PHYSICOCHEMICAL, MICROSTRUCTURAL AND ENGINEERING BEHAVIOUR OF NON-TRADITIONAL STABILISER TREATED MARINE CLAY

FAIZAL B PAKIR

UNIVERSITI TEKNOLOGI MALAYSIA

PHYSICOCHEMICAL, MICROSTRUCTURAL AND ENGINEERING BEHAVIOUR OF NON-TRADITIONAL STABILISER TREATED MARINE CLAY

FAIZAL B PAKIR

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2017

In the name of Allah, the Supremely Merciful and the Most Kind,

To my beloved family, who never give up to give me spiritual support and pray for my success.

ACKNOWLEDGMENT

Acknowledgments for the completion of this thesis must be extended to many people who provided me with precious time and invaluable advice. My gratitude to the Almighty God, due to all His blessings and grace, this thesis finally came to an end.

I wish to express my sincerest appreciations to my main supervisor, Prof. Dr. Aminaton Marto for her invaluable comments, genuine encouragement, constructive advice, and professional guidance during the formulation and writing of this thesis. Thank you for the opportunity you granted to me. I am also very thankful to my co-supervisors Dr. Nor Zurairahetty Mohd Yunus and Assoc. Prof. Dr. Saiful Azhar Ahmad Tajudin for their permanent support, continuing feedback and motivation.

My sincere gratitude also goes to all laboratory staff in the Geotechnical Engineering as well as the Structures and Materials laboratories for their genuine help in carrying out the laboratory tests and physical modeling works throughout the study.

Last but not least, my utmost appreciations go to my beloved parents for their eternal support, unconditional love, sacrifice, and encouragement. I am nothing without you. Not to forget, my special thanks go to my adorable wife, for all her support and tolerance throughout this research journey. Words really fail to appreciate her for everything she did for me.

ABSTRACT

The presence of marine clay underlying foundation has been responsible for failure in several geotechnical structures and chemical stabilisation is the usual practice to improve the strength of soils. Recently, non-traditional additives are extensively used to solve this problem and their effects on geotechnical properties of soils have been reported by many researchers. However, publications on the fundamental microstructural behaviour of non-traditional additives in treating marine clay soils and their influence on the engineering behaviour are limited. Therefore, this research aimed at determining the stabilisation mechanism and the performance of marine clay soil mixed with two types of non-traditional additives, namely calcium-based powder stabiliser (SH-85) and sodium silicate-based liquid stabilizer (TX-85). Microstructural study from different spectroscopic and microscopic techniques such as X-ray Diffractometry (XRD), Energy-Dispersive X-ray Spectrometry (EDAX), Scanning Electron Microscopy (SEM), Thermal Gravimetric Analysis (TGA) and pore size distribution had been conducted to elucidate the stabilisation mechanism. Unconfined compressive test, oedometer consolidation test and consolidated undrained triaxial compression test were conducted to assess the engineering properties of the stabilised soil. In addition, strip footing model tests were conducted to determine the performance of stabilised clay soils and the results were compared with simulation using PLAXIS 2D finite element. The laboratory tests showed that the addition of 12% SH-85 at early 7 days curing period had increased the compressive strength of treated marine clay by about 42 times while the addition of 6% TX-85 with similar curing period had increased the compressive strength of treated marine clay by about 3.6 times. The results of the microstructural tests indicated the formation of new gel products in the mixtures, which were identified as calcium silicate hydrate (CSH) and sodium aluminosilicate hydrate (NASH) for soils treated with SH-85 and TX-85, respectively. SEM images illustrated the formation of new cementitious compounds (CSH and NASH) which were shown within the pore spaces, resulting in the reduction of radius of pore spaces. In comparison to the untreated soil, the results of the physical model tests showed that the bearing capacity of strip footing on the treated soil at 7 days curing period increased significantly while the settlement reduced. In short, the selected additive had successfully increased the strength of marine clay at early period, thus the usage of selected non-traditional additives was considered as cost effective for geotechnical project.

ABSTRAK

Kehadiran tanah liat marin dibawah asas telah mengakibatkan kegagalan pada beberapa struktur geoteknik, dan penggunaan penstabilan kimia merupakan satu amalan biasa dalam meningkatkan kekuatan tanah tersebut. Baru-baru ini, bahan penstabil bukan konvensional telah digunakan secara meluas untuk menyelesaikan masalah ini dan kesan ke atas ciri-ciri geoteknikal tanah juga telah dilaporkan oleh ramai penyelidik. Walau bagaimanapun, penerbitan tentang sifat-sifat mikrostruktur asas bahan penstabil bukan konvensional ini dalam merawat tanah liat marin dan pengaruh ke atas kelakuan kejuruteraan adalah terhad. Oleh itu, kajian ini bertujuan untuk menentukan mekanisme penstabilan dan prestasi tanah liat marin yang dicampurkan dengan dua jenis penstabil bukan konvensional, iaitu penstabil serbuk berasaskan kalsium (SH-85) dan penstabil cecair berasaskan sodium silikat (TX-85). Kajian mikrostruktur daripada pelbagai teknik spektroskopi dan mikroskopik seperti *X-ray Diffractometry* (XRD), Spektrometri Sinar-X Serakan Tenaga (EDAX), Mikroskopi Imbasan Elektron (SEM), Analisis Termal Gravimetri (TGA), dan taburan saiz liang telah dijalankan untuk menjelaskan mekanisme penstabilan tersebut. Ujian mampatan tidak terkurung, ujian pengukuhan, dan ujian mampatan tiga paksi terkukuh tak tersalir juga dilakukan untuk menilai ciri-ciri kejuruteraan tanah yang dirawat. Di samping itu juga, ujian model asas jalur telah dijalankan untuk menentukan prestasi tanah liat dirawat tersebut dan hasilnya dibandingkan dengan menggunakan perisian unsur terhingga PLAXIS 2D. Ujian makmal menunjukkan bahawa penggunaan 12% SH-85 selepas pengawetan selama 7 hari telah meningkatkan kekuatan mampatan tanah yang dirawat sebanyak 42 kali ganda manakala penggunaan 6% TX-85 bagi tempoh rawatan yang sama telah meningkatkan kekuatan mampatan tanah yang dirawat sebanyak 3.6 kali ganda. Keputusan ujian mikrostruktur menunjukkan terdapat pembentukan produk baru berbentuk gel pada tanah yang dirawat yang dikenal pasti sebagai kalsium silikat hidrat (CSH) dan natrium aluminosilikat hidrat (NASH) untuk tanah yang dirawat dengan SH-85 dan TX-85, masing-masing. Imej SEM membuktikan pembentukan sebatian bersimen (CSH dan NASH) dalam ruang liang menyebabkan pengurangan jejari ruang liang. Berbanding dengan tanah liat yang tidak dirawat, keputusan ujian model fizikal menunjukkan bahawa keupayaan galas jalur bagi tanah yang dirawat selama 7 hari pengawetan semakin meningkat, manakala enapan tanah dapat dikurangkan. Kesimpulannya, bahan tambahan yang dipilih berjaya meningkatkan kekuatan tanah liat dalam masa yang singkat, sekali gus penggunaan bahan penstabil bukan tradisional dapat menjimatkan kos untuk projek geoteknik.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

Al	-	Aluminium
Al_2O_3	-	Aluminium oxide
ASTM	-	American society of testing material
B	-	Width of the shallow foundation
BS	-	British standard
c	-	Cohesion
CaO	-	Calcium oxide
CU	-	Consolidated undrained
C_c	-	Compression index
C_s	-	Swelling index
CSH	-	Calcium silicate hydrate
CO_2	-	Carbon dioxide
E	-	Young's modulus
EDAX	-	Energy dispersive x-ray spectrometer
Fe	-	Iron
Fe_2O_3	-	Ferric oxide
Gs	-	Specific gravity
ICP-MS	-	Inductively coupled plasma mass spectrometry
K_2O	-	Kalium oxide
LIR	-	Load increment ratio
LL	-	Liquid limit
LVDT	-	Linear variable displacement transducer
MDD	-	Maximum dry density
MgO	-	Magnesium oxide
Na^+	-	Sodium ion
p_c	-	Preconsolidation pressure
PI	-	Plasticity Index

PL	-	Plastic limit
SEM	-	Scanning electron microscopy
SH-85	-	Calcium based powder stabiliser
Si	-	Silicon
SiO_2	-	Silica
SO_4	-	Sulphate
TGA	-	Thermal gravimetric analysis
TX-85	-	Sodium Silicate Based Liquid Stabiliser
UCS	-	Unconfined compressive strength
UCT	-	Unconfined compressive test
XRD	-	X- ray diffraction
ν	-	Poisson's ratio
ϕ	-	Friction angle
ψ	-	Dilatancy angle

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Marine clay, which has low strength and high compressibility, is located in many coastal and offshore areas around the world. It is weak in nature due to the presence of swelling clay minerals like montmorillonite, vermiculite, and chlorite, hence causing a problematic foundation for structures to be built on it (Bjerrum, 1973). The physical and engineering behaviours of soil, such as marine clay, depend on the exchangeable cations, mineralogical composition, and pore water system chemistry (Egashira and Ohtsubo 1982; Ohtsubo *et al.*, 1985).

In the Ninth Malaysia Plan (2006-2010), Iskandar Malaysia was launched as one of the high-impact development projects (Ministry of Information Malaysia, 2008). Nusajaya, a 4% land area within Iskandar Malaysia, is the focal point of the whole development projects within that region. Both public and private sectors are required to build more buildings and roads, but the weak marine clay deposits in various sites surrounding Nusajaya need to either be replaced or improved. Therefore, various ground improvement methods have been introduced and tested in research and in practice. However, their respective suitability are considered to be project-specific, which depend on the cost, existing soil's characteristics, and the stabilisers potential impacts or effectiveness for the proposed application. In such cases, appropriate soil property modification measures are typically taken into consideration. Hence, it is necessary to improve the engineering behaviour of marine clays using appropriate ground improvement techniques.

Geotechnical engineers borrow the knowledge of geologists and soil scientists to seek appropriate method to enhance clay behaviour. Most of the basic ideas related to the enhancement of clay behaviour using stabiliser had been published since 1960 (Petry and Little, 2002). The soil stabilisation is a method which involves mixing natural soils with chemical stabilisers to increase the properties of the soil particularly in strength and decrease moisture content of soil. This method of stabilising or treating soil is an important and widely used method throughout the world. In the stabilisation process, stabiliser agent acts as filler in the pore spaces or reinforcing the bindings between the particles. The stabiliser is categorised as traditional, such as lime, cement and fly ash, as well as non-traditional stabiliser such as, acids, salts, enzymes, polymer, resin, and sulfonated oils (Harris *et al.*, 2006; Tingle et *al.*, 2007). Despite the fact that stabilisation of soil using traditional stabiliser such as cement and lime is well established (Yilmaz and Civelekoglu, 2009), there is a need of alternative technologies to be applied which are more environmentally friendly, sustainable, and economical.

In recent years, an increasing number of non-traditional stabilisers have been developed for soil stabilisation purposes. According to Tingle *et al.* (2007), the variety of stabilisers (powder and liquid form) are becoming popular due to their relatively low cost, ease of application, and short curing period. The effectiveness of non-traditional stabiliser to increase the properties of clay soils, particularly in strength, has been reported by many researchers such as Suganya *et al.* (2016), Onyejekwe *et al.* (2016), Phetchuay *et al.* (2016), Zhang *et al.* (2015) and Yi *et al.* (2015).

Lim *et al.* (2013), for example, reported the increased of unconfined compressive strength of low plasticity clay treated with biomass silica (non-traditional stabiliser) up to 36 times the untreated value. Using the same non-traditional stabiliser, Latifi *et al.* (2016) reported the increased strength of residual soil (high plasticity silt) up to 7 times the untreated value. Nevertheless, the lack of knowledge in selecting and using chemical additives to treat soils has induced the damage of losing millions of dollars (Wiggins *et al.,* 1978). Hence, suitable use of stabiliser is important to maximize the optimum use of stabiliser agent and to save cost.

1.2 Problem Statement

In recent years, an increasing number of non-traditional stabiliser have been developed for soil stabilisation purposes. The non-traditional stabiliser has been developed and marketed to meet the need of alternative technologies which are more economical, sustainable, and environmentally friendly. However, the effects of these stabilisers are still vague and yet to be understood. Besides that, the non-traditional stabilisers, in the form of powder or liquid, are becoming popular due to their relatively low cost, ease of application, and short curing period. In spite of the benefits of non-traditional stabiliser as a chemical agent, the engineers seldom use these product due to the variation of chemical data, process explanation, and engineering data. Besides that, the performance of a non-traditional stabiliser is rather difficult to evaluate due to the chemical formulas are often changing based on the market tendency and the exact chemical composition are not disclosed due to the commercial stabilisation product.

In this sense, understanding the mechanism of stabilisation process is very important. Thus, basic stabilisation mechanism should be studied to set these products according to different categories, depending on their primary chemical components and proposed enhancement properties. Considering the above current issues, it is concluded that there is a need to study the physico-chemical and microstructural behaviour of non-traditional stabiliser treated marine clay and use them to explain some aspects of the observed engineering behaviour in a well-controlled laboratory condition before extending it to the field condition. In this thesis, an attempt has been made to evaluate the stabilisation mechanism of treated marine clay soil with selected non-traditional stabilisers.

1.3 Research Aims and Objectives

This research aims to determine the stabilisation mechanism and performance of marine clay soils treated with non-traditional stabilisers, namely the SH-85 and TX-85. Hence, the main objectives of this research are as follows:

i. To determine the changes in the engineering properties of treated marine clay with various percentages of selected stabilisers at different curing periods;
ii. To determine the changes on the physico-chemical and microstructural behaviour of treated marine clay;
iii. To evaluate the influence of pyhsicochemical and microstructural changes of treated marine clay soil on engineering properties; and
iv. To determine the performance of strip footing on treated marine clay soils based on laboratory physical model tests and computer simulation.

1.4 Scope of Study

The soft marine clay soil used in this study was collected from the construction site in Nusajaya where the soils were excavated at the Southern coast Johor, Malaysia. The non-traditional stabilisers used in this study were obtained from a local company called Probase Sdn. Bhd. which is located in Johor.

To understand the changes on physico-chemical and microstructural behaviour of treated marine clay soils, X-Ray diffraction (XRD), energy dispersive x-ray spectrometry (EDAX), scanning electron microscopy (SEM), particle size analysis, thermal gravimetric analysis (TGA), and pH measurement were conducted. Meanwhile, for the engineering behaviour, Atterbeg's limits, unconfined compressive strength (UCS), oedometer consolidation, and consolidated undrained (CU) triaxial test were conducted.

The testing sample were prepared and cured in a similar manner described in the British Standard (BS 1924: Part 2: 1990). The percentages of the chemical used in the mixture of soil sample were 3%, 6%, 9%, 12%, and 15% cured at 3, 7, 14, 28, 90 and 180 days curing periods. Due to the high quantity of sample and high cost of microstructure test, test was limited to the sample that showed the highest degree of improvement. The 12% of SH-85 stabiliser and 6% of TX-85 stabiliser was chosen as the optimum percentage through the analysis of the results obtained.

Laboratory physical model tests were conducted on the untreated and treated soil (cured at 7 days) as foundation for strip footing. The model tests were carried out by applying loads to the strip footing placed until failure occurred to the footing. The settlement of the footing and the bearing capacity were monitored during loading tests to ascertain the performance of the treated soil as foundation. The commercial 2D finite element software called “PLAXIS” was used in numerical simulation to evaluate and compare the results obtained from laboratory physical model tests. The Mohr-Coulomb soil model under undrained condition was used in the simulation work.

1.5 Significance of Study

In regard to the importance of the study, the mechanism of the stabilisation of marine clay soils with non-traditional stabiliser had been established. The significance of the study includes the following:

i. Understanding the mechanism of the stabilisation process through the results from macro and micro-structural study;
ii. New finding from the changes of the minerology and physical of treated marine clay soils can be used for further study;
iii. The performance of strip footing foundation on treated soil could be used to produce practicing engineers in using non-traditional stabilisers to stabilise marine clay soils.

1.6 Outline of the Thesis

This thesis consists of six chapters. The first chapter gives a brief overall introduction of the entire research work done, followed by its problem statement and research objectives, as well as scope of study and significance of study.

Chapter 2 is devoted to a literature review on the chemical stabilisation by the traditional and non-traditional stabilisers. Also, the fundamentals of clay mineral are presented to understand the soil-chemical reactions. Moreover, previous research on the physical and numerical simulations of strip footing foundation are also discussed.

Chapter 3 describes the research methodology of study, detail of test apparatus, sample preparation, and procedure of testing. Furthermore, the characterization study of stabilised soil was done using spectroscopic and microscopic techniques previously published in papers and as standards. The descriptions of physical and numerical simulation test procedure are also explained at the end of this chapter.

The test results and discussions of the comprehensive testing program are presented in Chapter 4. In Chapter 4, the physico-chemical, as well as microstructural behaviour, together with an integration of the basic engineering properties of treated marine clays and the strength and compressibility behaviour of treated marine clays, are explained and clarified with the knowledge of induced microstructure. In addition, the descriptions of the physical and numerical simulation tests are also presented and discussed.

Finally, Chapter 5 concludes the findings and provides some recommendations for future studies.

REFERENCES

Abu-Farsakh, M., Chen, Q. and Sharma, R. (2013). An Experimental Evaluation of the Behaviour of Footings on Geosynthetic-Reinforced Sand. *Soils and Foundations*, 53(2), pp.335–348.

Ahmad, K. (2004). Improvement of a Tropical Residual Soil by Electrokinetic Process. PhD Thesis, Universiti Teknologi Malaysia, Skudai.

Ahmadi, H. and Hajialilue-Bonab, M. (2012). Experimental and Analytical Investigations on Bearing Capacity of Strip Footing in Reinforced Sand Backfills and Flexible Retaining Wall. *Acta Geotechnica*, 7(4), pp.357–373.

Åhnberg, H. (2006). Strength of Stabilised Soils – A Laboratory Study on Clays and Organic Soils Stabilised with Different Types Of Binder. PhD Thesis, Lund University, Sweden.

Al-Khafaji, A. W. and Andersland, O. B. (1992). Geotechnical Engineering and Soil Testing, New York: Saunders college Publishing.

Al-Mukhtar, M., Khattab, S. and Alcover, J. F. (2012). Microstructure and Geotechnical Properties of Lime-Treated Expansive Clayey Soil. *Engineering Geology*, 139–140, pp.17–27.

Al-Mukhtar, M., Lasledj, A., and Alcover, J. F. (2014). Lime Consumption of Different Clayey Soils. *Applied Clay Science*, 95, pp.133–145.

Ali, F. (2012). Stabilization of Residual Soils using Liquid Chemical. *Electronic Journal of Geotechnical Engineering*, 17, pp.115–126.

Ali, F., and Al-Samaraee, E. A. S. (2013). Field Behavior and Numerical Simulation of Coastal Bund on Soft Marine Clay Loaded to Failure. *Electronic Journal of*

Geotechnical Engineering, 18, pp.4027–4042.

Anggraini, V., Huat, B. K., Asadi, A., and Nahazanan, H. (2015). Effect of Coir Fibers on the Tensile and Flexural Strength of Soft Marine Clay. *Journal of Natural Fibers*, 12(2), pp.185–200.

Basack, S. and Purkayastha, R., (2009). Engineering properties of marine clays from the eastern coast of India. *Journal of Engineering and Technology Research*, 1(6), pp.109–114.

Bharati, S. K., (2012). Treatment of Marine Clay by using Cement-Copper Slag Grout in Low Pressure Grouting. PhD Thesis, National University of Singapore.

Bjerrum, L., (1973). Geotechnical Problems involved in Foundations of Structures in the North Sea. *Geotechnique*, 23(3), pp.319–358.

Bo, M. W., Arulrajah, A., Sukmak, P., and Horpibulsuk, S. (2015). Mineralogy and geotechnical properties of Singapore marine clay at Changi. *Soils and Foundations,* 55(3), pp.600–613.

Broms, B. (1986). "Stabilization of soft clay with lime and cement columns in Southeast Asia", Applied Research Project, RP 10/83, Nanyang Technical Institute, Singapore.

Carroll, D. and Starkey, H.C., (1971). Reactivity of clay minerals with acids and alkalies. *Clays and Clay Minerals*, 19(5), pp.321–333.

Celik, E. and Nalbantoglu, Z. (2013). Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils. *Engineering Geology*, 163, pp.20–25.

Chalermyanont, T., Arrykul, S. and Charoenthaisong, N. (2009). Potential use of lateritic and marine clay soils as landfill liners to retain heavy metals. *Waste Management*, 29(1), pp.117–127.

Chew, S. H., Kamruzzaman, A. H. M. and Lee, F. H. (2004). Physicochemical and Engineering Behavior of Cement Treated Clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), pp.696–706.

Cong, M., Longzhu, C. and Bing, C. (2014). Analysis of strength development in soft clay stabilized with cement-based stabilizer. *Computers and Chemical Engineering*, 71, pp.354–362.

Das, B. M. (2011). Principles of Foudation Engineering (7th Ed.). Cengage Learning, Edith Cowan University

Das, B. M. (2013). Fundamental of Geotechnical Engineering (4th ed.)., Cengage Learning, Edith Cowan University.

Dash, S. K. and Hussain, M. (2012). Lime Stabilization of Soils: Reappraisal. *Journal of Materials in Civil Engineering*, 24(6), pp.1239–1247.

Davoudi, M. H. and Kabir, E. (2011). Interaction of lime and sodium chloride in a low plasticity fine grain soils. *Journal of Applied Sciences*, 11(2), pp.330–335.

Dehghanbanadaki, A., (2014). ultimate bearing capacity of peat stabilized by a group of soil–cement column. PhD Thesis, Universiti Teknologi Malaysia, Skudai.

Dehghanbanadaki, A., Ahmad, K. and Ali, N. (2014). Experimental investigations on ultimate bearing capacity of peat stabilized by a group of soil–cement column: a comparative study. *Acta Geotechnica*, 11(2), pp.295–307.

Dolinar, B., Misic, M. and Trauner, L. (2007). Correlation Between Surface Area and Atterberg Limits of Fine-Grained Soils. *Clays and Clay Minerals*, 55(5), pp.519–523.

Dolinar, B. and Škrabl, S. (2013). Atterberg Limits in Relation to other Properties of Fine-Grained Soils. *Acta geotechnica Slovenica*, 10(2), pp.4–13.

Egashira, K. and Ohtsubo, M. (1982). Smectite in Marine Quick-Clays of Japan. *Clays and Clay Minerals*, 30(4), pp.275–280.

Eisazadeh, A. (2010). Physicochemical Behaviour of Lime and Phosporic Acid Stabilized Clayey Soils. PhD Thesis, Universiti teknologi Malaysia, Skudai.

Eisazadeh, A., Kassim, K.A. and Nur, H. (2011). Characterization of Phosphoric Acid- and Lime-stabilized Tropical Lateritic Clay. *Environmental Earth Sciences*, 63(5), pp.1057–1066.

ElectroScan Corporation, (1996). Enviromental Scanning Electron Microscopy : An Introduction to ESEM R. J. Associates, ed., Eindhoven, The Netherlands.

Fattah, M. Y., Al-saidi, A. A. and Jaber, M. M. (2015). Improvement of bearing capacity of footing on soft clay grouted with lime-silica fume mix. *Geomechanics and Engineering*, 8(1), pp.1–7.

Fei, K. (2016). Experimental study of the mechanical behavior of clay – aggregate mixtures. *Engineering Geology*, 210, pp.1–9.

Fernández-Jiménez, A., Vázquez, T. and Palomo, A. (2011). Effect of sodium silicate on calcium aluminate cement hydration in highly alkaline media: A microstructural characterization. *Journal of the American Ceramic Society*, 94(4), pp.1297–1303.

Futai, M. M., Almeida, M. S. S. and Lacerda, W. A. (2004). Yield , Strength , and Critical State Behavior of a Tropical Saturated Soil. Journal of Geotechnical and Geoenvironmental Engineering, 130(1), pp.1169–1179.

Galvão D. B. , T. C., Elsharief, A. and Simões, G. F. (2004). Effects of Lime on Permeability and Compressibility of Two Tropical Residual Soils. *Journal of Environmental Engineering*, 130(8), pp.881–885.

Ghobadi, M. H., Abdilor, Y. and Babazadeh, R. (2014). Stabilization of clay soils using lime and effect of pH variations on shear strength parameters. *Bulletin of Engineering Geology and the Environment*, 73(2), pp.611–619.

Harris, P., von Holdt, J., Sebesta, S., and Scullion, T. (2006). Recommendations for Stabilization of High-Sulfate Soils in Texas. Transportation Research Record, 1952(1), pp.71–79.

Heitor, A., Indraratna, B., Kaliboullah, C., Rujikiatkamjorn, C., and McIntosh, G. W. (2016). Drained and Undrained Shear Behavior of Compacted Coal Wash. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(5), pp.1–10.

Herwijnen R. V., Hutchings T.R., Ai-Tabbaa A., Moffat A.J., Johns M.L. and Ouki

S.K. (2007). Remediation of metal contaminated soil with mineral-amended composts. *Environmental Pollution*. 150, pp. 347-354

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., and Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials*, 24(10), pp.2011–2021.

Horpibulsuk, S., Miura, N. and Bergado, D. T. (2004). Undrained Shear Behavior of Cement Admixed Clay at High Water Content. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(10), pp.1096–1105.

Horpibulsuk, S., Rachan, R. and Suddeepong, A. (2011). Assessment of strength development in blended cement admixed Bangkok clay. *Construction and Building Materials*, 25(4), pp.1521–1531.

Ibrahim, K. M. H. I. (2016). Bearing Capacity of Circular Footing Resting on Granular Soil Overlying Soft Clay. *Housing and Building National Research Center Journal*, 12(1), pp.71–77.

Indraratna, B., Liu, M. D., Suebsuk, J., and Horpibulsuk, S. (2012). Variations in strength of lime-treated soft clays. *Proceedings of the ICE - Ground Improvement*, 165(4), 217–223

JCPDS, (1995). Index to the Powder Diffraction File, International Center for Diffraction Data.

Jha, A. K. and Sivapullaiah, P. V. (2015). Mechanism of improvement in the strength and volume change behavior of lime stabilized soil. *Engineering Geology*, 198, pp.53–64.

Kamruzzaman, A. H., Chew, S.H. and Lee, F.H. (2009). Structuration and Destructuration Behavior of Cement-Treated Singapore Marine Clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(4), pp.573–589.

Kamruzzaman, a H.M. (2002). Physico-Chemical and Engineering Behavior of Cement Treated Singapore Marine Clay. PhD Thesis, National university

Singapore.

Kaniraj, S. R. and Havanagi, V. G. (1999). Compressive strength of cement stabilized fly ash-soil mixtures. *Cement and Concrete Research*, 29(5), pp.673–677.

Katz, L., Rauch, A., Liljestrand, H., Harmon, J., Shaw, K., and Albers, H. (2001). Mechanisms of Soil Stabilization with Liquid Ionic Stabilizer. *Transportation Research Record*, 1757(1), pp.50–57.

Kumpiene J., Lagerkvist A. and Maurice C. (2008). Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments—a review. *Waste Management*, 28, pp. 215-225

Kok, K.C. and Kassim, K.A. (2001). Modification and Stabilization of Malaysian Cohesive Soils with Lime. *Proceedings of the Third International Conference on Soft Soil.*

Latifi, N. (2014). Geotechnical and Micro-Structural Behaviour of Chemically Stabilized Tropical Residual Soil. PhD thesis. Universiti Teknologi Malaysia, Malaysia.

Latifi, N., Horpibulsuk, S., Meehan, C.L., Abd Majid, M.Z., Tahir, M.M., and Mohamad, E.T. (2016a). Improvement of Problematic Soils with Biopolymer—An Environmentally Friendly Soil Stabilizer. *Journal of Materials in Civil Engineering*, 29(2), pp.1–11.

Latifi, N., Rashid, A.S.A., Siddiqua, S., and Horpibulsuk, S. (2015). Micro-structural analysis of strength development in low- and high swelling clays stabilized with magnesium chloride solution - A green soil stabilizer. *Applied Clay Science*, 118, pp.195–206.

Latifi, N., Marto, A., Rashid, A.S.A., and Yii, J.L.J. (2015a). Strength and Physico-chemical Characteristics of Fly Ash–Bottom Ash Mixture. *Arabian Journal for Science and Engineering*, 40(9), pp.2447–2455.

Latifi, N., Rashid, A. S. A., Siddiqua, S., and Majid, M. Z. A. (2016b). Strength measurement and textural characteristics of tropical residual soil stabilised with liquid polymer. Measurement: *Journal of the International Measurement*

Confederation, 91, pp.46–54.

Latifi, N., Eisazadeh, A. and Marto, A. (2014). Strength behavior and microstructural characteristics of tropical laterite soil treated with sodium silicate-based liquid stabilizer. *Environmental Earth Sciences*, 72(1), pp.91–98.

Latifi, N., Marto, A. and Eisazadeh, A. (2014a). Analysis of strength development in non-traditional liquid additive-stabilized laterite soil from macro- and micro-structural considerations. *Environmental Earth Sciences*, 73(3), pp.1133–1141.

Latifi, N., Marto, A. and Eisazadeh, A., (2016c). Experimental Investigations on Behaviour of Strip Footing Placed on Chemically Stabilised Backfills and Flexible Retaining Walls. *Arabian Journal for Science and Engineering*, 41(10), pp.4115–4126.

Latifi, N., Marto, A. and Eisazadeh, A. (2016). Physicochemical behavior of tropical laterite soil stabilized with non-traditional additive. *Acta Geotechnica*, 11(2), pp.433–443.

Latifi, N., Marto, A. and Eisazadeh, A. (2013). Structural Characteristics of Laterite Soil Treated by SH-85 and TX-85 (Non-Traditional) Stabilizers. *Electronic Journal of Geotechnical Engineering*, 18, pp.1707–1718.

Lee, F. H., Almeida, M. S. S. and Indraratna, B. (2010). Physical Modelling of Soft Ground Problems. *In 7th International Conference on Physical Modelling in Geotechnics 2010*. pp. 45–66.

Li, L. L., Dan, H. B. and Wang, L. Z. (2011). Undrained behavior of natural marine clay under cyclic loading. *Ocean Engineering*, 38(16), pp.1792–1805.

Lim, S. M., Wijeyesekera, D. C. and Bakar, H. (2013). Critical Overview of Laboratory Assessments used in Soil Road Design. *International Journal of Integrated Engineering*, 3, pp.1–9.

Lipi, A. W. J. and Wdowska, G. (2010). Saturation criteria for heavy overconsolidated cohesive soils. *Annal of Warsaw University of Life Sciences*, 42(2), pp.295–302.

Liu, J., Shi, B., Jiang, H., Huang, H., Wang, G., and Kamai, T. (2011). Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Engineering Geology*, 117(1–2), pp.114–120.

Maaitah, O.N. (2012). Soil Stabilization by Chemical Agent. *Geotechnical and Geological Engineering*, 30(6), pp.1345–1356.

Malaysian Highway Authority (1989). The Embankment built to Failure. In Hudson, *Proc. Of International Symposium on Trial Embankment on Marine Clay*. Kuala Lumpur, Malaysia.

Mallela, J., Quintus, H. Von and Smith, K.L. (2004). Consideration of Lime-Stabilized Layers in Mechanistic-Empirical Pavement Design, Arlington, Virginia, USA.

Marto, A., Latifi, N. and Eisazadeh, A. (2014). Effect of Non-Traditional Additives on Engineering and Microstructural Characteristics of Laterite Soil. *Arabian Journal for Science and Engineering*, 39(10), pp.6949–6958.

Marto, A., Aziz N., Jahidin M. R., Yunus N. Z. M., Kasim F. and Tan C. S. (2015). Soft soil improvement using chemical-rubber chips mixture. *Jurnal Teknologi*, 76 (2), pp. 103-108

Ministry of Information Malaysia (2008). Rancangan Malaysia Kesembilan,

Modarres, A., and Nosoudy, Y. M. (2015). Clay Stabilization using Coal Waste and Lime - Technical and Environmental Impacts. *Applied Clay Science*, 116–117, 281–288.

Mofiz, S. A. and Islam, M. N. (2010). Modeling and Numerical Analysis of Expansive Soil in Stress Path Tests. *GeoFlorida 2010: Advances in Analysis, Modeling & Design*, pp.747–756.

Naeini, S. A., Naderinia, B. and Izadi, E. (2012). Unconfined compressive strength of clayey soils stabilized with waterborne polymer. *KSCE Journal of Civil Engineering*, 16(6), pp.943–949.

Nontananandh, S. and Boonyong, S. (1998). Strength Development of Soft Marine Clay Stabilized with Cement and Fly Ash. *Kasetsart Journal*, 38(4), p.7.

Oh, E. and Chai, G. (2006). Characterization of Marine Clay for Road Embankment Design in Coastal Area. *Proceedings of Sixteenth (2006) International Offshore And Polar Engineering Conference*, pp.7–10.

Ohtsubo, M., Egashira, K. and Takayama, M. (1985). Properties of a Low-Swelling Smectitic Marine Clay of Interest in Soil Engineering. *Canadian Geotechnical Journal*, 22(2), pp.241–245.

Onyejekwe, S., and Ghataora, G. S. (2016). Stabilization of Quarry Fines Using a Polymeric Additive and Portland Cement. *Journal of Materials in Civil Engineering*, 28(1), pp.1–10.

Ouhadi, V. R., Yong, R. N. Amiri, M. and Ouhadi, M. H. (2014). Pozzolanic consolidation of stabilized soft clays. *Applied Clay Science*, 95, pp.111–118.

Peethamparan, S., Olek, J. and Diamond, S. (2009). Mechanism of stabilization of Na-montmorillonite clay with cement kiln dust. *Cement and Concrete Research*, 39(7), pp.580–589.

Petry, T. and Little, D. (2002). Review of stabilization of clays and expansive soils in pavements and lightly loaded structures-history, practice, and future. *Journal of Materials in Civil Engineering*, 14(6r), pp.447–460.

Phetchuay, C., Horpibulsuk, S., Arulrajah, A., Suksiripattanapong, C., and Udomchai, A. (2016). Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer. *Applied Clay Science*, 127–128, pp.134–142.

Pillai, A., Abraham, B. and Sridharan, A. (2015). Determination of Sulphate Content in Marine Clays. *International Journal of Engineering Research and Applications*, 1(3), pp.1012–1016.

Pillai, R.J., Bushra, I. and Robinson, R.G. (2013). Undrained Triaxial Behavior of Cement Treated Marine Clay. *Geotechnical and Geological Engineering*, 31(2), pp.801–808.

Polidori, E. (2003). Proposal for a new plasticity chart. *Géotechnique*, 53(4), pp.397–

406.

Quiroga, A. J., Muraleetharan, K. K., Cerato, A. B., and Miller, G. A. (2015). Stress-Strain Behavior of Cement-Improved Clays. , *IFCEE 2015*, pp.2328–2338.

Rafalko, S., Filz, G., Brandon, T., and Mitchell, J. (2007). Rapid Chemical Stabilization of Soft Clay Soils. Transportation Research Record: *Journal of the Transportation Research Board*, 2026, pp.39–46.

Rahardjo, H., Aung, K. K., Leong, E. C., and Rezaur, R. B. (2004). Characteristics of residual soils in Singapore as formed by weathering. *Engineering Geology*, 73(1–2), pp.157–169.

Rahman, Z. A., Yaacob, W. Z. W., Rahim, S. A., Lihan, T., Idris, W. M. R., and Mohd Sani, W. N. F. (2013). Geotechnical Characterisation Of Marine Clay As Potential Liner Material. *Sains Malaysiana*, 42(8), pp.1081–1089.

Rajasekaran, G. and Narasimha Rao, S. (2002). Compressibility behaviour of lime-treated marine clay. *Ocean Engineering*, 29(5), pp.545–559.

Ramasamy, Govindachettiar, Pusadkar, S.S. (2007). Settlement Of Footing On Compacted Ash Bed. *Journal of Geotechnical and Geoenvironmental Engineering.*

Rao, S.N. and Rajasekaran, G. (1996). Reaction Products Formed in Lime-Stabilized Marine Clays. *Journal of Geotechnical Engineering*, 122(no.5), pp.329–336.

Rauch, A., Harmon, J., Katz, L., and Liljestrand, H. (2002). Measured Effects of Liquid Soil Stabilizers on Engineering Properties of Clay. *Transportation Research Record*, 1787(1), pp.33–41.

Rauch, A., Katz, L. and Liljestrand, H. (2003). An Analysis of the Mechanisms and Efficacy of Three Liquid Chemical Soil Stabilizers: Volume 1, *Center for Transportation Research*, The University of Texas at Austin.

Rawat, A. and Mital, A. (2015). A Review Paper on Soil Stabilization using Different Traditional and Non-Traditional Additives. *International Journal of Research Review in Engineering, Science & Technology*, 4(1), pp.171–175.

Rayhani, M. H. T. and Naggar, M. H. (2008). Numerical Modeling of Seismic Response of Rigid Foundation on Soft Soil. *International Journal of Geomechanics*, 8(6), pp.336–346.

Salih, A. G. (2012). Review on granitic residual soils' geotechnical properties. *Electronic Journal of Geotechnical Engineering*, 17, pp.2645–2658.

Saride, S., Puppala, A.J. and Chikyala, S.R. (2013). Swell-shrink and strength behaviors of lime and cement stabilized expansive organic clays. *Applied Clay Science*, 85(1), pp.39–45.

Sharma, N. K., Swain, S. K. and Sahoo, U. C. (2012). Stabilization of a Clayey Soil with Fly Ash and Lime: A Micro Level Investigation. *Geotechnical and Geological Engineering*, 30(5), pp.1197–1205.

Sherwood, P. (1993). Soil stabilization with cement and lime: State of the Art Review. London: *Transport Research Laboratory*, HMSO.

Shi W. Y., Shao H. B., Li H., Shao M. and Du S. (2009). Progress in the remediation of hazardous heavy metal-polluted soils by natural zeolite. *Journal of Hazardous Materials*, 170(1), pp 1-6

Solanki, P. and Zaman, M. (2012). Microstructural and Mineralogical Characterization of Clay Stabilized Using Calcium-Based Stabilizers. *Scanning Electron Microscopy*, (4), pp.771–798.

Suganya, K., and Sivapullaiah, P. V. (2016). Role of Sodium Silicate Additive in Cement-Treated Kuttanad Soil. *Journal of Materials in Civil Engineering*, 28(6), pp.1–6.

Sunil, B. M., Nayak, S., and Shrihari, S. (2006). Effect of pH on the Geotechnical Properties of Laterite. *Engineering geology*. 85(1): 197-203.

Surarak, C., Likitlersuang, S., Wanatowski, D., Balasubramaniam, A., Oh, E., and Guan, H. (2012). Stiffness and strength parameters for hardening soil model of soft and stiff Bangkok clays. *Soils and Foundations*, 52(4), pp.682–697.

Sweeney, M. (1981). Differential Thermal Analysis Studies of some Soil-Clays from the Eastern Caribbean, West Indies. Part I. Antigua, Grenada and Trinidad (Montmorillonitic). *Thermochimica Acta*, 48(3), pp.277–285.

Tamadher, T.A., Anuar, B.K. and Zamri, B.C. (2007). Stabilisation of Silty Clay Soil Using Chloride. *Journal of Engineering Science and Technology*, 2(1), pp.102–110.

Thiry, M. (2000). Palaeoclimatic Interpretation of Clay Minerals in Marine Deposits: An Outlook from the Continental Origin. *Earth Science Reviews*, 49(1–4), 201–221.

Tingle, J., Newman, J., Larson, S., Weiss, C., and Rushing, J. (2007). Stabilization Mechanisms of Nontraditional Additives. *Transportation Research Record*, 2(1989), pp.59–67.

Usman, F., Hino, T., Negami, T., Harianto, T., and Jia, R. (2012). Basic Study of the Fundamental Behavior of Ariake Marine Clay. *8th International Symposium on Lowland Technology*, pp.75–81.

Vipulanandan, C., Kim, M. and Harendra, S. (2007). Microstructural and Geotechnical Properties of Houston-Galveston Area Soft Clays. *Advances in Measurement and Modeling of Soil Behavior*, pp.1–11.

White, W.A. (1949). Atterberg plastic limits of clay minerals. *American Mineralogist*, 34, pp.508–512.

Wiggins, J.H., Slossan, E.J. and Krohn, J.P. (1978). Natural Hazards: Earthquake, Landslide, Expansive Soil Loss Models. *Report for National Science Foundation*.

Wild, S., Arabi, M. and Ward, G. (1989). Fabric Development in Lime Treated Clay Soils. *Ground Engineering*, 22, pp.35–37.

Xiao, H. and Lee, F. (2009). Curing Time Effect on Behavior of Cement Treated Marine Clay. *International Journal of Engineering and Applied Sciences*, 2(7), pp.427–434.

Xiao, H. W., Lee, F. H. and Chin, K. G. (2014). Yielding of cement-treated marine clay. *Soils and Foundations*, 54(3), pp.488–501.

Yan, W. and Ma, Y. (2010). Geotechnical characterization of Macau marine deposits. *Engineering Geology*, 113(1–4), pp.62–69.

Yi, Y., Li, C., and Liu, S. (2010). Alkali-Activated Ground-Granulated Blast Furnace Slag for Stabilization of Marine Soft Clay. Journal of Material in Civil Engineering, 11(4), 246–250.

Yi, Y., Liska, M. and Al-Tabbaa, A. (2014). Properties of Two Model Soils Stabilized with Different Blends and Contents of GGBS, MgO, Lime, and PC. *Journal of Materials in Civil Engineering*, 26(2), pp.267–274.

Yilmaz, I. and Civelekoglu, B. (2009). Gypsum: An additive for stabilization of swelling clay soils. *Applied Clay Science*, 44(1–2), pp.166–172.

Yi, Y., Zheng, X., Liu, S., and Al-Tabbaa, A. (2015). Comparison of Reactive Magnesia- and Carbide Slag-Activated Ground Granulated Blastfurnace Slag and Portland Cement for Stabilisation of a Natural Soil. *Applied Clay Science*, 111, pp.21–26.

Yin, J. H. and Fang, Z. (2010). Physical Modeling of a Footing on Soft Soil Ground with Deep Cement Mixed Soil Columns under Vertical Loading. Marine Georesources & Geotechnology, 28(2), pp. 173-188

Yunus, N. Z. M., Wanatowski, D., Stace, R., Marto, A., Kassim, F., and Hassan, N. A. (2014). Undrained & Drained Behavior of Lime- Treated Organic Clay with Calcium Chloride. *Electronic Journal of Geotechnical Engineering*, 19, pp.1595–1620.

Zhang, M., Zhao, M., Zhang, G., Nowak, P., Coen, A., and Tao, M. (2015). Calcium-Free Geopolymer as a Stabilizer for Sulfate-Rich Soils. *Applied Clay Science*, 108, pp.199–207.

Zhang, M., Guo, H., El-Korchi, T., Zhang, G., and Tao, M. (2013). Experimental feasibility study of geopolymer as the next-generation soil stabilizer. *Construction and Building Materials*, 47, pp.1468–1478.

Zhao, H., Zhou, K., Zhao, C., Gong, B. W., and Liu, J. (2015). A long-term investigation on microstructure of cement-stabilized handan clay. *European Journal of Environmental and Civil Engineering*, (June), pp.37–41.

Zhao, H., Chun, Z., Xiao, Z., and Chan, L. (2013). Physicochemical Characterization of Cement Stabilized Highly Expansive Soil. *In Geo-Congress 2013*. pp. 2091–2100.