
PHYSICOCHEMICAL, MICROSTRUCTURAL AND ENGINEERING
BEHAVIOUR OF NON-TRADITIONAL STABILISER TREATED
MARINE CLAY

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PHYSICOCHEMICAL, MICROSTRUCTURAL AND ENGINEERING
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In the name of Allah, the Supremely Merciful and the Most Kind,

To my beloved family, who never give up to give me spiritual support and pray for
my success.

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ABSTRACT

The presence of marine clay underlying foundation has been responsible for failure in several geotechnical structures and chemical stabilisation is the usual practice to improve the strength of soils. Recently, non-traditional additives are extensively used to solve this problem and their effects on geotechnical properties of soils have been reported by many researchers. However, publications on the fundamental microstructural behaviour of non-traditional additives in treating marine clay soils and their influence on the engineering behaviour are limited. Therefore, this research aimed at determining the stabilisation mechanism and the performance of marine clay soil mixed with two types of non-traditional additives, namely calcium-based powder stabiliser (SH-85) and sodium silicate-based liquid stabilizer (TX-85). Microstructural study from different spectroscopic and microscopic techniques such as X-ray Diffractometry (XRD), Energy-Dispersive X-ray Spectrometry (EDAX), Scanning Electron Microscopy (SEM), Thermal Gravimetric Analysis (TGA) and pore size distribution had been conducted to elucidate the stabilisation mechanism. Unconfined compressive test, oedometer consolidation test and consolidated undrained triaxial compression test were conducted to assess the engineering properties of the stabilised soil. In addition, strip footing model tests were conducted to determine the performance of stabilised clay soils and the results were compared with simulation using PLAXIS 2D finite element. The laboratory tests showed that the addition of 12% SH-85 at early 7 days curing period had increased the compressive strength of treated marine clay by about 42 times while the addition of 6% TX-85 with similar curing period had increased the compressive strength of treated marine clay by about 3.6 times. The results of the microstructural tests indicated the formation of new gel products in the mixtures, which were identified as calcium silicate hydrate (CSH) and sodium aluminosilicate hydrate (NASH) for soils treated with SH-85 and TX-85, respectively. SEM images illustrated the formation of new cementitious compounds (CSH and NASH) which were shown within the pore spaces, resulting in the reduction of radius of pore spaces. In comparison to the untreated soil, the results of the physical model tests showed that the bearing capacity of strip footing on the treated soil at 7 days curing period increased significantly while the settlement reduced. In short, the selected additive had successfully increased the strength of marine clay at early period, thus the usage of selected non-traditional additives was considered as cost effective for geotechnical project.

ABSTRAK

Kehadiran tanah liat marin dibawah asas telah mengakibatkan kegagalan pada beberapa struktur geoteknik, dan penggunaan penstabilan kimia merupakan satu amalan biasa dalam meningkatkan kekuatan tanah tersebut. Baru-baru ini, bahan penstabil bukan konvensional telah digunakan secara meluas untuk menyelesaikan masalah ini dan kesan ke atas ciri-ciri geoteknikal tanah juga telah dilaporkan oleh ramai penyelidik. Walau bagaimanapun, penerbitan tentang sifat-sifat mikrostruktur asas bahan penstabil bukan konvensional ini dalam merawat tanah liat marin dan pengaruh ke atas kelakuan kejuruteraan adalah terhad. Oleh itu, kajian ini bertujuan untuk menentukan mekanisme penstabilan dan prestasi tanah liat marin yang dicampurkan dengan dua jenis penstabil bukan konvensional, iaitu penstabil serbuk berasaskan kalsium (SH-85) dan penstabil cecair berasaskan sodium silikat (TX-85). Kajian mikrostruktur daripada pelbagai teknik spektroskopi dan mikroskopik seperti *X-ray Diffractometry* (XRD), Spektrometri Sinar-X Serakan Tenaga (EDAX), Mikroskopi Imbasan Elektron (SEM), Analisis Termal Gravimetri (TGA), dan taburan saiz liang telah dijalankan untuk menjelaskan mekanisme penstabilan tersebut. Ujian mampatan tidak terkurung, ujian pengukuhan, dan ujian mampatan tiga paksi terkukuh tak tersalir juga dilakukan untuk menilai ciri-ciri kejuruteraan tanah yang dirawat. Di samping itu juga, ujian model asas jalur telah dijalankan untuk menentukan prestasi tanah liat dirawat tersebut dan hasilnya dibandingkan dengan menggunakan perisian unsur terhinnga PLAXIS 2D. Ujian makmal menunjukkan bahawa penggunaan 12% SH-85 selepas pengawetan selama 7 hari telah meningkatkan kekuatan mampatan tanah yang dirawat sebanyak 42 kali ganda manakala penggunaan 6% TX-85 bagi tempoh rawatan yang sama telah meningkatkan kekuatan mampatan tanah yang dirawat sebanyak 3.6 kali ganda. Keputusan ujian mikrostruktur menunjukkan terdapat pembentukan produk baru berbentuk gel pada tanah yang dirawat yang dikenal pasti sebagai kalsium silikat hidrat (CSH) dan natrium aluminosilikat hidrat (NASH) untuk tanah yang dirawat dengan SH-85 dan TX-85, masing-masing. Imej SEM membuktikan pembentukan sebatian bersimen (CSH dan NASH) dalam ruang liang menyebabkan pengurangan jejari ruang liang. Berbanding dengan tanah liat yang tidak dirawat, keputusan ujian model fizikal menunjukkan bahawa keupayaan gelas jalur bagi tanah yang dirawat selama 7 hari pengawetan semakin meningkat, manakala enapan tanah dapat dikurangkan. Kesimpulannya, bahan tambahan yang dipilih berjaya meningkatkan kekuatan tanah liat dalam masa yang singkat, sekali gus penggunaan bahan penstabil bukan tradisional dapat menjimatkan kos untuk projek geoteknik.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF ABBREVIATIONS AND SYMBOLS	xxi
	LIST OF APPENDICES	xxiii
1	INTRODUCTION	1
	1.1 Background of Research	1
	1.2 Problem Statement	3
	1.3 Research Aims and Objectives	4
	1.4 Scope of Study	4
	1.5 Significance of Study	5
	1.6 Outline of the Thesis	6
2	LITERATURE REVIEW	7
	2.1 Introduction	7
	2.2 Background of Soft Marine Clay Soils	7
	2.2.1 Clay minerals	10
	2.2.1.1 Illite	12

	2.2.1.2 Montmorillonite	13
	2.2.1.3 Kaolinite	14
	2.2.2 Physical Properties of Marine Clay Soils	14
	2.3 Soil Stabilisation using Chemical Stabilisers	19
	2.3.1 Traditional Stabilisers	20
	2.3.1.1 Lime	20
	2.3.1.2 Cement	21
	2.3.2 Non-Traditional Stabiliser	22
	2.4 Macrostructural Study of Stabilised Soils	26
	2.4.1 Plasticity	26
	2.4.2 Unconfined Compressive Strength	28
	2.4.3 Undrained Triaxial Compressive Strength	30
	2.4.4 Compressibility Characteristics	34
	2.5 Microstructural Study of Stabilised Soils	37
	2.5.1 X-Ray Diffraction	37
	2.5.2 Microscopic Studies	41
	2.5.3 Particle Size Distribution	44
	2.5.4 Thermal Studies	46
	2.6 Modelling the Bearing Capacity of Treated Soils	49
	2.7 Summary	52
3	RESEARCH METHODOLOGY	54
	3.1 Introduction	54
	3.2 Soil and stabilisers	58
	3.2.1 Soft Marine Clay Soil	58
	3.2.2 Stabilisers	59
	3.2.2.1 SH-85	59
	3.2.2.2 TX-85	60
	3.3 Determination of Basic Physical and Index Properties of Soil Samples	61
	3.3.1 Grain Size Distribution	62
	3.3.2 Atterberg Limits	62
	3.3.3 Specific Gravity	63
	3.3.4 Loss on Ignition	63

3.4	Preparation of Samples	63
3.4.1	Treated Soil Samples	64
3.4.2	Curing Period	65
3.5	Determination of Engineering Properties	66
3.5.1	Compaction Characteristics	67
3.5.2	Unconfined Compressive Test	68
3.5.3	Oedometer Consolidation Test	69
3.5.4	Consolidated Undrained Triaxial Compression Test	70
3.6	Determination of Physicochemical and Microstructural Properties	72
3.6.1	pH Determination	72
3.6.2	X-Ray Diffraction Analysis	73
3.6.3	Scanning Electron Microscope and Energy Dispersive X-Ray Spectrometry	74
3.6.4	Particle Size Analysis	77
3.6.5	Thermal Gravimetric Analysis	78
3.7	Physical Model Test	79
3.7.1	Size, Design and Fabrication of Test Box	79
3.7.2	Model Preparation and Test Procedure	83
3.7.2.1	Preparation of Soil Sample	83
3.7.2.2	Load Test	85
3.8	Numerical Model	87
3.8.1	Geometry Model	87
3.8.2	Performing Calculations	90
3.8.2.1	Initial Condition	90
3.8.2.2	footing Phase	91
3.8.2.3	Execution of Calculation	93
3.9	Summary	94
4	MACRO AND MICRO STRUCTURAL STUDIES	95
4.1	Introduction	95
4.2	General Properties of Marine Clay Soil	96

4.3	Basic Engineering and Macro Structural	
	Characterization of Treated Soil	99
4.3.1	Atterberg Limits	99
4.3.2	Unconfined Compressive Strength	101
4.3.3	Consolidated Undrained Triaxial Test	108
	4.3.3.1 Effect of confining pressure	108
	4.3.3.2 Effect of curing period	115
	4.3.3.3 Shear Strength Parameter	121
4.3.4	Compressibility Behaviour	124
4.4	Micro Structural Characterization	130
4.4.1	X-Ray Diffraction	130
4.4.2	Energy Dispersive X-Ray Spectrometry	133
4.4.3	Scanning Electron Microscopy	138
4.4.4	Particle Size Analysis	143
4.4.5	Thermal Gravimetric Analysis	146
4.4.6	pH Value	148
4.5	Physical Model and Numerical Simulation	149
4.5.1	Physical Model Test	150
	4.5.1.1 Physical Model Test of Treated Soils with SH-85	151
	4.5.1.2 Physical Model Test of Treated Soils with TX-85	153
	4.5.1.3 Summary of Physical Model Test	155
4.5.2	Numerical Simulation	156
	4.5.2.1 Numerical Simulation for Treated Soils with SH-85	157
	4.5.2.2 Numerical Simulation for Treated Soils with TX-85	158
	4.5.2.3 Summary of Numerical Simulation	159
4.6	Summary	161
5	CONCLUSION AND RECOMMENDATIONS	163
5.1	Introduction	163

5.2 Conclusion	163
5.2.1 Macro Structural Study	164
5.2.2 Micro Structural Study	165
5.2.3 Correlation Between Physicochemical and Microstructural on the Engineering Properties	166
5.2.4 Physical Modelling and Numerical Simulation	167
5.3 Recommendations for Further Research	168
REFERENCES	169
Appendices A-D	183-203

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Physical indices of marine clay soils from various places in Asia	15
2.2	Percentages of soil components based on particle size	17
3.1	Summary of laboratory test on untreated soil and standard references	56
3.2	Summary of laboratory test on treated soil and standard references	57
3.3	Chemical composition of SH-85 (Latifi, 2014)	60
4.1	Description of soil samples	96
4.2	Physical properties of marine clay soils	97
4.3	Chemical composition of the untreated marine clay	98
4.4	Unconfined compressive strength of untreated and soils treated with SH-85 and TX-85 at various curing period	102
4.5	Unconfined compressive strength of clay soils mixed with different type of stabilisers at 7 days curing period	105
4.6	Al:Si, and Ca:Si ratios of untreated and soils treated with 12% SH-85 obtained from EDAX analysis	136
4.7	Al:Si, and Ca:Si ratios of untreated and soils treated with 6% TX-85 obtained from EDAX analysis	138
4.8	Particle size distribution of untreated soil and soils treated with SH-85 and TX-85	145
4.9	Summary result of the physical model test	151

4.10	Parameters for soil sample and footing in PLAXIS modelling	156
4.11	Allowable pressure and pressure at failure of footing of the treated and untreated soil obtained from numerical simulation	157
4.12	Comparison of failure pressure and settlement of footing for treated and untreated soil from physical model and numerical model	160
4.13	Summary of macrostructure and microstructure structural characteristics of soil samples	161

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Marine clay soils in South East Asia (Malaysian Highway Authority, 1989)	9
2.2	Marine clay soils in Peninsular Malaysia (Malaysia Highway Authority, 1989)	10
2.3	Basic units arrangements of silicon and aluminum (a) silica tetrahedron, (b) silica sheet, (c) alumina octahedron, (d) octahedrol (gibbsite) sheet, (e) elemental silica-gibbsite sheet (Das, 2013)	11
2.4	Diagram of the structure of an illite (Das, 2013)	12
2.5	Diagram of the structure of a montmorillonite (Das, 2013)	13
2.6	Diagram of a kaolinite structure (Das, 2013)	14
2.7	Influence of lime content on Atterberg limits characteristics of soil (Jha and Sivapullaiah, 2015)	27
2.8	Variation of liquid limit and plasticity index with gypsum content (Yilmaz and Civelekoglu, 2009)	28
2.9	Strength gained for sodium silicate treated soil with different stabiliser content and curing period (Latifi <i>et al.</i> , 2014)	29
2.10	UCS at different curing days for CH and CL with additional of BS (Lim <i>et al.</i> , 2013)	30
2.11	Effect of confining pressure on (a) stress vs strain, (b) pore pressure vs strain behaviour of treated clay (Kamruzzaman <i>et al.</i> , 2009)	32

2.12	Consolidated undrained behaviour for 70% BA samples (a) 0 days curing period, (b) 28 days curing period (Latifi <i>et al.</i> , 2015a)	33
2.13	Consolidated undrained behaviour for 70% FA samples (a) 0 days curing period, (b) 28 days curing period (Latifi <i>et al.</i> , 2015a)	34
2.14	Void ratio versus effective stress for untreated and treated soft clay with different percentages of lime (Ouhadi <i>et al.</i> , 2014)	35
2.15	Void ratio versus effective stress for untreated and treated soft clay with different percentages of cement (Ouhadi <i>et al.</i> , 2014)	36
2.16	Compression index and swelling index at different curing period (Latifi <i>et al.</i> , 2014b)	37
2.17	X-ray diffraction of treated soft clay with different percentages of (a) lime and (b) cement at 7 days of curing period (Ouhadi <i>et al.</i> , 2014)	38
2.18	XRD patterns of metakaolin based geopolymer, unstabilised soil and soil stabilised with MKG at different concentrations (Zhang <i>et al.</i> , 2013)	39
2.19	XRD patterns for the untreated and treated soil with MgCl ₂ (a) High swelling clay and, (b) Low swelling clay at different curing period (Latifi <i>et al.</i> , 2015)	40
2.20	SEM image of (a) Clay soils, (b) treated clay soil with fly ash (Sharma <i>et al.</i> , 2012)	41
2.21	SEM photos of (a) untreated clay, (b) 10% OPC, (c) 20% OPC, (d) 8% SSCP, (e) 12% SSCP and (f)16% SSCP stabilised specimens for 28 days (Cong <i>et al.</i> , 2014)	43
2.22	Particle size analysis test results for untreated and treated soil with xanthan gum (a) bentonite; (b) kaolinite (Latifi <i>et al.</i> , 2016a)	45

2.23	Effect of cement content and curing period on particle size distribution curves of treated clays (a) measured by MIP analysis; (b) measured by Mastersizer (Chew <i>et al.</i> , 2004)	46
2.24	TGA results for untreated and stabilised soils stabilised with fly ash and lime (Sharma <i>et al.</i> , 2012)	47
2.25	TGA curves of untreated and CKD-treated Namontmorillonite clay at various curing periods (Peethamparan <i>et al.</i> , 2009)	48
2.26	Schematic of geosynthetic reinforced soil foundation (Abu-Farsakh <i>et al.</i> , 2013)	51
2.27	Sketch of field loading test (Ibrahim, 2016)	52
3.1	Flowchat of research methodology	55
3.2	Collection of soil sample	58
3.3	SH-85 stabiliser	60
3.4	TX-85 stabiliser	61
3.5	Curing box	66
3.6	Standard proctor compaction equipment	67
3.7	UCS equipment	69
3.8	One dimensional consolidation test equipment	70
3.9	Consolidated undrained triaxial test equipment	71
3.10	pH measurement equipment	73
3.11	X-ray diffractometer	74
3.12	SEM analysis	76
3.13	Sputter coat machine	76
3.14	CILAS machines	77
3.15	Thermal gravimetric analysis machine	78
3.16	Failure mechanism from general shear failure	80
3.17	Schematic picture of test box	82
3.18	Box test after coated	83
3.19	Steel plate compactor for compaction	84
3.20	Top surface of soil is leveled	85
3.21	Setting up the measurement instrument	86

3.22	Setup up the data logger	86
3.23	Typical geometry of strip footing foundation model	88
3.24	Parameter tabshet of the soil window	89
3.25	Mesh option windows	89
3.26	Finite element model and mesh	90
3.27	Phase window for initial phases	91
3.28	Phase window for the footing phase	92
3.29	Activation of the prescribed displacement	92
3.30	Active task window displaying th calculation progress	93
3.31	Deformed mesh	94
4.1	XRD diffractometer of soft marine clay soils	98
4.2	Effect of SH-85 content on the Atterberg limits of treated clay soils	100
4.3	Effect of TX-85 content on the Atterberg limits of treated clay soils	101
4.4	Effect of SH-85 content on unconfined compressive strength of treated marine clay	103
4.5	Effect of curing period on unconfined compressive strength of treated marine clay with SH-85	104
4.6	Effect of TX-85 content on unconfined compressive strength of treated marine clay	106
4.7	Effect of curing period on unconfined compressive strength of treated marine clay with TX-85	107
4.8	Effect of confining pressure on deviator stress of clay soils treated with 12% SH-85 at different curing period	111
4.9	Effect of confining pressure on excess pore pressure of clay soils treated with 12% SH-85 at different curing periods	112
4.10	Effect of confining pressure on deviator stress of clay soils treated with 6% TX-85 at different curing periods	113
4.11	Effect of confining pressure on excess pore pressure of clay soils treated with 6%TX-85 at different curing period	114

4.12	Effect of curing period on deviator stress of clay soils treated with 12% SH-85	117
4.13	Effect of curing period on excess pore pressure of clay soils treated with 12% SH-85	118
4.14	Effect of curing period on deviator stress of clay soils treated with 6% TX-85	119
4.15	Effect of curing period on excess pore pressure of clay soils treated with 6% TX-85	120
4.16	Mohr-Coulomb effective shear strength envelope for soil treated with 12% SH-85 at different curing periods	122
4.17	Effect of curing period on effective shear strength parameters of clay soils treated with 12% SH-85	122
4.18	Mohr-Coulomb effective shear strength envelope for soils treated with 6% TX-85 at different curing periods	123
4.19	Effect of curing period on effective shear strength parameters of clay soils treated with 6% TX-85	123
4.20	Compression curve of the untreated soil and soils treated with 12% SH-85 at different curing periods	125
4.21	Vertical strain versus pressure for the untreated and soil treated with 12% SH-85 at different curing periods	126
4.22	Coefficient of compression, swelling and preconsolidation of the untreated and soils treated with 12% SH-85	126
4.23	Compression curve of the untreated and soils treated with 6% TX-85 at different curing periods	128
4.24	Vertical strain versus pressure for the untreated soil and soils treated with 6% TX-85 at different curing periods	128
4.25	Coefficient of compression, swelling and preconsolidation of the untreated and soils treated with 6% TX-85	129
4.26	XRD pattern for the untreated and soils treated with 12% of SH-85 at different curing periods	131

4.27	XRD pattern for the untreated and soils treated with 6% of TX-85 at different curing periods	132
4.28	EDAX spectrum for the untreated soils	134
4.29	EDAX spectrum of soils treated with 12% SH-85 at different curing periods	135
4.30	EDAX spectrum of the soils treated with 6% TX-85 at different curing periods	137
4.31	SEM image of untreated soils	139
4.32	SEM image of soils treated with 12% SH-85 at different curing periods	140
4.33	SEM image of soils treated with 6% TX-85 at different curing periods	142
4.34	Particle size distribution of the untreated soil and soils treated with 12% SH-85 at various curing periods	144
4.35	Particle size distribution of the untreated and soils treated with 6% TX-85 at various curing periods	144
4.36	TGA spectrums for the untreated clay soils	146
4.37	TGA spectrums for the untreated soil and soils treated with 12% SH-85 at 7, 28 and 90 days curing periods	147
4.38	TGA spectrums for the untreated soil and soils treated with 6% TX-85 at 7, 28 and 90 days curing periods	147
4.39	pH for soils treated with various percentage of SH-85 at different curing periods	148
4.40	pH for soils treated with various percentage TX-85 at different curing periods	148
4.41	Pressure versus settlement ratio with different SH-85 contents at 7 days curing period	152
4.42	Variation of bearing capacity improvement factor with different of SH-85 content at 7 days curing period	153
4.43	Pressure versus settlement ratio with different TX-85 content at 7 days curing period	154
4.44	Variation of bearing capacity improvement factor with different of TX-85 content at 7 days curing period	155

4.45	Comparisons of numerical simulation and physical test of footing foundation treated with SH-85	158
4.46	Comparisons of numerical simulation and physical test of footing foundation treated with TX-85	159

LIST OF ABBREVIATIONS AND SYMBOLS

Al	-	Aluminium
Al ₂ O ₃	-	Aluminium oxide
ASTM	-	American society of testing material
B	-	Width of the shallow foundation
BS	-	British standard
c	-	Cohesion
CaO	-	Calcium oxide
CU	-	Consolidated undrained
C _c	-	Compression index
C _s	-	Swelling index
CSH	-	Calcium silicate hydrate
CO ₂	-	Carbon dioxide
E	-	Young's modulus
EDAX	-	Energy dispersive x-ray spectrometer
Fe	-	Iron
Fe ₂ O ₃	-	Ferric oxide
G _s	-	Specific gravity
ICP-MS	-	Inductively coupled plasma mass spectrometry
K ₂ O	-	Kalium oxide
LIR	-	Load increment ratio
LL	-	Liquid limit
LVDT	-	Linear variable displacement transducer
MDD	-	Maximum dry density
MgO	-	Magnesium oxide
Na ⁺	-	Sodium ion
p _c	-	Preconsolidation pressure
PI	-	Plasticity Index

PL	-	Plastic limit
SEM	-	Scanning electron microscopy
SH-85	-	Calcium based powder stabiliser
Si	-	Silicon
SiO ₂	-	Silica
SO ₄	-	Sulphate
TGA	-	Thermal gravimetric analysis
TX-85	-	Sodium Silicate Based Liquid Stabiliser
UCS	-	Unconfined compressive strength
UCT	-	Unconfined compressive test
XRD	-	X- ray diffraction
ν	-	Poisson's ratio
ϕ	-	Friction angle
ψ	-	Dilatancy angle

LIST OF APPENDICES

TABLE NO.	TITLE	PAGE
A	Organic content result of marine clay soils	183
B	Particle Size Distribution (hydrometer test)	184
C	EDAX result	185
D	Particle Size Distribution (CILAS method)	192

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Marine clay, which has low strength and high compressibility, is located in many coastal and offshore areas around the world. It is weak in nature due to the presence of swelling clay minerals like montmorillonite, vermiculite, and chlorite, hence causing a problematic foundation for structures to be built on it (Bjerrum, 1973). The physical and engineering behaviours of soil, such as marine clay, depend on the exchangeable cations, mineralogical composition, and pore water system chemistry (Egashira and Ohtsubo 1982; Ohtsubo *et al.*, 1985).

In the Ninth Malaysia Plan (2006-2010), Iskandar Malaysia was launched as one of the high-impact development projects (Ministry of Information Malaysia, 2008). Nusajaya, a 4% land area within Iskandar Malaysia, is the focal point of the whole development projects within that region. Both public and private sectors are required to build more buildings and roads, but the weak marine clay deposits in various sites surrounding Nusajaya need to either be replaced or improved. Therefore, various ground improvement methods have been introduced and tested in research and in practice. However, their respective suitability are considered to be project-specific, which depend on the cost, existing soil's characteristics, and the stabilisers potential impacts or effectiveness for the proposed application. In such cases, appropriate soil property modification measures are typically taken into consideration. Hence, it is

necessary to improve the engineering behaviour of marine clays using appropriate ground improvement techniques.

Geotechnical engineers borrow the knowledge of geologists and soil scientists to seek appropriate method to enhance clay behaviour. Most of the basic ideas related to the enhancement of clay behaviour using stabiliser had been published since 1960 (Petry and Little, 2002). The soil stabilisation is a method which involves mixing natural soils with chemical stabilisers to increase the properties of the soil particularly in strength and decrease moisture content of soil. This method of stabilising or treating soil is an important and widely used method throughout the world. In the stabilisation process, stabiliser agent acts as filler in the pore spaces or reinforcing the bindings between the particles. The stabiliser is categorised as traditional, such as lime, cement and fly ash, as well as non-traditional stabiliser such as, acids, salts, enzymes, polymer, resin, and sulfonated oils (Harris *et al.*, 2006; Tingle *et al.*, 2007). Despite the fact that stabilisation of soil using traditional stabiliser such as cement and lime is well established (Yilmaz and Civelekoglu, 2009), there is a need of alternative technologies to be applied which are more environmentally friendly, sustainable, and economical.

In recent years, an increasing number of non-traditional stabilisers have been developed for soil stabilisation purposes. According to Tingle *et al.* (2007), the variety of stabilisers (powder and liquid form) are becoming popular due to their relatively low cost, ease of application, and short curing period. The effectiveness of non-traditional stabiliser to increase the properties of clay soils, particularly in strength, has been reported by many researchers such as Suganya *et al.* (2016), Onyejekwe *et al.* (2016), Phetchuay *et al.* (2016), Zhang *et al.* (2015) and Yi *et al.* (2015).

Lim *et al.* (2013), for example, reported the increased of unconfined compressive strength of low plasticity clay treated with biomass silica (non-traditional stabiliser) up to 36 times the untreated value. Using the same non-traditional stabiliser, Latifi *et al.* (2016) reported the increased strength of residual soil (high plasticity silt) up to 7 times the untreated value. Nevertheless, the lack of knowledge in selecting and using chemical additives to treat soils has induced the damage of losing millions of dollars (Wiggins *et al.*, 1978). Hence, suitable use of stabiliser is important to maximize the optimum use of stabiliser agent and to save cost.

1.2 Problem Statement

In recent years, an increasing number of non-traditional stabiliser have been developed for soil stabilisation purposes. The non-traditional stabiliser has been developed and marketed to meet the need of alternative technologies which are more economical, sustainable, and environmentally friendly. However, the effects of these stabilisers are still vague and yet to be understood. Besides that, the non-traditional stabilisers, in the form of powder or liquid, are becoming popular due to their relatively low cost, ease of application, and short curing period. In spite of the benefits of non-traditional stabiliser as a chemical agent, the engineers seldom use these product due to the variation of chemical data, process explanation, and engineering data. Besides that, the performance of a non-traditional stabiliser is rather difficult to evaluate due to the chemical formulas are often changing based on the market tendency and the exact chemical composition are not disclosed due to the commercial stabilisation product.

In this sense, understanding the mechanism of stabilisation process is very important. Thus, basic stabilisation mechanism should be studied to set these products according to different categories, depending on their primary chemical components and proposed enhancement properties. Considering the above current issues, it is concluded that there is a need to study the physico-chemical and microstructural behaviour of non-traditional stabiliser treated marine clay and use them to explain some aspects of the observed engineering behaviour in a well-controlled laboratory condition before extending it to the field condition. In this thesis, an attempt has been made to evaluate the stabilisation mechanism of treated marine clay soil with selected non-traditional stabilisers.

1.3 Research Aims and Objectives

This research aims to determine the stabilisation mechanism and performance of marine clay soils treated with non-traditional stabilisers, namely the SH-85 and TX-85. Hence, the main objectives of this research are as follows:

- i. To determine the changes in the engineering properties of treated marine clay with various percentages of selected stabilisers at different curing periods;
- ii. To determine the changes on the physico-chemical and microstructural behaviour of treated marine clay;
- iii. To evaluate the influence of physicochemical and microstructural changes of treated marine clay soil on engineering properties; and
- iv. To determine the performance of strip footing on treated marine clay soils based on laboratory physical model tests and computer simulation.

1.4 Scope of Study

The soft marine clay soil used in this study was collected from the construction site in Nusajaya where the soils were excavated at the Southern coast Johor, Malaysia. The non-traditional stabilisers used in this study were obtained from a local company called Probase Sdn. Bhd. which is located in Johor.

To understand the changes on physico-chemical and microstructural behaviour of treated marine clay soils, X-Ray diffraction (XRD), energy dispersive x-ray spectrometry (EDAX), scanning electron microscopy (SEM), particle size analysis, thermal gravimetric analysis (TGA), and pH measurement were conducted. Meanwhile, for the engineering behaviour, Atterberg's limits, unconfined compressive strength (UCS), oedometer consolidation, and consolidated undrained (CU) triaxial test were conducted.

The testing sample were prepared and cured in a similar manner described in the British Standard (BS 1924: Part 2: 1990). The percentages of the chemical used in the mixture of soil sample were 3%, 6%, 9%, 12%, and 15% cured at 3, 7, 14, 28, 90 and 180 days curing periods. Due to the high quantity of sample and high cost of microstructure test, test was limited to the sample that showed the highest degree of improvement. The 12% of SH-85 stabiliser and 6% of TX-85 stabiliser was chosen as the optimum percentage through the analysis of the results obtained.

Laboratory physical model tests were conducted on the untreated and treated soil (cured at 7 days) as foundation for strip footing. The model tests were carried out by applying loads to the strip footing placed until failure occurred to the footing. The settlement of the footing and the bearing capacity were monitored during loading tests to ascertain the performance of the treated soil as foundation. The commercial 2D finite element software called “PLAXIS” was used in numerical simulation to evaluate and compare the results obtained from laboratory physical model tests. The Mohr-Coulomb soil model under undrained condition was used in the simulation work.

1.5 Significance of Study

In regard to the importance of the study, the mechanism of the stabilisation of marine clay soils with non-traditional stabiliser had been established. The significance of the study includes the following:

- i. Understanding the mechanism of the stabilisation process through the results from macro and micro-structural study;
- ii. New finding from the changes of the mineralogy and physical of treated marine clay soils can be used for further study;
- iii. The performance of strip footing foundation on treated soil could be used to produce practicing engineers in using non-traditional stabilisers to stabilise marine clay soils.

1.6 Outline of the Thesis

This thesis consists of six chapters. The first chapter gives a brief overall introduction of the entire research work done, followed by its problem statement and research objectives, as well as scope of study and significance of study.

Chapter 2 is devoted to a literature review on the chemical stabilisation by the traditional and non-traditional stabilisers. Also, the fundamentals of clay mineral are presented to understand the soil-chemical reactions. Moreover, previous research on the physical and numerical simulations of strip footing foundation are also discussed.

Chapter 3 describes the research methodology of study, detail of test apparatus, sample preparation, and procedure of testing. Furthermore, the characterization study of stabilised soil was done using spectroscopic and microscopic techniques previously published in papers and as standards. The descriptions of physical and numerical simulation test procedure are also explained at the end of this chapter.

The test results and discussions of the comprehensive testing program are presented in Chapter 4. In Chapter 4, the physico-chemical, as well as microstructural behaviour, together with an integration of the basic engineering properties of treated marine clays and the strength and compressibility behaviour of treated marine clays, are explained and clarified with the knowledge of induced microstructure. In addition, the descriptions of the physical and numerical simulation tests are also presented and discussed.

Finally, Chapter 5 concludes the findings and provides some recommendations for future studies.

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