IMPROVEMENT OF A TROPICAL RESIDUAL SOIL BY ELECTROKINETIC PROCESS

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To my beloved wife *Sufiah Salleh* and my three beautiful daughters;

Nabihah, Nuwairah and *Awadah.*

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In the name of ALLAH the Almighty, the most Beneficent and Merciful. All praise goes to ALLAH and may peace be upon Prophet Muhammad S.A.W. *Alhamdulillah*, with HIS blessings this thesis was completed successfully.

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ABSTRACT

Tropical residual soils are generally heterogeneous and partially saturated. These soils attain their strength from capillary stresses as well as cementation of soil particles by clay minerals and sesquioxides. The strength however reduces significantly upon saturation due to the collapse of capillary stresses and increase in pore water pressures. Such strength reductions may lead to soil instability. The effectiveness of additives to increase shear strength however is limited to small soil volume due to slow and restricted ion migration. Thus, electrokinetic (EK) processing was combined with chemical addition to increase ions diffusion. Experiments to study the feasibility of the combined methods to increase the shear strength of a compacted and saturated (C&S) tropical residual soil were performed using EK cells. The diameter and length of each EK cell were 10.0 cm and 5.0 cm, respectively. Open-anode and open-cathode systems were employed to treat soil samples densified to 90% of maximum dry density at the optimum moisture content. Injections of 1.0 M of calcium chloride, aluminium chloride and phosphoric acid were carried out via applications of 30 V DC electrical potential for 168 hours. Effects of EK treatments on compressibility and hydraulic conductivity were also investigated. The employment of distilled water (DW) as anolyte and phosphoric acid (PA) as catholyte resulted in the highest strength and lowest compressibility. The utilisation of the other chemicals as anolytes and DW as catholytes resulted either in strength reduction and higher compressibility or no significant changes in both the engineering properties both near the anodes and the cathodes. EK treatments also affected the values of hydraulic conductivity of the treated soils, depending on the utilised chemicals. On different molarity of PA as catholytes and DW as anolyte, the utilisation of 0.5 M PA resulted in the highest cohesion and lowest compressibility of the EK treated soil near the cathode. No significant changes were observed in the compressibility of the treated soils near the anodes from the utilisation of different PA concentrations. Regarding the EK parameters, the directions and quantities of net electroosmotic flows varied depending upon the chemicals used as the anolytes and catholytes. These chemicals influenced the pH of the soil-pore fluid chemistry, which determined the signs and values of zeta potential (ζ) during EK processing. No net flows were also observed because of isoelectric point (IEP) where $\zeta = 0$ were achieved. The values of electroosmotic hydraulic conductivity (k_e) varied with time and generally lower than the k_e values of temperate soils reported in literatures. On different concentrations of PA as catholytes, 0.5 M PA was considered as the optimum concentration in this study because the utilisation of it produced the highest in strength, current density and net electroosmotic flow besides the lowest compressibility. X-ray fluorescence (XRF) analyses on the EK treated samples showed that the distributions of the EK-injected ions after treatments were not uniform.

ABSTRAK

Umumnya tanah baki tropika adalah heterogen dan separa tepu. Tanah ini memperolehi kekuatannya dari tegasan rerambut dan penyimenan antara butiran tanah oleh galian tanah liat dan seskuioksida. Bagaimanapun, kekuatannya menurun dengan ketara disebabkan penepuan kerana tegasan rerambut musnah dan tekanan air liang meningkat. Penurunan kekuatan ini boleh menyebabkan ketidakstabilan kepada tanah. Untuk menaikkan kekuatan tanah menggunakan bahan kimia, pergerakan ion yang perlahan dan jarak serakan yang kecil membataskan keberkesanannya. Oleh itu, pemprosesan elektrokinetik (EK) telah digabungkan dengan penambahan bahan kimia untuk meningkatkan jarak pergerakan ion. Kajian tentang kesesuaian gabungan dua kaedah tersebut bagi meningkatkan kekuatan ricih tanah baki tropika terpadat yang tepu (C&S) dilakukan menggunakan sel EK. Setiap sel bergarispusat 10.0 sm dan 5.0 sm panjang. Sistem anod dan katod terbuka digunakan untuk merawat tanah baki yang dipadatkan 90% berbanding ketumpatan kering maksimum pada kandungan lembapan optimum. Penyuntikan 1.0 M kalsium klorida, aluminium klorida and asid fosforik ke dalam tanah dilakukan menggunakan tenaga elektrik arus terus (DC) 30 V selama 168 jam. Kajian tentang kebolehmampatan dan keberaliran hidraulik selepas rawatan EK juga dilakukan. Penggunaan asid fosforik (PA) sebagai katolit dan air suling (DW) sebagai anolit telah menghasilkan kejelekitan tertinggi dan kebolehmampatan terendah. Penggunan kalsium klorida dan aluminium klorida sebagai anolit dan DW sebagai katolit pula samada menurunkan kekuatan dan meningkatkan kebolehmampatan atau tidak menghasilkan perubahan ketara ke atas tanah yang dirawat samada di anod atau di katod. Rawatan EK juga mempengaruhi nilai keberaliran hidraulik tanah yang dirawat, bergantung kepada jenis bahan kimia yang digunakan. Berkaitan penggunaan kemolaran PA yang berlainan sebagai katolit dan DW sebagai anolit, 0.5 M PA menghasilkan kejelekitan tertinggi dan kebolehmampatan terendah berhampiran katod. Tiada perubahan ketara dalam kebolehmampatan tanah berhampiran anod hasil rawatan EK menggunakan kepekatan PA yang berbeza sebagai katolit. Berkenaan dengan parameter EK, arah dan kuantiti aliran bersih adalah berbagai, bergantung kepada bahan kimia yang digunakan. Bahan-bahan kimia tersebut mempengaruhi pH tanah, nilai dan tanda keupayaan zeta (ζ) semasa pemperosesan EK. Terdapat ketika di mana tiada aliran bersih disebabkan titik isoelektrik (IEP) iaitu $\zeta = 0$ tercapai. Keberaliran hidraulik elektroosmotik (k_e) juga berubah dengan masa dan nilainya lebih rendah daripada yang dilapurkan dalam literatur untuk tanah kawasan suhu lampau. Bagi kepekatan PA yang berbeza sebagai katolit, 0.5 M PA dianggap sebagai kepekatan optimum dalam kajian ini kerana penggunaannya menghasilkan nilai-nilai tertinggi bagi kekuatan tanah, ketumpatan arus elektrik dan aliran elektroosmotik bersih di samping kebolehmampatan terendah. Analisis pendarfluor sinar-X (XRF) menunjukkan taburan ion-ion yang disuntik secara EK adalah tidak seragam.

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A	-	Ampere
AAS	-	Atomic adsorption spectrophotometer
AEC	-	Anion exchange capacity
Al		Aluminium chloride
a_v	-	Coefficient of compressibility
Al-DW	-	Aluminium chloride – Distilled water
ASTM	-	American Society of Testing Material
BS	-	British Standard
BSCS	-	British Soil Classification System
C	-	Soil composition
Ca		Calcium chloride
c	-	Cohesion
c'		effective cohesion
C&S	-	Compacted and saturated
C&U	-	Compacted-unsaturated
C_c	-	Compression index
C_s	-	Swelling index
Ca-DW	-	Calcium chloride – Distilled water
CEC	-	Cation exchange capacity
CSH	-	Calcium silicate hydtare
CASH	-	Calcium aluminate silicate hydrate
cps	-	Counts per second
c_v	-	Coefficient of consolidation
d	-	Basal spacing between atomic planes in crystal
D	-	Dielectric constant

DC	-	Direct current
DW		Distilled water
DW-DW	-	Distilled water –Distilled water
DW-PA	-	Distilled water – Phosphoric acid
D_{50}	-	Diameter of soil that 50% finer
e	-	Void ratio
E	-	Voltage
e_c	-	Electronic charge
e_o	-	Initial void ratio
e_f	-	Final void ratio
EC	-	Electrochemical
EK	-	Electrokinetic
EO	-	Electroosmosis
G_s	-	Specific gravity
H_d	-	The longest flow path
i_e	-	Voltage gradient
I	-	Current
IEP	-	Isoelectric point
J	-	Current density
k	-	Boltzmann constant
k_h	-	Hydraulic conductivity
k_e	-	Electroosmotic hydraulic conductivity
k_i	-	Electroosmotic transport efficiency
L	-	Length of sample
LL	-	Liquid limit
LOI	-	Lost On Ignition
LVDT	-	Linear variable displacement transducer
meq	-	Milliequivalent
M	-	Molar
m	-	Mass
m_v	-	Coefficient of volume change
MPK	-	Magnesium potasium phosphate
n	-	Porosity
n_o	-	Ion concentration

OC	-	Organic content
PA		Phosphoric acid
PL	-	Plastic limit
PI	-	Plasticity index
q_{eo}	-	Electroosmotic flow rate
s	-	second
S	-	Siemen
S	-	Soil structure
SEM	-	Scanning electron microscope
SL	-	Shrinkage limit
S/S	-	Solidification and stabilisation
t	-	time
T	-	Temperature
T_v	-	Consolidation time factor
USCS	-	Unified Soil Classification System
v	-	Ionic valence
V	-	Volt
V	-	Volume
w	-	Moisture content
W	-	Power
w_{opt}	-	Optimum moisture content
XRD	-	X-Ray diffraction
XRF	-	X-Ray fluorescence
ZAV	-	Zero air void
ΔE	-	Potential difference
ε	-	Strain
$\dot{\varepsilon}$	-	Strain rate
ϵ_o	-	Permittivity of vacuum
ρ_{dmax}	-	Maximum dry density
λ	-	Wave-length
η	-	Viscosity
ρ	-	Soil resistivity
θ	-	Glancing angle of diffraction

Ω	-	Ohm
σ_o'	-	Present effective overburden pressure
σ_c'	-	Past maximum effective overburden pressure
σ_y	-	Yield stress
ζ	-	Zeta potential
$\frac{1}{K}$	-	Thickness of diffused double layer

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CHAPTER 1

INTRODUCTION

1.1 Background

Situated within the tropical zone with the annual rainfall between 1778 to 3556 mm and average temperature of 27° C, the Peninsular of Malaysia is covered by soils that are broadly grouped into residual sedimentary soils, residual granite soils and coastal and river alluvia (Ting and Ooi, 1976). Amongst these soil groups, more than 75% of the surface deposits are made up of residual soils derived from granite and sedimentary to metasedimentary rocks (Taha *et al.*, 1997). The other portion of the surface soils that mostly found along rivers and in coastal regions are alluvium or clays. Based on the three categories of soils mentioned previously, emphasis in this study will be given on residual granitic soil. A distinctive feature of the granitic soil is that it is a mixture of sand, silt and clay in varying proportions (Ting and Ooi, 1976).

Tropical residual soils are generally heterogeneous and highly textured in nature resulting from intense chemical weathering on the parent rocks as well as partially saturated due to high annual rainfall. They may retain elements of the parent material structure, where they are usually non-uniform and are characterised by highly variable thickness of depth to bedrock (Mitchell, 1993). Due to the nature of their development and formations, the chemical and mineralogical compositions as well as the physico-chemical and engineering properties are anticipated to be different from those of soils in temperate regions. Hence, oversimplification and extrapolation should be avoided when dealing with tropical soils because of the complex inter-relationships between the parent rock types, the environmental factors and the different chemical weathering processes.

Problems associated with tropical residual soils are often connected with the high annual rainfall. According to Broms (1988), the effects of water on erosion and stability of slopes and the control of water content during compaction are issues to be resolved. Examples of the impacts of high rainfall on erosion and slope stability can be observed on slopes along the north-south highway and other hilly areas in the Peninsular of Malaysia. In addition to the aforementioned problems, the effects of cementation on strength and compressibility of tropical residual soils are critically important to be established since strength and compressibility are the governing factors in foundation designs. It is noteworthy however that the presence of cementation or bonding between particles, giving a component of strength and stiffness may be easily destroyed due to brittleness effect.

Like soils of other regions in the world, some tropical residual soils are also subjected to problems associated with low strength and high compressibility. Such poor engineering properties may lead to bearing capacity failures and intolerable settlements upon placement of loads. Hence, effective remediation programs need to be undertaken so that structures to be built on this type of soil will not be exposed to devastating failures in terms of safety and cost. These mitigation measures include stabilisation at shallow depths as well as at great depths below the ground surface.

Several methods have been employed worldwide to improve engineering characteristics of soils. Such methods can be categorised into different classes of stabilisation, which are mechanical, chemical, thermal and electrical. Stabilisation at shallow depths may involve chemical treatment and compaction, whereas deep stabilisation may include piling, vibrocompaction, stone columns, lime piles, etc. The methods employed are normally chosen based on site conditions, soil characteristics, location, available technology and more importantly the cost.

Soils with competent engineering properties are becoming scarce due to rapid development. Thus, new and effective soil improvement techniques have to be developed. At the same time, the existing soil stabilisation methods or techniques may need to be refined or improved to make them more attractive in terms of cost effectiveness (i.e. smaller, lighter and environmental friendly) to suit the complex site conditions. In addition to improving soils at sites to be developed, soils with poor engineering properties beneath or between existing structures may also need to be stabilised due to poor engineering assessment of the soils on which the structures were built. These special rehabilitation programs may need to be performed to prevent unnecessary hazards from taking place, which may cause lost of lives and/or properties. In this case, special equipment or/and stringent procedures may need to be employed in carrying out stabilisation work as it involves the stability of the existing structures. Among the available means to overcome such problems are underpinning and chemical injection.

With regard to chemical stabilisation, the general objectives of mixing chemical additives with soils are to improve or control volume stability, strength and stress-strain properties, hydraulic conductivity and durability (Hausmann, 1990). Volume stability against swelling and shrinkage can be improved by replacement of high hydration cations such as sodium with low hydration cations such as calcium, magnesium, aluminium or iron. Several types of additives have been proven to successfully improve engineering characteristics of clayey soils worldwide. Among the chemicals that have been utilised to improve engineering properties of soils in the forms of either solution or powder include cement, fly ash, calcium chloride, sodium chloride, gypsum, bitumen and sodium silicate. In addition, chemicals normally used in grouting can also be applied to improve engineering characteristics of soil, but their costs are considered as prohibitive (Hausmann, 1990).

Reviews on literatures show that the most widely used chemical to improve engineering characteristics is lime. The utilisation of such additives to stabilise clayey soils for highway constructions and other transportation facilities such as airfields usually involves mechanical mixing followed by compaction. In addition to shallow stabilisation, deep soil stabilisation of clays using lime piles and lime columns are practiced in Japan, China and Russia. This method has also been employed in the USA, Thailand and some European countries to stabilise slopes. It is normally believed and understood that the installation of lime columns or piles have caused consolidation to the surrounding soil due to the generation and dissipation of positive pore pressures by lateral expansion of the piles. However, Rogers and Glendinning (1994) suggested that the consolidation of the clay is caused by dehydration and development of negative pore pressures.

Besides consolidation of the surrounding soils, reactions between lime and clays result in improved engineering properties of soils, especially strength. Davidson *et al.* (1965) and Rogers and Glendinning (1994) found that lime migration or calcium ions diffusion is the major stabilisation mechanism. Nevertheless, study performed by Glendinning and Rogers (1996) showed that the migration of calcium ions that involve in the reactions is restricted to a relatively small distance. As such, it is desirable to diffuse the calcium ions from sources such as lime columns or lime piles further into the surrounding soil in order to increase the volume of the stabilised soil.

Meanwhile, electroosmosis (EO), a complimentary of electrokinetic (EK), has been known traditionally as a means to dewater soils having low hydraulic conductivity such as clay. According to Gray and Mitchell (1967) in EO, when the movement of migrating ions of one sign exceeds the movement of migrating ions of the other sign, water flows on the direction of greater ionic movement due to the net friction force. By dewatering, soils will undergo consolidation process, which in turn increase the effective stress. As a consequence, the strength will be improved and the compressibility will be reduced. Although there is a wide range of applications of EO, there are many unknowns with respect to ion flow through soil and the resulting changes in soil properties (Thomas and Lentz, 1990).

Besides dewatering, EO also results in hardening of soil within the vicinity of the anode due to the dissolution of the anode material. The ions resulted from the corroded anode material especially iron react with clay minerals in the treated soil to form hard compounds, which in turn increase the strength of the soil (Bell, 1975 and Hausmann, 1990). EK processing also has been employed with the combination of chemical solutions to increase strength of cohesive soil. This process is known as electrochemical hardening, and the chemical substances utilised include amongst others calcium chloride (Harton *et al.*, 1967), aluminium chloride (Gray, 1970) and aluminium sulphate and phosphoric acid (Ozkan *et al.*, 1999). These chemical solutions can be fed at the anode or the cathode depending upon the ions to be transferred into the soil. These researchers are among those who reported successful application of this technique to temperate soils, especially commercial kaolin and illite.

It is noteworthy that besides its main function as foundation materials, soil is both a source of metals and a sink of metals contaminants. At the same time soil also functions as a filter protecting the groundwater from inputs of potentially harmful metals. The presence of heavy metals in soils due to natural causes or human activities such as mining and industrialisation has caused concern with regard to human, plants and other living organisms. Nonetheless, some heavy metals may be essential in small quantity but may become toxic and hazardous if their presence is excessive (Alloway, 1995). As such, attempts have been made to extract, immobilise or contain the contaminants in place so that the risks of contaminants migration and other associated consequences can be eliminated or reduced to acceptable levels.

Amongst the methods of decontamination such as excavation and stabilisation and solidification (S/S), EK is found to be more attractive as this method can be employed to extract both inorganic and organic contaminants provided that these species are mobile or in the form of ions in the pore water. In relation to soil contamination, researches have been conducted to decontaminate contaminated soils, where EK is an emerging technology to remove heavy metals from heterogeneous fine-grained soils in-situ (Hamed *et al.*, 1991; Acar *et al.*, 1994; Eykholt and Daniel, 1994; Khan and Alam, 1994; Rodsand *et al.*, 1995; Zagury *et al.*, 1999; Li and Li, 2000; and Mattson *et al.*, 2000) as well as to remove non-metals (Acar and Haider, 1990; Bruell *et al.*, 1992; Taha *et al.*, 1994; and Li *et al.*, 2000).

In EK method generally, heavy metals in the form of cations in pore water are attracted to the cathode upon application of a direct current (DC). These contaminants may be collected as solution or precipitates within the vicinity of the cathode. It is found that acid front sweeps across the soil during the EK processing from the anode toward the cathode, leading to acidic environment to the soil. Thus it is considered as an advantage since contaminants will remain ionic under acidic environment. On the other hand, base front migrating from the cathode toward the anode at a slower rate than the acid front may retard the cleaning process as the cations tend to precipitate under higher pH. In overall, prolonged EK processing will lead to acidification of the treated soils.

In summary, soil improvement needs to be performed to ensure unnecessary hazards will not take place upon application of loads. Several techniques of soil improvement have been proven applicable for both temperate and tropical soils. Nonetheless, special attention has to be emphasised on improving tropical residual soil since the established methods were studied and developed particularly for temperate soils. Hence, adoption of such techniques to tropical soils has to be done with great precautions. Both EK and chemical addition techniques are reported capable in improving engineering properties of soils as well as to remedy contaminated soils. The combined EK and chemical substances for the abovementioned purposes are also reported as successful (Murayama and Mise, 1953; Esrig and Gemeinhardt, 1967; Harton *et al.*, 1967; Gray, 1970; Puppala, 1994; Taha *et al.*, 1994, Taha, 1996 and Ozkan *et al.*, 1999). Nonetheless, the combination of those techniques need to be performed judiciously, especially the selection of appropriate chemical substances. Although several soil improvement techniques are available, the suitability of application of EK processing with the combination of additives to tropical residual soil was investigated in this study. The selection of chemical substances was based upon the types that have been utilised successfully on temperate soils, particularly kaolinite.

1.2 Problem Statement

Migration of chemical substances added to soil is generally very slow and restricted to small distance from their sources. Hence, additives and soil have to be mechanically mixed or the additives need to be forced by pumping to diffuse the chemical substances into the soil. Nonetheless, mixing mechanically and pumping may not be effective to be applied to fine-grained soils of low hydraulic conductivity such as clayey soils.

Due to the restricted migration of chemical substances into soils, a DC electrical field was applied to assist diffusing the ions. Principally, the application of a DC electrical field to a wet clayey soil mass will impart movements of cations and anions towards the cathode and the anode, respectively. Water movement towards the cathode or/and towards the anode would accompany the electromigration. Nonetheless, the applied electrical potential results in acidic environment in the soil as the H^+ ions generated at the anode sweep across the soil toward the cathode. Hence, suitable chemical substances need to be sought so that precipitation or ion exchange contributing to strength increase resulting from reactions between the chemical substance and the soil will take place in acidic environment.

1.3 Objectives of Study

This research is initiated based on the expectation that the combination of chemical addition and EK processing promise to improve the engineering properties of a tropical residual soil. Thus, the objectives of this research are:

a) To assess and identify appropriate chemical substances suitable to be combined with EK processing to strengthen and to reduce the compressibility of a tropical residual soil.
b) To examine the changes in hydraulic conductivity of the treated soils due to EK processing performed as in (a).
c) To investigate the changes in strength, compressibility and hydraulic conductivity of a tropical residual soil after treated by EK processing using different concentrations of a selected electrolyte.
d) To monitor and assess the changes in EK parameters during the course of the experiments.

In overall, this study primarily investigates the feasibility of strengthening and reducing compressibility of a tropical residual soil by diffusing chemical substances into the soil by the assistance of an electrical field. Enhancement of engineering properties is anticipated by homogeneous precipitation of the species and appropriate ion exchange mechanisms.

1.4 Scope Of Study

The study focused on a tropical residual soil stabilised using the combination of chemical solutions (i.e., distilled water, calcium chloride, aluminium chloride and phosphoric acid) and application of a specified electrical potential. The soil utilised in this study was a reddish residual soil of granite origin, obtained from approximately 2 to 3 m below the ground surface within the compound of the Skudai campus of Universiti Teknologi Malaysia.

A constant voltage of 30 V was applied to each sample for seven days or 168 hours. The applied voltage was selected based on several trials, where application of voltages lower than 30 V to soil with distilled water as the anolyte and catholyte failed to produce any flow. The treatment period was chosen based on experimental convenience and energy inputs not to exceed 30 kWh/yd^3 (23 kWh/m^3) of treated soil (Gray, 1970) as well as based on soil decontamination experiments performed by Thenavayagam and Wang (1994) and Taha *et al.* (1994). Harton *et al.* (1967) conducted their experiment for 116.5 hours.

Depending upon the selection of the appropriate chemical solutions as described before, four different EK systems were employed in this study consisted of:

a) Distilled water as both the anolyte and catholye (DW-DW)
b) 1.0 M $CaCl_2$ solution as the anolyte and distilled water as the catholyte (Ca-DW)

c) 1.0 M H_3PO_4 solution as the catholyte and distilled water as the anolyte (DW-PA)

d) 1.0 M $AlCl_3$ solution as the anolyte and distilled water as the catholyte (Al-DW)

Note that the left and right terms in the parentheses represent anolytes and catholytes, respectively.

A standard shear box with the dimensions of 60 mm x 60 mm x 20 mm was utilised to determine the strengths of both the untreated and the treated soils. Each sample that was treated electrokinetically was subjected to direct shear test immediately upon completion of the treatment. No attempts were made to cure the treated samples in view of the expectation that the treated samples should gain strength during or immediately after treatment. The concentration of the chemical that caused the highest shear strength and the lowest compressibility of the soil after EK treatment then was varied in order to examine the effects of concentrations on EK parameters, strength, compressibility and hydraulic conductivity.

1.5 Importance Of Study

With regard to the importance of this research, the findings may be viewed as an alternative or/and improvement to the existing stabilisation methods for tropical residual soils. The benefits that would be gained from the study may include the followings:

a) Establishment of solution concentrations to be combined with a specified voltage of electrical potential to achieve an optimum stabilisation.

b) Improvement of physical properties of the treated soil, especially strength and compressibility.

1.6 Thesis Organisation

This thesis consists of six chapters. The essence of each chapter will be briefly described hereafter.

Chapter 1 generally describes the background of problems associated to tropical residual soils in addition to the objectives, scope and importance of the study. Brief description on stabilisation of problematic soils was also presented.

Review of literatures is presented in Chapter 2. Such revision encompasses the origin of tropical residual soils and soil improvement using additives and EK processing. Reviews on utilisation of chemicals and EK processing to stabilise and decontaminate contaminated soils are also included.

Research methodology and laboratory experiments exercised in this study are explained in Chapter 3. The laboratory experiments to determine the basic properties of soil were performed in accordance to procedures outlined by the British Standard and the American Society of Testing Materials. Guidelines by established authors were adopted in the determination of parameters that are not included in these two standards such as cation and anion exchange capacities, X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) analyses.

Chapter 4 presents and discusses the results obtained from experimental programmes described in Chapter 3. The results comprising basic physical, chemical and engineering properties of both treated and untreated soils. Results of EK parameters are also presented and discussed. The conclusion of this chapter is the selection of the appropriate chemical for further study by varying its concentrations. The selection was based on the potential of the chemical combined with EK processing to produce the highest shear resistance and the lowest compressibility.

Results of experimental works exercised using different concentrations of the selected electrolyte in EK processing are presented and discussed in Chapter 5. The main subjects discussed in this chapter are the EK parameters and strength, compressibility and hydraulic conductivity of the EK treated soils.

Chapter 6 concludes the outcomes of this study as well as outlines recommendations for future research.

g. Combining electroosmotic consolidation with EK treatment may be carried out to examine the effects on the treated soils compared to EK treated samples.

h. Impacts on environment may be studied due to the utilisation of chemicals in EK treatment.

REFERENCES

Abduljauwad, S.N. (1995). Improvement of Plasticity and Swelling Potential Of Calcareous Expansive Clays. *Geotechnical Enginering, Journal of Southeast Asian Geotechnical Society*. 26(1): 3-16.

Acar, Y.B., Alshawabkeh, A.N. and Gale, R.J. (1993). Fundamentals of Extracting Species from Soils by Electrokinetic. *Waste Management*. 13: 141-151.

Acar, Y.B. and Haider, L. (1990). Transport of Low-Concentration Contaminants in Saturated Earthen Barriers. *Journal of Geotechnical Engineering, ASCE*. 116(7): 1031-1052.

Acar, Y.B., Hamed, J.T., Alshawabkeh, A.N. and Gale, R.J. (1994). Removal of Cadmium (II) from Saturated Kaolinite by the Application of Electric Current. *Geotechnique*. 44(2): 239-254.

Ali, R. ed. (1995). *Panduan Amali Kimia Asas*. Shah Alam: Penerbit Fajar Bakti Sdn Bhd.

Alloway, B.J. ed. (1995). Soil Processes and the Behaviour of Metals. In: *Heavy Metals in Soils*. 2nd edition, London: Blackie Academic & Professional. 11-34.

Al-Mhaidib, A.I. and Al-Shamrani, M.A. (1996). Swelling Characteristics of Lime-Treated Expansive Soils. *Geotechnical Engineering, Journal of Southeast Asian Geotechnical Society*. 27(2): 37-53.

Anson, R.W.W. and Hawkins, A.B. (1998). The Effect of calcium Ions in Pore Water on the Residual Shear Strength of Kaolinite and Sodium Montmorillonite. *Geotechnique*. 48(6): 787-800.

Araruna Jr, J.T., Rivas, B.M.M., Mergulhão, A.J.P.P., de Souza, M.V. and Antunes, F.S. (2002). Laboratory Investigation of Electroosmosis Flow Efficiency in a Residual Soil from Gneiss. *Proc. of the Environmental Geotechnics 4th Intl. Congress on Environmental Geotechnics (4th ICEG)*, Brazil. de Mello, L.G and Almeida, M. ed. 11-15 August 2002. Balkema. 881-886.

Barksdale, R.D. and Blight, G.E. (1997). Compressibility and Settlement of Residual Soils. In: Blight, G.E. ed. *Mechanics of Residual Soil*. Rotterdam: Balkema. 95-154.

Bell , F. G. ed. (1975). *Methods of Treatment of Unstable Ground*. London: Newnes-Butterworths. 26-36.

Bell. F.G. (1996). Lime Stabilized Clay Minerals and Soils. *Engineering Geology*. 42: Amsterdam: Elsevier, pp 223-237.

Berkeley, K.G.C. and Pathmanaban, S. (1990). *Cathodic Protection of Reinforcement Steel in Concrete*. London: Butterworths,.

Berry, L.G. ed. (1974). *Selected Powder Diffraction Data for Minerals*. Joint Committee on Powder Diffraction Standards. Philadephia.

Berry, P.L. and Reid, D. (1987). *An Introduction to Soil Mechanics*. London: McGraw-Hill Book Company.

Blight, B.E. ed. (1997). Origin and Formation of Residual Soils. In: *Mechanics of Residual Soil*. Rotterdam: Balkema. 1-15.

Bohn, H., McNeal, B. and O'Connor, G. (1985). *Soil Chemistry*. New York: John Wiley & Sons.

Brady, N.C. and Weil, R.R. (1996). *The Nature and Properties of Soils*. 11th edition. New Jersey: Prentice Hall.

British Standards Institution (1990). *British Standard Methods of Tests for Soils for Civil Engineering Purposes, Part 2. Classification Tests*. London, BS 1377.

British Standards Institution (1990). *British Standard Methods of Tests for Soils for Civil Engineering Purposes, Part 3. Chemical and Electro-Chemical Tests*. London, BS 1377.

British Standards Institution (1990). *British Standard Methods of Tests for Soils for Civil Engineering Purposes, Part 4. Compaction-related Tests*. London, BS 1377.

British Standards Institution (1990). *British Standard Methods of Tests for Soils for Civil Engineering Purposes, Part 5. Compressibility, Permeability and Durability Tests*. London, BS 1377.

British Standards Institution (1990). *British Standard Methods of Tests for Soils for Civil Engineering Purposes, Part 7. Shear Strength Tests (total stress)*. London, BS 1377.

Broms, B.B. (1988). Foreword. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soils, Singapore*. 12-14 Dec. 1988. Rotterdam: Balkema.

Bros, B., Dzidowska, K. and Koszela, J. (1983). Influence of Flocculants on the Process and Efficiency of Electro-Osmosis in Fine-Grained Soils. *Proc. of the 8th European Conference on Soil Mechanics and Foundation Engineering*. 23-26 May 1983. Helsinki: 587-590.

Bruell, C.J., Segall, B.A. and Walsh, M.T. (1992). Electroosmotic Removal of Gasoline Hydrocarbons and TCE from Clay. *Journal of Environmental* Engineering, *ASCE*. 118(1): 68-83.

Casagrande, L. (1951). *Electro-osmotic Stabilization of Soils.* Presented at a meeting of the Structural Section of the Boston Society of Civil Engineers, Jan 10, 1951.

Chappell, B. A. and Burton, P. L. (1975). Electro-Osmosis Applied to Unstable Embankment. *Journal of the Geotechnical Engineering Division, ASCE.* GT8: 733-739.

Charng, H.J. and Holtz, R.D. (1986). Fabric, Pore Size Distribution, and Permeability of Sandy Soils. *Journal of Geotechnical Engineering, ASCE.* 112(9): 855-868.

Chen, C-c. (1997). *An Investigation into the Relationship between Effective Stress and Permeability of Clays.* University of Newcastle upon Tyne: PhD Thesis.

Chen, J. L. and Murdoch, L. (1999). Effects of Electroosmosis on Natural Soil: Field Test. *Journal of Geotechnical and Geoenvironmental Engineerin, ASCE.* 125(12): 1090-1098.

Chen, J., Anandarajah, A. and Inyang, H. (2000). Pore Fluid Properties and Compressibility of Kaolinite. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE.*126(9): 798-807.

Cheng, K.Y. and Bishop, P.L. (1992). Sorption, Important in Stabilized/Solidified Waste Forms. *Journal of Hazardous Waste and Hazardous Materials.* 9(3): 289-296.

Cheung, C.K., Greenway, D.R. and Massey, J.B. (1988). Direct Shear Testing of a Completely Decomposed Granite. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soils, Singapore.* 12-14 Dec. 1988. Rotterdam: Balkema. 109-118.

Chin, F.K. (1988). Construction of Dams, Roads, Air Fields, Land Reclamation in or on Tropical Soils- General Report. *Proc.of the 2nd Int. Conference on Geomechanics in Tropical Soils (Supplementary Documentations), Singapore.* 12-14 Dec. 1988. 92-102.

Chung, H.I. and Kang, B.H. (1999). Lead removal from Contaminated Marine Clay by Electrokinetic Soil Decontamination. *Engineering Geology.* 53: Amsterdam: Elsevier. 139-150.

Collins, K. and McGown, A. (1974). The Form and Function of Microfabric Features in A Variety of Natural Soils. *Geotechnique*. 24(2): 223-254.

Das, B.M. (2002). *Principles of Geotechnical Engineering.* 5th ed. California: Brooks/Cole.

Davidson, L.K., Demirel, T. and Handy, R.L. (1965). Soil Pulverization and Lime Migration in Soil-Lime Stabilization. *44th Annual Meeting, Highway Research Record*, No. 92, Highway Research Board, Washington D.C. 103-118.

Day, S.R. and Ryan, C. (1995). Containment, Stabilizationand Treatment of Contaminated Soils using In-Situ Mixing. In Acar and Daniel ed. *Geoenvironment 2000.* Geotechnical Special Publication, No. 46: 1349-1365.

de Carvalho, J.B. and Simmons, J.V. (1997). Mineralogy and Microstructure. In *Mechanics of Residual Soil.* Blight, G.E. ed. Rotterdam: Balkema, 31-40.

Deelattre-Louvel, F., Lapeyre, C., Struillou, R. and Arnould, M. (1993). Retention Mechanisms for Toxic Cations Using Artificial Confinement Barriers of Clay-Cement Mixtures. *Engineering Geology.* 34: Amsterdam: Elsevier, 151-158.

Duncan, J.M. (1993). Limitations of Conventional Analysis of Consolidation Settlement. 27th Carl Terzaghi Lecture, *Journal of Geotechnical* Engineering, *ASCE.* 119(9): 1333-1359.

Eggestad, A and Fϕyn, T. (1983). Electroosmotic Improvement of a Soft Sensitive Soil. *Proc. of the 8th European Conf. On Soil Mechanics and Foundation Engineering. Helsinki.* 597-603.

Esrig, M.I. (1968). Pore Pressures, Consolidation and Electrokinetic. *Journal of Soil Mechanics and Foundation Div., ASCE.* 94(SM4): 899-921.

Esrig, M.I. and Gemeinhardt, Jr., J.P. (1967). Electrokinetic Stabilization of an Illitic Clay. *Journal of Soil Mechanics and Foundation Div., ASCE.* 93(SM3): 109-128.

Eykholt, G.R. and Daniel, D.E. (1994). Impact of System Chemistry on Electroosmosis in Contaminated Soil. *Journal of Geotechnical Engineering, ASCE.* 120(5): 797-815.

Eykholt, G.E. (1997). Development of Pore Pressures by Nonuniform Electroosmosis in Clays. *Journal of Hazardous Materials.* 55: Amsterdam: Elsevier, 171-186.

Fetzer, C.A. (1967). Electro-osmotic Stabilization of West Branch Dam. *Journal of Soil Mechanics and Foundation Div., ASCE.* 93(SM4): 85-106.

Fookes, P.G. ed. (1997). *Geological Society Professional Handbook: Tropical Residual Soils.* A Geological Society Engineering Group Working Party Revised Report. London: The Geological Society.

Ghazali, M.F. (1981). *Soil Stabilization by Chemical Additives.* The University of Washington, USA: PhD Thesis.

Gidigasu, M.D. (1976). *Laterite Soil Engineering: Pedogenesis and Engineering Principles.* Amsterdam: Elsevier.

Gigidasu, M.D. (1988). The use of non-traditional tropical and residual materials for pavement construction: A review. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soils, Singapore.* 12-14 Dec. 1988. Rotterdam: Balkema, 397-403.

Glendinning, S. and Rogers, C.D.F. (1996). Deep Stabilisation Using Lime. In *Lime Stabilisation.* Rogers *et al.*, ed. London: Thomas Telford, 127-136.

Gray, D.H. (1970). Electrochemical Hardening of Clay Soils. *Geotechnique*. 20(1): 81-93.

Gray, D.H. and Mitchell, J.K. (1967). Fundamental Aspects of Electro-osmosis in Soils. *Journal of Soil Mechanics and Foundation Div., ASCE*. 93(SM6): 209-236.

Grundl, T. and Reese, C. (1997). Laboratory Study of Electrokinetic Effects in Complex Natural Sediments. *Journal of Hazardous Materials*. Vol. 55, Amsterdam: Elsevier, 187-201.

Gurtu, J.N. (1977). *Colloids*. 6th ed. Meerut, India: Pragati Prakashan.

Hamed, J, Acar, Y.B. and Gale, R.J. (1991). Pb(II) Removal from Kaolinite by Electrokinetics. *Journal of Geotechnical Engineering, ASCE*. 117(2), 241-271.

Hamed, J.T. and Bhadra, A. (1997). Influence of current density and pH on electrokinetics. *Journal of Hazardous Materials*. Vol. 55, Amsterdam: Elsevier, 279-294.

Hamir, R.B., Jones, C.J.F.P. and Clarke, B.G. (1997). Soil Nailing Incorporating the Electroosmotic Phenomenon. *Proceeding of the 4th Geotechnical Engineering Conference (GEOTROPIKA 97)*. 11-12 November 1997. Universiti Teknologi Malaysia: 181-189.

Hanna, A. and Abd El-Rahman, M. (1990). Ultimate Bearing Capacity of Triangular Shell strip Footings on Sand. *Journal of Geotechnical Engineering, ASCE*. 116(12): 1851-1863.

Haran, B.S., Popov, B.N., Zheng, G. and White, R.E. (1997). Mathematical modeling of hexavalent chromium decontamination from low surface charged soils. *Journal of Hazardous Materials*, Vol. 55, Amsterdam: Elsevier, 93-107.

Harton, J.H., Hamid, S., Abi-Chedid, E. and Chilingar, G.V. (1967). Effects of Electrochemical Treatment on Selected Physical Properties of a Clayey Silt. *Engineering Geology,* 2(3), Amsterdam: Elsevier, 191-196.

Hausmann, M.R. (1990). *Engineering Principles of Ground Modifications.* New York: McGraw-Hill Publishing Company.

Head, K.H. (1984a). *Manual of soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests. ELE International Ltd.* London: Pentech Press.

Head, K.H. (1984b). *Manual of soil Laboratory Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests. ELE International Ltd.* London: Pentech Press.

Hesse, P.R. (1972). *A Textbook of Soil Chemical Analysis.* New York: Chemical Publishing Co. Inc.

Holm, G., Bredenberg, H. and Broms, B.B. (1981). Lime Columns As Foundation For Light Structures. *Proc. of the 10th Intl. Conf. on Soil Mechanics and Foundation Engineering,* Vol. 3: 687-694.

Hunter, R.J. (1981). *Zeta Potential in Colloid Science: Principles and Applications.* Sydney: Academic Press.

Johnston, I.W. and Butterfield, R. (1977) A Laboratory investigation of Soil Consolidation by Electro-osmosis. *Australian Geomechanics Journal.* G7: 21-32.

Kassim, K.A. and Kok, K.C. (1999). Mix design for lime Modification and Stabilisation. *Proc. of the 5th Geotechnical Engineering Conf. (GEOTROPIKA 99).* 22-24 November 1999. Univ. Teknologi Malaysia: 235-244.

Kassim, K.A. and Ahmad, K. (2001). SEM Study on Lime-Treated Contaminated Kaolin: Strenght and Hydraulic Conductivity. *Proc. of the 6th Geotechnical Engineering Conf. (GEOTROPIKA 2001)*. 5-7 November 2001. Univ. Teknologi Malaysia, 87-94.

Kassim, K.A., Taha, M.R. and Ahmad, K. (2003). Electrokinetic Processing on Tropical Residual Soil. *Proc. of the 2nd Intl. Conf. On Advances in Soft Soil Engineering and Technology (Asset2)*, 2-4 July 2003. Univ. Putra Malaysia, 833-844.

Khan, L.I. and Alam, M.S. (1994). Heavy Metal Removal from Soil by Coupled Electric-Hydraulic Gradient. *Journal of Environmental Engineering, ASCE*. 120(6): 1524-1543.

Kitsugi, K. and Azakami, H. (1982). Lime-column Techniques for the Improvement of Clay Ground. *Proceedings of the International Symposium on Recent Developments in Ground Improvement Techniques. Asian Institute of Technology Bangkok*. Balasubramaniam *et al.* ed. Rotterdam: Balkema. 105-115.

Koryta, J., Dvořák, J. and Boháčková, V (1966). *Electrochemistry*. London: Methuen & Co Ltd.

Lambe, T.W. and Whitman, R.V. (1979). *Soil Mechanics SI Version*. New York: John Wiley & Sons.

Lange, L.C., Hills, C.D. and Poole, A.B. (1997). Effects of Carbonation on Properties of Blended and Non-Blended Cement Solidified Waste Forms. *Journal of Hazardous Materials*. 52: Amsterdam : Elsevier,193-212.

Li, A., Cheung, K.A. and Reddy, K.R. (2000). Cosolvent-Enhanced Electrokinetic Remediation of Soils Contaminated with Phenantherene. *Journal of Environmental Engineering, ASCE*. 126(6): 527-533.

Li, L.Y. and Wu, G. (1999). Numerical Simulation of Transport of Four Heavy Metals in Kaolinite Clay. *Journal of Environmental Engineering, ASCE.* 125(4): 314-324.

Li, R.S. and Li, L.Y. (2000). Enhancement of Electrokinetic Extraction from Lead-Spiked Soils. *Journal of Environmental Engineering, ASCE.* 126(9): 849-857.

Li, L.Y. and Li, F. (2001). Heavy Metal Sorption and Hydraulic Conductivity Studies Using Three Types of Bentonite Admixes. *Journal of Environmental Engineering, ASCE.* 127(5): 420-429.

Lo, K.Y., Inculet, I.I. and Ho, K.S. (1991a). Electroosmotic Strengthening of Sensitive Clays. *Canadian Geotechnical Journal.* 28(2): 62-73.

Lo, K.Y. and Ho, K.S. and Inculet, I.I. (1991b). Field Test of Electroosmotic Strengthening of Soft Sensitive Clay. *Canadian Geotechnical Journal.* 28(2): 74-83.

Locat, J., Tremblay, H. and Leroueil, S. (1996). Mechanical and Hydraulic Behaviour of a Soft Inorganic Clay Treated with Lime. *Canadian Geotechnical Journal.* 33(4): 654-669.

Lockhart, N.C. (1983a). Electroosmotic Dewatering of Clays II: Influence of Salt, Acid and Flocculant. *Colloids and Surfaces.* 6: 239-251.

Lockhart, N.C. (1983b). Electroosmotic Dewatering of Clays III: Influence of Clay types, Exchangeable cations and Electrode Materials. *Colloids and Surfaces*, 6: 253-269.

Mattson, E.D., Bowman, R.S. and Lindgren, E.R. (2000). Electrokinetic Remediation using Surfactant-Coated Ceramic Casings. *Journal of Environmental Engineering, ASCE.* 126(6): 534-540.

Marto, A., Kassim, F. and Mohd Yusof, K.N. (2001). The Chemical compositions of Granitic Soils from Southern and Eastern Regions of Peninsular Malaysia. *Proc. of the 6th Geotechnical Engineering Conference (GEOTROPIKA 2001).* 5-7 November 2001. Universiti Teknologi Malaysia, 57-69.

Marto, A., Kasim, F. and Yusof, M.F. (2002a). Engineering Characteristics of Residual Granite Soils of Southern Peninsular Malaysia. *Proc. of the Research Seminar on Materials and Construction.* 29-30 October 2002. Univ. Teknologi Malaysia, 315-325.

Marto, A., Kassim, F and Mohd Yusof, K.N. (2002b). Mineralogy, Microstructure and Chemical Composistions of Granitic Soils at Central Regions of Peninsular Malaysia. *Proc. Of the Research Seminar on Materials and Construction.* 20-30 October 2002. Universiti Teknologi Malaysia, 352-366.

Marto, A., Kasim, F. and Yusof, M.F. and Mohd Yusof, K.N. (2002c). Physical and Chemical Compositions of Residual soils of Eastern Region of Peninsular Malaysia. *Proc. of the 2nd World Engineering Congress.* 22-25 July 2002. Univ. Putra Malaysia, 275-281.

Marto, A. and Novrial (1999). The Effect of lime-soil cylinders on laterite Slope Model. *Proc. of the 5th Geotechnical Conf. (GEOTROPIKA 99).* 22-24 November 1999. Univ. Teknologi Malaysia, 223-234.

Mattson, E.D., Bowman, R.S. and Lindgren, E.R. (2000). Electrokinetic Remediation using Surfactant-Coated Ceramic Casings. *Journal of Environmental Engineering, ASCE.* 126(6): 534-540.

Meegoda, N.J. and Rajapakse, R.A. (1993). Short-Term and Long-Term Permeabilities of Contaminated Clays. *Journal of Environmental Engineering, ASCE.* 119(4): 725-743.

Mise, T. (1961). Electroosmotic Dewatering of Soil and Distribution of the Pore Water Pressure. *Proc. 5th Int. Conf. On Soil Mechanics and Foundation Engineering*, 1: Paris: 255-257.

Mitchell, J. K. (1981). Soil Improvement – State-of- the-Art Report. *Proc. of the 10th Int. Conf. On Soil Mechanics and Foundation Engineering*. 4: Session 12, Stockholm: 509-565.

Mitchell, J.K. (1991). Conduction Phenomena: From Theory to Geotechnical Practice. The Rankine Lecture, *Geotechnique*. 41(3): 299-340.

Mitchell, J. K. (1993). *Fundamentals of Soil Behavior*. Second edition. New York: John Wiley & Sons.

Mitchell, J. K. and Wan, T. Y. (1977). Electro-osmotic Consolidation – Its Effects on Soft Soils. *Proceeding of 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo: 219-224.

Mohamad, H. (1997a). *Pengenalan Kepada Teknik Pendaflour Sinar-X (XRF)*. Universiti Kebangsaan Malaysia.

Mohamad, H. (1997b). *Pengenalan Kepada Teknik Pembelauan Sinar-X (XRD)*. Universiti Kebangsaan Malaysia.

Mohamad, H (2003). *Personal communication.*

Moris, N. and Singh, M.M. (1980). *Manual of Laboratory Methods of Chemical Soil Analysis*. Kuala Lumpur: Rubber Research Institute of Malaysia.

Morris, D., Hillis, S. and Caldwell, J. (1985). Improvement of Sensitive Clay/Silt by Electroosmosis. *Canadian Geotechnical Journal*. 22: 17-24.

Murayama, S. and Mise, T. (1953). On the Electrochemical Consolidation of Soil using Aluminium Electrodes. *Proceeding of the Third International Conference on Soil Mechanics and Foundation Engineering*. Zurich: 156-159.

Nagaraj, T.S., Vatsala, A. and Srinivasa Murthy, B.R. (1990). Discussion on Change in Pore Size Distribution due to Consolidation of Clays by Griffith, F.S. and Joshi, R.C. *Geotechnique*. 40(2): 303-305.

Newman, J.S. (1991). *Electrochemical Systems*. 2nd ed. New Jersey: Prentice-Hall.

Olson, R.E. and Mesri, G. (1970). Mechanisms Controlling Compressibility of Clays. *Journal of Soil Mechanics and Foundation Div., ASCE*. 6(11): 1863-1878.

Othman, M.Z. and Shafii, F. (1990). Effects of Current Modes in Electro-Osmosis Treatment of Clayey Soils. *Proc. of Tenth Southeast Asian Geotechnical Conference. Taipei*. 16-20 April 1990. 115-120.

Ozkan, S., Gale, R.J. and Seals, R.K. (1999). Electrokinetic Stabilization of Kaolinite by Injection of Al^{3+} and PO_4^{3-} Ions. *Ground Improvement*. 3: 135-144.

Pagilla, K.R. and Canter, L.W. (1999). Laboratory Studies on Remediation of Chromium-Contaminated Soils. *Journal of Environmental Engineering, ASCE*. 125(3): 243-248.

Pamukcu, S. (1996). Electro-chemical Technologies for In-Situ Restoration of Contaminated Subsurface Soils. *Electronic Journal of Geotechnical Engineering*, Premiere Issue, Fall 1996.

Pletcher, D. and Walsh, F.C. (1990). *Industrial Electrochemistry*. 2nd ed. London: Chapman and Hall.

Poon, C.S. and Boost, M. (1996). The Stabilization of Sewage Sludge by Pulverized Fuel Ash and Related Materials. *Environment International*. 22(6): Amsterdam: Elsevier, 705-710.

Prentice, G. (1991). *Electrochemical Engineering Principles*. New Jersey: Prentice-Hall.

Puppala, S.K.V. (1994). *Evaluation of Saturation Effects and Selected Enhancement Techniques in Electrokinetic Soil Remediation*. The Louisiana State University, USA: MSE Thesis.

Rahardjo, H., Aung, K.K., Leong, E.C. and Rezaur, R.B. (2002). Effect of Pore-Size Distribution on Engineering Properties of Residual Soils. *Proc. of the 2nd World Engineering Congress*. 22-25 July 2002. Universiti Putra Malaysia Press, 70-76.

Rao, S.M., Sridharan, A. and Chandrakaran, S. (1988). The Role of Iron Oxide in Tropical Soil Properties. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soils, Singapore*. 12-14 Dec. 1988. Rotterdam: Balkema, 43-48.

Reid, J.M. and Brooks, A.H. (1999). Investigation of Lime-Stabilized Contaminated Materials. *Engineering Geology*, 53: Amsterdam: Elsevier, 217-231.

Rodsand, T., Acar, Y.B. and Breedveld, G. (1995). Electrokinetic Extraction of Lead from Spiked Norwegian Marine Clay. In Acar and Daniel eds. *Geoenvironment 2000*. 2: Geotechnical Special Publication No. 46, 1518-1534.

Rogers, C.D.F. and Glendinning, S. (1994). Deep-Slope Stabilization Using Lime Piles. *Transportation Research Board*. No 1440. Washington D.C.: National Academy Press, 63-70.

Rowe, R.K. and Booker, J.R. (1985). 1-D Pollutant Migration in Soils of Finite Depth. *Journal of Geotechnical Engineering, ASCE*. 111(4): 479-499.

Segall, B.A. and Bruell, C.J. (1992). Electroosmotic Contaminant-Removal Processes. *Journal of Environmental Engineering, ASCE*. 118(1): 84-100.

Segall, B.A., O'Bannon, C.E. and Matthias, J.A. (1980). Electro-Osmosis Chemistry and Water Quality. *Journal of the Geotechnical Engineering Division, ASCE.* 106(GT10): 1148-1152.

Shang, J.Q. and Lo, K.Y. (1997). Electrokinetic Dewatering of a Phosphate Clay. *Journal of Hazardous Materials*, 55: Amsterdam: Elsevier, 117-133.

Shang, J.Q. and Ho, K.S. (1998). Electro-Osmotic Consolidation Behavior of Two Ontario Clays. *Geotechnical Engineering, Journal of Southeast Asian Geotechnical Society.* 29(2): 181-194.

Shang, J.Q., Lo, K.Y. and Huang, K.M. (1996). On Factors Influencing Electro-Osmotic Consolidation. *Geotechnical Engineering, Journal of Southeast Asian Geotechnical Society.* 27(2): 23-36.

Shapiro, A.P. and Probstein, R.F. (1993). Removal of Contaminants from Saturated Clay by Electroosmosis. *Journal of Environmental Science and Technology.* 27(2): 283-291.

Sharma, B.K. (1983). *Colloid Chemistry.* Meerut, India: Goel Publishing House,.

Shin, E.C., Omar, M.T., Tahmaz, A.A., Das, B.M. and Atalar, C. (2002). Shear Strength and Hydraulic Conductivity of Oil-Contaminated Sand. *Proc. of the Environmental Geotechnics 4th Intl. Congress on Environmental Geotechnics (4th ICEG).* de Mello, L.G and Almeida, M. ed. 11-15 July 2002. Brazil: Balkema, 9-13.

Sridharan, A. (1988). General Report –Technical session II: Engineering Properties of Tropical Soils. *Supplementary Documentation of the 2nd Intl. Conf. On Geomechanics in Tropical Soils.* 11-15 July 2002. Singapore: 42-56.

Taha, M.R. (1996). *Micellar Electrokinetic Remediation of TNT from Soil.* The Louisiana State Univ., USA: PhD Thesis.

Taha, M.R., Acar, Y.B., Gale, R.J. and Zappi, M.E. (1994). Surfactant Enhanced Electrokinetic Remediation of NAPLs in Soils. *Proc. Of First Intl. Congress on Env. Geotechnics. Edmonton, Canada.* Rotterdam: Balkema, 373-377.

Taha, M.R., Abdul Mofiz, Hossain, M.K. and Asmirza, M.S. (1999). Model Simulation of Residual Soil in Triaxial Extension Tests. *Proc. of the 5th Geotechnical Engineering Conf. (GEOTROPIKA 99).* 22-24 November 1999. Univ. Teknologi Malaysia, 105-114.

Taha, M.R. and Asmirza, M.S. (2001). Elasto-plastic Model Predictions for a Granite Residual Soil in Drained Triaxial Test. *Proc. of the 6th Geotechnical Engineering Conf. (GEOTROPIKA 2001).* 5-7 November 2001. Univ. Teknologi Malaysia, pp 73-86.

Taha, M.R., Sarac, D., Chik, Z. and Nayan, K.A. (1997). Geotechnical and Geoenvironmental Aspects of Residual Soils. *Proc. 4th regional Conference in Geotechnical Engineering (GEOTROPIKA 97).* 11-12 November 1997. Univ. Teknologi Malaysia, 331-341.

Tan, B.K. (1996). Physico-chemical Properties of Some Granite Soils from Peninsular Malaysia. *Proc. of 4th Intl. Conf. On Tropical Soils.* Kuala Lumpur: pp. 595-600.

Tanal, V., Wang, J.N., Samtani, N.C. and Lancellotti, A. (1995). Lime Stabilization and Disposal of Contaminated Dredged Harbor Sediments. In: Acar and Daniel eds. *Geoenvironment 2000.* Geotechnical Special Publication, No. 46, 1381-1394.

Thevanayagam, S. and Wang, J. (1994). Flow Behavior During Electrokinetic Soil Decontamination. *Proc. Of the 1st. Intl. Congress on Env. Geotechnics, Edmonton, Canada,* Rotterdam: Balkema, 379-385.

Thomas, T.J. and Lentz, R.W. (1990). Changes in Soil Plasticity and Swell Caused Electro-Osmosis. In: Hoddinott and Lamb ed. *Physico-Chemical Aspects of Soil and Related Materials*. ASTM 1095, Ann Arbor, pp 108 – 117.

Ting, W.H. and Ooi, T.A. (1976). Behaviour of a Malaysian Residual Granite Soil as a Sand-Silt-Clay Composite Soil. *Geotechnical Engineering, Journal of Southeast Asian Geotechnical Society*. 7: 67-79.

Tsai, T.D. and Vesilind, P.A. (1998). A New Landfill Liner to reduce Ground-Water Contamination from Heavy Metals. *Journal of Environmental Engineering, ASCE*. 124(11): 1061-1065.

Tuncer, E.R. (1988). Pore Size Distribution Characteristics of Tropical Soils in Relation to Engineering Properties. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soil. Singapore*. 12-14 Dec. 1988. Rotterdam: Balkema, 63-70.

U.S. Department of Energy (1999). Stabilization using Phosphate Bonded Ceramics. *Innovative Technology Summary Report* DOE/EM-0486.

Vane, L.M. and Zang, G.M. (1997). Effect of Aqueous Phase Properties on Clay Particle Zeta Potential and Electroosmotic Permeability: Implications for Electrokinetic Soil Remediation Process. *Journal of Hazardous Materials*. 55: Amsterdam: Elsevier, 1-21.

Vaughan, P.R. (1988). Characterising the Mechanical Properties of In-Situ Residual Soil. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soil (Supplementary Document)*, Singapore: 20-37.

Verhasselt, A.F. (1990). The Nature of the Immediate Reaction of Lime in Treating Soils for Road Construction. In: Hoddinott and Lamb ed. *Physica-Chemical Aspects of Soil and Related Materials*. ASTM 1095, Ann Arbor, 7-17.

Wesley, L.D. (1988). Engineering Classification of Residual Soils. *Proc. of the 2nd Int. Conference on Geomechanics in Tropical Soils, Singapore*. 12-14 Dec. 1988. Rotterdam: Balkema, 77-84.

Wittle, J.K. and Pamukcu, S. (1993). Electrokinetic Treatment of Contaminated Soils, Sludges and Lagoons. *Final Report to the US Department of Energy*.

Yamaguchi, T. and Matsuda, S. (1975). Stabilization of Sand Feasible to Liquefaction by Means of a Kind of Grouting Applying Electroosmosis. *Proc. of Symp. On Recent Developments in the Analysis of Soil Behaviour and Their Applications to Geotechnical Structures*. The University of New South Wales, Australia: 411-421.

Yeung, A.T., Hsu, C-n and Menon, R.M. (1997). Physicochemical Soil-Contaminant Interactions During Electrokinetic Extraction. *Journal of Hazardous Materials*. 55, Amsterdam: Elsevier, 221-238.

Zagury, G.J., Dartiguenave, Y. and Setier, J.C. (1999). Ex-situ Electroreclamation of Heavy Metals Contaminated Sludge: Pilot Scale Study. *Journal of Environmental Engineering, ASCE*. 125(10): 972-978.

Zemaitis, J.F., Clark, D.M., Rafal, M. and Scrivner, N.C. (1986). *Handbook of Aqueous Electrolyte Thermodynamics*. Design Institute for Physical Property Data (DIPPR), American Inst. of Chemical Engineers.