STRENGTH AND COMPRESSIBILITY CHARACTERISTICS OF CEMENT TREATED LATERITE SOIL UNDER SATURATED AND UNSATURATED CONDITIONS

NORSHAKILA ABDUL WAHAB

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Civil Engineering
Universiti Teknologi Malaysia

DECEMBER 2022

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.

ACKNOWLEDGEMENT

Acknowledgements for the completion of this thesis must be extended to many people who provided me with precious time and invaluable advice. My gratitude to the Almighty God, due to all His blessings and grace, this thesis finally came to an end.

I wish to express my sincerest gratitude to my supervisor, Assoc. Prof. Ir. Ts. Dr. Ahmad Safuan A Rashid for his invaluable comments, genuine encouragement, constructive advice, and professional guidance during the formulation of this thesis. Thank you for the opportunity you granted me. I am also very thankful to my co-supervisor Assoc. Prof. Ts. Dr. Nor Zurairahetty Mohd Yunus, and Ts. Muhammad Azril Hezmi, for their endless support, continuing feedback, guidance, and motivation.

My sincere gratitude also goes to all laboratory technicians in the D03, Geotechnical Laboratory and all my fellow postgraduate friends for their genuine help in carrying out the laboratory tests and data analysis throughout the study.

Last but not least, my utmost appreciations go to my much-loved parents for their endless support and everlasting love. Also, special gratitude to my lovely husband, Mohamad Zahierruden Ismail, for his encouragement and tolerance throughout this master's research journey.

ABSTRACT

Laterite soil is known as firm soil and is commonly used as a potential subgrade material for pavements. However, due to dry and rainy seasons caused by climate change, road infrastructure in Malaysia is affected massively, which weakens their natural bond. Hence, it is important to comprehensively emphasise the soil shear strength and compressibility to design a longer lifespan for the pavement subgrade. Therefore, soil stabilisation is a method for enhancing on-site materials to create a competent and stable subgrade. From previous researchers, cement is widely used as a stabiliser for building construction. Thus, the main objective of this research is to investigate the capability of cement as a stabiliser in laterite soil stabilisation. Therefore, several laboratory analyses had been carried out according to the mixture formulation between different cement percentages with laterite soil. The cement type used in this research was Ordinary Portland Cement (OPC) CEM I 42.5N. From the unconfined compression test (UCT) results, it is indicated that 6% cement-treated laterite soil at 7 days of curing is capable of achieving the stabilised soil required strength (800 kPa) of low-volume road by the Public Work Department of Malaysia for 1.0 million ESAL (Equivalent Single Axle Load). Moreover, the UCT results also implied that the cement addition improved the soil strength, which is also evidenced by the soil microstructure images from the microstructural analysis. The compressibility tests proved that laterite soil experienced high compressibility in fully saturated condition, while the compressibility was significantly reduced in partially saturated condition. Hence, the unsaturated oedometer tests showed a significant reduction in soil compressibility at a higher suction level (drying condition) compared to that of lower suction (wetting condition). In conclusion, this research output provides fundamental knowledge by proving the capability of cement to be applied as a stabiliser for the subgrade material in the design guidelines of road construction in Malaysia.

ABSTRAK

Tanah laterit dikenali sebagai tanah yang kuat dan kebiasaannya digunakan sebagai bahan subgred yang berpotensi untuk turapan. Walau bagaimanapun, disebabkan oleh musim kering dan hujan yang terjadi disebabkan oleh perubahan iklim, infrastruktur jalan raya di Malaysia telah terjejas dengan teruk, di mana ia melemahkan ikatan semula jadi mereka. Oleh itu, adalah penting untuk menekankan secara menyeluruh kekuatan ricih tanah dan kebolehmampatan untuk merekabentuk jangka hayat subgred jalan yang lebih lama. Oleh itu, penstabilan tanah adalah salah satu kaedah untuk mencipta dan mempertingkatkan kebolehan subgred sebagai bahan yang kuat dan stabil. Daripada kajian terdahulu, simen telah digunakan secara meluas sebagai bahan penstabil untuk pembinaan bangunan. Justeru, objektif utama penyelidikan ini adalah untuk mengkaji keupayaan simen sebagai bahan penstabil dalam proses penstabilan tanah. Oleh itu, beberapa analisis makmal telah dijalankan mengikut rumusan campuran antara peratusan simen yang berbeza dengan tanah laterit. Jenis simen yang digunakan dalam penyelidikan ini ialah Ordinary Portland Cement (OPC) CEM I 42.5N. Daripada keputusan ujian mampatan tidak tertutup (UCT), ia menunjukkan bahawa 6% tanah laterit yang dirawat dengan simen pada 7 hari pengawetan mampu mencapai kekuatan tanah yang stabil yang diperlukan (800 kPa) bagi jalan isipadu rendah oleh Jabatan Kerja Raya Malaysia untuk 1.0 juta Beban Gandar Tunggal Setara (ESAL). Selain itu, keputusan UCT juga menunjukkan bahawa penambahan simen meningkatkan kekuatan tanah, yang juga telah dibuktikan oleh imej mikrostruktur tanah daripada analisis mikrostruktur. Ujian kebolehmampatan membuktikan bahawa tanah laterit mengalami kebolehmampatan yang tinggi dalam keadaan tepu penuh, manakala kebolehmampatan berkurangan dengan ketara dalam keadaan separa tepu. Oleh itu, ujian oedometer tak tepu menandakan pengurangan besar dalam kebolehmampatan tanah pada tahap sedutan yang lebih tinggi (keadaan kering) berbanding sedutan yang lebih rendah (keadaan basah). Kesimpulannya, hasil penyelidikan ini merupakan satu pengetahuan asas dengan membuktikan keupayaan simen untuk digunakan sebagai penstabil bahan subgred dalam garis panduan reka bentuk pembinaan jalan raya di Malaysia.

TABLE OF CONTENTS

TITLE			PAGE
	DECLARATION		**iii**
	DEDICATION		**iv**
	ACKNOWLEDGEMENT		**v**
	ABSTRACT		**vi**
	ABSTRAK		**vii**
	TABLE OF CONTENTS		**viii**
	LIST OF TABLES		**xii**
	LIST OF FIGURES		**xiv**
	LIST OF ABBREVIATIONS		**xx**
	LIST OF SYMBOLS		**xxii**
	LIST OF APPENDICES		**xxiv**
CHAPTER 1	**INTRODUCTION**		**1**
1.1	Laterite Soil		1
1.2	Background Study		1
1.3	Problem Statement		3
1.4	Research Objectives		4
1.5	Scope of Study		4
1.6	Research Significance		5
1.7	Thesis Outline		6
CHAPTER 2	**LITERATURE REVIEW**		**9**
2.1	Introduction		9
2.2	Laterite Soil		9
2.3	Soil Stabilisation		14
	2.3.1	Biological Stabilisation	16
	2.3.2	Mechanical Stabilisation	16
	2.3.3	Chemical Stabilisation	17
2.4	Selection of Stabiliser		18
2.5	Cement Stabilisation		20

		2.5.1	Effect of Cement on the Compaction Properties of Laterite Soil	26
		2.5.2	Effect of Cement on the Unconfined Compressive Strength (UCS) of Laterite Soil	29
			2.5.2.1 Correlation between Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR)	31
	2.6	Compressibility Characteristics for Saturated and Unsaturated Laterite Soil		32
		2.6.1	Conventional Oedometer	34
			2.6.1.1 Untreated Laterite Soil	35
			2.6.1.2 Treated Laterite Soil	37
		2.6.2	Modified Oedometer	41
			2.6.2.1 Untreated Laterite Soil	45
			2.6.2.2 Treated Laterite Soil	49
	2.7	Microstructural Analysis of Untreated Laterite Soil		55
		2.7.1	Field Emission Scanning Electron Microscopy (FESEM)	55
		2.7.2	X-ray Diffraction (XRD)	57
		2.7.3	X-ray Fluorescence (XRF)	59
	2.8	Microstructural Analysis of Cement-Treated Laterite Soil		59
		2.8.1	Field Emission Scanning Electron Microscopy (FESEM)	60
		2.8.2	X-ray Diffraction (XRD)	60
		2.8.3	Mercury Intrusion Microscopy (MIP)	61
	2.9	Empirical Theories of Loading-Collapse (LC) Curve for Unsaturated Soil		62
	2.10	Chapter Summary		67
CHAPTER 3	**RESEARCH METHODOLOGY**			**69**
	3.1	Introduction		69
	3.2	Selection of Chemical Stabilisation Method		71
	3.3	Research Materials		71
		3.3.1	Laterite Soil	71
		3.3.2	Ordinary Portland Cement	73
	3.4	Determination of Materials Properties		74

3.5	Physical Properties of Laterite Soil	77
3.6	Mechanical Properties of Laterite Soil	77
	3.6.1 Consolidation	78
	3.6.2 Laboratory Test using Modified Oedometer	89
	3.6.2.1 Modified Suction-Controlled Oedometer Calibration	90
	3.6.2.2 Application of High Air Entry Value (HAEV) Ceramic Disk	92
	3.6.2.3 Ceramic Disk Saturation and Flushing Air Bubbles	93
	3.6.2.4 Ceramic Disk Permeability Checking	94
	3.6.2.5 Selection of Applied Suction	94
	3.6.2.6 Sample Preparation	95
	3.6.2.7 Experimental Programs of the Volume Change Test Performance at Constant Suction	96
3.7	Cement Testing	98
	3.7.1 Initial Consumption of Cement (ICC)	98
	3.7.2 pH Test	98
3.8	Microstructural Analysis	99
	3.8.1 Field Emission Scanning Electron Microscopy (FESEM)	99
	3.8.2 Energy Dispersive X-ray (EDX)	101
	3.8.3 X-ray Diffraction (XRD)	102
	3.8.4 X-ray Fluorescence (XRF)	103
	3.8.5 Mercury Intrusion Porosimetry (MIP)	105
3.9	Chapter Summary	106
CHAPTER 4	**RESULTS AND DISCUSSIONS**	**109**
4.1	Introduction	109
4.2	Properties of Untreated and Cement-Treated Laterite Soil	109
	4.2.1 Physical Properties	109
	4.2.2 Mechanical Properties	113
	4.2.2.1 Compaction	113

4.2.2.2 Unconfined Compressive Strength (UCS) 116

4.2.2.3 Consolidation 125

4.2.3 Cement Testing 139

4.2.4 Microstructural Properties 140

4.2.4.1 Field Emission Scanning Electron Microscopy (FESEM) 140

4.2.4.2 Energy Dispersive Energy (EDX) 148

4.2.4.3 X-ray Diffraction (XRD) 155

4.2.4.4 X-ray Fluorescence (XRF) 157

4.2.4.5 Mercury Intrusion Porosimetry (MIP) 158

4.3 Evaluation of Empirical Theory of Loading-Collapse (LC) Curve for Unsaturated Untreated and Cement-treated Soil 161

4.4 Chapter Summary 163

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS 167

5.1 Introduction 167

5.2 Research Outcomes 167

5.2.1 Outcomes Objective 1 168

5.2.2 Outcomes Objective 2 168

5.2.3 Outcomes Objective 3 169

5.2.4 Outcomes Objective 4 169

5.3 Contributions to Knowledge 170

5.4 Recommendations for Future Research 171

REFERENCES 173

LIST OF PUBLICATIONS 208

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Composition of laterite soil in different places	13
Table 2.2	Categories of residual soil (Gidigasu, 1974)	13
Table 2.3	Stabilised material requirements for pavement structure of traffic up to 1.0 million ESAL (Public work department of Malaysia, 2012)	20
Table 2.4	Different types of Portland Cement (Ali, 2019)	21
Table 2.5	Soil parameters in compaction test (Amir Husain, 2017)	27
Table 2.6	Summary of correlation between UCS and CBR	32
Table 2.7	Soil compressibility in Malaysia and other countries from various sources under saturated conditions	36
Table 2.8	Treated soil compressibility from various sources under saturated conditions	39
Table 2.9	Summary of heavy metals' effect on the compressibility of treated laterite (Saeed *et al.*, 2019)	41
Table 2.10	Soil compressibility in Malaysia and other countries from various sources under unsaturated conditions	49
Table 2.11	Treated soil compressibility from various sources under unsaturated conditions	54
Table 2.12	XRF analysis from various sources	59
Table 2.13	Various research on the unsaturated treated soil	68
Table 3.1	Physical properties testing program	75
Table 3.2	Mechanical properties testing program	76
Table 3.3	Microstructural properties testing program	76
Table 3.4	Stress paths for conventional oedometer (saturated condition)	81
Table 3.5	Experimental programs for the modified oedometer test	95
Table 3.6	Stress paths for modified suction-controlled oedometer (unsaturated condition) at constant suction test of 20 kPa and 400 kPa	97

Table 3.7	Overall laboratory testing programme	107
Table 4.1	Properties of laterite soil	110
Table 4.2	Residual soil properties at the UTM Johor Bahru campus	112
Table 4.3	Results of maximum compressive strength and strain for untreated and treated laterite soil	116
Table 4.4	Summary of correlation between UCS and CBR based on the previously generated correlation equations	124
Table 4.5	Compressibility results for untreated and cement-treated laterite	126
Table 4.6	Coefficient of volume compressibility, m_v (x10^{-4} m^2/kN) for all specimens at every loading stage	132
Table 4.7	Differences between void ratio for untreated and 6% cement-treated laterite	135
Table 4.8	pH test results for cement	139
Table 4.9	Elements ratios for untreated and cement-treated laterite soil from the EDX analysis	154
Table 4.10	XRF analysis for cement, untreated, and cement-treated laterite	158
Table 4.11	Effect of partial saturation (suction) from the obtained P_c	162
Table 4.12	Effect of cementation (bonding) from the obtained yield stress	162
Table 4.13	Compressibility parameters for conventional and modified suction-controlled oedometer tests	165

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Research model analysis of the factor that impacts road damage in Malaysia (Shehu *et al.*, 2014)	11
Figure 2.2	Weathering profile for residual soil (Salih, 2012)	12
Figure 2.3	Cross Section of Flexible Pavement (McHenry and Rose, 2012)	15
Figure 2.4	Chemical reactions and reaction products from different stabilisers (Hassan, 2009)	18
Figure 2.5	Stabilised material requirements for pavement structure of traffic up to 1.0 million ESAL (Public work department of Malaysia, 2012)	19
Figure 2.6	Process of cementitious hydration (Hall, 2012)	22
Figure 2.7	Process of pozzolanic reaction (Hall, 2012)	23
Figure 2.8	Process of particle restructuring (Hall, 2012)	24
Figure 2.9	Process of cation exchange (Hall, 2012)	24
Figure 2.10	Road condition after 18 months of construction	26
Figure 2.11	MDDs Comparison for 0% to 10% of lime and cement agents (Afolayan *et al.*, 2018)	28
Figure 2.12	Modes of failure in UCS test (Chakraborty *et al.*, 2019)	30
Figure 2.13	Strength comparison for clayey soil with OPC at different moisture conditions and curing periods (Ghadir & Ranjbar, 2018)	31
Figure 2.14	Conventional oedometer equipment (Jia, 2018)	35
Figure 2.15	CSP Oedometer Equipment (Por *et al.*, 2017)	37
Figure 2.16	Recompression index for various cement-treated soil (Mengue *et al.*, 2018b)	40
Figure 2.17	Principle of axis translation technique (Kholghifard, 2014)	44
Figure 2.18	Schematic Diagram of Suction Controlled Oedometer Equipment with (a) saline and (b) PEG Solutions (Cuisinier & Masrouri, 2005)	46

Figure 2.19	Variation of compression index, Cc for loose and dense residual soil (Kholghifard, 2014)	48
Figure 2.20	Compression curve results for untreated and lime-treated London clay (Mavroulidou *et al.*, 2013)	51
Figure 2.21	Void ratio versus net vertical stress for untreated and lime-treated loess soil (Haeri *et al.*, 2019)	52
Figure 2.22	FESEM micrograph of laterite soil (Bello *et al.*, 2018)	56
Figure 2.23	FESEM micrograph of untreated residual soil (Dhar and Hussain, 2021)	56
Figure 2.24	Kaolinite morphology (Latifi, 2014)	58
Figure 2.25	Illite morphology (Latifi, 2014)	58
Figure 2.26	FESEM image of cement-treated soil (Chew *et al.*, 2004)	60
Figure 2.27	XRD pattern before and after the cement addition (Jaritngam *et al.,* 2012)	61
Figure 2.28	Pore size distribution of cement stabilised silty clay (Horpibulsuk *et al.*, 2010)	62
Figure 2.29	Yield surface in three-dimensions based on BBM (Gens *et al.*, 2006)	64
Figure 2.30	LC curve evolution under constant suction (Chinkulkijniwat *et al.*, 2015)	64
Figure 2.31	Yield stress as a function of suction in LC curve (Pereira *et al.*, 2014)	66
Figure 2. 32	LC curve for unsaturated clayey soil under wetting and drying conditions (Kholghifard, 2020)	67
Figure 3.1	Research methodology flowchart for laboratory testing	70
Figure 3.2	Borrow pit location nearest to P16 block, Faculty of Electrical Engineering, UTM Johor Bahru	72
Figure 3.3	Digging work of the laterite soil	72
Figure 3.4	Test certificate of OPC/Holcim	74
Figure 3.5	TDS-540 data logger	79
Figure 3.6	Functions of TDS-540 data logger	79
Figure 3.7	Conventional oedometer equipment setup	82
Figure 3.8	Conventional oedometer assembly system	82
Figure 3.9	Conventional oedometer components	83

Figure 3.10	Modified oedometer schematic diagram	84
Figure 3.11	Modified oedometer equipment setup	85
Figure 3.12	Modified oedometer assembly system	86
Figure 3.13	Modified oedometer components	87
Figure 3.14	GDS data logger (USB 8 channel logger)	88
Figure 3.15	GDS advance pressure/volume controller (ADVDPC)	88
Figure 3.16	GDS pneumatic pressure controller	88
Figure 3.17	Flow chart for modified oedometer test	89
Figure 3.18	LVDT calibration graph	90
Figure 3.19	Pore water pressure calibration graph	91
Figure 3.20	Pore air pressure calibration graph	92
Figure 3.21	1500 kPa / 15 bar HAEV ceramic disk	93
Figure 3.22	Ceramic disk permeability checking graph	94
Figure 3.23	Sample is compacted into the oedometer	96
Figure 3.24	pH test for the ICC	99
Figure 3.25	FESEM machine	100
Figure 3.26	Sample preparation for FESEM test	100
Figure 3.27	QUORUM Automated Platinum Sputter Coater	101
Figure 3.28	FESEM machine with an EDX system	102
Figure 3.29	XRD machine	103
Figure 3.30	XRF machine	104
Figure 3.31	Inside view of the XRF machine	104
Figure 3.32	MIP machine	105
Figure 3.33	Sample preparation for MIP test	106
Figure 4.1	Particle size distribution curve of laterite soil	111
Figure 4.2	Dry density vs Moisture content for laterite soil	114
Figure 4.3	Maximum dry density vs optimum moisture content for untreated and treated laterite soil	115
Figure 4.4	Maximum dry density vs. optimum moisture content at different cement percentages	115

Figure 4.5 Axial stress (kPa) versus axial strain (%) for untreated and cement-treated laterite soil at 0 days curing 118

Figure 4.6 Axial stress (kPa) versus axial strain (%) for untreated and cement-treated laterite soil at 3 days curing 118

Figure 4.7 Axial stress (kPa) versus axial strain (%) for untreated and cement-treated laterite soil at 7 days curing 119

Figure 4.8 Axial stress (kPa) versus axial strain (%) for untreated and cement-treated laterite soil at 14 days curing 119

Figure 4.9 Axial stress (kPa) versus axial strain (%) for untreated and cement-treated laterite soil at 28 days curing 120

Figure 4.10 Sample failure damage for untreated and cement-treated laterite soil at 7 days curing 121

Figure 4.11 Maximum compressive strength (kPa) at different curing periods and cement dosages (%) 122

Figure 4.12 Variation of elastic modulus (E_{50}) and UCS 123

Figure 4.13 CBR versus UCS based on the previously generated correlation equations 124

Figure 4.14 Pavement structure for traffic category T1: < 1.0 million ESAL (80 kN) (Malaysia Public Work Department, 2013a) where SG: subgrade, CBR; California bearing ratio, BSC: bituminous surface course, CAB: crushed aggregate base course, GSB: granular subbase 125

Figure 4.15 Pc values for untreated and cement-treated laterite at 7 days curing 127

Figure 4.16 Compression index values for untreated and cement-treated laterite at 7 days curing 128

Figure 4.17 Recompression index values for untreated and cement-treated laterite at 7 days curing 129

Figure 4.18 Effective stress versus void ratio for untreated and cement-treated laterite at 7 days curing period 130

Figure 4.19 Variation of coefficient of consolidation for untreated and cement-treated laterite at various loading stages 131

Figure 4.20 Coefficient of volume compressibility, m_v ($x10^{-4}$ m^2/kN) for all specimens at every loading stage 132

Figure 4.21 Applied stress versus void ratio for untreated and 6% cement-treated laterite subjected to various suction 134

Figure 4.22	Preconsolidation pressure values for untreated and 6% cement-treated laterite subjected to various suction (best-fit line using power-law)	136
Figure 4.23	Compression index values for untreated and 6% cement-treated laterite subjected to various suction (best-fit line using power-law)	137
Figure 4.24	Recompression index values for untreated and 6% cement-treated laterite subjected to various suction (best-fit line using power-law)	138
Figure 4.25	pH test for the determination of ICC	140
Figure 4.26	FESEM image of laterite soil at (a) 5k, (b) 10k, (c) 30k, (d) 50k magnification	143
Figure 4.27	FESEM image of 30k magnification for (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 3 days curing	144
Figure 4.28	FESEM image of 30k magnification for (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 7 days curing	145
Figure 4.29	FESEM image of 30k magnification for (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 14 days curing	146
Figure 4.30	FESEM image of 30k magnification for (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 28 days curing	147
Figure 4.31	EDX analysis of cement	148
Figure 4.32	EDX analysis of natural laterite soil	149
Figure 4.33	EDX analysis of (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 3 days curing	150
Figure 4.34	EDX analysis of (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 7 days curing	151
Figure 4.35	EDX analysis of (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 14 days curing	152
Figure 4.36	EDX analysis of (a) 3%, (b) 6%, (c) 9%, and (d) 12% cement-treated laterite soil at 28 days curing	153
Figure 4.37	XRD spectrum for cement where Qz: Quartz, Pt: Portlandite, CAH: calcium aluminate hydrate	156
Figure 4.38	XRD spectrum for natural laterite soil where Qz: Quartz, Kao: Kaolinite, Illi: Illite, Geo: Geothite, Gib: Gibbsite	156

Figure 4.39	XRD spectrum for 6% cement-treated laterite at 7 days curing, where Qz: Quartz, Kao: Kaolinite, Illi: Illite, Geo: Geothite, Gib: Gibbsite, Cal: Calcite, Ett: Ettringite, Pt: Portlandite	157
Figure 4.40	Pore diameter versus incremental pore volume of the untreated and cement-treated laterite soil	160
Figure 4.41	Pore diameter versus cumulative intrusion of the untreated and cement-treated laterite soil	160
Figure 4.42	LC curve for both untreated and cement-treated laterites under various suction (best-fit line using power-law)	163

LIST OF ABBREVIATIONS

UCT	-	Unconfined Compression Test
ESAL	-	Equivalent Single Axle Load
UCS	-	Unconfined Compressive Strength
OPC	-	Ordinary Portland Cement
MIROS	-	Malaysian Institute of Road Safety Research
ADT	-	Average Daily Traffic
CBR	-	California Bearing Ratio
MDD	-	Maximum Dry Density
PEG	-	Polyethylene glycol
HAEV	-	High-Air-Entry Value
LS	-	Loose Soil
DS	-	Dense Soil
SWCC	-	Soil Water Characteristics Curve
CSP	-	Confined Swelling Pressure
FESEM	-	Field Emission Scanning Electron Microscopy
XRD	-	X-ray Diffraction
XRF	-	X-ray Fluorescence
BBM	-	Barcelona Basic Model
MCC	-	Modified Cam Clay
LC	-	Loading-Collapse
EDX	-	Energy Dispersive X-ray
MIP	-	Mercury Intrusion Porosimetry
ICC	-	Initial Consumption Cement
UTM	-	Universiti Teknologi Malaysia
USM	-	Universiti Sains Malaysia
MS	-	Malaysian Standard
ISO	-	International Organization for Standardization
BS	-	British Standard
ASTM	-	American Society of Testing Material

PSD	-	Particle Size Distribution
LDM	-	Laser Diffraction Method
PI	-	Plasticity Index
OMC	-	Optimum Moisture Content
TML	-	Tokyo Measuring Instruments Lab
LVDT	-	Linear Variable Displacement Transducer
ADVDPC	-	Advance Pressure/Volume Controller
PPC	-	Pneumatic Pressure Controller
ICL	-	Initial Consumption Lime
LL	-	Liquid Limit
PL	-	Plastic Limit
USCS		Unified Soil Classification System

LIST OF SYMBOLS

C_2S	-	Dicalcium Silicate
C_3S	-	Tricalcium Silicate
C_3A	-	Tricalcium Aluminate
C_4AF	-	Tetracalciumaluminoferrite
CAH	-	Calcium Aluminate Hydrate
CSH	-	Calcium Silicate Hydrate
CASH	-	Calcium Alumina Silicate Hydrate
$CA(OH)_2$	-	Calcium Hydroxide
H_2O	-	Water
Ψ	-	Total Suction
Ψ_0	-	Osmotic Suction
u_a	-	Air Pressure
u_w	-	Water Pressure
S_c	-	Compressibility Settlement
P_c	-	Preconsolidation Pressure
C_c	-	Compression Index
C_s	-	Swelling Index
C_v	-	Coefficient of Consolidation
a_v	-	Coefficient of Compressibility
m_v	-	Coefficient of Volume Compressibility
MgO	-	Magnesium Oxide
Na_2O	-	Sodium Oxide
K_2O	-	Potassium Oxide
Fe_2O_3	-	Ferric Oxide / Iron Oxide
Al_2O_3	-	Aluminium Oxide
SiO_2	-	Silicon Oxide
$\bar{\sigma}_{ij}$	-	Net Stress
σ_{ij}	-	Total Stress
s	-	Suction
δ_{ij}	-	Kroneckers's Delta

P	-	Effective Stress
E	-	Void Ratio
Ca	-	Calcium
O	-	Oxygen
Al	-	Aluminium
Si	-	Silicon
Fe	-	Iron
Qz	-	Quartz
Pt	-	Portlandite
Kao	-	Kaolinite
Ill	-	Illite
Geo	-	Geothite
Gibb	-	Gibbsite
Cal	-	Calcite
Ett	-	Ettringite
P_2O_5	-	Phosphorus Pentoxide
CaO	-	Calcium Oxide
V_2O_5	-	Vanadium Oxide
Cr_2O_3	-	Chromium Oxide
MnO	-	Manganese Oxide
NiO	-	Nickel Oxide
CuO	-	Copper Oxide
ZnO	-	Zinc Oxide
Rb_2O	-	Rubidium Oxide
PdO	-	Palladium Oxide
La_2O_3	-	Lanthanum Oxide
Eu_2O_3	-	Europium Oxide
Re_2O_7	-	Rhenium Oxide
PbO	-	Lead Oxide

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Compression curve in conventional oedometer test for (a) untreated, (b) 3% cement-treated, (c) 6% cement-treated, (d) 9% cement-treated, (e) 12% cement-treated	189
Appendix B	Coefficient of consolidation, C_v (m^2/year) versus effective stress, P (kPa) in conventional oedometer test for (a) untreated, (b) 3% cement-treated, (c) 6% cement-treated, (d) 9% cement-treated, (e) 12% cement-treated	191
Appendix C	Compression curve in modified oedometer test for (a) untreated at 20 kPa suction, (b) untreated at 400 kPa suction, (c) 6% cement-treated at 20 kPa suction, (d) 6% cement-treated at 400 kPa suction	193
Appendix D	Volume change (mm^3) versus time (s) for untreated laterite at 20 kPa suction	194
Appendix E	Volume change (mm^3) versus time (s) for untreated laterite at 400 kPa suction	197
Appendix F	Volume change (mm^3) versus time (s) for 6% cement-treated laterite at 20 kPa suction	200
Appendix G	Volume change (mm^3) versus time (s) for 6% cement-treated laterite at 400 kPa suction	204

CHAPTER 1

INTRODUCTION

1.1 Laterite Soil

Laterite soil occupies most of Asia's tropical areas significantly. It is one of the best raw materials to be used in road and highway construction. It is naturally well-graded soil, which comprises both cohesive (clay and silt) and non-cohesive (gravel and sand) elements. Indeed, the geotechnical properties of laterite soil are composed of micro-fabric, mineralogical composition, and geochemical environmental conditions. Hence, the clay minerals and sesquioxides in the laterite soil are very beneficial in the process of natural binding as well as in the presence of most chemical binders (Oyelami and Van Rooy, 2016).

The excellent quality and adequacy of laterite soil have satisfied the material specifications for road construction over the past years in Malaysia. However, the established laterite soil has become a problem for the road construction industry because of Malaysia's climate conditions. The use of laterite soil as a subgrade in pavement design for low-volume roads is considered collapsible due to the flooding season. The Flood Management Centre of Malaysia's Public Work Department reported that Johor spent more than RM60.7 million on flood-damaged roads in only one flood season (Ismail and Abdul Ghani, 2017). Therefore, it is evident that the weather conditions of flood and dry seasons create a risk of damage to the road structure.

1.2 Background Study

As laterite soils are naturally and originally in an unsaturated condition, using conventional saturated soil mechanics theory in analysing those soils may lead to bizarre results (Fredlund and Rahardjo, 1993). This is because the obtained compressibility characteristics and shear strength behaviour using conventional soil mechanics are dissimilar from the soil behaviour in unsaturated conditions since several factors substantially influence the variation of negative pore water pressure (suction) in unsaturated soils. The natural factors mainly refer to the soil's hydraulic properties or hydraulic conductivity, while the external factors refer to the climate conditions (rainfall and dry seasons). The alternate climate change affects the soil properties, which makes them weak. Hence, various problems will occur, such as soil collapse, slope failure, and road damage in Malaysia associated with those factors (Kholghifard, 2014).

The road is a passage for all people worldwide, as we depend on the road for the movement of goods, transport, travel, work, and social and service purposes. In building construction, the foundation must be vital to withstand tons of capacity. The same goes for the road infrastructure; the subgrade layer shall be stabilised with appropriate material to enhance the strength. Hence, highway engineers face the most difficulties in planning, designing, and constructing the desirable road layers (subgrade, subbase, road base, binder, and wearing course), which can sustain huge loads from tire pressure and wheel burden.

Consequently, the soil stabilisation technique has been widely applied in pavement construction. Soil stabilisation is a method of soil treatment (by adding materials to the soil) that is used to increase soil stability by improving its geotechnical properties. Nevertheless, complex problems in road paving work usually occur when the subgrade contains unsuitable materials. Unsuitable material is referred to the soil that consists of high organic silt and clay (LL > 80% or PI > 55%) (Malaysia Public Work Department, 2013b). Soil may swell when the clay content is excessive as the water content is permitted to increase. Therefore, the stabilisation process allows the use of unsuitable materials in road structures. The soil stabilising agents act as a binder to enrich the undesirable soil behaviour. With the addition of stabilising additives, the soil can maintain its particle cohesion and sustain its moisture content. Besides, these additives may be used as soil strengthening and waterproofing agents (Addo et al., 2004).

The use of stabilisation in enhancing material properties is becoming more extensive. This is because the stabilisation capability is particularly pertinent for heavily trafficked roadways where its advantages are starting to be valued. Due to various related parameters, the stabilisation procedures become very complicated. However, the typical soil stabilisation method involves eliminating and substituting weak soil with suitable materials such as geotextiles. Yet, such practices acquire higher costs and usually require a long time to execute.

1.3 Problem Statement

Climate change is a long-term alteration worldwide, including periodic temperature, rainfall averages, and wind patterns. Due to the effects of climate change, Malaysia experiences dry and rainy seasons every year. These weather conditions may cause massive damage to building and road structure. In road pavement construction, laterite soil is considered a suitable material to be used as subgrade material. A variety of subgrade options exist for constructing a low-volume road network. Material selection for subgrade depends on the road use (amount and traffic load), material availability, and cost. To attain a durable foundation section, subgrade reinforcement is most frequently used with a layer of crushed aggregate positioned over a weaker subgrade soil. In subgrade requirements, aggregates must consist of well-graded coarse particles with sufficient fines. Wherever aggregate is unavailable or high-priced, other soil stabilisation techniques may be used.

Hence, in this research, cement is chosen as the stabiliser to ensure that the subgrade layer has achieved a minimum of 800 kPa of Unconfined Compressive Strength (UCS) for the stabilised base according to pavement structure requirements for traffic up to 1.0 million ESAL (Equivalent Single Axle Load) by Malaysia Public Work Department (2017). Regarding Sheng *et al.* (2011), during the dry and rainy seasons, a moisture content variant triggered changes in the shear strength of compacted soils in unsaturated conditions. Unfortunately, the current pavement design is more concerned with the saturated condition, which may contribute to an unsustainable structure without acknowledging matric suction contribution. Thus, the changes in moisture content on the mechanical behaviour of cement stabilised soil should be considered. This is because the significance of stabilising unsaturated soil is to enhance the optimisation of the coupling effect of the stabiliser and soil matric suction in the subgrade for advanced sustainable design.

1.4 Research Objectives

The aims of this study are to provide basic knowledge in the design guidelines for road construction projects in Malaysia and to demonstrate the ability of cement to be applied as a stabiliser for subgrade material. Hence, there are several objectives are drawn to achieve in this study, which are:

1. To characterise the laterite soil by determining its physical and mechanical properties.
2. To determine the compressive strength and compressibility of the untreated and cement-treated laterite soil.
3. To examine the effect of microstructure on the cement contents and curing periods of the untreated and cement-treated laterite soil.
4. To evaluate the coupling effect of cementation and suction based on the empirical theory of the Loading-Collapse (LC) curve.

1.5 Scope of Study

Laterite soil was used in this study since it is abundant and widely available in tropical regions such as Malaysia (Hadi *et al.*, 2020). At the same time, the cement used in this research is from the Holcim brand of OPC (CEM I 42.5N), YTL Cement Sdn. Bhd. Cement is used as a stabiliser because soil-cement mixing is the most widely used method to improve the poor engineering properties of laterite soil (Mengue, 2017).

The laterite soil samples were obtained from the nearest borrow pit at Blok P16, Faculty of Electrical Engineering, Universiti Teknologi Malaysia Johor Bahru (1°33'32.9"N, 103°38'39.4"E). In order to extend these findings, various cement percentages were chosen and studied for the laterite soil stabilisation process. Hence, for further laboratory analysis, cement proportions used on the soil samples are 3%, 6%, 9%, and 12% at curing periods of 3, 7,14, and 28 days.

This study focuses on the strength and compressibility characteristics of untreated and cement-treated laterite soils. The soil strength is obtained from the UCS test, where the sample preparation is based on the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) values from the compaction test. Meanwhile, the soil compressibility is obtained through the conventional oedometer (indicating the saturated condition – rainy season) and modified suction-controlled oedometer (indicating the unsaturated condition – dry season) tests. In order to apply the test in constant suction of 0, 20, and 400 kPa, the modified suction-controlled oedometer test is conducted based on the technique of axis translation.

Additionally, numerous microstructural analyses have been conducted, such as Field Emission Scanning Electron Microscopy (FESEM), Energy Dispersive X-ray (EDX), X-ray Diffraction (XRD), X-ray Fluorescence (XRF), and Mercury Intrusion Porosimetry (MIP) to identify the behaviour, changes and mineral formation of the laterite soil after treated with cement.

1.6 Research Significance

Due to a lack of understanding of the geotechnical behavior of unsaturated soil, particularly related to suction changes; highway foundations and other structures have been destroyed due to drying or wetting conditions. Therefore, it is crucial to study the changes in the behaviour of untreated and cement-treated laterite soils subjected to drying (unsaturated condition) and wetting (saturated condition) through climatic changes.

Hence, conventional oedometer method was employed to perform compressibility tests under saturated conditions. Meanwhile, modified suction-controlled oedometer with the ability to apply and control the suction and automatic pressure adjustments, was used to conduct compressibility tests under unsaturated condition so that the outcomes of this research can be proposed in the design guidelines for Malaysia's road infrastructure.

1.7 Thesis Outline

This research comprises of five chapters. The description and explanation for each chapter are as follows:

Chapter 1 mainly outlines the background of research problems related to laterite soil improvements by stabilisation technique and also describes the study's aims, scope and importance.

Next, chapter 2 discusses the literature review for this research. The review includes the properties of lateritic soil and their purposes in building construction. Details of the soil stabilisation method with various agents have also been stated. A similar study that previous researchers have performed is also widely reviewed in this chapter.

Chapter 3 explains the research methodology, which includes numerous laboratory tests to analyse the strength and compressibility of lateritic soil with cement. Details of the experiment are also discussed in this chapter.

Chapter 4 elaborates on the outcomes and findings of geotechnical testing. Laboratory testing has been conducted to reveal the geotechnical properties of lateritic soil and cemented lateritic soil under cyclic saturated and unsaturated conditions.

Last but not least, the conclusion of this study and recommendations for future studies are discussed in Chapter 5.

REFERENCES

A Rashid, A. S. (2011) *Behaviour of Weak Soils Reinforced with Soil Columns Formed By The Deep Mixing Method*. PhD Dissertation. Department of Civil and Structural Engineering, University of Sheffield.

Abbey, S. J. (2020) 'Swell and microstructural characteristics of high-plasticity clay blended with cement', *Bulletin of Engineering Geology and the Environment*. Bulletin of Engineering Geology and the Environment, 79, pp. 2119–2130.

Addo, J. Q., Sanders, T. G. and Chenard, M. (2004) *Road Dust Suppression: Effect on Maintenance Stability, Safety and the Environment Phases 1-3, Department of Roads and Bridges, Colorado State University,*.

Ademila, O. (2017) 'Engineering Evaluation of Lateritic Soils of Failed Highway Sections in Southwestern Nigeria', *Geosciences Research*, 2(3), pp. 210–218.

Afolayan, O. D., Tijani, M. A. and Akinleye, M. T. (2018) 'Development of Analytical Relationships among Engineering Properties of Lateritic Soil as Pavement Materials', 8(1), pp. 15–20.

Ahmad, F., Yahaya, A. S. and Farooqi, M. A. (2006) 'Characterization and Geotechnical Properties of Penang Residual Soils with Emphasis on Landslides', *American Journal of Environmental Sciences*, 2(4), pp. 121–128.

Ahmad, K. (2004) *Improvement of a Tropical Residual Soil by Electrokinetic Process*. PhD Dissertation. Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Ahmad, K. Bin, Taha, M. R. and Kassim, K. A. (2011) 'Electrokinetic treatment on a tropical residual soil', *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 164(1), pp. 3–13.

Akinniyi, D. B. (2019) *Compressibility and shear behaviour of saturated and unsaturated lateritic clay rich in sesquioxide*. PhD Dissertation. The Hong Kong University of Science and Technology.

Al-Jabban, W., Laue, J., Knutsson, S. and Al-Ansari, N. (2019) 'A comparative evaluation of cement and by-product petrit T in soil stabilization', *Applied Sciences (Switzerland)*, 9(23), pp. 1–20.

Al-Swaidani, A., Hammoud, I. and Meziab, A. (2016) 'Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil', *Journal of Rock Mechanics and Geotechnical Engineering*. Elsevier Ltd, 8(5), pp. 714–725.

Alonso, E. (1990) 'A Constitutive Model for Partially Saturated Soils', *Geotechnique*, 40 (3)(January), pp. 405–430.

Alonso, E. E. and Gens, A. (1993) 'Keynote lecture: On the mechanical behaviour of arid soils', in *Engineering Characteristics of Arid Soils*, pp. 173–206.

Alonso, E. E., Gens, A. and Delahaye, C. H. (2003) 'Influence of rainfall on the deformation and stability of a slope in overconsolidated clays: A case study', *Hydrogeology Journal*, 11(1), pp. 174–192.

Amir Husain, A. N. (2017) *Soil Compaction For Natural Laterite Soil.* Degree Dissertation. Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Amu, O. O., Bamisaye, O. F. and Komolafe, I. A. (2011) 'Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study', *Int. J. Pure Appl. Sci. Technol*, 2(1), pp. 29–46.

Anggraini, V., Asadi, A., Syamsir, A. and Huat, B. B. K. (2017) 'Three point bending flexural strength of cement treated tropical marine soil reinforced by lime treated natural fiber', *Measurement: Journal of the International Measurement Confederation*. Elsevier, 111(February 2016), pp. 158–166.

Arroyo, M., Amaral, M. F., Romero, E. and da Fonseca, A. V. (2013) 'Isotropic yielding of unsaturated cemented silty sand', *Canadian Geotechnical Journal*, 50(8), pp. 807–819.

Ayininuola, G. M. and Akinniyi, B. D. (2016) 'Bone Ash Influence on Soil Consolidation', *Malaysian Journal of Civil Engineering*, 28(3), pp. 407–422.

Aziz, A. A., Ali, F. H., Heng, C. F., Mohammed, T. A. and Huat, B. B. K. (2006) 'Collapsibility and Volume Change Behavior of Unsaturated Residual Soil', *American Journal of Environmental Sciences*, 2(4), pp. 161–166.

Azri, Z. (2015) *Unconfined Compressive Strength of Laterite Soil Stabilized with Biopolymer*, *Universiti Teknologi Malaysia*. Degree Dissertation. Faculty of Civil engineering, Universiti Teknologi Malaysia.

Behnood, A. (2018) 'Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques', *Transportation Geotechnics*. Elsevier, 17(July), pp. 14–32.

Benatti, J. C. B., Miguel, M. G., Rodrigues, R. A. and Vilar, O. M. (2011) 'Collapsibility study for tropical soil profile using oedometric tests with controlled suction', in *Fifth International Conference on Unsaturated Soils*, pp. 1–7.

Bhattacharja, S., Bhatty, J. I. and Todres, H. A. (2003) 'Stabilization of Clay Soils by Portland Cement or Lime–A Critical Review of Literature', *PCA R&D Serial*, p. 60.

Billong, N., Melo, U. C., Louvet, F. and Njopwouo, D. (2009) 'Properties of compressed lateritic soil stabilized with a burnt clay-lime binder: Effect of mixture components', *Construction and Building Materials*. Elsevier Ltd, 23(6), pp. 2457–2460.

Bourman, R. P. and Ollier, C. D. (2002) 'A critique of the Schellmann definition and classification of "laterite"', *Catena*, 47(2), pp. 117–131.

Bruno, A. W., Gallipoli, D., Rouainia, M. and Lloret-Cabot, M. (2020) 'A bounding surface mechanical model for unsaturated cemented soils under isotropic stresses', *Computers and Geotechnics*, 125, pp. 1–33.

Chakraborty, S., Bisai, R., Palaniappan, S. K. and Pal, S. K. (2019) 'Failure modes of rocks under uniaxial compression tests: an experimental approach', *Journal of Advances in Geotechnical Engineering*, 2(3), pp. 1–8.

Chan, C. and Abdullah, S. H. (2006) 'Settlement Behaviour of a Cement-Stabilised Malaysian Clay', *6th International Conference on Case Histories in Geotechnical Engineering*, (Chan), pp. 1–6.

Chang, M. (2005) *Computer Architecture*, *The Electrical Engineering Handbook*. Elsevier Inc.

Chew, S. H., Kamruzzaman, A. H. M. and Lee, F. H. (2004) 'Physicochemical and Engineering Behavior of Cement Treated Clays', *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), pp. 696–706.

Chiet, K. T. P. (2016) *Microbial Induced Calcite Precipitation Treatment on Tropical Residual Soil*, *Universiti Teknologi Malaysia*. PhD Dissertation. Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Chinkulkijniwat, A., Horpibulsuk, S., Ph, D. and Yubonchit, S. (2015) 'Laboratory Approach for Faster Determination of the Loading-Collapse Yield Curve of Compacted Soils', *Journal of Materials in Civil Engineering*, 28 (3)(September), pp. 1–8.

Consoli, N. C., Párraga Morales, D. and Saldanha, R. B. (2021) 'A new approach for stabilization of lateritic soil with Portland cement and sand: strength and durability', *Acta Geotechnica*, 16, pp. 1473–1486.

Cuisinier, O. and Masrouri, F. (2005) 'Hydromechanical behaviour of a compacted swelling soil over a wide suction range', *Engineering Geology*, 81(3), pp. 204–212.

Delage, P. and Cui, Y. J. (2008) 'An evaluation of the osmotic method of controlling suction', *Geomechanics and Geoengineering*, 3(1), pp. 1–11.

Dhar, S. and Hussain, M. (2021) 'The strength and microstructural behavior of lime stabilized subgrade soil in road construction', *International Journal of Geotechnical Engineering*. Taylor & Francis, 15(4), pp. 471–483.

Djelloul, R., Mrabent, S. A. B., Hachichi, A. and Fleureau, J. M. (2017) 'Effect of Cement on the Drying–Wetting Paths and on Some Engineering Properties of a Compacted Natural Clay from Oran, Algeria', *Geotechnical and Geological Engineering*. Springer International Publishing, 36(2), pp. 995–1010.

Eisazadeh, A., Kassim, K. A. and Nur, H. (2011) 'Characterization of phosphoric acid- and lime-stabilized tropical lateritic clay', *Environmental Earth Sciences*, 63(5), pp. 1057–1066.

Eme, D. B., Nwofor, T. C. and Sule, S. (2016) 'Correlation Between the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of Stabilized Sand-Cement of the Niger Delta', *SSRG International Journal of Civil Engineering*, 3(3), pp. 7–13.

Eyles, R. J. (1970) 'Physiographic implications of laterite in West Malaysia', *Bulletin of the Geological Society of Malaysia*, 3(3), pp. 1–7.

Feng, T. W., Lee, J. Y. and Lee, Y. J. (2001) 'Consolidation behavior of a soft mud treated with small cement content', *Engineering Geology*, 59(3–4), pp. 327–335.

Ferro, V. and Mirabile, S. (2009) 'Comparing Particle Size Distribution Analysis By Sedimentation and Laser Diffraction Method', *Journal of Agricultural Engineering*, 40(2), p. 35.

François, B. and Laloui, L. (2010) 'An oedometer for studying combined effects of temperature and suction on soils', *Geotechnical Testing Journal*, 33(2), pp. 1–11.

Fredlund, D. G. and Rahardjo, H. (1993) *Soil mechanics for unsaturated soils*, *Freshwater Biology*.

Futai, M. M. and Almeida, M. S. S. (2005) 'An experimental investigation of the mechanical behaviour of an unsaturated gneiss residual soil', *Géotechnique*, 55(3), pp. 201–213.

Garakani, A. A., Ph, D., Haeri, S. M., Ph, D., Desai, C. S., Ph, D., Asce, D. M., Hosein, S. M., Ghafouri, S., Sadollahzadeh, B. and Senejani, H. H. (2019) 'Testing and Constitutive Modeling of Lime-Stabilized Collapsible Loess . II : Modeling and Validations', 19(4), pp. 1–10.

Gartner, E. (2010) 'Industrially interesting approaches to "low-CO2" cements', *Cement and Concrete Research*, 34(9), pp. 1489–1498.

Gens, A., Sánchez, M. and Sheng, D. (2006) 'On constitutive modelling of unsaturated soils', *Acta Geotechnica*, 1(3), pp. 137–147.

Ghadir, P. and Ranjbar, N. (2018) 'Clayey soil stabilization using geopolymer and Portland cement', *Construction and Building Materials*. Elsevier Ltd, 188, pp. 361–371.

Gidigasu, M. D. (1974) 'Degree of weathering in the identification of laterite materials for engineering purposes - a review', *Engineering Geology*, 8(3), pp. 213–266.

Griffiths, F. J. and Joshi, R. C. (1991) 'Change in pore size distribution owing to secondary consolidation of clays', *Canadian Geotechnical Journal*, 28(1), pp. 20–24.

Gross, J. and Adaska, W. (2020) *Cement-Stabilized Subgrade Soils*. Portland Cement Association, Washington, DC, and National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Gullà, G., Mandaglio, M. C. and Moraci, N. (2006) 'Effect of weathering on the compressibility and shear strength of a natural clay', 625, pp. 618–625.

Hadi, B. A., Md Noor, M. J., Ibrahim, A., Ismail, B. N., Ahmad, J. and Zakariah, Z. (2020) 'The effect of soaking on shear strength of a Malaysian granitic residual soil', *IOP Conference Series: Earth and Environmental Science*, 476, pp. 1–10.

Haeri, S. M., Akbari Garakani, A., Roohparvar, H. R., Desai, C. S., Seyed Ghafouri, S. M. H. and Salemi Kouchesfahani, K. (2019) 'Testing and Constitutive Modeling of Lime-Stabilized Collapsible Loess. I: Experimental Investigations', *International Journal of Geomechanics*, 19(4), pp. 1–11.

Hall, M. R. (2012) 'Soil stabilisation and earth construction: Materials, properties and techniques', *Modern Earth Buildings: Materials, Engineering, Constructions and Applications*, 9, pp. 222–255.

Han, Z., Vanapalli, S. K., Ren, J. and Zou, W. (2018) 'Characterizing cyclic and static moduli and strength of compacted pavement subgrade soils considering moisture variation', *Soils and Foundations*. Japanese Geotechnical Society, 58(5), pp. 1187–1199.

Hassan, M. M. (2009) *Engineering characteristics of cement stabilized soft Finnish clay - a laboratory study*. Licenciate Thesis. Faculty of Engineering and Architecture, Helsinki University of Technology.

Ho, M. H. and Chan, C. M. (2011) 'Some mechanical properties of cement stabilized malaysian soft clay', *World Academy of Science, Engineering and Technology*, 74(2), pp. 24–31.

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y. and Suddeepong, A. (2010) 'Analysis of strength development in cement-stabilized silty clay from microstructural considerations', *Construction and Building Materials*. Elsevier Ltd, 24(10), pp. 2011–2021.

Houben, H. and Guillaud, H. (1994) *Earth construction: a comprehensive guide*, *Habitat International*. Book Reviews. Elsevier Science Ltd.

Ibrahim, N. M., Rahim, N. L. and Amat, R. C. (2012) 'Determination of Plasticity Index and Compression Index of Soil at Perlis', *APCBEE Procedia*, 4, pp. 94–98.

Ikeagwuani, C. C. and Nwonu, D. C. (2019) 'Emerging trends in expansive soil stabilisation: A review', *Journal of Rock Mechanics and Geotechnical Engineering*. Elsevier Ltd, 11, pp. 423–440.

Ismail, M. S. N. and Abdul Ghani, A. N. (2017) 'An overview of road damages due to flooding : Case study in Kedah state', *AIP Conference Proceedings*, 1892(October), pp. 1–7.

Jaritngam, S., Prachasaree, W., Somchainuek, O. and Taneerananon, P. (2012) 'An investigation of lateritic soil cement for sustainable pavements', *Indian Journal of Science and Technology*, 5(11), pp. 3603–3606.

Jayakumar, M. and Sing, L. C. (2012) 'Experimental Studies on Treated Sub-base Soil with Fly Ash and Cement for Sustainable Design Recommendations', *International Journal of Civil and Environmental Engineering*, 6(8), pp. 611–614.

Jia, L. Z. (2018) *Effect of Macro Fabric and Matric Suction on Compressibility Behaviour of Tropical Residual Soil*. Degree Dissertation. Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Kamruzzaman, A. H. M., Chew, S. H. and Lee, F. H. (2009) 'Structuration and Destructuration Behavior of Cement-Treated Singapore Marine Clay', *Journal of Geotechnical and Geoenvironmental Engineering*, 135(April), pp. 573–589.

Kamtchueng, B. T., Onana, V. L., Fantong, W. Y., Ueda, A., Ntouala, R. F., Wongolo, M. H., Ndongo, G. B., Ze, A. N., Kamgang, V. K. and Ondoa, J. M. (2015) 'Geotechnical, chemical and mineralogical evaluation of lateritic soils in humid tropical area (Mfou, Central-Cameroon): Implications for road construction', *International Journal of Geo-Engineering*, 6(1), pp. 1–21.

Kasim, N. A., Azmi, N. A. C., Mukri, M. and Noor, S. N. A. M. (2017) 'Effect on physical properties of laterite soil with difference percentage of sodium bentonite', *AIP Conference Proceedings*, 1875(August), pp. 1–32.

Kholghifard, M. (2014) *Volume change and collapse potential of unsaturated residual granite soil, Civil Engineering*. PhD Dissertation. Universiti Teknologi Malaysia.

Kholghifard, M. (2020) 'Effective stress and compressibility of unsaturated clayey soil under drying and wetting cycles', *Periodica Polytechnica Civil Engineering*, 64(4), pp. 999–1006.

Kholghifard, M., Ahmad, K., Ali, N., Kassim, A. and Kalatehjari, R. (2014) 'Collapse/swell potential of residual laterite soil due to wetting and drying-wetting cycles', *National Academy Science Letters*, 37(2), pp. 147–153.

Kushwaha, P. K. and Mahiyar, H. K. (2017) 'Experimental Study to Correlate Soaked CBR with Index and Engineering Properties of Black Cotton Soil of Madhya Pradesh', *International Journal of Advanced Research Trends in Engineering and Technology*, 4(10), pp. 28–37.

Lade, P. V. and Trads, N. (2014) 'The role of cementation in the behaviour of cemented soils', *Geotechnical Research*, 1(4), pp. 111–132.

Laloui, L., Geiser, F. and Vulliet, L. (2001) 'Constitutive modelling of unsaturated soils', *Revue Française de Génie Civil*, 5(6), pp. 797–807.

Latifi, N. (2014) *Geotechnical and Micro-structural Behaviour of Chemically Stabilized Tropical Residual Soil*. PhD Dissertation. Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Latifi, N., Eisazadeh, A., Marto, A. and Meehan, C. L. (2017) 'Tropical residual soil stabilization: A powder form material for increasing soil strength', *Construction and Building Materials*. Elsevier Ltd, 147, pp. 827–836.

Latifi, N., Marto, A. and Eisazadeh, A. (2015) 'Physicochemical Behavior of Tropical Laterite Soil Stabilized with Non-Traditional Additive', *Acta Geotechnica*, 11(2), pp. 433–443.

Lemaire, K., Deneele, D., Bonnet, S. and Legret, M. (2013) 'Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt', *Engineering Geology*. Elsevier B.V., 166(0013–7925), pp. 255–261.

Lemougna, P. N., Melo, U. F. C., Kamseu, E. and Tchamba, A. B. (2011) 'Laterite Based Stabilized Products for Sustainable Building Applications in Tropical Countries: Review and Prospects for the Case of Cameroon', *Sustainability*, 3, pp. 293–305.

Leroueil, S. and Barbosa, A. (2000) 'Combined effect of fabric , bonding and partial saturation on yielding of soils', *Unsaturated Soils for Asia*, 2, pp. 527–532.

Little, D. N. (2009) *Recommended Practice for Stabilization of Subgrade Soils and Base Materials, National Cooperative Highway Research Program*.

Lohnes, R. A. and Demirel, T. (1973) 'Strength And Structure Of Laterites And Lateritic Soils', *Engineering Geology*, 21(July), pp. 13–33.

Lorenzo, G. A. and Bergado, D. T. (2006) 'Fundamental characteristics of cement-admixed clay in deep mixing', *Journal of Materials in Civil Engineering*, 18, pp. 161–174.

Maâtouk, A., Leroueil, S. and Rochelle, P. LA (1995) 'Yielding and critical state of a collapsible unsaturated silty soil', *Geotechnique*, 45(3), pp. 465–477.

Malaysia Public Work Department (2013a) *Manual For The Structural Design of Flexible Pavement*.

Malaysia Public Work Department (2013b) *Section 2: Earthworks*, *Standard Specification for Road Works*.

Malaysia Public Work Department (2017) *Section 18: Soil Stabilisation*, *Standard Specification for Road Works*.

Mavroulidou, M., Zhang, X., Gunn, M. J. and Cabarkapa, Z. (2013) 'Water Retention and Compressibility of a Lime-Treated, High Plasticity Clay', *Geotechnical and Geological Engineering*, 31(April), pp. 1171–1185.

McHenry and Rose (2012) 'A Review of Available Laboratory and In - Situ Testing Methods for Railroad Subgrade', *Kentucky Transportation Center*, pp. 1–36.

Mengue, E. (2017) 'Physicochemical and consolidation properties of compacted lateritic soil treated with cement', *Soils and Foundations*. Japanese Geotechnical Society, 57(1), pp. 60–79.

Mengue, E., Mroueh, H., Lancelot, L. and Eko, R. M. (2017) 'Mechanical improvement of a fine-grained lateritic soil treated with cement for use in road construction', *Journal of Materials in Civil Engineering*, 29(11), pp. 1–22.

Mengue, E., Mroueh, H., Lancelot, L. and Medjo Eko, R. (2018a) 'Design and parametric study of a pavement foundation layer made of cement-treated fine-grained lateritic soil', *Soils and Foundations*. Japanese Geotechnical Society, 58(3), pp. 666–677.

Mengue, E., Mroueh, H., Lancelot, L. and Medjo Eko, R. (2018b) 'Evaluation of the Compressibility and Compressive Strength of a Compacted Cement Treated Laterite Soil for Road Application', *Geotechnical and Geological Engineering*. Springer International Publishing, 36(6), pp. 3831–3856.

Miao, L. and Yin, Z. (1999) 'Shear strength of unsaturated soils', *Yantu Lixue/Rock and Soil Mechanics*, 20(3), pp. 1–6.

Millogo, Y., Hajjaji, M., Ouedraogo, R. and Gomina, M. (2008) 'Cement-lateritic gravels mixtures: Microstructure and strength characteristics', *Construction and Building Materials*, 22(10), pp. 2078–2086.

Mohamed Jais, I. B. and Md Noor, M. J. (2020) 'Collapse settlement of unsaturated soil from effective stress and shear strength interaction of soil', *IOP Conference Series: Materials Science and Engineering*, 527(1), pp. 1–17.

Netterberg, F. (2014) 'Review of specification for the use of laterite in road pavements', 60(May), pp. 1–60.

Ng, C. W. W., Akinniyi, D. B., Zhou, C. and Chiu, C. F. (2019) 'Comparisons of weathered lateritic, granitic and volcanic soils: Compressibility and shear strength', *Engineering Geology*, 249(2018), pp. 235–240.

Ng, C. W. W. and Menzies, B. (2007) *Advanced Unsaturated Soil Mechanics and Engineering*. Taylor & Francis.

Nordin, N. S., Tajudin, S. A. A. and Kadir, A. A. (2013) 'Stabilisation of Soft Soil Using Electrokinetic Stabilisation Method', *International Journal of Zero Waste Generation*, 1(2), pp. 5–12.

Nowamooz, H. and Masrouri, F. (2008) 'Hydromechanical behaviour of an expansive bentonite/silt mixture in cyclic suction-controlled drying and wetting tests', *Engineering Geology*, 101(3–4), pp. 154–164.

Oades, J. M. (1993) 'The role of biology in the formation, stabilization and degradation of soil structure', *Geoderma*, 56(1–4), pp. 377–400.

Obianyo, I. I., Onwualu, A. P. and Soboyejo, A. B. O. (2020) 'Mechanical behaviour of lateritic soil stabilized with bone ash and hydrated lime for sustainable building applications', *Case Studies in Construction Materials*. Elsevier Ltd., 12.

Oldecop, L. A. and Alonso, E. E. (2003) 'Suction effects on rockfill compressibility', *Geotechnique*, 53(2), pp. 289–292.

Omotoso, O. A., Ojo, O. J. and Adetolaju, E. T. (2012) 'Engineering Properties of Lateritic Soils around Dall Quarry in Sango Area, Ilorin, Nigeria', *Earth Science Research*, 1(2), pp. 71–81.

Omran, A., Soliman, N., Zidol, A. and Tagnit-hamou, A. (2018) 'Performance of ground-glass pozzolan as a cementitious material — A Review', *Advances in Civil Engineering Materials*, 7(1), pp. 237–270.

Oyediran, I. (2019) 'Effect of Increasing Cement Content on Strength and Compaction Parameters of some Lateritic Soils from Southwestern', *Electronic Journal of Geotechnical Engineering*, 16(October), pp. 1501–1514.

Oyediran, I. A. and Okosun, J. (2013) 'An attempt to improve geotechnical properties of some highway lateritic soils with lime', pp. 287–296.

Oyelami, C. A. and Van Rooy, J. L. (2016) 'A review of the use of lateritic soils in the construction/development of sustainable housing in Africa: A geological perspective', *Journal of African Earth Sciences*. Elsevier Ltd, 119, pp. 226–237.

Pastor, J. luis, Tomas, R., Cano, M., Riquelme, A. and Gutierrez, E. (2019) 'Evaluation of the improvement effect of limestone powder waste in the stabilization of swelling clayey soil', *Sustainability*, 11(3:679).

Pereira, J., Rouainia, M. and Manzanal, D. (2014) 'Combined effects of structure and partial saturation in natural soils', *Journal of Geo-Engineering Sciences*, 2, pp. 3–16.

Phanikumar, B. R. and Raju, E. R. (2020) 'Compaction and strength characteristics of an expansive clay stabilised with lime sludge and cement', *Soils and Foundations*, pp. 1–10.

Pongsivasathit, S., Horpibulsuk, S. and Piyaphipat, S. (2019) 'Assessment of mechanical properties of cement stabilized soils', *Case Studies in Construction Materials*. Elsevier Ltd., 11(e00301), pp. 1–15.

Por, S., Nishimura, S. and Likitlersuang, S. (2017) 'Deformation characteristics and stress responses of cement-treated expansive clay under confined one-dimensional swelling', *Applied Clay Science*. Elsevier, 146(June), pp. 316–324.

Portelinha, F. H. M., Lima, D. C., Fontes, M. P. F. and Carvalho, C. A. B. (2012) 'Modification of a lateritic soil with lime and cement: An economical alternative for flexible pavement layers', *Soils and Rocks*, 35(1), pp. 51–63.

Quadri, H. A. (2013) 'Impact of Compaction Delay on the Engineering Properties of Cement Treated Soil.', *IOSR Journal of Mechanical and Civil Engineering*, 4(6), pp. 9–15.

Rao, S. M. and Revanasiddappa, K. (2006) 'Influence of cyclic wetting drying on collapse behaviour of compacted residual soil', *Geotechnical and Geological Engineering*, 24(October), pp. 725–734.

Rao, S. M. and Shivananda, P. (2005) 'Compressibility behaviour of lime-stabilized clay', *Geotechnical and Geological Engineering*, 23(3), pp. 309–319.

Rashid, A. S. A., Kalatehjari, R., Noor, N. M., Yaacob, H., Moayedi, H. and Sing, L. K. (2014) 'Relationship between liquidity index and stabilized strength of local subgrade materials in a tropical area', *Measurement: Journal of the International Measurement Confederation*. Elsevier Ltd, 55, pp. 231–237.

Rashid, A.S.A., Latifi, N., Meehan, C. L. and Manahiloh, K. N. (2017) 'Sustainable Improvement of Tropical Residual Soil Using an Environmentally Friendly

Additive', *Geotechnical and Geological Engineering*. Springer International Publishing, 35(6), pp. 2613–2623.

Rashid, A S A, Shahrin, M. I., Horpibulsuk, S., Hezmi, M. A., Yunus, N. Z. M. and Borhamdin, S. (2017) 'Development of sustainable masonry units from flood mud soil: Strength and morphology investigations', *Construction and Building Materials*. Elsevier Ltd, 131, pp. 682–689.

Raveendiraraj, A. (2009) *Coupling of Mechanical Behaviour and Water Retention Behaviour in Unsaturated Soils*. PhD Dissertation. Department of Civil Engineering, University of Glasgow.

Razali, R. and Che Malek, M. S. (2019) 'The usage of cement for soil stabilisation in construction of low volume roads in Malaysia', *IOP Conference Series: Materials Science and Engineering*, 512(1).

Saeed, K. A., Kassim, K. A., Nur, H. and Yunus, N. Z. M. (2019) 'Comparison of Compressibility Behaviour of Lime-Cement Stabilized Lateritic Clay Soil Contaminated by Heavy Metals', *IOP Conference Series: Materials Science and Engineering*, 584(1).

Saffari, R., Habibagahi, G., Nikooee, E. and Niazi, A. (2017) 'Biological Stabilization of a Swelling Fine-Grained Soil: The Role of Microstructural Changes in the Shear Behavior', *Iranian Journal of Science and Technology - Transactions of Civil Engineering*. Springer International Publishing, 41(4), pp. 405–414.

Salih, A. G. (2012) 'Review on granitic residual soils' geotechnical properties', *Electronic Journal of Geotechnical Engineering*, 17, pp. 2645–2658.

Saputra, N. A. and Putra, R. (2020) 'The Correlation between CBR (California Bearing Ratio) and UCS (Unconfined Compression Strength) Laterite Soils in Palangka Raya as Heap Material', *IOP Conference Series: Earth and Environmental Science*, 469(1), pp. 1–9.

Sasanian, S. (2011) *The Behaviour of Cement Stabilized Clay At High Water Contents*. PhD Dissertation. Faculty of Engineering Science, The University of Western Ontario.

Sharma, L. K., Sirdesai, N. N., Sharma, K. M. and Singh, T. N. (2018) 'Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study', *Applied Clay Science*. Elsevier, 152, pp. 183–195.

Shehu, Z., Elma, N., Endut, I. R. and Holt, G. D. (2014) 'Factors influencing road infrastructure damage in Malaysia', *Infrastructure Asset Management*, 1(2), pp. 42–52.

Sheng, D., Fredlund, D. G. and Gens, A. (2008) 'A new modelling approach for unsaturated soils using independent stress variables', *Canadian Geotechnical Journal*, 45(4), pp. 511–534.

Sheng, D., Zhou, A. and Fredlund, D. G. (2011) 'Shear Strength Criteria for Unsaturated Soils', *Geotechnical and Geological Engineering*, 29(2), pp. 145–159.

Shipton, B. and Coop, M. R. (2012) 'On the compression behaviour of reconstituted soils', *Soils and Foundations*. Elsevier, 52(4), pp. 668–681.

Silveira, I. A. and Rodrigues, R. A. (2020) 'Collapsible Behavior of Lateritic Soil Due to Compacting Conditions', *International Journal of Civil Engineering*. Springer International Publishing, 18(10), pp. 1157–1166.

Simon, A. B., Giesecke, J. and Bidlo, G. (1973) 'Use of lateritic soils for road construction in North Dahomey', *Engineering Geology*, 7(3), pp. 197–218.

Sobhan, K., Ramirez, J. C. and Reddy, D. V (2012) 'Cement Stabilization of Highly Organic Subgrade Soils to Control Secondary Compression Settlement', *Journal of the Transportation Research Board*, 2310, pp. 103–112.

Solanki, P., Khoury, N. N. and Zaman, M. M. (2009) *Engineering Properties of Stabilized Subgrade Soils for Implementation of the AASHTO 2002 Pavement Design Guide*. School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma.

Soleimani-Fard, H., König, D. and Goudarzy, M. (2022) 'Plane strain shear strength of unsaturated fiber-reinforced fine-grained soils', *Acta Geotechnica*, 17(1), pp. 105–118.

Sounthararajah, A., Nguyen, N., Bui, H. H., Jitsangiam, P., Leung, G. L. M. and Kodikara, J. (2016) 'Effect of cement on the engineering properties of pavement materials', *Materials Science Forum*, 866, pp. 31–36.

Taha, M., Hossain, M., Chik, Z. and Mohd Nayan, K. (1999) 'Geotechnical Behaviour of a Malaysian Residual Granite Soil', *Pertanika Journal of Science & Technology*, 7(2), pp. 151–169.

Torres, C. E. and Colmenares, J. E. (2019) 'On the compressibility of two layer lateritic soil profile of Vichada region Colombia', *17th LACCEI International Multi-Conference for Engineering, Education, and Technology*, (July), pp. 24–26.

Trauchessec, R., Mechling, J. M., Lecomte, A., Roux, A. and Le Rolland, B. (2014) 'Impact of anhydrite proportion in a calcium sulfoaluminate cement and Portland cement blend', *Advances in Cement Research*, 26(6), pp. 325–333.

Tsozué, D. (2012) 'Morphology, Mineralogy and Geochemistry of a Lateritic Soil Sequence Developed on Micaschist in the Abong-Mbang Region, Southeast Cameroon', 115, pp. 103–116.

Vada, A. V (2000) 'A constitutive model for structured soils', *Geotechnique*, 50(3), pp. 263–273.

Vilar, O. M. and Rodrigues, R. A. (2011) 'Collapse behavior of soil in a Brazilian region affected by a rising water table', *NRC Research Press*, 48, pp. 226–233.

Wahab, N. A., Rashid, A. S. A., Roshan, M. J., Rizal, N. H. A., Yunus, N. M., Hezmi, M. A. and Tadza, M. Y. M. (2021) 'Effects of Cement on the Compaction Properties of Lateritic Soil', in *IOP Conference Science, Materials RCCE SDG 2020*, pp. 1–7.

Wahab, N. A., Roshan, M. J., Rashid, A. S. A., Hezmi, M. A., Jusoh, S. N., Daud, N., Norsyahariati, N. and Tamassoki, S. (2021) 'Strength and Durability of Cement-Treated Lateritic Soil', *Sustainability (Switzerland)*, 13(6430), pp. 1–23.

Wheeler, S. J. (1995) 'An elasto-plastic critical state framework unsaturated soil', *Geotechnique*, 45(1), pp. 35–53.

Woodward, C. L. (1996) 'Soil compaction and topsoil removal effects on soil properties and seedling growth in Amazonian Ecuador', *Forest Ecology and Management*, 82(April), pp. 197–209.

Xiao, H. W. and Lee, F. H. (2008) 'Curing time effect on behavior of cement treated marine clay', *Proceedings of World Academy of Science, Engineering and Technology (PWASET)*, 33(August), pp. 2070–3740.

Yamusa, Y. B., Alias, N., Ahmad, K., Sa'Ari, R., Osinubi, K. J., Adrian, E. O. and Moses, G. (2020) 'Engineering characteristics of compacted laterite soil as hydraulic barrier in waste containment application', *Journal of Engineering Science and Technology*, 15(1), pp. 508–523.

Yamusa, Y. B., Yunus, N. Z. M., Ahmad, K., Rahman, N. A. and Sa'ari, R. (2018) 'Effects of fines content on hydraulic conductivity and morphology of laterite soil as hydraulic barrier', in *E3S Web of Conferences*, pp. 1–8.

Yang, C., Cui, Y. J., Pereira, J. M. and Huang, M. S. (2008) 'A constitutive model for unsaturated cemented soils under cyclic loading', *Computers and Geotechnics*, 35(6), pp. 853–859.

Yang, Y., Wang, L., Wendroth, O., Liu, B., Cheng, C., Huang, T. and Shi, Y. (2019) 'Is the Laser Diffraction Method Reliable for Soil Particle Size Distribution Analysis?', *Soil Science Society of America Journal*, 83(2), pp. 276–287.

Yao, L., Yunzhi, T., Jing, J. and Chenfeng, X. (2012) 'Experimental Study on the Compressibility of Cement Improved Laterite Soil', *Applied Mechanics and Materials*, 170–173(May), pp. 371–374.

Yoobanpot, N., Jamsawang, P. and Horpibulsuk, S. (2017) 'Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue', *Applied Clay Science*. Elsevier B.V., 141, pp. 146–156.

Yu, C., Wang, H., Zhou, A., Cai, X. and Wu, Z. (2019) 'Experimental Study on Strength and Microstructure of Cemented Soil with Different Suctions', *Journal of Materials in Civil Engineering*, 31(6), pp. 1–11.

Zhang, X., Mavroulidou, M. and Gunn, M. J. (2015) 'Mechanical properties and behaviour of a partially saturated lime-treated, high plasticity clay', *Engineering Geology*. Elsevier B.V., 193(May), pp. 320–336.

Zidan, A. F. (2020) 'Strength and Consolidation Characteristics for Cement Stabilized Cohesive Soil Considering Consistency Index', *Geotechnical and Geological Engineering*. Springer International Publishing, 38(5), pp. 5341–5353.

LIST OF PUBLICATIONS

1. Wahab, N.A., Roshan, M.J., Rashid, A.S.A., Hezmi, M.A., Jusoh, S.N., Nik Norsyahariati, N.D., Tamassoki, S. (2021). ‘Strength and Durability of Cement-Treated Lateritic Soil’. Journal of Sustainability, 13, 6430. doi.org/10.3390/su13116430

2. Wahab, N.A, Rashid, A.S.A, Roshan, M.J., Rizal, N.H.A., Yunus, N.Z.M., Hezmi, M.A., Tadza, M.Y.M. (2021) ‘Effects of Cement on the Compaction Properties of Lateritic Soil’. IOP Conf. Series: Materials Science and Engineering, 1153, 012015. doi:10.1088/1757-899X/1153/1/012015