STABILISATION OF MARINE CLAY USING POLYURETHANE

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

The recent need driven by global population growth to build more infrastructures is forcing authorities to build on any soil type available within their vicinity, including weak soils like marine clay (MC). However, due to its poor engineering properties, MC is not suitable for construction purposes. Given this fact, many ground improvement techniques are being employed to improve the properties of MC and to reduce the potential damages caused by it. Although researchers have done a lot to improve the properties of MC using different materials and methods, attention has not been given to the application of polyurethane (PU) to stabilise MC. Therefore, this research focusing on the application of PU for the stabilisation of MC. The MC was characterised by testing its index and engineering properties as well as the geochemistry and microstructure. Correspondingly, PU was characterised by testing its rheological and mechanical properties alongside the microstructural analyses. The effectiveness of PU as a stabiliser was evaluated using unconfined compression tests, consolidated undrained (CU) triaxial tests and one-dimensional consolidation tests to determine the strength and stiffness. Furthermore, x-ray diffraction (XRD) analysis, field emission scanning electron microscopy (FESEM) and energy dispersive spectroscopy (EDX) were used to discern the roots of improvement in the strength of the MC that was stabilised with PU. PU properties were also improved using reinforcing fillers. Additionally, the bearing capacity of the MC before and after treatment with PU piles was evaluated using physical and numerical models. Finally, the potential for ground contamination resulting from the application of PU to stabilise MC was investigated using toxicity characteristic leaching procedures (TCLP). The results obtained show that PU improved the shear strength and the stiffness parameters of the MC. Neutralising the acidity of MC with NaOH nearly doubled the strength and stiffness of the PU-stabilised MC. The UCS of MC that was treated with PU and NaOH improved significantly. Likewise, the secant stiffness for the CU triaxial test and tangent stiffness for the primary oedometer loading, show improvement compared to the untreated MC sample. Results of the microstructure analyses revealed that no new compounds were formed during the stabilisation of the MC with PU. The improvement in MC strength was due to the densification and coating of MC particles with PU foam. PU improved with SiO_2 have superior strength, stiffness and crystallinity compared to the normal PU due to the cross-linking properties of the of SiO_2 particles in the chain of PU. The results from the numerical model showed that the bearing capacity of MC that was stabilised with PU piles increases with increase in an improvement area ratio and with a length over height ratio compared to the untreated MC. The TCLP results revealed that the quantity of heavy metals present in PU is far below the regulatory limits. The results further confirmed that PU is odourless, non-corrosive and both non-cyanide and non-sulphide bearing. However, PU is capable of igniting. Overall, the potential application of PU for ground improvement is promising due to its environmental friendliness and high strength.

ABSTRAK

Ekoran dari pertumbuhan penduduk mendorong pihak berkuasa untuk membangunkan lebih banyak keperluan infrastruktur pada setiap jenis permukaan tanah di persekitarannya termasuklah perancangan pembangunan di atas tanah yang lemah seperti tanah liat marin(marine clay – MC). Namun begitu, sebarang pembinaan atas permukaan tanah liat marin (MC) adalah tidak sesuai disebabkan oleh sifat kejuruteraannyanya yang kurang baik. Oleh itu, banyak teknik penambahbaikkan tanah telah dilaksanakan untuk memperbaiki sifat kejuruteraan tanah liat marin. Walaupun penyelidik telah melakukan pelbagai cara untuk meningkatkan sifat tanah liat marin dengan menggunakan bahan dan kaedah yang berbeza, perhatian masih belum tertumpu kepada penggunaan poliuretana (PU) untuk menstabilkan tanah liat marin. Oleh itu, fokus kajian ini adalah bertujuan untuk mengstabilkan sifat tanah liat marin dengan menggunakan PU. Tanah liat dicirikan dengan menguji sifat indeks dan kejuruteraan berserta sifat geokimia dan struktur mikro tanah tersebut. Sejajar dengan itu, PU dicirikan dengan menguji sifat reologi dan mekanikalnya bersama dengan analisis mikrostruktur. Keberkesanan PU sebagai bahan penstabil telah dinilai melalui ujian mampatan tidak terkurung, ujian triaksi gabungan (CU), dan ujian pengukuhan satu dimensi. Selanjutnya, analisis penyerakkan sinar-X, ujian pengimbasan mikroskop electron dan penyebaran tenaga spesktroskopi telah diaplikasikan ke atas tanah yang telah dirawat oleh PU untuk mengetahui dengan lebih mendalam punca peningkatan kekuatan tanah liat marin selepas dirawat oleh PU. Selain itu, daya galas tanah marin sebelum dan selepas dirawat oleh PU turut dianalisa dan dinilai menggunakan model fizikal dan numerik. Akhir sekali, potensi pencemaran tanah akibat penggunaan PU dalam kajian ini disiasat melalui Prosedur Ujian Ketoksikan Larut Resap (toxicity characteristic leaching procedures - TCLP). Keputusan ujian menunjukkan PU membantu meningkatkan kekuatan ricih dan batasan kekakuan tanah liat marin. Manakala, dengan meneutralkan keasidan tanah laut marin menggunakan sodium klorida (NaOH) hampir menggandakan kekuatan dan kekakuan tanah liat marin yang telah dirawat oleh PU. Ujian kekuatan mampatan tidak terkurung (UCS) terhadap tanah marin yang dirawat dengan PU dan NaOH menunjukkan kekuatan dalam tempoh pengawetan yang berbeza iaitu selama sehari, tujuh hari dan sebulan. Kejelikitan efektif, (c') dan sudut geseran (ϕ') tanah liat marin juga bertambah baik untuk tanah liat marin yang tidak dirawat dan tanah liat marin yang distabilkan oleh PU dan NaOH. Hasil analisis mikrostruktur meunjukkan bahawa tidak ada sebatian baru yang terbentuk semasa penstabilan tanah liat marin dengan PU. Peningkatan kekuatan tanah liat marin disebabkan oleh pemadatan dan pelapisan zarah antara tanah liat marin dengan busa PU. PU yang diperbaiki dengan SiO_2 mempunyai kekuatan, kekakuan dan kekristalan yang tinggi berbanding dengan PU biasa kerana sifat silang-silang zarah SiO_2 dalam rantai PU. Hasil dari model berangka menunjukkan bahawa daya dukung MC yang distabilkan dengan cerucuk PU menggunakan nisbah luas kepada terawatt, meningkat, dengan nisbah panjang kepada tinggi dibandingkan dengan MC yang tidak dirawat. Hasil ujian TCLP pula menunjukkan bahawa kuantiti elemen logam berat yang terdapat dalam PU masih jauh dibawah had peraturan yang ditetapkan oleh pihak berkuasa. Ujian tersebut juga mengesahkan bahwa PU tidak berbau, tidak menghakis dan kedua-duanya boleh menggalas elemen bukan sianida dan elemen bukan sulfida. Walaubagaimanapun, PU bersifat mampu menyalakan bahan bakar. Keseluruhannya, potensi applikasi PU dalam menambah baik tanah terbukti dengan sifat yang mesra alam sekitar dan kekuatan tanah yang tinggi.

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LIST OF ABBREVIATIONS

AASHTO	-	American Association of State Highway Transportation Officials
APHA	-	American Public Health Association
ASTM	-	American Society for Testing and Materials
CAHs	-	Calcium aluminate hydrates
CD	-	Consolidated drain
CES	-	Calcined eggshells
CH	-	Clay of high plasticity
CNC	-	Cellulose bionano composite
CNF	-	Cellulose nano fabrils
CSH	-	Calcium Silicate hydrate
CSR	-	Cyclic stress ratio
CU	-	Consolidated undrain
DABCO	-	1, 4-diazabicyclo-2,2,2-octaane
DEG	-	Diethylene glycol
DEPG-SG	-	Diethylene / propylene glycol benzoate
DIDP	-	Disodecyl phthalate
DINP	-	Diisononyl phthalate
DMCHA	-	Dimethylcycloheyl amine
DMEM	-	Dimethylethanol amide
DMM	-	Deep mixing method
DMT	-	Dimethyl terephthalate
DPPG-SG	-	Propylene glycol benzoate
EDX	-	Energy dispersive spectroscopy
FESEM	-	Field emission scanning electron microscopy
GGBS	-	Granulated blast furnace slag
HGEE	-	2-hydoxyethyl ether
HM	-	High magnification
HMDI	-	Hydrogenated MDI or 4,4-diisocyanato dicyclohexylmethane
HSM	-	Hardening soil model

IPDI	-	Isophorone diisocyanate
IPN	-	Interpenetrate polymer network
JCPDS	-	Joint committee on powder diffraction standards
JGM	-	Jet grouting method
LD_{50}	-	Lethal dose
LM	-	Low magnification
LVDT	-	Linear vertical displacement transducers
MC	-	Marine clay
MCM	-	Mohr-coulomb model
MDD	-	Maximum dry density
MDI	-	Methylene diphenyl diisocyanate
OMC	-	Optimum moisture content
OPC	-	Ordinary portland cement
PEG	-	Polyethylene glycol
PET	-	Polyethylene terephthalate
PU	-	Polyurethane
RHA	-	Rice husk ash
SP	-	Superplasticizer
SPP	-	Sodium pyrophosphate
SS	-	Sodium silicate
TDI	-	Toluene diisocyanate
TEDA	-	Triethylenediamine
UBC	-	Ultimate bearing capacity
UCS	-	Unconfined compressive strength
UCT	-	Unconfined compressive test
US EPA	-	United States of America environmental protection agency
USCS	-	Unified soil classification system
WG	-	Water glass
XRD	-	X-ray diffraction analysis

LIST OF SYMBOLS

ψ^1	-	Angle of dilatancy
D_{PU}	-	Density of PU
E_{50}	-	Moduli corresponding to effective stress, σ_3^1
E_{50}^{ref}	-	Secant stiffness in triaxial compression test
E_{oed}	-	Oedometer tangent modulus
E_{ur}^{ref}	-	Unloading / reloading stiffness
$G_{PU}s$	-	Specific gravity of PU
G_S	-	specific gravity
P_0'	-	Initial effective pressure
$\frac{dI}{dt}$	-	Velocity of grout
q^{ampl}	-	Amplitude of the variable deviatoric stress
ε_a^p	-	Permanent axial strain
σ_1^1	-	Effective major principal stress
σ_3^1	-	Effective minor principal stress
σ_{oed}^{ref}	-	Stress at which soil undergoes plastic straining
$\Delta \cup$	-	Excess pore-water pressure
μ_0	-	Viscosity of the liquid
μ_g	-	Viscosity of the penetration grout
A_p	-	Area of crystalline peaks
a_p	-	Improvement Area ratio
A_t	-	Total area of all peaks
B	-	Width of footing
b	-	Hydraulic aperture of the fracture
B_g	-	Piled area
B_r	-	Raft area
c	-	Cohesion
C_c	-	Compression index
C_s	-	Swelling index
C_u	-	Undrain shear strength

D	-	Diameter of the pile
d	-	Internal diameter of the pile
E	-	Elastic modulus
e_o	-	Initial void ratio
e^{ref}	-	Void ratio corresponding to stress σ_{oed}^{ref}
H	-	Height
I	-	Penetration length for Newtonian liquid with a constant viscosity
I_D	-	Maximum possible achievable penetration in one direction a grout can attain
IF	-	Improvement factor
I_r	-	Penetration radial distance to the pumping well
L	-	Length of the pile
L/H	-	Length over height ratio
m	-	Power for the stress-level dependency of stiffness
N	-	Number of load cycles
P_t	-	Pressure at failure for treated soils
P_u	-	Pressure at failure for untreated soil
Q	-	Flow (pumping rate)
t_G	-	Gel induction time
Δp	-	Difference between grout injection pressure and water pressure
Υ_{sat}	-	Saturated unit weight of soil
Υ_w	-	Radius of well
φ	-	Friction angle

CHAPTER 1

INTRODUCTION

1.1 Background

In recent times, there has been increased demand for more infrastructures like high-rise buildings, roads and bridges in coastal areas due to increase in population, urbanisation, technological advancement and many other reasons. These coastal areas have a large amount of marine clay (MC) deposit. One of the crucial requirements of constructing the said infrastructures is a good soil foundation due to the high amount of load they impose on the soil. However, MC undergoes significant swelling and shrinkage when exposed to moisture content fluctuations. It also has a low bearing capacity and low permeability. The natural moisture content of MC is higher than its liquid limit. The lateral swelling pressure of MC is typically 2–10 times greater than its vertical swelling pressure (Wang *et al*., 2013) while the unconfined compressive strength (*UCS*) of MC is between 25 and 50 kPa (Mohammed Al-Bared and Marto, 2017).

It is evident from these properties that MC is unsuitable for engineering purposes. Therefore, geotechnical engineers are to provide solutions to this problem. Various types of ground improvement approaches are used to accomplish this purpose. Examples of the methods include biotechnology, drainage, grouting, geosynthetics, heating, freezing, lime admixtures, fly ash, cement, mechanical stabilisation, micropiles, soil nails, stone columns and many others.

Ground improvement has received ample attention for providing the means of improving the properties of weak soils like MC. Previous researchers reported the use of lime (Rajasekaran and Rao, 2001; Mohd Yunus *et al*., 2015) and cement (Sasanian and Newson, 2014; Xiao *et al*., 2014; Kang *et al*., 2017) as the stabiliser of MC with successful results. However, the cost of cement and the prolonged curing period make it prohibitively expensive. Meanwhile, other researchers attempted using waste materials for the stabilisation of MC due to economical, sustainable and environmental reasons. Among the waste materials reported include rice husk ash, carbide slag (Phetchuay *et al*., 2016), sawdust (Rao *et al*., 2012), locust bean waste ash (Sani *et al*., 2014), banana fibre (Sunny and Joy, 2016), crumble rubber (Ravichandran *et al*., 2016), ceramic waste (Upadhyay and Kaur, 2016), ground granulated blast furnace slag (Yi *et al*., 2015), demolished tile (Zainuddin *et al*., 2019), demolished concrete (Ayub *et al*., 2018) and coal ash (Jamaludin *et al*., 2019). Nevertheless, the low effectiveness or small strength improvement, lack of availability of some of these waste materials in large quantities and problems with the curing period were some of the issues associated with these options. There have also been reports regarding the use of new approaches such the use of biomass (Marto *et al*., 2015, 2016), bioencapsulation (Ivanov *et al*., 2015), geotextile materials (Prasad *et al*., 2015), chloride compounds (Otoko and Simon, 2015) and inorganic materials such as sodium silicate (Pakir *et al*., 2015; Phetchuay *et al*., 2016; Yang *et al*., 2017). Yet, each of the mentioned methods has its limitation, for e.g., curing time for biomass material. Bioencapsulation may not be efficient for application in MC because the tiny size of the soil particle may not favour the growth of some species of microorganisms. At the same time, geotextile materials are more suitable for new construction; otherwise, it may require a lot of extra work.

Additionally, organic chemical stabilisers such as n-methylolacrylamide, polyurethane (PU), epoxy resin, aminoplast, phenoplast and lignosulfonate (Vik *et al*., 2000; Kazemian *et al*., 2010) were used for the stabilisation of MC. However, their rheological properties, the environmental impacts due to their toxicity and local regulations governing their usage is limiting the use of this option. Nonetheless, PU has many promising features such as low density, low viscosity, short gel time, high strength, and chemically inactivity once hardened. Despite these promising properties, however, detailed information about the mechanism of stabilisation using PU is still limited. Thus, PU is the proposed stabilising material for this research.

1.2 Problem Statement

As mentioned previously, the properties of MC are challenging in geotechnical engineering. MC has low strength and high compressibility because it contains swelling clay minerals such as montmorillonite, *vermiculite* and *chlorite*. Significant damage can occur to structures that are constructed on MC during variations of moisture content when under a light or non-load condition, as a result of erratic movements and large settlement.

Another concern when stabilising MC are the soil's pH levels as it can lead to chemical failure in the stabilised soil especially when cementitious materials like cement or lime are used as the stabilising agents. Moreover, soil's pH is significant as different chemicals perform differently under different pH conditions. For example, PU is most effective within non-acidic pH level, while aminoplasts (e.g., urea-formaldehyde) require acidic pH. The preliminary results of this study have shown that MC has a pH of 3.25. Therefore, due to acidic pH of the MC, it is important to improve the PU to reinforce the PU in order to minimise the risk of acid attacks. Thus, a reinforcing filler was integrated into the PU matrix so that there are both crystalline and amorphous parts in the morphology of the PU as suggested by Yang *et al*. (2017) during reinforcement of PU with water glass.

Furthermore, the toxicity of the stabilising material may cause groundwater contamination. Local regulations of some countries have banned the use of some chemicals due to their environmental effects. So, due to the environmental concerns regarding the application of PU for ground improvement, a toxicity characteristic leaching procedure analysis (TCLP) is important to investigate the potential for ground contamination that can result from the use of PU for the stabilisation of MC.

1.3 Aim and Objectives of the Research

The aim of this research is to determine the performance of MC that has been stabilised with PU and reinforced PU also known as improved PU (I-PU). In order to achieve this aim, the following objectives are identified:

1. To characterise the MC and PU used for the study.
2. To determine the effects of pH on the properties of MC that has been stabilised with PU.
3. To determine the effects of reinforcing fillers on the properties of I-PU.
4. To determine the bearing capacity of MC that has been stabilised with PU and I-PU piles by physical and numerical modelling.
5. To assess the toxicity of PU during MC stabilisation.

1.4 Scope of the Research

The MC that was used in this research was collected from the campus of Universiti Tun Hussein Onn Malaysia (UTHM) Johor, Malaysia. The stabiliser used in this research was PU that consists of two components: polyol and isocyanate. Reinforcing fillers that were used to improve the PU were nano-silica (SiO_2) and cellulose nanofabrils (CNF). Sodium hydroxide (NaOH) was used to neutralize the pH of the MC.

Laboratory tests of the engineering properties and microstructure of the untreated and treated MC, the PU and the I-PU were conducted in accordance with the British Standard (BS), American Society of Testing Material (ASTM), American Public Health Association (APHA) standards and previous researchers' methods.

Physical and numerical modelling were employed to determine the bearing capacity of the MC that was stabilised with PU and I-PU piles. Moreover, safety analysis based on the method of ϕ/c reduction was used to determine the safety factor of the numerical models. Numerical studies were carried out using the Hardening Soil model in Plaxis 3D software. A TCLP analysis was conducted to assess the toxicity of the PU and the MC that was stabilised with PU.

1.5 Limitation of Research

Due to short hardening time of the polyurethane, compaction test of MC treated with PU was not carried out. Toxicity of the reinforcing fillers SiO_2 and CNF as well as that of I-PU was not investigated.

1.6 Significance of the Research

Researchers in the past have discovered and created several solutions for the stabilisation of MC, each with its own pros and cons. None of the methods are exclusively acceptable or inaccurate. The literature review shows that PU has been used for civil engineering projects in many countries such as the USA, China, Italy, Korea, Malaysia and Iran, amongst others. However, the use of PU to stabilise MC has received no attention. Moreover, there is no information regarding the mechanism of the stabilisation of MC by PU. In addition, it is not known whether the use of PU to stabilise MC poses any threat to the public health or the ecosystem. This research attempts to cover this gap by providing significant knowledge regarding the application of PU for MC stabilisation. The mechanism of the stabilisation of MC with PU from the results of strength tests and microstructural analyses is described comprehensively. Furthermore, the properties of PU were improved by using reinforcing filler. The performance of the MC treated with PU and I-PU piles were assessed using physical and numerical models. Finally, this study explored the toxicity of the PU during stabilisation of MC.

1.7 Thesis organization

This thesis consists of five chapters. Chapter 1 presents the background, problem statements, objectives, scope and significance of the research. The literature review of previous research related to the current study is covered in Chapter 2. The topics discussed are MC and its properties, PU, its components, its applications for ground improvement and the improvement of PU to I-PU. Other themes are the stabilisation of MC and the methods and material of grouting and grouting. Reviews of previous studies on bearing and safety analysis as well as toxicity analysis are also reviewed. Chapter 3 describes the research methodology, including the details of the experiment schedules, sample preparation, apparatus, testing procedures and model designs. Chapter 4 conveys the results and discussions. The results of MC and PU characterisations, strength test and microstructural analyses of the untreated and treated MC, PU and I-PU, physical and numerical modelling and toxicity analyses are presented. Chapter 5 presents the conclusions and recommendations for upcoming studies.

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