UNIVERSITI PUTRA MALAYSIA

USE OF ALKALI-ACTIVATED PALM OIL FUEL ASH REINFORCED BY MICROFIBRES FOR SOFT SOIL STABILISATION

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By

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The construction of heavy structures on soft soils in tropical regions is a high challenging task. The soft soils are generally characterized by low undrained shear strength and poor bearing capacity. Deep mixing is one of the beneficial soil improvement techniques that could be applied successfully to overcome these problems by improving geotechnical characteristics of soils with cement and other traditional cementitious binders. Although such chemical binders can improve many engineering properties of soils, they have several shortcomings.

The primary motivation for this study was to investigate the innovative reuse of a locally available by-product to eliminate traditional binders from deep mixing projects. In this respect, the use of palm oil fuel ash (POFA) as a well-known agricultural waste deserves a special attention. This research consists of four main stages.

The first stage is the performance of the preliminary investigation in order to evaluate the effectiveness of POFA (individually and in combination with cement) on some basic geotechnical characteristics of soft soil. The unconfined compression strength (UCS) was used as a practical indicator to investigate the strength development. According to the test results, combining POFA with cement results in a sharp increase in the UCS of the samples, whereas in the same curing time, the strength development of POFA-stabilized soil was not remarkable.

In the second stage of this research, alkaline activation of POFA was adopted as a viable technique to fully eliminate cementitious binders from geotechnical applications. In simple words, alkali-activated binder is generally a synthetic alkali aluminosilicate which is produced from the reaction of a solid aluminosilicate with pre-designed concentrated aqueous alkaline solutes. Based on the obtained UCS values at curing periods of up to 6 months, using alkali-activated POFA increased the peak strength of soil by up to 70 times compared to that of natural soil.

Beside the shear strength development, in order to increase the tensile strength and ductility of treated soil, the combined effect of fibre inclusion and alkaline activation is described and reported in the third stage. In this stage, along with the POFA in presence of high alkali solutes, mineral wollastonite microfibres ($CaSiO_3$) were used as a strong reinforcement inclusion. Beside the UCS test, indirect tensile strength and flexural strength tests were carried out at curing periods of up to 6 months. The test results indicated that the inclusion of fibre reinforcement within alkali-activated POFA, caused a further increase in the peak stress and tensile strength, and decreased the loss of post-peak strength.

In the last stage of this research, a geotechnical design procedure of interaction between a strip footing and stabilized soil is modelled in the laboratory using the column technique. This part takes into account the geotechnical characteristics of the stabilized soil columns and simulates fairly well the coupled effect of alkali-activated POFA and reinforcement inclusion (APR) in deep mixing projects. The test results demonstrated the strong contribution of APR to the soil matrix, which led to a sharp increase in the bearing capacity of up to 204% in the treated soil columns.

Abstrak tesis yang telah dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan ijazah Doktor Falsafah

PENGGUNAAN ABU BAHAN API KELAPA SAWIT ALKALI-DIAKTIFKAN BERTETULANG MIKROGENTIAN DALAM KAEDAH PENCAMPURAN DALAM

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Pembinaan struktur berat pada tanah lembut di kawasan tropika adalah satu tugas mencabar yang tinggi. Jenis-jenis tanah ini umumnya mempunyai ciri-ciri kekuatan ricih tak bersalir rendah dan keupayaan galas yang lemah. Pencampuran dalam adalah salah satu daripada teknik pembaikan tanah bermanfaat yang boleh digunakan dengan jayanya untuk mengatasi masalah ini dengan meningkatkan ciri-ciri geoteknikal tanah dengan simen dan pengikat berperekat tradisionallain. Walaupun pengikat kimia boleh meningkatkan banyak ciri-ciri kejuruteraan tanah, mereka mempunyai beberapa kelemahan, terutamanya apabila dilihat dari perspektif alam sekitar. Motivasi utama bagi kajian ini adalah untuk mengenalpastiguna semula inovatif hasil sampingan tempatan sedia ada untuk menghapuskan pengikat tradisional dari projek pencampuran dalam. Dalam hal ini, penggunaan abu bahan api kelapa sawit (POFA) sebagai sisa pertanian terkenal patut diberi perhatian khusus. Kajian ini terdiri daripada empat peringkat utama.

Peringkat pertama ialah prestasi kajian awal untuk menilai keberkesanan POFA (secara individu dan dengan kombinasi simen) dalam mempengaruhi beberapa ciri-ciri asas geoteknikal tanah lembut. Kekuatan mampatan tak terkurung (UCS) telah digunakan sebagai penunjuk praktikal untuk mengenalpastiperkembangan kekuatan. Selain itu, analisis mikrostruktur telah dijalankan untuk mendapatkan tafsiran mekanisme penstabilan. Menurut hasil ujian, penggabungan POFA dengan hasil simen menyebabkan peningkatan mendadak dalam UCS sampel dalam masa 28 hari pengawetan, manakala pada tempoh pengawetan yang sama, perkembangan kekuatan tanah terstabil POFA adalah tidak baik.

Pada peringkat kedua kajian ini, pengaktifan alkali POFA diterima pakai sebagai teknik boleh jaya untuk menghapuskan sepenuhnya simen dan pengikat berperekat lain dari aplikasi geoteknikal. Dalam erti kata yang mudah, pengikat alkali-diaktifkan umumnya adalah aluminosilikat alkali sintetik yang dihasilkan daripada tindak balas aluminosilikat pepejal (sumber pengikat) denganlarutan alkali akueus pekat yang

direka bentuk awal. Berdasarkan nilai UCS diperolehi pada tempoh pengawetan sehingga 6 bulan, menggunakan POFA alkali-diaktifkan meningkatkan kekuatan puncak tanah sehingga 70 kali berbanding dengan tanah semula jadi. Selain perkembangan kekuatan ricih, untuk meningkatkan kekuatan tegangan dan kemuluran tanah dirawat, kesan gabungan rangkuman gentian dan pengaktifan alkali digambarkan dan dilaporkan di peringkat ketiga kajian. Selain ujian UCS, kekuatan tegangan tidak langsung dan ujian kekuatan lenturan telah dijalankan pada tempoh pengawetan sehingga 6 bulan. Keputusan ujian menunjukkan bahawa rangkuman gentian tetulang dalamPOFA alkali-diaktifkan, menyebabkan peningkatan lanjut dalam tekanan puncak dan kekuatan tegangan, mengurangkan kehilangan kekuatan selepas puncak.

Pada peringkat terakhir kajian ini, satu prosedur reka bentuk geoteknikal interaksi antara jalur landasan dan tanah terstabil dimodelkan dalam makmal menggunakan teknik lajur. Bahagian ini mengambil kira ciri-ciri geoteknikal daripada tiang-tiang tanah terstabil dan mensimulasikan agak baik kesan ganding POFA alkali-diaktifkan dan rangkuman pengukuhan tetulang (ARS) dalam projek-projek pencampuran dalam. Hasil ujian menunjukkan sumbangan ketara ARS matriks tanah, yang membawa kepada peningkatan ketara dalam keupayaan galas ruangan tanah yang dirawat.

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LIST OF ABBREVIATIONS

POFA	Palm oil fuel ash
DMCs	Deep mixing columns
C-S-H	Calcium silicate hydrate
C-A-H	Calcium aluminium hydrate
APR	Alkali-activated POFA reinforced with microfibres
A-S-H	Aluminium silicate hydrate
α	Replacement area ratio
UCS	Unconfined compression strength
CH	High-plasticity clay
LOI	Loss on ignition
MDD	Maximum dry density
OMC	Optimum moisture content
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
XRD	X-ray diffraction
XRF	X-ray florescence
SEM	scanning electron microscopy
S	Natural soil
NS	NOH-Soil
CS5	5% Cement + Soil
CS10	10% Cement + Soil
CS15	15% Cement + Soil
SP5	Soil + 5% POFA
SP10	Soil + 10% POFA
SP15	Soil+ 15% POFA
CSP	Cement +Soil + POFA
CS10	10% Cement-soil
CS15	15% Cement-Soil
KSP	Soil-KOH- POFA
NSP	Soil-NaOH-POFA
SR5	Soil + 5% microfibre
SR10	Soil + 10% microfibre
SR15	Soil + 15% microfibre
NSPR5	NaOH-Soil-20% POFA-5% microfibre
KSPR5	KOH-Soil-20% POFA-5% microfibre
NSPR10	NaOH-Soil-20% POFA-10% microfibre
KSPR10	KOH-Soil-20% POFA-10% microfibre
NSPR15	NaOH-Soil-20% POFA-15% microfibre
KSPR15	KOH-Soil-20% POFA-15% microfibre
ITS	Indirect tensile strength
N	Number of columns
C_{uc}	Undrained shear strength of stabilized column
C_{us}	Undrained shear strength of soil
λ	Dimensionless coefficient

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The utilization of soft and weak soils in tropical areas is currently low, although their construction has become increasingly necessary for economic reasons. These types of soils are generally characterized by low undrained shear strength (less than 25 kPa), extremely high compressibility, and poor bearing capacity (Bergado, Anderson, Miura, and Balasubramaniam 1996; Tingle and Santoni 2003). In such conditions, these soft soils pose obvious problems in the construction industry because of their low bearing capacity even when subjected to a moderate load, leading to liquefaction and/or significant strain softening (Kitazume and Terashi 2013).

Of the soil stabilising techniques, deep mixing columns (DMCs) is becoming well established in an increasing number of countries because it is a cost-effective approach with numerous technical and environmental advantages (Saitoh, Suzuki, and Shirai 1985; Fang, Chung, Yu, and Chen 2001). In DMCs, the chemical agents, which are either slurry (wet mixing) or powder (dry mixing), are mixed into the soft soil to form columns of soil binders. Due to their robustness, easy adoptability, and economic value, cement and lime are employed as stabilizing agents in DMCs to produce stronger and firmer soil, namely soil–cement/lime columns (Kawasaki and Suzuki 1981; Saitoh 1988; Prusinski and Bhattacharja 1999). Although these traditional binders (i.e., cement and lime) can improve many engineering properties of treated soil columns, they have several shortcomings, especially when viewed from an environmental perspective. Recent soil stabilization methods have highlighted the need for full or partial replacement of cement and lime with cleaner and more sustainable materials. These stabilizers should provide strength and durability performances that are either comparable to or better than those of cement and lime within a similar curing duration.

In this respect, alkali-activated binder can constitute an interesting option to fully eliminate traditional the usage of cemenititous binders in geotechnical projects, since calcium is not essential in any part of an alkali-activated structure (Davidovits 1991, 2005). Alkaline activation has a history starting from the 1940's which were first demonstrated by Purdon (1940) and the application as a binder in the construction industry started in Ukraine since the 1960s (Glukhovsky 1965). The theoretical basis of the alkaline activation system was established for the first time in 1979 by the French researcher Davidovits (1979), who introduced the term “geopolymer” to designate a new class of three-dimensional crosslinked chain.

Alkaline activation technique is a term covering synthetic aluminosilicate materials, which are formed by the reaction of any Si–Al raw material (with less or no CaO component) and an alkali solution. This process can be described as a polycondensation (a reaction that chemically integrates minerals), consisting of aluminum and silica alternately tetrahedrally interlinked by sharing all the oxygen atoms. The process starts when the high hydroxyl concentration of the alkaline medium favours the breaking of the covalent bonds Si–O–Si, Al–O–Al, and Al–O–Si from the vitreous phase of the source material, transforming the silica and alumina ions in colloids and releasing them into the solution. Under this condition, alumino-silicates are transformed into extremely reactive materials to form a well-structured aluminum silicate hydrate (A-S-H) polymerized framework (Davidovits 1988; Davidovits 2005; Khale and Chaudhary 2007).

A large and growing body of literature has investigated the mechanism of the alkaline activation from wide variety of alumino-silicate source materials (Davidovits 1988; Xu and Van Deventer 2000; MacKenzie, Brew, Fletcher, Nicholson, Vagana, and Schmücker 2006; Khale and Chaudhary 2007). A significant body of these studies validate the proposition that alkaline activation provides a promising and sustainable alternative to the use of cement and lime because of (i) the abundant raw material sources and (ii) its lower energy consumption and CO_2 emission. However, relatively little progress has been made towards the utilization of this technique as a viable technology for soil stabilization projects.

In very limited attempts, some geotechnical researchers have investigated the effectiveness of alkali-activated low-calcium and high-calcium fly ash as silica and alumina amorphous sources for soil stabilization (Cristelo, Glendinning, and Pinto 2011; Cristelo, Glendinning, Fernandes, and Pinto 2012a, 2013). Also, Zhang *et al*. (2013) investigated the feasibility of using metakaolin as an alkali-activated soil stabilizer at shallow depth. Their results suggested that the alkali-activated binder is a successful method of deep soil stabilization.

Despite such positive developments, several issues such as the curing condition, the type of alkaline solute, and the role of parent soil (i.e., natural water content, presence of Si and Al in soil and pH) in alkaline activation are not well recognized. Apart from that, to derive the economic benefits of this promising method for the purpose of soil treatment, there is a high need to explore the locally available materials, especially the materials that contribute to the volume of waste. Framed by this context, among the possibilities of utilizing various by-products and natural prime materials in the process of alkaline activation, the use of palm oil fuel ash (POFA) deserves a special attention.

Other than the POFA which was used as a source binder, in order to establish viable solution that provides satisfactory mechanical properties such as tensile strength and ductility in stabilized soil columns, study of a newly proposed mixture of reinforcement inclusion and alkali-activated POFA also described and reported in this research. A special focus is to select an appropriate reinforcement inclusion which is not only suitable in alkaline environments but also provides satisfactory mechanical properties in stabilized soil. As such, amongst various reinforcement inclusions, wollastonite microfibres with chemical composition of $CaSiO_3$ (40.0- 50.0% of CaO, and 40.0 - 55.0% of SiO_2) deserve special attention. These mineral microfibres have been formed in nature from the interaction of silica (SiO_2) with calcite ($CaCO_3$) under high pressure and temperature. It is reasonable to anticipate that utilizing wollastonite microfibres in conjunction with alkali-activated POFA can act as a bridge to lock the particles firmly, to fill voids and pores, resulting in positive effect on the mechanical properties of treated soil.

1.2 Problem Statement

Although traditional calcium-based binders (i.e., cement and lime) can improve many engineering properties of soils, they have several shortcomings, especially when viewed from an environmental perspective. In the case of cement, this traditional binder generates around 7% of artificial CO_2 emissions, because of carbonate decomposition (Gartner 2004; Matthews, Gillett, Stott, and Zickfeld 2009). It is estimated that every ton of cement produces around one ton of CO_2, a major greenhouse gas implicated in global warming (Kim and Worrell 2002; Taylor, Tam, and Gielen 2006; Lothenbach, Scrivener, and Hooton 2011). Beside the emission of CO_2, another by-product of cement production is NO_x. Most of these nitrogen oxides are produced in cement kilns, which can contribute to the greenhouse effect and acid rain (Hendriks, Worrell, De Jager, Blok, and Riemer 1998).

Beyond these problems, the use of cementitious binders in soil stabilization shows poor tensile and flexural strength and a brittle behaviour (Sukontasukkul and Jamsawang 2012; Correia, Oliveira, and Custódio 2015). For instance, when the cemented soil column is subjected to seismic loads, either lateral earth pressures (as for deep-mixed soil walls) or horizontal displacements (as in the case of columns installed under the sides of embankments and in slopes), the stabilized soil tends to fail under tension, due to its brittleness (Sukontasukkul and Jamsawang 2012; Correia *et al.* 2015).

POFA is one of the most abundantly produced waste materials in Malaysia which has a strong potential to be used in this technique due to its high siliceous content. It should be mentioned that oil constitutes only 10% of the palm production, while the rest of 90% is the biomass (Ahmad et al., 2008). Despite efforts that have gone into finding reuse applications, considerable amounts of POFA continue to require disposal through landfilling every year and Malaysian government needs to allocate additional hectares of landfill for disposal and spends a ton of money for transporting this waste and maintenance functions. However, by recycling this agro-waste, it can reduce the dumped waste in addition to make sure environmental sustainability.

1.3 Objectives of the Study

The main objective of this study is to develop alkali-activated palm fuel ash reinforced with fibre (APR) for the soft soil stabilization. This study not only focuses on the strength and mechanical performance of stabilized soil but also to understand the underlying mechanisms of stabilization. The specific objectives of the study are:

1. To investigate the effect of POFA (individually and in combination with cement) on the geotechnical behaviour of soft soil in order to evaluate the effectiveness of this new soil stabilizer.

2. To investigate the effect of alkali-activated POFA on the strength and underlying mechanisms of stabilized soft soil.

3. To evaluate the effect of incorporating reinforcement inclusion with alkali-activated POFA on the mechanical performance and underlying mechanisms of stabilized soft soil.

4. To determine bearing capacity and settlement for a model of APR-stabilized soft soil with group of columns to simulate a foundation.

1.4 Organization of This Dissertation

In addition to the introduction, this thesis is composed of five more chapters. In Chapter 2, in the first stage, different soil stabilization materials including traditional cementitious materials (i.e., cement and lime), pozzolanic materials (supplementary traditional binders), alkali-activated materials (new generation of binders), and reinforcement materials are introduced and reviewed. The second stage of this research chapter describes the fundamental of deep mixing as one of the promising methods of soil stabilization. Chapter 3 presents the effect of POFA (individually and in combination with cement) on some geotechnical behaviour of parent soil to provide a framework for evaluation of this new soil stabilizer for soft soil stabilization. Moreover, this chapter of study describes the alkaline activation technique for the purpose of soil stabilization. In this respect, the role of various factors on the strength and underlying mechanisms of stabilized soil using alkali-activated POFA is investigated. Chapter 4 summarizes the effect of alkali-activated POFA reinforced by wollastonite microfibres (APR) on mechanical performance and underlying mechanisms of stabilized soft soil. Chapter 5 provides further insight about the behaviour of APR-treated soft soil when used as a foundation for a relatively lightweight structure. In this respect, the bearing capacity and settlement of a model APR-stabilized soft soil ground is determined by a group of columns. Chapter 6 presents the conclusions and recommendations of this research.

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