GEOTECHNICAL AND MICRO-STRUCTURAL BEHAVIOUR OF CHEMICALLY STABILIZED TROPICAL RESIDUAL SOIL

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Specially dedicated to my beloved parents and my adorable wife

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ABSTRACT

The stabilization of soils with additives is a chemically modified method that can be used to improve soils with weak engineering properties. Non-traditional additives such as ionic, enzymes, salts, polymers, and tree resins are widely used for treating problematic soils. The effects of non-traditional additives on the geotechnical properties of soils have been the issue of investigation in recent years. The publications on macro-structural, micro-structural, and molecular characteristics of tropical residual soil stabilized by non-traditional stabilizers are limited. This research aimed at determining the stabilization mechanism and performance of the tropical residual (laterite) soil mixed with two types of non-traditional stabilizer; namely the calcium based powder stabilizer (SH-85) and sodium silicate based liquid stabilizer (TX-85). Macro-structural study including the compaction, unconfined compression strength, direct shear, and consolidation tests were used to assess the engineering properties of the stabilized soil. The physico-chemical bonding mechanisms contributed to the stabilization process were discussed based on the results of micro-structural study from different spectroscopic and microscopic techniques such as X-ray Diffractometry, Energy-Dispersive X-ray Spectrometry, Field Emission Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy, Surface Area Analysis and Thermal Gravimetric Analysis. In addition, the performance of treated laterite backfill stabilized with the selected additives was evaluated using series of physical model tests. The model tests consisted of strip footing placed on stabilized backfill behind sheet pile wall. The numerical simulation using PLAXIS finite element (FE) software was carried out to compare and evaluate the results obtained from the physical models. The laboratory tests showed that the addition of 9 % (as the optimum amount) of both additives increased more than 80% of compressive strength after 7 days of curing periods while the consolidation settlement had been effectively reduced. The micro-structural study revealed that the stabilization process modified the porous network of laterite soil. The pores of the soil had been filled by the newly formed compounds known as calcium aluminate hydrate cementitious material for SH-85 treated samples and sodium aluminosilicate hydrate gel-like product for TX-85 treated samples. Hence, the stabilization mechanism of two selected non-traditional additives was by cationic exchange and physical bonding. The numerical simulation and physical modelling showed identical trends. Therefore the finite element method using elasto-plastic Mohr-Coulomb model is suitable to be used in evaluating and predicting the behaviour of chemically stabilized backfill. The results from the physical model tests showed that the ultimate capacity of the footing placed on the stabilized backfill soil increased greatly while the settlement reduced compared to untreated backfill laterite soil, after just 7 days of curing. It can be concluded that the quick reaction of the selected stabilizers with laterite soils is very advantageous and cost-effective for geotechnical engineering projects.

ABSTRAK

Penstabilan tanah menggunakan bahan tambah merupakan suatu kaedah pengubahsuaian kimia yang boleh digunakan untuk memperbaiki sifat tanah yang mempunyai sifat-sifat kejuruteraan yang lemah. Bahan tambah bukan konvensional seperti ionik, enzim, garam, polimer dan resin pokok digunakan secara meluas untuk rawatan tanah bermasalah. Kesan bahan tambah bukan konvensional kepada sifat geoteknikal tanah telah menjadi isu penyelidikan dalam tahun-tahun kebelakangan ini. Penerbitan mengenai makrostruktur, mikrostruktur dan sifat-sifat molekul tanah baki tropika yang distabilkan dengan bahan penstabil bukan konvensional adalah terhad. Penyelidikan ini bertujuan untuk menentukan mekanisme penstabilan dan prestasi tanah baki (laterit) tropika yang dicampur dengan dua jenis penstabil bukan konvensional, iaitu penstabil serbuk berasaskan kalsium (SH-85) dan bahan penstabil cecair berasaskan sodium silikat (TX-85). Kajian makrostruktur termasuk ujian pemadatan, ujian kekuatan mampatan tak terkurung, ujian ricih, dan ujian pengukuhan telah dijalankan untuk menilai sifat kejuruteraan tanah laterit yang distabilkan. Mekanisme ikatan fizikokimia yang menyebabkan proses penstabilan dibincangkan berdasarkan hasil kajian mikrostruktur melalui kaedah spektroskopik dan mikroskopik seperti *X-ray Diffractometry, Energy-Dispersive X-ray Spectrometry, Field Emission Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy*, Analisis Luas Permukaan dan *Thermal Gravity Analysis*. Prestasi tanah laterit yang distabilkan dengan bahan tambah yang digunakan sebagai tanah kambus balik telah dinilai melalui satu siri ujian model fizikal. Ujian model terdiri daripada asas jalur di atas kambus balik yang distabilkan dan terletak di belakang dinding cerucuk turap. Simulasi berangka dengan perisian unsur terhingga PLAXIS telah dijalankan untuk membandingkan dan menilai hasil ujian model fizikal. Ujian makmal menunjukkan bahawa penggunaan bahan tambah sebanyak 9% (nilai optimum) bagi kedua-dua bahan tambah meningkatkan kekuatan mampat tanah laterit sebanyak 80% selepas tempoh pengawetan selama 7 hari, dan mampu mengurangkan enapan pengukuhan secara efektif. Berdasarkan kajian mikrostruktur, didapati bahawa proses penstabilan telah mengubahsuai rangkaian liang tanah laterit. Liang-liang tanah diisi dengan kompaun yang baru terbentuk, iaitu kompaun bersimen kalsium aluminat hidrat bagi sampel yang distabilkan dengan SH-85, dan sodium aluminosilikat hidrat berbentuk gel bagi sampel yang distabilk dengan TX-85. Mekanisme penstabilan bagi kedua-dua bahan tambah bukan konvensional disebabkan oleh pertukaran kation dan ikatan fizikal. Simulasi berangka dan pemodelan fizikal menunjukkan tren yang serupa. Oleh itu, kaedah unsur terhingga yang menggunakan model elasto-plastik *Mohr-Coulomb* didapati sesuai digunakan untuk menilai dan meramal perilaku kambus balik yang distabilkan menggunakan bahan kimia. Hasil ujian model fizikal menunjukkan bahawa kapasiti muktamad asas di atas tanah kambus balik yang distabilkan mengalami peningkatan yang banyak dan mengurangkan enapan tanah selepas 7 hari tempoh pengawetan berbanding dengan tanah kambus balik yang tidak dirawat. Kesimpulannya, reaksi pantas bahan penstabil untuk menstabilkan tanah laterit adalah sangat berfaedah dan kos-berkesan bagi projek-projek kejuruteraan geoteknik.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	-	Activity
ADU	-	Acquisition data unit
AEC	-	Anion exchange capacity
Al	-	Aluminum
Al^{3+}	-	Aluminum cation
ASTM	-	American society of testing material
BET	-	Brunauer emmett and teller
BS	-	British standard
c	-	Constant
c	-	Cohesion
Ca	-	Calcium
Ca^{2+}	-	Calcium cation
CAH	-	Calcium aluminate hydrate
CaO	-	Calcium oxide
$Ca(OH)_2$	-	Calcium hydroxide
CASH	-	Calcium aluminate silicate hydrate
CaSO4	-	Calcium sulphate
CEC	-	Cation exchange capacity
C_c	-	Compression index
C_s	-	Swelling index
c_v	-	Coefficient of consolidation
CO_2	-	Carbon dioxide
cps	-	Counts per second
Cu	-	Copper
d	-	Distance of interplanar spacing as function of θ
D	-	Day
D_f	-	Depth of the foundation

DTA	-	Differential thermal analysis
DTG	-	Derivative thermal gravimetric
e	-	electronic charge
EDAX	-	Energy dispersive x-ray analysis
F	-	Fluoride
Fe	-	Iron
Fe^{2+}	-	Iron (II) cation
Fe^{3+}	-	Iron (III) cation
Fe_2O_3	-	Ferric Oxide
FESEM	-	Field emission scanning electron microscopy
FTIR	-	Fourier transform infrared
H	-	Hydrogen
H^+	-	Hydrogen cation
HCL	-	Hydrochoric acid
H_2O	-	Water
H_s	-	Depth of failure zone
ICP	-	Inductively coupled plasma
K	-	Potassium
K^+	-	Potassium cation
KBr	-	Potassium bromide
LC	-	Laterite Clay
LL	-	Liquid limit
LOI	-	Loss on ignition
LST	-	Liquid Stabilizer Treated
LVDT	-	Linear variable displacement transducer
L_{sh}	-	Length of horizontal failure line
MDD	-	Maximum dry density
Mg	-	Magnesium
MgO	-	Magnesium oxide
MM	-	Mercury microporosimetry
m_v	-	Coefficient of volume change
n	-	Order of diffraction
n_0	-	electrolyte concentration
Na	-	Sodium

Na^+	-	Sodium cation
Na_2O	-	Sodium oxide
NASH	-	Sodium AluminoSilicate Hydrate
NO_3	-	Nitrate
NUM	-	Numerical Modelling
O	-	Oxygen
OC	-	Organic content
$(OH)^-$	-	Hydroxide ion
OMC	-	Optimum moisture content
P	-	Phosphorous
PHM	-	Physical Modelling
PI	-	Plasticity index
PL	-	Plastic limit
ppm	-	Parts per million
PST	-	Powder Stabilizer Treated
Pt	-	Platinum
q_{ult}	-	Ultimate pressure
q_a	-	Allowable pressure
S	-	Sulfur
Sec	-	Seconds
SEM	-	Scanning electron microscope
Si	-	Silicon
SiO_2	-	Silica
SO_4	-	Sulphate
SSA	-	Specific surface area
T	-	Temperature
TEM	-	Transmission electron microscopy
TG	-	Thermal gravimetric
TGA	-	Thermal gravimetric analysis
UCS	-	Unconfined compressive strength
UNT	-	Untreated
ν	-	Volume of gas adsorbed per unit weight of clay at a ressure
ν_m	-	Volume of gas adsorbed for monolayer coverage
XRD	-	X-ray diffraction

XRF	-	X-ray fluorescene
Zn	-	Zinc
1/k	-	The effective thickness of the diffuse layer
ε	-	Strain
μ	-	Micro
λ	-	Wave-length
θ	-	Critical angle of incidence of the x-ray beam on the crystal plane
ϕ	-	Internal friction angle

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CHAPTER 1

INTRODUCTION

1.1 Background

High quality soil as materials for geotechnical engineering construction are rare in many parts of the world, and most often than not, engineers are forced to seek alternatives to reach the stipulated requirements. In addition, the gradual increase in population as well as rapid development in the construction industry in recent years have make it more urgent than ever to gain the sufficient knowledge and information needed to improve existing soil for geotechnical engineering purposes.

Soil stabilization is the process of improving the physical and engineering properties of soil to obtain some predetermined targets. It operates in various ways such as mechanical, biological, physical, chemical and electrical. Nowadays, among the different methods of soil improvement, using chemical additives for soil stabilization in order to increase soil strength parameters and loading capacity is catching more attention. Engineers in construction industry particularly in the geotechnical sector use chemically soil stabilization techniques in many ways such as road construction, slope stabilization and erosion control, foundation and embankment treatment, and improving the coastal line for construction. This popularity is due to their low cost and convenience, particularly in the geotechnical projects that require a high volume of soil.

Each type of chemical additives has different mechanism and influence on soil properties. For instance, there have been noticeable important dissimilarities between tropical soils from the more ordinary soils of moderate climates. Rock weathering in these areas is very rigorous that can be described by fast disintegration of feldspars as well as ferromagnesian raw materials, the displacement of bases including Na_2O, K_2O, and MgO and silica, and the absorption of aluminum and iron oxides (Eisazadeh *et al*., 2011). This procedure which includes leakage of silica and decomposition of iron and aluminum oxides is called laterization (Gidigasu, 1972).

There are six areas of the globe that laterite soil is found and they are; Africa, India, South- East Asia, Australia, Central and South America. However, there is an emphasis that, due to the movement of climatic zone in the geological past, relevant regions of laterite can be located in places that are not within the tropics (Zilalem, 2005). This soil category is affluent in aluminum, iron, and kaolinite clays (Townsend, 1985). This soil group usually exists at hillside and offers brilliant borrow areas for wide adoption in many different construction operations. The optimum utilization is determined by the quantity of issues encountered in construction connected to their workability, field compaction, and strength. Studies shows that the laterite soil forms a large part of Malaysia's soil, and it has been used in different areas and projects as natural soil (Salih, 2012; Eisazadeh, 2013).

The stabilization of soils with additives is a chemical method that can be used to improve soils with poor engineering properties. However, sometimes it is necessary to add some additives to the soil in order to improve certain properties of the soil to be used for specific purpose of the project. The soil stabilizers are categorized as traditional and non-traditional (Eisazadeh, 2010). Traditional additives include cement, lime, fly ash, and bituminous materials, while non-traditional additives consist of various combinations such as enzymes, liquid polymers, resins, acids, silicates, ions, and lignin derivatives (Tingle *et al.*, 2007; Hafez *et al.,* 2008).

The non-traditional additives can be produced using different kinds of chemical agent that give different reactions while added to soil. Nevertheless, published reports on such additives are still scarce compared to traditional additives, either in terms of their geotechnical performance or basic stabilization mechanisms. Moreover, their exact chemical components are mostly kept confidential by their respective owners. In recent years studies have been done by some researchers on the mixtures of different types of soil and calcium-based powder type of non-traditional stabilizers. The results of their assessment indicated that these additives has potential to improve soil parameters, in particular the soil strength (Peethamparan *et al*., 2008; Obuzor *et al*., 2012; Manso *et al*., 2013; Agapitus, 2013).

Non-calcium-based liquid soil stabilizers are actively marketed by a number of companies. In addition to being cheaper to transport than traditional bulk stabilizer materials, these products are a potentially attractive alternative for soil treatment. The exact chemical composition of these stabilizers has not been released due to their commercially registered brand. These are mostly sold as concentrated liquids, which are diluted with water at site. Some are directly applied to the soil before compaction while other is pressure injected into deeper layers. It should be noted that the result of previous study indicated that the non-traditional liquid additives can help to increase soil strength with curing time (Zhu and Liu, 2008; Fon, 2010; Liu *et al*., 2011; Ahmad *et al*., 2013).

Unfortunately, millions of dollars are lost in some occasions due to improper use of chemical stabilizers (Eisazadeh, 2010). Therefore, proper knowledge on soil-additive reactions is an essential part of this technique. In this research the mechanisms responsible for improving the soil properties of Malaysian laterite soil using domestic non-traditional additives has been studied. In addition, the changes on physicochemical and engineering characteristics of stabilized soil and its performance as a field material has been discussed.

1.2 Problem Statement

Traditional stabilizers such as cement, lime, fly ash, and bituminous products have been intensely researched, and their fundamental stabilization mechanisms have been identified (Obuzor *et al*., 2012). Nowadays, various types of non-traditional additives in liquid and powder form are actively marketed by a number of companies. The stabilizing mechanisms of these products are not fully understood, and their confidential chemical composition makes it hard to evaluate the stabilizing mechanisms and predict their performance. In addition, laboratory experimentation had focused only on evaluating the effects of stabilized materials on engineering properties.

During recent years, many studies have been done on traditionally stabilized laterite soil, which forms a large part of Malaysia's soil and their relevant mechanism is well understood (Eisazadeh *et al*., 2011). Nevertheless, no research on the macro- and micro- structural study and efficiency of the tropical residual soil, in particular the laterite soil, mixed with domestically produced chemical additives known as SH-85 and TX-85 has been carried out. It is therefore important to fully understand the physicochemical behaviour of this soil stabilized with those stabilizers and its performance in field applications.

1.3 Objectives of Study

In view of the current understanding and the incomplete research to date, this study was conducted to determine the stabilization mechanism and performance of the laterite soil mixed with non-traditional additives. Hence, the following objectives had been established to achieve the aim of the research:

1. To assess the changes of soil engineering properties due to treatment with selected chemical stabilizers through "macro-characterization" study.
2. To determine the changes induced on the mineralogy, morphology, molecular structure, and elemental composition of soil-stabilizer matrix at the particle level through "micro-characterization" study of untreated (laterite) and treated soil (laterite treated with optimum percentage of additives).
3. To verify and complement the data obtained in the macro and micro-characterization studies by performing pH test, thermal gravimetric, particle size and surface area analysis on the cured samples.

4. To determine the performance of untreated and selected additives treated laterite soil as the backfill materials retained by sheet pile wall through laboratory physical model tests.
5. To determine the suitability of elasto-plastic Mohr-Coulomb model in numerical simulation of the laterite soil as the backfill materials treated with selected additives, through comparison with laboratory physical model tests.

1.4 Scope and Limitation of Study

The scope and limitation of the research are as follows:

1. The soil used in this study was granitic residual soil obtained from the campus of Universiti Teknologi Malaysia, Johor Bahru, Johor. Results from the ratio of Silica oxide (SiO_2) and Alumina oxide (Al_2O_3) showed that this soil was categorized as laterite soil.
2. The chemical used, considered as non-traditional additives, were obtained from a company called Probase Sdn. Bhd., located in Johor.
3. The percentages of the chemical used in the mixture of laterite-additives were 3%, 6%, 9%, 12% and 15% cured at 3, 7, 14, 28 and 90 days curing periods. The 9% optimum value was determined through the analysis of the results obtained. Then the soil treated with 9% additives (later used as “treated” soil) had been subjected to various tests after being cured at 7, 28 and 90 days curing period to determine the stabilization mechanism of the treated soil.
4. The macro-structural study involved compaction test, unconfined compression test, direct shear test and consolidation test while the micro-structural study involved X-ray Diffraction, Field Emission Scanning Electron Microscopy and X-ray Spectrometry, Fourier Transform Infrared Spectroscopy, Thermal Gravimetric Analysis, Surface Area Value, Particle Size Analysis and pH measurement.

5. Nine laboratory physical model tests had been conducted on the untreated and treated soil (cured at 7 days) as materials, retained 30 cm by sheet pile. The sheet pile was embedded 15 cm into compacted untreated laterite soil. The model tests were carried out by applying loads to the strip footing placed on the retained soil until failure occurred to the footing. The footing was placed at 5, 10 and 15 cm behind the wall. The settlement of the footing, horizontal displacement of the wall and strain distribution through the depth of the wall had been monitored during loading tests to ascertain the performance of the treated soil as backfill material.
6. The commercial 2D finite element software called "PLAXIS" Version 2010 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

From this study, the mechanism of the stabilization of laterite soil treated with locally produced additives had been established. The significant of the study includes:

1. Results of the study could contribute to existing knowledge, in particular regarding the behaviour of laterite soil treated with these selected non-traditional additives. It can close the gap in understanding the mechanism of the stabilization through the results from macro and micro-structural study, verified by physico-chemical tests.
2. The mineralogical changes, morphological changes, molecular changes and physical changes of the laterite soil treated with the selected non-traditional additives are new findings and can be used for further and other research on laterite soils.

3. Treating of soils using the chosen additives could be an economical alternative method in soil stabilization. This is due to the time taken to obtain increment up to 70% strength of the treated soil could be achieved only after 7 days curing periods. Besides that, stabilizing the soil with these non-traditional additives is easy and quick at the level of implementation compared to other methods of soil reinforcement.
4. Good performance shown by the treated laterite soil as backfill materials could give the confident to the practicing engineers in using these non-traditional additives for treating soils to be used in Geotechnical Engineering project especially in regions with laterite clay as foundation soils. This could also be supported by the results of macro-structural tests from UCT, direct shear tests and consolidation tests which shows the increased resistant of treated soil to settlement and shear failure.

1.6 Thesis Organization

This thesis consists of six chapters. The first chapter has presented a brief introduction on the role of chemical additives in soil stabilization practices and the need to understand its underlying mechanisms. The research philosophy including ‘problem statement’, ‘objectives of study’, ‘scope of study’, and ‘significance of study’ have also been discussed.

Chapter 2 lays out the fundamentals of clay mineralogy to understand more sophisticated soil-chemical reactions. Different chemical stabilization techniques as well as traditional and non-traditional soil additives are discussed, followed by some hypotheses on the formatting mechanisms of reaction products. Previous researches on the physical and numerical simulation of backfills and retaining walls had also been discussed briefly. Based on the current scientific knowledge on soil stabilization, a research framework was established taking into consideration the gap in the current research.

Chapter 3 presents the research methodology of the study by elucidating the chemical analyses and methods used in depth. Laboratory experiments were done to determine the soil's geotechnical properties according to British Standard. Furthermore, the characterization study of stabilized soil was done using spectroscopic and microscopic techniques previously published in papers and standards. This chapter ends with an elaborated description on the physical and numerical simulation tests procedures. The results obtained from these tests are presented and discussed comprehensively in Chapter 4 and 5.

Finally, Chapter 6 gives the conclusion of this study and highlights the contributions of the work. Besides that, recommendations for future studies are also specified.

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