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REINFORCEMENT EFFECTS OF NANO-MODIFIED COIR FIBRES ON LIME-TREATED MARINE CLAY

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By

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DEDICATED

Mum and Dad, ***Hj. Rasiha*** and ***Ir. H. Abdullah***

And

Beloved sons, ***Athar*** and ***Tariq***

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilmentof the requirement for the Degree of Doctor of Philosophy

REINFORCEMENT EFFECTS OF NANO-MODIFIED COIR FIBRES ON LIME-TREATED MARINE CLAY

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November 2015

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Faculty : Engineering

Marine clay soils under land-based structures develop shrinkage cracks due to the uneven distribution of moisture. Treatment of marine clay soils with lime is one of the widely used methods. However, the soils treated with lime will cause to brittle failure. Therefore, to improve the mechanical properties of treated soil, the lime treatment technique combined with inclusion of randomly distributed tensile reinforcement elements such as natural fibres (e.g., coir fibre) were used. However, the mechanical performance of the treated soil depends not only on the nature of the soil, moreover on the mechanical properties of the fibre as well the interaction between the fibre and the lime-treated soil.

This research was developed to further increase the performance of coir fibre in lime-treated soil as pile-supported earth platform. A nano impregnation method was applied through chemical treatment with different chemicals including $CaCl_2$, $MgCl_2$, $AlCl_3$ and $FeCl_3$ in order to impregnate fibres with nano-particles. To confirm the alteration of morphology in the fibres and understand the underlying mechanisms of chemically treated fibres, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) tests were performed. Furthermore, the mechanical properties of the composites were assessed. Unconfined compressive strength tests, indirect tensile strength tests, flexural strength tests, and triaxial compressive strength tests were carried out on original soil, lime-treated soil, and lime-treated soil reinforced with nano-treated and untreated fibre. Moreover, a durability test was conducted to scrutinize the change in the strength of the reinforced soil. Finally, the experimental results were used in a numerical analysis using commercially available software (ABAQUS CAE) to investigate the performance of the proposed treatment as pile supported earth platform. The physical model experiments were performed to validate numerical model.

The results revealed that the nano impregnation of fibres increased the tensile strength up to 200% compared with untreated fibres. The fibres modified with $Ca(OH)_2$ showed higher mechanical performance compared with the fibres modified by $Mg(OH)_2$, $Al(OH)_3$, and $Fe(OH)_3$. The SEM/EDX results showed that cellulosic pores of the fibres

were filled with Ca nano-sized crystals ranging from 25 to 150 nm. The mechanical performance of the treated soil increased when chemically treated fibres were used. The compressive strength, indirect tensile strength, and flexural strength of the treated soil increased by 66, 122, and 60% when $Ca(OH)_2$-treated fibres were used compared with those of limed soil reinforced with untreated fibres. Moreover, the addition of nano impregnated fibres using $Ca(OH)_2$ increased the shear strength parameters of marine clay soil with increases in the level of confining pressure and consequently led to a more ductile behaviour. The numerical analyses show the importance of the mechanical properties of the treated soils are effective in reducing the differential settlement up to 50% when the height of the earth platform used is 0.3 m. The research is important in that it confirms that the nano modification technique can not only increase the mechanical performance of the coir fibres but also improve the interfacial mechanical interactions between the fibre surface and soil particles, resulting in a higher performance of the composites used as a pile-supported earth platform.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai mementuhi keperluan untuk Ijazah Doktor Falsafah.

KESAN PENETULANGAN OLEH SABUT KELAPA TERUBAH SUAI NANO TERHADAP TANAH LIAT MARINE YANG TERAWAT KAPUR

Oleh

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Tanah liat marin di bawah struktur berasaskan tanah membangunkan retak pengecutan disebabkan oleh pengagihan kelembapan yang tidak sama rata. Rawatan tanah liat marin dengan kapur adalah salah satu kaedah yang digunakan secara meluas. Walaubagaimanapun, tanah yang dirawat dengan kapur akan menyebabkan kegagalan rapuh. Oleh itu, untuk menambahbaik prestasi mekanikal tanah dirawat, teknik rawatan kapur digabungkan dengan kemasukan secara rawak elemen tetulang tegangan seperti gentian semula jadi (contohnya, gentian sabut kelapa) di dalam tanah telah digunakan. Walaubagaimanapun, prestasi mekanikal tanah yang dirawat bukan sahaja bergantung kepada jenis tanah tetapi juga sifat-sifat mekanik gentian dan interaksi antara gentian dan tanah kapur yang dirawat itu.

Kajian ini telah dibangunkan untuk meningkatkan lagi prestasi sabut kelapa di dalam tanah yang telah dirawat dengan kapur sebagai sokongan cerucuk platform bumi. Satu kaedah pengisitepuan nano telah diaplikasikan melalui rawatan kimia dengan bahan kimia yang berbeza termasuk $CaCl_2$, $MgCl_2$, $AlCl_3$ dan $FeCl_3$ untuk mengisitepukan serat dengan zarah-zarah nano. Untuk mengesahkan perubahan morfologi dalam gentian dan memahami mekanisme asas sabut kelapa yang telah dirawat secara kimia, Ujian Mikroskop Imbasan Elektron (SEM) dan X-ray Serakan Tenaga Spektroskopi *(*EDX*)* telah dijalankan. Tambahan pula, sifat-sifat mekanikal komposit adalah dikaji. Ujian Mampatan Tak Terkurung, Ujian Kekuatan Tegangan Tak Langsung, Ujian Kekuatan Lenturan, Ujian Mampatan Tiga Paksi telah dijalankan ke atas tanah asli , tanah yang dirawat dengan kapur, dan tanah yang dirawat dengan kapur yang diperkukuhkan lagi dengan gentian yang dirawat dan tidak dirawat oleh nano . Selain itu , ujian ketahanan telah dijalankan untuk meneliti perubahan dalam kekuatan tanah yang bertetulang.Akhirnya, keputusan eksperimen telah digunakan di dalam analisis berangka dengan menggunakan perisian yang tersedia secara komersil (ABAQUS CAE) untuk menyiasat prestasi rawatan yang dicadangkan sebagai longgokan disokong platform bumi sebagai sokongan cerucuk platform bumi. Eksperimen model fizikal telah dijalankan untuk mengesahkan model berangka.

Keputusan menunjukkan bahawa pengisitepuan nano di dalam sabut kelapa telah meningkatkan kekuatan tegangan gentian sehingga 200% berbanding dengan gentian yang tidak dirawat. Gentian yang diubahsuai dengan $Ca(OH)_2$ menunjukkan prestasi mekanikal yang lebih tinggi berbanding dengan gentian diubahsuai oleh $Mg(OH)_2$, $Al(OH)_3$, dan $Fe(OH)_3$. Keputusan SEM / EDX menunjukkan bahawa liang berselulos sabut kelapa dipenuhi dengan Ca bersaiz nano kristal antara 25-150 nm. Prestasi dari sifat –sifat mekanik tanah tanah yang dirawat adalah meningkat apabila gentian yang dirawat secara kimia telah digunakan. Kekuatan mampatan , kekuatan tegangan tidak langsung , dan kekuatan lenturan tanah yang dirawat didapati meningkat sebanyak 66 , 122 , dan 60 % apabila gentian yang dirawat dengan $Ca(OH)_2$ digunakan berbanding dengan tanah yang dirawat oleh kapur diperkukuh dengan gentian yang tidak dirawat.

Selain itu, penambahan pengisitepuan nano di dalam gentian menggunakan Ca(OH)2 meningkatkan parameter kekuatan ricih tanah liat marin dengan peningkatan dalam tahap tekanan mengurung dan seterusnya menjadikan kepada tingkah laku yang lebih anjal. Analisis berangka menunjukkan kepentingan sifat-sifat mekanik tanah dirawat bagi keberkesanan dalam pengurangan penyelesaian pengkamiran platform bumi. Nilai keberkesanan untuk tanah yang dirawat dengan kapur serta diperkukuhkan dengan semua jenis pengisitepuan nano gentian sabut kelapa adalah sehingga 50% di bawah pelbagai beban struktur apabila ketinggian efektif platform bumi adalah 0.3 m. Penyelesaian pengkamiran pada ketinggian kepala cerucuk semakin berkurangan sehingga 100%.

Kajian ini adalah penting kerana ia mengesahkan bahawa teknik pengubahsuaian nano bukan sahaja boleh meningkatkan prestasi mekanik gentian tetapi juga meningkatkan interaksi mekanikal antara muka di antara permukaan gentian dengan zarah tanah, menyebabkan prestasi yang lebih tinggi bagi komposit yang digunakan sebagai sokongan cerucuk platform bumi.

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I certify that a Thesis Examination Committee has met on 5 November 2015 to conduct the final examination of Vivi Anggraini on her thesis entitled "Reinforcement Effects of Nano-Modified Coir Fibres on Lime-Treated Marine Clay" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

A	Area of cross-section of sample
Al	Aluminium
$Al(OH)_3$	Aluminium hydroxide
$AlCl_3$	Aluminium chloride
ASTM	American society for testing and material
BS	British Standard
C	Clay
c	Apparent cohesion
CEC	Cation exchange capacity
Ca	Calcium
$CaCl_2$	Calcium chloride
$Ca(OH)_2$	Calcium hydroxide
CU	Consolidated-undrained triaxial test
CD	Consolidated-drained triaxial test
D	Diameter of sample
D	Constrained modulus
D	Depth of soft ground
E	Young's modulus of elasticity
E	Efficacy
E'	Drained modulus
EDX	Energy dispersive X-ray spectrometer
F	Applied force
Fe	Iron
$FeCl_3$	Ferric chloride
$Fe(OH)_3$	Iron (III) hydroxide
G	Shear modulus
Gs	Spesific gravity
H	Height of sample
H_2O	Water
L	Length of sample
LL	Liquid limit
Mg	Magnesium
$MgCl_2$	Magnesium chloride
$Mg(OH)_2$	Magnesium hydroxide
NaOH	Sodium hydroxide
NaCl	Sodium Chloride
OH	Hydroxide
OC	Overconsolidated

OCR	Overconsolidated ratio
OMC	Optimum moisture content
P	Applied force
PL	Plastic limit
PI	Plasticity Index
Rc	Compressive strength
Rt	Tensile strength
Rb	Bending strength
SEM	Scanning Electron Microscopy
UU	Unconsolidated-Undrained triaxial test
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
E_s	Elastic modulus of soft ground
Es	Secant modulus
Et	Tangent modulus
ESP	Effective stress path
e	Voids ratio
n	Porosity
r	Radius of soil sample
R	Radius of circular arc of geosynthetic
u	Pore pressure
ε	Strain
v	Poisson's ratio
v_u	Poisson's ratio (undrained)
v'	Poisson's ratio (drained)
γ_d	Dry density
σ	Normal stress
σ'	Normal effective stress
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma'_1, \sigma'_2, \sigma'_3$	Principal effective stresses
σ_v, σ_h	Vertical and horizontal stresses
σ'_v, σ'_h	Vertical and horizontal effective stresses
σ_n	Stress normal to surface of failure
σ_1	Axial stress
σ_3, σ_c	Confining pressure
σ'_3, σ'_c	Effective confining pressure
$(\sigma_1 - \sigma_3)$	Deviator stress
$(\sigma_1 - \sigma_3)_f$	Deviator stress at failure
ϕ'	Angle of shear resistance based on effective stresses

σ_s	Vertical stress acting on top of soft ground midway between pile head
γ	Unit weight of earth platform
$\emptyset$	Angle of shearing resistance of earth platform
s	Center to center spacing of piles
s'	Clear spacing between piles, $s' = s - b$(m)
K_p	Rankine passive earth pressure coefficient $K_p = (1 + sin\emptyset_s)/(1 - sin\emptyset_s)$;
θ	Half angle subtended by geosynthetic circular arc (degree)
t	maximum displacement of soft ground midway between pile heads
T	Axial tension force in geosynthetic

CHAPTER 1

INTRODUCTION

1.1 Introduction

Marine clay soils under land based structures develop shrinkage cracks due to uneven moistures distribution. Consequently, they exhibit considerable variation of shear strength, compressibility and tensile strength which cause differential movement, severe damage in foundations, buildings, roads, embankments, retaining structures, canal lining and etc. (Sivakumar Babu et al., 2008; Ramesh et al., 2010). The problems associated with marine clay soils can be controlled by different techniques such as isolating the soil using geo-membranes or providing an adequate thickness of cohesive non-swelling soil specially given in large-scale projects (Miller, 1997). However, they are expensive in small scale projects such as construction of bunds of smaller height.

One possible solution to this problem is addition of lime in order to immobilize water in marine clay by its chemical reactions and reduce plasticity index of the clay. A reduction in plasticity is usually accompanied by reduction of potential for swelling. Rajasekaran and Rao (1997) reported that lime is commonly used to change properties of soils due to its more stable performance, lower prices, and abundance. Lime is most effective for treating soils capable of holding large amounts of water (Locat et al., 1990; Bell, 1996; Rajasekaran et al., 1997; Rajasekaran and Rao, 2002; Dash and Hussain, 2011). However, soils treated with lime are subjected to a brittle failure (Ninov and Donchev, 2008). Therefore, it is better to amend it with a technique of reinforcement (Ranjan et al., 1994; Ziegler et al., 1998; Yetimoglu and Salbas, 2003; Ninov and Donchev, 2008). So, a possible solution involves inclusion of randomly distributed tensile reinforcement elements in the marine clay. Adding fibres can effectively reduce the number and width of shrinkage cracks and help to obstruct them (Ziegler et al., 1998; Estabragh et al., 2012).

The effectiveness of fibres depends upon the strength of fibre as well as how they interact with soil at normal stresses through adhesion. When a tensile force needs to mobilize in the fibres, as in drying shrinkage and desiccation cracks, adhesion restrains the fibres from pull out and thus allows its tensile resistance to develop. The mechanical properties of fibres reinforced lime treated soil have been investigated by various authors. A number of triaxial tests, unconfined compression tests, california bearing ratio (CBR) tests, direct shear tests, tensile strength tests and flexural strength tests have been conducted on the subject by several researchers in the last few decades (Prabakar and Sridhar, 2002; Yetimoglu and Salbas, 2003; Yetimoglu et al., 2005; Cai et al., 2006b; Tang et al., 2007; Tang et al., 2010; Estabragh et al., 2012; Hejazi et al., 2012; Divya et al., 2013; Estabragh et al., 2013; Hamidi and Hooresfand, 2013). All the previous studies have shown that the addition of fibre-reinforcement caused significant improvement in the strength and increased the stiffness of the soil.

At the same time, there has been a growing environmental consciousness and understanding of the need for sustainable development in recent years, which has raised interests in using natural fibres as reinforcements in soil. The reinforcement of soils with natural fibres such as roots, sisal, coir and palm has recently received a great deal of attention (Ghavami et al., 1999; 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). Of all the natural fibres, coir fibres has the greatest tensile strength and it retains this property even in wet conditions (Eze-Uzomaka, 1991a; Ghavami et al., 1999; Sen and Reddy, 2011b). The reinforcing effectiveness of coir fibre is related to the nature of cellulose and its crystallinity. Generally, tensile strength and youngôs modulus of coir fibres increase with increasing cellulose content. Cellulose is a natural polymer consisting of D-anhydro-glucose ($C_6H_{11}O_5$) repeating units joined by β-1,4-glycosidic linkages at C1 and C4 position (Nevell and Zeronian, 1985). Each repeating unit contains three hydroxyl groups. These hydroxyl groups and their ability to hydrogen bond play a major role in directing the crystalline packing and also govern the physical properties of cellulose.

Recently, few efforts have been made to enhance the interaction between soil and the coir fibres by modification of the fibres surface. One of the applied methods is the alkali treatment. In this method, a strong sodium hydroxide were used to remove lignin, hemicellulose and other alkali soluble compounds from the surface of the fibres in order to increase the number of reactive hydroxyl groups on the fibre surface to enhance chemical bonding. The removal of these substances also enhanced the surface roughness which increased the unconfined compressive strength of clay soil by 5 to 10% (Dutta et al., 2012). In another study by Ramesh et al. (2011) kerosene, bitumen and varnish were used to coat the coir fibres in order to modify the surface of fibres. It was observed that kerosene increased compression strength by 55% compared to uncoated coir fibre in soil. So far, however, no studies addressed the enhancement of tensile strength in coir fibre to be used in soil.

Nanotechnology has been a recent approach to modify natural fibres by impregnation of nano particles into fibres to improve their mechanical properties as well as introducing a new function onto the surface of fibres. (Chattopadhyay and Patel, 2009; Castellanos et al., 2012; Chowdhury et al., 2013; Khandanlou et al., 2013; Ridzuan et al., 2013).

In this study, the application of using randomly distributed coir fibre as tensile reinforcement elements and lime in the marine clay soil is investigated to be used as pile supported load transfer base layer. Finite element analyses of pile supported load transfer platform are performed using the program ABAQUS CAE 6.11 to investigate the load-transfer mechanism in the piled earth platforms by considering two major factors of influence: the mechanical properties of the earth platform and its height. The differential settlement is used to acquire experimental data for numerical model validation.

1.2 Problem of statement

Marine clays soils are present in many parts of the world and these deposits characterized by poor engineering properties such as high compressibility and very low shear strength. This sediment is mainly deposited along coastal areas of Peninsular Malaysia.

The rapid growth of industrialisation requires and extensive construction of infrastructure in Malaysia. Especially to new projects, the maintenance and upgrading of facilities also provided significant input to the overall developments include the coastal regions where ports and highways are located.

Even though some systematic studies are available on compressibility characteristic and shear strength of marine clay, not much work has been done its tensile strength aspects. Stabilization using lime was successfully done to increase strength and stiffness of marine clay soil. However, this method did not solve brittle problem of treated marine clay. For the utilisation of treated marine clay for the geotechnical structures, care should be taken to ensure that treated soil retains its ductile behaviour after failure.

The idea of reinforcing soil with tensile resisting elements such as synthetic and natural fibre has been commonly recognized in engineering practice. Using coir fibre as soil reinforcement has much advantages due to high tensile strength, good durability, environmentally friendly material and its ability to absorb water. However, the performance of the matrix (lime, fibre and soil) depends not only on fibres strengths but also how they interact with soil. Various techniques have been developed to modify natural fibres such as biological, physical, thermoplastic and nanotechnology. So far, no study addressed the enhancement of tensile strength of the fibres as well as its interaction with soils.

1.3 Objectives of the thesis

This study aims to investigate the mechanical properties of lime treated marine soil reinforced with modified coir fibre as pile supported load transfer platform. A practical approach was developed to impregnate fibres with nano particles of calcium hydroxide, magnesium hydroxide, ferric hydroxide and aluminum hydroxide. The overarching purpose of this study was to increase the tensile strength of fibres and to enhance their interaction with marine clay soil. The following objectives are identified for the successful completion of the aim of this research:

1. To investigate the morphological and mechanical characteristics of nano treated coir fibres as soil reinforcement.
2. To determine the effect of the nano modification of coir fibre and its interaction with lime reinforced marine clay soil.

3. To evaluate the performance of using nano modified coir fibre in lime treated soil as pile supported load transfer platform.

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, in order to increase the strength as well as interactions of natural fibres and soil, green nano- impregnation method is applied. To improve the structures of the fibre, chemical treatment of fibre using different chemicals such as calcium chloride, magnesium chloride, aluminium chloride, and sodium hydroxide were carried out. To confirm the alteration of morphology in the fibres and understand the underlying mechanisms of chemically treated coir fibres, Scanning electron microscopy (SEM), X-Ray diffraction (XRD) and Energy-dispersive X-ray spectroscopy (EDX) tests were performed.
ii. Phase two, to identify the applicability of the proposed nano-fibre treatment, the mechanical properties of the composites was assessed. Unconfined compressive strength tests, indirect tensile strength tests, flexural strength tests, and triaxial compressive strength tests were carried out on pure soil, lime-treated soil, and lime-treated soil reinforced with nano-treated and untreated fibres. Microstructure tests were performed to observe the interaction between fibres and soil. Moreover, a durability test was conducted to scrutinize the change in the strength of the reinforced soil due to the excessive moisture content in the soil.
iii. Phase three, the experimental results from phase two were used in a numerical analysis using commercially available software (ABAQUS CAE). The physical model experiments were performed to validate numerical model of pile supported load transfer platform.

The followings are limitations of the present study:

i. Marine clay soil samples are collected from Klang, Peninsular Malaysia.
ii. 5% lime of dry weight of soil is used as additive.
iii. The differential settlement is used to acquire experimental data for numerical model validation.
iv. Two-dimensional numerical model is analysed to perform pile supported load transfer platform.
v. Parametric study is developed based on numerical analysis.

1.5 Thesis organisation

This thesis presents different aspects of the potential of coir fibres as reinforcement in lime treated soft marine clay soil as pile supported earth platform. This thesis was organized into 5 chapters.

Chapter 1 gives a general introduction to the subject, problem statement, scope and limitation of the study and in addition of the objectives and outline of the thesis.

In providing a relevant background for the work described in this thesis, Chapter 2 contains a general literature review on characteristics and problem of Klang marine clay was used in the study. Special attention is given to various methods that have been used in marine clays stabilization for many years with various degrees are described. The gaps are identified and the importance of embarking on the current research work has been justified. In addition, the benefit of soft soil reinforcement for structural application such as pile supported earth platform including computational modelling, design method and lab-scale model are elaborated.

Chapter 3 describes the methodology used to fulfill the designated objectives for the research for reinforcing of marine clay soil. 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 marine clay soil, continue with coir fibre treatment, identification of the performance of lime and untreated coir fibre and treated coir fibre reinforced soil by performing mechanical tests, durability and microstructural tests. Finally, the numerical and physical models of the proposed composites as pile supported load transfer platform are analyzed.

Chapter 4 presents the results of the testing programs described in chapter three. The mechanical characterisation of untreated/treated single coir fibre as soil reinforcement has been investigated. Mechanisms of nano modified coir fibre and their interaction with soil matrix are also explained. The highest reinforcement potential of nano particles modified coir fibre and lime is exploited for marine clay reinforcement (i.e strength and durability). Attention is also paid to the mode of failure of fibre surface modification mixed with marine clay soil subjected to tensile and flexural loading. Furthermore, the interaction between fibres and limed soils are showed. Finally, numerical modelling is discussed and analysed and experimentally validated to reliably model the behaviour of nano modified coir fibre reinforced marine soil as pile supported load transfer platform over soft soil.

Chapter 5 is devoted to conclusions drawn from this study along with highlights topics for future work.

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