UNIVERSITI PUTRA MALAYSIA

STABILIZATION OF RESIDUAL SOIL WITH ALKALI-ACTIVATED FLY ASH AND INCLUSION OF TREATED COIR FIBRE

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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STABILIZATION OF RESIDUAL SOIL WITH ALKALI-ACTIVATED FLY ASH AND INCLUSION OF TREATED COIR FIBRE

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May 2019

Chairman : Professor Bujang Kim Huat, PhD
Faculty : Engineering

Residual soils have not been always conducive to construction road and other structures. Alkaline activation (AA) is one of the beneficial soil improvement techniques used to improve the geotechnical characteristics of soils with a new generation of cementitious binders. However, soil stabilized with alkali-activated binders will cause to post-peak brittleness. Therefore, coir fibres were incorporated in the stabilized soil as a source of discrete reinforcement to improve the mechanical properties of the soil. The mechanical performance of the reinforced soils depends on the nature of the soil and fibre as well the interaction between the fibre and the alkaline activation stabilized soil.

The present work focuses on investigating the use of a locally available by-product (fly ash) as precursor in alkaline activation reactions as well as treated coir fibres as discrete reinforcement. Surface treatment was applied through an agent including linseed oil and turpentine oil in order to improve its durability in alkaline environment as well as tensile strength and to minimize the biodegradable nature of fibre in soil. Moreover, to confirm the alteration of morphology in the fibres and understand the underlying mechanisms of treated fibres, field emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDX) tests were performed. Furthermore, the mechanical properties of soil matrix were assessed. A series of laboratory tests including compaction, unconfined compressive strength tests (UCS), indirect tensile strength tests (ITS), flexural strength tests (FS), direct shear tests (DS) and California bearing ratio tests (CBR) were carried out on original soil, alkali activated stabilized soil, alkali activated stabilized soil reinforced with untreated and treated fibres. The contents were varied from 40% to 70% of dried soil by weight for fly ash and 1% of dried soil by weight for treated coir fibres. The specimens were cured in for 7 and 28 days.

The results revealed that the linseed oil treated fibres increased the tensile strength up to 183% compared with untreated fibres. The fibres treated with linseed oil showed higher mechanical performance compared with the fibres treated by turpentine oil. The

FESEM/EDX results showed that cellulosic pores of the fibres contain Al and Si which form network like bonds, tightly wrapped around the fibres. The compressive strength, indirect tensile strength and flexural strength of the treated soil increased by 37, 7 and 93%, respectively, when linseed oil treated fibres were used compared with those of alkali activated stabilized soil with untreated fibres. Moreover, the addition of linseed oil-treated fibres increased the shear strength parameters and California bearing ratio of soil. According to the microstructural analysis, the interaction between the fibre surface and the geo-polymeric matrix is the main factor contributing to enhanced behaviour of the reinforced mixtures. This research is important that it confirms that the surface treatment can-not only increase the mechanical performance of coir fibres but also improves the interfacial mechanical interactions between the fibre surface and soil particles, resulting in a higher performance of the composites used as the road subgrade.

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STABILISASI TANAH BAKI DENGAN ABU TERBANG TERAKTIF ALKALI DAN SABUT KELAPA TERUBAHSUAI

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Tanah baki tidak sentiasa kondusif untuk pembinaan oleh para jurutera awam semasa reka bentuk jalan dan pembinaan struktur. Pengaktifan alkali adalah salah satu teknik pembaikan tanah yang bermanfaat untuk meningkatkan ciri-ciri geoteknikal tanah melalui penggunaan pengikat bersimen generasi baru. Walau bagaimanapun, tanah yang stabil dengan pengikat teraktif alkali akan menyebabkan kerapuhan pasca puncak. Oleh itu, sabut kelapa telah dimasukkan ke dalam tanah yang stabil sebagai sumber tetulang diskret untuk memperbaiki sifat-sifat mekanik tanah. Prestasi mekanik tanah bertulang bergantung pada sifat tanah dan gentian serta interaksi antara serat dan tanah distabil oleh pengaktifan alkali.

Kajian ini memberi tumpuan kepada penyiasatan penggunaan produk sampingan (abu terbang) tempatan sebagai prekursor dalam tindak balas pengaktifan alkali dan sabut kelapa yang diperlakukan sebagai tetulang diskret. Rawatan permukaan sabut kelapa diaplikasikan melalui agen termasuk minyak biji rami dan minyak turpentin untuk meningkatkan ketahanannya dalam persekitaran alkali serta kekuatan tegangan dan untuk meminimumkan sifat gentian yang boleh degradasi dalam tanah. Selain itu, untuk mengesahkan perubahan morfologi dalam gentian dan memahami mekanisme asas sabut kelapa yang telah dirawat, ujian mikroskop elektron pengimbasan pelepasan medan (FESEM) dan pemeriksaan spekroskopi sinar-X (EDX) telah dijalankan. Tambahan pula, sifat-sifat mekanikal komposit juga dikaji. Ujian makmal yang bersifat pemadatan, ujian kekuatan mampatan tidak terkurung (UCS), ujian kekuatan tegangan tidak langsung (ITS), ujian kekuatan lenturan (FS), ujian ricih langsung (DS) dan ujian nisbah galas California (CBR) telah dijalankan ke atas tanah, tanah yang distabil dengan pengaktifan alkali, tanah yang distabil dengan pengaktifan alkali yang diperkukuhkan lagi dengan serat yang tidak dirawat dan dirawat. Kandungannya berbeza-beza dari 40% hingga 70% tanah kering mengikut berat untuk abu terbang dan 1% berat tanah kering untuk serat coir yang dirawat. Spesimen telah sembuh selama 7 dan 28 hari.

Keputusan menunjukkan bahawa sabut kelapa dirawat dengan minyak biji rami telah meningkatkan kekuatan tegangan sehingga 183% berbanding dengan serat yang tidak dirawat. Serat yang dirawat dengan minyak biji rami menunjukkan prestasi mekanikal yang lebih tinggi berbanding dengan serat yang dirawat oleh minyak turpentin. Keputusan FESEM / EDX menunjukkan bahawa liang berselulos serat coir dipenuhi dengan Al dan Si yang membentuk rangkaian seperti bon, dengan ketat bersama serat. Kekuatan mampatan, kekuatan tegangan tidak langsung dan kekuatan lentur atas tanah yang dirawat meningkat sebanyak 37, 7 dan 93% apabila diperkukuhkan dengan serat dirawat dengan minyak biji rami berbanding dengan serat yang tidak dirawat. Selain itu, penambahan serat yang dirawat menggunakan minyak biji rami meningkatkan parameter kekuatan ricih dan nisbah bearing california tanah. Menurut analisis mikrostruktur, interaksi antara permukaan serat dan matriks geo-polimer adalah faktor utama yang menyumbang kepada kelakuan yang dipertingkatkan dari campuran bertetulang. Penyelidikan ini adalah penting kerana ia mengesahkan bahawa rawatan permukaan bukan sahaja boleh meningkatkan prestasi mekanikal sabut kelapa tetapi juga meningkatkan interaksi mekanikal interfacial antara permukaan serabut dan zarah tanah, menyebabkan prestasi yang lebih tinggi bagi komposit yang digunakan sebagai sokongan subgrade jalan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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a	Width of the flattened portion
Al	Aluminium
Al_2O_3	Aluminium oxide/ Aluminous
A-S-H	Aluminium silicate hydrate
ASTM	American Society for Testing and Materials
BS	British standard
c	Cohesion
Ca	Calcium
CaO	Calcium oxide/ lime
$Ca(OH)_2$	Calcium hydroxide
C-A-H	Calcium aluminium hydrate
C-A-S-H	Calcium aluminosilicate hydrate
CBR	California bearing ratio
CE	Compactive energy
CO_2	Carbon dioxide
C-S-H	Calcium silicate hydrate
d	Diameter of sample
DS	Direct shear
EDX	Energy dispersive X-ray spectroscopy
E_s	Modulus of elasticity
F	Maximum load applied
FA	Fly ash
Fe	Iron
Fe_2O_3	Ferric oxide
FESEM	Field emission scanning electron microscopy
FS	Flexural strength
FTIR	Fourier transform infrared spectroscopy
g(x)	Flattening coefficient
G_s	Specific gravity
I_B	Brittleness index
I_D	Deformability index
ITS	Indirect tensile strength
k	Ratio of the sample length to diameter
K	Potassium
KOH	Potassium hydroxide
l	Length of sample
LL/ w_L	Liquid limit
LOI	Loss of ignition
MDD/ γ_{dmax}	Maximum dry density
Na	Sodium
NaOH	Sodium hydroxide
N-A-S-H	Sodium aluminosilicate hydrate
NO_x	Nitrogen oxide
$nSiO_2K_2O$	Potassium silicate
$nSiO_2Na_2O$	Sodium silicate
OMC/ w_{opt}	Optimum moisture content
PI/ I_p	Plasticity index

PL/ w_p	Plastic limit
q_p	Peak stress
q_r	Critical undrained shear strength
r	Radius of specimen
Si	Silicon
SiO_2	Silicon dioxide/ Siliceous
UCS	Unconfined compressive strength
USCS	Unified soil classification system
x	Flattening ratio
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
y	Distance between the flattened portion at failure
α	Shape parameter
ε_r	Failure strain
ε_{ct}	Axial strain at peak UCS
ε_{cu}	Axial strain at peak UCS in untreated soil
φ'	Angle of friction

CHAPTER 1

INTRODUCTION

1.1 Introduction

Residual soils commonly found under unsaturated conditions which are weathering products of rocks. Generally, they are widespread in all parts of the world especially in humid tropical regions, such as Malaysia, Ghana, Northern Brazil, Singapore, Nigeria, Philippine, Sri Lanka and the Southern India. Geotechnical properties of residual soil are influenced by the parent rock, climate and the degree of lateralization (Mahalinga-Iyer and Williams, 1991). They are widely used for the construction of roads, embankments, and dams, and to support foundations of buildings, bridges and load-bearing pavement. However, certain residual soils are not always conducive to road construction material, either due to excessive volume change with varying moisture content or loss of strength on wetting, or because of inadequate strength (Simmons & Blight, 1997). Nowadays, underperforming soils are critical issue in engineering projects related with foundation materials.

Over the last few years, developing alternative materials have been able to help to environmental and economic problems. Soil stabilization is a reliable and effective technique that is vital in geotechnical practice for embankment, bearing capacity of road pavement, slope stability and strengthening and solving problems of foundation capacities (Kumar et al., 2015; Cui et al., 2018). The chemical stabilization through addition of calcium-based binders (i.e., lime and cement) is a common method for improving the performance of soil in civil engineering applications especially for residual soils because of their cost-effectiveness, adaptability and robustness (Akpokodje, 1985; Prusinski and Bhattacharja, 1999; Miura et al., 2001; Khan et al., 2018). Nevertheless, these traditional binders can enhance numerous engineering properties of soils, but they have several defects, particularly when viewed from an environmental perspective. Recent soil stabilization techniques have emphasized the need of full or partial replacement of traditional binders with more sustainable and cleaner materials. These stabilizers should provide durability and strength performances that are either comparable to or better than those traditional binders within a similar curing duration.

In this respect, alkali-activated binder is introduced as good replacements for traditional binders due to its environmentally friendly characteristics as it allows the reutilization of industrial wastes (Davidovits, 2008; Cristelo et al., 2015; Rios et al., 2018). Alkaline activation resulting from the dissolution of mineral aluminosilicates, followed by the formation of a three-dimensional amorphous aluminosilicate gel from hydrolysis and condensation of the aluminium (Al) and silica (Si) components (Weng and Sagoe-Crentsil, 2007; Yunsheng et al., 2008). The constitutive water is gradually consumed throughout the development of reactions, forming a well-structured aluminium silicate hydrate (A-S-H) framework (Davidovits, 1991; Duxson et al., 2007). Majority of the industrial wastes are used as precursors in alkaline activation because they are rich in silica (SiO2) and alumina (Al2O3) in an amorphous state. Several researchers have addressed the performance of alkaline activated binders for soil stabilization, based mainly on ground granulated blast-furnace slag (GGBS) (Singhi et al., 2016; Thomas et al., 2018) and palm oil fuel ash (Pourakbar et al., 2015; Pourakbar and Huat, 2017) as precursor for alkaline activation. Among the possibilities of using various kind of natural prime materials and by-products during the alkaline activation process, utilize class F fly ash (FA) deserves a particular attention.

Other than the fly ash 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, study of a newly proposed mixture of reinforcement inclusion alkali-activated fly ash 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. Recently, there has been a growing environmental consciousness and understanding of the need for sustainable development that has raised interests in utilizing natural fibres as reinforcement material in soil. As such, amongst various reinforcement inclusions such as palm, coir, sisal and roots, coir fibres deserve special attention (Prabakar and Sridhar, 2002; Babu and Vasudevan, 2007; Sivakumar Babu et al., 2008; Subaida et al., 2008; Mwasha, 2009; Vinod et al., 2009; Ramesh et al., 2010; Bateni et al., 2011). Coir fibres have the highest tensile strength among all natural fibres, and this property is retained even in wet conditions (Eze-Uzomaka, 1991; Ghavami et al., 1999; Sen and Reddy, 2011).

Nevertheless, few efforts have been made to enhance the durability of coir fibres in alkaline environments as well as interaction between coir fibres and soil by modification of the fibres surface. As such, amongst various modification techniques, physical coatings method deserves special attention. In this method, the fibre's surface is modified by physical means, mostly using synthetic polymers or resins. The life of natural fibres can be enhanced by coating with water-repellent substances. This method is a suitable technique for natural fibre treatment, as it will physically prevents the entry of moisture into fibre making it more durable in the alkaline environment while increasing the mechanical strength of the fibre (Lee and Amaylia, 2015; Bordoloi et al., 2017; Sumi et al., 2018). Therefore, this method is suitable for civil engineering applications, since the treatment can be produced in bulk, is simple to treat, and is cost-effective. Ramesh et al. (2011) reported that kerosene treated coir fibres increased compression strength by 55% compared to untreated coir fibre in soil. Linseed oil and turpentine oil are introduced as an agent for fibre's surface treatment to improve its durability in alkaline condition as well as tensile strength. Besides, these treatments utilized also to minimize the moisture absorption capacity and biodegradable nature of fibre in soil (Manikanta, 2015). However, no studies addressed the enhancement of coir fibre properties using treatment as discussed above and reinforced in alkali activation (AA) stabilized soil. In this study, it is reasonable to anticipate that utilizing treated coir fibres in conjunction with alkali-activated fly ash can act as a bridge to lock the particles firmly, to fill voids and pores, resulting in positive effect on the mechanical properties and subgrade performance for pavement of treated soil.

1.2 Problem Statement

Residuals soils are widespread in many tropical regions, including Malaysia, which make them economically attractive for use as materials for construction. Nevertheless, certain modifications to their properties are often necessary in order to meet the design criteria. For instance, if the residual soil is used as a subgrade for road construction, the strength of the soil should be sufficiently high and avoid excessive volume change with varying moisture content.

Although traditional calcium-based binders (i.e., cement and lime) can enhances many engineering properties of soils, but they have several defects when viewed from their cost and environmental prospective. Cement generates about 7% of artificial carbon dioxide (CO_2) emissions from decomposition of carbonate (Gartner, 2004; Matthews et al., 2009; Miller et al., 2018). Each ton of cement is predicted to produces about one ton of carbon dioxide released as a major greenhouse gas implicated in global warming (Kim and Worrell, 2002; Worrell et al., 2001; Lothenbach et al., 2011). Apart from CO2 emissions, another by-product of the cement production namely nitrogen oxides (NOx) is produced. The majority of NOx is produced in cement kilns that can cause to the acid rain and greenhouse effects (Hendriks et al., 1998).

Alkaline activation process can be a good technique to strengthen the soil. However, several issues are not well recognized, such as the alkaline agent, curing conditions and efficacy of high percentage of fly ash. Besides these problems, the use of cementitious binders in soil stabilization shows poor flexural and tensile strength and a brittle behaviour (Pourakbar et al., 2015; Correia et al., 2015). Utilization of treated residual soil for geotechnical structures, care should be taken to ensure that treated soil retains its ductile behavior after failure. The idea of reinforcing the soil with tensile resisting elements such as synthetic and natural fibres has been widely used in engineering practice. Despite coir fibres has much advantages such as high tensile strength, good durability and environmentally friendly material, it has certain drawbacks (i.e., poor interfacial bonding and biodegradation when exposed to the alkaline environment). Various techniques have been developed to modify the natural fibres such as chemical, physical, biological and nanotechnology. New method of fibre treatment through linseed oil and turpentine oil are used in this study. So far, no study addressed the enhancement of tensile strength of coir fibres as well as its interaction with alkaline activation stabilized soils.

1.3 Research Objectives

This study aims to investigate the mechanical properties of alkali-activated fly ash reinforced with treated coir fibre for soil stabilization. A practical approach was developed to modify fibres with linseed oil and turpentine oil. This study not only focuses on the strength and mechanical performance of stabilized soil but also to understand the underlying mechanisms of stabilization. The following objectives are identified for the successful completion of the aim of this research:

1. To investigate the effect of fly ash (individually and alkali-activated) on the compressive strength and underlying mechanisms of stabilized soil.

2. To determine the morphological and mechanical characteristics of treated coir fibres in alkaline environment.

3. To evaluate the effect of incorporating treated coir fibres with alkali-activated fly ash on the mechanical performance and underlying mechanisms of stabilized soil.

1.4 Scope and Limitation of The Study

The scope of the study can be presented in a form of three phases and these phases are:

i. Phase one, to increase the compressive strength of residual soils, the soil stabilization method is applied by using alkali-activated binders. Unconfined compressive strength (UCS), Field emission scanning electron microscopy (FESEM) and Energy-dispersive X-ray spectroscopy (EDX) tests were performed on original soil, fly ash treated soil and alkaline activation stabilized soil.

ii. Phase two, in order to enhances the longevity of fibres in an alkaline environment and mechanical performance of the soil-fibre composite, physical treatment is applied. To improves the structures of the fibres, physical treatment of fibre using different agents such as turpentine oil and linseed oil were carried out. To confirm the alteration of morphology in the fibres and understand the underlying mechanisms of physically treated coir fibres, tensile strength, Field emission scanning electron microscopy (FESEM) and Energy-dispersive X-ray spectroscopy (EDX) and X-Ray diffraction (XRD) tests were performed.

iii. Phase three, to identified the applicability of the inclusion of treated coir fibre in alkali-activated fly ash stabilized soil, the mechanical properties of the composites was assessed. Unconfined compressive strength (UCS), indirect tensile strength (ITS), flexural strength (FS), direct shear (DS), California bearing ratio (CBR), Field emission scanning electron microscopy (FESEM), Energy-dispersive X-ray spectroscopy (EDX) tests and Fourier transform infrared spectroscopy (FTIR) tests were carried out on original soil, alkali activation stabilized soil, alkali activation stabilized soil reinforced with untreated and treated fibre. Microstructural tests were performed to observe the interaction between soil and fibres.

The followings are limitations of the present study:

i. Residual soil samples are obtained from University Putra Malaysia campus area in Selangor, Malaysia.

ii. The range of 40%-70% fly ash of dry weight of soil is used as precursor.

iii. The alkaline activator used is potassium hydroxide (KOH) with concentration of 10 molar.

iv. 1% coir fibre of dry weight of soil is used as reinforced material.

1.5 Organization of This Dissertation

This thesis explores the possibility of using sustainable materials in the form of fly ash as a precursor in alkali activation reactions, as well as treated coir fibres as discrete reinforcement. This thesis was organized into 5 chapters.

Chapter 1 gives a general introduction to this research work, problem statement, scope and limitation of the study, objectives to be achieve and outline of the thesis.

Chapter 2 contains a general literature review on problem and characteristics of residual soil was used in the study. Besides, previous studies on different soil stabilizing materials including traditional cementitious materials (i.e., lime and cement), pozzolanic materials (supplementary traditional binders), alkali-activated materials (new generation binders), and reinforcement materials (natural and synthetics fibres), and natural fibre treatment method are reviewed. The gaps are identified and the importance of embarking on the current research work has been justified.

Chapter 3 discusses the elaborate steps in achieving the set research objectives that is hypothesized. This chapter begins with a flow chart describing the general plan for the study, sampling location and continues with the required laboratory tests on some of the most significant physical, chemical and mechanical properties of natural residual soil, continue with coir fibre treatment, identification of the performance of alkali-activated fly ash and untreated coir fibre and treated coir fibre reinforced soil by performing mechanical tests and microstructural tests.

Chapter 4 presents all obtained results and discussions on the outcome of all findings, validations and testing. This chapter discussed the effect of fly ash (individually and alkali-activated) on some geotechnical behavior of parent soil to provide a framework for evaluation of this new soil stabilizer for soil stabilization. Moreover, the mechanical characterization, durability in alkaline environment and underlying mechanisms of untreated/treated single coir fibre as soil reinforcement has been investigated and explained. The effect of alkali-activated fly ash reinforced by treated coir fibres on mechanical performance and underlying mechanisms of stabilized soil are showed.

Chapter 5 the derive conclusion on the research work, discussion on the research contributions and recommend with some potential future researches' improvement.

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LIST OF PUBLICATIONS

Teing, T.T., Huat, B.B.K., Anggraini, V. and Shukla, S.K. (2019). Improving the engineering behaviour of residual soil with fly ash and treated natural fibres in alkaline condition. *International Journal of Geotechnical Engineering*, UK, DOI: 10.1080/19386362.2018.1564854.

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