions at the electrodes. Acar & Alshawabkeh (1993) stated that electrolysis reactions dominate the chemistry at the boundaries. Oxidation of water at the anode result in the release of oxygen and hydrogen ions while reduction of water at the cathode result in the formation of hydrogen and hydroxide ions as described by the following electrolysis reactions, anode: $2H_2O - 4e^- \rightarrow O_2\uparrow + 4H^+$ (2.15)

cathode: $2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^-$ (2.16)

If these resulting ions are not removed or neutralised, an acid front will developed at the anode, while a base front develops at the cathode. Hydrogen ions that are produced at the anode by electrolysis of water are moved towards the cathode via electromigration, diffusion and electroosmotic resulting in an area of low pH near the anode. Hydroxide ions produced at the cathode are transported into the soil against the flow of water via electromigration and diffusion resulting in an area of high pH near the cathode (Barker *et al.,* 2004). These fronts will migrate towards each other under electrical gradient, with the soil being neutral where these fronts meet. However, the counterflow due to electroosmosis retards the back-diffusion and migration of the base front. The advance of this front is slower than the advance of the acid front because of the counteracting electroosmotic flow and also because the ionic mobility of hydrogen ion is 1.8 times faster than hydroxide ions (Asavadorndeja & Glawe, 2005). As consequences, the acid front dominates the chemistry across the specimen except for small sections close to the anode (Acar *et al.,* 1990). Moreover, the change in pH at electrodes that occurs under an applied electric potential causes the development of pH gradient across the soil sample and influences the solubility of the electrolytes.

The acid front produced at the cathode causes desorption, dissolution and ionization of cationic metals which then migrate toward the cathode. Chlorine may also form in a saline environment. Some of the exchangeable cations on the clay may be replaced by hydrogen ions. Because hydrogen clays are generally unstable and high acidity and oxidation cause rapid deterioration of the anodes, the clay will soon alter to the aluminium or ion form depending on the anode material. As a result, the soil is usually strengthened in the vicinity of the anode (Mitchell & Soga, 2005).

2.9.2 Electrode Reaction

When the electric current passes through an electrode surface in one direction or the other, an electrochemical reaction always takes place. This is called an electrode reaction. The electrode reaction at the anode, i.e. the anode reaction, is always an oxidation reaction. The cathode reaction on the other hand is always a reduction reaction (Liaki, 2006).

The reactions that occur between the electrodes and pore water depend on the characteristic of the pore water and the material properties of the electrodes (Barker *et al.,* 2004). Electrodes constitute the point where the current has to change from an ‘electronic character’ to the ‘ionic’ one. Therefore at the electrodes electrons are exchanged between the metallic phase and electrolyte in solution. In order for this to occur, some reactions are required. Faraday’s law determine the rate of the reactions happening, while the electrochemical potential of species in the system determines which reactions have to occur. Faraday’s law can be formulated in a quantitative framework by the sentence: “*When 96485 Coulombs pass through solution, at both the electrodes a gram equivalent of* *substances is released*". That implies the definition of Faraday's constant F=96485 C/gram equivalent (Musso, 2000).

High acidity and oxidation at the cathode cause rapid deterioration of the anode, especially if it is made of metal. Corrosion is an electrochemical process in nature which involves the spontaneous oxidation reaction in the presence of an aqueous environment. The product of the metal-dissolution reaction (corrosion) is ionic species:

$$\mathrm{Me} \rightarrow \mathrm{Me}^{n+} + n\mathrm{e}^- \qquad (2.17)$$

Where Me refer to metal used as electrodes, Me^{n+} is ions of the metal and ***n*** is the number of electrons (e^-), taking part in reaction. The metal ions further can create chemical species which can act as a cementing agent when precipitate at interparticle contact, resulting in a strength increase (Micic, 1998).

Mild steel have been used by Barker *et al.* (2004) at early stage of this research. Therefore, from corrosion theory, it is known that oxidation occurs at the anode due to loss of electrons, while reduction occurs at the cathode (Owen & Knowles, 1994):

Oxidation at the anode: $\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^-$ (2.18)

Reduction at the cathode: $\mathrm{O_2} + 2\mathrm{H_2O} + 4\mathrm{e}^- \rightarrow 4(\mathrm{OH})^-$ (2.19)

Combined: $\mathrm{Fe}^{2+} + 2(\mathrm{OH})^- \rightarrow \mathrm{Fe(OH)_2}$ Ferrous hydroxide (2.20)

Further oxidation: $Fe^{2+} \rightarrow Fe^{3+} + e^{-}$ (2.21)

Cations in solution are driven to the cathode where they combine with OH- and form hydroxides, Eq. (2.20), which easily precipitate, causing cementation of soil particles and stronger interparticle bonds (Micic, 1998).

2.10 Summary

Mechanism by which water and chemical solutions are migrated through soil medium under applied electric fields involved several contributory processes were highlighted in this chapter which later can be interpreted from the result and discussion chapter. Therefore, the review on clay system before treatment which not subjected to applied electric field i.e. mineralogy, physicochemistry of clay and clay-water-electrolyte was discussed here to understand the behaviour of the clay under the system. It can be seen that much advancement has been made in the development of theory for electrokinetic. The knowledge obtained during this theoretical stage is useful to promote a deeper understanding and to lead to important guidelines for soil improvement by electrokinetic. Consequently, laboratory test setup will be design in this study base on the approach and theoretical development from past research as to propose new hypotheses on how to improve the operation of the EKS system as discussed in methodology chapter later.

Chapter 3

ELECTROKINETIC APPLICATION

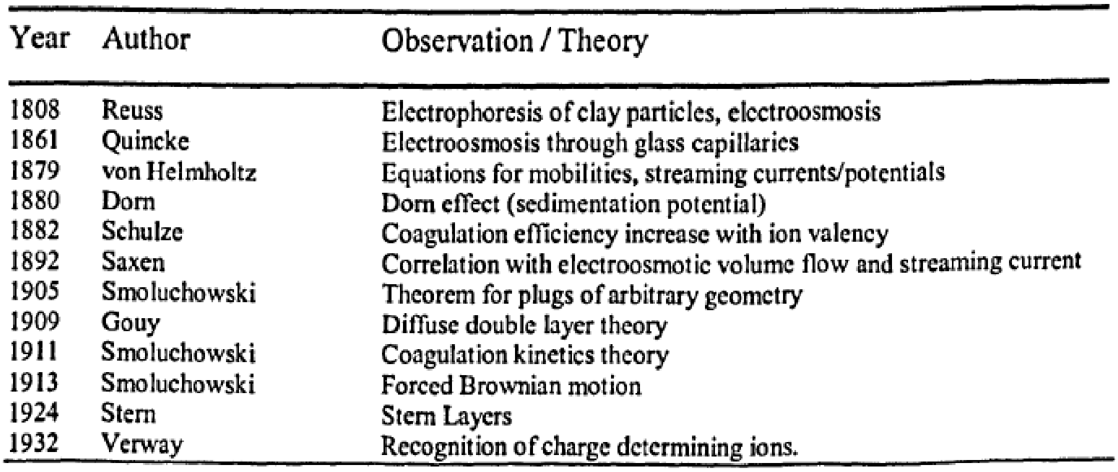
3.1 Introduction

This chapter will discuss the application of electrokinetic and to investigate current knowledge of electrokinetic in geotechnical application through a comprehensive literature search and review, including consideration of geoenvironmental aspects that may be relevant to this study and at the same time addressing some key issues and their implications on soil behaviours which is related to the current research. Most of the successful applications of electrokinetics previously reported in literature (discussed in section 3.2) have focused on dewatering and consolidation processes to improve properties of soft clays. Subsequently, the electrokinetic stabilisation method is being utilised which is the combination of the electroosmosis and electromigration process.

3.2 Development of Electrokinetic Application

Electrokinetic phenomena which was first observed by Reuss early in 1808 has led to development of first theory of electroosmosis by Helmholtz followed by Smoluchowski and many others as shown in Table 3.1. Despite the various applications benefited from electrokinetic phenomena, those theories are still widely used until now and extensive based laboratory studies are still conducted among researchers to improve understanding of the behaviour of the electrokinetic system. Due to the fact of adoption and invention of the new materials, various chemical stabilisers used, and emerging technologies in various applications caused this electrokinetic application to become more complicated and need good understanding of the basic electrokinetic phenomena. Consequently, this has contributed to a small number of electrokinetic applications to be implemented in the field compared to the conventional techniques either in geotechnical (etc; preloading with or without vertical drain, stone column and lime/cement column) or geoenvironmental engineering (etc; bioremediation, flushing and washing techniques).

Table 3.1: Some key developments in early understanding of electrokinetics (after Faulkner, 2010).



Year	Author	Observation / Theory
1808	Reuss	Electrophoresis of clay particles, electroosmosis
1861	Quincke	Electroosmosis through glass capillaries
1879	von Helmholtz	Equations for mobilities, streaming currents/potentials
1880	Dorn	Dorn effect (sedimentation potential)
1882	Schulze	Coagulation efficiency increase with ion valency
1892	Saxen	Correlation with electroosmotic volume flow and streaming current
1905	Smoluchowski	Theorem for plugs of arbitrary geometry
1909	Gouy	Diffuse double layer theory
1911	Smoluchowski	Coagulation kinetics theory
1913	Smoluchowski	Forced Brownian motion
1924	Stern	Stern Layers
1932	Verway	Recognition of charge determining ions.

The utilisation of electrokinetic in geotechnical engineering for dewatering (electroosmosis) and stabilisation of low permeability soil started in an early 1930s by Casagrande (Pugh, 2002; Ou *et al.* 2009). It has demonstrated that a large reduction in water content will increase the shear strength of the soils due to the electrosmosis effect by electrical gradient. Since then, electrosmosis has been successfully implemented in the field for various geotechnical application including stabilisation of slopes (Bjerrum *et al.,* 1967; Wade, 1976), embankment (Chappel & Burton, 1975), improving friction pile capacity (Soderman & Milligan, 1961; Milligan, 1995), electrosmotic strengthening of soft sensitive clays (Lo *et al.,* 1991; Lo & Ho, 1991). More recently, numerous field applications include electrosmotic consolidation technique combine with vertical drains (Chew *et al.,* 2004; Rittirong *et al.,* 2008) and new innovative geosynthetic electrodes (Glendinning *et al.,* 2007; Lamont-Black & Weltman, 2010).

After a number of successful applications in the laboratory studies and field applications, researchers realised that the electrokinetic energy does not only induce electroosmosis, but also transports chemical species (electromigration) in the soil-water system either from degradation of electrodes or introduction of chemical stabilisers at the electrodes. This opened new opportunities for application in geotechnical and geoenvironmental engineering. Earlier works on EKS were done by Muruyama & Wise (1953), Harton *et al.* (1967) and Gray (1970), who discovered electrochemical hardening or electrokinetic cementation also contributes to the soil strengthening near the electrode areas. This has lead to further extensive research in laboratory studies (Ozkan *et al.,* 1999; Rogers *et al.,* 2003; Alshawabkeh & Sheahan, 2003; Barker *et al.,* 2004; Asavadorndeja & Glawe, 2005; Ou *et al.,* 2009) using different chemical stabilisers and electrodes in the EKS system to improve the soil properties.

As for geoenvironmental application, the idea of electrokinetic remediation started in the 1980s after scientists noticed that water transported by electroosmosis contained high amounts of heavy metals and other chemical species (Azzam & Oey, 2001). Initially, the applications of electrokinetic remediation in the laboratory studies to remove heavy metal have been conducted by Hamnett (1980), Segal *et al.* (1980) and Agard (1981). Subsequently, progress in this technique in field application has been conducted by Lagemen *et al.* (1989) and Lageman (1993). Even though this application of electrokinetic remediation is not the main purpose of this study, the subject has benefited from research carried out in relation to the chemical stabilisation of soils in situ by Rogers *et al.* (2003). However, to date very limited appraisal of the use electrokinetic stabilisation as a technique to strengthen the soils has taken place, due to the complexity of electrochemical processes involved when chemical stabilisers are introduced. Therefore, it is essential to review the electrokinetic application in various fields to gain better understanding of numerous electrochemical effects which include electrolysis, hydrolysis, ion exchange, adsorption and precipitation.

3.3 Electrokinetic Dewatering

One of the main effects of applying electrical current across a wet soil is the dewatering or drying of the soil. Figure 3.1 shows how through careful installation of electrodes, the flow of water toward the face of the bank or the bottom of an excavation can be reversed. The economical use of electroosmosis is confined to a narrow range of fine-grained soils, where other methods of drainage or consolidation would be too expensive (Fang & Daniels, 2006). In addition, for relatively low permeability clay soils, drainage by normal gravity flow often cannot be accomplished therefore the electroosmosis process is very important.

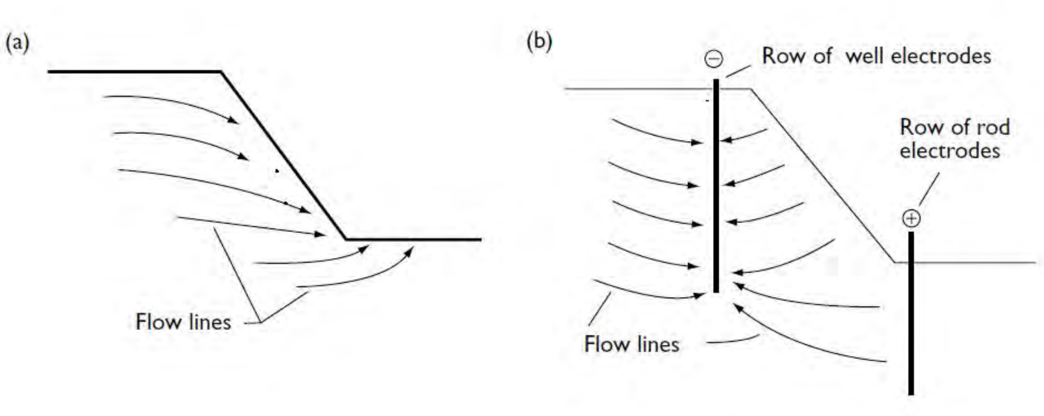


Figure 3.1: Comparison of flow characteristics. (a) Hydraulic flow; and (b) Electrokinetic flow (after Casagrande, 1952).

Experimental studies on electrokinetic dewatering by Hamir *et al.* (2001), Rittirong *et al.* (2008), Mohamedelhassan (2009) have resulted a constant rate of electroosmosis flow only at the beginning of the process. However, after a prolonged electrokinetic test, the electroosmosis flow was found to decrease with time. The decreased in electroosmosis flow can be observed from the monitoring of current profiles and water collected at the cathode due to desiccation and electrochemical changes within the soil mass which lead to decrease in soil electrical conductivity. Despite many successful laboratory studies and field applications of electrokinetic dewatering, there are few problems encountered to limit the efficiency of the electrokinetic system include high power consumption in certain cases (Lockhart, 1983), electrode corrosion (Rogers *et al.,* 2003; Barker *et al.,* 2004; Liaki *et al.,* 2010), improper design configuration (Rittirong *et al.,* 2008; Fourie *et al.,* 2007), voltage drop at the contact between the soil electrode (Mohamedelhassan & Shang, 2001; Lefebvre & Burnotte, 2002; Burnotte *et al.,* 2004; Ahmad *et al.,* 2011) and bubbles of gases such as hydrogen and oxygen produced by electrolysis cause fluid flow to become minimal (Page & Page, 2002; Rittirong *et al.,* 2008). These problems can be related with the electrochemical reaction across the soil sample during the electrokinetic treatment include cessation due to the heating and water removal at the anode (closed anode system), ion exchange processes caused reduction of diffused double layer, thus change the clay-water electrolyte system, and precipitation at the cathode which clogged the pore fluids.

Shang *et al.* (1996) suggested that the heating effect can be minimised using polarity reversal and intermittent (pulse) current. These approaches can reduce pH gradient, corrosion (if used metallic electrodes at the anode) and increase the permeability of the soil, thus improving the efficiency of the system. Rittirong *et al.* (2008) conducted a field trial and reported the electroosmosis flow stopped after one day treatment and applied polarity reversal in the second day to induced electroosmosis flow. However, the polarity reversal was lasted for 20 hours. They suggested that the gas accumulation in the EVD electrodes probably diminished the effectiveness of the electrokinetic treatment, and resulted in the cessation of electroosmosis flow.

In some cases the electrode materials used have often proved problematic in environmental terms, for instance; aluminium is toxic and can be quite readily bio-available and mobile under certain redox/pH conditions (Faulkner, 2010). In addition, high energy costs and limited knowledge relating to electrokinetic phenomena by geotechnical engineers who are more comfortable with the traditional approaches of ground improvement techniques, have limited the more widespread adoption of electrokinetic techniques for soil strengthening. Therefore, the invention of new electrode materials such as electrokinetic geosynthetics

(EKG) in geotechnical applications has overcome most the problems related to electrochemical process. This EKG electrode can provide the durability of electrodes and introduction of electrolytes to maintain the continuous electrosmosis flow and at the same time can migrate the selected ions into the soil system resulted in a large increase of soil shear strength compared the conventional electrokinetic dewatering which relied on reduction of water content and limited improvement at certain area at the electrodes.

In recent years, the progress made in the development of new material of electrodes used in electrokinetic dewatering applications to replace a conventional method used in earlier research (see Table 3.2). Therefore, the new development of EKG has been conducted extensively to enhance dewatering capabilities of soils in geotechnical application. Based on the study conducted by Hamir *et al.* (2001), the following conclusions have been drawn in their research:

(i) The performance of electrically conductive geosynthetic electrodes in electro-osmotic consolidation trials is comparable to that of copper disk electrodes.

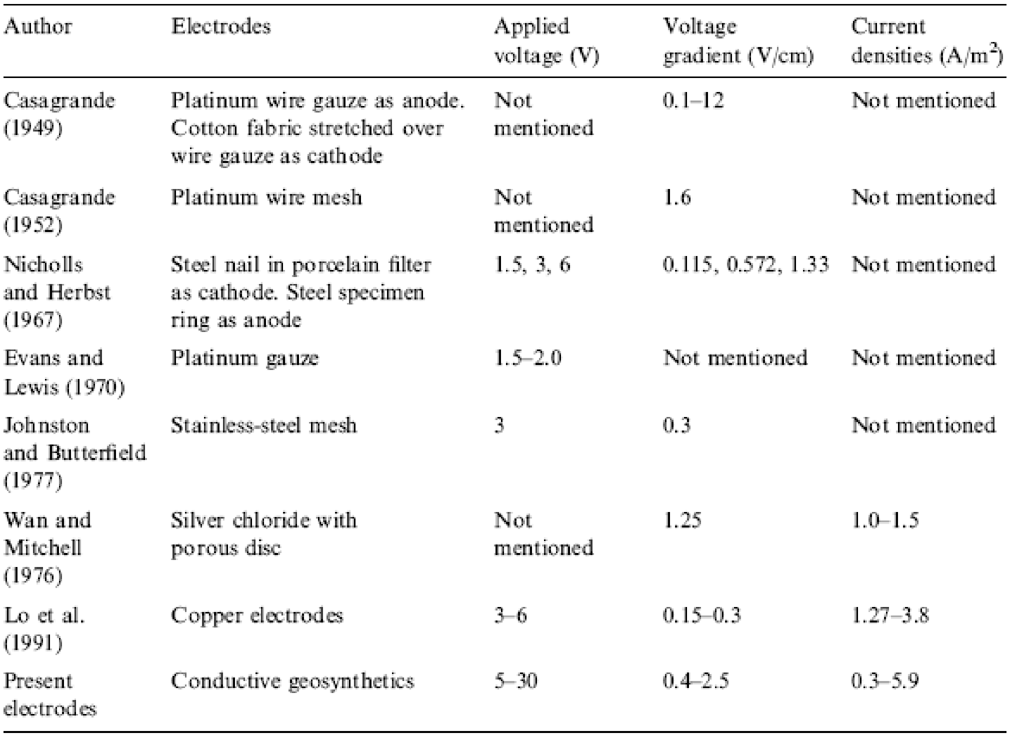
(ii) Electrically conductive geosynthetic electrodes are fully effective when the polarity is reversed.

(iii) The soil/filtration requirements of EKG electrodes can be based on the filtration criteria used for cohesive soil under normal hydraulic applications.

(iv) Conventional geosynthetic soil reinforcing materials can be made electrically conductive. The use of EKG reinforcement can increase the

> shear strength of fill and can provide a significant increase in reinforcement–soil bond strength, suggesting that formerly unsuitable wet fine-grained soils can be used to form reinforced soil structures.

Table 3.2: Types of electrodes used in other EO studies together with the applied voltages, voltage gradients and current densities applied (After Hamir *et al.,* 2001).



Author	Electrodes	Applied voltage (V)	Voltage gradient (V/cm)	Current densities (A/m^2)
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	Not mentioned
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	1.0–1.5
Lo et al. (1991)	Copper electrodes	3–6	0.15–0.3	1.27–3.8
Present electrodes	Conductive geosynthetics	5–30	0.4–2.5	0.3–5.9

Electrokinetic dewatering has also been used to treat the sewage sludge (Lamont-Black, 2001; Glendinning *et al.,* 2007) and dewatering of mine tailings using similar electrode by Fourie *et al.* (2007). In addition, electrokinetic dewatering has been successfully attempted in football pitches by the application of an electric field to the near surface of the pitch via buried EKG which utilises the movement of water through the soil to prevent water-logging of the playing surface (Lamont-Black, 2001). The EKG comprises conducting elements coated in a corrosion resistant material, incorporated into a geosynthetic material (see Figure 3.2).

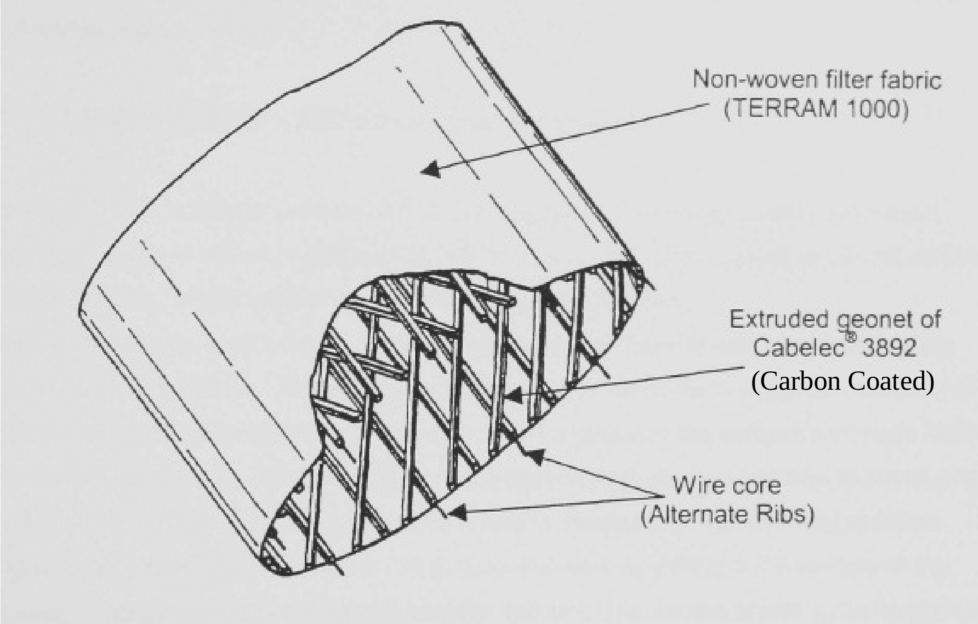


Figure 3.2: Electrically conductive band drain (After Netlon Ltd, 1998).

This patented design overcomes the problem of electrode corrosion. Therefore, no new electrodes can be replaced during electrokinetic testing in the field caused by degradation of electrodes under high acidity environment which affect the efficiency of the system and high cost of installation. By forming the electrode as a geosynthetic, EKG overcomes the problem of removing clean water by utilising the drainage and filtration functions of geosynthetics. The ability of EKG to take on wide variety of shapes and forms means that they can be manufactured to suit a range of different application (Glendinning *et al.,* 2007). EKG has been utilised for slope remediation by Lamont-Black & Weltman (2010) as both active and passive roles. EKG drains actively attract water while EKG reinforcement not only provides reinforcement but also increases the shear strength of soils in which they are placed as well as improving soil bond. Therefore, EKG used for electrokinetic dewatering provides a potential alternative method in various applications that not only creates electrosmotic flow from the anode to the cathode but also provides reinforcement of weak soils and improving the shear strength of soil due to electrochemical effects (Pugh, 2002). This promising result of EKG electrode has led the used of this electrode in this study which was initiated by Liaki (2006).

3.4 Electroosmotic Consolidation

In addition to the electrokinetic dewatering, electroosmosis process also causes consolidation of compressible soil. Electroosmosis process causes removal of water content in the soil thus changes its soil structure to give higher strength and stability of soil. Since the movement of the water from the anode to cathode under electrical gradient, the soil water content will decrease at the anode and increase at the cathode. Water accumulated at the cathode then can be discharged by providing the drainage system at the cathode (see Figure 3.3). Application of electric current through a soil mass has similar effect with preloading technique, commonly used to consolidate and improve soft soils. Consolidation settlement is time dependent and can take from several months to several years to develop (usually 1 to 5 years) especially for low permeability soils (Charles & Watts, 2002; Atkinson, 2004). Consolidation of soil by an applied load requires a lengthy time period because it relies on hydraulic gradient while consolidation by electroosmosis is more effective in producing water flow under application of electric gradient (Alshawabkeh & Sheahan, 2003).

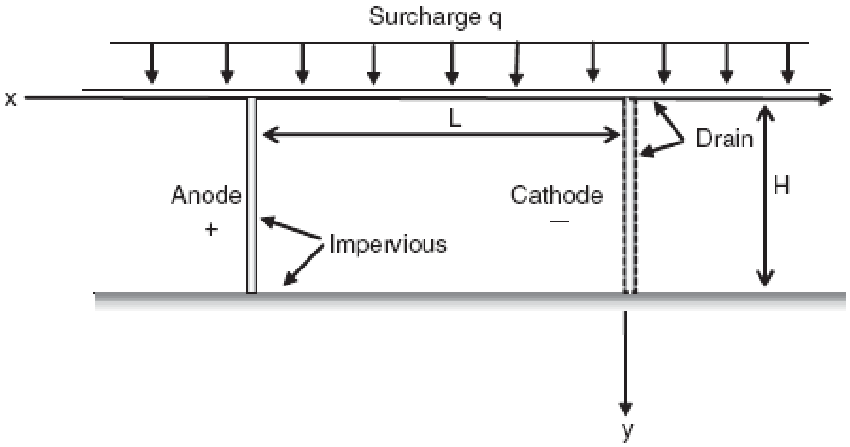


Figure 3.3: Schematic of electroosmotic consolidation (Shang, 1998)

Electroosmotic consolidation can be described when a direct current passes through soil mass, electroosmosis draws water towards cathode where it is drained away and is no water is allowed to enter at the anode, then consolidation of the soil between the electrodes occurs in an amount equal to the volume of water removed. This term of electroosmotic consolidation can be applied if drainage is provided at the cathode and prohibited at the anode (Mitchell & Soga, 2005). The migration of water to the cathode generates a negative pore water pressure at the vicinity of the anode. Since the total stress in the vicinity of the anode remains constant, the effective stress increases. The increase in the effective stress causes consolidation. While at the cathode, there are no significant changes of effective stress and pore water pressure (Hamir *et al.*, 2001). As a result, hydraulic gradient develops that tends to cause water flow from cathode to anode. Consolidation continues until the hydraulic force that drives water back toward the anode exactly balances the electroosmotic force driving toward the cathode (Mitchell & Soga, 2005). Therefore, the electroosmotic consolidation depends on boundary condition at the anode and the cathode. However, typical boundary conditions that normally associated with electroosmotic consolidation are anode close – cathode open (Hamir *et al.,* 2001). However, the effect of production of oxygen and hydrogen gas at the anode and cathode, respectively is to decrease the degree of saturation of the soil near the electrodes and consequently to decrease the area available for flow pore fluid and ions. At the anode especially, the production of oxygen gas may significantly minimise the development of the negative pore water pressure resulting in zero tension in the pore water, thus impact the electroosmotic consolidation of the soil after certain period of time (Schifano, 2001).

The electrokinetic process had changes the chemical composition of the pore fluid including pH, electrical conductivity which resulted in changes of the structure and fabric of the soil. This change can be related to the mechanical, physical and physicochemical properties of the soil. Therefore, many researchers have reported that those changes are affecting the increase of soil shear strength (Micic *et al.,* 2001; Micic *et al.,* 2003; Liaki *et al.,* 2008), Atterberg limits (Thomas & Lentz, 1990; Rittirong *et al.,* 2008; Liaki *et al.,* 2010), permeability (Shang & Lo, 1997; Mohamedelhassan & Shang, 2002), and compressibility (Gabrieli *et al.,* 2008; Mohamedelhassan & Shang, 2002; Mohamedelhassan, 2009; Ahmad *et al.,* 2011).

Micic *et al.* (2001) reported the average undrained shear strength increased approximately about 1 to 11.3 kPa using vane shear test due to the combined effect of electrokinetic and preloading. The increase in shear strength at the anode and central regions was predominantly a result of electroosmosis, whereas the increase in shear strength in the cathode region resulted from cementation due to intensive precipitation of amorphous cementing agents and degradation of steel electrode used in their research. Another research conducted by Micic *et al.* (2003) which focused on electrokinetic strengthening of soft marine deposits surrounding skirted foundations of offshore structure also has shown the increased from 12.3 kPa (control sample) to about 35 kPa after 28 days of electrokinetic treatment using the same electrode materials.

Mohamedelhassan (2009) developed the laboratory electrokinetic testing cell, designed with different electrode configurations. These experiments were conducted using two parallel-plates made of steel mesh to investigate the increase of undrained shear strength and preconsolidation pressure after electrokinetic treatment. The results showed that electrokinetics increased the undrained shear strength and preconsolidation pressure but decreased the water content near the area of the anode. The highest shear strength has reported near the cathode from 6.3 kPa (control sample) to about 62.5 kPa is attributed to the decrease in the water content. At the cathode the shear strength was increased at about 7.3 kPa due to the cementation compound generating by electrochemical reactions during electrokinetic process. However, the increase in the preconsolidation pressure is attributed to the negative pore pressure generated during the electrokinetic process thus increases the soils shear strength at the anode area. Meanwhile, at the cathode the improvement of soil shear strength is due to the cementation generated by the electrochemical reaction that occurs during the electrokinetic process.

Laboratory studies conducted by Chew *et al.* (2004) in electroosmotic consolidation testing reported a large increase of shear strength at the anode area and become less significant at the cathode area (see Figure 3.4). They suggested that the slight increase at the cathode is attributed to the tiny of bubbles of water noticed surfacing at the little gap between the soil-electrode interfaces, thus affects the efficiency of the system. The open system configuration (see Figure 3.5) developed by Chew *et al.* (2004) in the large tank had caused this phenomenon to happen. They also found similar results and trends in the large field trial with an electric vertical drain on reclaimed land in Singapore.

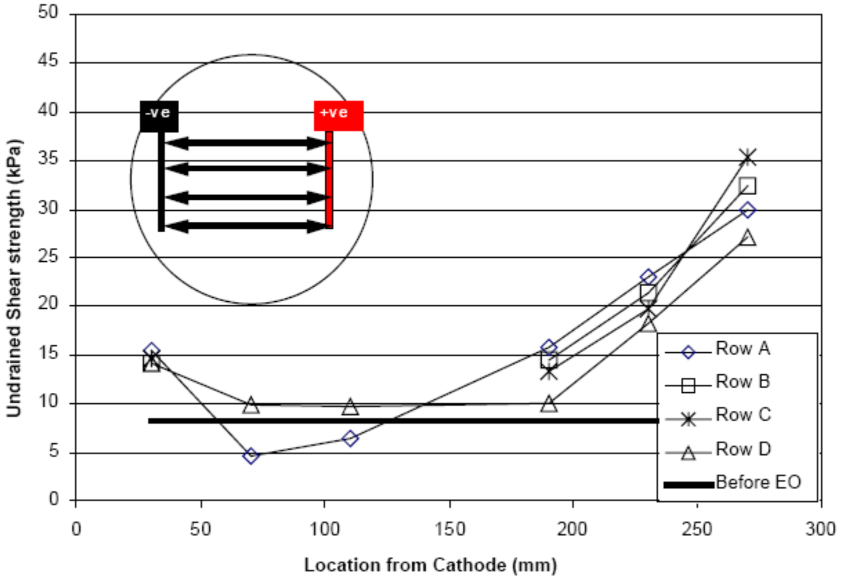


Figure 3.4: Undrained shear strength of clay after treatment (Chew *et al.*, 2004).

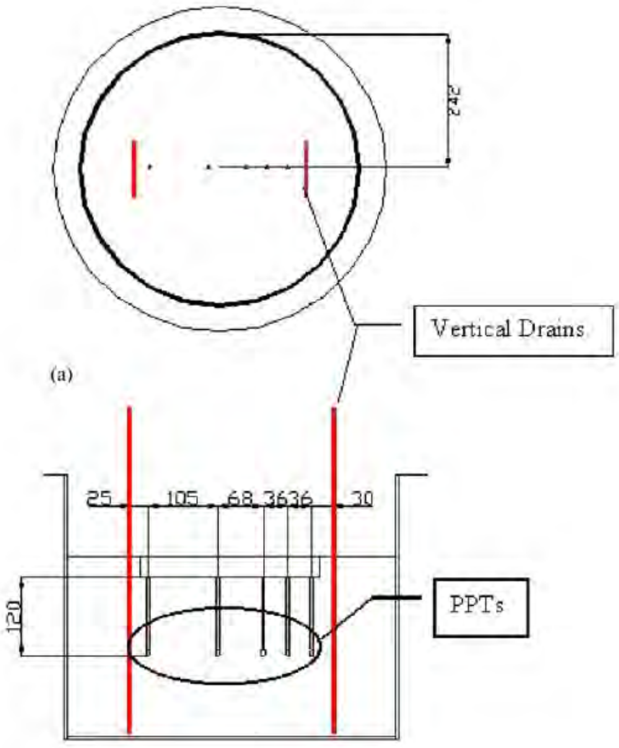


Figure 3.5: Schematic diagram of test set-up adopted by Chew *et al.* (2004).

However, Rittirong *et al.* (2008) reported that the soil near the cathode had the largest increase in shear strength (in the range of 27 and 36 kPa) but slight increase at the anode (around 15 kPa) as seen in Figure 3.6 compared to the control sample (8 kPa). In author point of view, the design configuration of their test (see Figure 3.7) which is prevent the water coming out between the soil and electrode and capability to apply a surcharge load on the top of the sample had caused development of negative pore water pressure resulted in efficiency of the system thus allow the cementation occurred at the cathode.

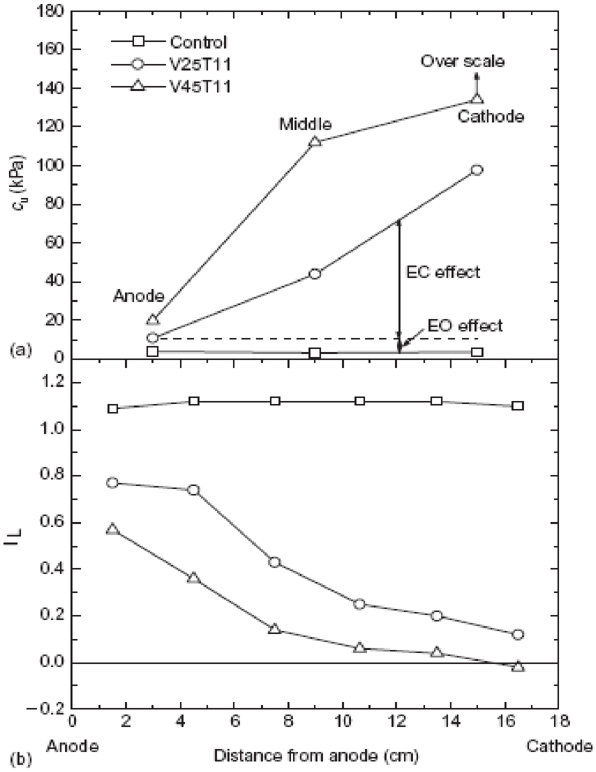


Figure 3.6: (a) Soil shear strength and (b) liquidity index after test (Rittirong *et al.,* 2008).

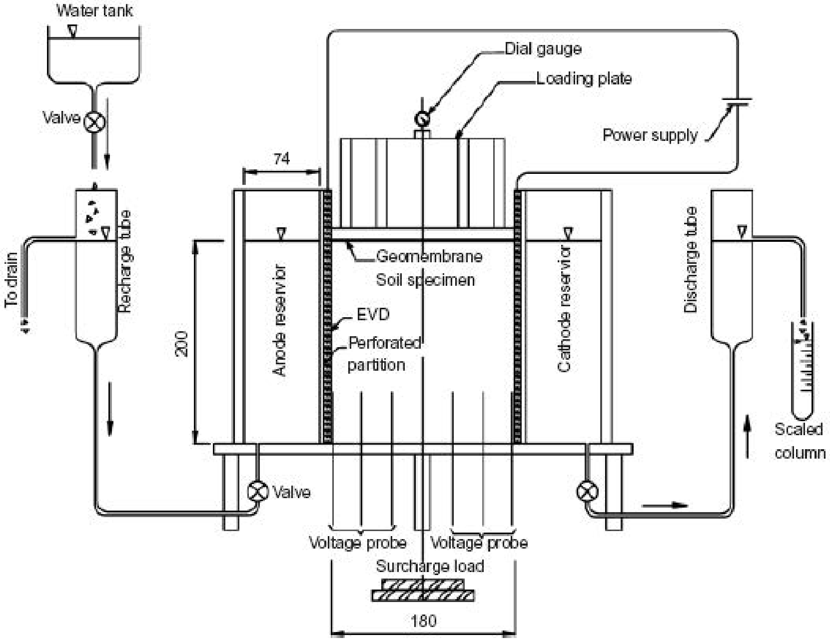


Figure 3.7: Schematic diagram of test set-up adopted by Rittirong *et al.* (2008).

Similarly, this system was adopted by Hamir *et al.* (2001) with the addition of surface charge loading in confinement cell tank. The results had shown the highest increase in shear strength of about 24 kPa as seen in Figure 3.8 compared to control sample which range between 7 to 14 kPa depend on the application of surcharge loading condition. The increase in bond strength is the same irrespective of whether the soil was consolidated by external pressure or electroosmosis induced pressure. However, they argued that the application of an external pressure, or surcharge loading to reinforced soil, is not possible in practice except by using prestressed soil which requires complete confinement of soil in the field application. Overall, at the anode area the increased of shear strength is attributed to the reduction of water content and heating effect while at the cathode is due to the precipitation effect. However, the accumulation of water at the cathode and the absence of certain ion to form precipitation of cementation agent have resulted a slight increased at the cathode area.

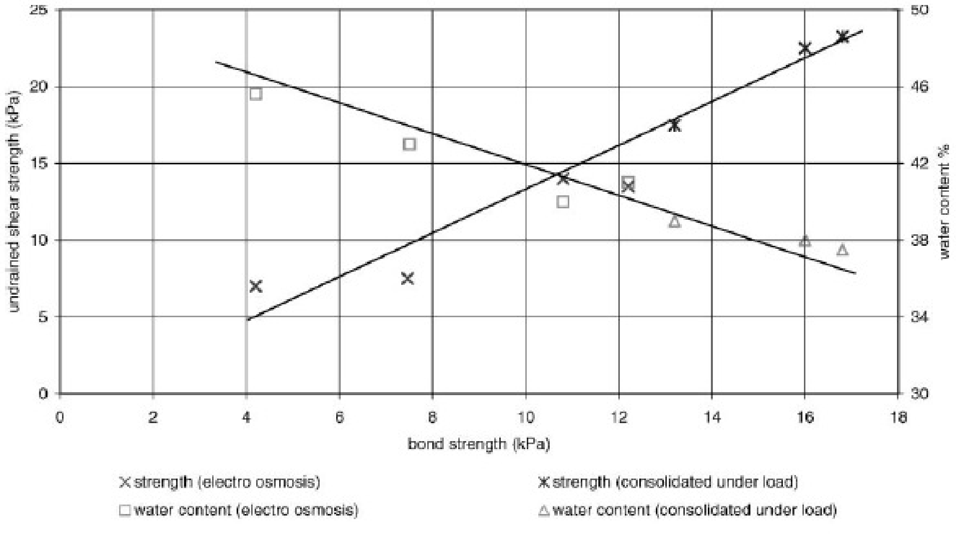


Figure 3.8: Pull-out tests reinforcement bond versus shear strength for consolidated and electroosmotic consolidated soil (After Hamir *et al.,* 2001).

More recently, Ahmad *et al.* (2011) conducted a series of laboratory studies on tropical soils to know the effect of electrochemical effects on soil compressibility of treated soils using distilled water only and combination of other chemical stabilisers at both electrodes in open-anode and open-cathode system. They found that the introduction of phosphate ions significantly decreased the compression index of treated soil at the cathode from 0.25 to 0.14 due to the formation of phosphate compounds.

Gabrieli *et al.* (2008) have reported the results of the compression test from 3 specimens from anode to cathode on Scanzano clay as shown in Figure 3.9. They concluded that the stiffness of the sample at the anode side was not affected significantly compared with natural clay. In contrast, a strong increase in stiffness was observed for samples near the cathode side. Therefore, the results of consolidation parameters at the cathode has more significantly at the cathode due to precipitation which change the mineralogy of the soil thus improving the stability and soil compressibility.

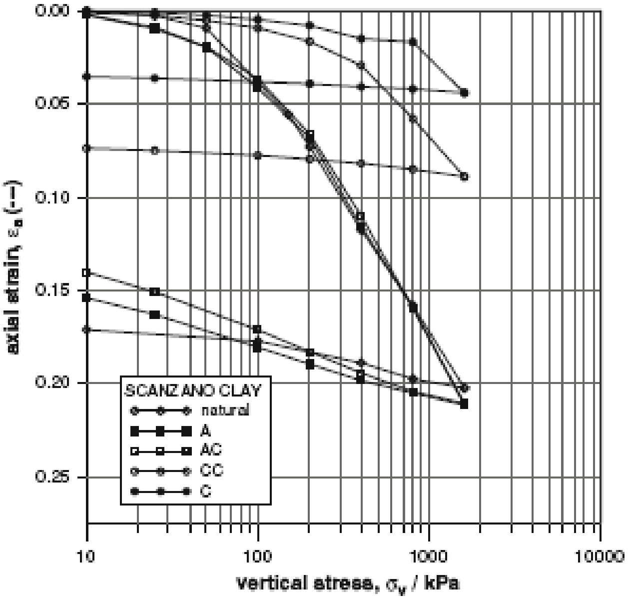


Figure 3.9: Results of one-dimensional compression test performed on Scanzano clay after long term electrokinetic treatment (after Gabrieli *et al.,* 2008).

Morris *et al.* (1985) conducted a laboratory test program using noncorrosive electrodes (stainless steel and galvanised mesh) to assess the effectiveness of electroosmotic treatment in the field in reducing water content of soft sensitive silty clay. The results showed significant reduction in water content from 27 – 30 kPa at different depth to about 11 – 20 kPa at the anode area thus increased the soil strength from 5 – 20 kPa of untreated soil to the highest value of 300 kPa especially at the anode area. In addition, cyclic deformation and consolidation characteristic of silty clay have shown increased in values compared to the untreated values. The liquid limit of the soil was also increased from 27 – 39 % to the highest value of 42 % at the anode area, which is indicative of further improvement of soil properties as a result of the electrical treatment.

Lefebvre & Burnotte (2002) conducted laboratory study to investigate the potential losses at the soil electrode contact points that could affect the performance of electroosmotic consolidation of the system. Therefore, a series of tests have been performed under different conditions including an assessment of the impact of overconsolidated and normally consolidated clay conditions and the injection of saline solution at the anodes. The voltage gradient effectively transmitted to the soil at about 70 % of the applied voltage with injection of saline solution compared to about 35% with no chemical injection. The results from this laboratory investigation have confirmed that the loss of electrical potential is related to the resistivity of the soil-electrode contact and not only due to the soil pressure applied on the electrodes. Therefore, the addition of chemical has significantly improved conductivity of electrokinetic treatment along the soil profile and the effect of chemical stabiliser introduced into the system which will be discussed later in this chapter (see section 3.5).

Apart from laboratory studies on electroosmotic consolidation, this technique has been established by a number of successful field applications since Casagrande (1959) and Bjerrum *et al.* (1967). Electroosmotic consolidation has been considered for projects requiring a rapid improvement in the properties of soft clayey soils replacing conventional methods that require longer time to complete. Even though there are many factors that need to be considered when using this technique including technology, cost and expertise available, this technique can be widely used in the field if the electrokinetic effects are fully understood. Recently, many researchers have come out with the technology to solve problems faced in the field. This includes a combination of electrokinetic with vertical drain using electric vertical drains (EVD) as used by Chew *et al.* (2004) to speed up the process of consolidation. Other researchers that used the combination of preloading or prefabricated vertical drains include Shang (1998) and Rittirong *et al.* (2008).

3.5 Electrokinetic Stabilisation

Electrokinetic stabilisation is a ground improvement technique in which stabilising agents are induced into soil under a direct current. The movement of stabilising agents into soil mass is governed by the principles of electrokinetics, while the mechanisms of stabilisation can be explained by the principles of chemical stabilisation (Barker *et al.,* 2004). Therefore, this technique has considerable potential for creating volume stability in shrinking and swelling clay soils (Rogers *et al.,* 2002). Nagaraj & Miura (2001) noted that the stabilising effects due to strengthening by electroosmosis can be enhanced by appropriate choice of the electrode material (aluminium instead of steel) or by the addition of sodium silicate or calcium chloride at the anode.

In geotechnical application, the electrokinetic stabilisation processes has been reported by many researchers to cause a significant increase in the shear strength of soils (Ozkan *et al.,* 1999; Alshawabkeh & Sheahan, 2003; Asavadorndeja & Glawe, 2005), changes in Atterberg limits (Ozkan, *et al.,* 1999; Rogers et al, 2003; Barker *et al.,* 2004 Asavadorndeja & Glawe, 2005; Jayasekara & Hall, 2006) and soil compressibility (Lefebvre & Burnotte (2002); Ahmad *et al.,* 2011).

Changes in the physical properties are attributed to the electrochemical effects under influence of electrical gradient include electroosmosis, electromigration, electrolysis, hydrolysis, degradation of electrodes (see Chapter 2). These processes are invariable across the soil samples from anode to cathode which contributes to the changes of physicochemical of treated soil. This electrochemical effect can also be associated with the changes of clay-water-electrolytes system which leads to the dissolution of chemical compounds or clay minerals, ion exchange capacity, adsorption, desorption, complexation, precipitation and mineralisation (secondary mineral). When a direct current is applied to a soil liquid medium, water in the immediate vicinity of the electrodes is electrolysed. Oxidation occurs at the anode, generating an acid front, while reduction takes place at the cathode, producing an alkaline front (see Chapter 2). These reaction cause the pH to decrease at the anode and increase at the cathode (Jayasekera & Hall, 2006). The development of this pH gradient (known as acid/base profile) and its effects on the species transport through soil porous medium have been investigated in detail and well documented by many researchers, including Ozkan, *et al.* (1999), Rogers *et al.* (2003), Alshawabkeh & Sheahan (2003), Barker *et al.* (2004), Asavadorndeja & Glawe (2005) and Liaki *et al.* (2010).

In electrokinetic stabilisation methods, when cations are used as stabilising agents, ions migrate into soils through processes of electroosmosis and electromigration. These ions improve the soil strength by three mechanisms, namely cation replacement, precipitation of species in the pore fluid and mineralisation. It is precipitation or mineralisation that provides the greatest contribution to increase in strength (Barker *et al.,* 2004; Jayasekera, 2004; Ou *et al.,* 2009). However, this type of reaction usually occurs when pH values of the soil solution are greater than seven (Barker *et al.,* 2004; Asavadorndeja & Glawe, 2005). Therefore, the pH values of the soil solution need to be maintained above seven during treatment in order to maximise its efficiency by appropriate injection of chemical ions at both electrodes (Asavadorndeja & Glawe, 2005). According to Boardman *et al.* (2004), the solubilities of some common metal hydroxides as a function of pH are illustrated in Figure 3.10 and Figure 3.11.

In short term tests, some researchers have observed that at the beginning of test, the soil weakening occurred at the anode due to acidification of the soils causing dissolution of carbonates, silicates and hydroxides of aluminium and iron (depends on solubilities of metal compound at low pH).

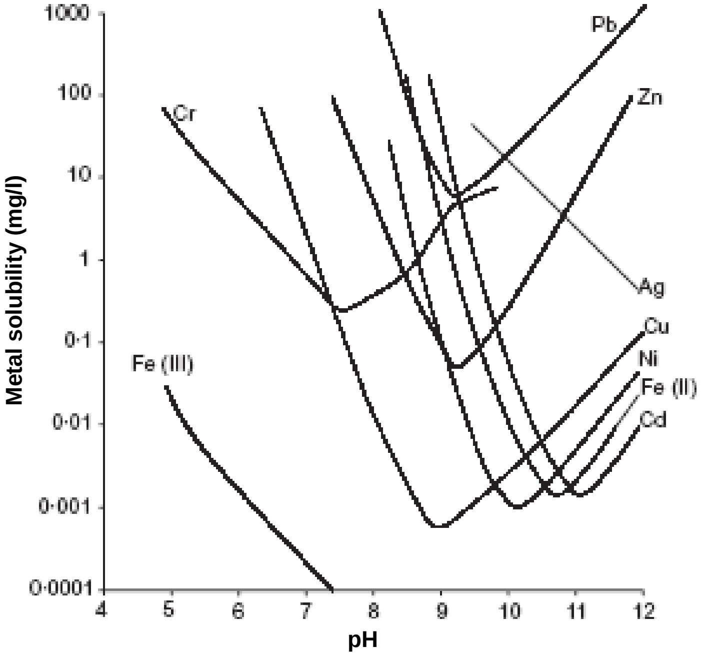


Figure 3.10: Solubilities of metal hydroxides as a function of pH (Boardman *et al.*, 2004).

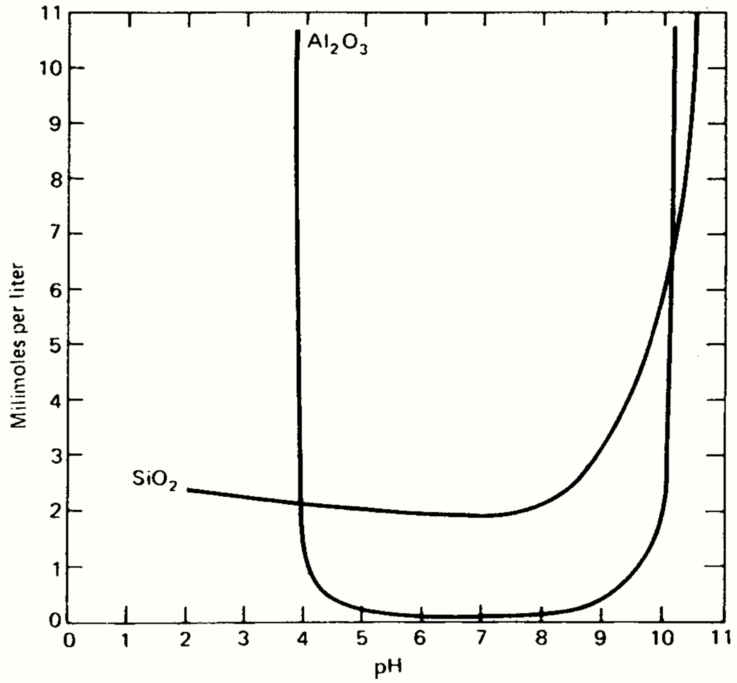


Figure 3.11: Solubility of alumina and amorphous silica in water (Mitchell & Soga, 2005).

In the long term, as time progressed and subsequent reduction of the water content, the release of the these cations from the clay surface or clay mineral lattice will be replaced by stronger valence cations, larger cations or a concentration of cations by mass action. This displacement leads to a decrease in the thickness of the diffuse double layer, thus promoting the edge to edge attraction, closer contact of clay platelets, or flocculation, and results in improvement of soil properties (Rogers *et al,* 2003; Barker *et al.,* 2004). This is also called as molecular bonds and these bonds are weakened on moistening (Zhinkin, 1960; Adamson *et al.,* 1966). Subsequently, stronger and more stable bond arise between the soil particles and the strength as a whole can be attributed to a coagulational-crystallisational process.

On other hand, crystallisation bonds are the main role of stabilisation process at the cathode area due to the precipitation in regards to electrokinetic treatment (Zhinkin, 1960). Naturally occurring metal oxides, oxyhydroxides and hydrous oxide in natural clay as listed in Table 3.3, may exist as discrete crystals, as coatings on phylosilicate and humic substance, as mixed gel, and are collectively part of the secondary mineral (Faulkner, 2010).

Table 3.3: Some naturally occurring oxides, oxyhydroxides, and hydroxides found in soils (after Faulkner, 2010).

Aluminium oxides	Bayerite α-$Al(OH)_3$ Boehmite γ-$AlOOH$ Diaspore α-$AlOOH$ Gibbsite γ-$Al(OH)_3$
Iron oxides	Akaganite β-$FeOOH$ Ferrihydrite $Fe_{10}O_{15}.9H_2O$ Feroxyhyte δ-$FeOOH$ Goethite α-$FeOOH$ Hematite α-Fe_2O_3 Lepidocrocite γ-$FeOOH$ Maghemite γ-Fe_2O_3 Magnetite Fe_3O_4
Manganese oxides	Birnessite δ-MnO_2 Pyrolusite β-MnO_2
Titanium oxides	Anatase TiO_2 Rutile TiO_2

However, under extreme environment (high pH) cause by electrokinetic process this compound may disassociate and react with the other metal cations available and then re-precipitated to form a new secondary mineral which completely changes the mineralogy of soil. These crystalline bonds are also intensified with time and retained regardless of consequent wetting of the soils. The growth of these bonds increases the density and stability of the soils and known to be permanent in time (Adamson *et al.,* 1966). Therefore, these phenomena which contributed in the soil strengthening and weakening is a function of time and configuration of the system (normally shrinkage or swelling at the open anode system) due to the dynamic (continuation of the process) and complexation of the electrokinetic phenomena.

Barker *et al.* (2004) also suggested that an alkaline environment developed at the cathode causes the dissolution of the clay mineral (possibly alumina and silica) and subsequent reaction with available metal cations (e.g. calcium or iron) which could precipitate to form amorphous aluminate and/or silicate gels. This cementation agent will harden with time (due to crystalline process) and consequently increased the soil shear strength. Therefore, subsequent studies based on electrokinetic stabilisation method which initiated by Rogers *et al.* (2003) have confirmed that this phenomenon is permanent if sufficient calcium ions are introduced into the system (Barker *et al.,* 2004) or Fe ions from degradation of a steel electrode (Liaki *et al.,* 2010) especially at the cathode area. Barker *et al.* (2004) have used the combination of calcium chloride and sodium silicate in the field trial to bring about the classic stabilisation which similar to the lime stabilisation. The basic of lime stabilisation is that alumina (Al_2O_3) and/or silica (SiO_2) are dissolved from the clay mineral which then formed CAH and CSH gels and subsequently crystallise (Rogers *et al.,* 2003). According to Barker *et al.* (2004), the pH was found to increase from pH 7.5 to about pH 8.5 (see Figure 3.12) and suggested the dissolution of alumina and silica at higher pH ($pH > 8$) which caused the formation of CAH and CSH gels. Therefore, the results from those studies have demonstrated the ability of the EKS method to promote the precipitation of insoluble salts based on results of pH, conductivity and insufficient sample for plastic limits test. This has lead to the current research study in laboratory to further investigate the effect of calcium and silicate ions to strengthen the soft clay by cations exchange and precipitation and mineralisation.

Ozkan, *et al.* (1999) employed the technique to simultaneously inject aluminium ions at the anode and phosphoric ions at the cathode to stabilise kaolin soils. After 15 days of treatment, an average shear strength increase from 7 kPa to about 60 kPa in the region of the cathode.

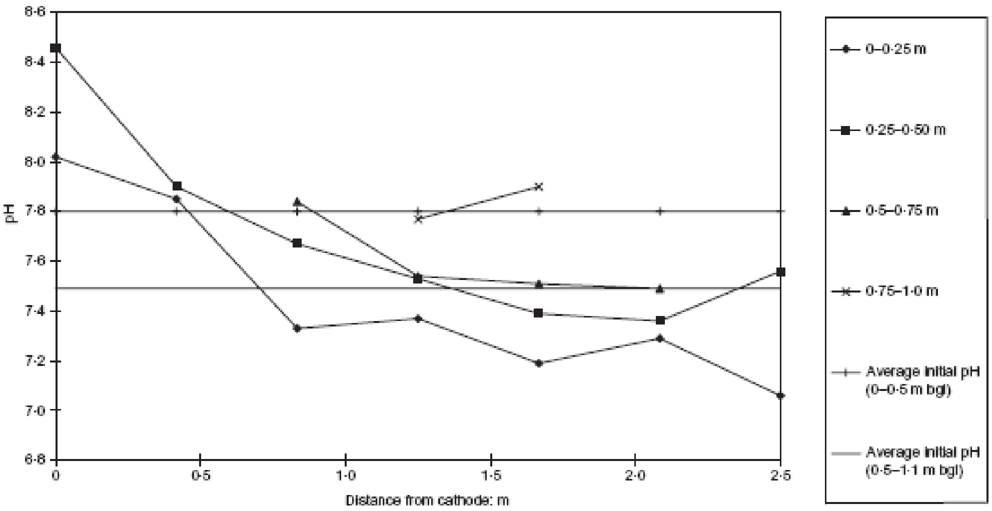


Figure 3.12: Variation of pH with distance from cathode for various depths after 27 days (Barker *et al.,* 2004).

Despite the widely use of kaolin soil in electrokinetic application, some researchers have used different types of soils which include illitic soils (Esrig & Gemeinhardt, 1967; Gray, 1970; Alshawabkeh & Sheahan, 2003; Ou *et al.,* 2009), montmorillitic soils (Adamson *et* *al.,* 1966; Gray, 1970) and bentonite soils (Gray & Schlocker, 1969; Rogers *et al.,* 2003). More recently, Ahmad *et al.,* (2011) have conducted the electrokinetic stabilisation method using different chemical stabilisers at both electrodes on tropical residual soils. They found significant improvement of the soil properties include an increase in shear strength and reduction of soil compressibility at the cathode area using distilled water as anolyte and phosphoric acid as catholyte due to the precipitation of sulphate compound. Similarly, Alshawabkeh & Sheahan (2003) had applied this technique to inject phosphoric acid at the cathode to stabilise marine illitic soil (Boston Blue Clay) over 14 days. The results show that the shear strength increased by 160% at the side of cathode while the water content was maintained at its initial value.

Most of the studies on electrokinetic stabilisation as discussed above have reported a significant increase of soil shear strength at the cathode area due to the precipitation compared than of the anode area. However, Chien *et al.* (2009) have found the undrained shear strength with the introduction $CaCl_2$ during electrokinetic treatment was greater at the anode area (see Figure 3.13) after 1 day treatment and no improvement at the cathode area. It was expected due to the short period of treatment time for precipitation to happen and need longer period of time for crystallisation process as discussed earlier. However, after 7 days treatment, they found an increase in shear strength at the cathode which showed a sign of precipitation. In overall, the soil shear strength showed significant increase at the anode followed by an increase at the cathode compared than of the untreated soil after 7 days treatment. In addition, no attempt was made in their study to introduce anions at the cathode to intensify specific insoluble salt precipitation and made a greater impact on soil shear strength at the cathode area compared at the anode area.

Therefore, all of these experimental studies utilising different chemical stabilisers at both electrodes indicated that electrokinetic stabilisation provides non uniform strength increase profiles after the treatment and the efficiency of the technique is limited to the area of the cathode and even though some studies observed an increased of shear strength near the anode. However, most of them agreed that ion exchange, precipitation and mineralisation are major stabilisation mechanisms in regards to soil.

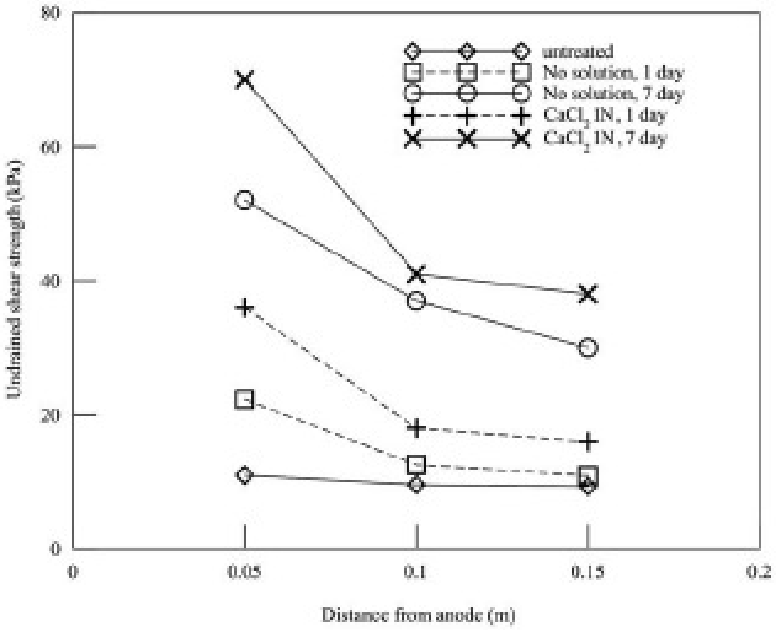


Figure 3.13: Variation of undrained shear strength with distance for different treatment times (Chien *et al.,* 2009).

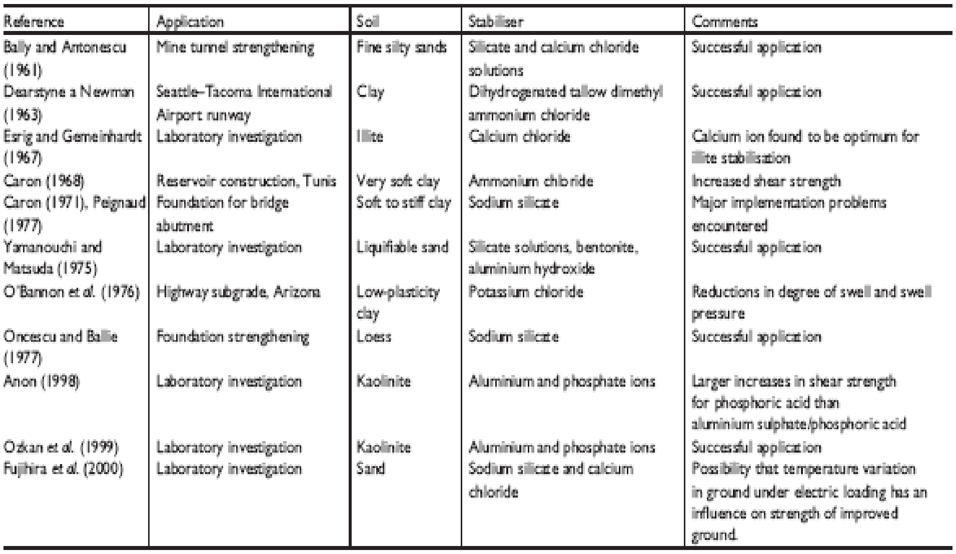
In geotechnical engineering, the changes of physicochemical properties of the soil can be determined from Atterberg limit values. Therefore, most researchers in electrokinetic studies have found significant changes on Atterberg limits across the soil samples due to the electrochemical effects. The introduction of ions into the system in the electrokinetic stabilisation had caused variation of plastic and liquid limit values among different clay mineral groups.

According to Mitchell & Soga (2005), increasing cation valence decrease the liquid limit values of expensive clays (e.g. montmorilinite), but tends to increase the liquid limit of the inexpensive clays (e.g. kaolinite). Increases in liquid limit have been observed by many research studies due to the soil cementation at the vicinity of cathode generated by electrochemical reactions after introduced chemicals at the electrodes or caused by degradation of electrode at the anode (Ozkan, *et al.,* 1999; Asavadorndeja & Glawe, 2005; Jayasekara & Hall, 2006). However, Gray & Schlocker (1969) has observed a decrease of liquid and plastic limit after treatment in the bentonite soil. The decrease was more pronounced close to the anode area from around 70 to 80 % of liquid limits which is half of its untreated value (LL= 160 %) than the cathode area (from 90 to 110 % of liquid limits). However, no detailed explanation was given to discuss this phenomenon.

Liaki *et al.* (2010) have found an increase of liquid limit at the anode and a decrease at the cathode while liquid limits were in opposite trend when using inert electrode (steel) and no chemical were introduced at the electrodes for kaolinite clays. This was due to the additional higher valency positive ions (i.e. Fe ions) coming into the system from the degradation of electrode at the anode and further thinning of the diffuse double layer via cation exchange. The low liquid limit occurred at the cathode due to the opposite phenomenon i.e. raised pH causing the zeta potential to become more negative and thickening of the diffuse double layer. Therefore, the changes of Atterberg limits are govern by electrochemical effects which also changes across the soil sample under electric current. The factors contributing the Atterberg limits include pH, electrolyte concentration, thickness of double layer relate to cation exchange and precipitation, types of clay mineral, secondary mineral from crystallisation process, and the types of exchangeable ions (Schifano, 2001).

Table 3.4 shows the literature data reported by various researchers in laboratory studies and field application using electrokinetic stabilisation. Despite successful laboratory studies and field application, some of the studies have reported the problems encountered during electrokinetic stabilisation as similar with the electrokinetic dewatering and electroosmosis techniques as discussed earlier in this chapter. To date, a limited number of field applications on electrokinetic stabilisation are due to the complexity of the system involving electrochemical effects which have been discussed in this chapter.

Table 3.4: Various reported research and case studies relating to electrokinetic stabilisation (Barker *et al.*, 2004).



Reference	Application	Soil	Stabiliser	Comments
Bally and Antonescu (1961)	Mine tunnel strengthening	Fine silty sands	Silicate and calcium chloride solutions	Successful application
Dearstyne a Newman (1963)	Seattle–Tacoma International Airport runway	Clay	Dihydrogenated tallow dimethyl ammonium chloride	Successful application
Esrig and Gemeinhardt (1967)	Laboratory investigation	Illite	Calcium chloride	Calcium ion found to be optimum for illite stabilisation
Caron (1968)	Reservoir construction, Tunis	Very soft clay	Ammonium chloride	Increased shear strength
Caron (1971), Peignaud (1977)	Foundation for bridge abutment	Soft to stiff clay	Sodium silicate	Major implementation problems encountered
Yamanouchi and Matsuda (1975)	Laboratory investigation	Liquifiable sand	Silicate solutions, bentonite, aluminium hydroxide	Successful application
O'Bannon *et al.* (1976)	Highway subgrade, Arizona	Low-plasticity clay	Potassium chloride	Reductions in degree of swell and swell pressure
Oncescu and Ballie (1977)	Foundation strengthening	Loess	Sodium silicate	Successful application
Anon (1998)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Larger increases in shear strength for phosphoric acid than aluminium sulphate/phosphoric acid
Ozkan *et al.* (1999)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Successful application
Fujhira *et al.* (2000)	Laboratory investigation	Sand	Sodium silicate and calcium chloride	Possibility that temperature variation in ground under electric loading has an influence on strength of improved ground.

3.6 Electrokinetic Remediation

The wide interest on the application of electrokinetics phenomena to site remediation started from 1980s (Segall *et al.,* 1980; Acar *et al.,* 1990; Acar & Alshawabkeh, 1993. Most of the applications since then were based on laboratory data and only few papers describe in-situ applications (Lageman, 1993). When an electric field is applied into the soil, some physicochemical reactions take place simultaneously under different pH environment conditions. Therefore, some of these reactions such as electromigration, electroosmosis, the development of acid front, hydrolysis, oxidation and reduction may enhance the efficiency of the removal of contaminants while certain chemical reaction such as heat and gas generations at the electrodes, precipitation of metal ions, and adsorption of metal ions onto soil surfaces may reduce it efficiency. Therefore, many electrokinetic remediations have been focused on the laboratory scale to control some of the processes that may hinder and enhance the removal efficiency. Unlike in geotechnical application, reactions such as precipitation, dissolution and adsorption are needed and to some extent to improve the properties of the soils.

Water removal efficiency in clayey soils by means of electroosmosis can be very high, so that the convenience of adopting it when removing pollutants was the first motivation to investigate the use of the technique for environmental purposes. In geotechnical engineering, electroosmosis is aimed at dewatering the soil in order to improve the strength and stability of soils, while in the environmental application the objective is to ‘wash’ the soil of hazardous materials that cause problem to the humans and environment. In order to lower the pollutant concentration it is necessary to let water flow for an adequate number of pore volumes. Practically when consolidation is needed, water must leave the soil domain at one boundary and not enter from the opposite one. By comparison, in the case of flushing, water or soluble chemical solutions must enter on one side and leave the soil from the other (Musso, 2000). In addition, most of the electrokinetic processes have been controlled in order to remove certain hazardous material that absorbed around the soil particles.

Electrokinetic remediation uses direct electrical currents to extract heavy metals, radionuclides, certain organic compounds, or mixed inorganic species and organic wastes from soils (Acar & Alshawabkeh, 1996). In addition, the technique may be used to mobilise and transport pollutants to a treatment or collection zone, or to degrade, i.e., treat, pollutants by delivering nutrients, microorganisms or chemicals to the pollutants in-situ. Heavy metals are absorbed electrostatically onto the soil surfaces due to the excess of negative charges arising from isomorphous substitution (Altaee, 2004).

The effect of different soil types and mineralogy on the efficiency of contaminants removal has been studied by Altaee (2004). Three different types of soils have been used which are kaolinite, London clay and saline sediment of Pagham harbour, West Sussex. The study investigated metal contaminants transport in different types of soil under different environmental conditions. In addition, the acetic acid and reversal of the polarity charge also applied to know the efficiency of the system. Acetic acid was used as an enhancement agent at the electrodes for all soil types to prevent the precipitation that may affect the efficiency of the process while reversal of polarity charge was only applied in kaolinite soils. This investigation showed that for kaolinite soil a combination of these two techniques showed the greatest copper removal. For London clay, the highest amount of copper removal has demonstrated when acetic acid at pH 2 was added to the cathode. In contrast, the addition of acetic acid with different pH in saline sediment of Pagham Harbour did not result in any significant increase in the removal of copper from sediment. It was suggested that the low electroosmotic flow in saline sediment, the precipitation of low solubility copper-sulphide and the presence of organic matter made the electrokinetic removal process ineffective (Altaee, 2004).

The efficiency of certain heavy metals in electrokinetic remediation is dependent on the mineralogy and composition of treated soils. Therefore, most of initial studies used kaolinite (Acar & Alshawabkeh, 1996; Hamed *et al.,* 1991; Vane & Shang 1997; West *et al.,* 1999) in laboratory bench-scale studies. Kaolinite soil has been used as model soil because of the simple chemical composition, contain insignificant amount of organic matter, low buffering capacity and exhibits high electroosmotic water transport efficiency. It is important to use simple soil for better understanding of the electrokinetic process in geotechnical and geoenvironmental applications.

Another laboratory bench-scale study in kaolinite clay in electrokinetic remediation was conducted by Kalumba (2006) using EKG which is similar to this study. The study was performed to remove specific heavy metal (zinc ions) from kaolin soil under closed and opened anode condition. Different physical characteristic such as effect of water flushing, sample depth, intermittent current, and addition of replenished draining chambers along the cell length have been explored to investigate the efficiency of metal removal under different setup and conditions. It is clear that from the study certain conditions may favour the efficiency of the system. Therefore, the electrokinetic remediation studies may give better fundamental understanding related to electrokinetic processes which is similar to the current study, especially migration of metal ions, ph development, dissolution, adsorption and precipitation that may occur during the treatment for under certain boundary conditions. This is also important for future research to gain the knowledge from those electrokinetic processes in various applications. Therefore the migration of specific chemical ions can be controlled whether such ions need to be removed completely (electrokinetic remediation) or need to be left in the soil (electrokinetic stabilisation).

3.7 Summary

The chapter here follows with the findings discussed in Chapter 2. The relevance and applicability of the technique in geotechnical and geoenvironmental applications were also highlighted to help the direction and method of this current study might utilise, and with ideas for improved technical designs for specific purposes and the use of an electrode design as well as other design and implementation improvements. Various laboratory tests and field tests have been conducted to assess the efficiency of electrokinetic in various applications. Most of the findings showed encouraging results and great potential that electrokinetic can be an effective means of soil improvement and heavy metal remediation.

There is no apparent evidence in the literature of electrokinetic being used to study the effect of desired ions (calcium and silicate ions) that contributing the increase of shear strength due to the development of CSH and CAH precipitation gels using an EKG electrode. The proposed technique which induced those chemical ions, therefore, is novel, although the combination of those chemical stabilisers has been made in the past but yet establish the key mechanism that contributing the increase in shear strength together with the interpretation of chemical results such as pH, electrical conductivity and metal concentration in soil matrix.

The key mechanisms of electrokinetic for further research are the performance of EKG under different conditions, comparative performance of EKG with conventional metal electrodes in geotechnical and geoenvironmental application. The performance of the EKG need to be assessed in terms of the changes in various electrical and geotechnical properties such as current variation, pH gradient, undrained shear strength increment, water content changes, Atterberg limits changes and most importantly effective migration of chemical ions when continuously added into the system.

From monitoring data, it is possible that the current density will increase during the constant application of voltage, with the increase of electrical conductivity due to electromigration process until some point where the current density drops which caused by precipitation of insoluble metal hydroxides. A detailed study will hence be carried out to investigate these aspects and discussed in result and discussion chapter (Chapter 6 and 7).

Chapter 4

RESEARCH METHODOLOGY AND PRELIMINARY TESTINGS

4.1 Introduction

This chapter provides detailed of materials, apparatus and method employed in the preliminary testing and the main EKS testing. Preliminary testing was divided into two categories. First category is a basic geotechnical testing programme to determine the engineering properties of clay soil including index soil properties testing. All of the physical and chemical properties of clay soil were investigated according to appropriate British Standards. Second category is batch testing which was performed to assess the effects of chemical stabilisers used in this study before applying electric current. These results will be used to compare with the results of treated soils from the main EKS testing to know the effect of applying current and chemical stabilisers into the EKS system. The overall process of research methodology is summarised in Figure 4.1.

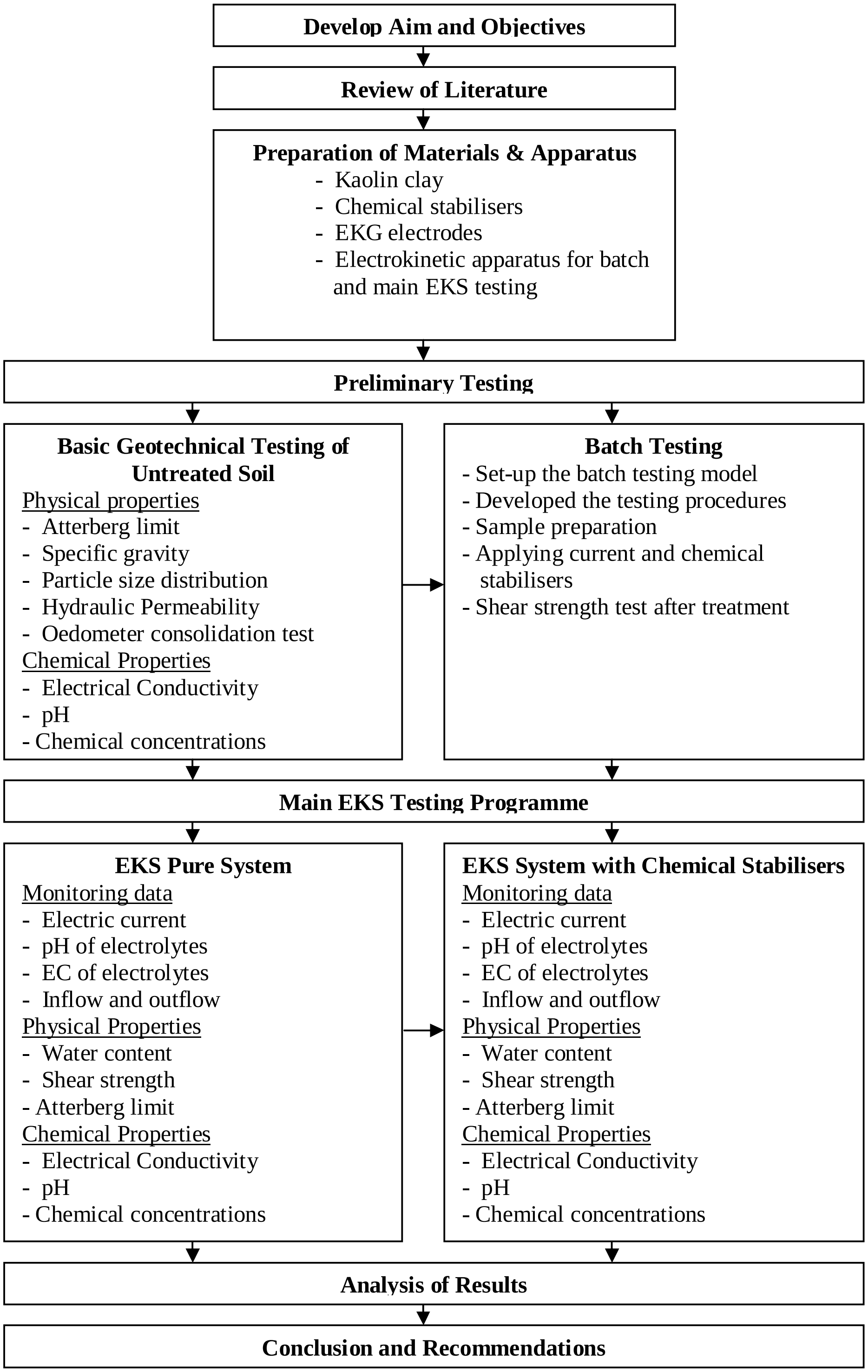


Figure 4.1: Flowchart of Research Methodology

4.2 Research Philosophy

The theoretical aspect related to the electrokinetic phenomena discussed in Chapter 2 and the review of electrokinetic applications in civil engineering in Chapter 3 have drawn attention from this study to establish the design procedures and a new approach of EKS technique to suite with the objectives and fill a gap in the existing knowledge of EKS technique. The most significant knowledge gap identified relates to the limited knowledge of physicochemical processes and electrochemical effects that contribute the increase of shear strength after EK treatment.

There has been much discussion in geotechnical literature on the variation of pH, water content and electrical conductivity on the physical properties of soft clays (i.e. shear strength, Atterberg limits and compressibility indices) but very little work to relate these factors to the physicochemical processes (i.e. cation exchange, precipitation, cementation and soil hardening) and electrochemical effects (i.e. electrolysis, electroosmosis and electromigration) within the soil matrix during and after treatment. Most of the researchers in geotechnical aspect have mentioned the possibility of these processes (ion exchange, precipitation and cementation) occurred during and after the electrokinetic treatment but very little explanation of the process occurring within the soil matrix under an influence of electric field due to the limitation knowledge related to electrokinetic phenomena and the scope of their studies which only concerning about the changes of physical properties (see Chapter 3). However, in geoenvironmental aspect, the fundamental of electrokinetic process in the soil matrix is significant to them study to ensure the effectiveness of the system to remove the organic or inorganic contaminants in the soils. Drawn from the aspect of both studies, this research study has provided a useful knowledge of the main mechanisms and factors that contributing to the soil improvement. These main mechanisms and factors of EK processes can be evaluated and assessed to determine the performance and effectiveness of the system to improve soil properties (shear strength parameter, in this context of this study) for ground improvement. Therefore, the physical and chemical laboratory testing was chosen based on the ability of these tests to relate to such phenomena. For example, the Atterberg limit test was conducted to relate the changes in mineralogy after electrokinetic treatment and validated with other chemical test such as pH, electrical conductivity and chemical concentration of certain ions.

As discussed earlier in the literature (see section 2.8), the direction and quantity of chemical migration in the soil matrix is influenced by the chemical concentration, soil type and structure and the mobility of chemical ions, as well as the interfacial chemistry and the conductivity of pure water. Therefore, the selection of chemical stabilisers is crucial to effectively change the physicochemical properties of natural soils. The use of higher valence of ion i.e. calcium based (Esrig & Gemeinhardt, 1967; Asavadorndeja *et al.,* 2006; Chien *et al.,* 2009) have shown the suitability of this chemical to be adopted in this study and discussed in subsection 4.4.2.

Previously, the experimental cell used for electrokinetic for dewatering or consolidation purposes were mostly modified from oedometer cells or triaxial cells (Casagrande, 1952, Esrig, 1968, Chien *et al.,* 2009). Previous tests in various applications (see Chapter 3) have also developed the experimental programme based on small scale or bench study to asses the effectiveness of EK method for ground improvement tool but have practical limitation to be considered in design approach similar to field condition. Therefore, in the absence of any relevant standard methods or apparatus as discussed earlier in literature chapter for geotechnical purposes, a rectangular open to the surface configuration was chosen to be more representative of the field conditions compared with the cylinder closed cells configuration as proposed by Altaee (2004) and Kalumba (2006) in the geoenvironmental application.

At the same time, in order to develop a reliable practical test which is a key requirement for field condition, certain factors were prioritised in selection of materials used (clay soil, electrode and chemical stabilisers), method of sample preparation (slurry sample and consolidation devices) and setup of EKS testing programme (Mariotte bottle and tank design). These factors include practicality, availability, economics, environmental aspects concerning health and safety, sustainability and reliability. All these considerations are discussed in section 4.4. However, the above prioritised factors have to be balanced with achieving a fundamental aspect of ground improvement goals (to increase shear strength and bearing capacity, reduce settlement and compressibility after EK treatment) and continuation with the research programme in University of Birmingham. Ultimately, this research study can increase the confidence level of this technique to be adopted in field in the future and solved the problems associated with the uncertainty of the results and complexity of the process involved during electrokinetic testing.

4.3 Research Process

The adopted research methodology was divided into three key methods. These include preliminary testing, batch testing and main electrokinetic testing (EKS pure system and

EKS system with chemical stabilisers). The batch testing initially focused on designing, developing and trialling equipment sand procedures of EKS testing to facilitate chemical stabilisers and efficiency of the setup to migrate chemical into the system continuously using Mariotte bottle method. At the same time, evaluation of voltage used and concentration of chemical stabilisers are also taken into consideration before actual setup can be performed in main EKS testing programme.

In the main experimental programme, the soil sample was divided into 8 sections equally to know the variation of this parameter across the soil medium. Each section was performed for both physical and chemical properties. Table 4.1 shows testing programme of this study and number of tests performed after EKS treatment. The first phase of EKS pure system was associated with conceptual design, development of the EKS method to be compared with Liaki (2006). Each test of development of pure system was evaluated, and where required, amendment was made to achieve the objectives of this research and dealing with problem associated with boundary conditions and efficiency of the EKS setup as raised by Liaki (2006) and other researchers in Chapter 3. These amendments are listed as below:

1. Adoption of Mariotte bottle setup to continuously supply distilled water or chemical stabilisers in a large amount and for long period of time. This method is also maintaining the level of fluid at the both electrolytes compartments when the fluids start to flow across the soil sample. Consequently, this is allows a constant hydraulic gradient to be established across the soil sample being treated. 5 litre of fluid storage containers at

both electrodes were able to supply the distilled water and chemical stabilisers during the EKS testing and directly measure the amount of fluid used in the EKS test.

2. The base of the tank does not have to change from the perforated base (used during consolidation stage) to the solid base (used during EKS testing) as adopted by Liaki (2006) which can cause soil disturbance prior to EKS testing. This has been dealt with combination of both bases (discussed in section 5.2).
3. The combined filter paper has adopted in this study at both perforated wall between electrolyte chamber and main compartment (see in section 5.2) and at the perforated base to prevent soil particles from blocking the flow of fluid or escaping from the main compartment into the electrolyte chamber (especially near the cathode area). According to Liaki (2006), the use of Vyon sheet filter alone had caused migration of very fine solid particles across the filter at the cathode compartment.
4. Maintaining the contact between EKG electrodes and vertical soil surface after removed the thin solid Perspex sheet of 3 mm by reapply the surcharged pressure as same loading pressure of final consolidation.
5. The corrosion of stainless steel inside the coated carbon at the bottom of the EKG electrode after cutting was prevented by using durable epoxy resin. Liaki (2006) had reported the use of silicon to seal the stainless steel had damaged and exposed during insertion of electrode into the soil sample.

Finally, the second and third phases of EKS system with chemical stabilisers are important to know the effects of certain ions when introduced at one side or simultaneously at both sides in the EKS system (see detailed discussion in section 5.4, 5.5 and 5.6).

Table 4.1: Number of samples for main EKS testing.

Testing Programme	EKS Duration (days)	Number of Samples for Physical tests				Number of Samples for Chemical tests			Total of Samples for Each Experiment
		Water Content	Shear Strength	Liquid Limit	Plastic Limit	pH	EC	Metal Content	
Phase 1									
1. DW-DW	3	8	8	8	8	8	8	8	56
2. DW-DW	7	8	8	8	8	8	8	8	56
3. DW-DW	14	8	8	8	8	8	8	8	56
Phase 2									
1. CaCl-DW	3	8	8	8	8	8	8	8	56
2. CaCl-DW	7	8	8	8	8	8	8	8	56
3. CaCl-DW	14	8	8	8	8	8	8	8	56
Phase 3									
1. DW-NaSiO	3	8	8	8	8	8	8	8	56
2. DW-NaSiO	7	8	8	8	8	8	8	8	56
3. DW-NaSiO	14	8	8	8	8	8	8	8	56
Phase 4									
1. CaCl-NaSiO	3	8	8	8	8	8	8	8	56
2. CaCl-NaSiO	7	8	8	8	8	8	8	8	56
3. CaCl-NaSiO	14	8	8	8	8	8	8	8	56
Total Durations	**96 days**	**Total of Samples for All Experiments**							**672**

4.4 Material Properties

4.4.1 Soil

The soil used in this study was English China Clay (ECC) supplied by WBB Devon Clays and the technical data provided is shown in Table 4.2. Kaolin soil has been selected in this study because of its low activity, low adsorptive capacity and high electro-osmotic transport efficiency compared with other clays (discussed in section 2.6, 2.6.1 and 2.9.1).

Therefore, many researchers using kaolin soil reported significant increased of its properties after electrokinetic treatment (see section 3.5). Typically, most of those previous studies used fine grained soil such as silts and clays due to the efficiency of the soils to transport water under electric current. According to Mitchell & Soga (2005), soils with low cation exchange capacities such as silty clay and kaolinite exhibit a very high electroosmotic water transport when they are saturated by dilute electrolyte solution due to the high water counter ion ratio in the internal phase. Thus, kaolin soils have been widely used in electrokinetic application; to reduce water content of high permeability soils (electrokinetic dewatering and electroosmosis consolidation); to migrate certain ions into the soils (electrokinetic stabilisation); and to remove metal heavy metal from contaminant soils (electrokinetic remediation).

4.4.2 Chemical Stabilisers

There are several criteria for the selection of chemical stabilisers used in this study:

(a) Significant improvements of the properties of soils after treatment are expected to be seen.
(b) Stabilisers are soluble in water so can be transported by electric current.
(c) They are inexpensive.
(d) They are environmentally safe.

Based on these criteria and the work of previous researchers in bench studies (see Rogers *et al.,* 2002) and field trial (see Baker *et al.,* 2004), the chemical stabilisers selected for this study were calcium chloride ($CaCl_2$) and sodium silicate (Na_2SiO_3) at the anode and cathode respectively. These were place at either anode or cathode, and efficiency evaluated.

$CaCl_2$ is a common salt with properties that make it particularly suitable for certain geotechnical application (Jensen, 2003). $CaCl_2$ can attract and absorb moisture from the atmosphere, otherwise means as hygroscopic, it is highly soluble and can replace the Na^+ ions within the diffuse double layers of clay particles with Ca^{2+} ions, thus this will reduce the thickness of double layer and thereby decrease the plasticity and increase the strength of the soil. Na_2SiO_3 solutions are generally considered to be non-toxic and noncorrosive. They are considered to be free of health hazards and environmental effects. However, sodium salts can leach from gelled silicate and raise the pH of the surrounding environment (Reuben, 1990).

4.4.3 Electrode

In order to eliminate the complexity within the test system, it is essential to use an inert electrode to prevent the dissolution of electrode and resulting variability. Previous studies have shown that metal electrodes used in conventional electrokinetic treatment such as steel, aluminium and copper corroded rapidly over short period of time during treatment (see Chapter 3). Corrosion of the electrodes reduces the electrical contact with the soil thus reduces the electrical efficiency of the system. Therefore, these corroded electrodes need to be replaced prior to use to avoid inefficiency of the treatment. Other problems created by metal electrodes include significant voltage losses at the electrodes hence loss of energy efficiency as reported by Lefebvre & Burnotte (2002) as discussed in section 3.4. There are many inert electrodes available that are used by other research to prevent corrosion of the electrode such as carbon, graphite and titanium. The carbon electrodes performed better initially but disintegrated with time (Fourie *et al,* 2007).

Recently, electrokinetic geosynthetic (EKG) electrodes were developed to overcome problems associated with electrode corrosion. The EKG provides two functions. Firstly, they provide drainage path and secondly, they act as an electrically conductive electrodes allowing the application of electrokinetic techniques. Therefore, EKG electrodes have been used successfully in a number of civil and environmental engineering applications. Most of the early research (discussed in Chapter 3) mainly focused on electroosmotic consolidation as a soil improvement method (Hamir *et al.,* 2001; Glendinning *et al.,* 2005). More recently, EKG has seen in environmental industry for treatment of sludge and tailings (Glendinning *et al.* 2007; Fourie *et al.* 2007). However, EKG has potential for use as part of an electrokinetic stabilisation method, using a combination of the processes including chemical stabilisation and electroosmosis.

Liaki (2006) has carried out some initial testing; focusing more on electroosmosis approaches and this work demonstrated reasonable success. For this reason, it is important for this study to investigate the efficiency of this electrode (EKG) with comparison with other inert electrodes or non-inert electrodes focusing on ground improvement aspects. Therefore, EKG type of electrode as shown in Figure 4.2 was chosen for this research because its durability and can provide constant performance during the electrokinetic treatment.

Table 4.2: Technical data of English China Clay (Puraflo 50)

Chemical Analysis :
(Ultimate Analysis)

	(%)
SiO_2	48.8
TiO_2	<0.1
Al_2O_3	35.4
Fe_2O_3	0.8
$Ca0$	0.1
MgO	0.2
K_2O	2.8
Na_2O	0.2
Loss on Ignition	11.4

Calculated Mineralogical Composition :
(Rational Analysis)

Kaolinite	64
Potash Mica	24
Soda Mica	2
Quartz	6

(The quoted mineralogical composition has been derived from X-ray diffraction measurements and calculations based upon chemical analysis)

Particle Size Distribution :
(Equivalent Spherical Diameter)

Microns:	1	2	5	10	20
% Undersize	37	49	76	94	99

Residue : Average < 0.1%

Measured by wet screening on a 53 mesh (equiva. 300 BSS)

Reflectance : 78.0 – 80.0%

(Effective Wavelength 457 ± 0.5 nm)

pH value : 5.1

Surface Area : 8 – 10 m^2 / gm

Note: These technical data were obtained from WBB Devon Clays Ltd

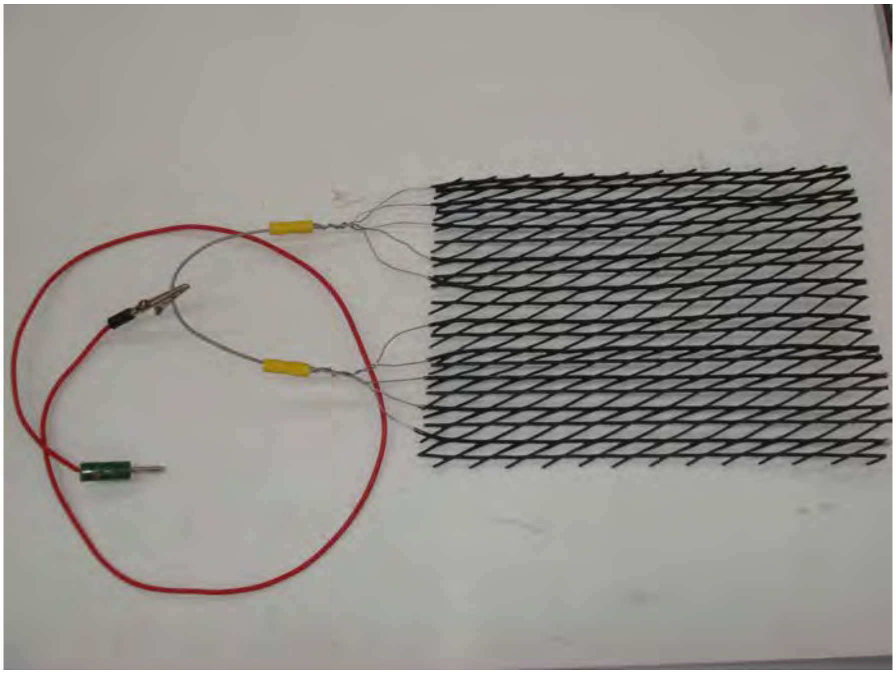


Figure 4.2: Electrokinetic geosynthetic (EKG) electrode.

4.4.4 Power Supply

A DC power supply obtained by Thurlby Thandar Instruments (model TS3022S) was used to supply power to the electrodes throughout this study. It is capable of supplying a maximum voltage of 30 volts and a maximum current of 2 amps. A constant voltage gradient of 50 V/m was used for all electrokinetic treatment that have been suggested by many researchers as an optimum voltage gradient for geotechnical purposes and also in the range of 40 – 60 V/m which proposed by Mitchell & Soga (2006). According to Hamir (1997), in terms of the properties of the treated soil, there is no difference between applying of constant current or constant voltage could be found.

4.5 Basic Geotechnical Testing

Basic geotechnical laboratory testing was performed to establish the physical and chemical properties of the kaolin clay used in this study. Firstly, physical properties testing such as Atterberg limits, specific gravity, falling head permeability test, oedometer consolidation tests were conducted to assess the behaviour of clay soils used in this experiment before applying the EKS method. Then, soil chemical testing for untreated soil (kaolin clay) was carried including pH, electric conductivity and metal ion concentration.

4.5.1 Tests for Physical Properties of Untreated Soil

The result of physical properties of untreated soils are summarised in Table 4.3 and also compared with the results obtained from other researchers using the same type of soil. It should be noted that a total of 9 samples from 3 different bags in the same batch were used and reported as an average value to ensure reproducibility of results and consistency across the bags used in the main test programme.

4.5.1.1 Atterberg Limit

The objective of the Atterberg limits test is to obtain basic index information about the soil used to correlate its relationship with the soil strength behaviour. The plastic and liquid limits were determined according to BS 1377 Part 2: 1990. The liquid limit, plastic limit and plasticity index values are given in Table 4.3. The Atterberg limit values obtained in the present study compared well with greater variability exhibited with plastic limit results as expected. It is well known that the value of plastic limits is prone to human error.

Table 4.3: Physical properties of English China Clay obtained from other researchers.

Source	**Description**	**Specific gravity**	**Clay fraction* (%)**	**Liquid Limit, (%)**	**Plastic Limit, (%)**	**Permeability (m/s)**
Author	English China Clay (Puraflo 50)	2.63	51	60	34	2.2×10^{-8} (Falling head test) 2.6×10^{-10} (Oedometer test)
Musso (2000)	English China Clay (Speswhite)	2.61	78.5	50	27	1.0×10^{-8} (Oedometer test)
Altaee (2004)	English China Clay (Speswhite)	-	90	-	-	4.0×10^{-10} (Falling head test)
Liaki (2006)	English China Clay (Puraflo 50)	-	49	55.6	34.6	-
Kalumba (2006)	English China Clay (Speswhite)	2.63	40	57	15	3.0×10^{-9} (Falling head test)
Marquez (2009)	English China Clay (Speswhite)	2.60	-	65	33	-
	English China Clay (Puraflo 50)	-	-	56	31	-
Thomas (2010)	English China Clay (Speswhite)	2.58	-	62	28	-

4.5.1.2 Specific Gravity (G_s)

The specific gravity of English China clay was determined according to BS 1377 Part 3:1990: 8.3. Dry clay soil in the bag was placed in an oven to make sure the soil is completely dry to eliminate any water content that still contain from the factory process. Even small amount of moisture content will had greatly impact on specific gravity measurement. The dried clay also was sieved through 2 mm sieve to make sure the clay soil is free from any coarse grain during production of kaolin clay from the factory. A known weight of dried soil was placed in 50 cm^3 small pyknometer and filled with distilled water before placed in a vacuum chamber to remove the air present in soil voids.

The specific gravity (G_s) of this soil was in an average of 2.63. Therefore, the specific gravity of the clay soil obtained in this study is in an agreement with the values reported by most other researchers as shown in Table 4.3. In general, the specific gravity values of English China clay from different authors were in the range between 2.58 and 2.63.

4.5.1.3 Particle Size Distribution

The particle size distribution was determined using hydrometer test in accordance to BS 1377 Part 2: 1990: 9.5 since the soil used in this study is in silt to clay range. About 50 g of dried soil passing 2.00 mm sieve was first treated using sodium hexametaphosphate to disperse clay particles. Then the treated soil was washed through a 63 µm sieve and collected for sedimentation test using hydrometer test (see Figure 4.3). The results are shown in Figure 4.4. These results compare well with those given by supplier. From the graph, the particle size distribution of English China Clay was constituted by percentage of 50% of clay and 50% of silt material. However, the clay fraction values of English China clay were variable with other researchers as shown in Table 4.3. These values normally depend on the source of clay and purity of the clay used.

4.5.1.4 Hydraulic Permeability

The hydraulic permeability test was performed as outlined by Head (1992) with slight modification to suit the size and condition of the equipment (see Figure 4.5(a) and 4.5(b)). The loading plastic plate was designed to place on the top of the sample to consolidate the sample until reach the required level (see 4.5(a)). The dial gauge was attached at the top of loading plate to measure the settlement of the soil during consolidation. The sample was loaded incrementally as same procedures performed in the main electrokinetic testing (see Chapter 5). The final water content after consolidation was 51 % which was similar to the final water content of the sample in the tank for EKS testing. The Hydraulic permeability using falling head method was found to be approximately 2.2 x 10^{-8} m/s. This value is about 2 orders of magnitude higher than the value obtained from oedometer test which is 2.6 x 10^{-10} m/s. This was expected because the variations of void ratios in respect to loading from oedometer test. However, for falling head test the initial void ratio value is similar to the value prepared for electrokinetic testing. Since the initial water content of sample for falling head test is 51 % reflect to the higher void ratio value, this will result in higher permeability. According to Mitchell & Soga (2005), changes in fabric, void ratio and water content may exhibit a few orders of magnitude variation even in a same soil.

Figure 4.3: Hydrometer test setup

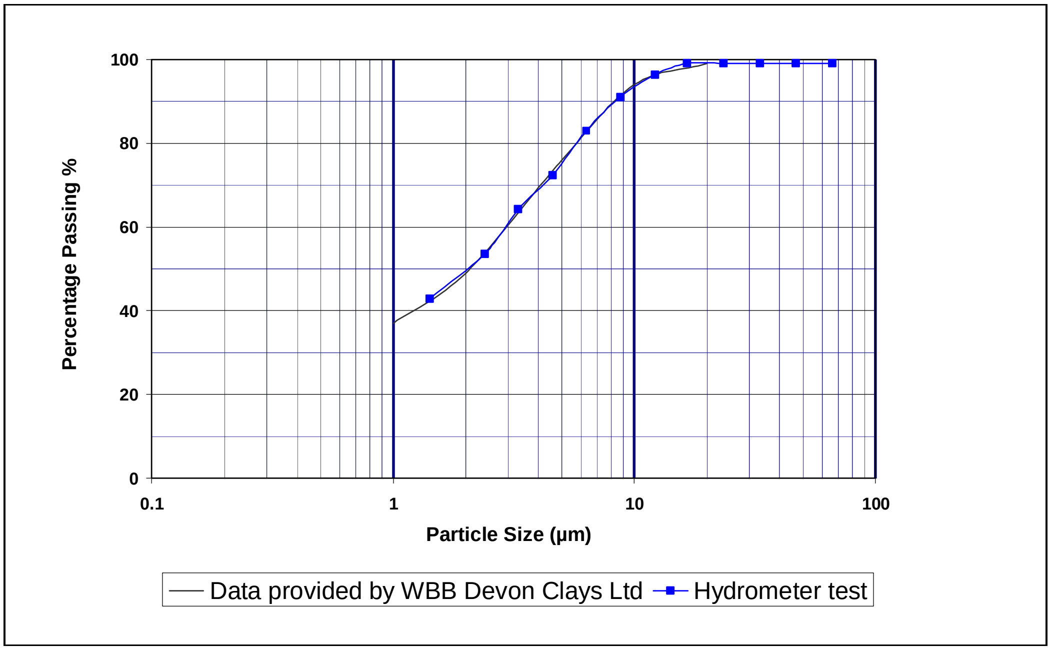


Figure 4.4: Particle size distribution.

(a) (b)

Figure 4.5: Hydraulic permeability test (a) Sample preparation using consolidation test method and (b) Testing setup.

4.5.1.5 Oedometer Consolidation Test

Oedometer consolidation tests were conducted in accordance to BS 1377: Part 5: 1990. This test was used in soil laboratory testing to determine the consolidation characteristics of soils of low permeability. In addition, most of the previous study used this test to determine hydraulic conductivity of fine soil. The oedometer test result conducted on the English China Clay is illustrated in Figure 4.6. From the void ratio-log pressure graph, the compression index of English China Clay was 0.365. This value was considered as a high compressibility according to Reeves, *et al.* (2006) and falls within the establish range from other researchers especially for kaolin clay.

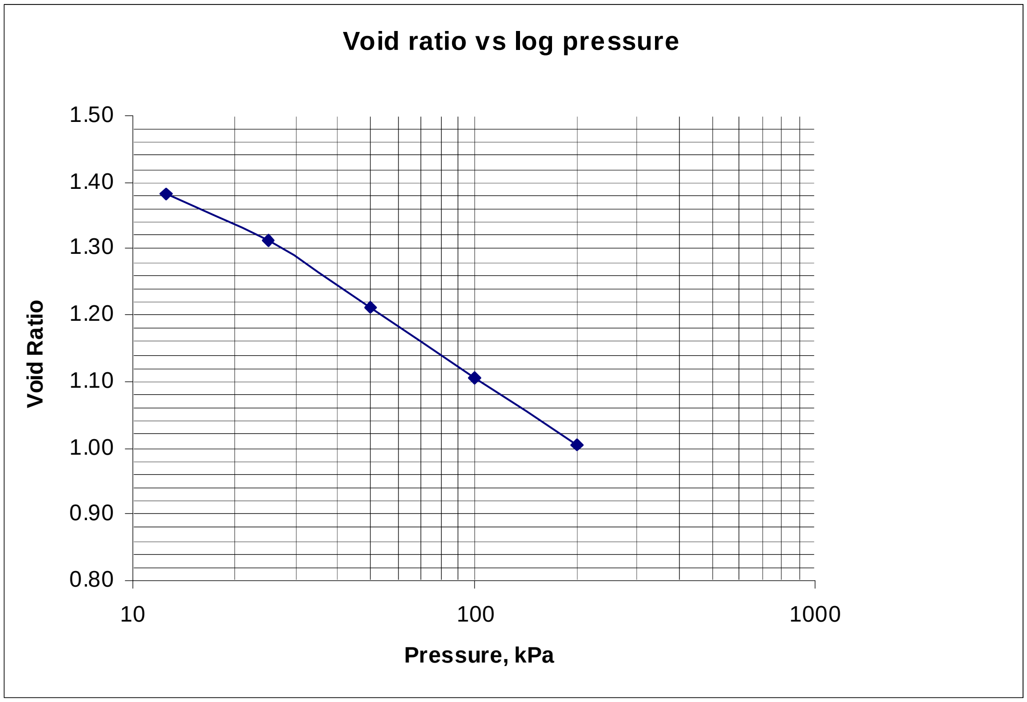


Figure 4.6: Results of one-dimensional compression test performed on English China Clay.

4.5.2 Tests for Chemical Properties of Untreated Soil

Chemical tests were performed to determine pH and conductivity of English China clay prior to EKS testing. Results of chemical test were then compared with results from other researchers that used the same type of soil as summarised in Table 4.4. In addition, the initial condition of clay used for EKS testing is important to know the effect of soil after treatment that may change the physical and chemical properties of the clay soil.

Table 4.4: Soil pH and electrical conductivity (EC) of English China Clay from other researchers.

Source	Description	pH	Electrical Conductivity, S/cm
Author	English China Clay (Puraflo 50)	5.05	19.6
Altaee (2004)	English China Clay (Speswhite)	6.6	576 (higher because using tap water instead of deionised water)
Liaki (2006)	English China Clay (Puraflo 50)	5.68	37.6
Kalumba (2006)	English China Clay (Speswhite)	5.4	-

4.5.2.1 Electrical Conductivity

The electrical conductivity indicates the amount of soluble (salt) ions in soil. The determination of electrical conductivity was made with a conductivity cell by measuring the electrical resistance of a 1:5, soil: water suspension ratio. Therefore, 50 ml of deionised water is added to 10 g dried samples. The sample solutions were placed in the mechanical end-over mixer for 1 hour. Before any actual measurements were taken the conductivity meter was first calibrated according to the manufacturer's instructions. Then, the sample solutions are tested for electric conductivity measurement using a Hanna HI9033 conductivity meter. This conductivity meter operates within the range of 0.0 - 199.9 mSiemens/cm and 0 - 50˚C, for conductivity and temperature, respectively. The probe was rinsed with deionised water before and after the measurements to ensure no cross-contamination. Results are presented in Table 4.4.

The electrical conductivity values of English China clay from various authors were varied from 19.6 to 576 S/cm might due to the different conductivity probes used which has different sensitivity, different soil water ratio used by those authors and not using distilled or dionised water as reported by Altaee (2004) in Table 4.4.

4.5.2.2 pH

The same sample solution used for conductivity test (see section 0) was used to measure soil pH. To ensure consistency, the electrical conductivity must be measured first (Liaki, 2006). The pH value is measured using a British Drug House (BDH) rapid renew epoxy probe connected to an Orion Model 520A Benchtop pH meter. The pH meter was calibrated prior to use according to manufacturer’s instruction manual using the buffer at pH 4, 7 and 12.68 at temperature 20˚C. The probe could operate the pH and temperature value in the range of 0 – 14 pH and 0 - 100˚C respectively to an accuracy of 0.004 pH. The pH value was obtained when the equilibrium is reached while stirring with a mechanical stirrer. The probe was also rinsed with deionised water before and after the measurements, again to prevent cross-contamination. Results are shown in Table 4.4. From the table, it clearly shows that the pH values of English China clay are between pH 5 to 6.6 from various researchers and slightly below the pH neutral.

4.5.2.3 Metal Ions Concentration

The amounts of cations in the soil after treatment are determined by using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES). Limits of detection in micro grams per litre are shown in Table 4.5.

Table 4.5: Limits of detection in micro grams per litre for ICP-AES analysis

Element	**Concentration (μg/l)**
Sodium Na	0.25
Magnesium Mg	0.009
Potassium K	0.8
Calcium Ca	0.01
Strontium Sr	0.01
Chromium Cr	0.18
Manganese Mn	0.02
Iron Fe	0.2
Zinc Zn	0.07
Aluminium Al	0.04
Silicon Si	0.9
Phosphorus P	1
Sulphur S	1.9
Tin Sn	0.6
Lead Pb	1.5

The laboratory preparation of soil samples for ICP-AES analysis involved acid digestion method to dissolved metal ions into solution. A combination of hydrochloric acid and nitric acid with 1:3 ratios was chosen for this testing. Soil specimens from each of the 8 locations are first oven dried at 105˚C to remove any pore water in the soils. Then, 1.0 g of the soil sample was weighed and placed into 150 ml beaker followed by adding 6 ml concentrated hydrochloric acid and 2 ml of nitric acid. Deionised water was added to reach a total volume of 50 ml. The mixture was heated on a hotplate, which was located in a fume cupboard and evaporated until the volume had been reduced to 5 ml. The mixture was cooled to room temperature (20°C) for about 10 minutes. The same amount of hydrochloric acid, nitric acid and deionised water were added as before and the evaporation process was repeated. The mixture was cooled again and filtered through a Whatman 540 filter paper into volumetric flasks. Deionised water was added to reach 100 ml volume. The sample was filtered again through a Whatman 0.20 m membrane filter to avoid any subsequent blockages of the aspirator in ICP-AES. All the samples was then stored in a controlled temperature room at 4.0 ± 0.5˚C before conducted the ICP-AES analysis.

4.6 Batch Testing

Batch testing was conducted in advanced before commencement of the main experimental programme in order to determine the effect of calcium chloride alone on shear strength of English China Clay using four different concentration (0.5, 1.0, 1.5, 1.5 and 2.0 mol/litre) for 3 days treatment durations. In addition, the batch testing was also conducted to check the efficiency of the electrokinetic setup using the Mariotte bottle method to maintain the water level when the chemical solution was continuously supplied at the anode electrode.

This method was originally designed by the author to check the efficiency of the system before large model were developed for EKS testing. Figure 4.7, Figure 4.8 and Figure 4.9 show the devices used in the EK batch testing. It consisted of EK cylinder, 2 EKG electrodes, two plastic filters, loading plastic plate that has steel rod to place the loading equipment, DC power supply, Mariotte bottle, and graduated cylinder. EK cylinder (50 mm diameter and 90 mm long) was equipped with an outlet port located at the middle of the bottom base to allow discharge of water during consolidation and EK testing. EKG electrodes used for anode and cathode and were cut in circular shape to fit in the EK cylinder and able to connect to the DC power supply.

The loading plastic plate (see Figure 4.9) was placed on the top of the sample to consolidate the sample until reach the required level. It has three holes to supply the electrolyte during EK testing and to connect a wire from electrode to the power supply. The dial gauge was attached at the top of loading hanger to measure the settlement of the soil during consolidation and EK testing (see Figure 4.10). The sample was loaded incrementally by using the loading plate and dead weights (see Figure 4.11). All the sample preparation in this batch testing was similar to the main experimental programme as discussed in Chapter 5. After consolidation, the inflow tube was connected from the bottom of Mariotte bottle to top of the plate to continuously supply the water during the EK testing. Then, the water discharge was collected at the graduated cylinder for monitoring purpose. After testing, the shear strength of the soil is measured using vane shear test in the small cylinder. The batch test results were utilised to assess the strength behaviour of English China Clay mixed with different concentrations of calcium chloride.

Based on the results in Figure 4.12, there was an increasing trend in the shear strength with 0.5, 1.0, 1.5 and 2.0 mol/litre sodium silicate compared to the distilled water only (0 mol/litre). However, highest shear strength was achieved at 22 kPa with 1.5 and 2.0 mol/litre sodium silicate compared with distilled water of 8 kPa. Thus, this indicates that 1 mol/litre sodium silicate used for main experimental programme at the anode chamber was effective dosage to give a reasonable strength.

Figure 4.7: Batch testing apparatus.

Figure 4.8: EKG electrodes and Vyon sheet filter used in batch testing to be attached at the top and bottom of the sample during electrokinetic treatment.

Figure 4.9: Loading plate for EK batch testing to be placed on top of the sample during consolidation.

Figure 4.10: Setup and design configuration of EK batch testing.

Figure 4.11: Setup of batch testing using the Mariotte bottle method.

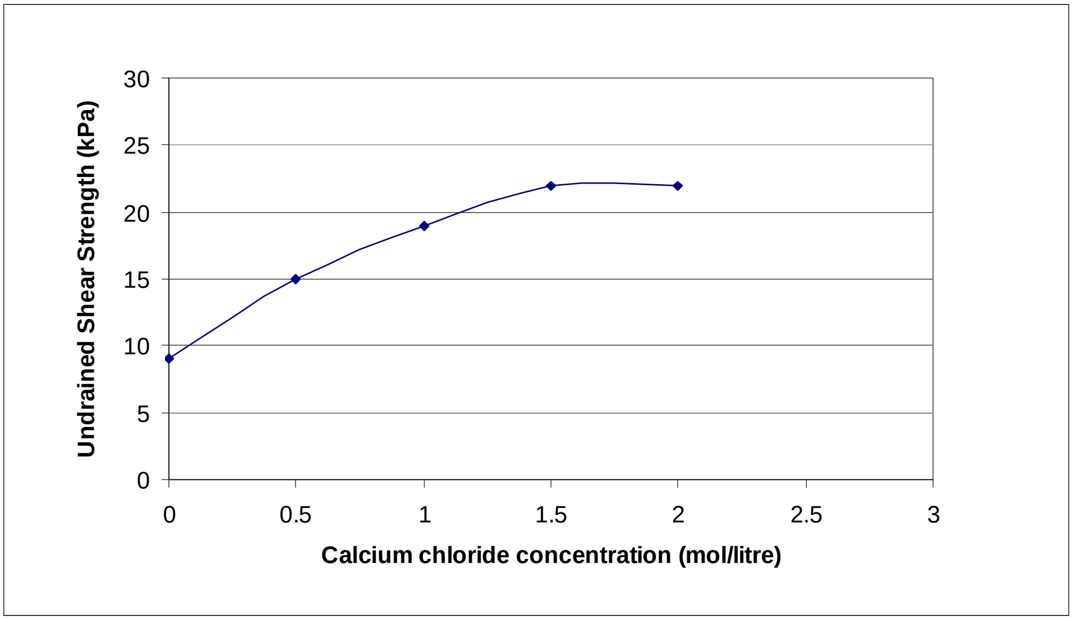


Figure 4.12: Calcium chloride concentration in the Mariotte bottle versus undrained shear strength.

4.7 Summary

In this chapter, the details of laboratory test setup and procedures for preliminary testing before commencement of the main EKS testing are discussed in detail. The detailed laboratory experiment for main EKS testing is reported in the following chapter (Chapter 5). The choice of the soil, materials and apparatus discussed in this chapter had been considered appropriately with previous studies in literature chapter and continual research in University of Birmingham. First, just in order to achieve the successful study in this research and as justified in the literature, an English China Clay (Kaolin clay) was adopted. Then calcium chloride and sodium silicate were chosen as chemical stabilisers in the main experiment together with an EKG electrode.

Chapter 5

EKS METHOD AND PROCEDURES

5.1 Introduction

This chapter focuses the procedures of main electrokinetic stabilisation programme used in the study. The electrokinetic stabilisation testing was divided into three phases as shown in Table 5.1. It also shows the code used in electrokinetic stabilisation programme to indicate the different of electrolytes used at both electrode chambers.

5.2 Design of EKS Testing Model

The Electrokinetic Stabilisation (EKS) testing model was designed and manufactured for this study. A schematic diagram of the model is shown in Figure 5.1. The model was originally designed by Liaki (2006) but has been modified to achieve the objectives of this study (see section 4.3 in Chapter 4)**.** The rectangular model tank was made of non-conductive transparent perspex sheet to prevent short circuiting while transparent material enabled monitoring of the soil level during consolidation and monitoring the level of water or chemical solution in small compartments during electrokinetic treatment. The perspex sheet was 12 mm thick and the rectangular tank had internal dimensions of 450 x 220 x

550 mm. The tank consisted of main compartment of internal dimension 370 x 220 x 550 mm, where soil samples for treatment were placed and two small compartments that had internal dimension of 40 x 220 x 550 mm to supply the chemical stabilisers into the soil. The both sides of small compartments were filled with anolyte and catholyte solution respectively (see Figure 5.1).

Table 5.1: Main experimental programme.

Code	**Anolyte**	**Catholyte**	**EK Durations**	**Purpose**
Phase 1				
DW-DW	Water	Water	3 days	- Effects of pure system.
	Water	Water	7 days	
	Water	Water	14 days	
Phase 2				
CaCl-DW	$CaCl_2$	Water	3 days	- Effects of migration of Ca^{2+} ions in the system.
	$CaCl_2$	Water	7 days	
	$CaCl_2$	Water	14 days	
DW-NaSiO	Water	Na_2SiO_3	3 days	- Effects of migration of SiO_3^{2-} ions in the system.
	Water	Na_2SiO_3	7 days	
	Water	Na_2SiO_3	14 days	
Phase 3				
CaCl-NaSiO	$CaCl_2$	Na_2SiO_3	3 days	- Combination effects of Ca^{2+} ions and SiO_3^{2-} ions in the system.
	$CaCl_2$	Na_2SiO_3	7 days	
	$CaCl_2$	Na_2SiO_3	14 days	

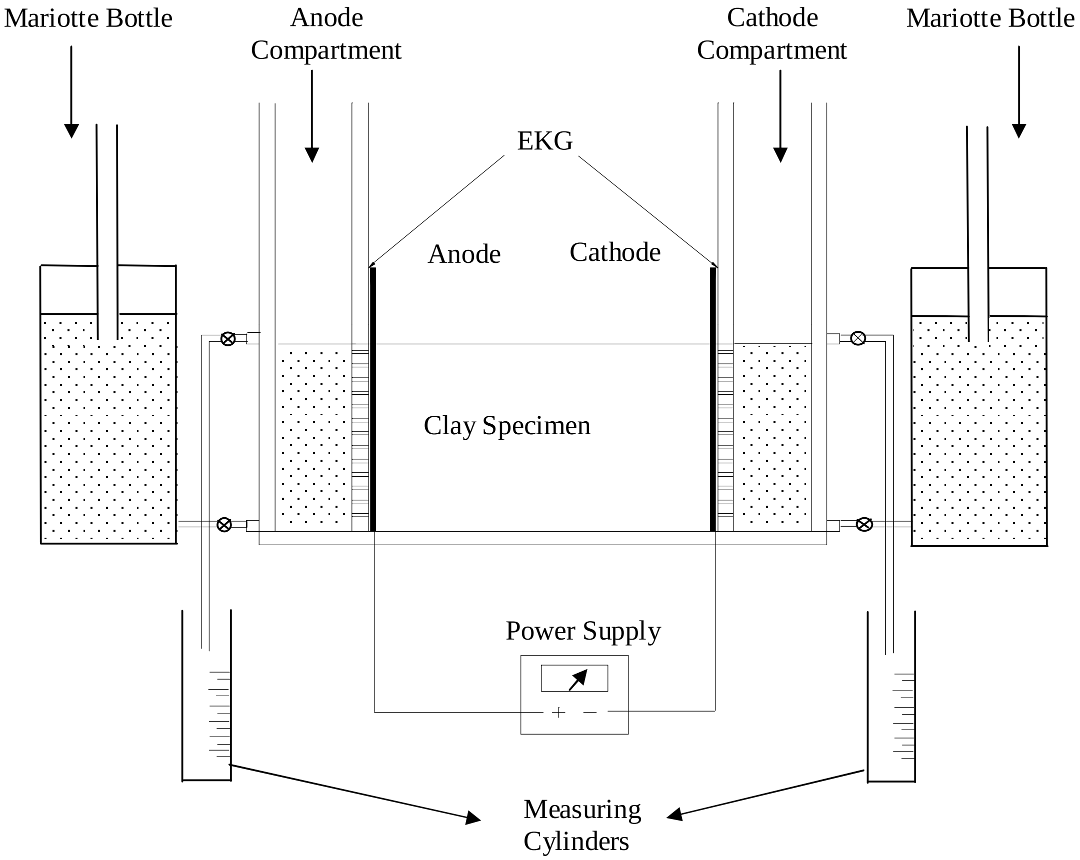


Figure 5.1: Schematic diagram of EKS testing model.

The bottom of the tank was made up of two layers of different bases; the first base (perforated base) was placed on the second base (solid base), which enabled drainage of water from main compartment during consolidation to take place (see Figure 5.2). The second solid base was grooved to discharged water at the edge of the tank to a volume measuring tube. A drainage valve was detached at the edge of the second base so that the valve could be closed during electrokinetic treatment. The combined filter system was attached on the base before placing the soil sample into the main compartment. The lower part of the walls between the main compartment and small compartment were also perforated to allow water and chemical ions migration without interruption across the soil sample in the main compartment during electrokinetic treatment. The holes of perforated walls and the base are 2mm in diameter and the spacing between the holes is 17 mm centre to centre (see Figure 5.3).

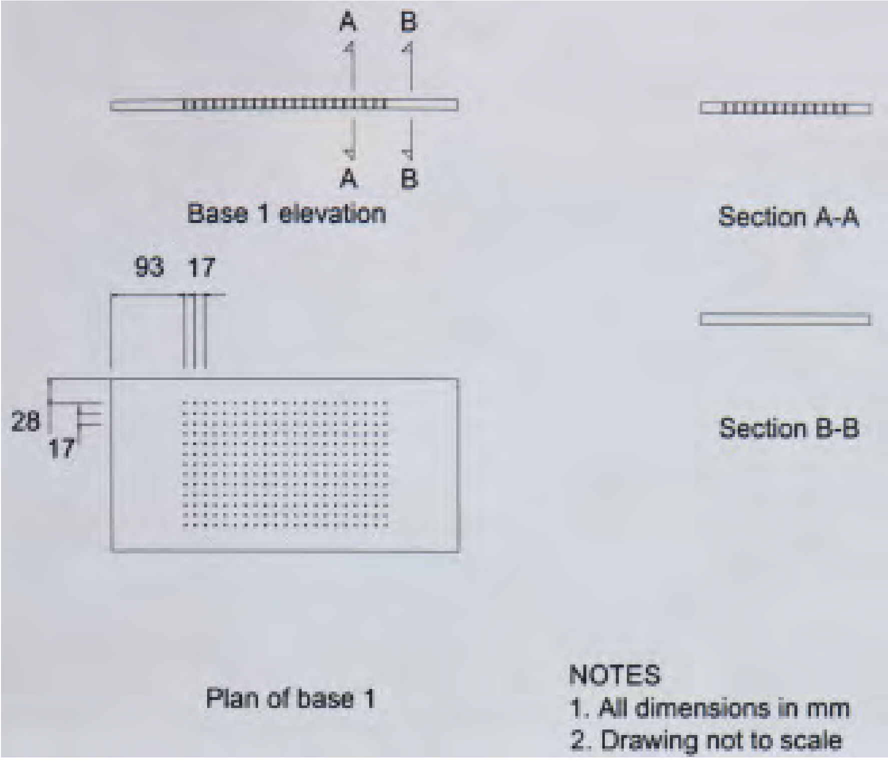
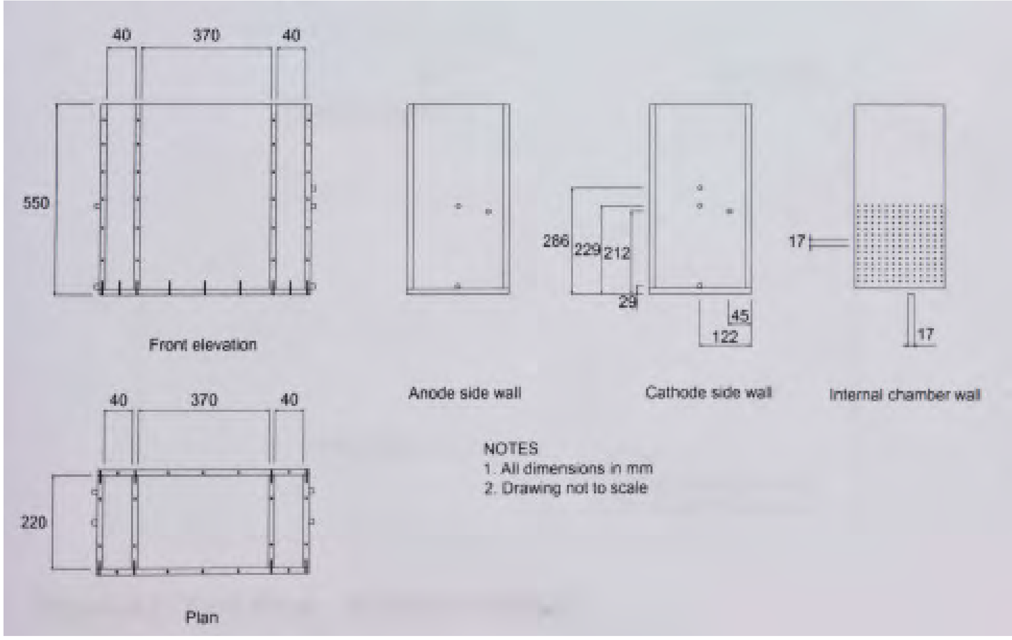


Figure 5.2: First tank base-AutoCad drawing (after Liaki, 2006).



NOTES
1. All dimensions in mm
2. Drawing not to scale

Figure 5.3: Testing tank-AutoCad drawing (after Liaki, 2006).

A combined filter systems were also attached at both perforated sides of the wall from inside the main compartment during electrokinetic treatment to prevent soil particles movement into the electrode chambers. The combined filter system consisted of a Whatman Grade 1 filter paper and Vyon F filter plastic made of High Density Polyethylene (HDPE). A filter paper was attached first on both of perforated walls then followed by Vyon F filter. The filter paper has particle retention of 11 m and specification of Vyon F filter is shown in Table 5.2. During consolidation, both sides of filter systems were closed using solid perspex sheet of 3 mm thick to ensure drainage of water only occurred at the top and bottom of the soil. After completed the consolidation process, the solid perspex sheets were carefully removed from the tank to create spaces between the soil sample and the walls so that the EKG electrodes can be inserted. The circular shape of EKG electrode was cut along its length and expanded as a sheet electrode (see Figure 4.2 in Chapter 4).

The exposed of stainless steel wires at the bottom edge of electrodes after cutting were sealed properly using epoxy resin to prevent the corrosion of the electrode which may affect the efficiency of the system. The EKG electrodes were weight before and after the each EKS test to check if there was any weight loss caused by corrosion of stainless steel. The stainless steel wires inside the core EKG electrode were coated by conductive carbon polymer as seen in Figure 3.2 in Chapter 3.

Table 5.2: Vyon F filter data sheet.

THICKNESS	1.00 ± 0.12 mm
TYPICAL REMOVAL EFFICIENCIES	
Air Normal	20 m
Water Normal	30 m
TYPICAL PORE SIZE	
Mean Flow	38 m
Max	120 m
Min	10 m
TYPICAL AIR FLOW AT VARIOUS PRESSURES	
2.45 mBar	22 m^2/min/m^2
10 mBar	56 m^2/min/m^2
20 mBar	92 m^2/min/m^2

During consolidation, a loading plate was placed on top of the sample in the main compartment of the tank using a hydraulic jack. Two ways drainage was provided through open holes on the top and bottom of the tank during consolidation process. A steel loading plate was designed with nine 10 mm diameter holes of spacing 21 mm and 36 mm centre-to-centre across its width and length, respectively allowed drainage at the top (see Figure 5.4). A loading plate with was covered with a plastic sheet to avoid direct contact of metal plate and the soil. The holes of the plastic sheet are made at same position with the holes of the plate to avoid blocking of water during consolidation. Vyon F filter sheet was then cut to size and attached to the bottom of the plate. Then a commercial draught excluder tape was then attached around the side edges of the plate to prevent leakage of slurry material between the plate and the tank walls. A dial gauge was set up on the loading plate to measure soil settlement with time.

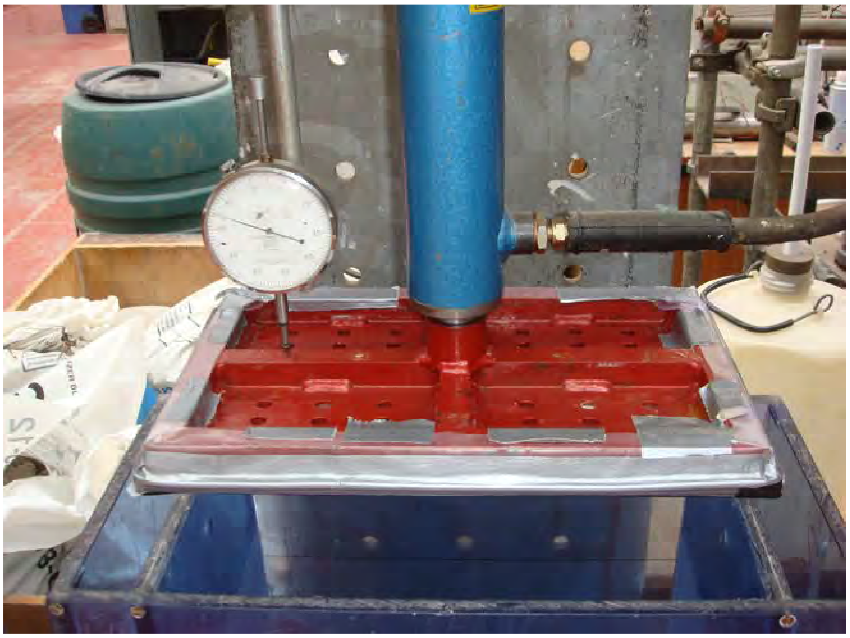


Figure 5.4: Set-up of loading plate.

5.3 Sample Preparation

The slurry sample was prepared by mixing the clay soils with deionised water to achieved 90% water content. The water content of slurry has been chosen based on 1.5 times liquid limit (LL). Many researchers have used water content of 2 times liquid limit for their slurry preparation to produce homogeneous sample. However, Anderson *et al.* (1989) found that water content of 1.5 times LL caused no apparent detrimental effect on the uniformity of the sample. Firstly, 10.66 kg of deionised water was poured into the mixer bowl and then 11.84 kg of dry English China clay was gradually added to ensure consistency of mixing. The slurry sample was then mixed using Hobart mechanical mixer and blended thoroughly for 30 minutes. The mechanical mixer was set at the lowest speed to prevent sample splashing out from the mixer bowl. It was necessary to stop the mixer and scrape unmixed portions around the sides and bottom of the bowl into the mixture and continue mixing to promote uniform blending. Two mixtures of slurry samples were placed in the tank and these mixtures were mixed a bit to prevent a layer forming. The total of amount of soil and water in the tank was 23.68 and 21.32 kg, respectively, achieving a water content of 51 % for all test samples. At this stage, two mixtures of slurry samples were poured into the main compartment that had been setup as shown in Figure 5.5. A vibrator was used for every mixture placed into tank to remove air trapped inside the soils and to level the top of the soils slurry after finished pouring the second mixture. Then, the slurry sample was left overnight to ensure homogeneity. The initial height of the slurry is 386 mm for all tests samples. The load was applied to consolidate the slurry sample until it reached final height of about 271 mm using hydraulic jack as shown in Figure 5.6 to achieve water content of 51%. The final water content of 51 % was chosen due to practical reasons, such as the easy removal of the 3 mm thin solid plastic sheets with minimal disturbance of the soil and the insertion of the electrodes at each end of the main compartment of the tank and as suggested by Liaki (2006) which in the trial test, 45 % water content had caused soil disturbance in such situation.

Before conducting any consolidation test, the hydraulic jack system was calibrated (as shown in Figure 5.7) to know actual stress applied on the sample. The first consolidation pressure was set at approximately 10 kPa for about 24 hours to prevent soil particle migration via the drainage. Head (1992) suggested that initial pressures for consolidation test for very soft soil (slurry sample in this case) is from 6 to 10 kPa to prevent soil squeezing out during consolidation. The subsequent surcharge pressures were gradually increased in four increments over a 4 days period until final height was reached, as shown in Table 5.3. After consolidation thin solid plastic sheet walls were removed at both end of soil compartment and the gaps left were then inserted by the EKG electrodes. The soil samples were reconsolidated under the same loading as the last consolidation (67.9 kPa) for about 24 hours before the loading was released upon EKS testing. Subsequently, the electric current were turned on and monitored throughout the test durations. This was performed to make sure a good contact between soils and electrodes during the EKS testing.

Figure 5.5: Setup of electrokinetic testing.

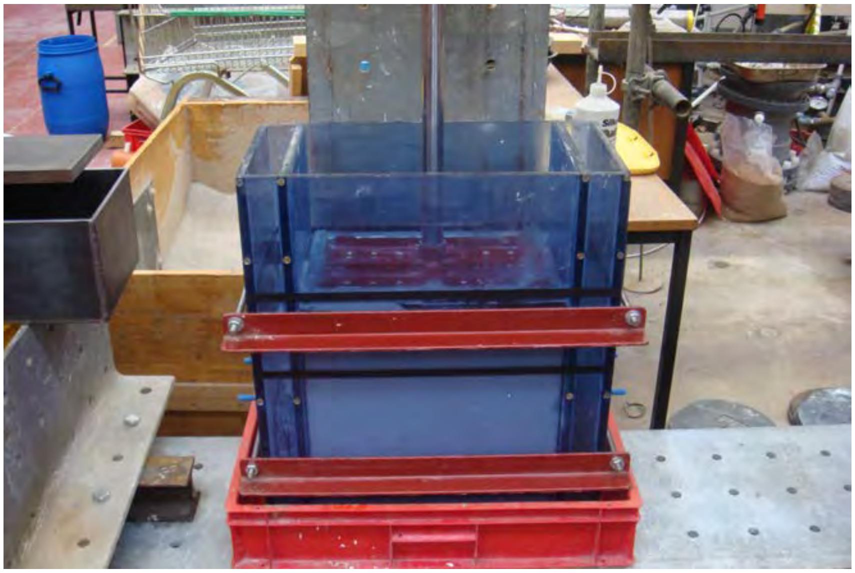


Figure 5.6: During consolidation stage.

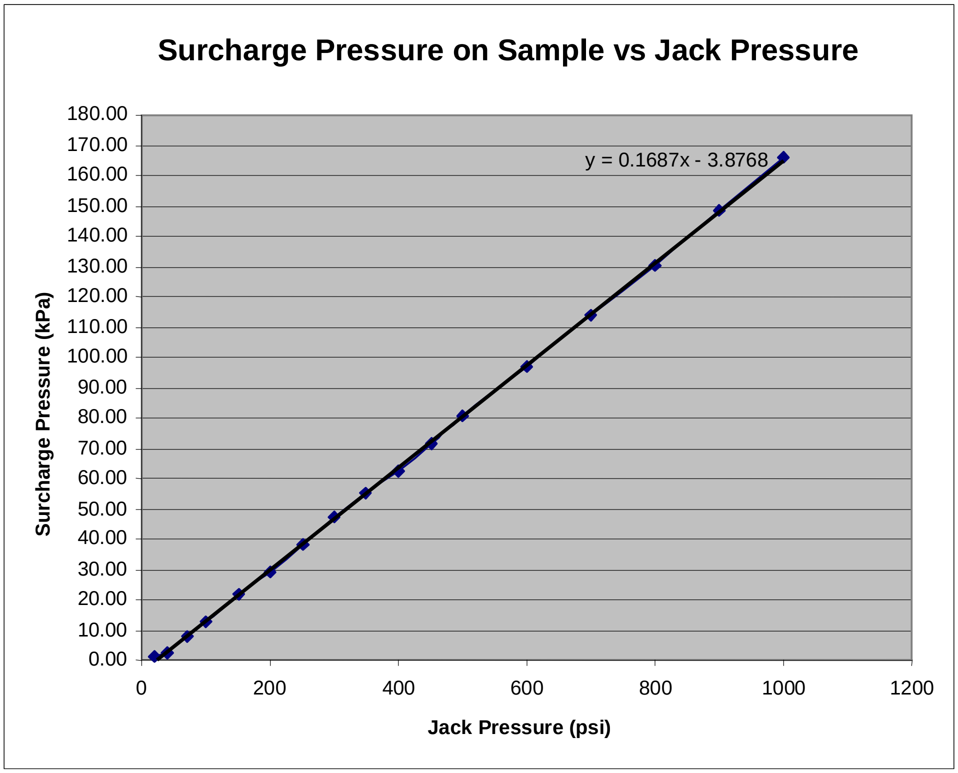


Figure 5.7: Calibration of load cell for hydraulic jack pressure.

Table 5.3: Sequence of stress application to consolidate the samples.

Loading **(kPa)**	**Jack Pressure** **(psi)**
10.1	82.9
26.4	179.5
42.8	276.7
67.9	425.5

5.4 Phase 1 of EKS

The first set of test was conducted for the phase 1 to assess influence of treatment time. The pure system of electrokinetic stabilisation method was compared with a previous study conducted at University of Birmingham that was initiated by Liaki (2006). Distilled water was used as electrolytes in that were filled in electrode chambers and subject to electric current for 3, 7, and 14 days. Results are discussed in details in Chapter 6.

5.5 Phase 2 of EKS

The next series of tests were conducted for the phase 2 over 3, 7, and 14 days treatment intervals. The first set was performed using calcium chloride solution fed at the anode chamber and distilled water at the cathode chamber supplied continuously using electric current to transport calcium ions from anode toward cathode. While, the second set of test was performed using sodium silicate solution at the cathode and distilled water at the anode chamber to transport silicate ions from cathode toward anode (see Table 5.1).

5.6 Phase 3 of EKS

For phase 3, one series of electrokinetic testing was designed to study the effect of electrokinetic mechanisms that contribute the increase of soil shear strength in electrochemical process by transportation of cations and anions at anode and cathode, respectively by combining the chemical stabilisers used in phase 2. The test was conducted by feeding calcium chloride and sodium silicate at the anode and cathode respectively to know the effects of cation and anion of species into the system. Calcium chloride was introduced to transport calcium ions from anode towards cathode throughout the soil sample. This test also performed the same period of time as performed in phase 1 and phase 2, i.e. for 3, 7 and 14 days so allowing direct comparisons throughout.

5.7 Monitoring of EKS Testing

During electrokinetic testing the variation of current, electric resistance, anolyte and catholyte solutions were monitored as this depends on time durations. The amount of effluent water from the Mariotte bottles and effluent water collected at graduated cylinders were also monitored over the same period of time. For the first day of the treatment, the reading of current value was taken at 1, 2, 4, 6 and 8 hours to establish profile and data was subsequently taken every 24 hours for the remainder of the test duration, while the second day and afterward data was taken every 24 hours. Samples of anolyte and catholyte solutions were taken every 24 hours together with water collected at graduated cylinders. 50 ml of anolyte and catholyte solutions are extracted from the small compartments using syringe. The bottles of samples were labelled and then stored in a controlled temperature room at 4.0 ± 0.5˚C for pH and conductivity measurement.

5.8 Laboratory Testing of Treated Soil

The treated soil samples were tested to assess the physical and chemical properties of the soil. Laboratory testing for treated soils were carried out immediately after the power supply was switched off. The soil sample in the main compartment was divided into 8 sections to investigate changes of soil properties along the soil profile, from anode to cathode. Some sample extractions were taken at the top, middle and bottom of the sample at each section for repeatability test to know any effect of soil properties with depth that might have occurred and to know the efficiency of the treatment at all areas of treatment, especially near the surface (see section 7.5). The main electrokinetic testing was performed with different periods of treatments corresponding to 3, 7, and 14 days to assess the changes of soil properties with respect to time during electrokinetic treatment.

Undrained shear strength and water content were first assessed inside the tank after disconnecting the electric current together with moisture content tests. Samples were cored using 38 mm diameter thin wall steel tube in the middle of each section. The undisturbed samples were extracted for chemical analysis such as pH, electric conductivity and metal concentration. The remainder of the samples were removed carefully from the tank to conduct the plastic and liquid limits tests of treated soils for every section.

5.8.1 Tests for Physical Properties of Treated Soil

5.8.1.1 Atterberg Limit

The plastic and liquid limits were determined in accordance to BS 1377: Part 2:1990. It should be noted that for liquid limit test, the wet soils extracted from the tank were not oven dried because it may affect the soil properties due to the high temperature. However, for plastic limit it is impossible to wait the soil to dry before test was undertaken, thus samples for plastic limit were dried in the oven and ground before the test was performed.

5.8.1.2 Moisture Content

The moisture contents of the samples were determined according BS 1377: Part 2:1990. The soils left on the vane blade after conducting vane shear test were immediately taken for moisture content determination. Moisture content was also double checked after extraction of samples for chemical testing using 38 mm diameter steel thin walled steel tubes.

5.8.1.3 Hand Vane Shear Test

Undrained Shear Strength tests were determined using hand vane hear test manufactured by Pilcon Engineering Ltd. This type of test is widely used in soil laboratory testing and when determines the undrained shear strength of soft soils in the field. Therefore, comparison of the results achieved from this study can be made with previous studies either laboratory or field study. In addition, most of the previous related study (e.g. Liaki, 2006) used vane shear test to determine undrained shear strength of soil after electrokinetic treatment due to the fewer disturbances when preparing the samples. In addition, the size of the treatment samples in the tank was too small to allow strength to be reliable determined by another method. This test was performed immediately after application of the current for different periods of time had ceased. The size of vane blade was 30 mm in diameter suitable for very soft soils. The rotation speed of the vane was 1 rpm for all tests as suggested by Kim (1996). The test was performed at three locations in the middle of every section (130 mm from soil surface) along to soil profile that has been divided into 8 sections. Vane shear test was also conducted at the top, middle and bottom corresponding to the depths for replicate test to know the different of soil properties with depth due to electrokinetic stabilisation process. It was essential for every testing to check that the vane head and blade were always clean and dry. The hand vane shear was held perpendicular to the soil and then the vane blade was pushed into the soil to a depth at least twice the length of the vane blade sufficient to ensure that shearing will take place on the vertical edges of the vane blade without movement of the undisturbed soil surface. The vane head was held using both hands and rotated slowly at a uniform rate of approximately one revolution per minute. The value of undrained shear strength from this test was taken directly from the scale on the top of hand vane shear test which measured strength in kPa.

5.8.2 Test for Chemical Properties of Treated Soil

Electrical conductivity, pH and metal ion concentration tests were described in Chapter 4. However, for the monitoring tests, electrolytes solutions subjected to pH and electrical conductivity measurement were extracted directly from electrode chambers.

5.9 Quality Assurance

The reproducibility of testing procedures and results were verified by conducting one replicate experiment for main EKS system with chemical stabilisers of CaCl-DW test for 7 days treatment time. The selected repetitions were based on the monitoring data presented in section 7.2.1 which showed fluctuation of the electric current at the beginning of the test until 3 days due to the electrolysis process which released of hydrogen ions and oxygen gas at the anode. After 3 days treatment, the current started to stabilise until the end of the test. Therefore, this replicate test can be comparable and represent the other tests so that the subjective judgement from the laboratory results could be drastically minimised.

Sample were prepared and conducted in the same manner and same procedures as described in Chapter 5. The results of this replicate test were presented in Chapter 7 for further discussion.

Additionally, to confirm that the test conditions were properly reproduced, the following precautions were taken into consideration:

a. New EKG electrode, Vyon sheet filter and filter paper were used after every experiment.

b. The tank experiment and some of the equipment used for physical and chemical tests (i.e. tools for Atterberg limit, vane shear, pH and conductivity measurements) were properly washed with tap water and when appropriate were immersed in 10% of nitric acid for one day. Lastly, it was rinsed with distilled water avoid cross contamination between the tests.

c. pH and conductivity meter were calibrated in accordance to user manual.

In the replicate test, all the physical and chemical measurements were taken as an average at three different depths (top, middle and bottom) for some of the sections across the soil sample as shown in Table (Chapter 7). This was conducted to validate the effect of soil depth and its variability on the physical and chemical properties of treated soils so as to compare the results with the other tests. Due to the design configuration of electrode was in sheet shape and cover the cross section of the soil sample, the electrical field distribution should be effective throughout the soil medium in the main compartment. Consequently, the physical and chemical results with depth should also be consistent and uniformed for every section. In addition, this design configuration of electrode can eliminate the development of ineffective areas which was normally occurred if electrode was installed in circular shape. At the same time, it can reduce the number of electrodes installed at anode and cathode.

5.10 Summary

This chapter highlights the sample setup for the main EKS tests in order to determine the physical and chemical behaviours of EKS system developed in this study. First phase of the testing was performed to assess the effects of pure system, in other means, no chemical stabiliser used at either electrode chamber, with only distilled water. This test was conducted to compare to the results from Liaki (2006) and also to make sure the electrokinetic stabilisation design and setup was working properly before any chemical stabilisers were added.

The second phase of the testing was conducted to assess the effects of certain ions (anion or cation) in the system when a continuously current was applied under constant voltage gradient for different times from 3, 7 and 14 days. However, distilled water was maintained at each chamber to eliminate the hydraulic gradient across the test cell (see Figure 5.1). This setup was designed in such way to be able to investigate the effectiveness of selected ion migration through soil either from anode or cathode chamber. The third and final phases of the testing were performed to assess the effects of anions and cations when simultaneously apply at both electrode chambers using electric current for 3, 7 and

14 days. In order to make sure the consistency and repeatability of the results obtained during this study, one test was repeated. The samples were also extracted randomly across the soil profile at different depths to check the boundary effect of laboratory testing that may affect the results of overall testing.

Chapter 6

RESULTS AND DISCUSSION OF PURE SYSTEM

6.1 Introduction

This chapter will present and discuss the results of EKS testing using distilled water only as the electrolytes at both electrodes. By providing a better understanding of the ‘pure’ relatively inert system, which has no chemicals introduced, this pure system will provide a baseline to assess the effectiveness of the EKS approach when applied to soft compressible soils.

6.2 Monitoring Data

During the main experimental programme, the electric current and the voltage were monitored continuously until the end of each test. A voltage of 18.25 V was maintained throughout the test, equating to a voltage gradient of 50 V/m. The pH and the electrical conductivity of the electrolytes were also monitored during the electrokinetic. The electrolyte solutions were extracted from both electrolyte compartments for pH and electrical conductivity over the respected time intervals as described in Chapter 5.

6.2.1 Electric Current

Figure 6.1 shows monitoring of electric current for 3, 7 and 14 days of DW-DW system. It has observed that electric current of those 3 different periods shows similar trend except for 14 days treatment period which has lower value of about 9 mA at the beginning of test, compared with 3 days and 7 days treatment periods which with values of 12 and 13 mA, respectively.

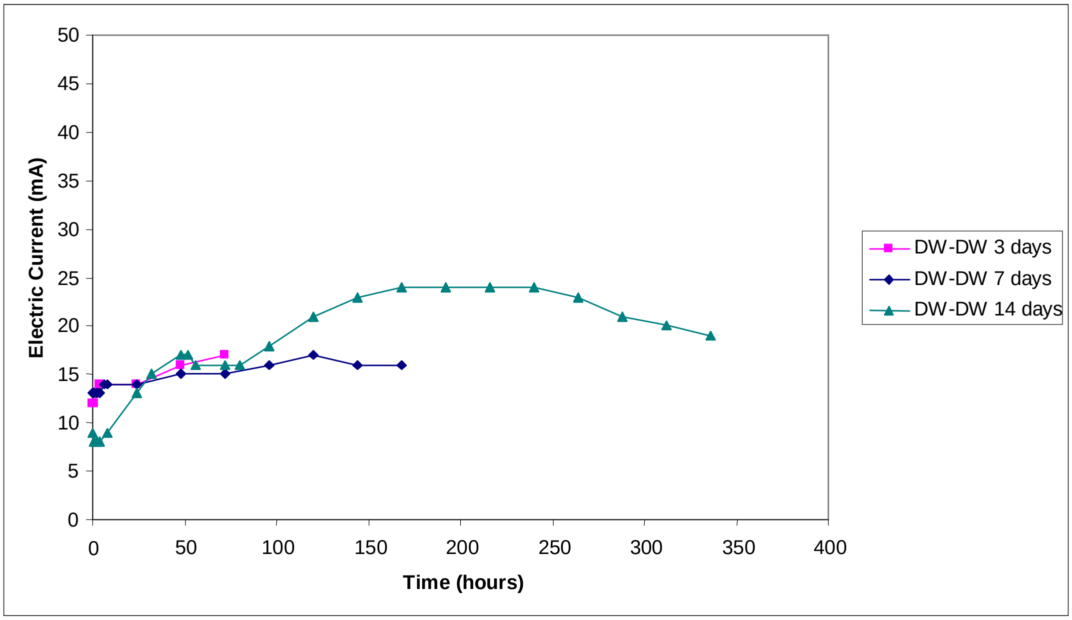


Figure 6.1: Electric Current of DW-DW system with time.

After 24 hours duration of EKS testing, the electric current values for 3, 7 and 14 days treatment periods were reached at about 13 to 14 mA. The value of electric current maintained at these values until 96 hours for both 7 days and 14 days tests whereas the 3 days test was stopped at 72 hours. However, after 96 hours for the 14 days test current rose, peaking at around 170 hours at 24 mA before dropping over the last 4 days (after 10 days) to a value of 19 mA (see Figure 6.1). The current trend in this pure system was attributed to the electrochemical effects in the clay-water electrolyte system which varied across the samples with time, thus affected the current profiles during tests.

The electric current variations with treatment time for the same type of electrode are comparable with Liaki (2006) as seen in Figure 6.2 who reported that the electric current initially increase at about 14 mA, while it then drops within the first 100 hours of treatment, as resistance of the materials increases and the voltage was set at the constant level. It has observed in Figure 6.2 that a large variation of electric current distribution is reported especially at the beginning of the test with different treatment time (varied from 14 to 22 mA) compared to the current research (varied from 9 to 14 mA). This was due to the soil electrode contact which varied and not consistent upon insertion of electrode during sample preparation prior to EKS test as observed by the author in Liaki (2006) study. Therefore, the improvement of the procedures and design configuration made for the current research (see section 5.9) has overcome the problem related to the soil-electrode interfaces during soil preparation. It should be note that after consolidation thin solid plastic walls were removed at both end of soil compartment and the gaps left were then inserted by the EKG electrodes. In order to make sure a good contact between soils and electrodes during sample preparation, the soil samples were subjected to load under the same loading of the last consolidation for about 24 hours before electric current were turned on.

In term of performance of the experiment and quality assurance, the monitoring data of electric current and volume of effluent can give indirect measurement of the efficiency of the system during EK treatment. This also gives indication of the cost of operation, i.e. an increase in electrical resistance results in higher energy expenditure. The electric current varied in time depending upon the changes in the electrical conductivity of the soil.

According to Alshawabkeh & Sheahan (2003), the increase in electric current is due to the effect of electrolysis on the anolyte and catholyte to release ion hydrogens and hydroxides, respectively, and addition of chemical solution at the electrodes in the first 24 hours. However, after 24 hours, the electrical current trends seem to decrease with time due to the precipitation, thus decreasing the ionic content and the electrical conductivity of the soil. In addition, the decrease in electric current is attributed to the soil-electrode interface resulting in voltage drop as reported by Rittirong *et al.* (2008). Similarly, Liaki (2006) has stated that the variation of current throughout the test is due to contact between soil and electrode interface as shown in Figure 6.2.

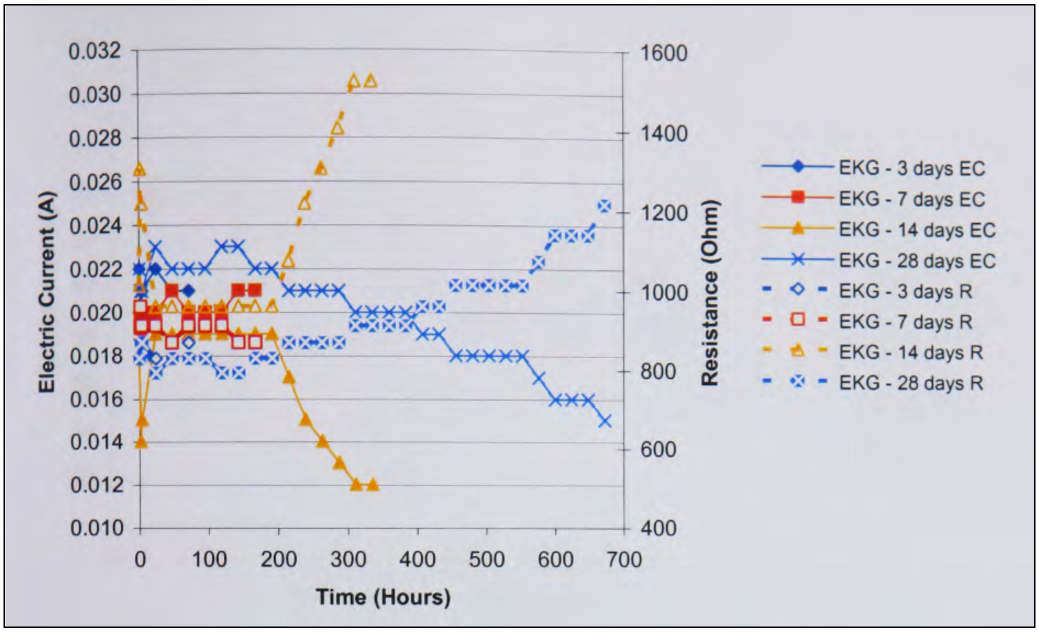


Figure 6.2: Distribution of electric current and resistance with time (Liaki, 2006).

6.2.2 pH of Electrolytes

The pH values of anolytes for 3, 7 and 14 days started between pH 6.8 and 7.2 as shown in Figure 6.3. For 3 and 7 days tests the pH values increased steadily until the end of the test. However, it would be expected that this trend should be decreased as shown in the graph for 14 days test after approximately 120 hours (5 days) from pH 6.8 until pH 5.1. Theoretically, applying electric current would be expected to produce hydrogen ions from electrolysis process producing an acidic environment around the anode (see Chapter 2 section 2.10 for further details). However, due to the direction of movement of hydrogen ions toward the cathode, the pH of anolyte inside the small compartment changed at a relatively slow rate. In addition, the EKG electrodes were placed inside the main compartments, which have direct contact with soil via a perforated wall and plastic filter that separated both compartments. Some researchers (e.g. Ahmad, *et al.*, 2011; Ozkan *et* *al.*, 1999; Alshawabkeh & Sheahan, 2003) inserted the electrodes inside the electrolyte compartments to allow the gas generated on the electrodes to escape from the system and to maintain the contact between electrodes and soils. However, this setup was design in such a way to be more realistic to any potential field application.

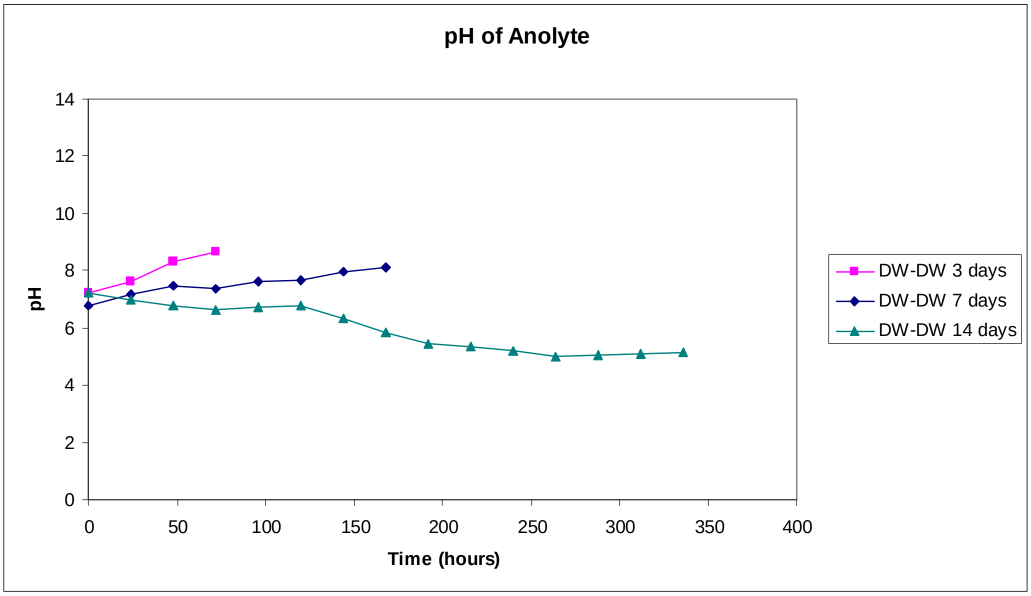


Figure 6.3: pH of anolyte for DW-DW system with time.

The pH values of catholyte in Figure 6.4 increased with time for 3, 7 and 14 days from approximately pH 7 to about pH 12. These values remained constant until the current was stopped after 14 days treatment. This trend was expected due to the electrolysis process around the cathode that produces hydroxide ions (see Chapter 2 section 2.10 for further details). In contrast with pH values of anolyte, the pH values of catholyte changed quite significantly due to flow of water, which carried some of the hydroxide ions into the catholyte compartment. Even though, the movement of hydroxide ions are toward the anode, the water flow cause by electroosmosis and electromigration of cations (coupled flow) retards the movement of anions by electromigration, thus this suggests that the net movement was towards the catholyte compartment which contributes to the changes of pH of catholytes.

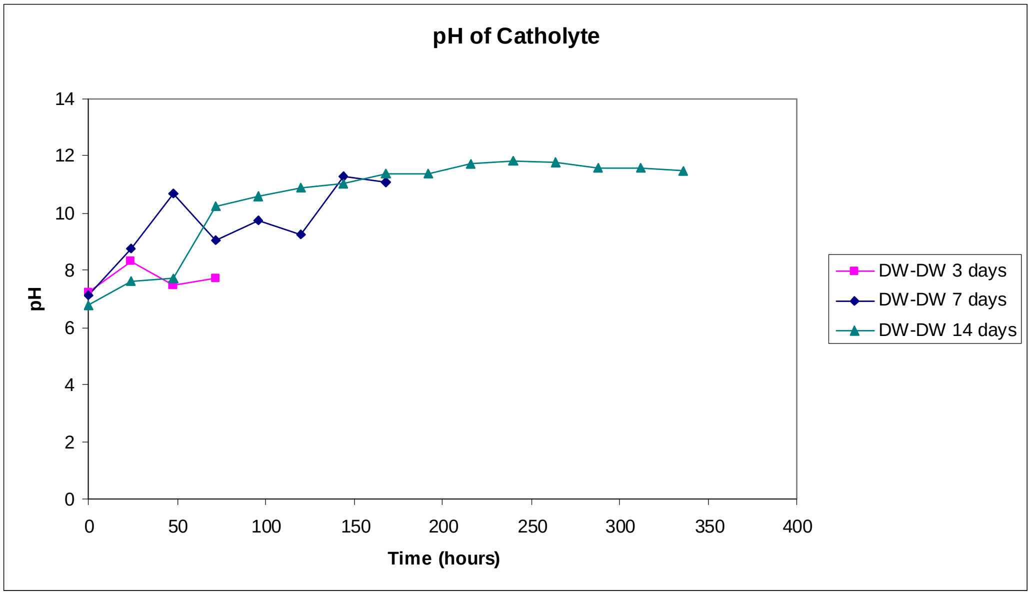


Figure 6.4: pH of catholyte for DW-DW system with time.

The pH variations with time for anolyte and catholyte have similar trend as reported by Liaki (2006) as shown in Figure 6.5 and 6.6 due to improvement made as discussed in section 6.2.1. The pH results reported by Liaki (2006) showed a large variation of pH value for anolyte and catholyte as shown Figure 6.5 and Figure 6.6, respectively especially at the beginning of the test (within 24 hours), thus affecting the variation of electric current as well (see Figure 6.2).

It should be noted that, even though, the improvement of soil-electrode interface have been solved during soil preparation that could affect the variability of the results in Liaki (2006), the problem of soil-electrode contact still happening due to the electrolysis process which generated oxygen and hydrogen around the soil-electrode interface during EK treatment. Therefore, some researchers have placed the electrode inside the electrolyte compartment to counter this issue. The implication of the electrode placement in practical aspects and its effect on overall performance to treat problematic soils needs further investigation.

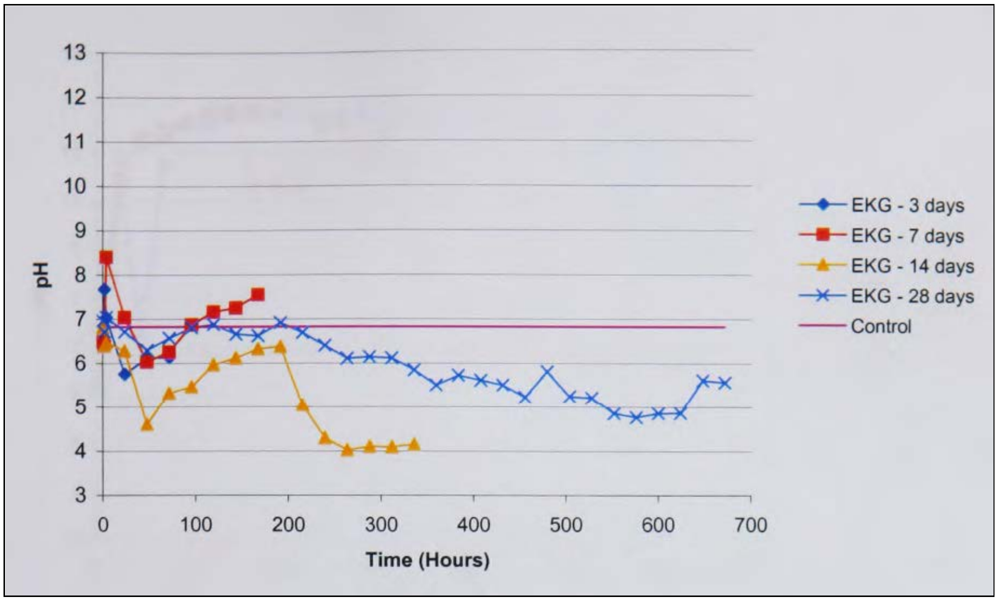


Figure 6.5: pH of anolyte for DW-DW system with time (Liaki, 2006).

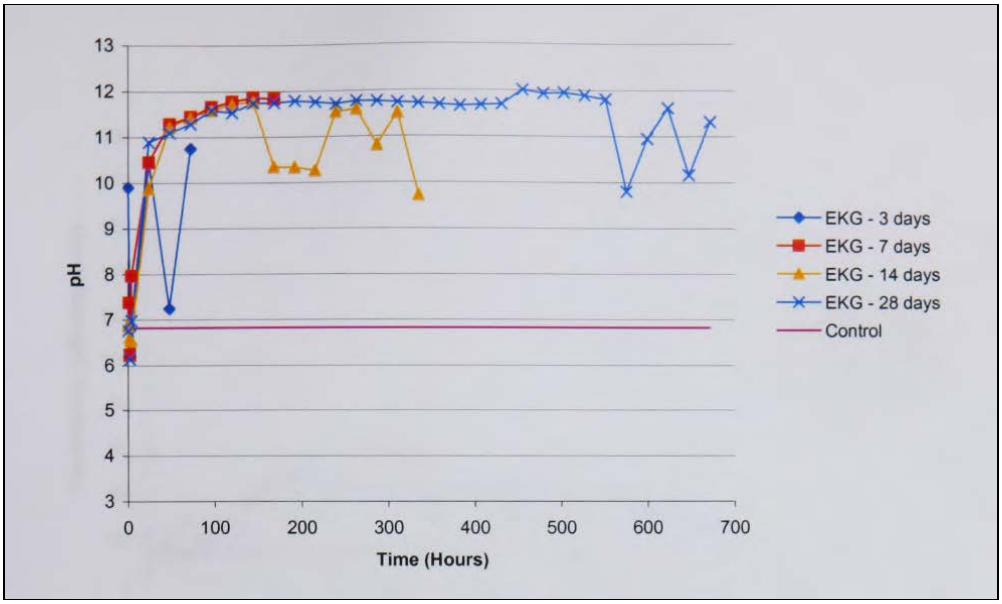


Figure 6.6: pH of catholyte for DW-DW system with time (Liaki, 2006).

6.2.3 Electrical Conductivity of Electrolytes

The electrical conductivity of anolyte shows in Figure 6.7 increased slightly from 10 S/cm to maximum value of 63.6 S/cm at 240 hours (10 days) then dropped significantly to 24.4 S/cm.

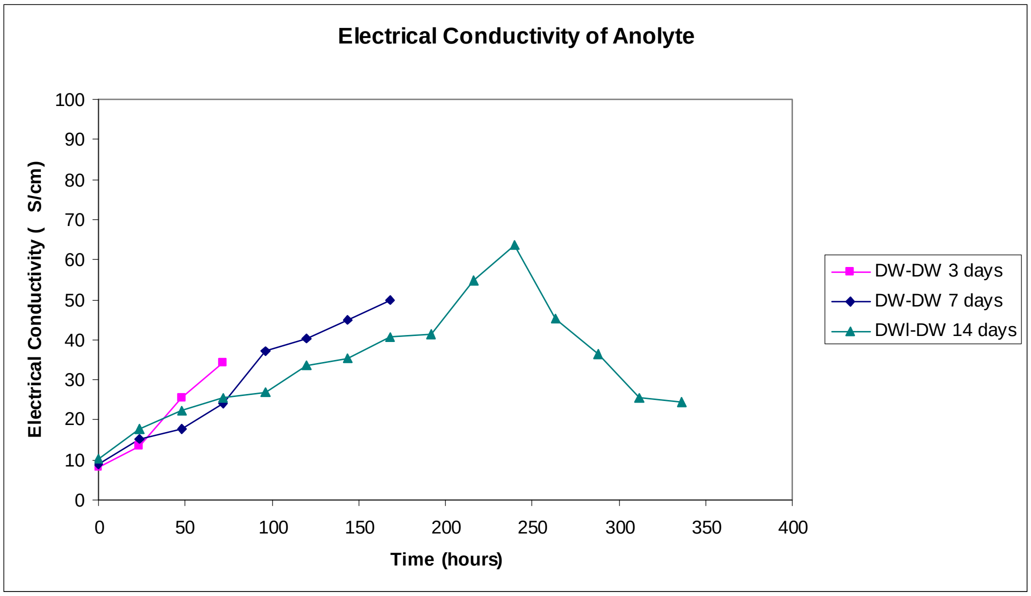


Figure 6.7: Electrical conductivity of anolyte for DW-DW system with time.

As seen in Figure 6.8**,** the electrical conductivity values of catholyte also show similar trend as anolyte but increased steadily from less than 50 S/cm to maximum value of 784 S/cm at 264 hours (11 days) and then decreased significantly to 367 S/cm. This trend was consistently seen for all 3 sets of test duration. These results indicate significant ion movement from the soil samples into the anolytes compartment during the test which contributes an increase in electrical conductivity of anolyte. While, the migration of ions from the soil samples into the catholyte compartment also contributes to this trend. In addition, this values also correspond and complicated with the chemical reactions occurred at both electrodes such as electrolysis than change the pore fluid chemistry within the soil structure.

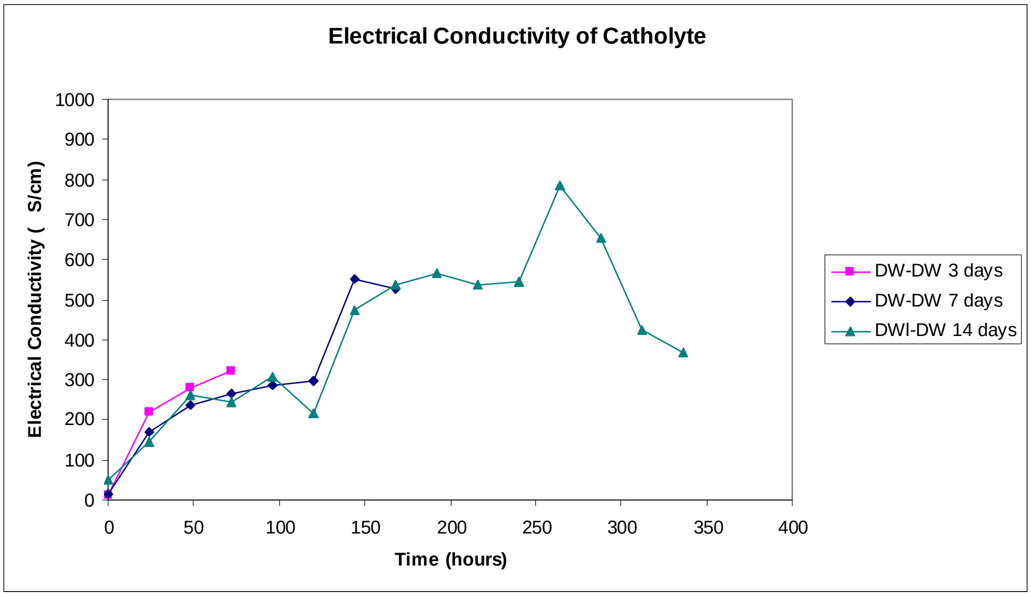


Figure 6.8: Electrical conductivity of catholyte for DW-DW system with time.

In overall, the electrical conductivity values of catholyte are higher than of the values of anolytes which indicates the migration of ions towards the cathode are more dominant rather than the opposite direction. This is attributed to the coupled flow of electroosmosis and electromigration in that direction. This trend is consistent with the results conducted by Liaki (2006) as observed in Figure 6.9 and Figure 6.10.

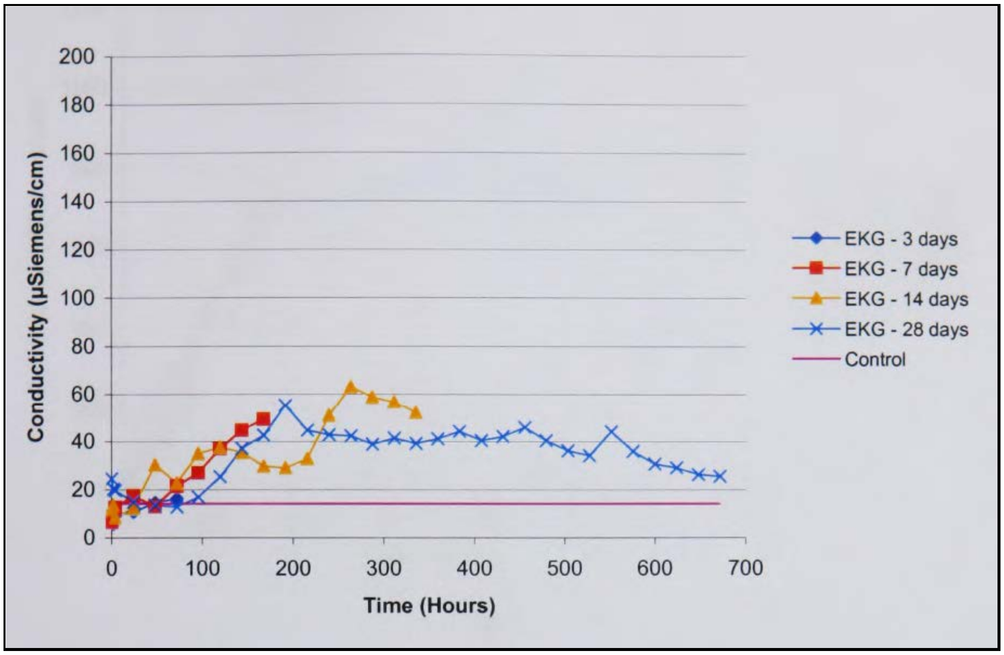


Figure 6.9: Electrical conductivity of anolyte for DW-DW system with time (Liaki, 2006).

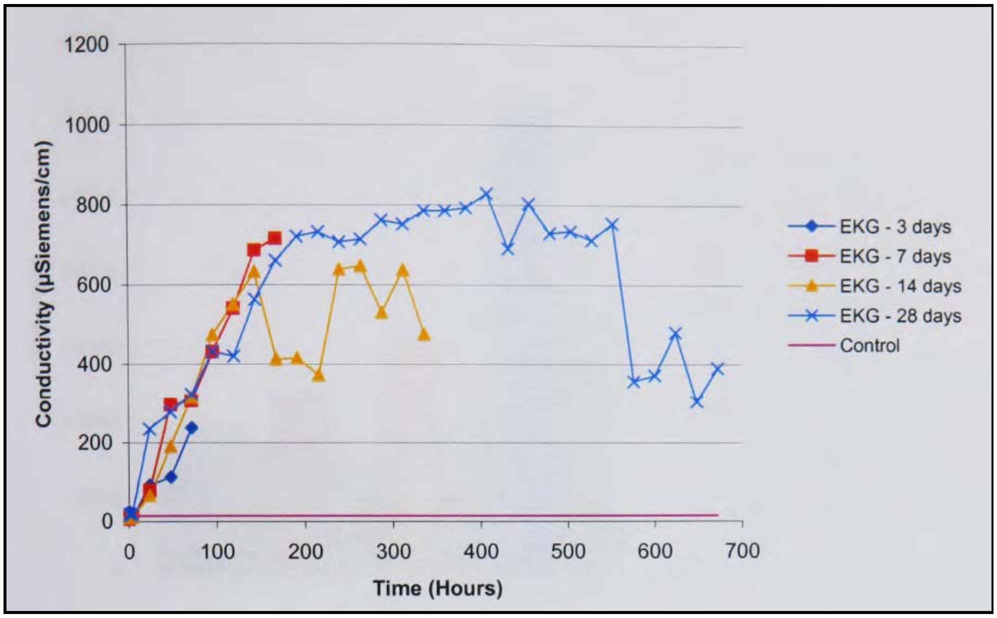


Figure 6.10: Electrical conductivity of catholyte for DW-DW system with time (Liaki, 2006).

6.2.4 Inflow and Outflow

Amount of water entering the system (inflow) and leaving the system (outflow) were monitored continuously to check the efficiency and the balance of the system. This was done by checking whether data points or the amount of inflow and outflow show similar trend between these curves in Figure 6.11. The amount of inflow and outflow should be the same throughout the testing provided the electrokinetic setup is a closed geometry allowing water to enter at the anode and leaving at cathode only. However, due to the open geometry of this setup it was no surprised that amount of inflow and the outflow were not the same during electrokinetic treatment as shown in Figure 6.11. During the test it was observed that after certain time water escaped between soil and electrode at the cathode as seen in Figure 6.12. Gas bubbles were noticed when water started to flow out through the electrode resulting from electrolysis that produces hydrogen gas at the cathode area. After 3 days, soil erosion occurred on the surface between the soil electrode interfaces affecting the efficiency of the system due to the placement of electrode directly into the wet soil as discussed earlier in section 6.2.2. However, there was no further soil erosion has been seen after 7 and 14 days.

It was clear that the decrease of the current as discussed in section 6.2.1 was attributed the increase of the resistance at the soil electrode interfaces as confirmer from these results. This resulted in voltage drop at the soil electrode interfaces as also reported by other research (Mohamedelhassan & Shang, 2001: Rittirong *et al.*, 2008). Therefore, the accumulation of gas increases the electrical resistance of the system hence decreases the treatment efficiency.

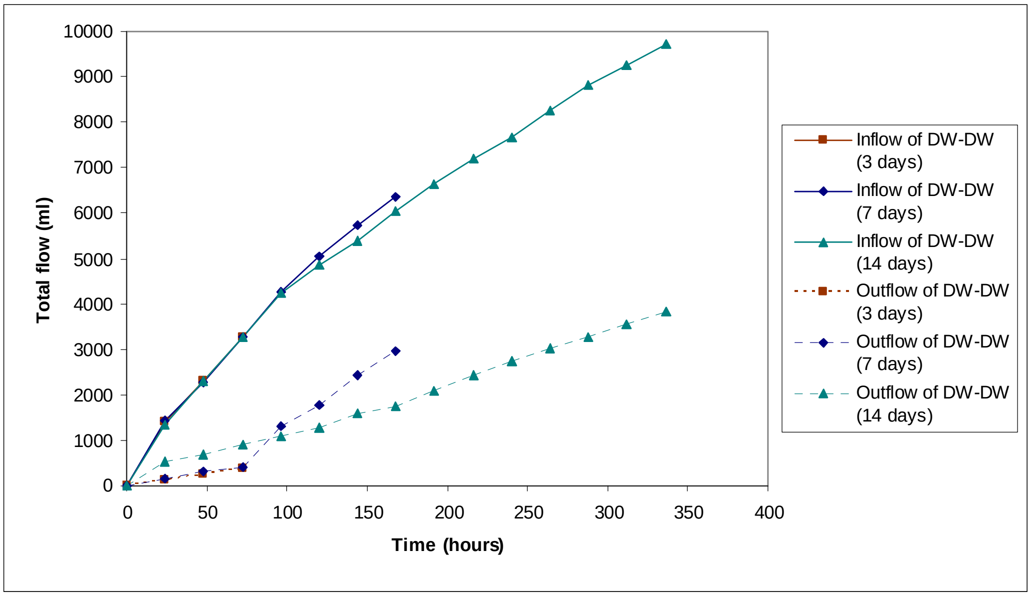


Figure 6.11: Inflow and outflow of DW-DW system with time.

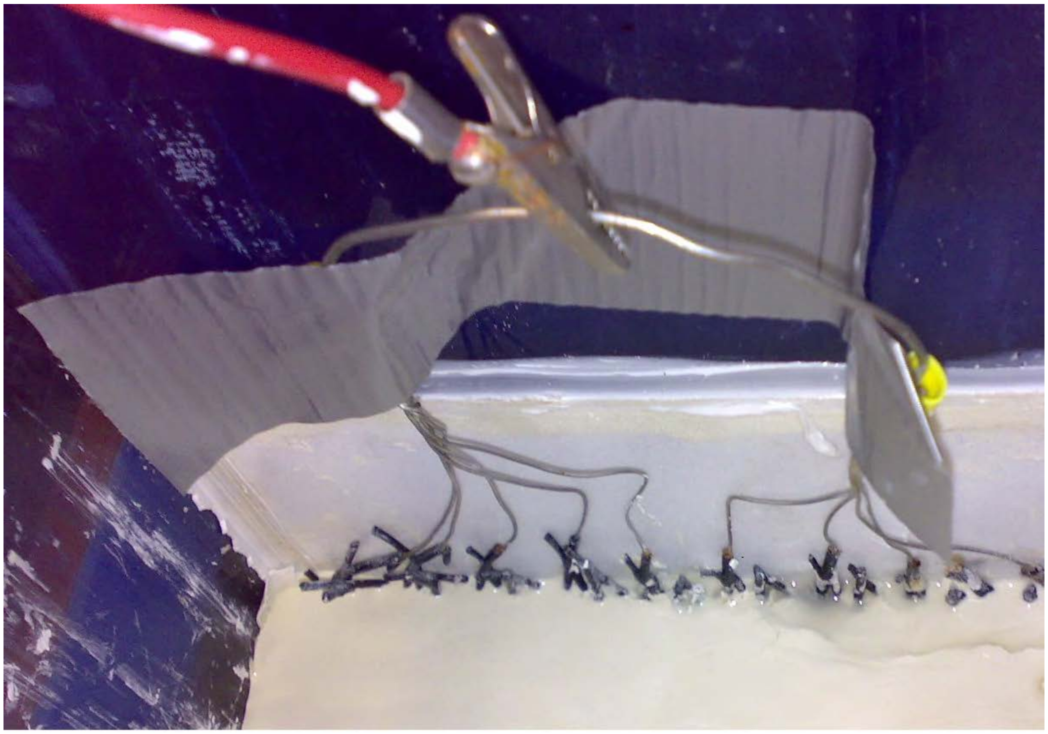


Figure 6.12: Picture of soil electrode interface at the cathode after 3 days during EKS testing.

6.3 Results of Physical Testing After EKS Treatment

6.3.1 Water Content

The variations of soil water content across the soil sample are illustrated in Figure 6.13 for all treatment periods. With respect to distance from the anode towards the cathode, the water content values for 3 days test near the anode (at 25 and 70 mm from the anode) are gradually increase, starting below the control value of 51 %. At the mid-point of the sample are constant at 52% then drop close to the control value at the cathode area (at 340 mm from the anode). For 7 days test period, all the water content values across the soil sample were at a constant value that of the control value. As for 14 days, the values across the soil were above the control value except near the cathode. The values towards the cathode increase gradually from 51.8 % to a maximum value of 55.4 %.

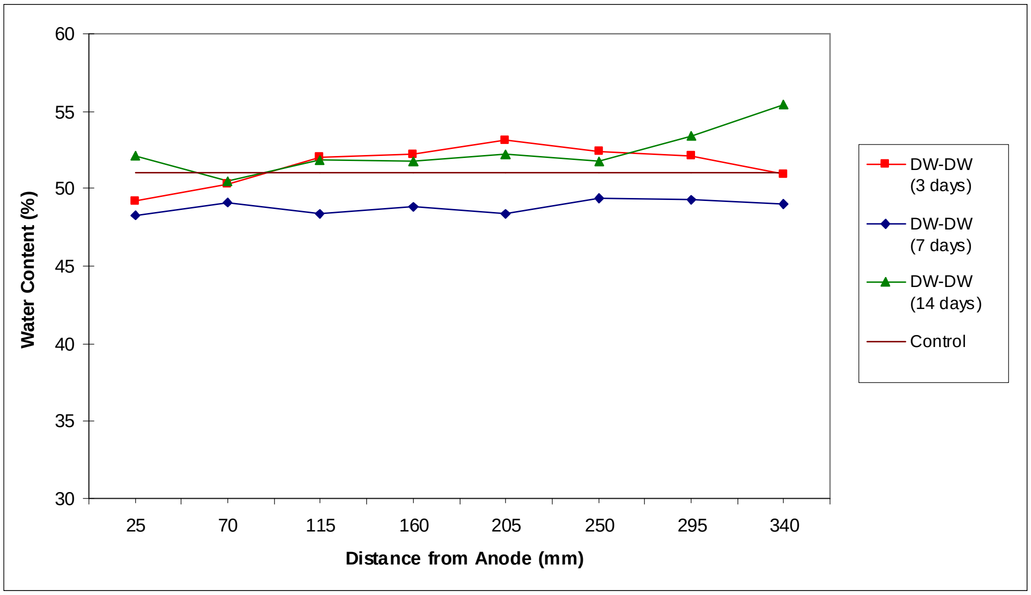


Figure 6.13: Water content of DW-DW system with distance from anode.

With respect to the treatment period, this shows no clear trend with variations of water content values. However, there were significant changes of water content near the anode and the cathode. This was probably due the contact between electrode and the soil caused by the electrolysis process that produce gases at both electrodes as discussed earlier (see section 6.2). In addition, the open anode and cathode configuration allowing water enter at the anode and leaving at the cathode may have caused fluctuation of the soil water content around the boundary areas.

In general, the variations of water content along the soil profiles of pure system do not show any significant trend due to movement of water triggered by the electroosmosis process from anode towards cathode. In addition, the continuous supply of distilled water at the anode may cause variation of the water content in respect of distance or treatment period. According to Ahmad *et al.* (2011) and (Liaki *et al*., 2008) for open anode and cathode configuration, their results showed high water content at both ends of the samples because of the swelling effect due to the direct contact of the soil with the electrolytes. Therefore, it can be concluded that variation of water contents of current study is comparable to those previous studies when open anode and cathode was adopted as seen at dotted line in Figure 6.14 as reported by (Liaki *et al.*, 2008) and Figure 6.15 as reported by Ahmad *et al.* (2011) when using distilled water only at both electrodes.

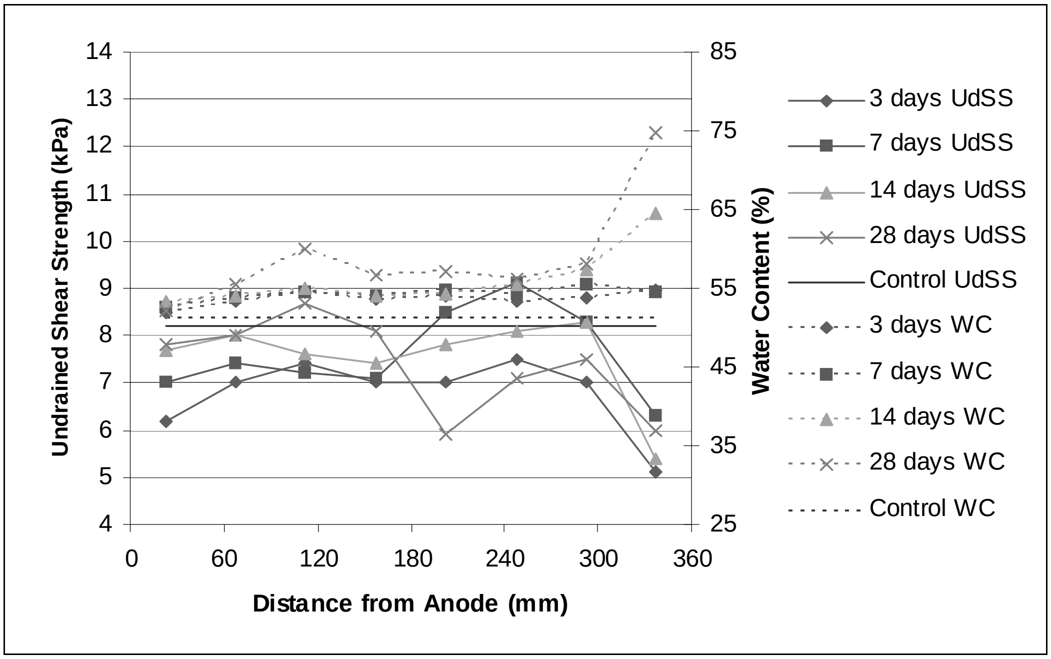


Figure 6.14: Variation of water content and undrained shear strength with distance from anode (Liaki *et al.*, 2008).

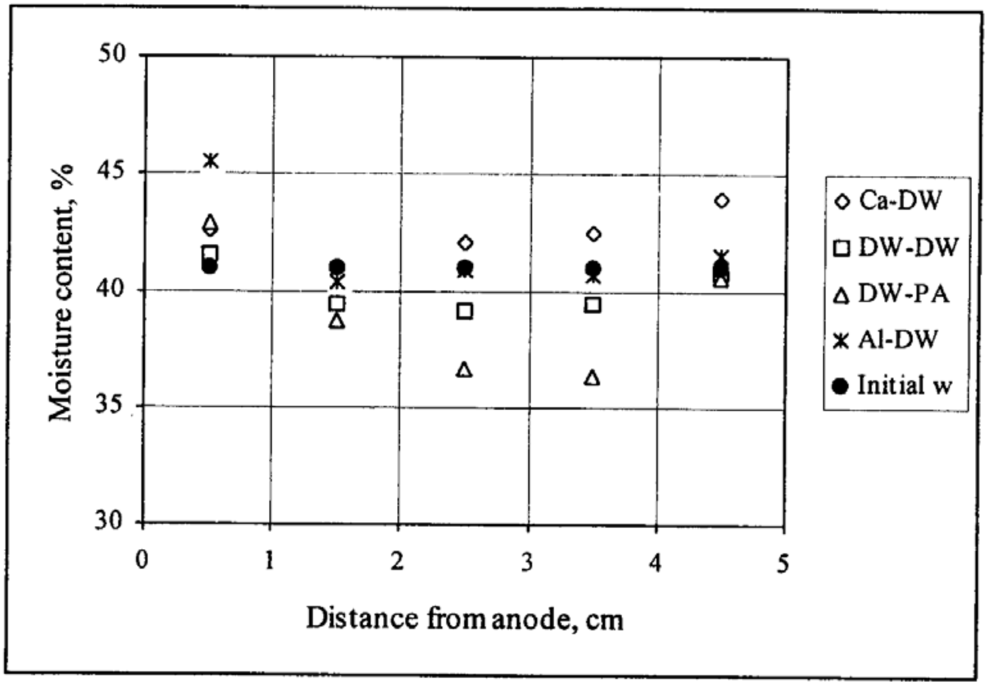


Figure 6.15: Water content at different segments of EK treated samples (Ahmad *et al.*, 2011).

6.3.2 Shear Strength

The data plots of undrained shear strength versus distance from anode in Figure 6.16 show the undrained shear strength values of 3 and 7 days tests are uniform along the soil where the 14 days was varied. Most of the undrained shear strength values for 3 and 14 days tests were below the control value (8.2 kPa). In contrast, all the undrained shear strength values of 7 days test were above the control value. The undrained shear strength values of 3 days test were in the range between 5.3 and 6.0 kPa, whereas for the 7 days test were in the range between 10.0 and 11.5 kPa. Considering the low margin of undrained shear strength value which was ± 1.5 kPa, the undrained shear strength of 3 and 7 days tests were not considered not to have changed significantly, especially considering their determination by vane shear and its relatively insensitivity to such changes. However, the values are varied in the 14 days test which is in the range between 5.3 and 8.5 kPa.

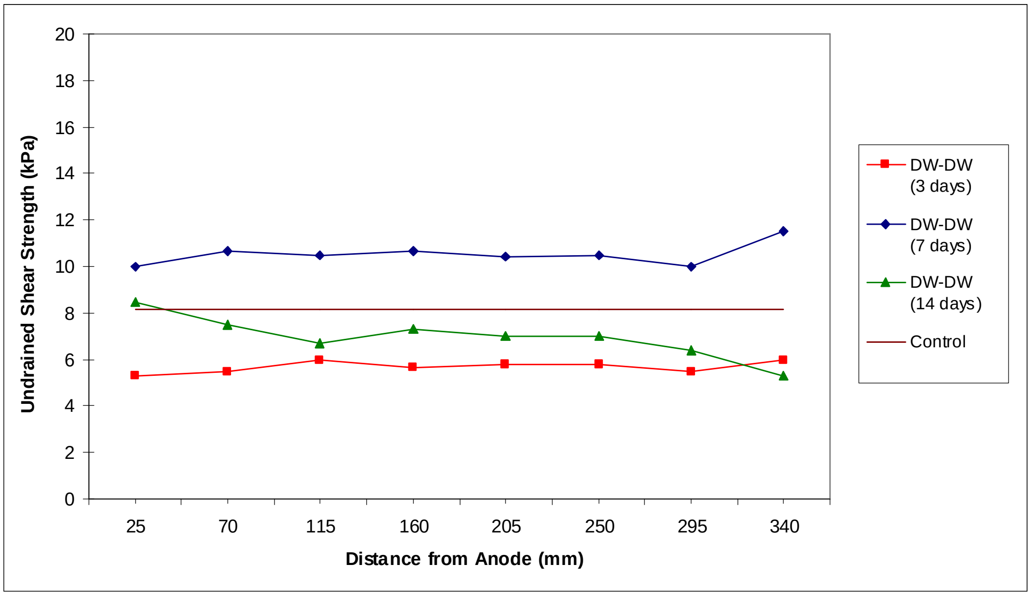


Figure 6.16: Undrained shear strength of DW-DW system with distance from anode.

In Figure 6.16, it can be observed that the undrained shear strength results depend on the result of the water content as seen in Figure 6.13 as expected. This trend was similar with Liaki (2006) as seen in Figure 6.14 who reported that the changes of the shear strength attributed to the changes of water content and electrochemical effects.

In order to determine whether the application of EKS method results are caused by electrochemical processes and are not caused by the variation of water content, the relationship between undrained shear strength and variation of water content was performed using the same preparation samples as falling head test method as seen in Figure 4.4(a). In this test, the sample preparation is similar as described in Chapter 5, section 5.3 but using cylinder cell instead of rectangular tank for main test. However, the final water contents were varied to know the effect of water contents with soil shear strength so the graph could be plotted as shown in 6.17 and represent as a control line. The slurry samples were consolidated after reached the target final water content in 100 diameter and 200 mm long cell and the hand vane shear test was performed. The hand vane shear were performed after each different water contents at 3 different locations with depth and plotted in the graph relationship of water content and shear strength. It should be noted the preparation of this using similar sample preparation as the main experimental programme for comparison purpose and eliminated the variability of the results caused by different sample preparation, e.g. using consolidation method. The results of this relationship were then plotted in Figure 6.17 combining the control line together with the EKS results of DW-DW system. The data points located above the control or shifted to the right of the control line indicates an area of soil strengthening, whereas the data points located below the control line or shifted to the left of the control line indicates an area of soil weakening.

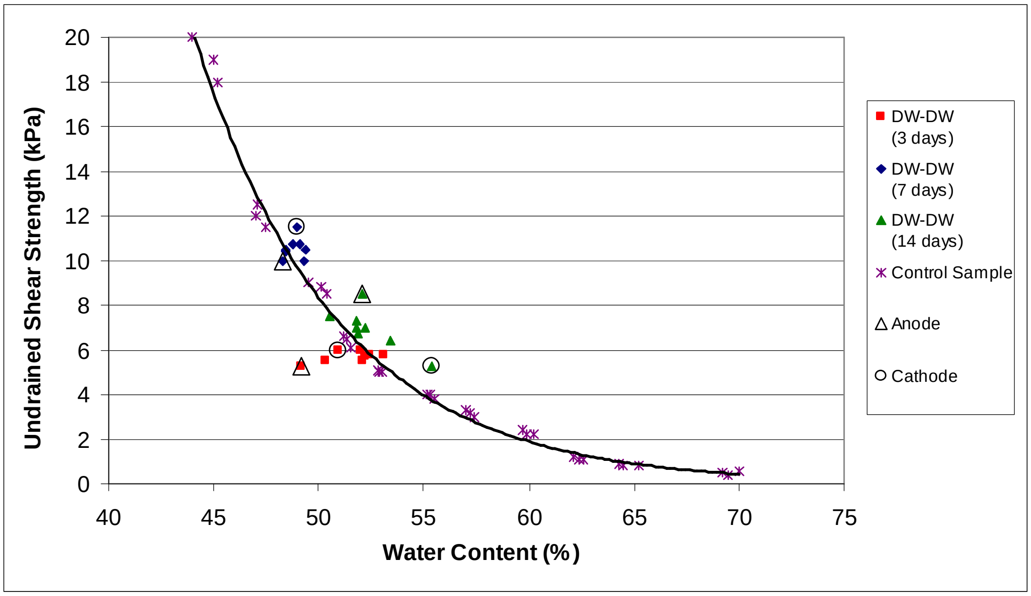


Figure 6.17: Relationship between undrained shear strength and water content of DW-DW system.

In general as seen in Figure 6.17, most of data points for DW-DW for 3, 7 and 14 days treatments lie essentially along the control line except for a few data points near to the anodes and cathodes. This was due to the electrochemical reactions taking place at the anode and the cathode that caused the changes of acid or alkaline environment respectively. Thus, results in soil strengthening or weakening during electrokinetic treatment.

It can be seen that the data points near the anode and the cathode for 3 days test shift away below control line, whilst the remainder of the data do not change much. The soil weakening for this short term duration test near the anode can be attributed to electrolysis of water generated oxygen gas that causes cavitations. While, hydrogen gas generation at the cathode may contribute to the soil weakening. Since only distilled water was supplied at both electrodes, therefore no higher valence ions to replace the lower valence ions into system are present and only hydrogen ions and hydroxide ions were released from electrolysis product. Small changes of pH values near the anode from pH 5.1 to pH 4.8 and at the cathode from pH 5.1 to pH 5.3 (see Figure 6.24) indicate that the electrolysis of water was still in the early stage and limiting the contribution to significantly increasing the soil shear strength near both electrodes. During the early stages of the treatment, there was not much release of hydrogen ions and hydroxide ions from electrolysis of water to change the pH environment near both electrodes. This also can be confirmed from the results of monitoring data as shown in Figure 6.3 and Figure 6.4, where the pH values of those anolyte and catholyte were increased in a small increment from pH 7 to 7.5 for anolyte (± 0.5 pH) and pH 7 to 8.5 (± 1.5 pH) for catholyte in 24 hours duration. A small variation of pH value in those electrolyte compartments were expected due to introduction of distilled water only at both electrodes. The effect of chemical stabilisers on the physical and chemical properties after treatment will be discussed later in Chapter 7.

Test for 7 days shows that the data points close to the anode are lie slightly below the control line whilst the rest of the values toward the cathode are slightly shifted away, above the control line. This shows that the values increasing towards the cathode due to the electrochemical processes that change the soil properties after certain time which in this case was over 7 days treatment period. At the anode, even though the data point was slightly away from the control line, there was sign of improvement when compared with the data points of the 3 days test near the anode; these had shifted further away from the control line. At the cathode, the data point of 7 days test (340 mm from the anode) shows the greatest improvement. This can be explained by electromigration process cause the positive ions (from the soil itself) migrating towards the cathode and then precipitated when the alkaline environment starts to develop at the cathode (see section 2.9.3 in Chapter 2). This was supported by the pH results for 7 days test with the pH value at the cathode changing to a ph of 7.4 creating an alkaline environment near the cathode (see Figure 6.24). It also suggests that hydroxide ions release from electrolysis product may react with cations within the pore fluid to form metal hydroxide gels, thus change the soil properties near the cathode. Precipitation normally occurs in an alkaline environment to form a cementing compound that bind soil particles together resulted in soil strengthening. According to Asavorndeja & Glawe (2005), precipitation happens when pH values rise above pH 7. In this case the migration of hydrogen ions across the soil may change the pH at the cathode.

Data points for DW-DW for 14 days treatment also show similar trends as 7 days treatment except for data points in the proximity of anode. According to Liaki *et al.* (2008), the data points in the proximity of the anode shifted away, above the control line (see Figure 6.18) due to the establishment of physical mechanism under acidic environment, thus changes the soil structure and the arrangement of the clay fabric. Since no cations such as calcium or iron were introduced into the system, therefore the abundance of hydrogen ions were caused the changes of the pore fluid in clay-water electrolyte system which results in changes of soil structure of the soil. This was supported by the pH values at the anode which decreased from pH 5.5 to pH 3.72 to form acidic environment (see Figure 6.23).

Therefore, the use of distilled water as an electrolyte will not affect the soil shear strength for short term duration but in fact caused soil weakening at the anode area for 3 days test. The shear strength show significant change for longer term duration as demonstrated by the 14 days test. The trend was similar with the results from (Liaki *et al.*, 2008) for the 3, 7 and 14 days tests as seen in Figure 6.18. However, the 28 days of treatment period conducted by (Liaki *et al.*, 2008) has significantly increased the soil shear strength at the cathode but did not much change at the remainder of the samples.

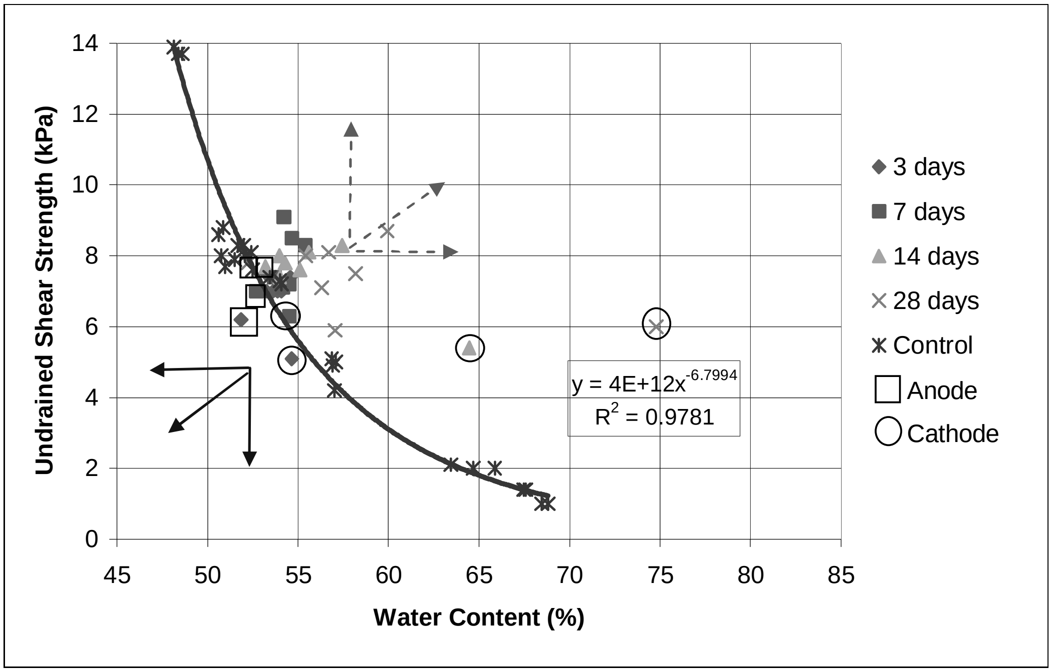


Figure 6.18: Relationship between undrained shear strength and water content of DW-DW system (Liaki *et al.*, 2008).

6.3.3 Liquid Limit

Figure 6.19 shows the variation of liquid limit from anode to cathode at different treatment periods. All plots show data cross the control line value which indicating that the liquid limit increased steadily from the lower value to the higher values of liquid limit from anode to cathode. The liquid limit values at the vicinity anode (25 mm away from anode) for all test periods decreased to between 53.3 and 54.5 %. However, near the cathode the liquid limit values increased steadily above that of the control value (55.6 %) except for 3 day test which was still remained at the control value. The highest value of 62.4 % was recorded near the cathode (340 mm away from anode) for 7 days test.

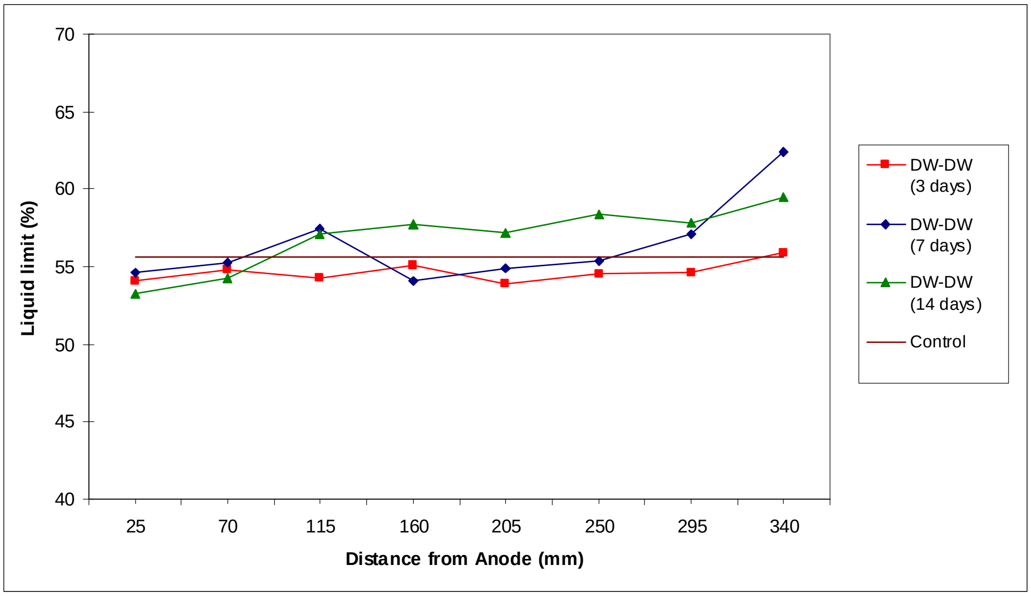


Figure 6.19: Liquid limit of DW-DW system with distance from anode.

The liquid limit values decreased at the vicinity of anode and increased at the vicinity of cathode. This trend shows that there is significant change of the soil properties after EKS treatment using distilled water even though some results from the shear strength in Figure 6.17 for short term test not shows any significant change after electrokinetic stabilisation process. This is probably due to insensitivity of vane shear test used on the higher soil water content. Therefore, the liquid limit test can show any small changes happened in the soil behaviour caused by electrokinetic stabilisation, and provide a useful tool to assess any potential changes. In contrast, the results from Liaki *et. al.* (2008) using an EKG electrode showed an increase of liquid limit at the anode than of the control value and start to decrease at the cathode area as seen in Figure 6.20. There was no relationship between liquid limit and shear strength reported by Liaki *et. al.* (2008) to explain such phenomena. In other hand, the Fe ion had migrated towards cathode and then precipitated as $Fe(OH)_2$ under high alkaline environment, resulted in significant decrease in liquid limit at the cathode area. This was also contradicted with the other researchers (Ozkan, *et al.*, 1999; Asavadorndeja & Glawe, 2005; Jayasekara & Hall, 2006), who reported that the precipitation at the cathode have resulted an increase in liquid limit at the cathode area.

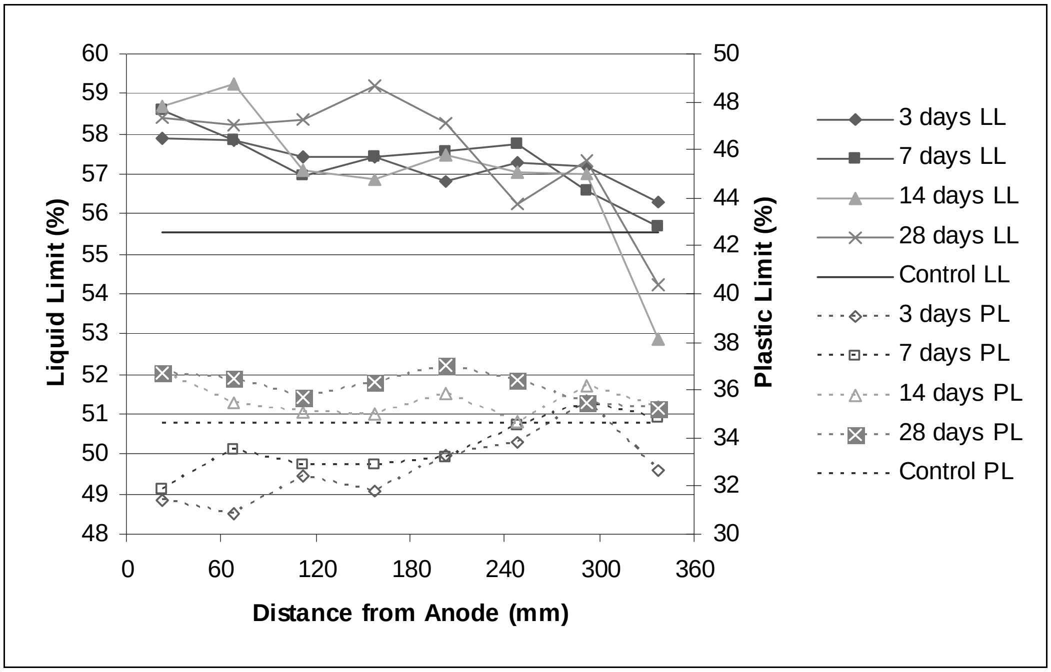


Figure 6.20: Variation of Atterberg limits with distance from anode (Liaki *et. al.*, 2008).

6.3.4 Plastic Limit

Figure 6.21 illustrates the variation of plastic limit from anode to cathode at different treatment period. The plot of plastic limit results shows a similar trend as that demonstrated by the liquid limit results as seen in Figure 6.19. However, all test periods show gained in shear strength near the cathode when compared to the liquid limit result of 7 days test, which has remained at control value. Near the anode, the plastic limit values decreased away from control value (34.6%) which is in the range between 31.2 and 33.7 %. The lowest value of plastic limit is recorded at 31.2 % near the cathode for 7 day test, whereas the highest plastic limit value is recorded at 39.2 % near the cathode.

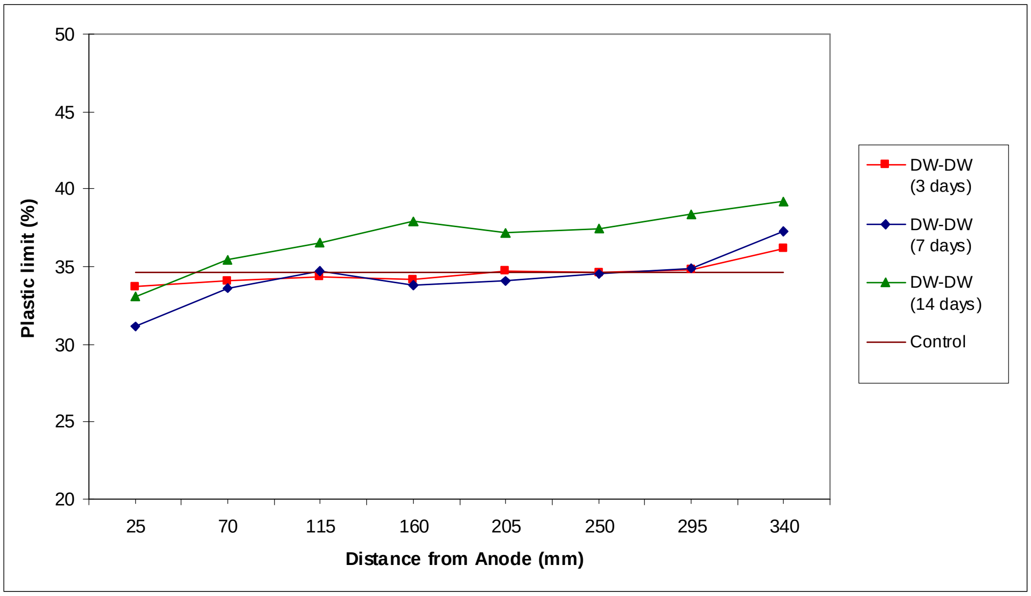


Figure 6.21: Plastic limit of DW-DW system with distance from anode.

As will be discussed later (see Chapter 8) and described earlier from the results of liquid limits (see section 6.3.3), this phenomena happened in the proximity of both electrodes and was caused by physicochemical reactions of electrokinetic stabilisation processes. Thus, there is a clear need to compare the results of physical and chemical properties to validate this phenomenon. However, Liaki *et al.* (2008) has reported that the results of plastic limits have a large variation of across the soil samples and with regards to treatment periods (see Figure 6.20).

For the 3 and 7 days test, there was a large reduction of plastic limit values at the anode than of the control value and increased towards the cathode and showed slightly increased in plastic limit at the cathode area than of the control value. In contrast, for the 14 and 28 days test, there was opposite trend than of the 3 and 7 days test. It was suggested that the changes of pH across the soil samples and with time has resulted in such a large variation in the plastic limit.

6.3.5 Plasticity Index

Figure 6.22 shows the variation plasticity index values of DW-DW system plot against distance from anode. The values increase significantly near the anode and cathode areas for 7 days test while decrease slightly across the soil samples when compared with control value (21 %) for 3 and 14 days tests. The plasticity index values were reflected to the liquid limit and plastic limit values as discussed earlier in section 6.3.3 and 6.3.4 due to the electrochemical effects under influence of electric current which resulted in a large pH gradient across the soil profiles. However, there were no results of plasticity index values presented and discussed by Liaki *et al.* (2008) for comparison with the current research.

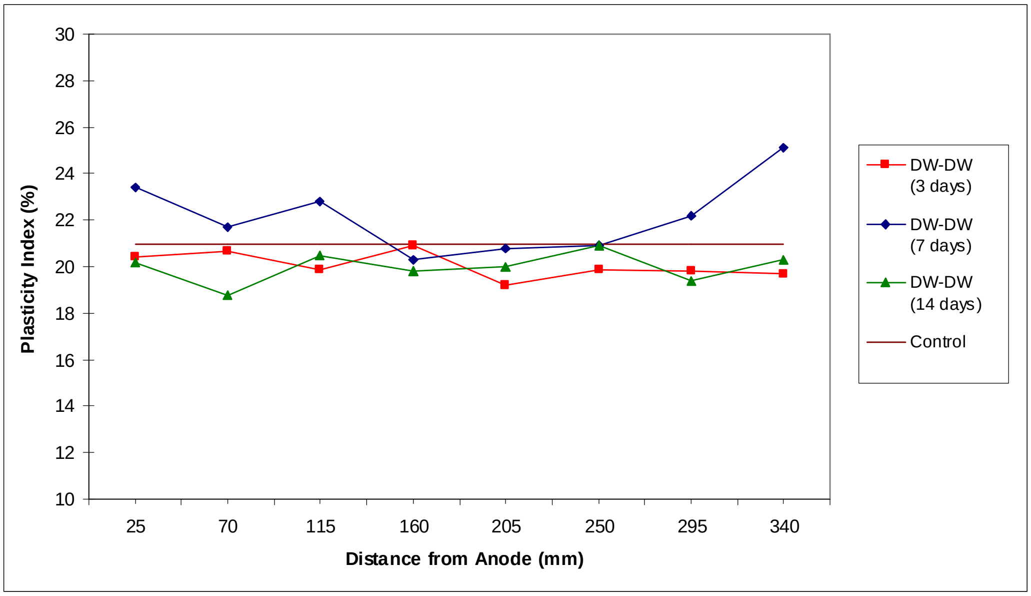


Figure 6.22: Plasticity index of DW-DW system with distance from anode.

6.4 Results of Chemical Testing After EKS Treatment

6.4.1 pH

Figure 6.23 shows the results of pH for 3, 7 and 14 days of DW-DW system. It was observed that pH of all different treatment periods shows similar trend except for 3 days experiment which remained constant close to the control value (pH 5.1) across the soil sample. The pH values of 7 and 14 days tests near the anode (25 mm from anode) was reduced to pH of 3.9 and 3.7, respectively. The reduction of pH values near the anode over longer treatment period show that there was a release of hydrogen ions from electrolysis process, which then contribute to the acidity environment near the anode. In contrast, the increment of pH values near the cathode over time is due to the release of hydroxide ions that contribute to the alkalinity environment near the cathode.

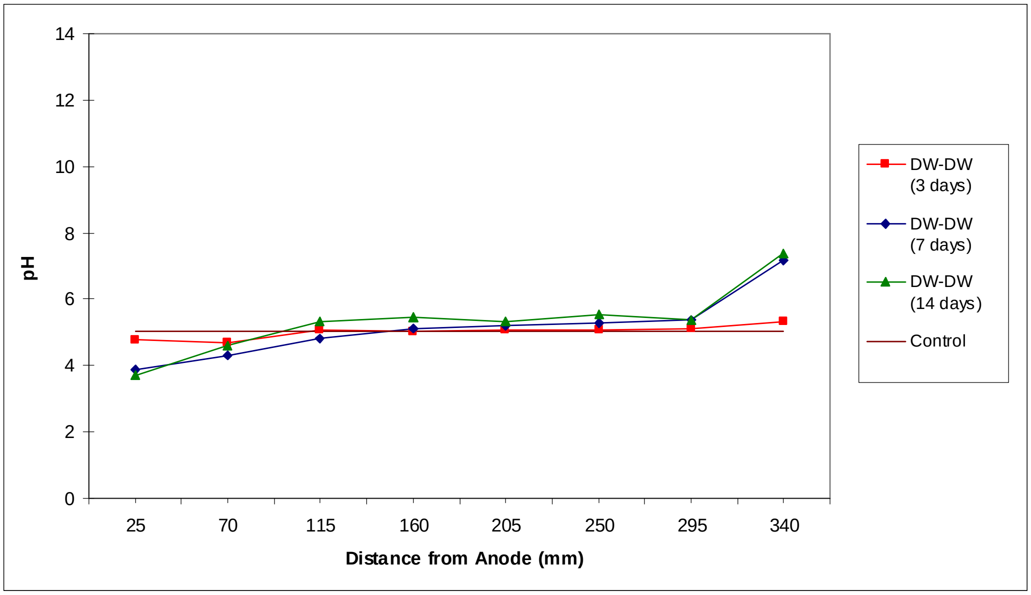


Figure 6.23: pH of DW-DW system with distance from anode.

The pH values of 7 and 14 days tests were increased to about pH 7.2 and 7.4, respectively. The rest of pH values for 7 and 14 days tests were consistent at the mid-point of soil sample from 115 mm to 295 mm away from anode. The results of pH vales were consistent with the results from Liaki (2006) as shown in Figure 6.24 indicating that the electrolysis processes produce a large pH gradient across the soil sample due to the production of hydrogen and hydroxide ions at the anode and cathode areas, respectively.

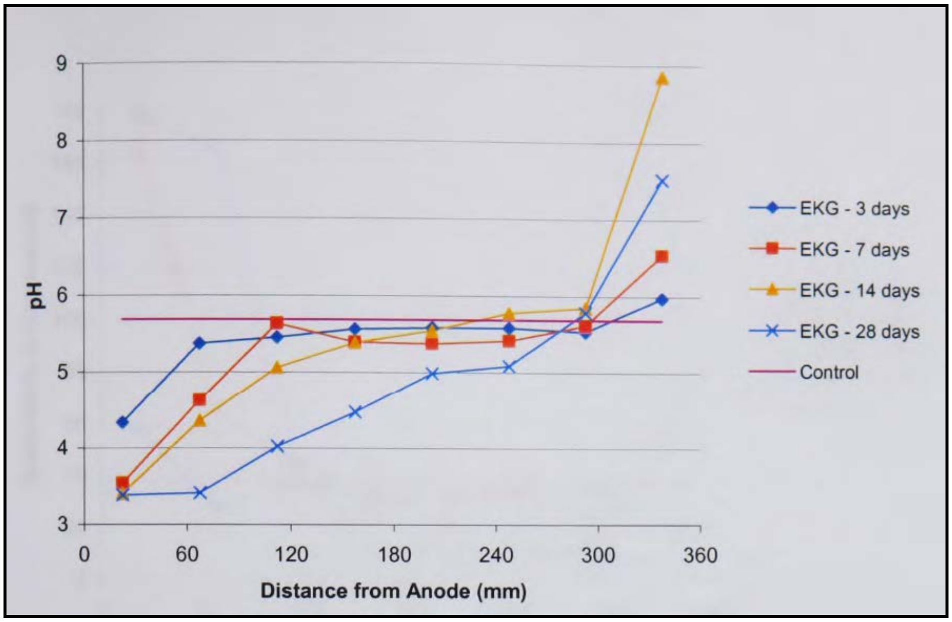


Figure 6.24: pH of DW-DW system with distance from anode (Liaki, 2006).

6.4.2 Electrical Conductivity

Figure 6.25 shows the results of electrical conductivity for all test period of DW-DW system. The results show greater variation electrical conductivity values across the soil samples. However, all the values are above the control value (19.6 µS/cm). The highest value of 134.5 µS/cm recorded at 70 mm from the anode for 14 days test while the lowest value is close to the control value at 295 mm from the anode for 7 days test.

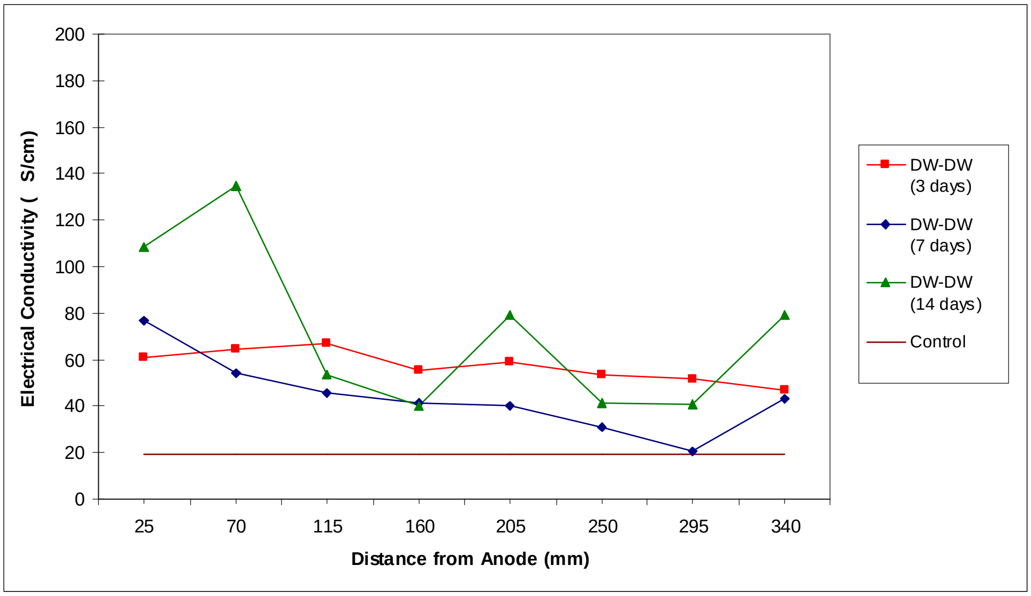


Figure 6.25: Electrical conductivity of DW-DW system with distance from anode.

The trend was similar with the results from Liaki (2006) for the 3, 7 and 14 days tests as seen in Figure 6.26 even for longer treatment period of 28 days which was not performed in current research. There was significantly increased in the electrical conductivity at the anode area due to the high acid environment which caused dissolution of certain chemical compound and clay minerals. As discussed in Chapter 3, certain ions, i.e. Al, Fe and Si ions from dissolution process and hydrogen ions from electrolysis process were released into the pore fluid under an acid environment resulted an increase in ionic strength between the clay particles and migrate towards the cathode. However, in alkaline pH environment the solubility of these ions were reduced due to the precipitation of metal hydroxides to bind the clay particles, thus reduce the ionic strength of the pore fluid. The solubility of ions in the pore fluids and electrolysis process are the main contributors to the variation of electrical conductivity values across the soil samples. In addition, this has also contributed to the decrease in electric current with time as discussed in section 6.2.1.

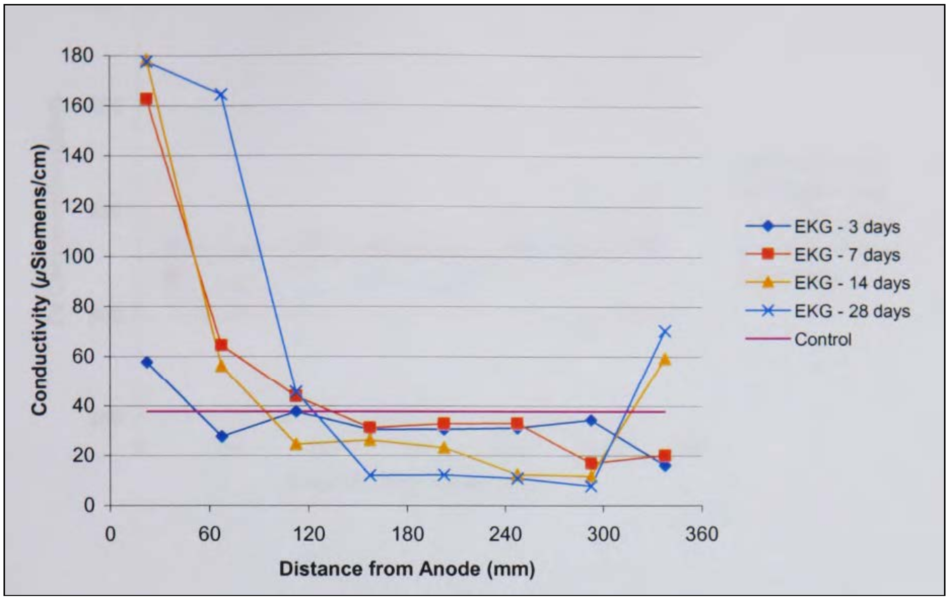


Figure 6.26: Electrical conductivity of DW-DW system with distance from anode (Liaki, 2006).

6.4.3 Metal Concentration

Figure 6.27, 6.29, 6.30 and 6.32 show the variation of metal concentration of DW-DW system from anode to cathode in this research for pure system. The Fe values for all DW-DW tests as shown in Figure 6.27 are generally lower than of the control sample. For all the test periods experiment a similar trend from anode the cathode was observed. The highest Fe concentration value of 1787 mg/kg was recorded at 250 mm away from anode. Since there is no source of Fe introduced into the system, the lower values of Fe concentration were due to the some of the Fe migrate from anode to cathode and were drained out through the cathode. The Fe ions which adsorbed on the clay surface or as part of chemical compound in the natural clay were released in the pore fluid. During the electrokinetic process, these ions were migrated towards the cathode and will precipitate under high alkaline environment or otherwise will flush out through the cathode chamber. In contrast, the results of Fe concentrations from Liaki (2006) as observed in Figure 6.28 showed a slight increase in Fe concentration across the soil samples even though there was no source of Fe ions introduced into the system. This was probably due to the steel corrosion occurred at the bottom edge of EKG electrodes if not sealed properly after cut it or exposed during the insertion of the electrode after consolidation stage. Therefore, the current research has used an epoxy resin to prevent such phenomena happening. The corroded EKG was observed by Liaki (2006) during the trial test using silicon to cover the expose steel at the bottom edge of the EKG electrodes. To make sure the EKG electrodes did not corrode, the EKG electrodes were weighted before and after the EKS testing and no significant weight loss was found to affect the results of Fe concentration in this study.

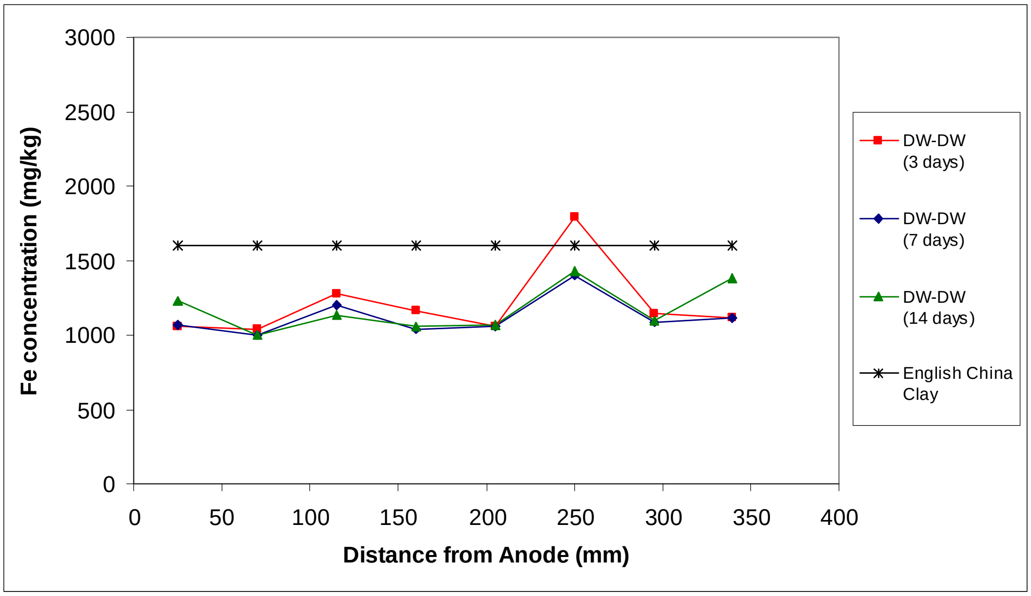


Figure 6.27: Fe concentration of DW-DW system with distance from anode.

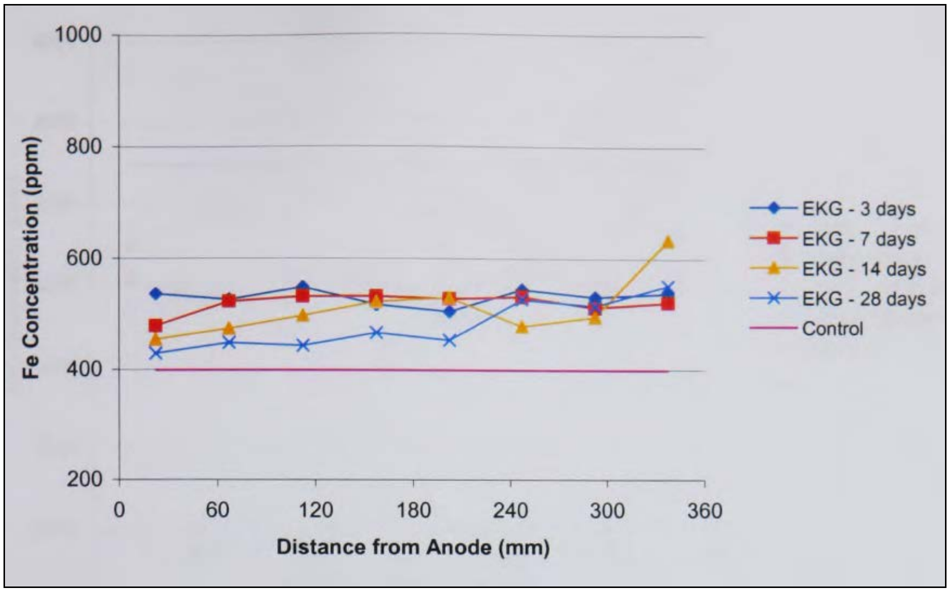


Figure 6.28: Fe concentration of DW-DW system with distance from anode (Liaki, 2006).

The Si values in Figure 6.29 were fluctuated across the soil samples. Therefore, it was suggested the solubility of Si ions were varied and complex with the electrochemical process during the EKS treatment. As shown in Figure 3.11 in Chapter 3, the solubility of Si is depending on higher pH which is about pH above 9. This can be confirmed from results of pH in Figure 6.24. The pH results show that a small changes of pH from 4 to 5 at the anode and 5 to 7.5 at the cathode. There were no results of Si concentration presented by Liaki (2006) to compare with the current results. Liaki (2006) has reported that Si ions were not analysed due to a significant variance of unacceptable ranges were found. Similarly, the low solubility of Si ions on Oxford clay was also observed by Barker (2002) which affects the variability of Si concentration. They both suggested the used of strong acid e.g. hydrofluoric acid to completely dissolve Si ions. However, the Health of Safety Regulations of the laboratory was not allowed them to use this type of acid. Therefore, the volume of hydrochloric and nitric acid used in current study was increased (see section

4.5.2.3 in Chapter 4) which different with the volume of acids used by Barker (2002) and Liaki (2006).

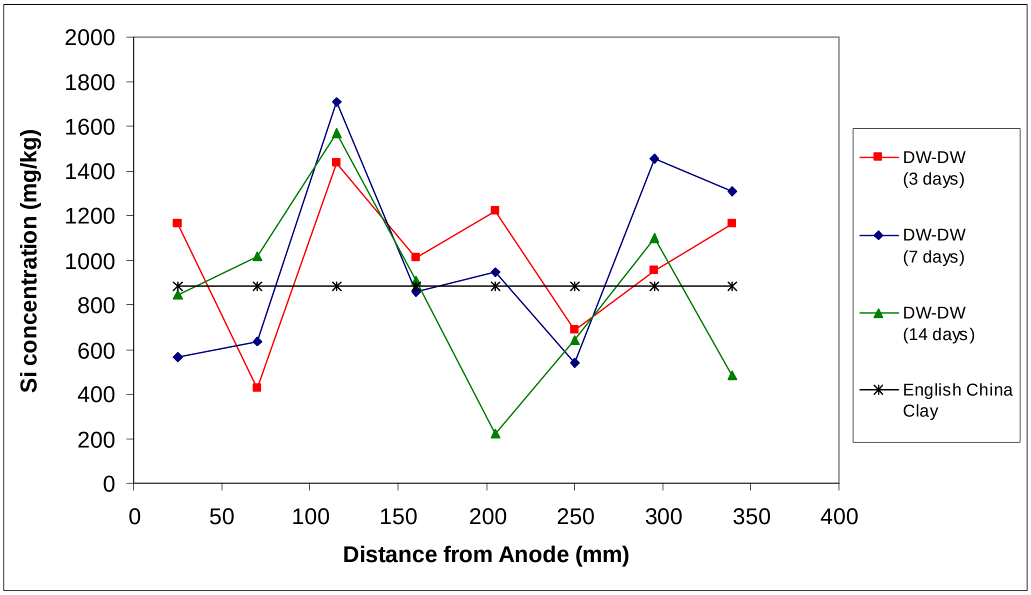


Figure 6.29: Si concentration of DW-DW system with distance from anode.

Figure 6.30 show the Al values are generally lower than of the control sample. This trend is similar with the result from Liaki (2006) as observed in Figure 6.31 however no explanation was given to explain this trend. In addition, this trend is also similar and consistent with Fe concentration results. An extreme pH condition developed across the soil samples caused dissolution of Al ion and have been discussed details in section 6.4.2.

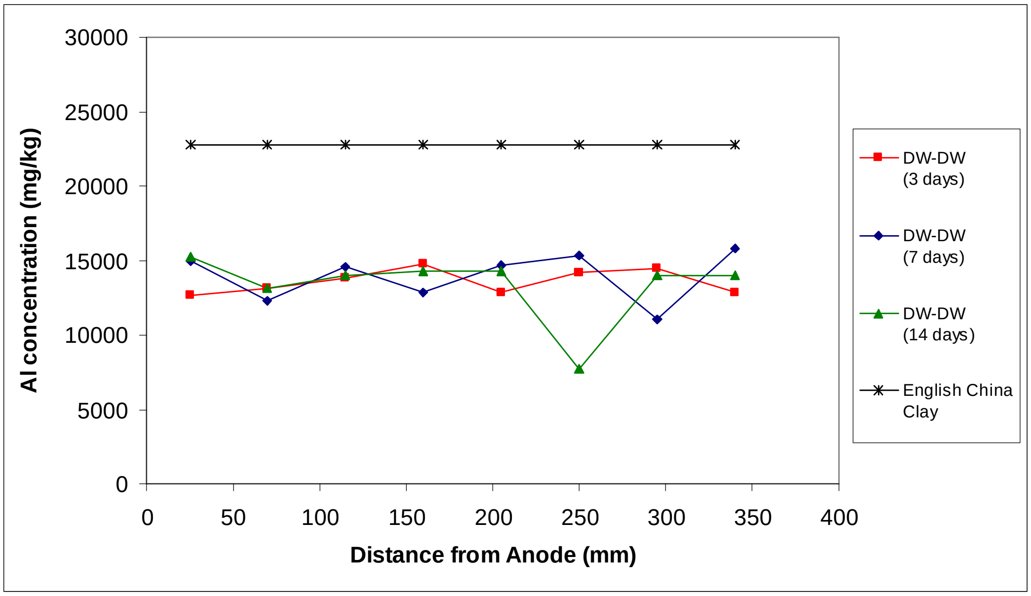


Figure 6.30: Al concentration of DW-DW system with distance from anode.

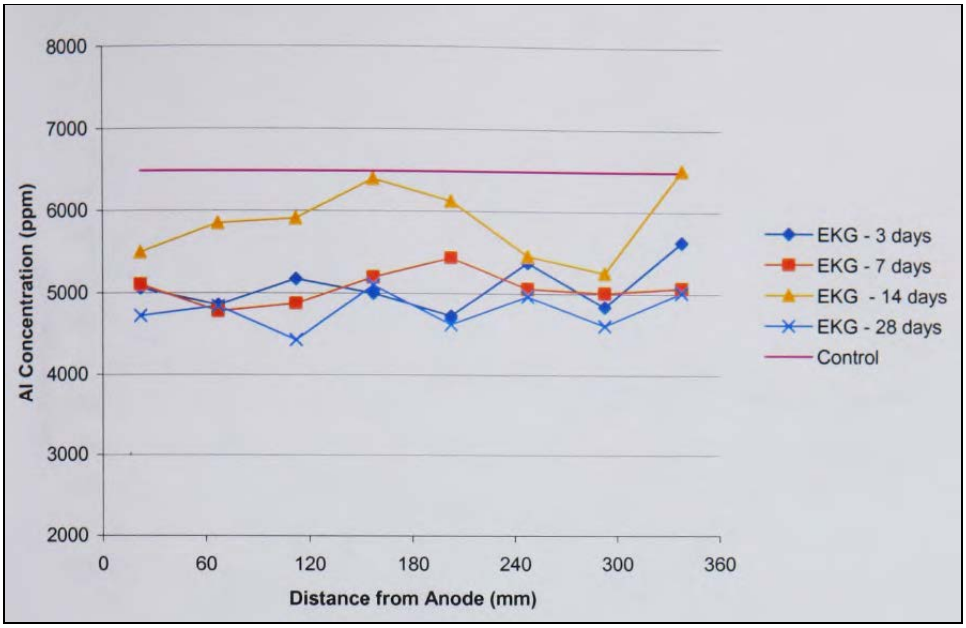


Figure 6.31: Al concentration of DW-DW system with distance from anode (Liaki, 2006).

The K concentration values are shown in Figure 6.32, which is also below that of the control sample. However, the trend of K concentrations is less variable than the other metal concentration such as Fe and Al, but this suggest a similar mechanism occurs as those ions. There were no results of K concentration presented by Liaki (2006) to compare with the current results.

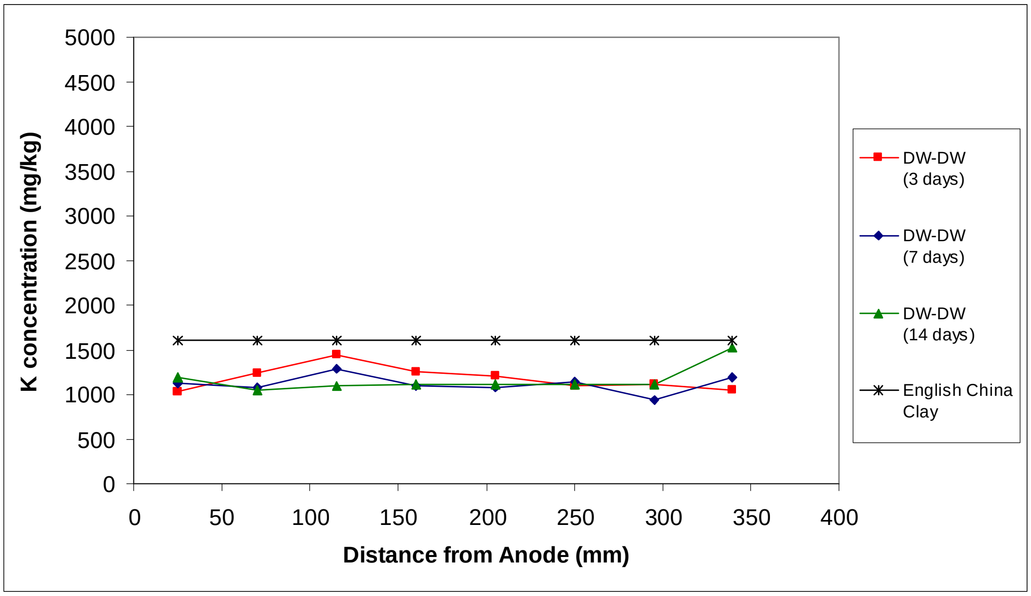


Figure 6.32: K concentration of DW-DW system with distance from anode.

6.5 Summary

The result present and discussed in this study is comparable with previous study performed by Liaki (2006). However, the improved version of the procedures and design considerations has been made to solve the problem faced by Liaki (2006) and to achieve the objectives of this study before any chemical stabilisers were introduced into the system. This baseline study of the pure system in this chapter is important for the analysis of results discussed in the next chapter, to take into consideration the electrochemical effects which might occur in the pure system during the test. This was observed from the results of monitoring data, physical and chemical properties of the pure system which caused e.g., the development of pH gradients, the changes of the electrical conductivity, the changes in Atterberg limits and chemical concentrations with regards to distance from anode and treatment periods due to the electrochemical effects. This electrochemical effect will occur during the EKS testing even though there were no chemical stabilisers introduced or released from the degradation of electrodes.

Chapter 7

RESULTS AND DISCUSSION OF EKS SYSTEM WITH CHEMICAL STABILISERS

7.1 Introduction

Analysis of results from pure system demonstrated the validity of the approach and its modification (see Chapter 6). This allowed the main experimental programme using chemical stabilisers to be added into the EKS system (see Chapter 5). This chapter is divided into three main sections and includes monitoring data during EKS testing, physical and chemical properties of clay soil after EKS testing for 3, 7 and 14 days of treatment period for all test systems. The CaCl-DW system was performed to understand the effect of calcium ions on EKS testing when they are continuously supplied at the anode, whereas the DW-NaSiO system was performed to study the effect of silicate ions when continuously supplied at the cathode. Lastly, the CaCl-NaSiO system was performed to know the effect of both selective ions when added simultaneously into the system. Therefore, the results and discussion of the EKS tests are presented in this chapter together with a discussion about the repeatability tests to reduce uncertainty of the results.

7.2 Monitoring Data

7.2.1 Electric Current

Figure 7.1, 7.2 and 7.3 show the profile of electric current for all 3 systems during EKS testing. For the CaCl-DW system, the 3 days and the 14 days tests of electric current value start at the same value (27 mA) while the 7 days test start at a lower values which is around 11 mA (see Figure 7.1). However, after 72 hours the electric currents stabilised at almost same level for all 3 tests from about 45 to 52 mA. The fluctuation of current at the beginning of the test is attributed to the additional ions introduced at the anode chamber by calcium chloride. After that point, the 3 days test was stopped however from the 7 and 14 days tests, the electric current values start to decline steadily after reaching their maximum value of 72 and 81 hours, respectively.

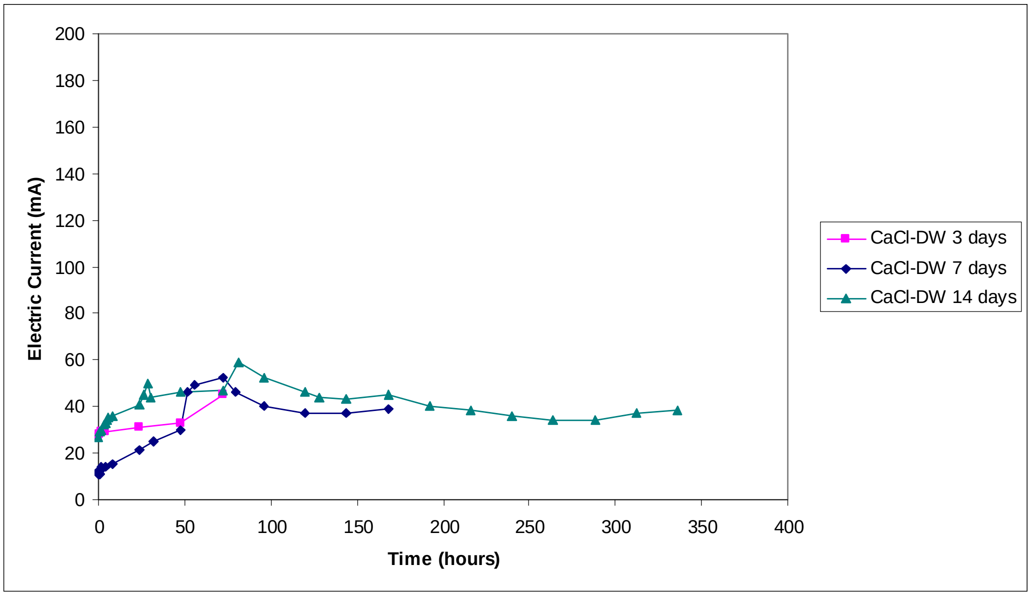


Figure 7.1: Electric Current of CaCl-DW system with time

As seen in Figure 7.2, the electric current value of DW-NaSiO system starts at a highest value from about 16 to 18 mA and then decreases significantly to a value below 10 mA within the first 24 hours. Finally, the electric current stabilises at a lowest value around 5 mA with the increased treatment time. This was consistent for all three test periods.

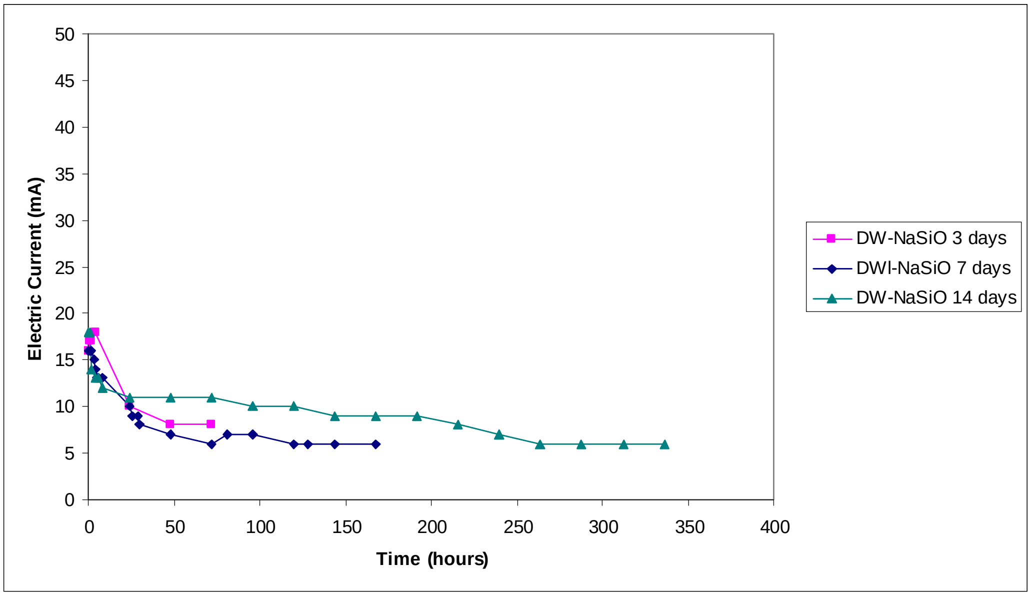


Figure 7.2: Electric Current of DW-NaSiO system with time.

For the CaCl-NaSiO system, the electric current profile as shown in Figure 7.3 has similar trend as compared with the DW-NaSiO system. Therefore, the addition of sodium silicate at the cathode chamber significantly affects the current drop in both tests. However, the CaCl-NaSiO system start at the higher electric current from 40 to 50 mA compared with the DW-NaSiO which used distilled water at the anode chamber. The higher electric current for the CaCl-NaSiO system is due to the abundances of dominate ions i.e., Ca and Si (both electrolytes compartments), Al, Fe, Si (dissolution of chemical compound and clay minerals), and hydrogen and hydroxide ions (electrolysis product) within a soil-water system that migrate from both electrodes, resulting in a significant increase the conductivity of the soil thus the increase in electric current value at the beginning of the test. The electric current values then decreased rapidly until they reach at about 10 mA and then stabilise until the end of the tests. The electric current profiles were attributed to the changes in pH (see Section 7.4.1), electrical conductivity (see Section 7.4.2) and chemical concentrations (see Section 7.4.3, 7.4.4 and 7.4.5) across the soil samples.

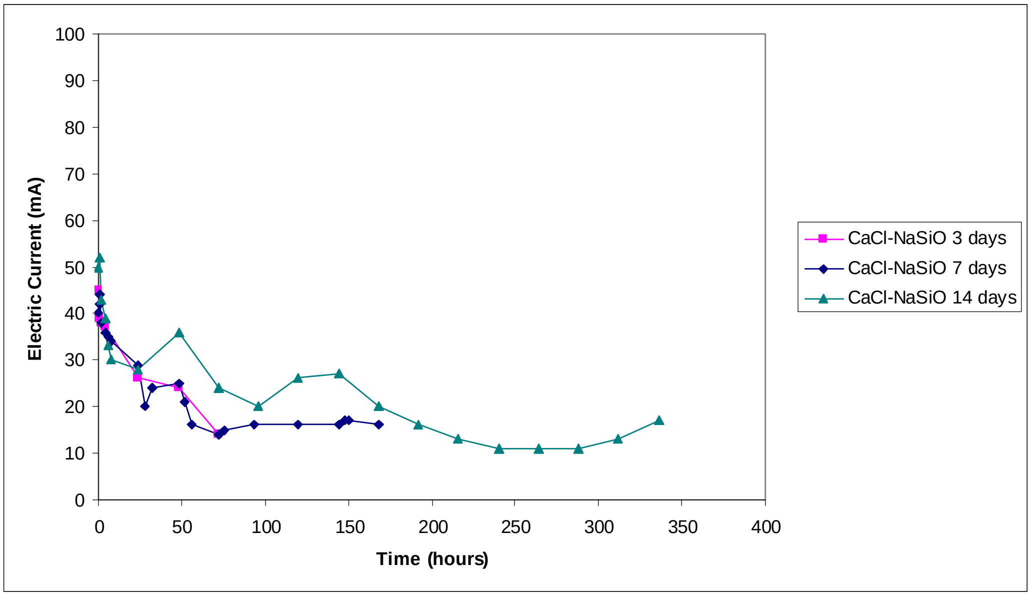


Figure 7.3: Electric Current of CaCl-NaSiO system with time.

A large pH gradient contributed to the dissolution of certain chemical compound and clay minerals, and which released into the pore fluid, thus increased the electric current at the beginning of the test, while the development of precipitation at the cathode after certain time caused a decreased in electric current with time. At the anode area, this phenomenon can be validated from the high electrical conductivity values due to the higher solubility of these ions under acid environments (see Figure 7.40, 7.41 and 7.42). At the cathode, the precipitation resulted in a decrease of electrical conductivity values compared to the values at the anode due to the lower solubility of these ions under an alkaline environment. The insoluble of metal hydroxide amorphous act as a cementations agent which is filled the voids between soil particles.

The comparison between EKS testing with chemical stabilisers in this chapter and without chemical stabiliser (pure system) in Chapter 6 shows significant relationship of the all the test systems. A similar trend of electric current was observed in tests for the CaCl-DW (see Figure 7.1) and DW-DW system(see Figure 6.1) while a similar trend is observed between the CaCl-NaSiO (see Figure 7.3) and DW-NaSiO system (see Figure 7.2). For the CaCl-DW and DW-DW systems, it can be seen a sudden increase in electric current at the start of the test until around 100 hours and 200 hours, respectively. Then, the current level gradually dropped until the end of the tests. In both tests, deionised water was added at the cathode chamber therefore no chemical ions introduce in the system from the cathode side. In contrast with the DW-NaSiO and CaCl-NaSiO systems, the electric current reach at the peak at the beginning of the test and then decreased significantly at the lowest value until the end of the test. Interestingly, both tests used sodium silicate at the cathode. Hence, the type of solution added in the cathode chamber will affect the electric current profile during EKS testing.

The decrease of electric current for all systems towards the end of the test was caused by the decrease of soil electrical conductivity that developed across the soil profiles due to the electrokinetic effects such as precipitation. The electrical conductivity of soil is a function of ionic strength of the soil pore fluid and the surface characteristics of the particles (Ozkan *et al.*, 1999). Thereby, the higher electric current in the beginning of the system is due to the increase of ionic strength of the soil pore fluid from the addition of chemical ions at the cathode, electrolysis product and dissolution of chemical compounds and clay minerals.

7.2.2 pH of Electrolytes

Figures 7.4 to 7.9 show the variations of pH at anolyte and catholyte all tests condition with different treatments time. The pH of anolytes for the CaCl-DW and CaCl-NaSiO in Figure 7.4 and 7.8 have similar trend which both start a very high pH of 10 and decreased to a very low pH of 2 throughout the test. However, the pH of anolyte for the CaCl-NaSiO system (see Figure 7.8) seem to decrease sharply over 120 hours (5 days) and then stabilised at the pH around 2 until the end of the test. While, the pH of anolyte for the CaCl-DW system decreased steadily until the end of the test.

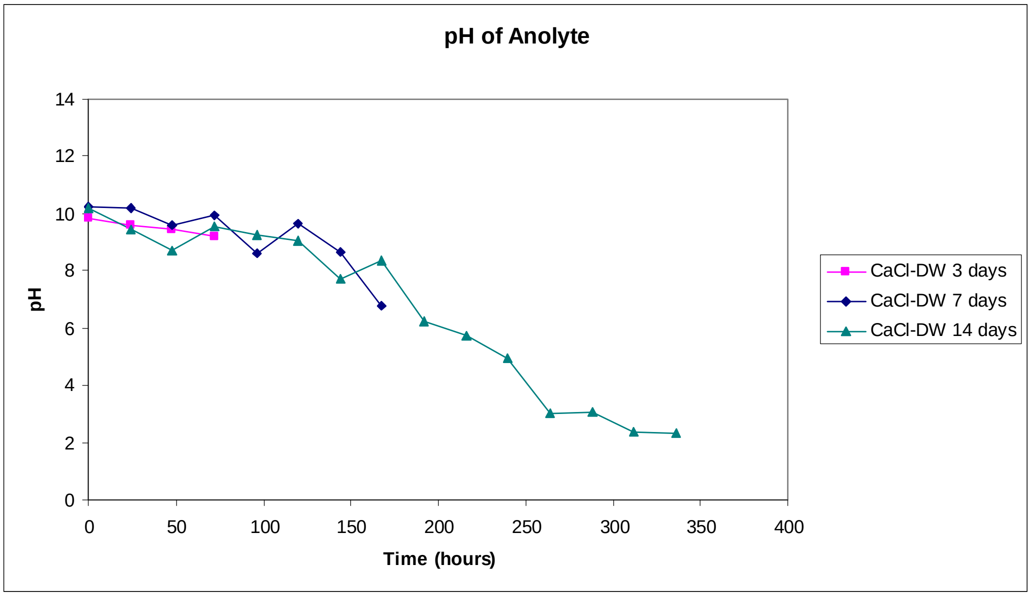


Figure 7.4: pH of anolyte for CaCl-DW system with time.

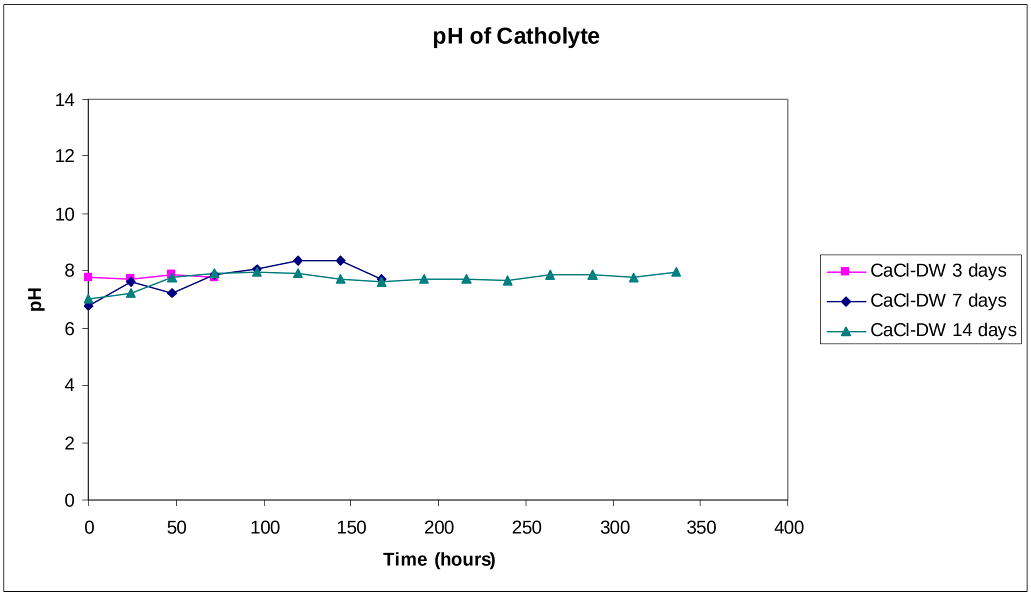


Figure 7.5: pH of catholyte for CaCl-DW system with time.

Contrarily, for the DW-NaSiO test in Figure 7.6, the pH of anolyte at the beginning of the test was recorded at around pH 7 and then maintained for about 144 hours. After that point, the pH increased sharply to reach a maximum pH value of 12 at 264 hours (11 days) and then constant until the end of 14 days treatment time. It should be noted that the further increase of pH can be seen only for 14 days experiment due to the longer period of treatment time.

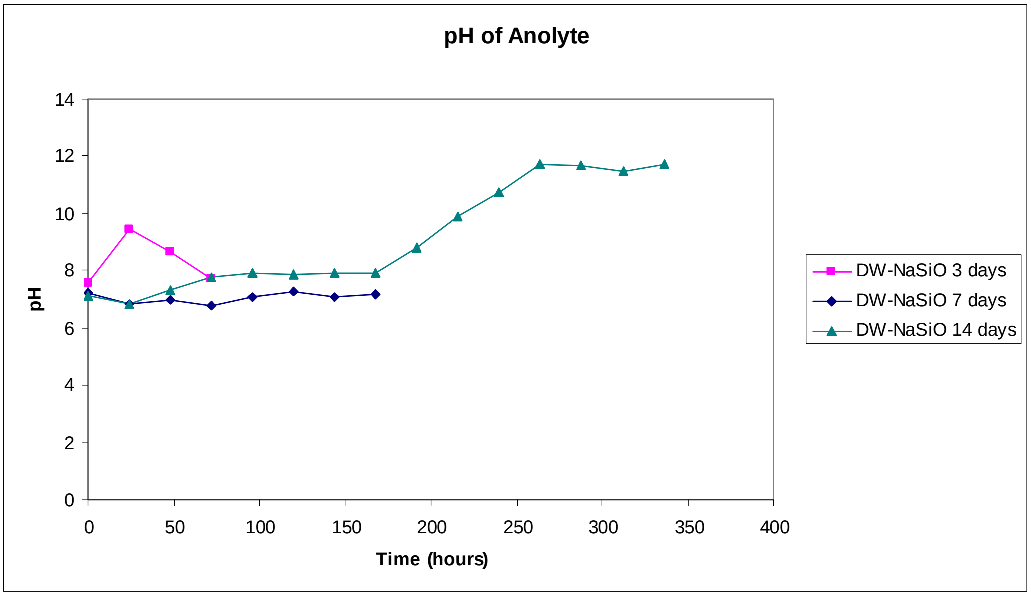


Figure 7.6: pH of anolyte for DW-NaSiO system with time.

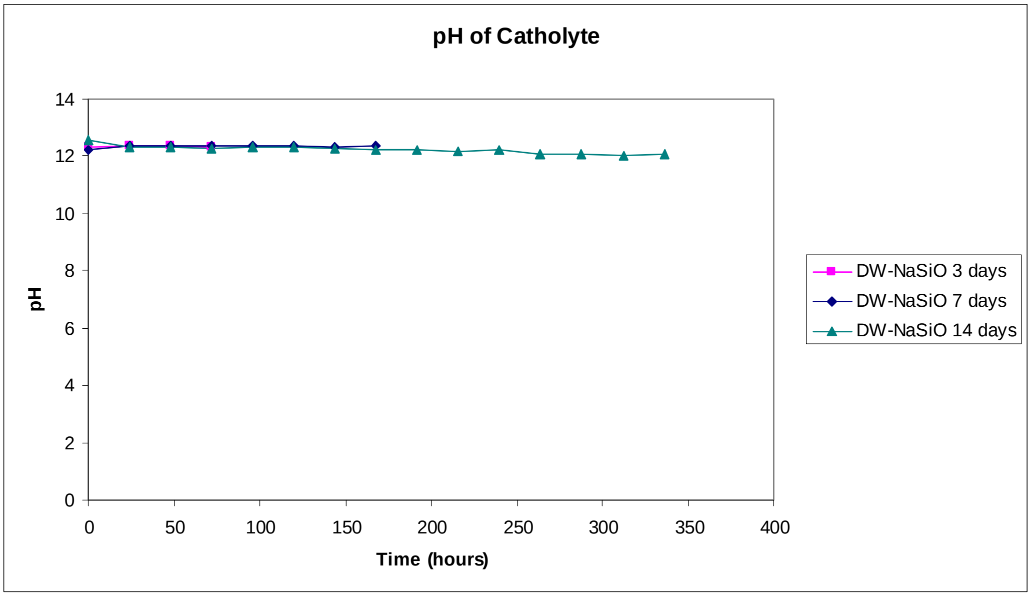


Figure 7.7: pH of catholyte for DW-NaSiO system with time.

A significant change in pH of the anolyte for the CaCl-DW and CaCl-NaSiO indicates the development of an acid front at the vicinity of the anode due to the electrolysis process. As shown in Figure 7.5, 7.7 and 7.9, the pH of catholytes were constant throughout the test for all systems. However, for the CaCl-DW system the pH of catholytes maintained at around pH neutral (pH 7) but lower than both of the DW-NaSiO and the CaCl-NaSiO system, which was maintained at pH around 12 during most of the treatment time.

The value of pH depends on the types of the electrolytes used at the cathode. The constant value of the pH show the indication that during EKS testing, the pH of the catholytes were not changes due to the continuous supply of electrolytes that will balance the changes of pH by electrolysis reaction at the cathode.

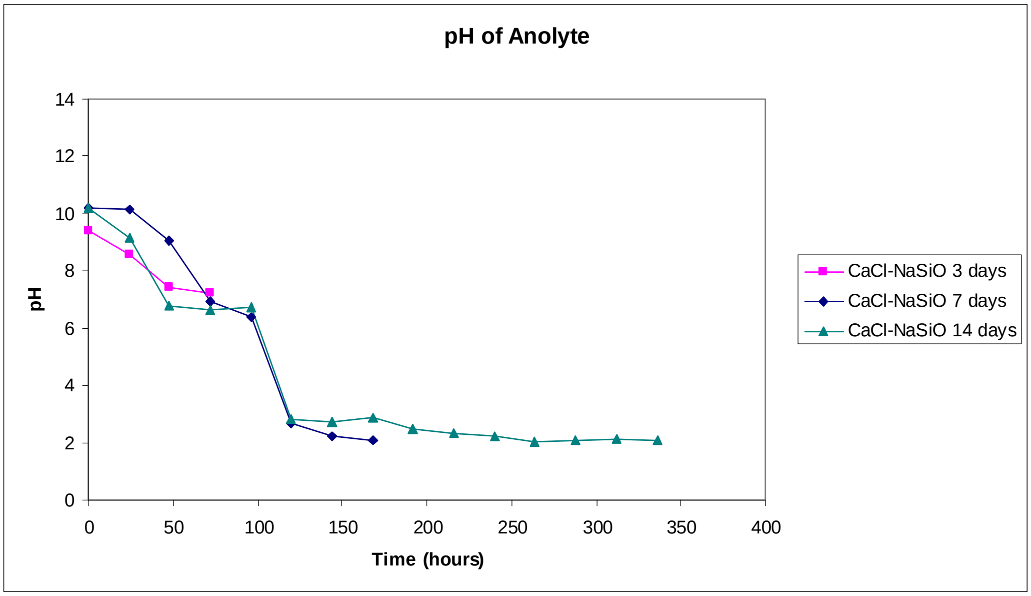


Figure 7.8: pH of anolyte for CaCl-NaSiO system with time.

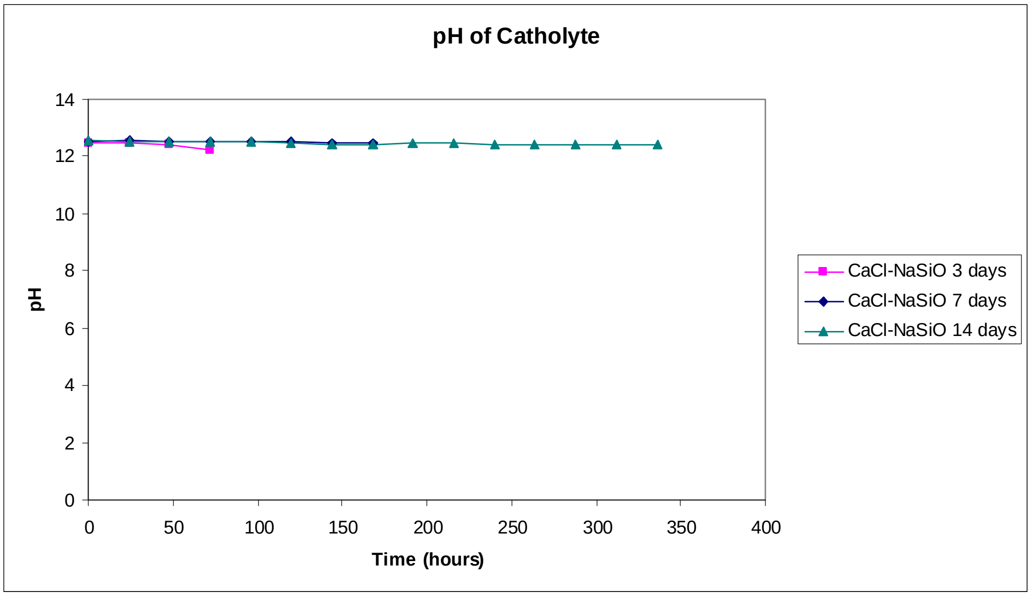


Figure 7.9: pH of catholyte for CaCl-NaSiO system with time.

7.2.3 Electrical Conductivity of Electrolytes

Figure 7.10 to 7.15 show the changes in the values of electrical conductivity at anolyte and catholyte for different test systems over time. Electrical conductivity values of anolyte for the CaCl-DW and the CaCl-NaSiO system as seen in Figure 7.10 and 7.14, respectively show constant and very high values over time ranging from 110 000 to 160 000 S/cm due to continues supply of calcium chloride solution in the anolyte chambers. The results of electrical conductivity for both tests show similar pattern suggesting that the electrical conductivity of anolyte is strongly affected by the type of chemical stabiliser used at the anolyte. The pattern of electrical conductivity of anolytes distribution is constant throughout the soil profile due to continuously supply of chemicals using Mariotte bottle method which make sure the calcium ions are adequately migrate into the soil sample.

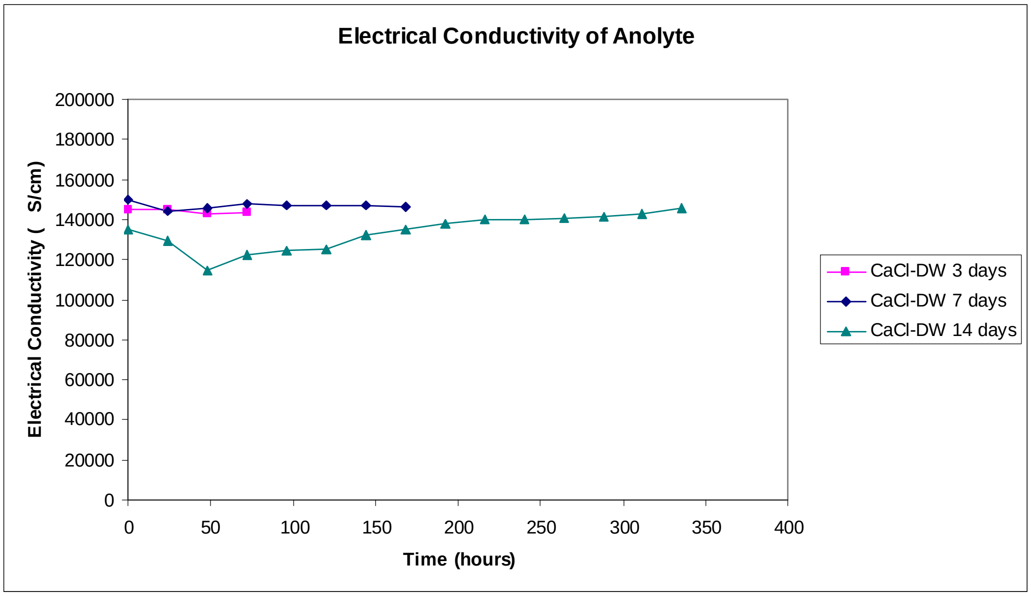


Figure 7.10: Electrical conductivity of anolyte for CaCl-DW system with time.

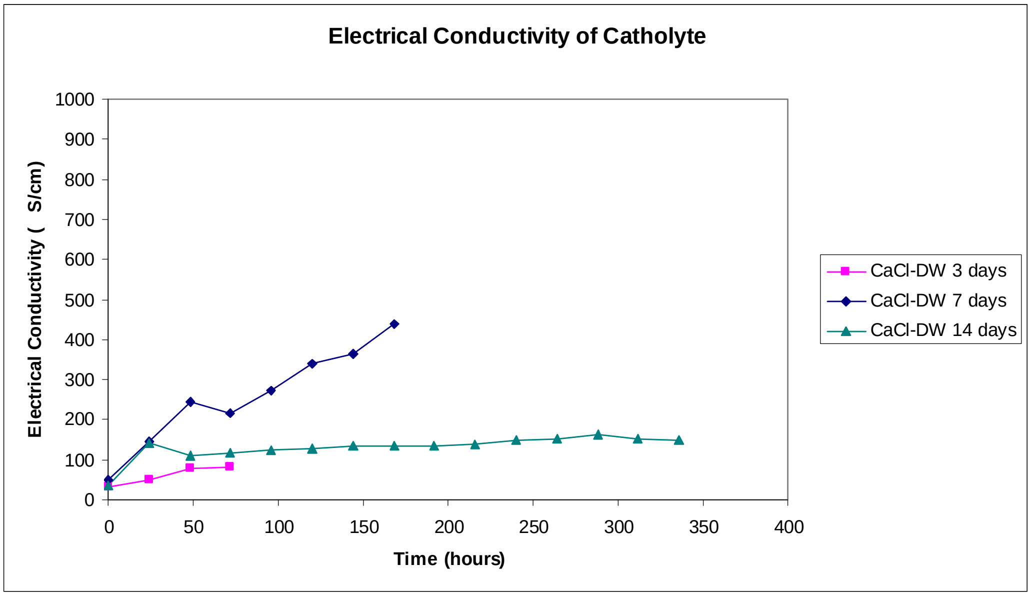


Figure 7.11: Electrical conductivity of catholyte for CaCl-DW system with time.

In contrast, the electrical conductivity of anolyte the DW-NaSiO system as shown in Figure 7.12 began at very low values between 15 and 35 μS/cm at first 120 hours (5 days) and then increased steadily until the end of the test as observed in the 14 days experiment. The low electrical conductivity of the DW-NaSiO system was expected due to the use of distilled water at the anolyte chamber. The sudden increased for the 3 days experiment at 24 hours as seen in Figure 7.12 was due to the cross contamination that occurred during sample preparation prior to electrical conductivity test. With regards to treatment time of the DW-NaSiO system, the slight increased of the 3 days test compared with the 7 and 14 days tests was minimal (± 20 μS/cm) considering the micron unit recorded measurements at the anolyte.

From the results of DW-DW system in Chapter 6 (see Figure 6.7), the pattern is also similar from the beginning of the test until 10 days. However, after 10 days the electrical conductivity values of DW-DW system seem to drop significantly due to the electrolysis process had ceased after 10 days. This can be validated from the results of anolyte pH of DW-DW system in Figure 6.3 which showing the pH values are constant after 10 days duration at pH 5.1. Therefore, the electrolysis process to release of hydrogen ions at the catholyte compartment for DW-NaSiO and DW-DW system resulted in an increase in electrical conductivity at the anolyte.

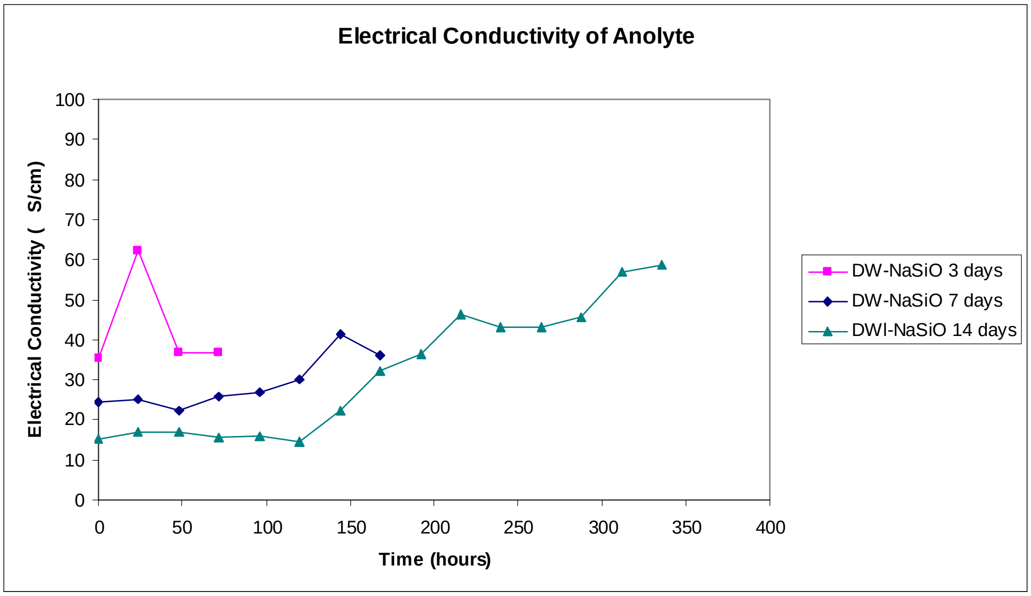


Figure 7.12: Electrical conductivity of anolyte for DW-NaSiO system with time.

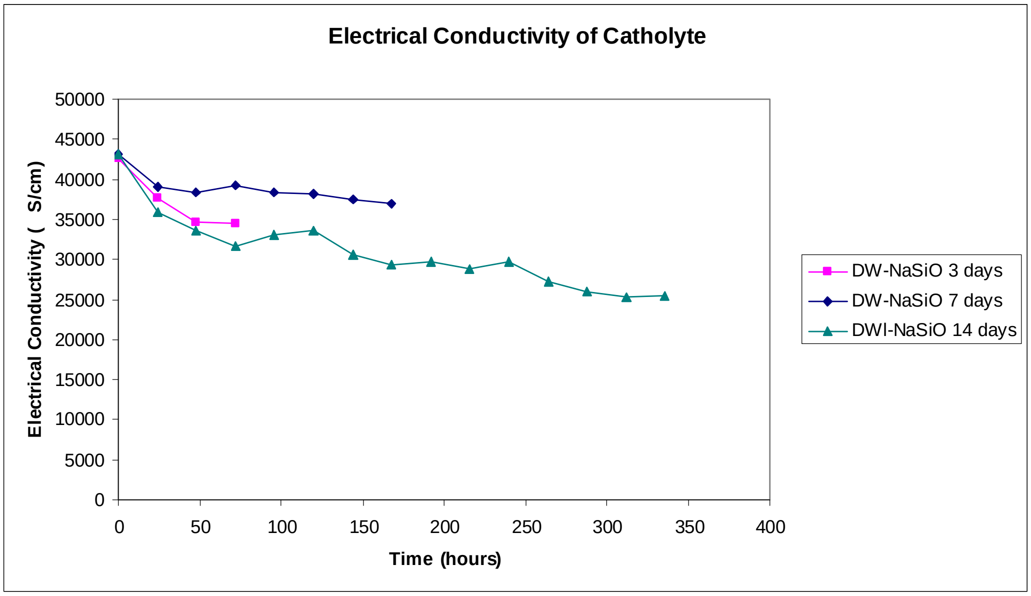


Figure 7.13: Electrical conductivity of catholyte for DW-NaSiO system with time.

As seen in Figure 7.11, the electrical conductivity of catholyte for the CaCl-DW system is increased slowly from about 50 S/cm at the beginning of the experiment to about 150 S/cm. The lower electrical conductivity of catholyte for the CaCl-DW system is due to the addition of distilled water at the cathode chamber. However, for the 7 days test, the electrical conductivity seems to increase significantly to about 400 S/cm. This trend is similar with the DW-DW system as seen in Figure 6.8 in Chapter 6 when using distilled water at the catholyte. The increase of electrical conductivity of catholytes is due to the electrolysis process to release hydroxide ions and coupled flows (electromigration and electroosmosis processes) into the catholyte compartment.

In the DW-NaSiO system, the electrical conductivity of catholyte is decreased significantly from 43 000 S/cm to about 25 000 S/cm throughout the duration of the experiment as shown in Figure 7.13. However, the higher the electrical conductivity values compared to the CaCl-DW system is because of addition of sodium silicate at the catholyte chamber. The decrease of electrical conductivity at the catholyte with time is due introduction of distilled water at the anode which caused water to flow toward the cathode with little ions present compare with the CaCl-DW system. In the CaCl-DW system, the calcium moving toward the cathode, thus increase the electrical conductivity of the catholyte significantly.

In the CaCl-NaSiO system has similar trend with the DW-NaSiO system however the values are decreased steadily with time from about 43,000 to almost 30,000 S/cm as observed in Figure 7.15. Therefore, the types of the chemical stabilisers used at both electrolytes affecting the ionic concentration of the fluid due to the electrochemical effects. Thus, it is important to select the right conditioning of the chemical stabilisers to achieve the desired results (i.e. to increase the shear strength due to the precipitation and cation exchange).

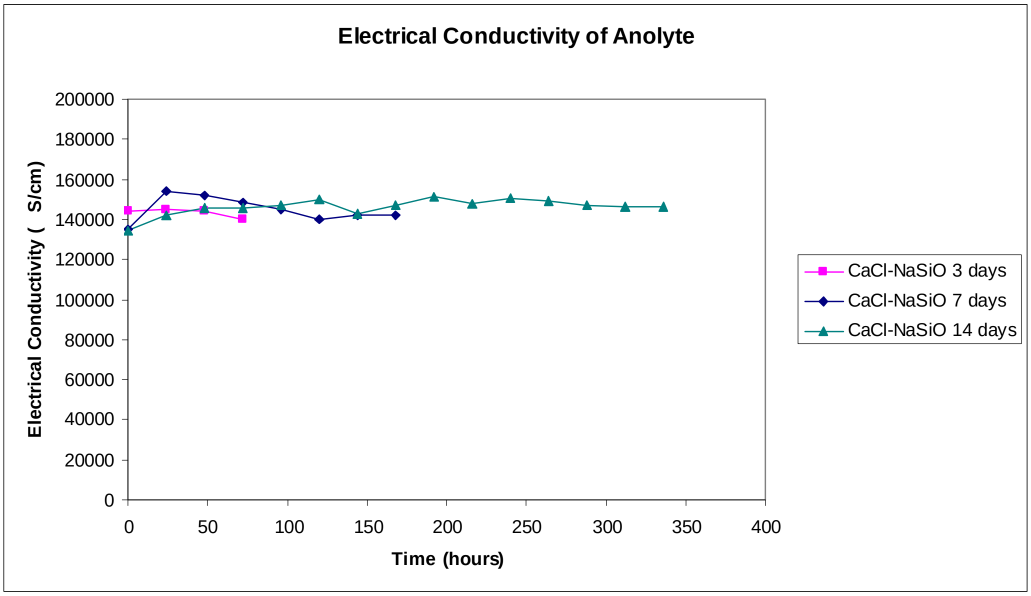


Figure 7.14: Electrical conductivity of anolyte for CaCl-NaSiO system with time.

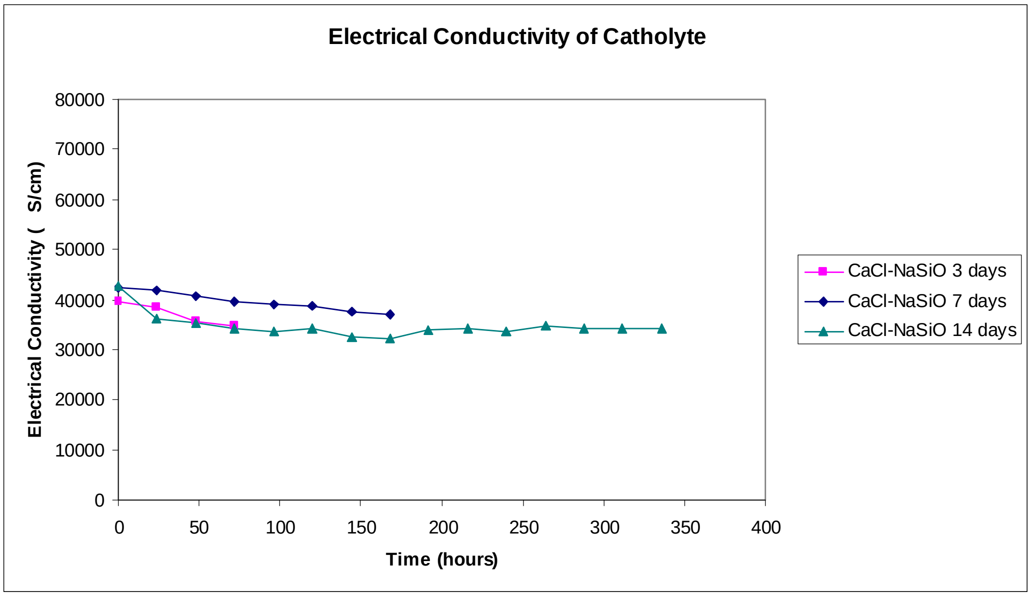


Figure 7.15: Electrical conductivity of catholyte for CaCl-NaSiO system with time.

7.2.4 Inflow and Outflow

Figure 7.16 to 7.18 present the results of total inflow and outflow of water during EKS testing. For the CaCl-DW system, the inflow and outflow of water were increased rapidly with the increase of duration time as presented in Figure 7.16. After 72 hours (3 days), the outflow of water seems to increase less than inflow of water. This is an indication of imbalance of the flow in the system due to the water retention in the system or water escaped throughout the gaps between soil-electrode interfaces, hence reduce the efficiency of the system. From the results of soil water content show that the water content is not increased significantly across the sample therefore it was suggested the latter phenomenon is responsible for the loss of water discharged at the catholyte chamber. After 264 hours (11 days), the inflow and outflow of water remained constant until the end of the test to reach the total flow of 1190 and 940 ml, respectively. Thus, there was no water added and discharge at the anolyte and catholyte chamber, respectively after 11 days of treatment duration.

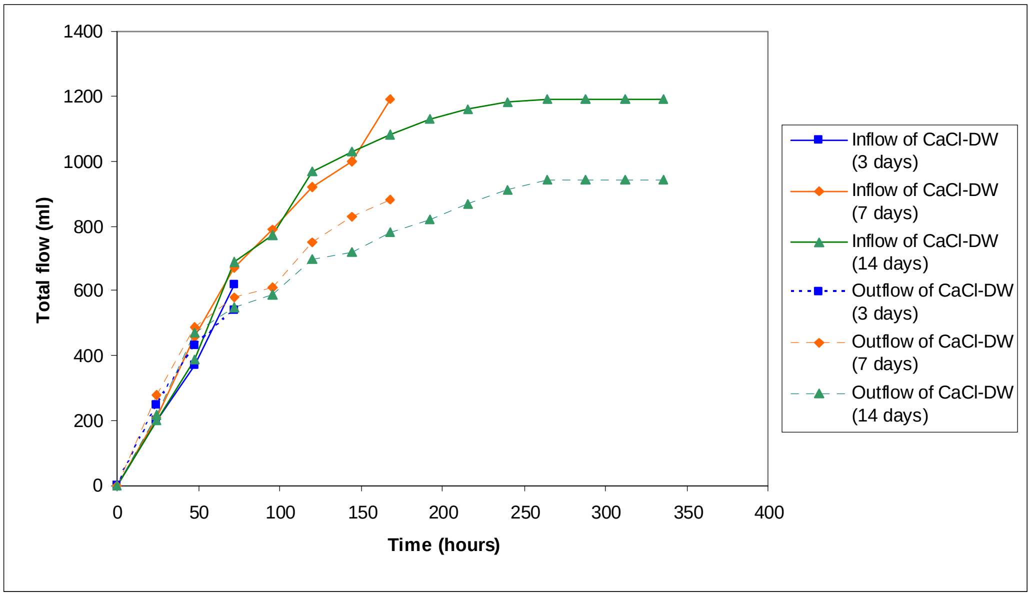


Figure 7.16: Inflow and outflow of CaCl-DW system with time.

Interestingly, the DW-NaSiO system in Figure 7.17 shows different trend to the other systems. It is clearly shows that the inflow of water was higher than of the outflow of water until 144 hours (6 days). After that period, the inflow of water starts to decrease below the outflow of water until the electric current was stopped. This was attributed to the use of sodium silicate at the cathode and the use of distilled water at the anode affect elecroosmosis and electromigration processes in the system. The migration of silicate and hydroxide ions towards the anode was likely to dominate movement of ions in the system after 6 days compared to the cation movement or electrosmosis toward the cathode. Since no ions were introduced at the anode, the movement of higher concentration of anions toward the anode will retard the movement of less concentration of cations toward the opposite direction thus slow the electroosmosis process towards the cathode.

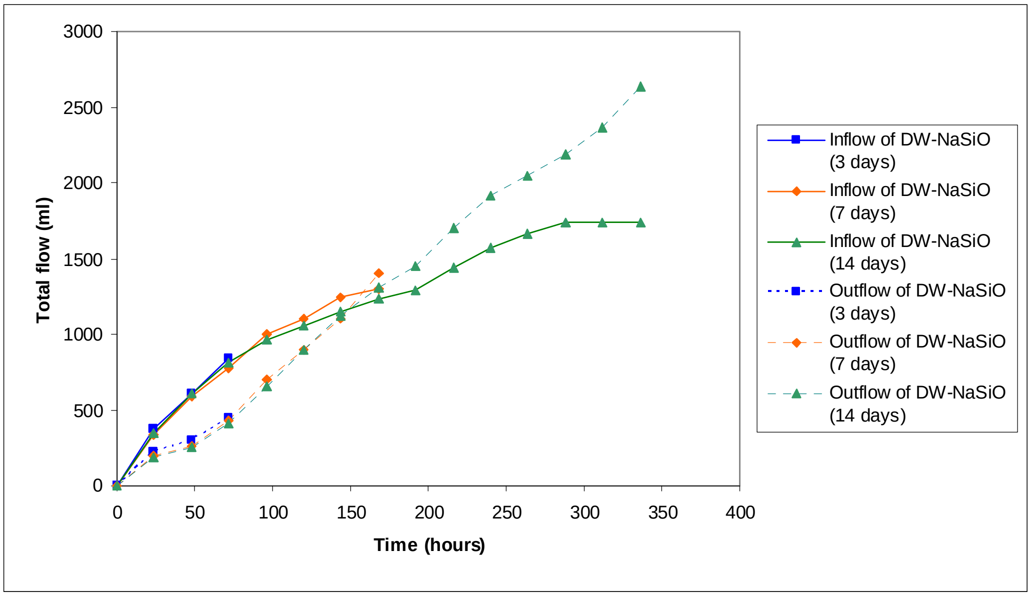


Figure 7.17: Inflow and outflow of DW-NaSiO system with time.

Meanwhile, for the CaCl-NaSiO system, when calcium ions and silicate ions were supplied at the anode and cathode, respectively, the total outflows were always significantly less than the total inflows. This trend shown in Figure 7.18 was due to the electromigration process, which was far greater than electroosmosis process during the EKS testing. Therefore, less water was discharged caused by electroosmosis and electromigration process was dominated the whole system which cause anions and cations moving in opposite direction during EKS testing.

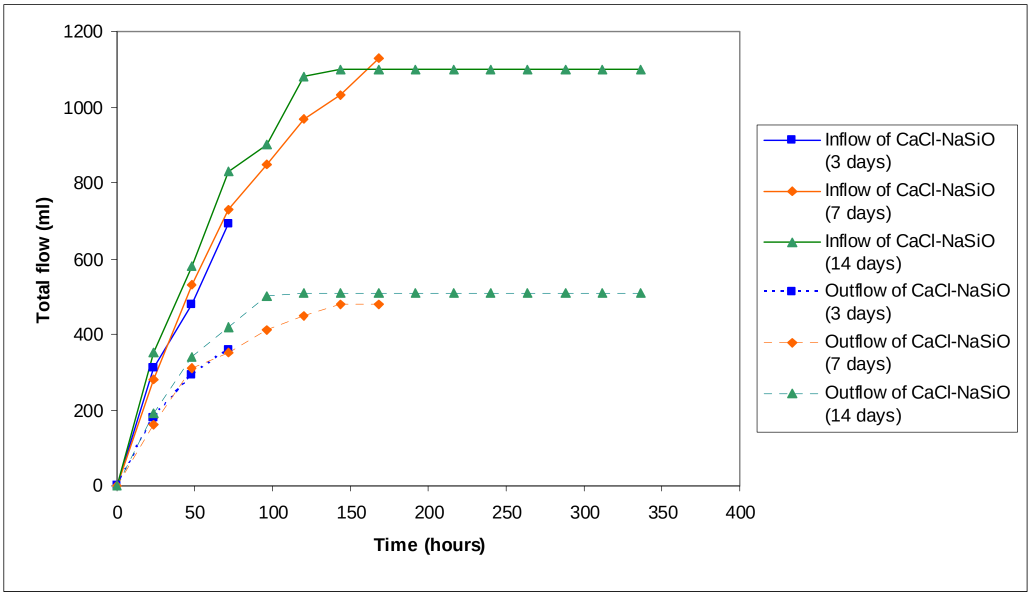


Figure 7.18: Inflow and outflow of CaCl-NaSiO system with time.

7.3 Results of Physical Testing After EKS Treatment

Table 7.1, Table 7.2 and Table 7.3 show a summary of the physical properties for CaCl-DW, DW-NaSiO and CaCl-NaSiO system, respectively for different periods of time.

Table 7.1: Summary of the physical properties results for CaCl-DW system.

<table>
<tr><th colspan="6">CaCl-DW(3 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>49.4</td><td>3.2</td><td>32.7</td><td>54.6</td><td>21.9</td></tr>
<tr><td>70</td><td>51.3</td><td>4.5</td><td>34.2</td><td>54.0</td><td>19.8</td></tr>
<tr><td>115</td><td>51.8</td><td>5.5</td><td>34.9</td><td>55.1</td><td>20.2</td></tr>
<tr><td>160</td><td>51.7</td><td>5.7</td><td>34.1</td><td>55.9</td><td>21.8</td></tr>
<tr><td>205</td><td>51.8</td><td>6.0</td><td>34.5</td><td>55.8</td><td>21.3</td></tr>
<tr><td>250</td><td>53.1</td><td>6.0</td><td>35.3</td><td>55.6</td><td>20.3</td></tr>
<tr><td>295</td><td>53.5</td><td>6.0</td><td>35.0</td><td>55.7</td><td>20.7</td></tr>
<tr><td>340</td><td>52.5</td><td>5.8</td><td>34.9</td><td>56.1</td><td>21.2</td></tr>
<tr><th colspan="6">CaCl-DW(7 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>49.6</td><td>11.0</td><td>30.5</td><td>53.4</td><td>22.9</td></tr>
<tr><td>70</td><td>49.6</td><td>10.5</td><td>33.2</td><td>53.7</td><td>20.5</td></tr>
<tr><td>115</td><td>49.6</td><td>11.0</td><td>33.4</td><td>54.2</td><td>20.8</td></tr>
<tr><td>160</td><td>52.0</td><td>11.5</td><td>33.8</td><td>54.4</td><td>20.6</td></tr>
<tr><td>205</td><td>50.8</td><td>11.5</td><td>34.2</td><td>55.6</td><td>21.4</td></tr>
<tr><td>250</td><td>50.3</td><td>11.5</td><td>34.5</td><td>55.2</td><td>20.7</td></tr>
<tr><td>295</td><td>50.5</td><td>11.8</td><td>35.1</td><td>55.9</td><td>20.8</td></tr>
<tr><td>340</td><td>51.5</td><td>13.3</td><td>35.7</td><td>55.6</td><td>19.9</td></tr>
<tr><th colspan="6">CaCl-DW(14 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>48.2</td><td>18.0</td><td>29.4</td><td>50.3</td><td>20.9</td></tr>
<tr><td>70</td><td>49.9</td><td>15.5</td><td>31.2</td><td>50.4</td><td>19.2</td></tr>
<tr><td>115</td><td>49.5</td><td>15.0</td><td>32.2</td><td>50.2</td><td>18.0</td></tr>
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<tr><td>250</td><td>49.3</td><td>14.8</td><td>34.6</td><td>52.9</td><td>18.3</td></tr>
<tr><td>295</td><td>50.9</td><td>15.4</td><td>35.5</td><td>54.3</td><td>18.8</td></tr>
<tr><td>340</td><td>51.3</td><td>16.0</td><td>36.9</td><td>56.7</td><td>19.8</td></tr>
</table>

Table 7.2: Summary of the physical properties results for DW-NaSiO system.

DW-NaSiO(3 days)

Distance from anode (mm)	w(%)	C_u(kPa)	PL(%)	LL(%)	PI(%)
25	55.9	5.0	34.1	53.7	19.6
70	54.9	4.3	34.9	53.4	18.5
115	53.9	4.8	34.2	54.4	20.2
160	54.1	4.8	33.5	54.8	21.3
205	54.1	4.8	34.7	54.1	19.4
250	53.9	5.1	34.1	54.6	20.5
295	52.5	5.7	35.4	55.3	19.9
340	52.9	5.7	34.6	55.4	20.8

DW-NaSiO(7 days)

Distance from anode (mm)	w(%)	C_u(kPa)	PL(%)	LL(%)	PI(%)
25	48.2	7.7	33.4	51.2	17.8
70	49.0	7.7	33.9	51.3	17.4
115	48.9	7.7	34.0	52.4	18.4
160	48.7	7.5	33.6	54.3	20.7
205	49.1	7.7	34.1	54.2	20.1
250	49.4	7.6	33.7	53.6	19.9
295	49.0	6.8	34.3	53.1	18.8
340	49.3	5.5	34.5	53.2	18.7

DW-NaSiO(14 days)

Distance from anode (mm)	w(%)	C_u(kPa)	PL(%)	LL(%)	PI(%)
25	47.8	13.4	32.0	47.4	15.4
70	48.8	11.0	33.7	48.3	14.6
115	49.0	11.8	33.0	48.6	15.6
160	49.2	11.0	33.6	48.2	14.6
205	49.1	11.6	33.7	48.6	14.9
250	48.8	11.8	33.8	48.7	14.9
295	49.2	12.0	32.5	49.0	16.5
340	49.2	11.4	34.0	52.6	18.6

Table 7.3: Summary of the physical properties results for CaCl-NaSiO system.

<table>
<tr><th colspan="6">CaCl-NaSiO(3 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>51.1</td><td>7.5</td><td>34.3</td><td>56.1</td><td>21.8</td></tr>
<tr><td>70</td><td>50.4</td><td>8.0</td><td>34.5</td><td>56.5</td><td>22.0</td></tr>
<tr><td>115</td><td>51.5</td><td>8.2</td><td>34.8</td><td>56.3</td><td>21.5</td></tr>
<tr><td>160</td><td>52.6</td><td>9.2</td><td>34.6</td><td>56.0</td><td>21.4</td></tr>
<tr><td>205</td><td>53.5</td><td>9.0</td><td>34.7</td><td>56.5</td><td>21.8</td></tr>
<tr><td>250</td><td>53.6</td><td>9.0</td><td>34.6</td><td>57.2</td><td>22.6</td></tr>
<tr><td>295</td><td>51.8</td><td>9.0</td><td>34.5</td><td>58.4</td><td>23.9</td></tr>
<tr><td>340</td><td>54.6</td><td>8.7</td><td>35.4</td><td>60.5</td><td>25.1</td></tr>
<tr><th colspan="6">CaCl-NaSiO(7 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>49.8</td><td>**7.5**</td><td>33.2</td><td>61.2</td><td>28.0</td></tr>
<tr><td>70</td><td>52.2</td><td>7.8</td><td>33.8</td><td>63.4</td><td>29.6</td></tr>
<tr><td>115</td><td>55.1</td><td>8.0</td><td>34.2</td><td>65.1</td><td>30.9</td></tr>
<tr><td>160</td><td>53.3</td><td>8.8</td><td>33.7</td><td>66.2</td><td>32.5</td></tr>
<tr><td>205</td><td>54.1</td><td>9.2</td><td>34.0</td><td>62.1</td><td>28.1</td></tr>
<tr><td>250</td><td>53.4</td><td>9.0</td><td>34.7</td><td>61.5</td><td>26.8</td></tr>
<tr><td>295</td><td>55.4</td><td>9.4</td><td>34.8</td><td>66.8</td><td>32.0</td></tr>
<tr><td>340</td><td>50.9</td><td>11.2</td><td>36.3</td><td>69.6</td><td>33.3</td></tr>
<tr><th colspan="6">CaCl-NaSiO(14 days)</th></tr>
<tr><th>Distance from anode (mm)</th><th>w(%)</th><th>C_u(kPa)</th><th>PL(%)</th><th>LL(%)</th><th>PI(%)</th></tr>
<tr><td>25</td><td>49.4</td><td>8.4</td><td>27.1</td><td>48.8</td><td>21.7</td></tr>
<tr><td>70</td><td>53.3</td><td>7.9</td><td>28.3</td><td>49.7</td><td>21.4</td></tr>
<tr><td>115</td><td>52.9</td><td>7.5</td><td>29.1</td><td>51.3</td><td>22.2</td></tr>
<tr><td>160</td><td>53.9</td><td>8.4</td><td>30.8</td><td>53.8</td><td>23.0</td></tr>
<tr><td>205</td><td>53.3</td><td>8.5</td><td>32.7</td><td>53.7</td><td>21.0</td></tr>
<tr><td>250</td><td>54.9</td><td>9.0</td><td>31.8</td><td>55.4</td><td>23.6</td></tr>
<tr><td>295</td><td>54.8</td><td>7.8</td><td>32.2</td><td>59.2</td><td>27.0</td></tr>
<tr><td>340</td><td>52.7</td><td>18.5</td><td>38.7</td><td>65.8</td><td>27.1</td></tr>
</table>

7.3.1 Water Content

In Figure 7.19, the water content of the 3 days experiment is slightly above the control value (51 %) across the soil profiles. By contrast, the water contents of the 7 days test were slightly below than the control value at 25 to 115 mm from anode but then varied close to the control value from the middle of the samples toward the cathode.

However, most of the water content values for the 14 days test across the soil profile were slightly below the control value except the values near the cathode (295 and 340 mm from anode) which is close to the control value. The decreased of water content near the anode and values in the mid-point range was expected due to the electroosmosis flow induced by the electric field as discussed in section 7.2.4. At the cathode, the water content did not decreased because it was a boundary of water being moved away from the system.

For a short period of time, the water content would be expected to rise due to the continuous supply of electrolytes at the anode. Over the course of treatment especially for the longer time periods (7 and 14 days tests), the electrochemical process during the EKS testing has changed the soil properties with time due to the increase of ionic concentration of the soil-water system.

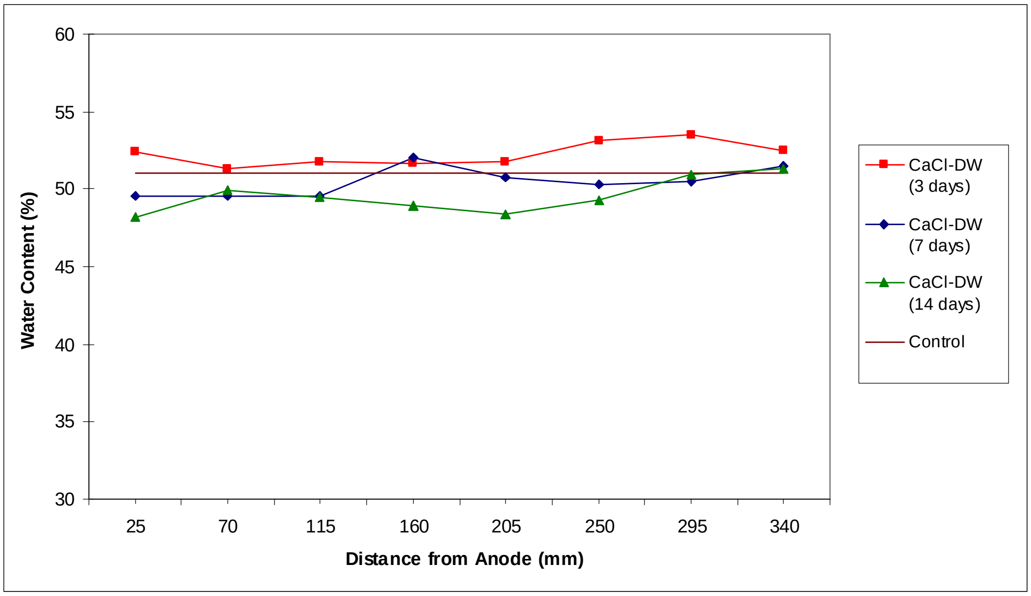

Figure 7.19: Water content profile of CaCl-DW system with distance from anode.

For the DW-NaSiO system, the water content profiles in Figure 7.20 have a similar trend but clearer with those of the CaCl-DW system with respect to time except some values near to the cathode. With regards to distance from anode, the water content values of the 3 days test rose from a high water content of 55.9 % at the anode and then gradually decreased to reach water content of 52.9 % towards the cathode. However, all the values were still above the control value. Whereas in the 7 and 14 days tests, the values were constant across the soil samples ranging between 47.8 and 49.4 %, being lower nearest to anode, but with all values consistent below to the control value. The use of distilled water at the anolyte chamber and sodium silicate at the catholyte chamber were the reason why such phenomenon happens to the water content profile as discussed details from the monitoring results of inflow and outflow of water in section 7.2.4. At the beginning of test until 144 hours (6 days), the amount of inflow was higher than of the amount of outflow caused an increase in the water contents (see water content profile of 3 days test) across the soil sample due to the coupled flow (electroosmosis and electromigration) towards the cathode. After that period, the amount outflow of water was higher than the inflow of water caused the reduction of water content (see water content profile of 7 and 14 days tests) due to the dominant movement of higher concentration of anions which retarded the electroosmosis flow at the opposite direction.

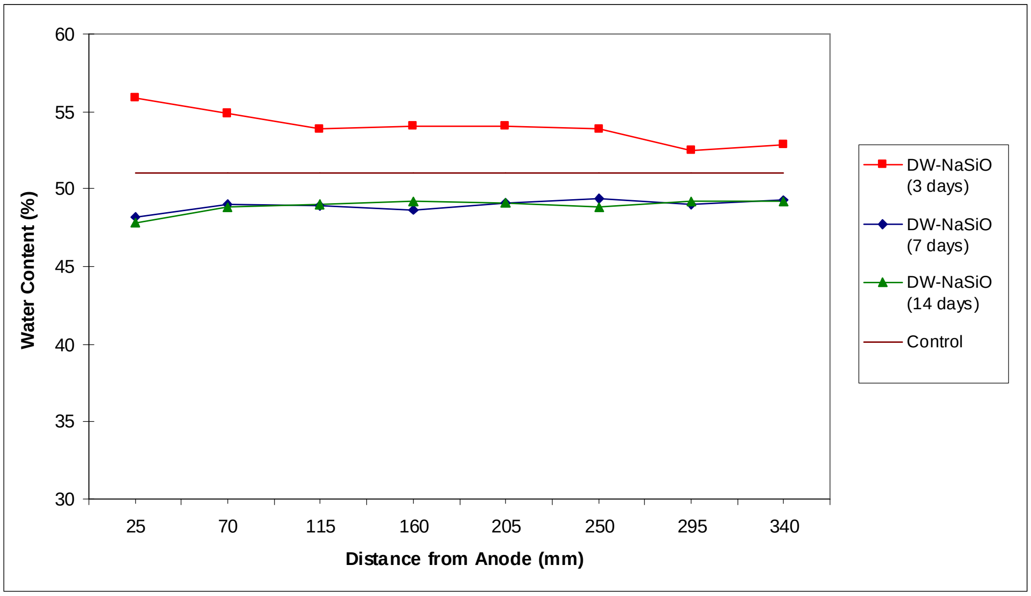

Figure 7.20: Water content profile of DW-NaSiO system with distance from anode.

Figure 7.21 for the CaCl-NaSiO system showing changes in water content between the anode and the cathode of soil samples. Mostly, all the water content values lie well above the control line except for the 7 and 14 days tests near the anode which is lie at the water content of 49.8 and 49.4 %, respectively. However, this ties in with the results discussed in Figure 7.8, which showed the inflow of water was higher than the outflow of water. This contributes to the increase of the water content above the control values across the soil samples. This also indicates the electromigration process was the main contributor in this system configuration compared to the electroosmosis process. The precipitation of cementitous agents between the soil particles at the cathode was another reason to slow the electrosmosis process, which blocking the flow path of water out of the system. The detail about development of precipitation in the CaCl-NaSiO system will be discussed in detail in section 7.32.

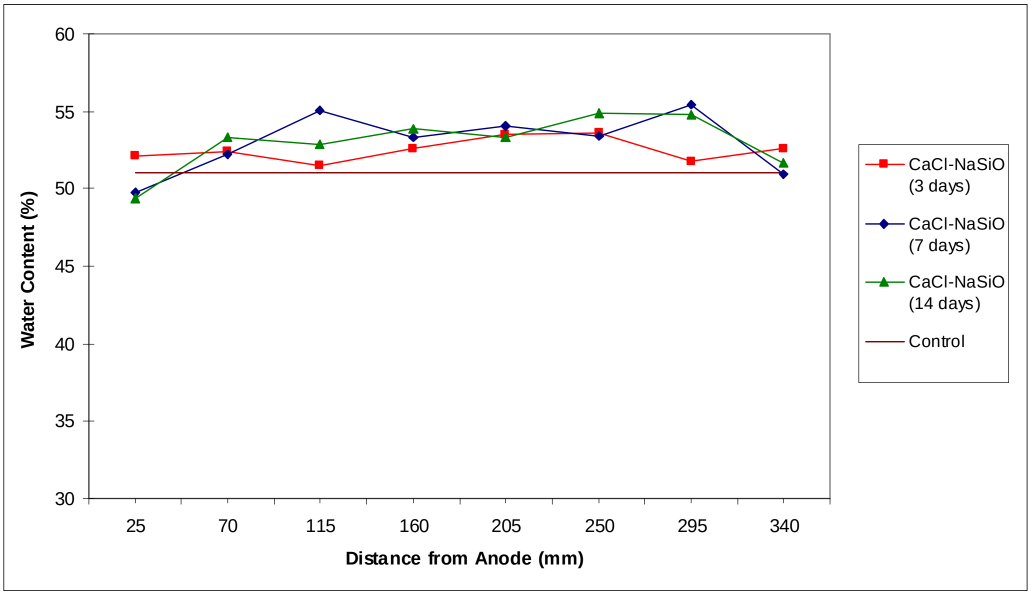

Figure 7.21: Water content profile of CaCl-NaSiO system with distance from anode.

There are many possibilities for the changes in water content have been drawn from this study and proven by Liaki *et al.* (2008, 2010) and Ahmad *et al.* (2011) due to the complexity of the electrokinetic process during EKS testing. Surprisingly, those studies have shown significant increase in shear strength especially near the cathode area. They have reported that from the relationship between the undrained shear strength and the water content of the soil and revealed that electromigration treatment generally strengthened the soil, even with a small increase in water content (see further discussion in section 7.3.3). One of the reasons for water content to increase across the soil sample is due to the setup of this EKS testing, which allow continuous addition of soluble chemical stabiliser and the contact between the soil-electrode. Therefore, it is difficult to predict to what extent the variation of water content would likely to be across the soil sample. Other reasons are soil temperature due to heating effect, swelling effect due to the direct contact of the soil with the electrolytes, thinning and thickening of double layer which change fabric of clays, precipitation, electroosmosis flow and electromigration of certain ions, and electric current variations are the factors that change the soil water content. Therefore, in some extent, it is essential to verify these factors with the other parameters to support any hypothesis before any conclusions can be made.

7.3.2 Shear Strength

The undrained shear strength profile of the CaCl-DW system show clear pattern of improvement with regards to treatment time (see Figure 7.22). The 3 day test profile is consistent across the samples, which lies below the control line ranging between 4 and 6 kPa. However, the 7 days test values are increased above the control line, raised to about 11 kPa near the anode and then the values are constant toward the cathode until it gained a higher strength of about 13 kPa at the proximity of the cathode.

The 14 days test shows the greatest improvement with regards to treatment time and distance from anode, which ranged between 14 and 18 kPa with the highest strength occurring at the proximity of the anode. The increase of strength with the increase of treatment was due to the changes of water content and electrochemical effect caused by electrokinetic process occurring concurrently. However, as seen in Figure 7.19, the water content changes are variable due to other effects and discussed later in this section.

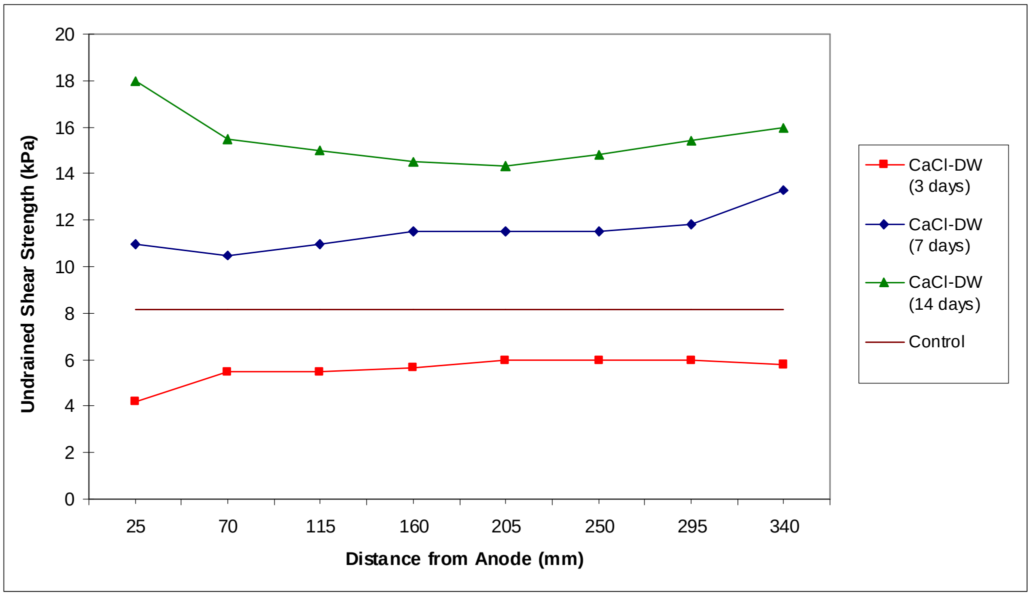

Figure 7.22: Undrained shear strength of CaCl-DW system with distance from anode.

For the DW-NaSiO system, the trend is similar to that of the CaCl-DW system (see Figure 7.23). The undrained shear strength values at 3 days dropped to an average value of 5 kPa from the control value of 8.1 kPa due to the changes of water content as seen in Figure 7.20. The distribution of undrained shear strength is fairly constant from anode to the cathode. On the other hand, the 7 days test seem to increase slightly from control value to an average of 8.7 kPa except near to the cathode (340 mm from anode), the value is drop to about 7.5 kPa. However, for the longest treatment time of 14 days, the overall values are significantly increased to approximate value of 11 kPa across the soil samples. However, an increase in undrained shear strength from 8.1 to 12.4 kPa is noticed at the proximity of the anode, even though the water content remained unchanged compared to the 7 days test as seen in Figure 7.20. Therefore, it is shows that the other factor had caused this phenomenon to occur and need to be validated with the other results of physical and chemical properties, e.g. Atterberg limit, pH, electrical conductivity and chemical concentration.

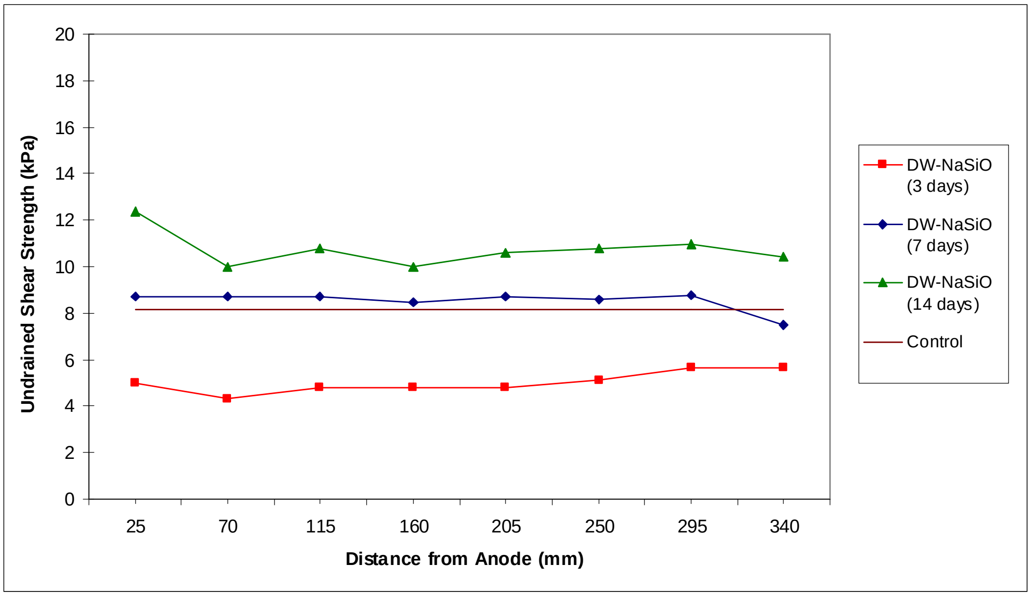

Figure 7.23: Undrained shear strength of DW-NaSiO system with distance from anode.

Interestingly, the CaCl-NaSiO system has different trend with the rest of the system as seen in Figure 7.24. This shows that the undrained shear strength values at the proximity to the electrode improved significantly with the greatest change occurring at the cathode. At the anode (25 mm from the anode), the value dropped at 6.5 kPa for the 3 days test but after the 7 days test the value is increased to about 10.5 kPa. It then continues to increase to reach the value of 11.4 kPa after 14 days. This trend was also similar to that seen at the cathode but the increase was at the greatest after 14 days, with a raise as high of 15.5 kPa compared to 13.2 kPa after 7 days test. The undrained shear strength after 3 days for the CaCl-NaSiO system are still below the control line across the soil sample. However, the values in the middle of the sample between 70 and 295 mm from anode are more uniform and close to the control value as seen in the 7 and 14 days tests. This contradicts with the other 2 systems which have shown greater improvement with time. The increased of water contents across the soil sample as seen in Figure 7.21 should have reduced the shear strength. However, the undrained shear strength values as seen in Figure 7.24 after 7 and 14 days remained unchanged at the mid-point of the sample and even increased at the anode and cathode, suggesting the other factors (precipitation due to the cementatious gels) caused this trend and will be discussed later in this Chapter.

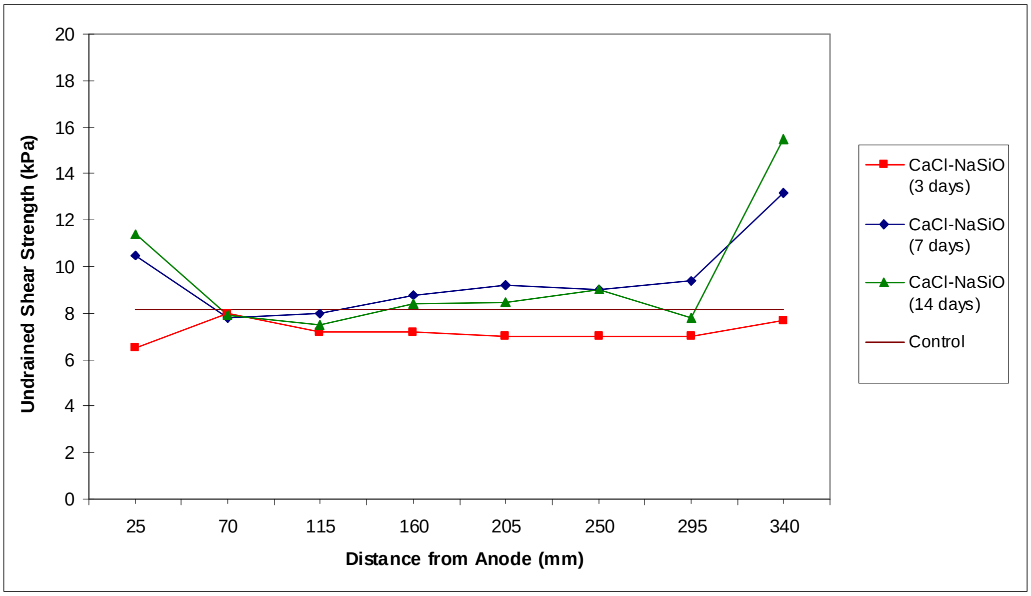

Figure 7.24: Undrained shear strength of CaCl-NaSiO system with distance from anode.

In general, this clearly shows the undrained shear strength values after 3 days for all those 3 systems depend on the water content values. The undrained shear strength distributions across the soil samples after 3 days are generally below the control value (low shear strength) due to the increased of water content. However, after 7 and 14 days especially for the CaCl-DW and CaCl-NaSiO systems, the increase of water content is not greatly reduced the undrained shear strength compared to the control value. Therefore, this suggests that the increased of shear strength is due to the electrochemical reactions during EKS treatment after certain periods of time. The error that could happen due to the shear strength determination using vane shear strength is discussed in section 7.5 to verify the accuracy of the data plotted across the soil sample. This phenomena can be confirmed when the graph of water content versus undrained shear strength were plotted as seen in Figure 7.25 until 7.27 for all systems.

Figure 7.25 shows most of data for the CaCl-DW system after 7 and 14 days are located above the control line indicating the area of soil improvement that not caused by water content variation. In comparison with the 3 days test, most of the data points almost lie along the control line with the exception of data corresponding to measurements close to the cathode, which are slightly further away from control line. Therefore, it is suggested that the short time period of this system is not influencing the shear strength of the treated soil with regards to electrochemical effects. On the other hand, the data points across the soil samples after 7 and 14 days lie well above the control line suggesting the soil strengthening due to the addition of calcium ions at the anode that are migrating towards the cathode, which in turn affects the soil behaviour.

For the DW-NaSiO system, all the data points are lie along the control line with the exception of certain points close to the anode or cathode, which are slightly moved either above or below the control as seen Figure 7.26. There is no evidence to suggest soil strengthening at the anode after 3 days occurs. Thus, utilising of distilled water and sodium silicate solution at the anode and cathode chamber, respectively does not affect the shear strength of the soil even after longer treatment times. The introduction of silicate ions alone without addition of calcium at the other side is important to promote the precipitation of the calcium silicate hydrate (CSH) and subsequently crystallising in the void spaces.

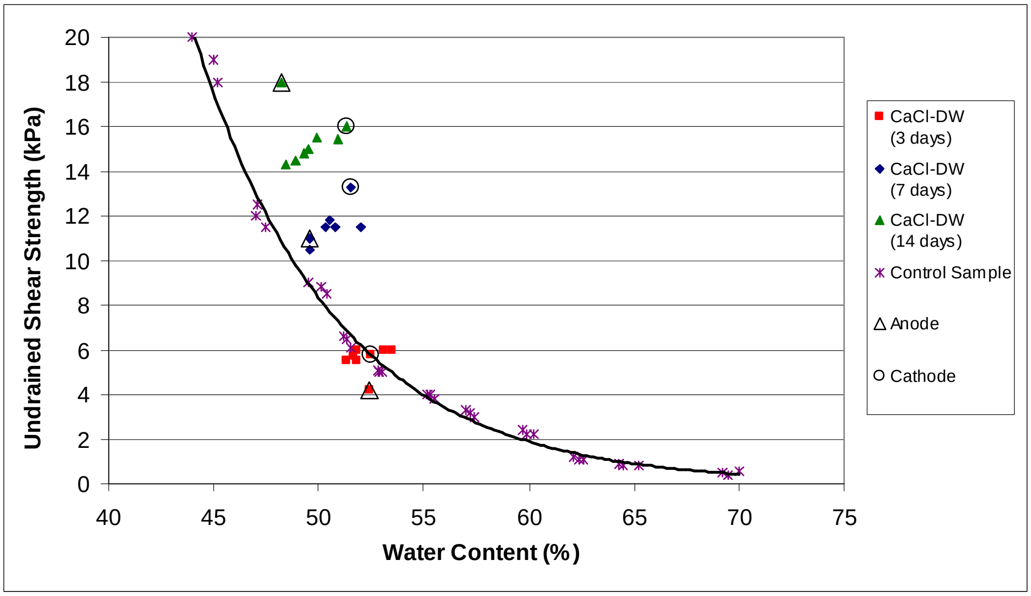

Figure 7.25: Relationship between undrained shear strength and water content of CaCl-DW system.

In Figure 7.27, most of data points for CaCl-NaSiO for 3, 7 and 14 days tests lie above the control line. It can be seen that the data points after 3 days are located slightly above the control line as expected because at this stage the electrochemical reactions have just started to take place. This was confirmed from pH result (discussed in section 7.4.1). Soil strengthening of this system across the soil samples due to the high concentration of calcium ions and silicate that dominates the ionic concentration of the pore fluid (see section 7.4.5) causes numerous electrochemical effects in soil; electrolysis, cations exchange, precipitation of salts or secondary mineral, physical and chemical adsorption, and fabric change. All these factors are inter-related with each other and contribute to the changes of soil behaviour due to the electrokinetic stabilisation treatment. The soil strengthening at the anode and in the middle of the sample was due to the calcium ions reducing the double layer thickness (cations exchange process) and allowed a more densely packing of the particles.

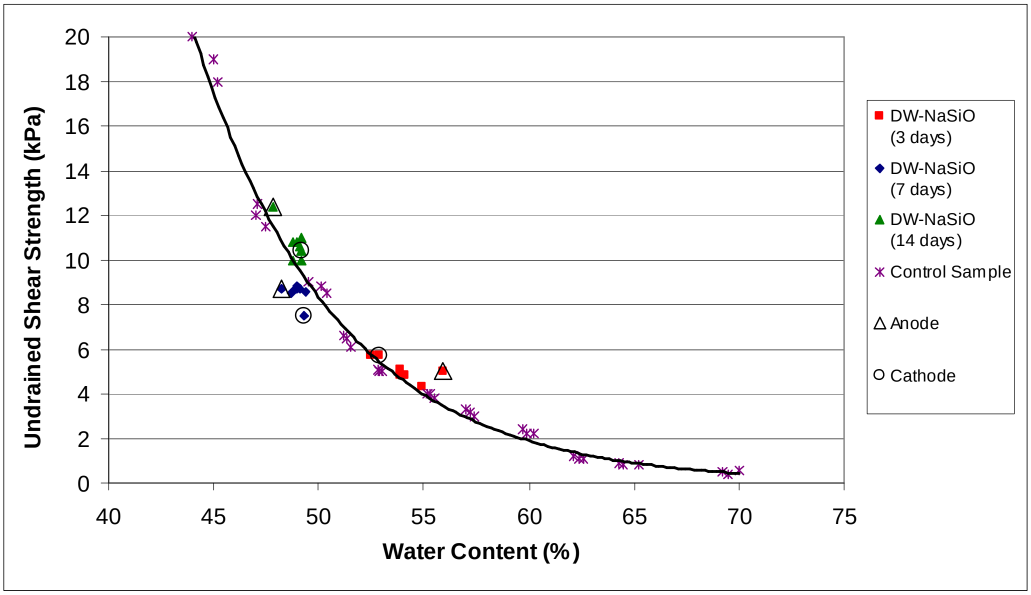

Figure 7.26: Relationship between undrained shear strength and water content of DW-NaSiO system.

However, it can observed that after 7 and 14 days the data points at the cathode showed a greater increase in soil strength compared with the rest of data point for both durations. Therefore, it can be concluded that the precipitation of insoluble salt has greater influence on the shear strength of the soil under electrokinetic stabilisation treatment and will be validated with the other physical and chemical parameters later on. The soil strengthening at the cathode attributed to the precipitation of calcium and silicate ions form cementing agent that bind the soil particles together. Many researchers have reported (Ozkan *et al.*, 1999; Alshawabkeh & Sheahan, 2003; Barker *et al.*, 2004 Asavadorndeja & Glawe, 2005) that the precipitation of metal hydroxide and cation exchange cause the increase of the shear strength after treatment.

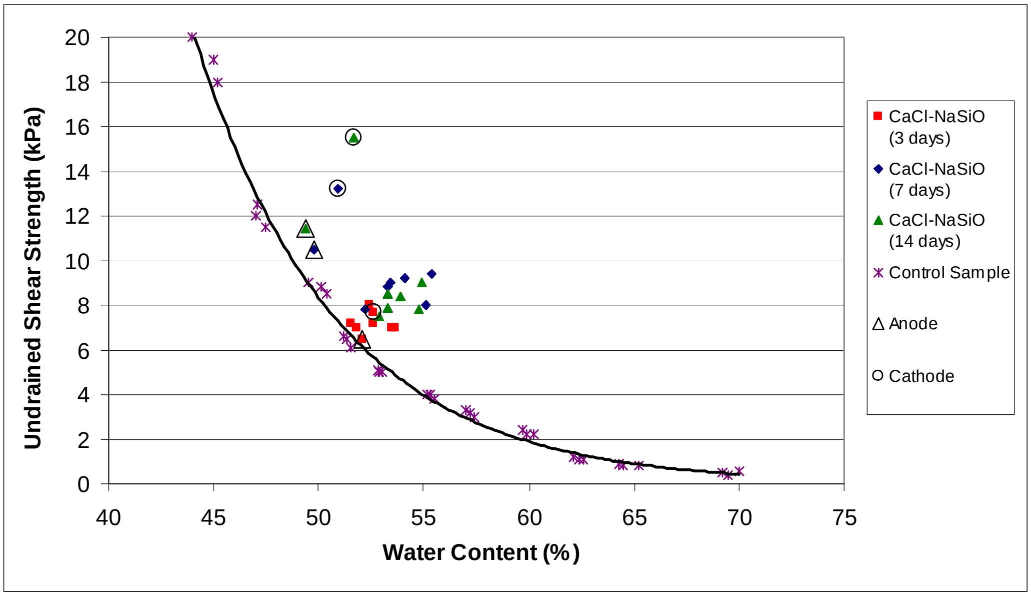

Figure 7.27: Relationship between undrained shear strength and water content of CaCl-NaSiO system.

7.3.3 Liquid Limit

The distribution of liquid limit values in Figure 7.28 for the CaCl-DW system show a clear trend with regards to treatment time along with the distance from anode. In all treatment time, the liquid limit values are decreased at the vicinity of the anode compared to the control values (55.6 %) and gradually increased toward the cathode to reach a value close to the control value. The 14 days test shows the lowest values of 50.3 % at 25 mm from anode and remained constant at the mid-point (between 25 to 115 mm from anode) before it reach the similar value of the control sample. It is followed by the 7 days test which lie at 53.4 % and remained unchanged from at 205 mm from anode onward. It is also has similar trend with the 3 days test but slightly increased to about 54.6 % before it remained unchanged at the same mid-point with the 7 days test toward the cathode. The decrease of liquid limits was due to the high acid environment (see section 7.4.1), thus causing the reduction of thickness double layer, which resulted in increase in shear strength at the anode as seen in Figure 7.25 and can be further confirmed from the chemical results discussed in section 7.4.3.

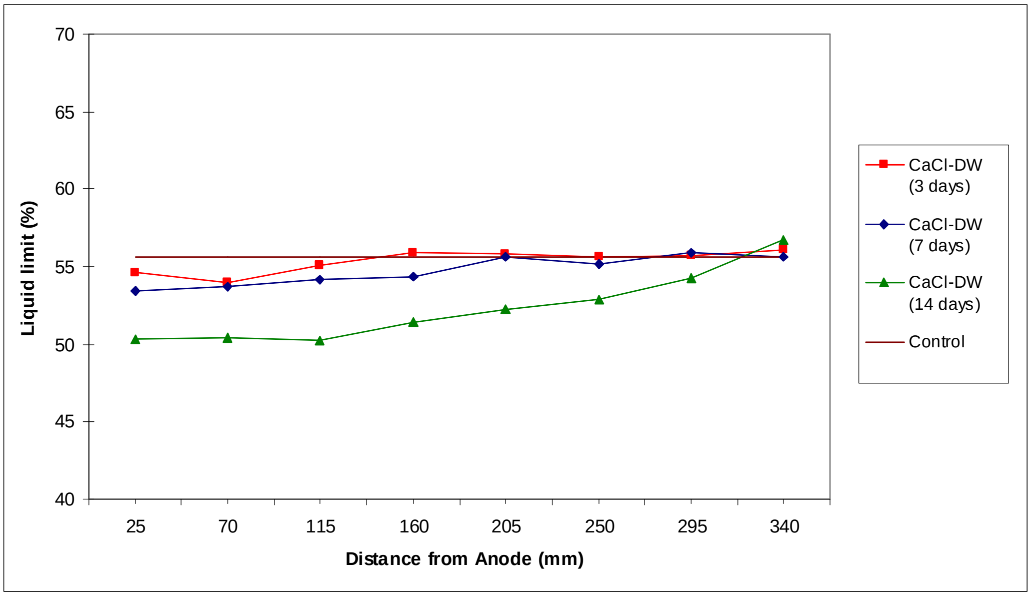

Figure 7.28: Liquid limit of CaCl-DW system with distance from anode.

For the DW-NaSiO system, all the liquid limit profiles also lie below the control value except some point near the cathode in the 3 day tests as shown in Figure 7.29. Therefore, it could be suggested that this trend is very similar trend to that of the CaCl-DW system. However, after 14 days, a significant decrease of liquid limit in the range between 47.4 and 49 % at 25 mm to 295 mm away from anode was observed, with a sudden increase to about 52.6 % at the vicinity of cathode (340 mm from anode). While, the 3 days test seem fairly consistent throughout the soil sample in the range between 53.7 and 55.6 %. The pH results in Figure 7.38 suggest a similar trend with other systems but does not increased the shear strength. According to Alshawabkeh & Sheahan (2003), the increase in shear strength would likely to occur if appropriate ions are introduced into the system, which in turn changes the soil fabric. Therefore, the introduction of silicate ions into the system would appear to have insignificant effect on shear strength of the treated soil.

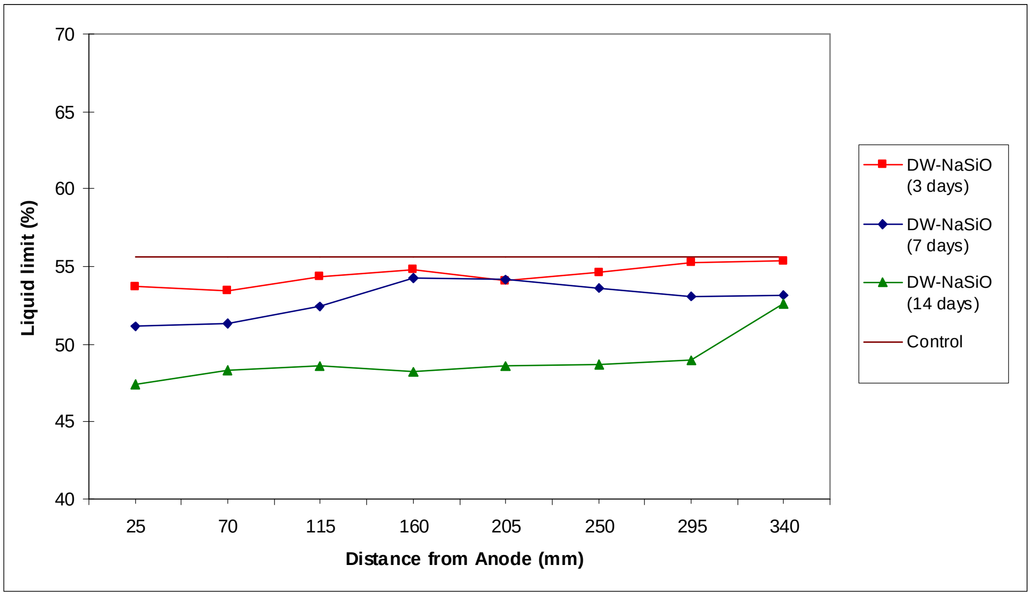

Figure 7.29: Liquid limit of DW-NaSiO system with distance from anode.

There is completely different trend as seen in Figure 7.30 for the CaCl-NaSiO system when compared to the other 2 systems. The overall distributions of liquid limits are widely spread across the soil samples in the range between 48.8 and 69.6 %. The 3 day tests shows a fairly constant value at about 56.1 % between 25 mm and 160 mm from anode but then gradually increased to about 60.5 % toward the cathode. The 7 day test shows greater increase of the liquid limit across the soil sample compared with the control value is in the range between 61.2 and 69.6%. By contrast, the 14 days test has the lowest value at the anode (48.8%) and increased significantly to cross the control value until reach as higher as 65.8 %. This was probably due to the movement of the acid font towards the cathode and met with the alkaline font at the mid-point of the sample, thus alter the clay structure. The movement of acid font towards the cathode also can neutralise the high pH near the cathode as seen in Figure 7.39, where pH dropped from pH 10 to pH 5 at 295 mm from anode. However, this acid font cannot move closer to the cathode (340 mm from anode) due to the precipitation of insoluble salt between the soil particles blocking any further movement through this area. Therefore, the pH is remain unchanged (pH >10) after 7 days compared to the 14 days. The significant change of liquid limits in this system confirmed the changes of clay structure due to the electrochemical effects, which in turn increase the soil shear strength as discussed in section 7.3.2.

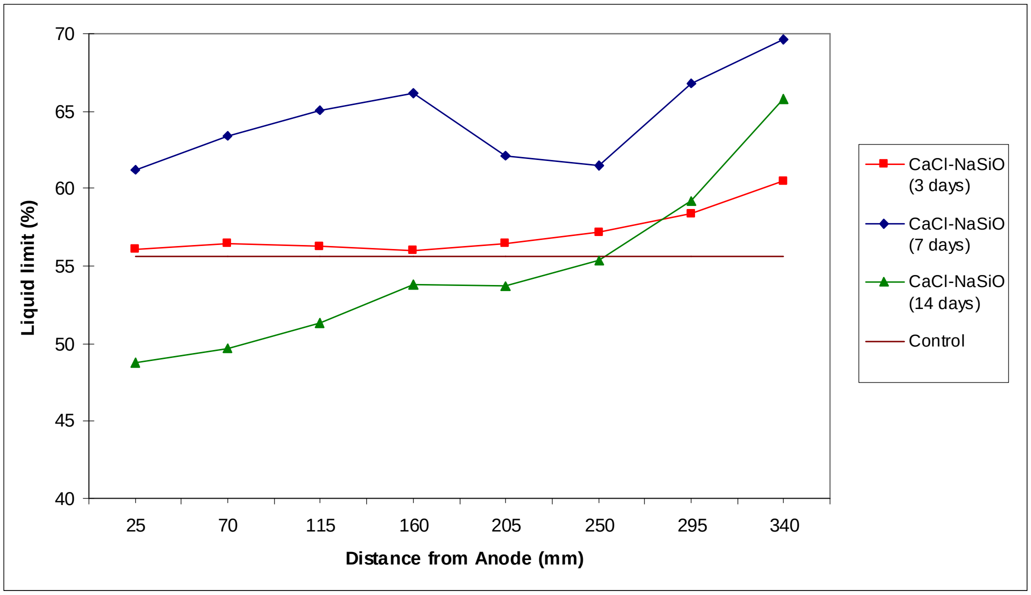

Figure 7.30: Liquid limit of CaCl-NaSiO system with distance from anode.

7.3.4 Plastic Limit

Figure 7.31 shows plastic limit distribution for the CaCl-DW across the soil samples. There is a clear trend observed at the vicinity of anode to a certain point in the middle of the sample especially after 7 and 14 days (between 25 and 205 mm from anode). At 25 mm from anode, the plastic limits of both experiments are decreased significantly below the control value (34.6 %) with the 14 days test showing the lowest reduction (29.4 %) followed by the 7 days test with a value of 30.5 %. The plastic limit of both experiments are gradually increased towards the cathode until they reach similar values to that of the control value at 250 mm from anode and remained constant to 290 mm from the anode. However, these values increased slightly when reach close to the cathode (340 mm from anode). By contrast, the 3 days test shows a little change at about 32.7 % (25 mm from anode) and remained stable close to the control value at the rest of the point towards the cathode. This trend is similar with the results of Gray & Shlocker (1969) and Gray (1970) and also discussed in section 3.5, Chapter 3. They observed a decrease of plastic limit after treatment for most of the samples. This contradicts with findings by Ozkan *et al.* (1999), Asavadorndeja & Glawe (2005) and Jayasekera & Hall (2006). Therefore, it is suggested the plastic limit distribution depends on several factors such as type of clay minerals, electrolyte concentration, pH gradient and release of certain ions (i.e. Al, Fe, Mg and Si) from the clay lattice or by introduction of certain ions (i.e. Ca and Si for this research study) into the soil sample through electrodes.

In the CaCl-DW system, the introduction of Ca ions into the system together with the changes of pH (ranging from 3.8 to 4.3) under acidic near the anode for longer treatment time (7 and 14 days treatment) had caused a decrease in plastic limit due to the dissolution of clay mineral, thereby alter the physicochemical of the clay structure. This is also confirmed from the results of electrical conductivity in Figure 7.40 which show significant increase with treatment time. The electrical conductivity is increased significantly from 790 µS/cm (7 days treatment) to 8320 µS/cm (14 days treatment).

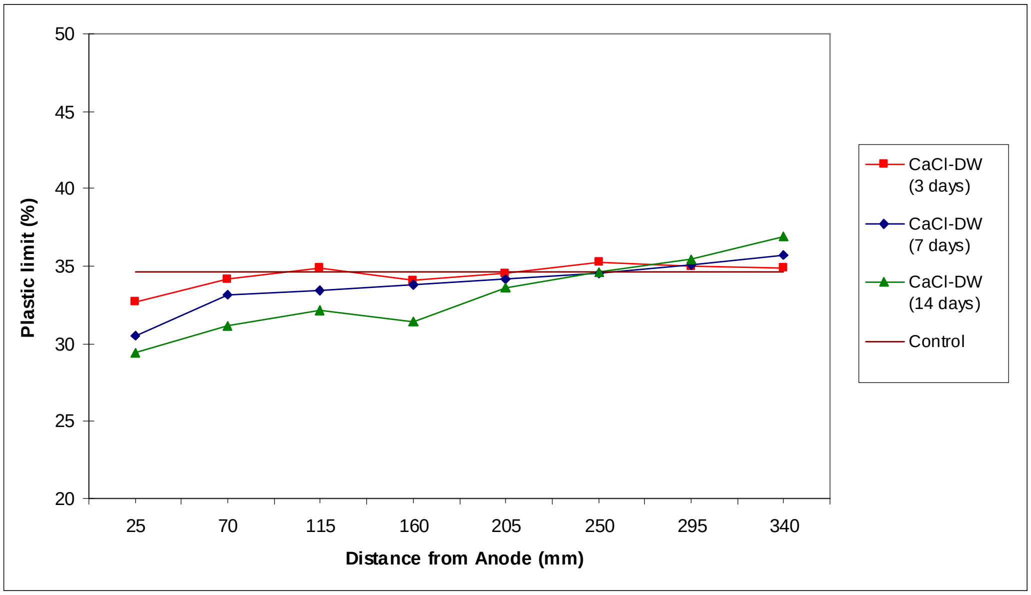

Figure 7.31: Plastic limit of CaCl-DW system with distance from anode.

For the DW-NaSiO system, the plastic limit values are decreased slightly across the soil profiles in the range between 32 % and 34.6 % (see Figure 7.32). However, the plastic limit values of the 3 days test varied along the soil sample ranging between 33.5 and 35.4 %. A low margin of about ± 1 % for the 3 days test can be considered not significantly affect the plastic limit for short period of time, especially given its method of determination (see BS 1377: Part 2: 1990). Therefore, it is suggested that the introduction of distilled water at the anode and sodium silicate at the cathode had not caused significant changes for plastic limit with the exception of the 14 days treatment at the anode area (25 mm from anode). In this system, a longer treatment time had caused an increase in pH drastically from acidic environment (pH 4.2 and pH 3.9 for 3 days and 7 days treatment, respectively) to alkaline environment (pH 10.3 for 14 days treatment) as observed in Figure 7.38. This is due to the migration of Si from the cathode had reached at the anode thus change the physicochemical of soil at the vicinity of anode and will be discussed further in term of pH, electrical conductivity and ions concentration values in chemical testing data in section 7.4 in this chapter.

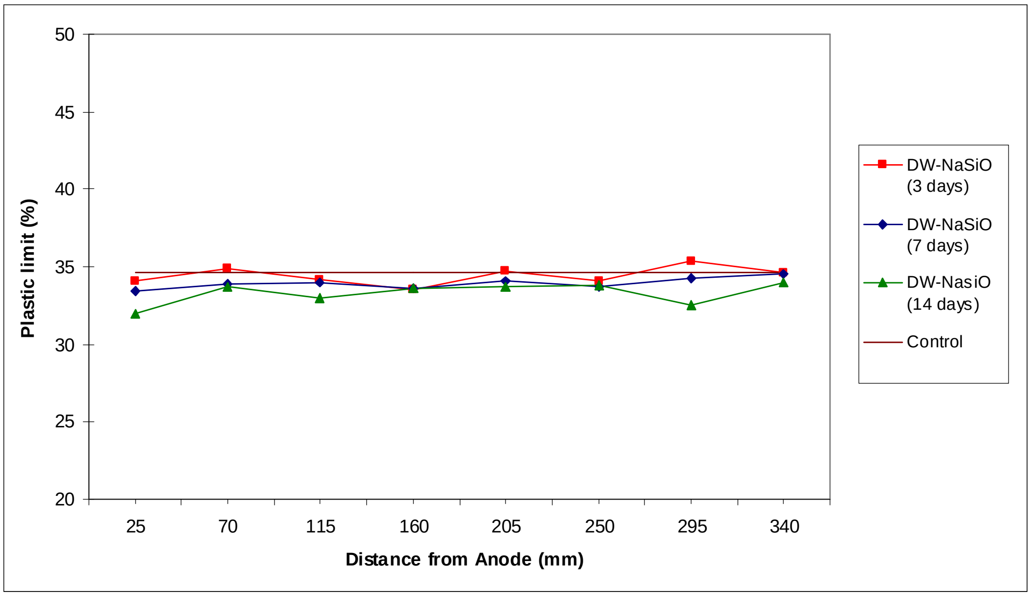

Figure 7.32: Plastic limit of DW-NaSiO system with distance from anode.

Again, the plastic limit values of the CaCl-NaSiO system show an interesting trend after 14 days. This can be seen from the result of liquid limit as mentioned earlier in Figure 7.30, which shows that after 14 days significant impact on the soil behaviour occurs. As seen in Figure 7.33, a large reduction of about 27.1 % is observed near the anode. The plastic limit values then steadily increased towards the cathode until they reach the value of 32.7 %

(205 mm from anode) and still below the control value. However, in the vicinity of the cathode a sharp increased from about 32.2 % to about 38.7 % is seen. A large decrease of the plastic limit is observed at the proximity of anode (25 to 115 mm from anode) for 14 days treatment is due to an acidic environment as can be observed in Figure 7.39 which showed the pH drop from pH 6.4 of 3 days treatment to pH 4.5 after 14 days treatment. Bohn *et al.* (2001) stated that the low pH of about pH < 4.7 had caused multivalent cations of Al, Fe and Mg released from the degradation of the clay minerals into the pore fluid. These multivalent cations strongly attracted by negatively charged clay surface and contribute to the thickening of diffuse double layer.

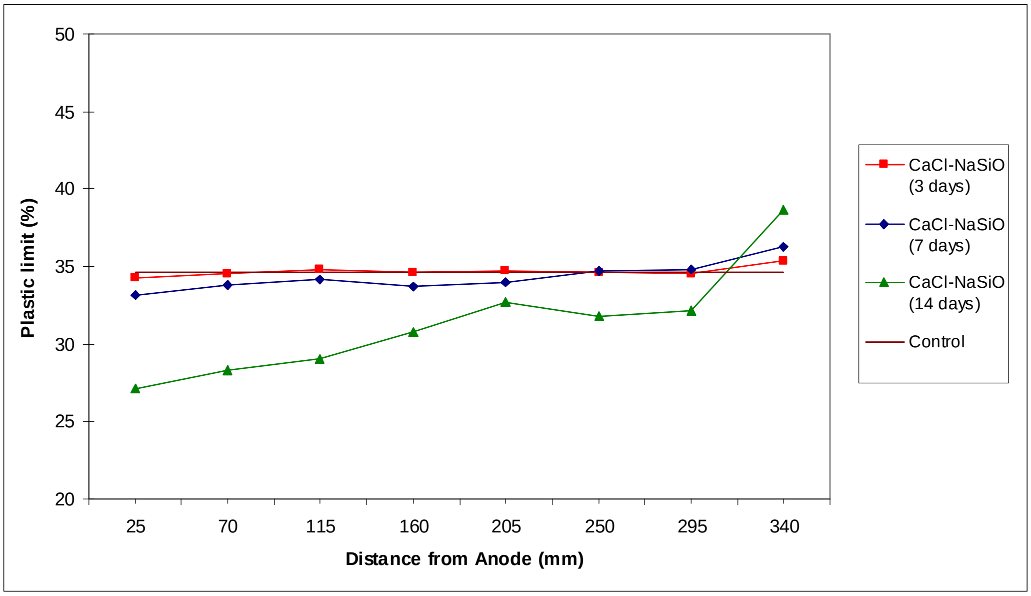

Figure 7.33: Plastic limit of CaCl-NaSiO system with distance from anode.

7.3.5 Plasticity Index

For the CaCl-DW system, the plasticity index values of all treatment time varied across the sample ranging between 17 and 23 % compared to the control value (21%) as seen in

Figure 7.34. In general, the values remained close to the control values except certain points at the anode, which slightly increased to reach a maximum value 23 %. By contrast, the values slightly decrease below the control line especially for the 14 days test. Therefore, the longer time period of 14 days has significantly reduced the plasticity index values of the CaCl-DW system due to the changes of liquid limit and plastic limit values discussed in section 7.3.3 and 7.3.4 due to the electrochemical effects.

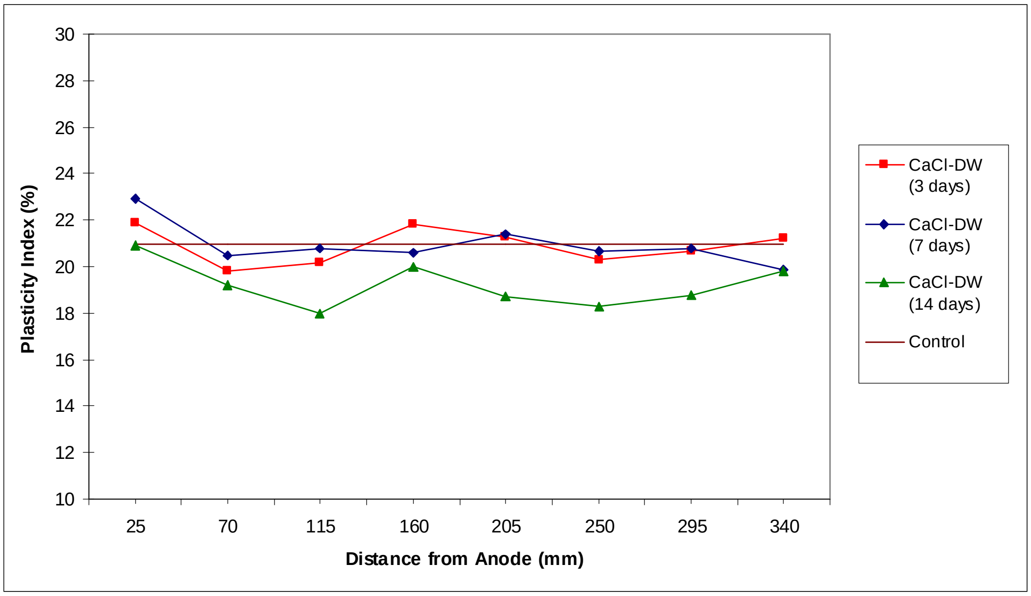

Figure 7.34: Plasticity index of CaCl-DW system with distance from anode.

In the DW-NaSiO system, the plasticity index values of the 7 and 14 days test are lie below the control value (see Figure 7.35). The significant decreased is seen after 14 days throughout the soil sample, ranging between 14 and 19 %. By contrast, the 3 days test remained consistent throughout the soil sample at about same value as control sample. A huge variation can be seen for the CaCl-NaSiO system in Figure 7.36 especially at the cathode area for all test periods. However, the 7 days test shows the greatest increased and consistent across the soil sample, ranging between 27 and 33 % higher than of the control sample (21 %). This indicates that after 7 days, the introduction of calcium and silicate ion has caused significant changes in soil fabric due to the cation exchange and precipitation.

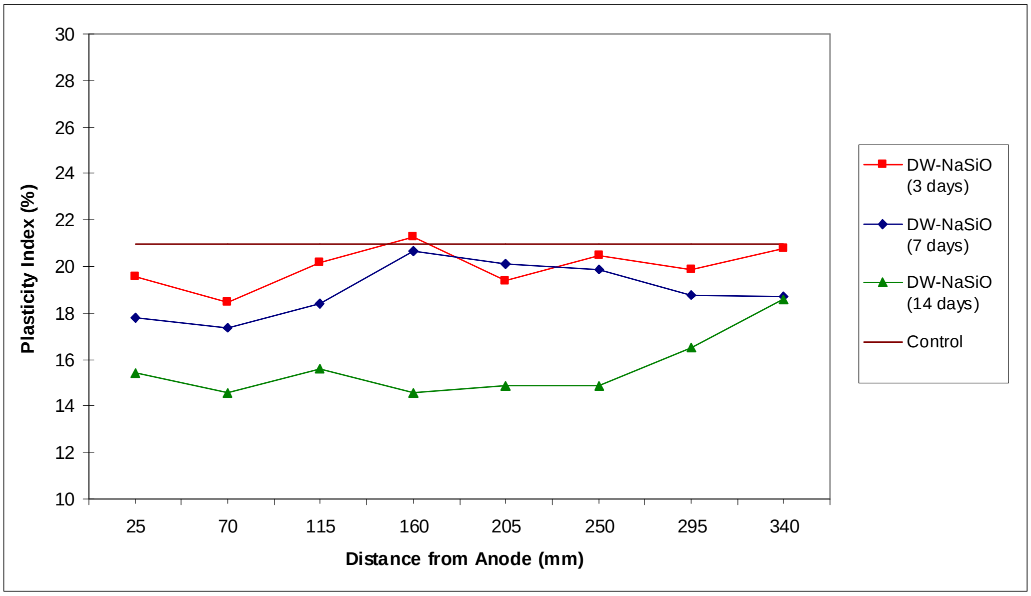

Figure 7.35: Plasticity index of DW-NaSiO system with distance from anode.

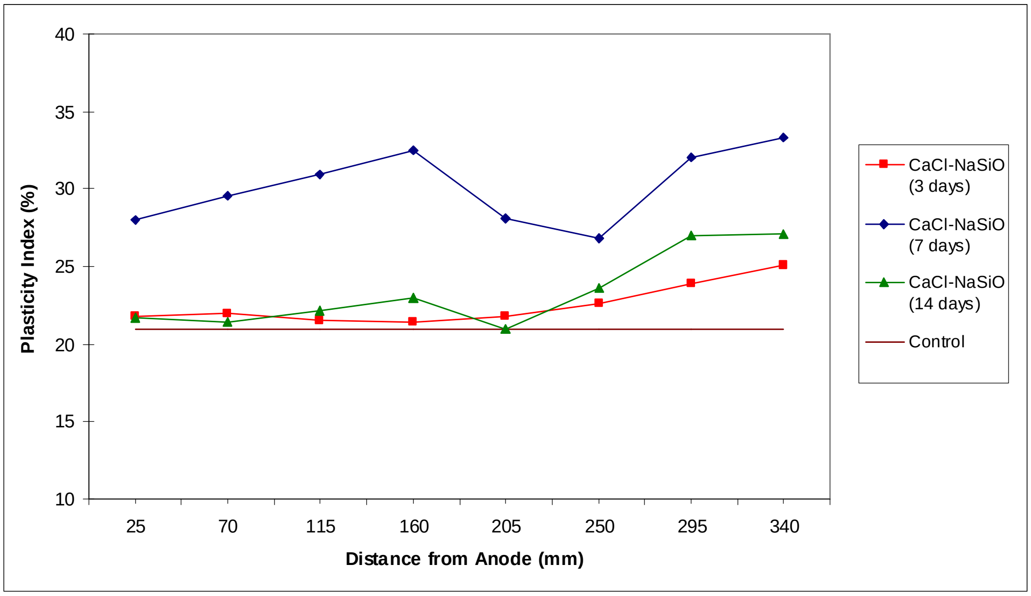

Figure 7.36: Plasticity index of CaCl-NaSiO system with distance from anode.

7.4 Results of Chemical Testing After EKS Treatment

Table 7.4 below shows a summary of the pH and electrical conductivity values for EKS systems conducted in this research.

Table 7.4: Summary of the pH and electrical conductivity values for 3 different EKS systems.

Distance from anode (mm)	**CaCl-DW(3 days)**		**CaCl-DW(7 days)**		**CaCl-DW(14 days)**	
	pH	**EC(µS/cm)**	**pH**	**EC(µS/cm)**	**pH**	**EC(µS/cm)**
25	6.5	4020	3.9	790	3.8	8320
70	5.4	840	4.3	550	4.0	6540
115	5.5	320	4.7	330	4.1	3410
160	5.4	290	5.4	80	4.2	2600
205	5.1	65	5.4	50	4.5	2390
250	5.0	56	4.9	20	4.9	3140
295	4.8	49	5.1	40	8.2	2790
340	5.5	54	6.5	60	6.7	650
Distance from anode (mm)	**DW-NaSiO(3 days)**		**DW-NaSiO(7 days)**		**DW-NaSiO(14 days)**	
	pH	**EC(µS/cm)**	**pH**	**EC(µS/cm)**	**pH**	**EC(µS/cm)**
25	4.2	48	3.9	109	10.3	476
70	4.9	42	4.4	53	7.4	163
115	5.1	35	5.0	36	5.2	55
160	5.4	31	5.2	35	5.3	48
205	5.4	32	5.3	31	5.3	45
250	5.6	29	5.4	33	5.3	43
295	5.7	25	5.4	20	5.4	47
340	8.3	70	7.2	67	10.7	1170
Distance from anode (mm)	**CaCl-NaSiO(3 days)**		**CaCl-NaSiO(7 days)**		**CaCl-NaSiO(14 days)**	
	pH	**EC(µS/cm)**	**pH**	**EC(µS/cm)**	**pH**	**EC(µS/cm)**
25	6.4	6770	4.4	5110	4.5	12050
70	6.6	4530	4.5	2860	4.9	6620
115	7.3	4350	4.8	1250	5.1	2670
160	6.3	380	5.3	2510	5.5	2740
205	5.0	110	5.3	940	5.7	2950
250	5.1	64	5.3	2410	5.2	1200
295	5.6	61	9.0	220	5.1	1050
340	10.8	1970	10.4	2100	10.7	2500

7.4.1 pH

Results of pH distribution across the soil samples for the CaCl-DW system show clear indication of electrokinetic effects on pH at the anode and cathode for longer periods of time (the 7 and 14 days tests) as presented in Figure 7.37. The pH value of 3 days test at the anode (25 mm from anode) was significantly higher above the control value (pH 5.1) reaching about pH 6.5 but then stabilised toward the cathode ranging between pH 4.8 and 5.5. This was expected due to the introduction of highly alkaline calcium chloride solution at the anolyte chamber.

However, after longer treatment times were applied for the 7 and 14 days tests, the pH was decreased significantly to pH 3.9 and pH 3.8, respectively creating an acid font near to the anode region. At the cathode, there were significant increases of pH values for 7 and 14 days tests from pH close to the control value (295 mm from anode) to about pH 6.5 and 6.7, respectively creating a neutral pH font near to the cathode.

Interestingly, there is drastic pH change after 14 days at the anode region (25 mm from anode) in the DW-NaSiO system when distilled water and sodium silicate were applied at the anode and cathode, respectively (see Figure 7.38). The pH was increased significantly to about pH 10.3 creating a highly alkaline environment at the anode region. By comparison with the 3 and 7 days tests, these pH values are 4.2 and 3.9, respectively at the same position. This is attributed to the introduction of distilled water at the anode that may neutralise the acidity environment after certain times. This contradicts with the pure system when both distilled water were applied at the anode and cathode. It was assumed that the after 14 days, the alkaline font migrates from cathode to the anode creating a high alkaline environment at the anode region. Since hydroxide ion moves slower than hydrogen ions, it takes longer for hydroxide ions to migrate from cathode to anode. However at the cathode, the pH values are increased considerably for all treatment times which for the 14 days test reached a pH value of 10.7 followed by the 3 day test (pH 8.3) and the 7 days test (pH 7.2).

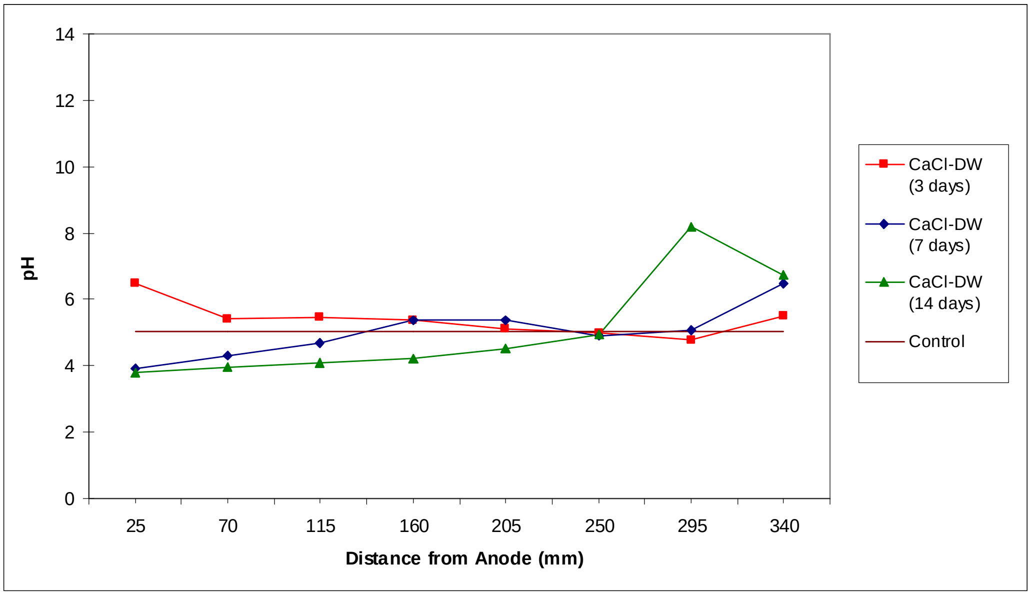

Figure 7.37: pH of CaCl-DW system with distance from anode.

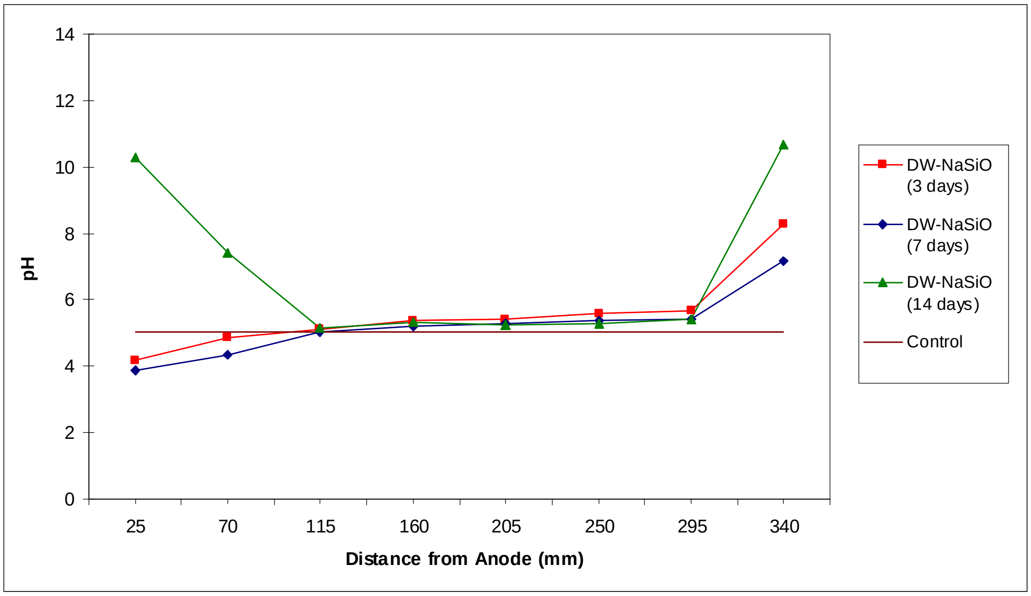

Figure 7.38: pH of DW-NaSiO system with distance from anode.

As with other two systems, the CaCl-NaSiO system produced a similar pH distribution especially at the anode and cathode regions (see Figure 7.39). As with the CaCl-DW system, after 3 days the CaCl-NaSiO system showed a pH of 6.4 around the anode region for short period of time due to the addition of highly alkaline calcium chloride solution at the anode. However, after 7 and 14 days the pH values start to decrease significantly to a low pH around pH 4.5. The generation of high acidity environment due to electrolysis process at the anode was neutralised by the calcium chloride solution during EKS testing. This can be validated from the pure system presented in Chapter 6 which used distilled water only at the anode electrode thus creating a very significant acid font in this region. In general, there was not much change in pH values happened in the middle of the samples for all the systems. This was due to the both hydrogen and hydroxide ions meeting at mid-point creating a neutral pH condition.

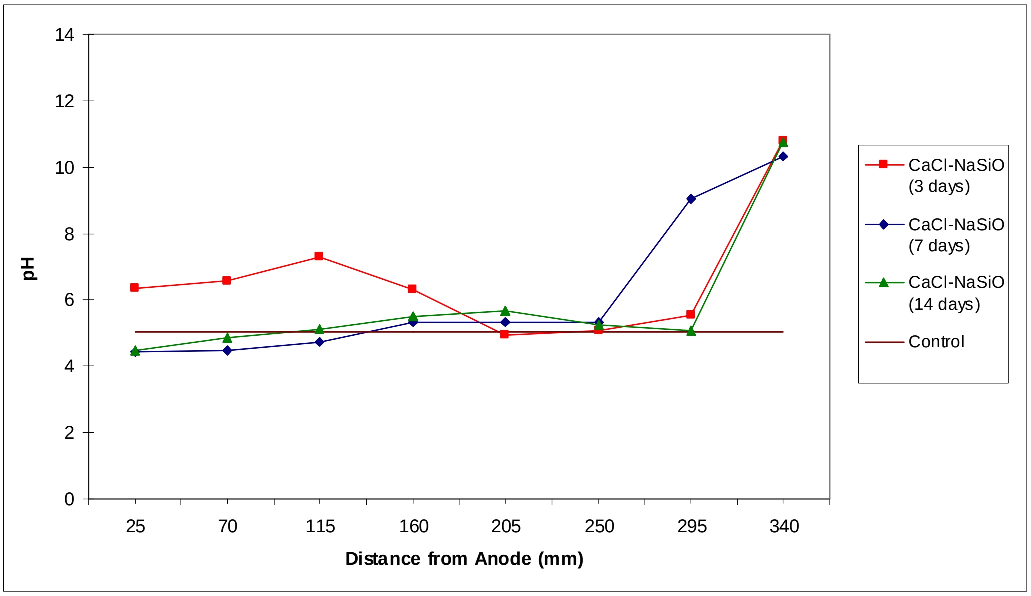

Figure 7.39: pH of CaCl-NaSiO system with distance from anode.

7.4.2 Electrical Conductivity

The electrical conductivity distribution of the CaCl-DW presented in the Figure 7.40 shows the large values at the anode (25 mm from anode) compared with the vicinity of the cathode. This was expected due to the fact that calcium ions are introduced into the system and hydrogen ion generated from the electrolysis process that contribute to the highly conductive solution in pore fluid of clay (see section 7.4.3). For the short period of time as seen in the 3 and 7 days tests, the values are 4020 and 720 µS/cm, respectively. The 14 days test shows the highest value of about 8320 µS/cm. It was clearly showed that the dissolution of chemical compound and clay mineral was likely to take place after 14 days, which released certain ions into the pore fluid and remain in ionic state under acid environment, which contributes to the highest electrical conductivity at the anode area. Thus contributes to the cation exchange process due to the introduction of calcium ions, which are continuously supplied at the anode, thus changes the clay fabric of the soils. This acid font has moved further towards the cathode due to the coupled flow thus dominates the pH changes across the soil samples and neutralised the alkaline font generated at the cathode. Therefore, there was no sign of precipitation would likely to occur in this system due to the pH below 7 at the cathode as seen in Figure 7.37 and no silicate ions were introduced at the cathode to magnify the precipitation process compared to the CaCl-NaSiO system.

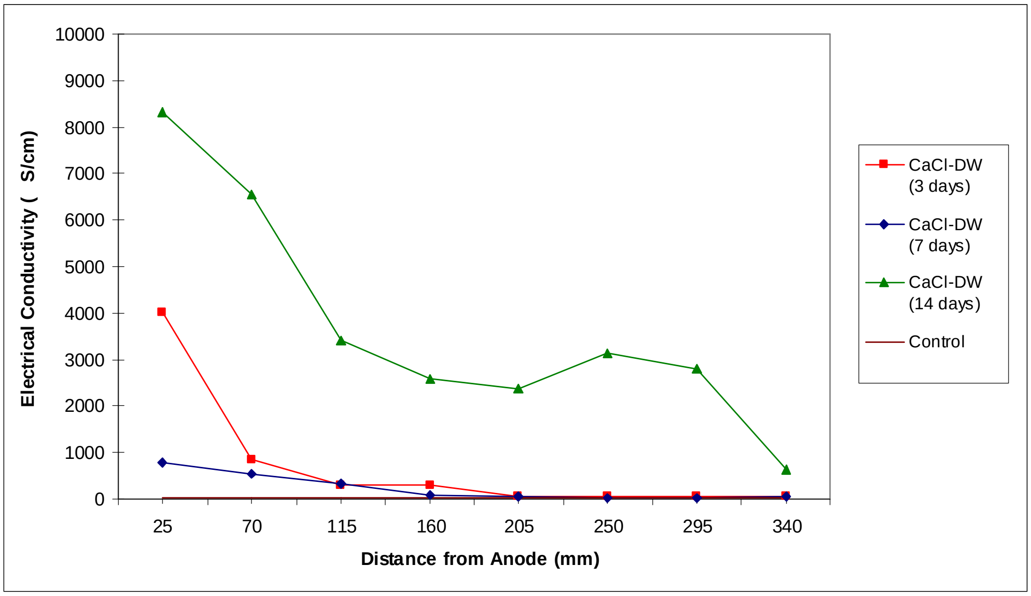

Figure 7.40: Electrical conductivity of CaCl-DW system with distance from anode.

For the DW-NaSiO system, the electrical conductivity distributions show a great variation especially at the anode and cathode, which has value of 500 and 1200 µS/cm, respectively (see Figure 7.41). The highest value at the cathode is due to the addition of sodium silicate at the cathode chamber. In addition, the precipitation of the insoluble salt or gels also can contribute to the higher value of electrical conductivity at the cathode region was proven by Ozkan *et al.* (1999) and Jayasekera & Hall (2006). However, the slight increase of electrical conductivity values at the anode region is thought to be due to the dissolution of mineral in the high acidity environment causing release of ions into the pore solution after certain time as seen in the 7 and 14 days tests.

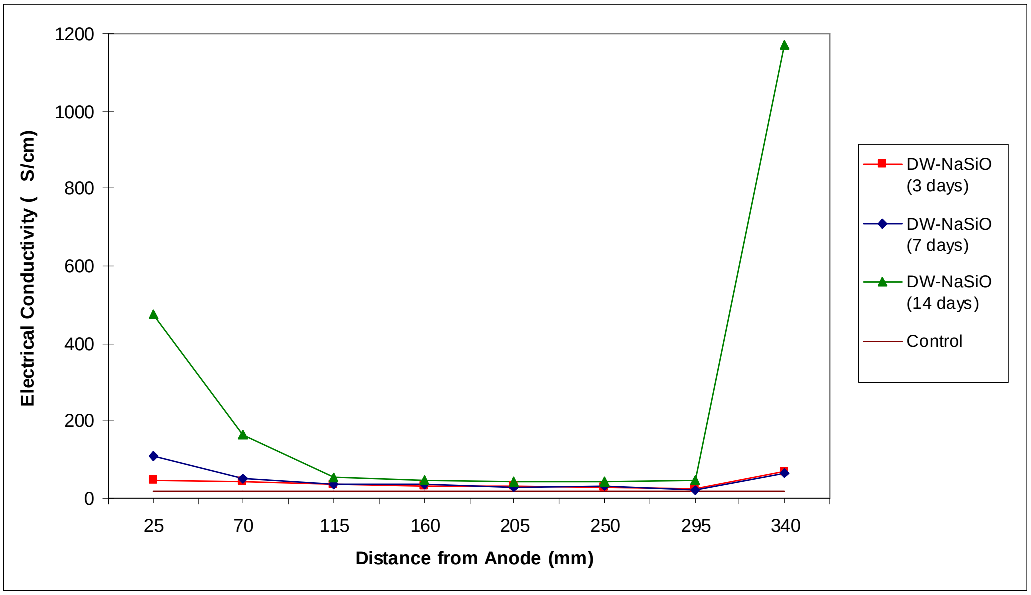

Figure 7.41: Electrical conductivity of DW-NaSiO system with distance from anode.

For the CaCl-NaSiO system, the trend was almost similar with the CaCl-DW but at a significantly higher electrical conductivity in the middle of the samples after 3 and 7 days (see Figure 7.42). This was an indication of the mobile ions from both directions flowing across the soil samples that contribute to the variation of higher electrical conductivity. The higher values at the anode were due to the dissolution of minerals, resulting in cation exchange processes and the lower values at the cathode attributed the precipitation of insoluble salt.

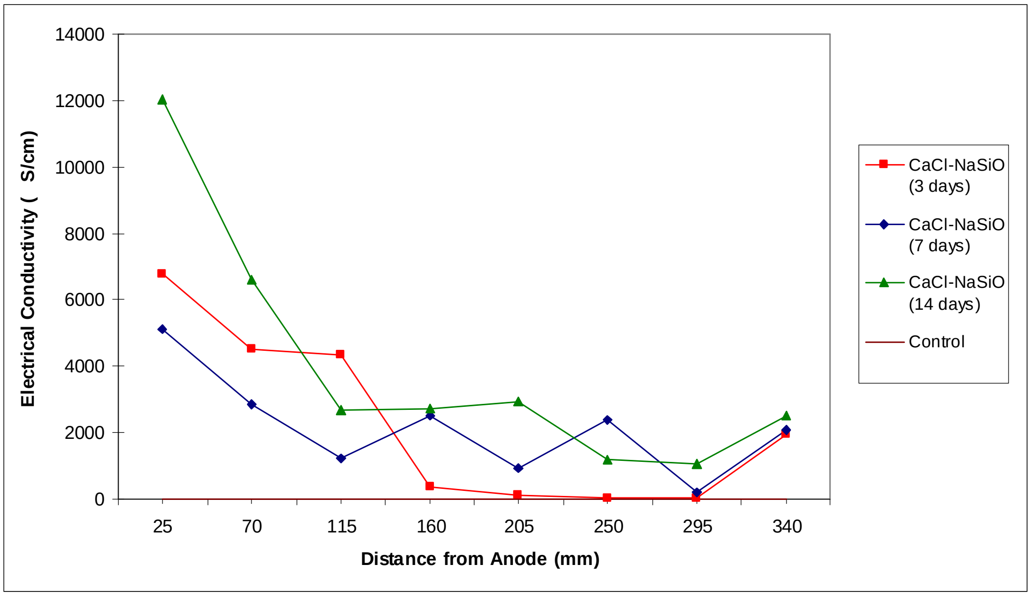

Figure 7.42: Electrical conductivity of CaCl-NaSiO system with distance from anode.

7.4.3 Metal Concentration of CaCl-DW system

7.43 to 7.48 show the variation of metal concentration of CaCl-DW system from anode to cathode. In regards to treatment time, the calcium concentration shows significant increase across the soil samples as seen in Figure 7.43. This indicated the migration of calcium ions due to electrokinetic process (electroosmosis and electromigration) towards the cathode thus increased the calcium concentration along the soil profile.

In the short term (after 3 days), the calcium concentration increased from 76 mg/kg (control value) to about 5500 mg/kg (between 25 and 70 mm from anode). Further away from anode at 115 and 160 mm from anode the values decreased suddenly to about 404 and 652 mg/kg, respectively until reaching the value of 87 mg/kg at 205 mm from anode (in the middle of the sample). Hence, after 3 days the calcium ions have moved to approximately half way across the sample towards the cathode. It was observed the calcium ions are reached the end of the sample ranging from 1791 to 13331 mg/kg after 7 days.

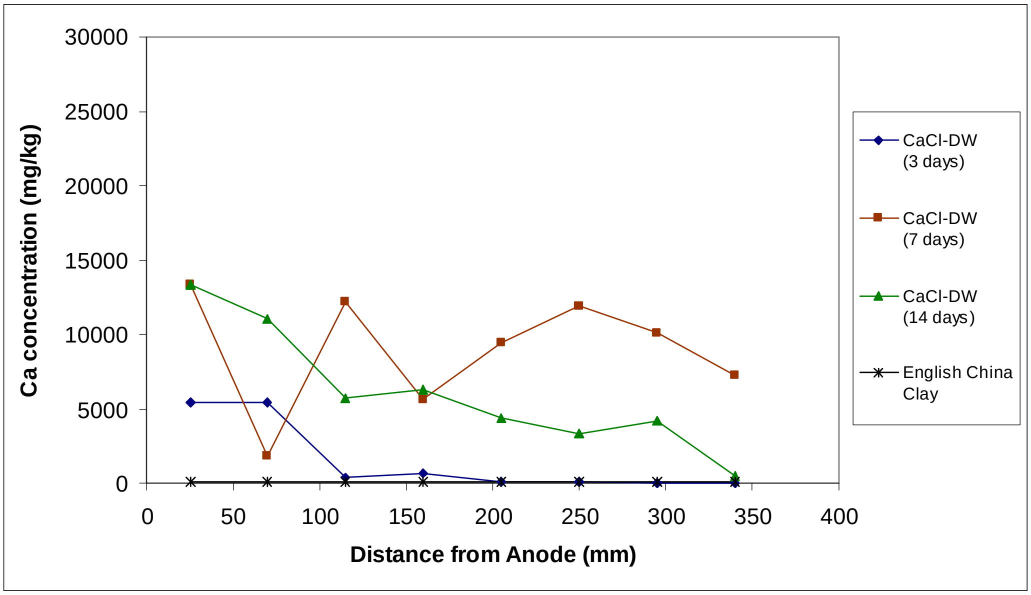

Figure 7.43: Ca concentration of CaCl-DW system with distance from anode.

However, when much longer period was applied (after 14 days), the calcium concentration dropped at the middle of sample from about 11000 mg/kg to about 5000 mg/kg(between 115 and 295 mm from anode) and dropped further to about 445 mg/kg when it reach the end sample (340 mm from anode). The lower concentration of calcium ions towards the cathode suggested that the precipitation had occurred at this region as supported from the lower value of electrical conductivity at the cathode after 14 days. Another reason could be the calcium ions were flushed away from the system through the catholyte chamber after 14 days thus decreased its concentration toward the cathode. At the same time, the flow of water was stopped after 240 hours (10 days) as seen Figure 7.16 suggesting the electroosmosis flow was also stopped after that time. Therefore, the movement of calcium ion was relied on the electromigration flow only. A coupled flow phenomena (electroosmosis and electromigration) was the reason why the migration of cations moves faster toward the cathode than anions toward the anode (electromigration only).

As observed in Figure 7.44, the Fe concentrations are varied along the soil profiles ranging between 1400 and 2500 mg/kg. The small different compared to control value (1600 mg/kg) suggested that the Fe ions within the soil sample are not changing due to the electrokinetic processes with regards to treatment time and distance from the anode. A continuous supply of calcium ions at the anode chamber was unlikely to replace the Fe ions due to the lyotropic series as discussed in Chapter 2.

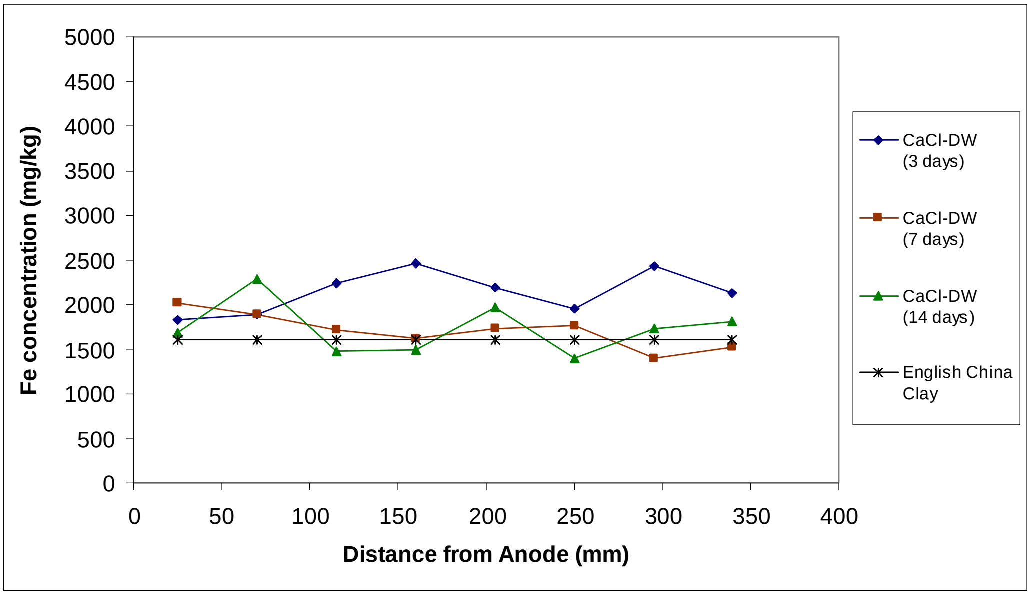

Figure 7.44: Fe concentration of CaCl-DW system with distance from anode.

The Si concentration level in Figure 7.45 are also fluctuated across the soil profiles for the 7 and 14 days test but slightly decreased below the control value. As discussed in Chapter 3, the high solubility of Si under certain pH environment had caused the Si ion released into the pore fluid thus varied across the soil samples. This can be confirmed from the results of pH and electrical conductivity as discussed in section 7.4.1 and 7.4.2, respectively.

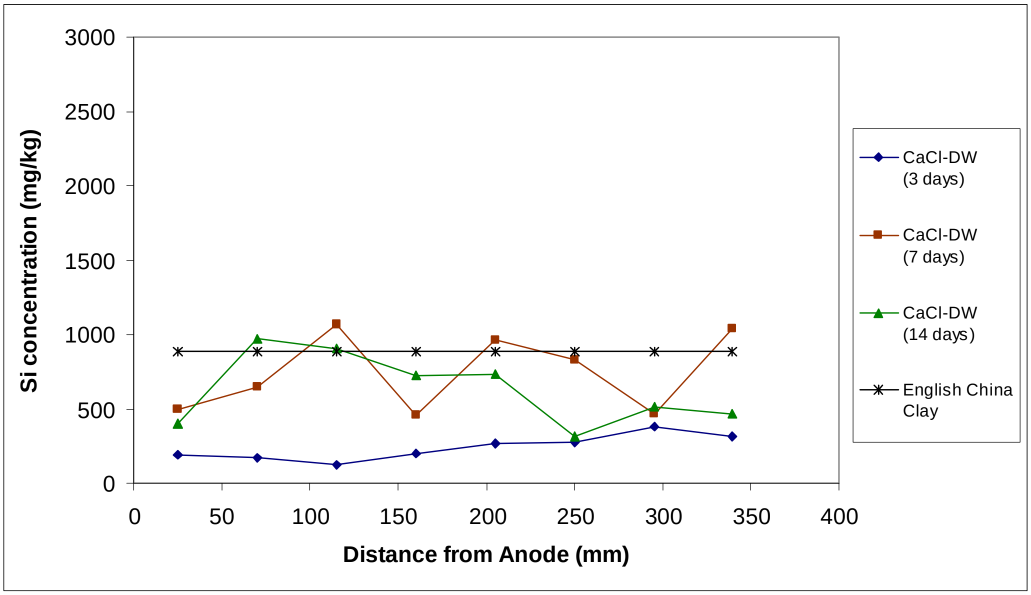

Figure 7.45: Si concentration of CaCl-DW system with distance from anode.

Figure 7.46 shows the Al concentration are increased considerably for the 3 days test ranging between about 40000 and 65000 mg/kg across the soil samples. The higher concentration compared to the control value was due to the migration of Al ions within the system from anode to cathode for short term period. However, the concentration level was then reduced with the increasing treatment time to reach the same level with the control value as observed at the 7 and 14 days tests. For short term, the aluminium ions are released into the pore fluid within the clay particles due to the increased ionic concentration resulted from calcium ions addition at the anode. Even though for the lyotropic series the higher valence or larger cations replace those of a lower valence or smaller cations, higher concentration of cations that introduced into the system will eventually replace those of lower concentration that attached to clay surface.

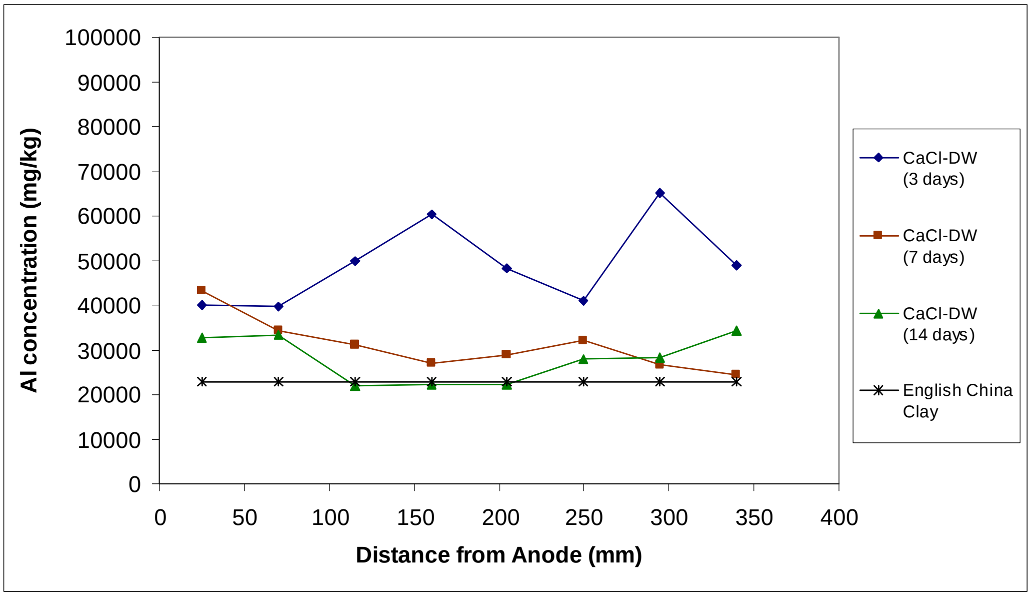

Figure 7.46: Al concentration of CaCl-DW system with distance from anode.

Figure 7.47 shows the Na concentration values are generally lower than of the control sample. The lower values of Na concentration is attributed to the migration of the Na ions by electrokinetic process and this release being flushed away from the system at the end of the cathode chamber. Conversely, the K values as seen in Figure 7.48 are generally higher than the control values. However, the trend of K values is less variable than the other metal concentration such as Fe and Al and seems to decrease gradually close to the control value when approaching the cathode except for the 3 days test.

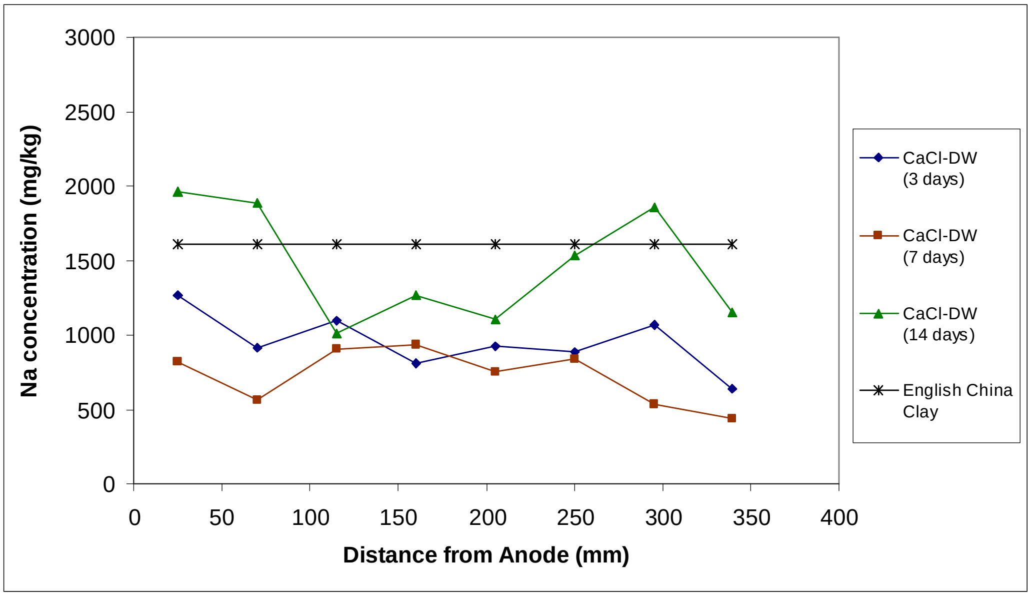

Figure 7.47: Na concentration of CaCl-DW system with distance from anode.

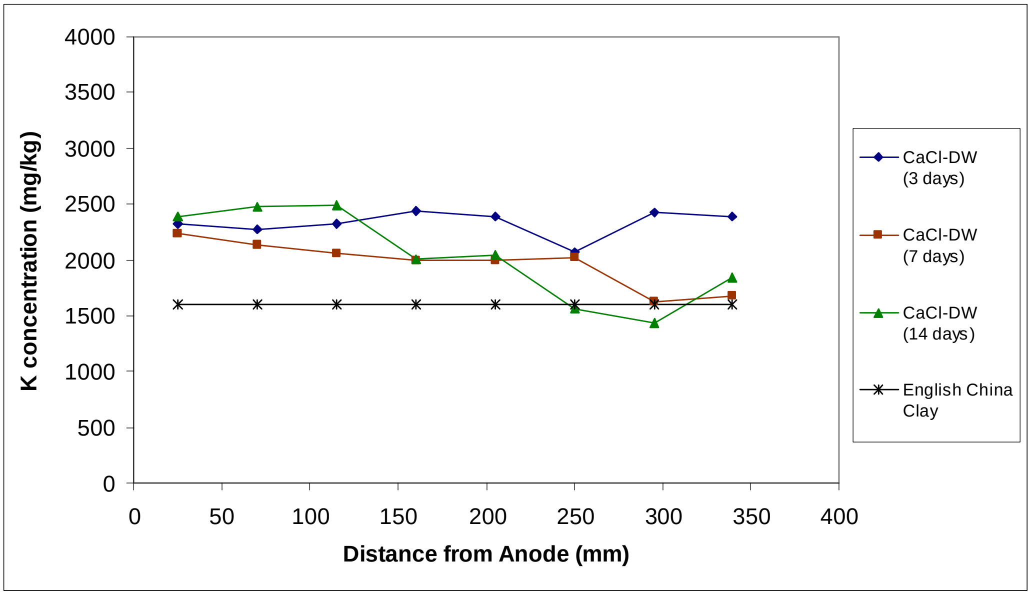

Figure 7.48: K concentration of CaCl-DW system with distance from anode.

7.4.4 Metal Concentration of DW-NaSiO system

As observed in Figure 7.49, the Si concentration of the DW-NaSiO system shows significant trend due to the addition of Si ions at the cathode chamber to investigate the migration of the Si ions toward the anode. For the 3 days test, the Si concentration is slightly increased to about 1800 mg/kg at the vicinity of anode (340 mm from anode) compared to the control value of 900 mg/kg but significantly away from the cathode (250 mm from anode), which had similar value with the control value. This indicated the Si ions moved due to the electromigration towards the anode after 3 days to approximately a quarter of distance from cathode.

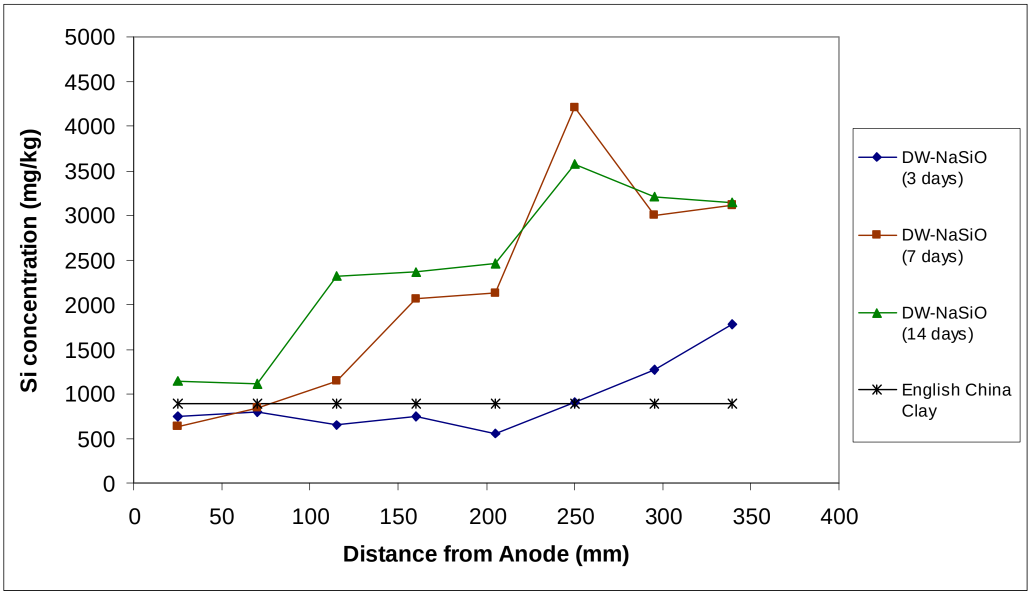

Figure 7.49: Si concentration of DW-NaSiO system with distance from anode.

However, after longer treatment time were applied for 7 and 14 days tests, the Si concentration are increased significantly to about 3200 mg/kg for both durations near the cathode (340 mm from anode) and then reach to maximum values of 4213 and 3564 mg/kg after 7 and 14 days, respectively at 250 mm from anode. After that point, the Si concentration level is dropped significantly towards the anode at 70 mm from anode. Therefore, for both treatment times the Si ions show sign of movement towards the anode but still not reached the end of the anode side i.e. had not continue for sufficient time. The low rate of Si ions migration compare to the rate of calcium ions migration in the CaCl-DW system is due to electroosmosis flow from opposite direction, which retarded its movement towards the anode.

Figure 7.50 and 7.51 shows the Fe and Al concentrations of the DW-NaSiO system are generally lower than the control value. However, the Na concentration level as observed in Figure 7.52 show significant increased at the cathode as expected (340 mm from anode) due chemical diffusion of Na ions from the cathode chamber. The significant variation of the K ions as observed in Figure 7.53 is probably due to the migration of K ions across the samples but not likely to flushed away from the system as happened to other cations such as Fe and Al ions.

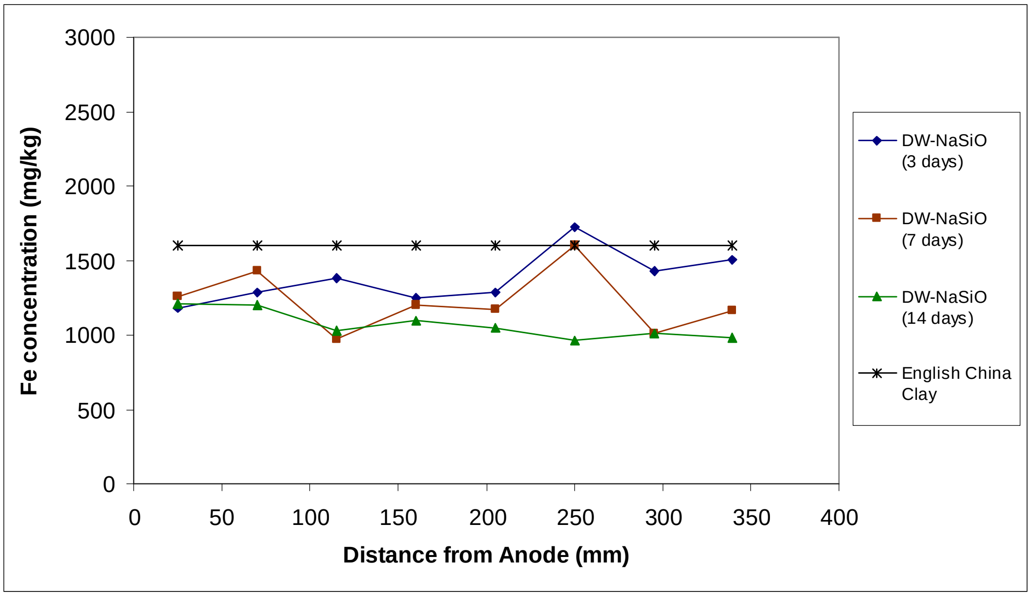

Figure 7.50: Fe concentration of DW-NaSiO system with distance from anode.

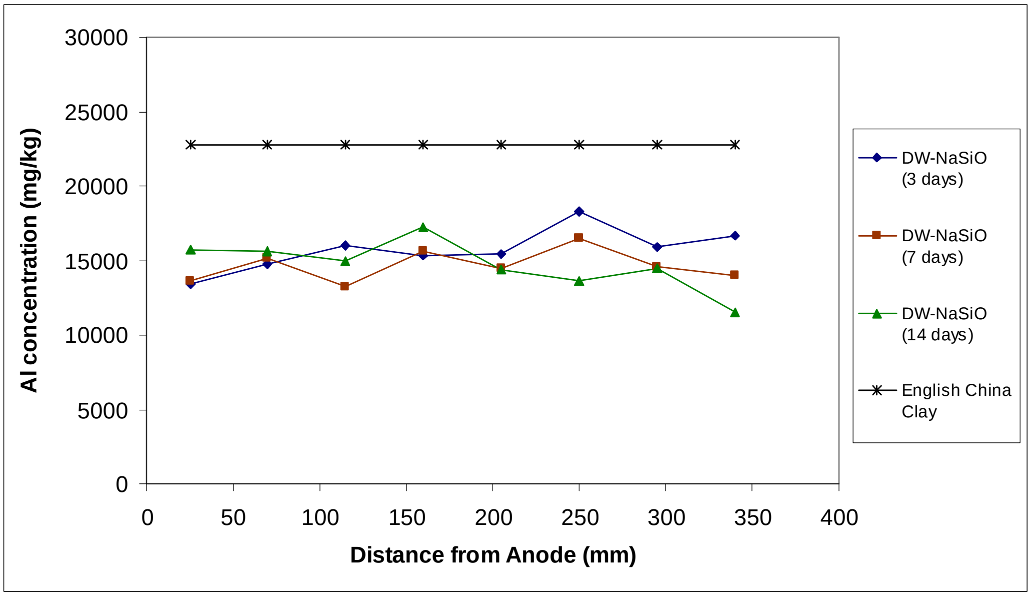

Figure 7.51: Al concentration of DW-NaSiO system with distance from anode.

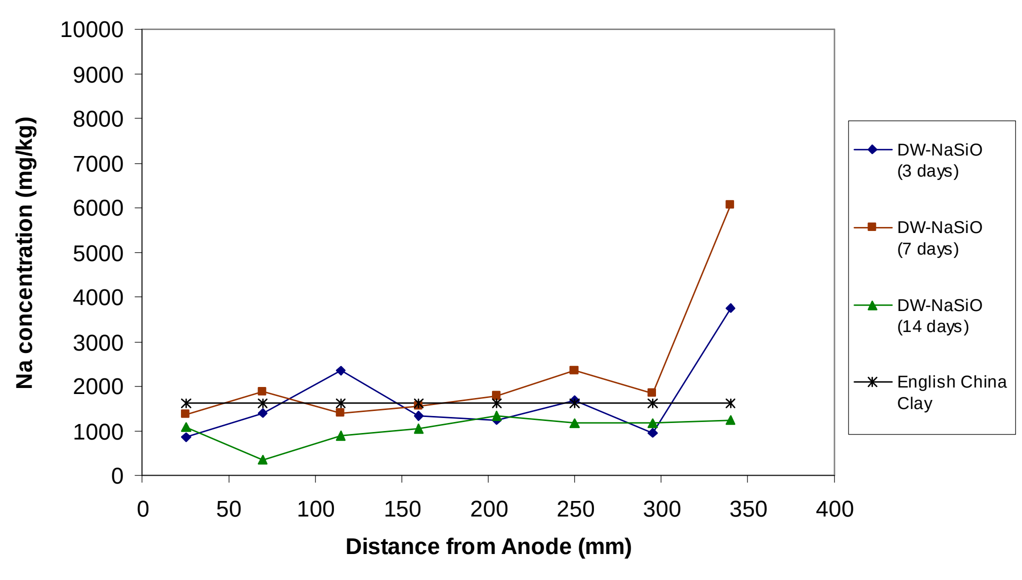

Figure 7.52: Na concentration of DW-NaSiO system with distance from anode.

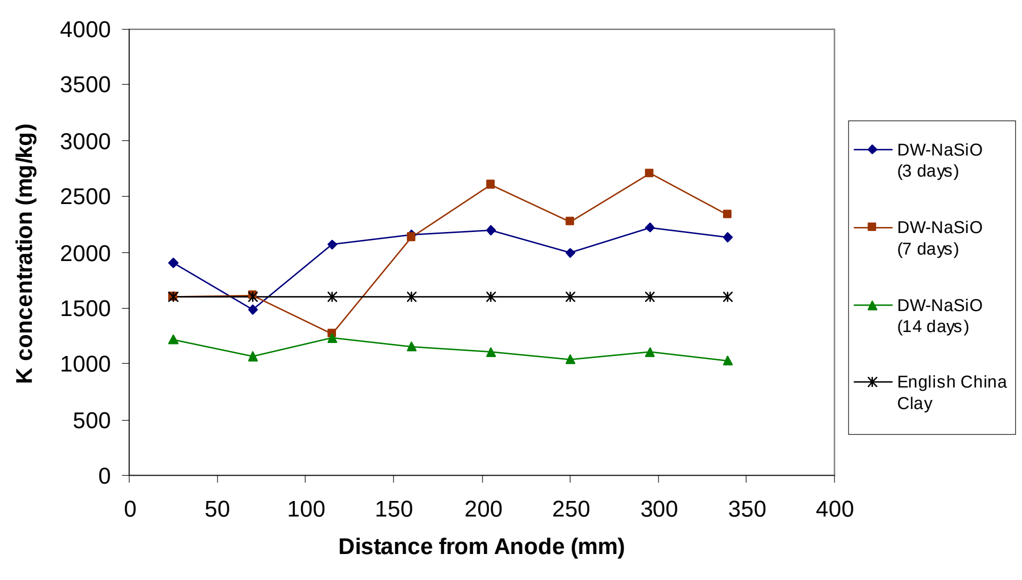

Figure 7.53: K concentration of DW-NaSiO system with distance from anode.

7.4.5 Metal Concentration of CaCl-NaSiO system

As expected in Figure 7.54 and 7.55, the combination of two different chemical stabilisers utilising Ca ions and Si ions toward cathode and anode, respectively show significant trend across the soil samples. In Figure 7.54, the Ca concentration levels at the anode (25 mm from anode) are increased significantly to reach maximum values of 8541 and 7681 mg/kg for the 3 and 7 days tests, respectively. After 14 days, the Ca concentration reached further to the highest concentration of 15521 mg/kg. This indicated the longer term has a considerable increase of Ca concentration at the anode region due to the addition of calcium ions at the anode chamber.

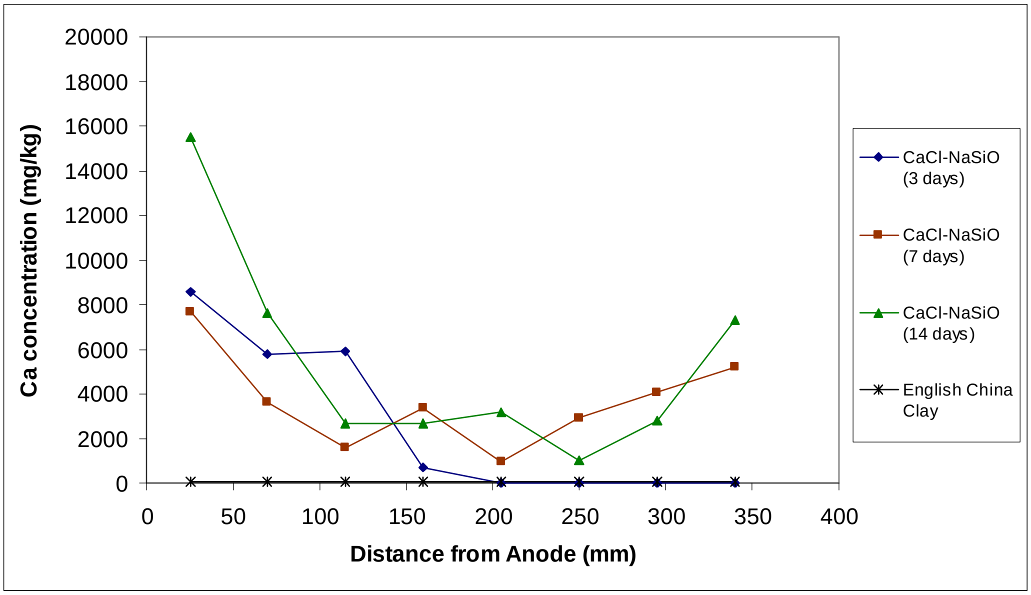

Figure 7.54: Ca concentration of CaCl-NaSiO system with distance from anode.

For the short term (the 3 days test), the Ca ions migrate towards the cathode for half the sample width. However, when the longer treatment (7 days test) was applied the trend shows Ca ions dominate the ion concentrations within the pore fluid from the anode side until the end of the cathode side. There was a significant increase of Ca ion at the cathode region after 7 days, which indicated that precipitation had occurred near the cathode and can be supported from the results of other parameters such as shear strength (Figure 7.27), Atterberg limits (Figure 7.30 and 7.33), and pH (Figure 7.39) and electrical conductivity (Figure 7.42).

As for Si concentration level as seen in Figure 7.55, there is significant increase of Si that should be expected especially around the cathode region due to the Si ions being continuously supplied at the cathode chamber. However, the Si ions migrate to a distance of about 250 mm from anode (after 7 days) and 295 mm from anode (after 14 days) compared with the DW-NaSiO system, which migrated further from the cathode until they almost reached the end of the anode side.

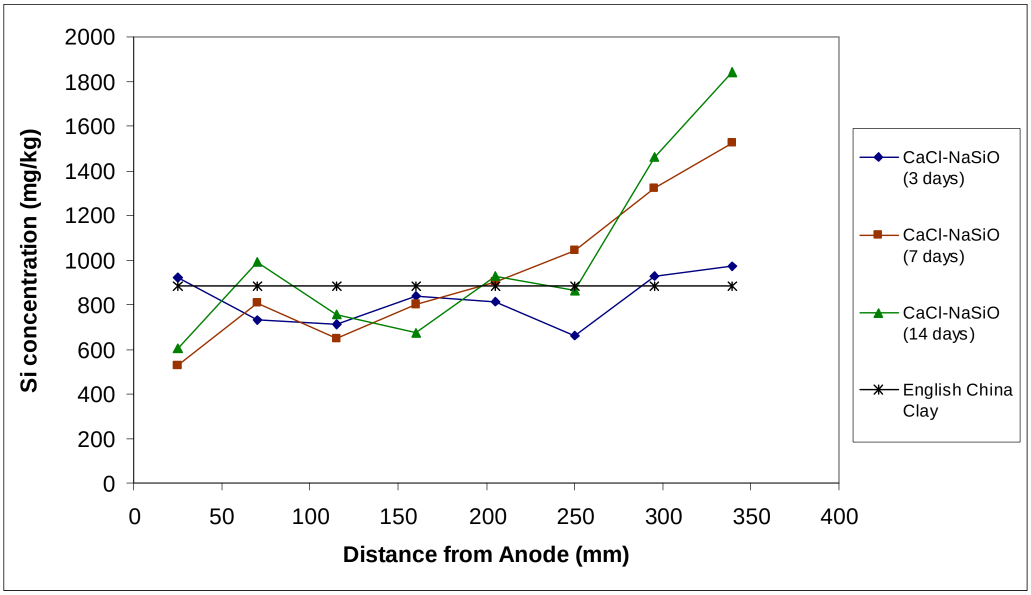

Figure 7.55: Si concentration of CaCl-NaSiO system with distance from anode.

Therefore this suggests that the electroosmosis flow and electromigration of calcium ions (due to the increase in ionic concentration in pore fluid) or other cations retarded or prevented the Si ions movement towards opposite direction. This was supported by the previous research by Barker *et al.* (2004) on the field electrokinetic stabilisation trial testing using similar chemical stabilisers at both electrodes. They also reported the first attempt to introduce Si ions at the cathode has relatively little effect on the amount of Si ions drawn into the soil. However, after added sodium silicate centrally in the middle of the sample, there was a marked increase in chemical addition into the soil thus enhanced the formation of calcium silicate hydrate after 27 days in the middle of the samples.

A similar trend has been observed in the Figure 7.56, 7.57 and 7.58 of the CaCl-NaSiO system for cations concentration of Fe, Al and Na, respectively as discussed earlier in the DW-NaSiO system (see section 7.4.4). The Fe and Al concentrations had values below the control values throughout the system while the Na concentration had increased significantly at the cathode region but remained relatively constant for the rest of distance towards anode. In Figure 7.59, the concentration of K showed no significant variation ranging between about 1200 and 1800 mg/kg compared with the DW-NaSiO system which has varied considerably along the soil samples.

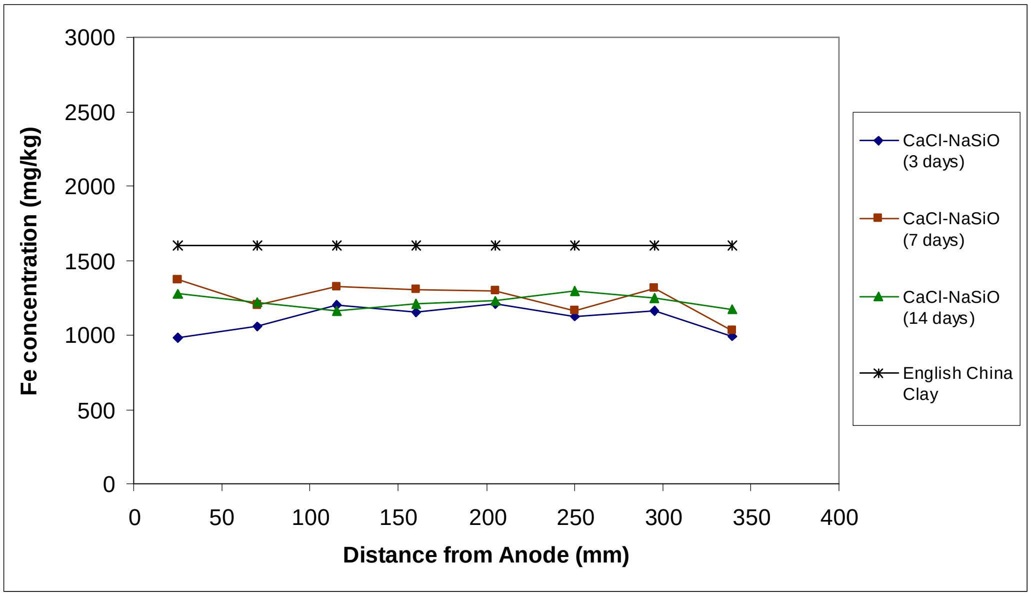

Figure 7.56: Fe concentration of CaCl-NaSiO system with distance from anode.

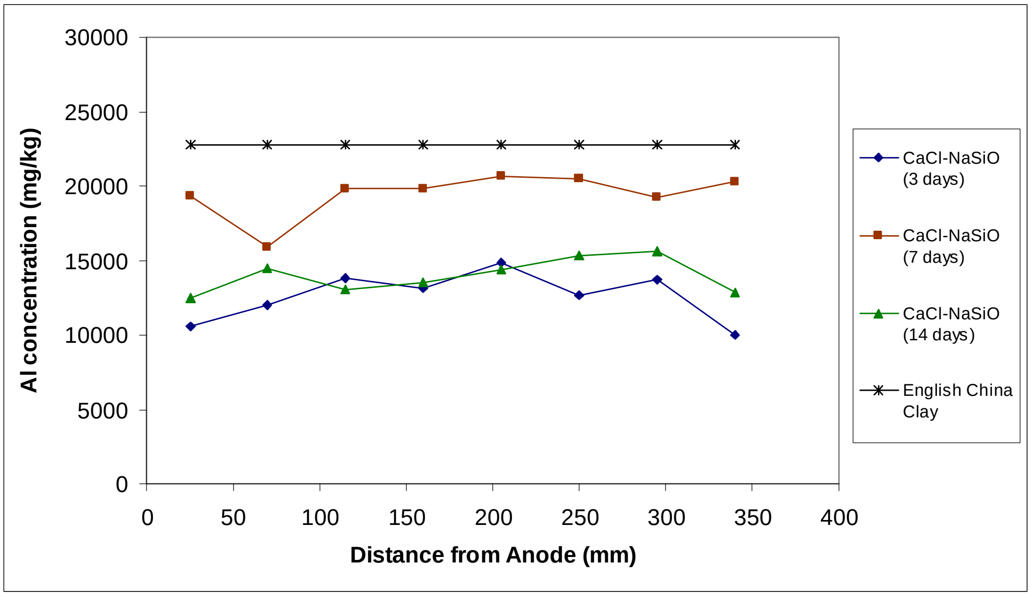

Figure 7.57: Al concentration of CaCl-NaSiO system with distance from anode.

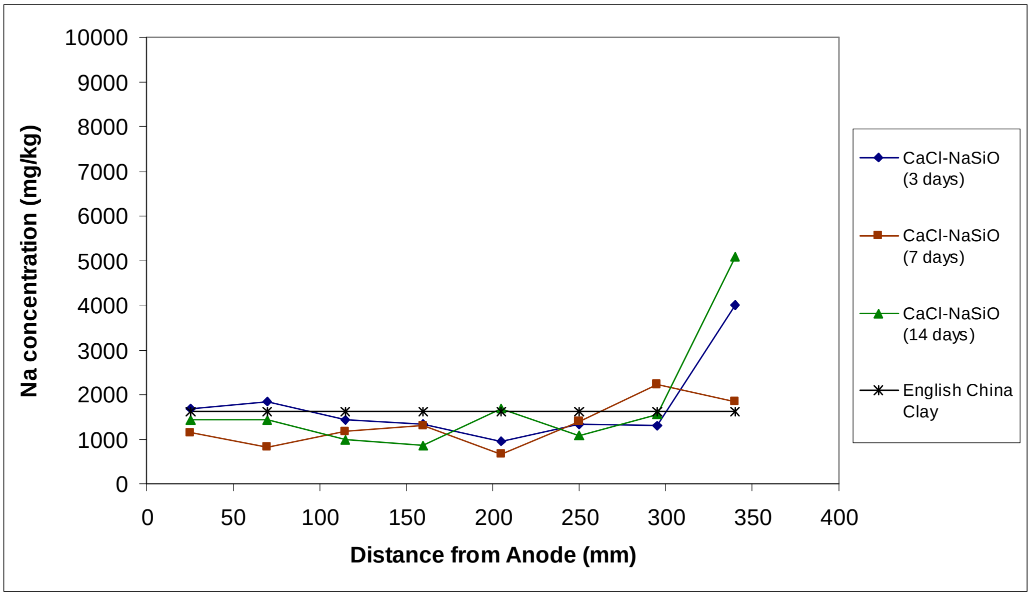

Figure 7.58: Na concentration of CaCl-NaSiO system with distance from anode.

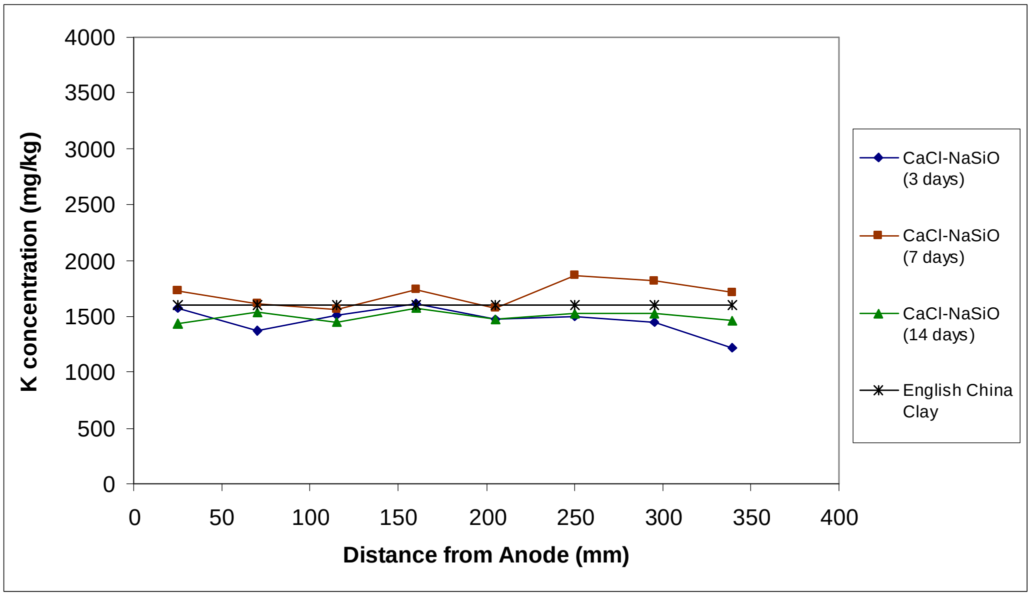

Figure 7.59: K concentration of CaCl-NaSiO system with distance from anode.

7.5 Repeatability Test Results

As discussed earlier in section 5.9 (Chapter 5), this section is presented the result of replicate test conducted to determine the accuracy and repeatability of this research study for EK system with chemical stabilisers. Some sections as shown in Table 7.5 were conducted in 3 different layers (top, middle and bottom) in this replicate test to increase the accuracy and determine the boundary effects with depths to the electroosmosis and electromigration processes.

At every layer, for example, vane shear test was conducted at three different points in every section and conducted in the same manner as the main experiment (see section 5.8 in Chapter 5). The water content was recorded after vane shear test was conducted for every point and depth. The data points were reported in 3 readings and the statistical study i.e. the mean (an average reading), the standard deviation and coefficient of variation (standard deviation divided by the mean or best estimate) were tabulated for each physical or chemical test as shown in Table 7.5. Atterberg limits and chemical test such as determination of metal content in the soil after EK treatment could not be undertaken due to the cost, time and resource constraints.

Table 7.5: Results of repeatability tests for CaCl-DW (7 days) system.

No	**Distance from anode (mm)**	**Distance from surface (mm)**	**w (%)**			**C_u (kPa)**			**pH**		
			1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	25	70	48.4	48.7	48.1	10.5	10.8	10.8	3.7	3.6	3.9
		130	49.3	48.9	48.6	11.0	11.2	10.8	3.6	3.8	3.9
		200	49.2	48.3	48.5	11.4	11.5	11.2	3.5	3.4	3.4
	Mean		48.7			11.0			3.6		
	Standard deviation		0.4031			0.3270			0.1944		
	Coefficient of variation		0.0083			0.0297			0.0533		
2	70	130	48.7	49	48.7	11.6	11.5	11.4	4.1	4.1	4.2
	Mean		48.8			11.5			4.1		
	Standard deviation		0.1732			0.1000			0.0577		
	Coefficient of variation		0.0035			0.0087			0.0140		
3	115	70	49.3	49.8	49.5	10.3	10.4	10.6	5.0	4.8	4.6
		130	49.8	50.1	49.6	10.4	11.0	11.2	5.0	4.9	4.7
		200	51.6	49.2	50.6	11.3	11.4	11.6	4.6	4.6	4.1
	Mean		49.9			10.9			4.7		
	Standard deviation		0.7518			0.4936			0.2784		
	Coefficient of variation		0.0151			0.0452			0.0592		
4	160	130	50.6	50.8	50.9	11.8	11.3	11.6	4.7	4.5	4.5
	Mean		50.8			11.6			4.6		
	Standard deviation		0.1528			0.2517			0.1155		
	Coefficient of variation		0.0030			0.0218			0.0253		
5	205	70	48.7	50.3	50.1	11.3	11.6	11.4	5.3	5.3	5.2
		130	49.2	50.2	50.2	11.4	11.5	11.7	5.6	5.4	5.2
		200	50.3	49.6	49.2	12.1	12.1	12.0	5.0	5.3	4.9
	Mean		49.8			11.7			5.2		
	Standard deviation		0.5981			0.3153			0.2068		
	Coefficient of variation		0.0120			0.0270			0.0394		
6	250	130	50.6	50.3	50.6	11.4	11.6	11.6	5.6	5.1	5.3
	Mean		50.5			11.5			5.3		
	Standard deviation		0.1732			0.1155			0.2517		
	Coefficient of variation		0.0034			0.0100			0.0472		
7	295	70	51.8	52.2	52.0	10.5	10.3	10.3	5.8	5.8	5.9
		130	51.0	51.6	51.7	10.5	10.3	10.8	5.6	5.9	5.4
		200	52.1	51.8	52.0	11.7	10.7	11.4	5.7	5.0	5.1
	Mean		51.8			10.7			5.6		
	Standard deviation		0.3571			0.5069			0.3383		
	Coefficient of variation		0.0069			0.0473			0.0607		
8	340	70	48.6	50.1	49.0	13.6	12.2	12.6	7.6	7.6	7.2
		130	49.2	51.4	52.2	13.5	14.1	14.7	7.9	6.8	6.6
		200	52.4	52.3	48.8	14.6	14.7	15.7	6.6	6.3	6.2
	Mean		50.4			14.0			7.0		
	Standard deviation		1.6249			1.1091			0.6180		
	Coefficient of variation		0.0322			0.0794			0.0886		

It is demonstrated in Table 7.5 that the standard deviation obtained lies within a small range between 0.06 – 1.62. Therefore, it can be concluded that some of the physical and chemical tests are repeatable and satisfactory. From the results, the effects of depth for water content and pH have not shown significantly different for all 3 layers. However, the shear strength values have higher values with the increase of sample depth from the soil surface. The reason for these differences and the significance with respect to depth is due to impose self weigh of soil at the top which also cause the increase of stress with depth. From the pH results, it can be concluded that the distribution of ions due to the electrochemical effects (i.e. electrolysis, electroosmosis and electromigration processes) are uniform with depth and showed the effectiveness of the current distribution across the soil sample.

The measured properties of treated soils are more uniform with depth but have coefficients of variation from about 0.3 % to as much as 8 %, depending on the property. The strength parameters are most variable, while the water contents and pH are less variable. This latter observation should not be surprising due to the tests are less prone to error, whereas for strengths are measured on much larger specimens that are water contents or pH. In addition, the use of vane shear test to measure undrained shear strength which normally used for in situ test is reported to have a large variation compare to the laboratory measurement such as quick compression test and triaxial test. According to Baecher & Christian (2003), the variability among laboratory measurements of effective friction angle, φ, is considerably less than that among in situ tests. First, greater care is usually taken with laboratory tests than with in situ tests, and, second, the specimen quality for laboratory tests is almost always better than for in situ tests. Even though, the vane shear test was conducted in the laboratory but the more accurate shear strength determination in the control laboratory (quick compression or triaxial test) should be taken into account in the future study for comparison. As a general rule, the most intact and least disturbed section of soil sample for laboratory testing, creating an implicit sampling bias that reduces variability (Baecher & Christian, 2003).

Table 7.6, 7.7 and 7.8 show the comparison of average values for some physical and chemical properties results between replicate and actual test in CaCl-DW (7 days) system. In overall, it is illustrated that from these two tests, the obtained average results were similar based on the statistical point of view. The estimated error of water content is between ± 0.10 and 0.65 % and clearly lower compared to the average water content value reported by Kalumba (2006) as shown in Table 7.9 which is between ± 0.05 and 3.80 %.

Table 7.6: Comparison of average water content results between actual test and replicate test of CaCl-DW (7 days) system.

Section No.	**Distance from anode (mm)**	**Average Water Content (%)**		**Mean Water Content (%)**	**Deviation (± %)**	**RPD from Mean (%)**
		Actual Test	**Replicate Test**			
1	25	49.6	48.7	49.1	0.47	0.95
2	70	49.6	48.8	49.2	0.40	0.81
3	115	49.6	49.9	49.8	0.17	0.35
4	160	52.0	50.8	51.4	0.62	1.20
5	205	50.8	49.8	50.3	0.52	1.04
6	250	50.3	50.5	50.4	0.10	0.20
7	295	50.5	51.8	51.2	0.65	1.27
8	340	51.5	50.4	51.0	0.53	1.04

The estimated error of the average shear strength of these two tests is between ± 0.00 and 0.55 kPa. This is almost similar with the estimated error of the average water content. As for the average pH, the estimated error is between ± 0.00 and 0.40 pH which is much lower than water content and shear strength.

Table 7.7: Comparison of average shear strength results between actual test and replicate test of CaCl-DW (7 days) system.

Section No.	**Distance from anode (mm)**	**Average Shear Strength (kPa)**		**Mean Shear Strength (kPa)**	**Deviation (± kPa)**	**RPD from Mean (%)**
		Actual Test	**Replicate Test**			
1	25	11.0	11.0	11.0	0.00	0.00
2	70	10.5	11.5	11.0	0.50	4.55
3	115	11.0	10.9	11.0	0.04	0.41
4	160	11.5	11.6	11.5	0.03	0.29
5	205	11.5	11.7	11.6	0.09	0.77
6	250	11.5	11.5	11.5	0.00	0.00
7	295	11.8	10.7	11.3	0.55	4.89
8	340	13.3	14.0	13.7	0.35	2.56

Table 7.8: Comparison of average pH results between actual test and replicate test of CaCl-DW (7 days) system.

Section No.	**Distance from anode (mm)**	**Average pH**		**Mean pH**	**Deviation (±)**	**RPD from Mean (%)**
		Actual Test	**Replicate Test**			
1	25	3.9	3.6	3.8	0.15	4.00
2	70	4.3	4.1	4.2	0.10	2.38
3	115	4.7	4.7	4.7	0.00	0.00
4	160	5.4	4.6	5.0	0.40	8.00
5	205	5.4	5.2	5.3	0.10	1.89
6	250	4.9	5.3	5.1	0.20	3.92
7	295	5.1	5.6	5.4	0.25	4.67
8	340	6.5	7.0	6.8	0.25	3.70

Precision of the results was expressed as relative difference (RPD) from the average value. RPD is defined as the deviation divided by the mean and reported in percentage (%). The level of accuracy between these two tests for water content, shear strength and pH measurement was less than 8% of RPD. Kalumba (2006) reported that the RPD was less than 40 % in the replicate test for zinc concentration and water content determination, but no detail explanation was given. However, it was observed that the determination of zinc concentration has shown variability of results in Kalumba (2006) due to the use of complex procedure and machine (Atomic Absorption Spectrometer). The likely error would be due to the sample preparation prior to analytical test such as an error during acid digestion method, dilution and cross contamination between the glassware used.

Table 7.9: Comparison of average water content from two experiments (Kalumba, 2006).

Location along Cell		**Measured Water Content (%)**		**Mean WC (%)**	**Deviation (± %)**	**RPD from Mean (%)**
		Test 1	**Test 2**			
Middle	Anode	75.38	75.70	75.54	0.16	0.2
	(1/4)L	57.57	49.96	53.77	3.80	7.1
	(1/2)L	52.15	46.87	49.51	2.64	5.3
	(3/4)L	55.01	52.19	53.60	1.41	2.6
	Cathode	55.14	55.04	55.09	0.005	0.1

Chapter 8

IMPLICATION OF THE EKS METHOD AS A GROUND IMPROVEMENT TOOL

8.1 Introduction

The results of EKS testing performed in this study have demonstrated the possibility and feasibility of EKS method as a potential ground improvement method. Therefore, this chapter will discuss key findings related to electrochemical effects on soil behaviour when an electric current is applied and when selected cations and anions are introduced into soil system. The comparison also has been made with the preliminary testing of 'pure system' to provide a benchmark before any conclusions are made related to the electrokinetic phenomena. As shown in Chapter 7, all the test systems showed encouraging results and the potential that EKS has to be an effective means of soil improvement.

8.2 Effect of Design Consideration of EKS method

The design and configuration used in this study have been made based on many criteria, including the practicability of this method for field scale approaches (see section 4.2), minimisation or reduction of the effect of variable parameters (see section 7.5), which caused uncertainty of the results, overall cost and time constraints (discussed in Chapter 3). Furthermore, a growing awareness of environmental and sustainability issues globally have been taken into consideration in material selections such as the use of less toxic chemicals and durable re-useable Electrokinetic Geosynthetic (EKG) electrodes (see section 4.4). Conventional metallic electrodes degrade under extreme acid environment due to the electrokinetic process (see section 2.9.2) and could potentially release into underground water as reported by Rogers *et al.* (2003) and Liaki *et al.* (2010). Therefore, this research discusses the effects of the design and configuration approach used in this research when using an EKG electrode as a guideline for the EKS method to be implemented successfully in the field.

The use of newly EKG electrode in this study, which developed at the University of Newcastle, has resolved the corrosion of conventional metallic electrodes that caused problem during electrokinetic field application. The corrosion of electrodes resulted in the additional increase of the operational cost and replacement cost of the electrode, which prevents it from being applied extensively in the field. Recently, further development of the use of the EKG electrode in contaminated soil by Kalumba (2006) and in this study using the EKS approach have lead to new findings that give confident in the use of inert electrodes for soil improvement and soil remediation. The performance of EKG electrode in this study is comparative with the conventional inert electrodes such as copper

(Srinivasaraghavan & Rajasekaran, 1994), graphite (Gabriella *et al.*, 2008), and titanium (Ozkan *et. al.,* 1999; Asavadorndeja & Glawe, 2005; Otsuki *et al.,* 2007; Ahmad *et al.,* 2011). Therefore, in terms of material used and also as part of design consideration, findings presented in Chapter 7 have provided better understanding regarding the performance of EKG electrode in the use of EKS method. The performance of the EKG electrode in this study can be assessed in terms of the changes in electrochemical and mechanical properties such as current variations, water content changes, pH gradients, Atterberg limits changes and most importantly the increase of undrained shear strength of the treated soil.

Open electrode configuration used in this study allowed the good contact between the soil and electrode through the use of a continuous supply of water soluble chemical or distilled water. A common problem that is encountered in the field during EK testing using close anode configuration (discussed in section 3.3 and 3.4, Chapter 3) is soil desiccation due to the heat generation causing very poor contact and ultimately ceased the current especially in electrokinetic dewatering and electroosmotic consolidation applications. In those applications, the increase of shear strength is relying on the decrease of water content to improve the soil properties because no chemical is introduced at the anode (close anode). However, in the electrokinetic stabilisation, the anode drainage is opened (open electrode) to allow chemical introducing at the anode. Therefore, the increase of shear strength is due to the electrochemical effect as opposed to the water content reduction. As we can see in Figure 7.21 for the CaCl-NaSiO system, the water content values are mostly higher (between 52 and 55 %) than the control value (51 %) but the results of shear strength are not reduced even increased at certain sections especially near the anode and cathode. This is further confirm with the correlation results of shear strength and water content in Figure 7.27 which showed that most the data point located above the control line (this control line is produced separately to know the shear strength due to the water content variations as discussed in section 6.3.2). Electroosmosis process cause water flow from anode to cathode and if pore water is not replaced at the anode, soil desiccation will occur thus diminishing the soil electrical conductance. However, in the present study, the continuity of chemical or water introduced into the soil prevents such phenomena. Open electrode configuration and continuous supply of chemical stabilisers also have some drawbacks. The continuous supply of chemical stabiliser caused an increased in water content even though, they did not affect the undrained shear strength as a whole as discussed in section 7.3.2, Chapter 7. However, in terms of the performance compared with other ground improvements techniques, which rely on the dewatering process only, the electrochemical effect in EKS method has a greater impact in soil shear strength.

A problem associated with effectiveness of EKS is the generation of oxygen and hydrogen gas by electrolysis reactions at the anode and cathode, respectively. These phenomena can be observed visually between the soil electrode interfaces. In this study, the generation of gas was observed at the cathode area, which then caused soil erosion between the soil electrode interfaces after a certain time. Consequently, it prevented the effective flow of water through the cathode chamber. Instead flow occurred upwards between the soil electrode interfaces. Therefore, for practical applications, the design must consider the escape of this gas (gas vent) to increase the efficiency of the system. Alternatively, to counter this effect, the electrode can be inserted in the electrolytes chamber. This allows the gas generation to freely escape through the electrolytes chamber into the air. Many researchers (Ozkan *et. al.,* 1999; Alshawabkeh & Sheahan, 2003; Asavadorndeja & Glawe, 2005; Otsuki *et al.,* 2007; Ahmad *et al.,* 2011) have adopted this approach to enhance the efficiency and the performance of their systems. Moreover, during the installation of electrodes into the soil, the approach used in this study can simulate the real situation of implementation of this method in the field. Regardless of the material used in the field, the electrode has to be installed properly in order to make good electrical contact with the subsurface and able to facilitate exchange of solution with the subsurface through the electrode (Alshawabkeh *et al.* 1999).

During the electroosmosis, the water flow from the soil mass shall be due to both hydraulic and electrical gradient, occurring as coupled flow. Therefore, in order to verify the effectiveness of water flow under electrical gradient only, the Mariotte bottle method was utilised in this study. This allowed the water level to be maintained at both electrolytes chamber when soluble chemical or water flow into the main compartment occurred, driven by the electric gradient. However, in the field application the coupled flow must be taken into consideration to assess the efficiency of EKS technique.

8.3 Effectiveness of the EKS Method from the Results of Monitoring Data

The results from monitoring test during the EKS treatment are important as an indicator of the electrokinetic processes happening throughout the system. Therefore, the monitoring data are useful as an indirect measurement to check the effectiveness of the electrokinetic setup and the electrokinetic stabilisation achieved. This becomes vital in the field applications because once the performance drops it will increase the overall cost of the testing. The results of the CaCl-DW of 14 days test (Figure 7.1) suggest that after the initial increase of electric current, it reach a maximum value of about 60 mA (81 hours), then decreased gradually and eventually become constant with time at almost 40 mA until the end of the test duration. While, in the DW-DW of 14 days test (Figure 6.1), after an initial increase the electric current remained constant at the highest value (24 mA) for several hours (from 168 to 240 hours) and decreased until the end of the test at 19 mA. It seems that the Ca ions introduced at the anode in the CaCl-DW test were able to sustain a high electric current compared to the DW-DW test. The higher soil electrical conductivity is responsible for the higher current in the CaCl-DW test. In Figure 7.40, the electrical conductivity values are less than 9000 µS/cm compared to the DW-DW test (less than 140 µS/cm as seen in Figure 6.25). From this phenomena, it is concluded that the performance of EK system can be evaluated in the real field test by monitoring the in situ electrical current profile, for example the higher electrical current profile is an indicator that the Ca ions are distributed well across the soil sample (as proven in the results of electrical conductivity and Ca concentration in Figure 7.40 and 7.43, respectively). The electric current is not the only parameter to establish the efficiency of the EKS treatment. Other important parameters include pH of electrolytes, and the inflow and the outflow of water, which can also be monitored during EKS testing in the laboratory scale or field application. In addition with monitoring, further action can be undertaken immediately, to enhance the process and prevent any adverse effects that might happen during application of electrokinetics in the field. These include using a polarity reversal or an intermittent current, change the voltage gradient, time requirements of the treatment process (ceased the current and allowed the mineralisation process to happen), change the electrode spacing and configuration, addition of chemical stabilisers at different time, and change the chemical stabilisers at both or either electrolyte compartments after certain time to achieved specific precipitation.

It was observed that the electric current profiles are influenced by the ionic concentration of the pore fluid within the soil matrices. Therefore, the addition of chemical ions at either or both anode and cathode cause the increased of the electric current initially but this then decreased with treatment time. As EKS treatment progresses, the electric current values change with time due to the electrochemical processes. In the pure system, the increase of electric current was not as high as compared to the other system (added chemical stabilisers), i.e. about 25 mA with ‘pure’ system and 60 mA for system with chemical additives. This was attributed to the lower ionic concentration in the pore fluid using distilled water and reliant of the electrolysis process to produce hydrogen and hydroxide ions at the anode and cathode, respectively thus dominating into the pore fluid. The other systems where chemical additives are provided, a larger increase of electric current observed initially and was due to the migration of the calcium ions or silicate ion under the influence of electrical gradient, together with the release of hydrogen and hydroxide ion from the electrolysis process. Thus this increases the ionic concentration in the pore fluid (see section 7.2.1 in Chapter 7). A sharp drop of electric current profile with time indicated that high resistivity zones occurred due to precipitation of metal hydroxide at the cathode and that caused the fluid flow to become minimal, which in turn decreased the electric current of the system. Therefore, the electric current profiles provided indirect assessment of the electrochemical effect under EKS methods. Thus, potentially an electrical base resistivity or conductivity base assessment, utilising geophysical approach could be developed.

The pH of anolytes and the pH of catholytes profile provide useful information about possible chemical reactions due electrochemical effects, such as the electrolysis processes near the electrodes (see section 7.2.2). The pH of anolytes for most of the systems shows the decrease of pH to a high acid solution with time. This indicates the production of hydrogen ions at the anode. Whereas the pH of catholytes was maintained during the treatment and this indicates the production of hydroxide ions and effectiveness of certain cations, which were subsequently flushed out from the system due to the electroosmosis and electromigration process. In addition the pH values at both electrolytes also depend on the pH of electrolytes solution, which continuously supply from the Mariotte bottle.

The inflow and outflow of water or solution are also important to assess the efficiency of the system (see section 7.2.4). The continuous addition of chemical at the anolyte chamber and amount of discharge water at the catholyte chamber indicate the efficiency of chemical ion migration within the soil system to improve the properties of treated samples under electric gradients. After certain times, this efficiency was reduced due to electrochemical reactions taking place and further application of electric current under this circumstance will increase the cost of EK treatment. For the CaCl-NaSiO system, when a longer treatment time was applied, continuation of second mineral formation was occurred and increases the shear strength significantly. The formation of secondary mineral is not an instantaneous reaction but mainly occurs after certain curing time (typically after 14 days, based on the data presented in Chapter 7). Thus allows the crystallisation process associated with these minerals, resulted in a large increase in shear strength.

8.4 Effect of EKS on Soil Properties

Significant changes in the properties of the soil under the influence of an electric gradient have been presented and discussed in Chapter 6 for pure system and 7 for chemically stabilised system. However, rigorous discussion on both physical and chemical of the treated soil are needed before this method can be considered for adoption in field applications. In addition, this provides a better understanding of the electrochemical effects under controlled laboratory performance.

8.4.1 Shear Strength Effect

The most important factor when considering EKS method as potential ground improvement technique is the changes in shear strength due to the electrochemical effects. The three mechanisms associated with the electrochemical effects that caused an increased in shear strength are dewatering, cation exchange and precipitation. From a design view point, especially when stabilisers have been added, the key mechanism causing an increase in shear strength were found to be preliminary cation exchange and precipitation (see section 7.3.2) and validated by the Atterberg limits (see section 7.3.3, 7.3.4 and 7.3.5), pH (see section 7.4.1), electrical conductivity (see section 7.4.2) and chemical concentration results (see section 7.4.3 and 7.4.5 for CaCl-DW and CaCl-NaSiO system, respectively) as discussed in Chapter 7.

The results presented in chapter 7 demonstrated that electrokinetic can be applied effectively to migrate calcium and silicate ions from anode and cathode, respectively within a soil system. Analysis of these results suggested that the precipitation of secondary minerals generated better shear strength in the CaCl-NaSiO system compared with cation exchange capacity in the CaCl-DW. In the CaCl-NaSiO system, when both calcium and silicate ions were added simultaneously at the anode and cathode respectively, the greater increase of shear strength was observed at the cathode region compared with the increase of shear strength near the anode and in the middle of the samples (see Figure 7.27, in Chapter 7).

The cation exchange phenomena was observed to occur due to the introduction of calcium ions, which replace cations of a lower valence and smaller hydrated radius according to the Lyotropic series at the anode and in the middle of the samples CaCl-DW and CaCl-NaSiO (see results of calcium concentration from Chapter 7). Despite the preference for ions of high replacing power, cations with lower replacing power can still replace cations with higher replacing power by mass actions, provided that the concentration of the cations of lower replacing power is sufficiently higher compared to that of the ions of higher replacing power (Mitchell & Soga, 2005). The cations exchange will stop after reaching equilibrium and the abundance of calcium ions in the pore fluid (continuously supplied) together with other cations (released under acid conditions) will migrate to form precipitation of metal hydroxide at the cathode for the CaCl-NaSiO systems. In addition, for the CaCl-NaSiO system, Si ions introduce at the cathode had magnified the precipitation of CSH gel (higher concentration of Ca and Si ions at the cathode, see Figure 7.54 and 7.55, respectively). However, the CAH gels did not occur due to the lower concentration of Al ions at the cathode (see Figure 7.57). Al ions were released under high alkaline condition and then flushed out from the system due to the electromigration process and the abundance of the Ca ions in the pore fluid. Again the precipitations of CSH gels need to be confirmed from pH results. The pH values above 10 at the cathode for all treatment period of the CaCl-NaSiO system indicate the precipitation of CSH gels occurred after 7 and 14 days. For short period of time (3 days), the precipitation was yet to occur due to the lower concentration of Ca (see Figure 7.54).

In contrast, for the CaCl-DW system, there was no indication that CSH and CAH gels were formed at the cathode for all treatment period due to the lower pH values (pH about 6.7) even though the higher concentration of Ca ions and Al ions were observed after 7 days. The precipitation of calcium hydroxides gels will occur in high pH environment (pH>7). The concentration of Ca and Al ions were seen to decrease considerably at the cathode after 14 days. This indicates the continuation of current for longer period of time caused the Ca and Al ions to be flushed out through the cathode chambers due to their ionic conditions with a pH below 7 in this case. At the point, where the pH changes suddenly, the solubility of these metal ions is minimal and they precipitate as metal hydroxides. Most of the studies reported by Ozkan *et al.* (1999), Rogers *et al.* (2003), Alshawabkeh & Sheahan (2003), Barker *et al.* (2004), Asavadorndeja & Glawe (2005), Ou *et al.* (2009) and Ahmad *et al.* (2011) are in the agreement, all observing an increase in shear strength through the influence of the precipitation of metal hydroxides or secondary minerals.

The research presented here provided further explanation supporting the hypothesis that the cation exchange and precipitation are the main contributory factors increasing soil shear strength due to the electrochemical reactions. As indication, this was achieved through the results of liquid and plastic limits, pH gradient, and metal concentration and discussed later in this chapter. For pure system, the results of relationship between water content and undrained shear strength in Figure 6.17 clearly indicates that the soil in the middle of the sample showed no significant improvement in shear strength. However, at the anode and cathode region increases in shear strength after 14 days were clearly visible. In contrast, the 3 days experiment shows reduction of shear strength at the anode and cathode due to the initial chemical reaction taking place causing a decrease of the shear strength, prior to any increased. Thus, the process of soil strengthening will be established after a period of time, in this case, 14 days after treatment started. Therefore, from the pure system, even though, there were no chemical stabilisers introduced into system, the increased of shear strength will occur after certain period of time due to the changes in the pH gradient and most likely to change in the clay fabric. The longer term effect after 14 days was due to the released of hydrogen and hydroxide ions from electrolysis process into the pore fluid, which subsequently migrates towards each other depending on their charge. This was also driven by a change in the soil-water electrolytes system under different pH environment across the soil sample. Some chemical elements i.e., Al, Fe or Si which are available in the pore fluid between the soil particles, adsorbed on the clays surface, or within the clay mineral itself, may release under an extreme environment and be replaced by other favourable ions. Some of them may complex with other ions and some will be flushed out from system under electrokinetic processes.

For stabilised systems, the strength gain demonstrates variability, depending on what chemical added, at the cathode or anode. The CaCl-DW system showed significant increase in shear strength similar to the CaCl-NaSiO system. This suggested that the introduction calcium ion alone is enough to have great impact in the soil-water system due to the ability of Ca ions to act as an effective stabiliser agent.

Contrarily, the introduction of silicate ions alone at the cathode in the DW-NaSiO system has no significant impact on the soil improvement. It can be concluded that silicate ion alone have limited or no benefit in increasing the shear strength in the EKS method. Clay particles have positive charged edge due to the broken and a net negative charge on their basal surface. According to Mitchell & Soga (2005), the broken bond is the major source of exchange cation capacity of kaolinite and in the clay material the importance of broken sites increases with the decreasing particle size. Thus as kaolinite was used in this study and when sodium silicate was added to the clay system, the negative silicate ions from the sodium silicates attached to clay soil particle edges causing repulsion of particles generating a weaker disperse fabric (Fang & Daniel, 2006; Moayedi *et al.,* 2011). This phenomenon was true in their studies under certain pH environments without influence of electric current. Since this study had developed a large pH gradient, the positive and negative charges, these factors will affect the kaolinite soil due to their strong pH dependence change. This is supported by Mitchell & Soga (2005), who stated that kaolinite particles are charged positively on their edge when in a low pH environment, but negatively charged in a high pH environment. Moreover, the introduction of silicate anions alone may reduce soil strength, and could only increase soil strength if calcium ions are added to the soil system in addition. The presence of both calcium ions and silicate ions as observed in the CaCl-NaSiO system allow a formation of possible CSH gels which then hydrate, and harden with time, thus bond the clay particles together. This is a time dependent process as seen most clearly after 14 days. This implies longer treatment may have significant benefits, outweighing costs of longer treatment times.

Comparison with the EK literature shows that undrained shear strength increases after EK treatment. However, the trend with shear strength increases from the literature is not similar due to the different design configuration, electrodes, and concentration of chemical stabilisers. Some researchers (Lefebvre & Burnotte, 2002) reported higher increments in strength for soil located near anode after treatment. Meanwhile, other researchers like Ozkan *et al.* (1999), Rogers *et al.* (2003) and Asavadorndeja & Glawe (2005) reported the opposite trend where soil at the cathode had shown a higher strength improvement. It is most likely that the different conclusions in the literature amongst various researchers on where the location of shear strength improvement occurs are due to the varying boundary condition of the EK tests setup used. Therefore, the key difference between this research study with those studies is the cations present in soil after treatment by introduction of higher valence of ions (Ca ions). This has improved the soil properties due to the electrochemical effects. In Lefebvre & Burnotte (2002) study, the increased of strength near the anode is due to the consolidation and not to secondary effects such as chemical hardening. However, in this study and the similar EKS studies (Ozkan *et al.*, 1999; Rogers *et al.*, 2003; Asavadorndeja & Glawe, 2005), the soil improvement especially at the cathode is essentially due to the electrochemical effects i.e. precipitation and mineralisation, while at the anode is due to the cation exchange. The former is more significant than the latter in this research study as discussed in earlier in this section or seen in Figure 7.27.

Thus, it is important to set the configuration up to maximise strength gain potential. This can be done in the future study by a combination of different chemical stabilising agents by sequential, which give better results than the individual agent alone. For example, addition of the sodium silicate first at the cathode until silicate ions are well distributed across the soil sample and followed by addition of calcium chloride at the anode after certain time to have more uniform strength gained across the soil sample.

8.4.2 Atterberg Limit Effect

In order to verify the two mechanisms contributing to the increase of soil shear strength, it is important to look at results from the Atterberg limits. Changes in Atterberg limit are responsive to the electrochemical process under electric current and chemical stabilisation through alterations made to the structure and fabric of the clay, modifications to clay mineralogy and the types of exchangeable ions. According to Barker *et al.* (2004), the result of cation exchange is a considerable reduction in the thickness of the diffused double layer. This allows closer contact between the clay platelets, which promotes edge to edge attraction, or flocculation and results in changes in the soil workability, permeability, plasticity and swell properties. On the other hand, the precipitation of metal hydroxide can also be assessed by changes in plasticity of the soil. This again is the result of changes in thickness of diffuse double layer coupled to crystallisation with time to form a relatively strong and brittle solid of clay soil. Even though, these two mechanisms have opposite effect in term of thickness double layer, interestingly both mechanisms have resulted in increase in shear strength. Thus Atterberg limits are a useful diagnostic test to assess these mechanisms, which occurred across the soil. This is especially useful when coupled with the other tests including water content, shear strength and other chemical tests in order to confirm these phenomena.

From the CaCl-DW system, a decrease of liquid limit and plastic limit values are greatest close to the anode. The Atterberg limits values then increased gradually toward the cathode to reach almost the same values as with the control sample. This confirms that the cation exchange is the main contributor due to the addition of calcium ions at the anode. Calcium dominated the ionic concentration in the pore fluid (see Figure 7.43, Chapter 7). There were no significant changes in liquid limit and plastic limit values observed at the cathode region suggesting that precipitation is unlikely to have occurred. This was also supported by the pH values in Figure 7.37, which shows slight increased of the pH value at the cathode from 5.1 (control sample) to about pH 6.7. Asavadorndeja & Glawe (2005) and Ahmad *et al.* (2011), who also used the same chemical solution (calcium chloride) reported that precipitation of metal hydroxide only occur when pH greater than 7. Therefore, the finding presented herein is in agreement with the findings reported by many researchers using the same chemical solution. This trend was even observed with different chemical solutions i.e., aluminium sulphate and phosphoric acid (Ozkan *et al.*, 1999), and nitric acid and phosphoric acid (Alshawabkeh & Sheahan, 2003).

The precipitation of metal hydroxide at the cathode in the CaCl-NaSiO system caused significant improvements in soil shear strength as demonstrated by the liquid limit and plastic limit values presented in Figure 7.30 and 7.33, respectively. The liquid limit values significantly increased from 55.6 % (control sample) to about 70 % after 7 days compared to the plastic limit values at the cathode, which slightly increased from 34.6 % (control sample) to about 37 %. The Atterberg limit values have also increased significantly after 14 days at the cathode. This indicated that precipitation of metal hydroxide started to crystallise with time. This results in soil hardening (mineralisation) as reported by Barker *et al.* (2004). Further supportive evidence was provided by pH values greater than 10 at the cathode, which contributes to the precipitation of CSH gels. There was no significant change in plastic limit in the DW-NaSiO system across the soil samples suggesting the electrochemical effect had less impact in the Atterberg limit of the treated soil consistent with the result of shear strength taken in the same system.

In general, a decrease of the Atterberg limit at the anode zone was due to the acid environment that tends to cause the dissolution of certain mineral on clay structures, whereas a large increase of Atterberg limit is due alkaline environment which tend to cause precipitation of metal hydroxides that act as cementing agents. This resulted in great impact on the physicochemical behaviour of the soil after treatment. This phenomenon has also confirmed by the result of pH and metal concentration (see next section 8.4.3 and 8.4.4, respectively). Result from pure system showed no significant relationship between undrained shear strength and Atterberg limits due to the absence of ions that contributed to changes of soil properties even though there was a significant changes in pH at the anode and cathode. Therefore, it is evident that pH changes together with the type of exchange ions in the pore fluid either released from the degradation of electrode or introduction of cations at the anode are the main contributor to significantly improve the properties of clay soil in the EKS method. Subsequently, these ions migrate towards the cathode, which then precipitate contributing to a much greater improvement in soil behaviour, e.g. strength.

8.4.3 pH Effect

The pH distribution observed in all test systems indicates that the pH changes throughout the electrochemical processes under electric current regardless of electrolyte types added into the system. In addition, pH plays a significant role in the process overall. This is consistent with the electrolysis processes taking place at both electrodes. A large pH gradient across the soil samples changes the chemistry of pore fluid, which leads to alteration of soil structure or even soil mineralogy especially at the anode and cathode. This was demonstrated by results of the mechanical behaviour and supported by the chemical aspect in this study. Therefore, this study tried to relate the changes of pH with the physical properties of soil such as shear strength and Atterberg limit. Therefore, the pH value can act as a direct measurement to evaluate the effectiveness of cation exchange and precipitation phenomena and so indirectly to the changes that occur to the shear strength of the soil throughout the treatment process.

As discussed earlier in section 8.4.1 and 8.4.2, cation exchange and precipitation improve the soil shear strength due to the changes in structure and mineralogy of clay soil. This agrees with many researchers, who have reported changes to the clay structure and its mineralogy. These therefore, can be determined from the Atterberg limits. However, the main contributing factors that lead to these phenomena are pH changes and concentration of certain cations available in the pore fluid. The latter phenomena will be discussed later in this chapter (see section 8.4.4).

For the DW-DW system, it can be seen at both electrodes there was no significant changes in term of shear strength in the middle of the samples with regards to treatment time but there was a slight increase at the anode and cathode after 14 days (see Figure 6.17). When comparing with the pH values in the middle it was observed that the pH values were maintained at the value of control sample (see Figure 6.23), whereas there were high acid and alkaline conditions at the anode and cathode, respectively. Therefore, this confirms that change of pH alone do not make an impact on shear strength of the soil. Thus these must be accompanied by a second improvement factor, which includes the introduction of certain ions into the system. A slight increase of shear strength at the cathode with time is due to dissolution of certain metal ions within the clay mineral itself (probably Fe, Mg, K, and Na) or hydrogen ions (from electrolysis product) in acidic environments that migrate toward the cathode. However, when these ions reach the cathode, a drastic pH change (from pH 5.1 to 7.4 as seen in Figure 6.23) at the cathode caused these ions in the pore fluid to react with other ions available at the cathode released from clay mineral (aluminium and silicate ions) and electrolysis product (hydroxide ions) under an alkaline environment. Therefore, it can be concluded that these ions whether coming from the anode or the cathode area cause precipitation of metal hydroxides to form cementatious agents that contribute to the increase in shear strength at the cathode. However, due to the lower concentration of metal ions and the absence of certain ion like calcium, it is not enough to increase the shear strength and hardened with time. As discussed in the literature (see Chapter 3), the clay mineral is associated with high surface area. Therefore, in order to bind the clay particles, the cementations agent or insoluble metal hydroxide gel must be abundant in the pore fluids within the clay particles to have such impact. The results from the pure system presented herein is in full agreement with Ahmad *et al.* (2011) who used distilled water at both electrodes and is supported by the earlier work of Liaki (2006) using the same electrodes.

For the CaCl-DW system, the increase of shear strength in this system was mainly due to the cation exchange. No cementation was observed during the EKS testing to suggest the precipitation occurred even after 14 days experiment (see Figure 7.25). This was supported by the pH data (see Figure 7.37) that showed pH of about 6.7 close to the cathode, which unlikely the precipitation to happen. Another factor that caused the slightly alkaline environment near the cathode was due to the migration of acid font (hydrogen ions) towards the cathode, which neutralised the pH around the cathode as well as in the middle of the samples. Thus, this prevents possible precipitation to take place. This can be considered likely as the mobility of hydrogen ions is 1.8 faster than hydroxide ion (Asavadorndeja & Glawe, 2005). This causes hydrogen ions to dominate the chemistry of pore fluid together with calcium ions. Due to the replacing power of calcium ions compared to hydrogen ions, the cations exchange have resulted an increase in shear strength across the soil samples as shown by the undrained shear strength and Atterberg limit results (see Figure 7.25, 7.28 and 7.31). The hydrogen ions were flushed away from the system through the drainage provided at the cathode, due to being contained within the pore fluid.

In the DW-NaSiO system, the development of high acid and alkaline environments at the anode and cathode, respectively, still caused insignificant increases in shear strength. This was demonstrated by the changes of pH together with and appropriate chemical ions available in the soil system. These are inter-related factors and contribute to the increase of soil shear strength. Previous researcher, e.g. Moayedi *et al.* (2011) has argued that the addition of only sodium silicates to hydrated clay may actually negatively affect on soil improvement. After 14 days, the development of high pH at the anode was observed due to the indication of silicate ions that travel to the positively charge electrode causing no significant increase of shear strength in that area. This was due to the absence of certain cations available in the pore fluid under such an alkaline environment

When both calcium ions and silicate ions were added into the system simultaneously in the CaCl-NaSiO system, the desired precipitation took place at the cathode under a highly environment (pH >10 as seen in Figure 7.39 for all treatment durations). The results of Atterberg limits also suggest the precipitation had occurred in the alkaline zone near the cathode. A large increase in liquid limit (see Figure 7.30) and plastic limit (see Figure 7.33) were observed in the zone of high pH at the cathode. The changes in Atterberg limits are governed by dissolution of clay mineral under highly alkaline environment, multivalent of Ca ions migrated from anode to cathode and hydroxide ions released from electrolysis process, then react with Si ions added at the cathode to form a new precipitation of metal hydroxide (CSH gels). These insoluble gels would have undergone transformation process, such as crystallisation and cemented the clay particles (Schifano, 2001). This indeed has similar results with lime stabilisations which reported by previous researchers (Rogers & Glendinning, 1996; Boardman *et al.,* 2002; Rogers *et al.,* 2003). Those studies have reported that the increase of Atterberg limits values under high pH environment due to the production of cementation gels, thus alter the properties of clay soils. Therefore, this EKS method has potential to be applied further in the field application. However the precipitation of insoluble gel limited at the cathode area as also reported by Barker *et al.* (2004), who added the silicate ions at mid-point between the electrodes. This approach showed quite good results in term of shear strength during a field trial using the same chemical stabiliser. The phenomena relating the ease of silicate ion movement towards the anode will be discussed further (see section 8.4.4). At the anode and in the middle of the samples, the generation of a low pH environment (high acidity), which migrated toward the middle of the samples contributed to the soil strengthening via cation exchange (discussed in section 8.4.1) and to a lesser extent causes the precipitation of CSH gels at the cathode.

8.4.4 Chemical Concentrations Effect

Results of metal concentration in the pure system (see section 6.4.3) indicated the continuous introduction of distilled water at both electrodes resulted in reduction of metal concentration of Fe, Al, and K in the soil water system. This was attributed to the migration of these ions across the soil samples, which subsequently flushed out through the cathode drainage. Metal ions such as Fe and Al exist in soils as multivalent cations, either in the pore fluid or absorbed on soil surface. They also occur within the clay mineral itself.

The acid digestion preparation used in the metal concentration analysis caused all the elements to be digested before analysis. Therefore, the amount of metal concentration must be taken into account that is available from whole system of clay samples. The much lower concentration of Fe and Al than of control sample were also observed by Liaki (2006) using the same electrodes and electrolytes (distilled water). The dissolution of clay mineral is dependent on the pH environment. For example, dissolution of alumina can occur in small quantity at a pH less than 7 and starts to increase significantly at a pH > 8, reaching a maximum at pH > 10 (Barker *et al.,* 2004). The results of pH profiles as observed in Figure 6.23 in this pure system have shown the dissolution of alumina was likely to occur at the anode at low pH and become more significantly at the cathode area when pH rose to higher value. However, certain elements have different solubility rates under different pH environments. Dissolution of silica is negligible at pH < 8 but becomes significant at pH more than 10. This can be observed in variation of silica concentration along the soil profile (see Figure 6.29). Furthermore, the low solubility of silica ions even after acid digestion using less strong acid in this study (hydrochloric acid) might be the reason of variation of silica concentration and according to Liaki (2006) a strong acid such as hydrofluoric acid is required to completely dissolve it.

The results shown in the CaCl-DW system have indicated that the introduction of calcium ions alone into to the system showed an increase in calcium concentration with distance from anode and treatment time. The metal concentration of Fe in the clay system shows no significant change as seen in Figure 7.44, therefore it would suggest the Fe ions did not migrate towards the cathode and did not flush out from the clay samples. However, the higher concentration of Al and K ions which varied along the soil profiles after 3 days indicated the release of Al and K into the pore fluid and caused it to fluctuate along the way (see Figure 7.46 and 7.48). These values seem to decrease with time after 7 and 14 days. This indicates that the aluminium was flushed out from the system in small quantity compared with the pure system. Conversely, the Na concentrations were much lower than of the control value as seen in Figure 7.47. This indicated the release of Na ions into pore fluid, which then migrate towards the cathode before being flushed out from the system. In order to balance the system, the abundance of calcium ions from the anode chamber was likely to replace such ions and be absorbed on the clay surface, due to the replacing power of calcium ions by mass action, higher ion valence and its larger hydrated radius cations compared to Na ions.

In the case of DW-NaSiO system, the Si ions migrated at a slower rate compared with the calcium ions in the CaCl-DW system (see Figure 7.49). This was attributed to water flow caused by electroosmosis in opposite direction and retarded the migration of silicate ions. The result from chemical analysis show that the Si ion had been reached at the anode after 14 days treatment time compared to calcium ions which reach at the cathode after 7 days.

For the CaCl-NaSiO system, the high concentration of silicate ions at the cathode as observed in Figure 7.55 was expected due to the introduction of Si ions. However, the migration Si ion in the CaCl-NaSiO system was slower than in the DW-NaSiO system. This is due to cementation of soil particles caused by precipitation of metal hydroxide, which clogged the fabric of the clay at the cathode thus preventing the silicate ions moving further. The concentration of calcium ions across the soil samples has shown similar trend with the CaCl-DW system.

Therefore, it can be concluded that the migration of calcium ions has not been effected by the introduction of Si ions at the other electrode side when applied at the same time but will affect the migration of Si ions. The lower concentration of Al and Fe ions than of the control value has similar effect as discussed in the CaCl-DW system due to the dissolution of those mineral under certain pH environment and flushed out from the system. However, no significant effect was observed for Na and K ions suggesting these ions were remained in the system under such condition. However, higher concentration of Na ions at the cathode was observed due to the diffusion of sodium ions from the sodium silicate placed at the cathode chamber.

8.5 Implication for Field Use

This research study has established that the application of EKS method has potential to be implemented successfully in the field application and the viability of this technique has been proven in this laboratory study. Some important practical aspects related to the field application have to be taken into consideration with EKS procedures and design considerations adopted in this study. Thus, the problems that may be encountered during field application can be assessed and appropriate action taken by the engineers to increase the efficiency of this method. These problems include i.e., gas generation at the electrodes, durability of the electrode materials and contact between soil electrode interfaces encountered in previous field can be eliminated during the EKS testing. The electrode material can be inserted in the electrolytes chamber to maintain the electric contact between electrode and the soil if electrolyte solution level is maintain in the solution and providing the gas escapes through the electrolytes solutions into the air without effect on the soil electrode contact.

A sharp drop of electric current profile with time indicates the high resistivity zone due to the precipitation of metal hydroxides at the cathode cause fluid flow to become minimal thus decreased the electric current of the system. Therefore, continuous current supply can increase the cost of the treatment and not increase the performance of the system. In fact the performance can be increased even the current was stopped due to the chemical reaction process which take a longer time to occur. Therefore, further action can be made to optimise the cost and operation, and at the same time increase performance. In field applications, when the current was shut off, continuation of second mineral changes need to be taken into consideration, as curing after certain period of time significantly increased the shear strength. The formation of secondary mineral is not an instantaneous reaction but mainly occur after certain curing times thus allow the crystallisation of these mineral, resulting a large increase in shear strength.

The experimental data indicated that the introduction of certain ions at both electrodes make a significant impact in shear strength due to the electrochemical effects compared to the other related ground improvement techniques, which only rely on the reduction of water content and consolidation processes i.e., preloading, vertical drain and electroosmosis dewatering and electroosmosis consolidation. This method has brought about the combination of those techniques to reduce the water content and chemical stabilisation (e.g. lime stabilisation) to act as cementation agent to bind to soil particles and thus, cause a large increase in shear strength as a whole. This latter phenomenon is the main contributor in this technique if sufficient time is allowed. The precipitations of amorphous compounds act as cementation gels to bind the soil particles thus increase the soil cohesion. After a certain time, this precipitation will harden with time due to the mineralisation process thus change the fabric and mineralogy of the soil.

For a better performance in EKS methods, there are two methods that can be implemented in the future. In the first method, the calcium ions are introduced at the anode until they reach at the cathode at considerable amount of concentration and allow sufficient time for cation exchange or precipitation to occur across the soil samples. Then, the calcium ion addition can be stopped. Following this, the closed anode and open cathode configuration (normally for electroosmosis consolidation setup) can be applied to allow dewatering processes to withdraw excessive water, thus increase the shear strength of soil due to the decrease in water content together with electrochemical effects. A second method, introduces sodium silicate first at the cathode allowing migration of silicate ions across the soil. After certain time, calcium chloride is introduced at the anode to promote Ca ions migration and allowing reaction with Si ions and hydroxide ions to take place and produced the precipitation of CSH at location desired.

Another factor that needs to be considered is coupled flow due to the hydraulic gradient, electrical gradient (electroosmosis and electromigration) and chemical diffusion. The hydraulic gradient effect was eliminated in this study using Mariotte bottle method to maintain the water level at both electrolyte chambers, which resulted in variable parameters. The design configuration in this study only allows the electroosmosis and electromigration process to occur in order to assess the effect of electrical gradient during the EKS testing. However, in the field application this coupled flow must be taken into consideration to assess the efficiency of EKS technique. The hydraulic gradient in the actual field condition can be manipulated to provide favourable flow conditions and increase the electroosmosis and electromigration process to effectively migrate the desirable ions into the system.

In conclusion, successful field application can be achieved if appropriate chemical stabilisers are added together with selection of electrode materials and other design considerations.

Chapter 9

CONCLUSION AND RECOMMENDATIONS

9.1 Introduction

Many issues arise from dealing with soft ground, with a number of structures and building suffering distress as a result of weaknesses of the ground, which cause adverse settlements or even failure. A number of approaches can be used but EKS offers the key advantage of effecting a treatment under a building whilst not exacerbating these problems further. A number of previous studies have demonstrated the potential for this technique. However, there still remains uncertainty with a lack of understanding of the electrochemical effects and physiochemical changes that take place during the treatment process. In particular there is still uncertainty about the combination of stabilisation and the configuration that should be used. This has led to reluctance in the adoption of the EKS approach for field applications.

It is essential that a full breath of physicochemical understanding of clay soils is achieved including clay mineralogy, clay-water-electrolyte system, flow theories and electrokinetic phenomena. This enables a better understanding of physical and chemical processes that occur during the application of electrokinetics. This is important as a number of different sometimes counteracting processes are taking place including electroosmosis dewatering, electroosmotic consolidation, exchange reaction and stabilisation. Therefore, a number of mechanisms and processes involved in electrokinetic stabilisation to strengthen soft clay soils take place over differing periods of time. Thus changes that occur are environmentally, spatially and temporally driven. In turn physical and chemical properties of treated soil need to be assessed with respect time and distribution and this thesis presents results to both demonstrate how this can be done and discusses approaches best suited to undertake this. This includes relatively inexpensive and repeatable methods drawn from well establishes approaches, such a pH monitoring and Atterberg limit testing.

The following section details key pertinent findings drawn from the two main stages of testing, namely stage 1 results from the ‘pure’ system and stage 2 results from the stabilised system. The conclusions from these two stages are presented together to demonstrate key findings. This then allows implication for field developed to be considered and these are outlined below in Section 9.5, below.

The aim of this work was to evaluate the use of EKS as a method to strengthen soils. This was achieved through three objectives, namely:

(1) The development of a new EKS treatments methods monitored through adapted experimental process draw from (Liaki, 2006)

(2) To assess the degree of strengthening that takes place when different stabilisers are added under a given voltage gradients.

(3) To investigate various electrochemical effects on physical, chemical and physicochemical behaviour of soft clay soil.

Importantly, the work present herein has allowed development of the EKS technique through the use of the base model developed by Liaki (2006), allowing both a better understanding of how the EKS process takes place and how monitoring can be conducted. This provides details essential for ultimate application of the EKS to field situations. In particular evaluation of different treatment solutions provide key information on what can be achieved and importantly what is needed to ensure successful enhancement of given properties can take place.

9.2 Monitoring Data

The results from monitoring data from both of pure system and EKS with chemical stabilisers showed that there are several important mechanisms relating to the electrochemical effects and these can be drawn from this study. The key conclusions made are:

i. The electric current profiles are influenced by the ionic concentration of the pore fluid within the soil matrices. Therefore, the addition of chemical ions at either or both anode and cathode had caused an increase in the electric current at the beginning of the test, but then a decrease with treatment time indicating that a high resistivity zone forms due to precipitation of metal hydroxide at the cathode. Thus this causes the fluid flow to become minimal decreasing the electric current across the system.

ii. Higher electric currents were seeing for the CaCl-DW, DW-NaSiO and CaCl-NaSiO systems, under the same voltage gradient. These changes were due to increases in the ionic strength of pore fluid, i.e., Ca and Si (both or either one from electrolytes compartments), Al, Fe, Si (dissolution of chemical compound and clay minerals), and hydrogen and hydroxide ions (electrolysis product) in the soil-water system that migrate from both electrodes. The result showed a significant increase in the conductivity of the soil thus increase the electric current value relative to that at the start of the test.

iii. The results of pH anolyte for most of the systems show the decrease of pH to a high acid solution with time due to the production of hydrogen ions at the anode. The notable exception was for the DW-NaSiO system. This was attributed to the introduction of distilled water at the anode and the migration of hydroxide ions from the cathode toward anode that may neutralise the acidity environment at the anode. In addition, the increase of ionic strength at the cathode caused by introduction of silicate ions and hydroxide ions from the electrolysis product retards the movement of water (electroosmosis) and hydrogen ions (electromigration) toward the cathode. Thus, a change in the pH environment at the anode and affect the pH at the anolyte.

iv. Whereas the pH of the catholyte was maintained during the treatment due to the production of hydroxide ions and the effect of certain cations, which were flushed out from the system by electroosmosis and electromigration processes. In addition the pH values at both electrolytes are also dependent on the pH of the electrolytes solutions which were continuously supplied from the Mariotte bottle, thus this modified the measurements made. Importantly pH is a useful parameter to measure as it gives a reliable indication of net changes to chemical environment, thus this should be incorporated in any field measurements.

v. The results of electrical conductivity of anolyte and catholyte depend on the type of electrolyte used and electrolysis process to produce hydrogen ions and hydroxide ions. These results also indicate the efficiency of the system to promote migration of Ca and Si ions in the CaCl-DW, DW-NaSiO and CaCl-NaSiO systems.

vi. The inflow and outflow of water or solution are also important to assess the efficiency of the electromigration and electroosmosis process to migrate Ca ions and Si ions into the system, and thus to improve the properties of soft clay. These are particularly useful to assess breakthrough of various additives thus enabling a gauge of the stage and progress of the treatment processes.

Results from the monitoring data are inter-related to assess the efficiency of the system to transport chemical ions and provide indirect information relating to the electrochemical effects during the EKS testing. This is more important in the field application where it is necessary to take immediate action if the performance of the EKS testing is decreases due to the problems that may as a result of design consideration, selection of electrode materials, method of installation or problems caused by electrochemical effects (e.g. gas generation). Therefore, engineers can take appropriate action whether to increase /

decrease the voltage or the current, using intermittent current or polarity reversal, and change the electrolyte types at either or both anode and cathode compartment, thus improving the performance of the system and reduce the overall cost of EKS testing.

9.3 Electrochemical Effects on Physical Properties of Soft Clay

Regarding the physical properties of soft clays, there are several important mechanisms relating to the electrochemical effects could be drawn from this study:

i. The results from the water content reflect the changes of shear strength of the treated soils to some degree. However, from the graph of relationship between water content and undrained shear strength, there was a significant increase of shear strength due to electrochemical effects in the CaCl-DW and CaCl-NaSiO systems. By contrast, the DW-NaSiO system showed insignificant improvement related to the shear strength, and in fact caused a decrease in shear strength in some of the data points.

ii. Cation exchange is the main mechanism contributing a significant increase in shear strength for the CaCl-DW system and the increase is relatively uniform across the soil sample. This is supported from the results of Atterberg limits, pH, electrical conductivity and chemical concentrations. No sign of precipitation had occurred at the cathode due to the low pH and the absence of silicate ions to promote the development of CSH and/or CAH gels.

iii. Precipitation and cation exchange are the main contributors to the increase of shear strength for the CaCl-NaSiO system after 7 days treatment. However, precipitation of CSH gels has greater influence on the shear strength in the proximity of cathode followed by cation exchange in the proximity of anode and in the remainder of the soil sample.

iv. This pozzolanic reaction take place and form cementing bonds and cementing compounds within the pore space and between soil particles for a short time. These consequently modify the soils engineering properties including strength, plasticity, and in turn will improve volume change potential, permeability and compressibility properties.

v. With time, the precipitation of insoluble metal hydroxides crystallise with time to form a strong and brittle solid of clay soil. This can be seen after 14 days treatment, when there was a further incremental gain at the cathode area. However, this phenomenon was at the initial stage and could be more significant, if longer treatment was applied or the sample was allowed to cure after current was ceased.

vi. It can be concluded that silicate ion alone have limited or no benefit in increasing the shear strength in the EKS method. The negative charge of silicate ions caused them to be attached to clay soil particle edges due to the positively charged Kaolinite clay in their edge of broken bonds, thus causing repulsion of particles and generating a weaker disperse fabric.

vii. The liquid limit and plastic limit of the soil will both be increased, though causing the plasticity index to decrease, indicating increases in soil compressive strength and workability, where chemical reactions had occurred near the cathode

viii. A decrease of liquid limits and plastic limits occurred due to the high acidic environment for the CaCl-DW system, which is assumed to cause reduction of thickness of the double layer, thus allowing closer contact between the clay platelets, which resulted in an increase in shear strength at the anode; this was confirmed from the chemical results.

ix. There were variation in the liquid limits and plastic limits profiles across the soil samples for the CaCl-NaSiO system due to the cation exchange and precipitation effects with time.

9.4 Electrochemical Effects on Chemical Properties of Soft Clay

Regarding the chemical properties of soft clays, there are several important mechanisms relating to the electrochemical effects could be drawn from this study:

i. A clear pH gradient developed across the soil sample creating an acid front at the anode and a base front at the cathode.

ii. A large pH gradient across the soil samples changes the chemistry of the pore fluid, which leads to alteration of soil structure or even soil mineralogy, especially at the anode and cathode area. This was proven by results of shear strength and supported by electrical conductivity and chemical concentrations.

iii. The pH values can act as a direct measurement to evaluate the effectiveness of cation exchange and precipitation phenomena to increase the shear strength of the soil.

iv. The pH profiles show a similar trend for all systems indicating the significant role of electrolysis process as one of the important electrochemical effects in EKS testing, leading to other electrochemical effects, i.e. cation exchange, precipitation, mineralisation and particle arrangement (clay structure). Thus, the pH changes the physiochemical properties of soft clay soil.

v. The electrical conductivity profile shows indication of dissolution of chemical compound between soil particles and clay minerals, production of hydrogen and hydroxide ions as electrolysis products, and migration of ions from both or either anode and cathode compartments.

vi. The higher electrical conductivity at the anode was attributed to the increase of ionic strength and remained in an ionic state in the pore fluid due to the acidic environment, whilst the lower conductivity was attributed to low solubility of certain elements under alkaline environments. This also indicates the precipitation of insoluble salts in the pore fluid, which act as a cementations agent to bind soil particles.

vii. Calcium ions migration in the CaCl-DW system are more efficient than in the CaCl-NaSiO system due to the coupled flow and no precipitation after 14 days treatment to prevent this flow towards the cathode area. In addition the use of distilled water at the cathode also contributes to this effect.

viii. The distribution of calcium ions contributes to the cation exchange at the anode and the remainder of the samples towards cathode for the CaCl-DW system. It also contributes to the development of CSH gels at the cathode for the CaCl-NaSiO system.

ix. The distribution of silicate ions has significant impact in the CaCl-NaSiO system compared to the DW-NaSiO system at the cathode area, where they react with the calcium ions and hydroxide ions (electrolysis product) to form CSH gels. No significant development of precipitation for the DW-NaSiO occurred due to the absence of calcium ions being released into the system.

x. The lower concentration of Al and Fe ions for the DW-DW, DW-NaSiO and CaCl-NaSiO systems indicate the dissolution of Al and Fe ions from chemical compounds between soil particles and clay mineral lattices, which were released into the pore fluid under acid and alkaline environment and flushed out from clay sample.

9.5 Recommendations

There are several recommendations to improve the implementation of EKS method for further study in the laboratory and for implementation of this technique in the field:

i. Effect of coupled flow due to the electrical and hydraulic gradient to assess the migration of ions in the EKS method to simulate real field conditions.

ii. Applying surcharge during EKS testing to test under a stress condition that depends on the depth of electrode inserted in the ground.

iii. Facilitate an inert electrode inside an electrolyte chamber to avoid the problem relating to the poor contact of soil-electrode interfaces due to the heating effect or gas generation. Thus, it could improve the performance of the EKS method and reduce the cost of electric current due to the voltage drop at the soil-electrode interface.

iv. Using different types of chemical stabilisers could potentially increase the properties of the soft clay. Based on the data presented in this thesis the best combination suggested is calcium chloride at the anode and sodium silicate at the cathode.

v. Determine the effects of applying polarity reversal or intermittent current in terms of the properties of the soft clay, overall cost, efficiency and performance of the EKS method.

vi. Use different types of soils which has different mineralogy that may affect the electrochemical process i.e., soil with high buffering capacity, high organic matter, high cation exchange capacity and different soil composition.

vii. Explore in more detail the hypothesis that the pH values can act as a direct measurement to evaluate the effectiveness of cation exchange and precipitation phenomena to increase the shear strength of the soil.

This technique needs further studies to gain better understanding of the effect of numerous physicochemical processes involved, to allow the development of a proven field-based electrokinetic stabilisation method. Ultimately, the key aim of research effort into electrokinetic stabilisation is to provide a viable and consistent stabilisation method that can be used under existing foundations without adversely affecting the ground in ways that other improvement techniques can do.

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