ENGINEERING AND MICROSTRUCTURAL CHARACTERIZATION OF MARINE CLAY TREATED WITH CEMENT AND LIME

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SCHOOL OF CIVIL ENGINEERING

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ENGINEERING AND MICROSTRUCTURAL CHARACTERIZATION OF MARINE CLAY TREATED WITH CEMENT AND LIME

by

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
CBR	California Bearing Ratio
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
SEM	Scanning Electron Microscope
UCS	Unconfined Compression Strength Test
USCS	Unified Soil Classification System
USM	Universiti Sains Malaysia
UTHM	Universiti Tun Hussein Onn Malaysia
UTM	Universiti Teknologi Malaysia
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

LIST OF SYMBOLS

%	Percentage
ºC	Degree Celsius
º	Degree
ml	Milliliter
µm	Micrometer
mm	Millimeter
cm^3	Cubic Centimeter
g	Gram
kg	Kilogram
kN	Kilonewton
kg/m^3	Kilogram per Cubic Meter
Mg/m^3	Megagram per Cubic Meter
kPa	Kilopascal

ABSTRAK

Tanah adalah sangat penting dalam pembinaan jalan raya dan asas struktur bangunan. Tanah bermasalah seperti tanah liat marin akan menyebabkan gangguan yang ketara dan impak buruk kepada infrastruktur awam. Dalam kajian ini, tanah liat marin dipilih sebagai sampel tanah dalam penstabilan tanah. Tujuan penyelidikan ini adalah untuk menentukan ciri-ciri kejuruteraan dan mikrostruktur tanah liat marin yang distabil dengan simen dan kapur. Kandungan lembapan semula jadi telah ditentukan dan diikuti dengan ujian *specific gravity*, ujian *Atterberg Limt* dan analisis saiz zarah. Untuk ujian *standard proctor,* 3 %, 5 %, 7 %, 9 % dan 11 % kapur dan 10 %, 15 % dan 20 % simen dicampur dengan tanah liat marin untuk penstabilan kimia. Ujian *UCS* dan analisis *X-ray Fluorescence* dijalankan untuk membandingkan nilai UCS dan perubahan mikrostruktur tanah liat marin dengan peratusan optimum 11 % bahan tambah kapur dan 20 % simen selepas pengawetan selama 7 hari. Kenaikan peratusan kedua-dua kapur dan simen mengakibatkan peningkatan ketumpatan kering maksimum dan penurunan kandungan lembapan maksimum. Ujian UCS tanah liat marin dengan campuran seperti kapur dan simen mendapat nilai yang lebih besar berbanding dengan tanah liat marin yang belum distabil melalui tindak balas *pozzolanic*. Dalam ciri mikrostruktur, tanah liat marin belum distabil didominasi oleh tiga sebatian termasuk alunimium oksida (Al_2O_3), silika oksida (SiO_2) dan ferik oksida (Fe_2O_3). Walau bagaimanapun, tanah liat marin stabil dengan 11 % kapur dan 20 % simen didominasi oleh tiga sebatian dominan oksida di atas dan kalsium oksida. Penyelidikan dan penemuan ini akan menyumbang pengetahuan tambahan untuk memahami mekanisme agen penstabil ini.

ABSTRACT

Soil is significant in the construction of roads and the foundation of building structures. Problematic soil such as marine clay soil would cause significant disruption and poor performance of civil infrastructure. In this study, marine clay soil is selected as soil samples in soil stabilization. The aim of this research is to determine the engineering and microstructural characteristics of marine clay treated with cement and lime. The natural moisture content is determined and followed by specific gravity test, Atterberg limit test and particle size analysis. For standard proctor test, 3 %, 5 %, 7 %, 9 % and 11 % of lime and 10 %, 15 % and 20 % of cement are mixed to the marine clay soil for chemical stabilization. Unconfined compression strength test and X-ray Fluorescence analysis are carried out to compare the UCS value and microstructural changes of non-stabilized marine clay with optimum percentage of 11 % lime additives and 20 % cement additives after curing for 7 days. The increment of percentage of both lime and cement result in the increase of maximum dry density and decrease of optimum moisture content. The UCS test of marine clay with admixture such as lime and cement have larger value compared to non-stabilized marine clay through pozzolanic reaction. In microstructural characteristics, non-stabilized marine clay were dominants by three element oxides including aluminium oxide (Al_2O_3), silica oxide (SiO_2) and ferric oxide (Fe_2O_3). However, marine clay stabilized with 11 % of lime and 20 % of cement were dominants by three dominants element oxides above and calcium oxide (CaO). This research and findings will contribute extra knowledge on understanding the mechanism of these stabilizing agents.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Soil is of utmost crucial in the construction of roads or foundation of building structures. Problematic soil would cause severe distress and poor performance to civil infrastructure. These soils have poor strength and are prone to substantial volume deformations owing to seasonal fluctuations in moisture content (Puppala et al., 2015). Therefore, soil exploration is done during site investigation involves sample collecting and carrying out laboratory tests to identify the soil's geotechnical properties. The main composition of soil should be tested for strength, density, water absorption, compaction, contamination and content.

Soil stabilization improves soil strength while enhancing resistance to water softening via soil particle bonding. Mechanical stabilization, chemical stabilization, thermal stabilization and electrical stabilization are the four primary kinds of stabilization treatments via the processing of soil improvement mechanisms. Chemical additions are the most often used method of soil stabilization by increasing its inherent properties (Yunus et al., 2015).

Unbound materials may be chemically stabilized using cementitious materials such as cement, lime and etc. These soil stabilizing materials are stiffer, have low permeability and are low compressible than natural soil.

Cement stabilization is a hydration process without altering the structure of the soil. However, lime stabilization is a pozzolanic reaction in which the reaction of lime with pozzolana in presence of water forms cementitious compounds (Makusa, 2012). Throughout the rest of this report, soil stabilization refers to chemical stabilization with cement and lime only.

1.2 Problem Statement

As a result of climate change impact, numerous areas of the nation may be affected by floods and dry seasons throughout the year. These cyclical changes can alter the soil conditions. Marine clay soils need to be improved before they can be used in roads, airports, pavements and highways. Improved soil gradation, a reduction in the plasticity and swelling potential of soil and an increase in the strength and workability of soil generally improve the stabilization of soil (Attom et al., 2000). Stabilization is applied via mechanical or chemical methods. As a result, soil stabilization may raise a soil's shear strength and regulate its shrink-well properties, boosting the load bearing capability of a sub-grade in pavements and foundations.

In cases of insufficient mechanical stability, chemical stabilization is used. To improve the strength, durability and compressive characteristics of soil, soil should be replaced or improved by stabilization using additives. Soil stabilization has been achieved by mixing additives, such as cement, lime, asphalt and fly ash, with soil. Soil stabilization with additives comprises the oldest and most common method of soil improvement.

Look into area around USM Engineering Campus, Nibong Tebal is covered with soft marine clay deposits. Therefore, the primary concern of the construction of building is the stability and settlement of the ground foundation. Soils support the foundation of structure that is constructed above it. The foundation acts as a medium between structure and underlying soil which function to transmitting the loads sustained by the foundation and its self-weight. Marine clay soils that are weak and compressible have issues with bearing capacity and settlement. These expansive soils have negative impact on buildings due to their tendency to shrink and swell in response to changes in seasonal moisture. To protect the building and structure, it is necessary to identify and understand marine clay soil.

The performance of pavement might have a detrimental impact if the problematic soils are present in the pavement or bed layers. Fluctuations in moisture content in clay throughout dry and rainy seasons can cause pavement distress due to structural deformation. The road pavement is not able to transfer load causing to have lower load bearing capacity. Thus, the structure and behaviour of marine clay soil vary depending on the origin, type of soil mineralogy, location, stress history and climate.

In this laboratory work, marine clay soil is selected as weak soil sample. It is a soft soil that is common along the coast and in offshore areas. Marine clay soil is typically associated with severe settlement and instability, as well as unsuitable soil qualities for engineering applications. Hence, soil stabilization is required to implement on the marine clay soil to improve the stability of the soil properties.

1.3 Objectives

The main objective of this study is to assess the competency of the cement and lime admixture. Various percentage of lime admixture used in soil sample will measure the ability of additives to achieve soil stabilization. The improved soil will be examined by its shear strength, permeability and compressibility.

To achieve aim of this thesis, three primary goals of conducting this research are:

1. To determine the index properties of marine clay.
2. To determine the optimum percentage of cement and lime admixture for marine clay improvement.
3. To evaluate the changes in the mineralogy of cured stabilized marine clay.

1.4 Scope of work

The scope of study can be divided into two phases. The first phase of this study will be focusing on the physical properties of non-stabilized marine clay. The determination of physical properties like specific gravity, liquid limit, plastic limit and particle size analysis in improving the stability of existing marine clay soil.

The second phase is about the addition of admixtures such as lime and cement to the marine clay soil for soil stabilization purpose. The optimum moisture content and maximum dry density is a measure of compaction level of soils. It determined the soil suitability for stabilization. Unconfined compression strength value is an important parameter. The optimum percentage of each admixture and non-stabilized marine clay soil curing with seven days are further tested with unconfined compression strength test to determine the UCS value of the mixed to experience axial loading. Later, microstructural analysis is carried out on the samples to determine the percentage of compounds in the soil sample.

1.5 Dissertation Outline

The structure of the dissertation is divided into five chapters:

Chapter 1: Description of the background of utilization of chemical admixtures in stabilization of clay, problem statement, objective and scope of the study and thesis outline.

Chapter 2: An overview of the literature on the effect of lime, cement as stabilizing agents on marine clay soil sample by previous researchers and microstructural changes when treated with stabilizing agents.

Chapter 3: Methodology used in this research. It includes site selection, geotechnical research, laboratory test for physical characteristics of marine clay soil, Unconfined Compression Test and X-Ray Fluorescence.

Chapter 4: Results obtained from the experimental works. The results are presented in graphical form and analysis and discussion are made in detail.

Chapter 5: Conclusions on findings of the research and recommendations for improvement in future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Building foundations must be built on strong and stable soil. The foundation of a building could crack, sink, or collapse if the soil beneath it is unstable. The strength and stability of soil depends on its physical properties. The overall strength and performance the subgrade layer of a pavement is determined not only by its design but also by the load bearing capability of the subgrade soil.

Marine clay is a sensitive soil with significant settlement, low stability, poor soil characteristics and low unconfined compressive strength (Mohammed Al-Bared & Marto, 2017). The clay is highly susceptible to changes in moisture content. When they are discovered beneath pavements or foundations, marine clay soil is unstable with unpredictable performance. Liquid limit of marine clay is lower than its natural moisture content. The difficulties are caused by stronger compressibility and weaker shear strength. As a result, marine clay must be treated and improved before functioned as a foundation for subgrade or construction projects.

This chapter provides a thorough overview of the primary factors that are employed to stabilize problem soil. Chemical additives improve the stability of marine clays soil in order to meet the requirements of a good subgrade. In this study, lime and cement are used as stabilizing agents and the optimum percentage utilization of additives will be tested to allow marine clays soil to stabilize. As a result, various tests are performed on the soil to determine its strength, permeability and compressibility.

2.2 Marine Clay

Marine Clay can be located in a variety of coast and offshore environments around the world (Mohammed Al-Bared & Marto, 2017). This soil has a poor strength, high compressibility, and is heavily influenced by moisture. The marine clay will shrink when dry and swell when moisture content rises.

A laboratory test performed was using marine clay collected from Viaskhapatnam, India. Sieve analysis and hydrometer test was performed to determine grain size distribution of marine clay. The particle size distribution curve was found that the soil consists of 14% sand, 27% silt and 59% clay by weight (Purkayastha, 2009). Figure 2.1 shows the grain size distribution curve.

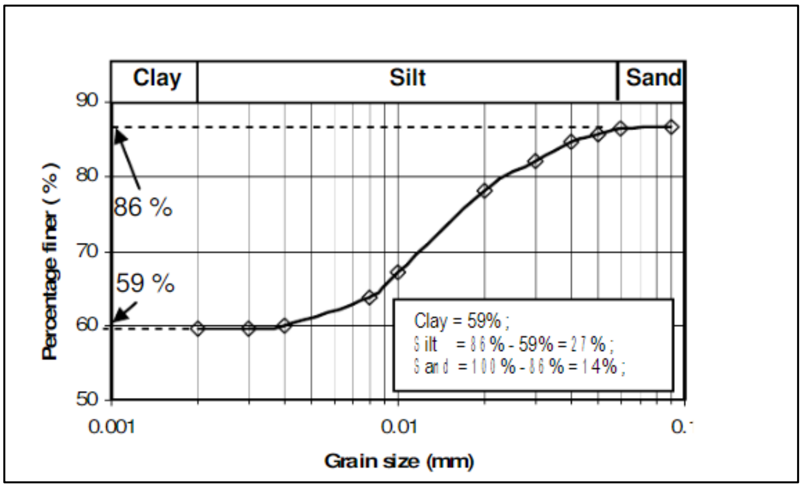

Figure 2.1: Grain size distribution curve (Purkayastha, 2009)

From Figure 2.1, clay is more abundant in marine clay soil than silt and sand. Finer grain particles have a larger surface area than larger particles in soil. Large surface area allows clay to hold more water. Moisture content is crucial in influencing the strength, compaction, and optimum moisture content capacity of soil.

According to early site assessment and geophysical survey data, the Singapore marine clay at Changi consists of two marine components known locally as the upper and lower marine clays (Bo et al., 2008). A layer of medium stiff to stiff clay 2 to 5 m thick separates the upper and lower marine clays. The clay profile of Changi Airport is shown in Figure 2.2, which is made up of two layers of marine clay members.

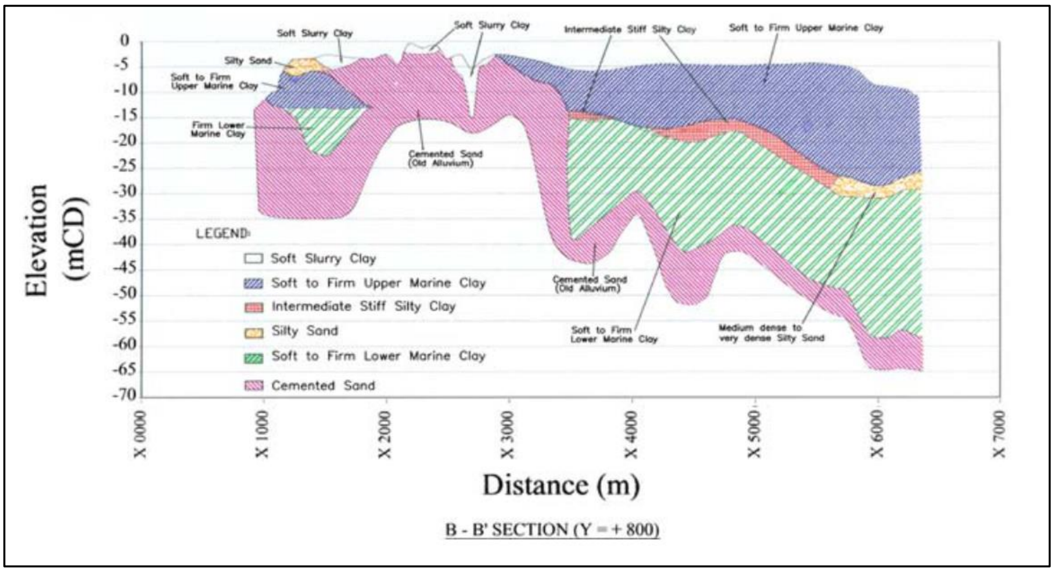

Figure 2.2: : Clay profile of Changi Airport (Bo et al., 2008)

In Table 2.1, the analysis revealed the presence of two obvious layers of marine clay, the top marine clay layer and the lower marine clay layer. The intermediately stiff marine clay layer divides two different marine clay layers. Except for the moderately stiff clay, Singapore marine clay is malleable silty clay.

Table 2.1: Range of physical characteristics of Singapore marine clay (Bo et al., 2008)

Parameters	Upper marine clay	Intermediate stiff clay	Lower marine clay
Specific gravity	2.6-2.72	2.68-2.76	2.7-2.75
Water content (%)	70-88	10-35	40-60
Liquid limit (%)	80-95	50	65-90
Plastic limit (%)	20-28	18-20	20-30

Shahri & Chan (2015) investigated the physical properties of dredged marine clay soil of few states in Malaysia. The dredged marine clays were collected from Lumut (Perak), Marina Melaka (Melaka), Tok Bali (Kelantan) and Pasir Gudang (Johor). Furthermore, Salim et al. (2012) also reported the physical properties of dredged marine clay from Kuala Perlis (Perlis). The data of the both research papers tabulated are natural moisture content, liquid limit, plastic limit and plasticity index of marine clay soil. All data of five states is clearly shown in the Figure 2.3 to make comparison between each state.

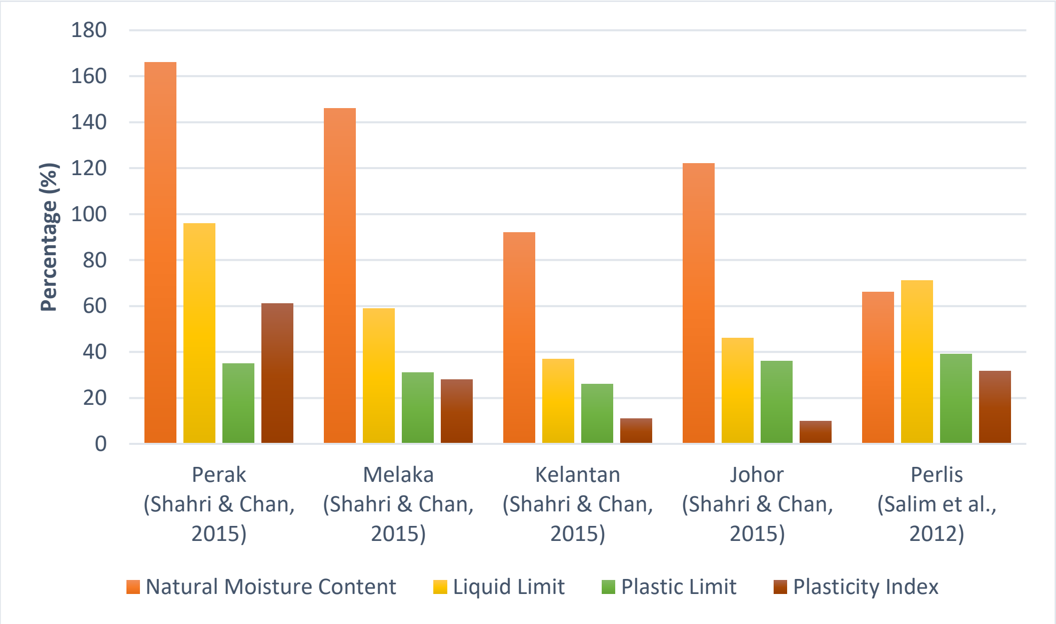

Figure 2.3: Analysis studies physical studies of marine clay in different states (Shahri & Chan, 2015).

Yunus et al. (2015) conducted research on performance of marine clay treated with lime from Nusajaya in Gelang Patah, Johor. The test aimed on the strength and compressibility characteristics of marine clays with and without the addition of lime. The soil sample was taken from the seabed off of Nusajaya, where a harbour project is being built. It was dumped to a different location. Then, the soil was collected and delivered to the laboratory in oil tanks.

Table 2.2: Physical Properties of Marine Clay (Yunus et al., 2015)

Properties	Marine Clay
Specific gravity	2.62
Liquid limit (%)	58
Plastic limit (%)	36
Plasticity index (%)	22
OMC (%)	21
MDD (Mg/m^3)	1.6
Organic content (%)	4.2

Table 2.2 shows the physical properties of marine clay which specific gravity of the marine clay soil is 2.62. Besides, Table 2.3 shows the findings of chemical composition and index testing on untreated Marine clay respectively. The main composition of marine clay is dominating by silicon dioxide, aluminium oxide and iron oxide. Figure 2.4 shows XRD analysis to determine the mineralogical of marine clay.

Table 2.3: Chemical Composition of Nusajaya Marine Clay (Yunus et al., 2015)

Chemical formula	SiO_2	Al_2O_3	Fe_2O_3	K_2O	SO_3	TiO_2	MgO	Cl	Na_2O	ZrO_2
Concentration (%)	36.8	13.3	2.61	2.4	1.47	0.66	0.35	0.32	0.26	0.20

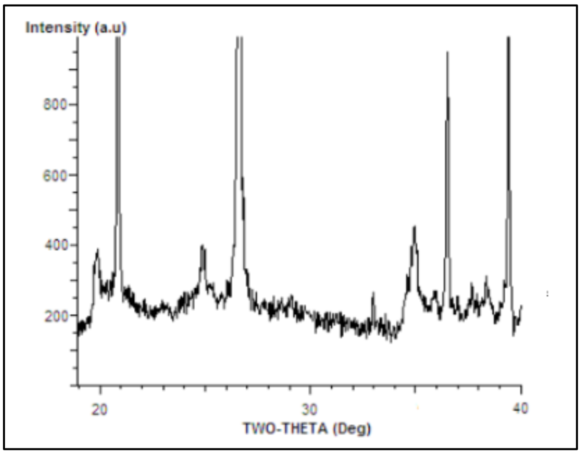

Figure 2.4: X-Ray Diffraction pattern for the marine clay (Yunus et al., 2015)

This study explored and addressed the physical properties of treated and untreated lime stabilized marine clays (Yunus et al., 2015). Marine clay is classed as high silt on the plasticity chart. Due to the Plastic Index value is greater than ten, marine clay is fit for lime stabilization. In Standard Proctor Compaction Test, optimum moisture content (OMC) is 21 % and maximum dry density (MDD) is 1.6 Mg/m^3. Unconfined Compression Test (UCS) demonstrated that enhancement of strength after 7 days is less obvious. However, the strength of the treated soils rises fast after 28 days, which might be linked to the stabilizing process. In general, interactions between lime and clay particles improve soil compression and shear strength, hence stabilizing the marine clay.

Few studies have been done with different types of stabilizing materials for marine clay soil in Malaysia from Table 2.4. The result of unconfined compression strength analysis has been extracted from the previous research to look into the improvement of marine clay stabilization with different types of additives.

Table 2.4: Summary of previous research related to stabilizing material used on marine clay soil in Malaysia

Reference	Stabilizing Material	Marine Clay Location	Result
Emmanuel et al., 2022	Forsteritic Olivine	Jeram, Selangor	The UCS increases with increasing olivine content up to 30% olivine content after which it declines. The percentage increase for 30% olivine-treated sample over untreated clay after 7 days improved 121%.
Pakir et al., 2015	Sodium Silicate	Southern coast of Johor	UCS value increased rapidly with increment of sodium silicate from 3% to 6%. However, UCS decrease for the treated samples of more than 6% of sodium silicate after 7 days of curing.
Marto et al., 2016	Biomass Silica-Rubber Chips (BS-RC) mixture	Teluk Intan, Perak	The UCS strength of 8%BS-1%RC was higher than 7%BS-2%RC. As curing time increased, the void ratio decreased, thus strength of treated soil increased.
Saleh et al., 2018	Polyurethane	UTHM, Johor	Stabilizing the marine with 5% of polyurethane improved the shear strength of the marine clay from 75 kPa to 250 kPa which correspond to improvement by 230% increase in shear strength.

2.3 Stabilizing Agent

Soil stabilization is used to improve the characteristics of soil shear strength and bearing capacity. It lowers the soil mass's permeability and compressibility. It enhances geotechnical qualities such as compressibility, strength, permeability, and durability in poor soils by using stabilizing agents (Afrin, 2017).

Soil stabilization divided into mechanical stabilization and chemical stabilization (Makusa, 2012). Mechanical stabilization may be accomplished by vibration, compaction of natural soil particles, or the addition of additional physical features such as barriers and nails. To achieve the intended effect, chemical stabilization depends on chemical interactions between the stabilizer (cementitious material) and soil minerals (pozzolanic materials).

Chemical stabilization is the major emphasis of this project throughout the remainder of this report. Cementitious materials like cement, lime, fly ash, or a mixture of these can be used to stabilize unbound materials. Throughout the rest of this study, chemical stabilization is the most important aspect of this undertaking. Cementitious materials such as cement, lime, and fly ash, as well as a combination of these can be used to stabilize unbound materials (Makusa, 2012).

2.4 Cement

Cement is the major stabilizing agent or hydraulic binder due to the necessary stabilizing effect on its own. It can be used to alter and improve the quality of the soil or to convert the soil into a mass with improved strength and durability (Youdeowei et al., 2020). The cement reaction occurs during the complicated hydration process. The hardening process begins when cement is combined with water and other components. Bonding not only increases the cohesive character of the treated material to withstand increased loading, but it also inhibits swelling and softening due to moisture absorption (Puppala et al., 2015).

A study from Rivers State University, Nigeria assess the stabilization of marine clay using cement and lime to improve subgrade material (Youdeowei et al., 2020). The types of stabilization used were mechanical and chemical. The percentage of cement by mass of soil used is 5%, 10%, 15% and 20%.

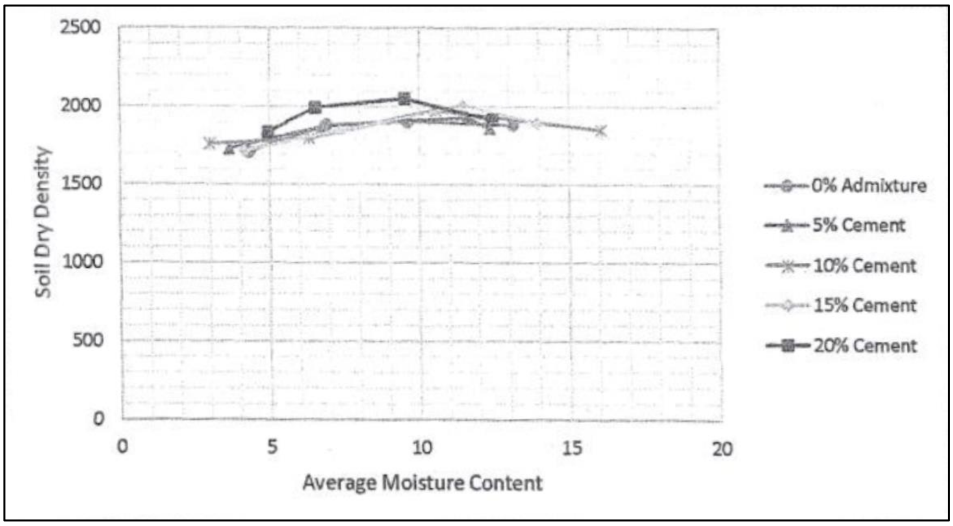

Figure 2.5: Graph of Dry Density against Average Moisture Content for Percentage addition of Lime (Youdeowei et al., 2020)

Based on the Figure 2.5 above, the maximum dry density for clay soil stabilization ranges between 1910 kg/m^3 to 2050 kg/m^3 for sample containing 20% cement content. The highest CBR values of 33.24 % and 424.25 % were obtained at 20% cement content for both unsoaked and soaked. According to the findings, adding cement to clay soil in the presence of water enhances the CBR values for soft clay stabilization for highway construction (Youdeowei et al., 2020). The use of cement increases the marine clay soil's bearing capacity and maximum dry density.

Bushra (2010) investigated the treatment of marine clay with cement that was extracted at 1.5 m depth from the sea. Percentages of cement used were 10%, 15%, and 20% of the dry weight of marine clay soil, respectively. To represent samples at depths of 10 m, 15 m, and 20 m, treated samples were cured for 28 days under 100 kPa, 150 kPa, and 200 kPa stresses.

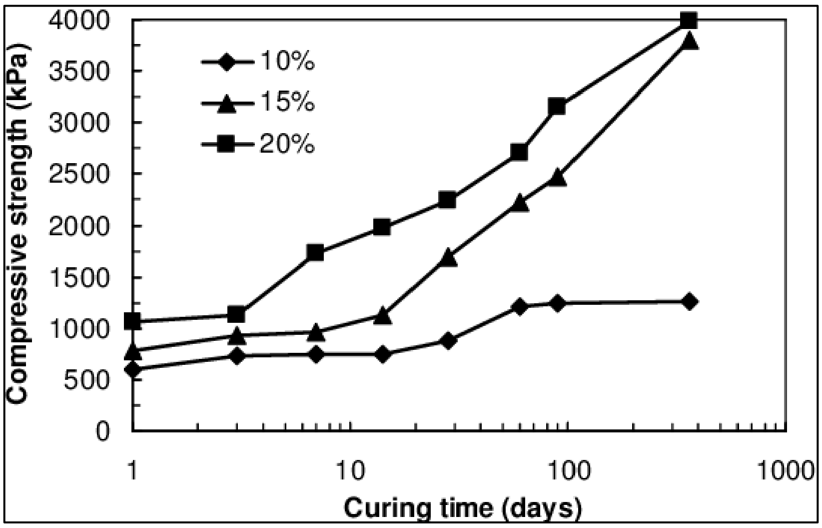

Figure 2.6: Graph of compressive strength against curing time (Bushra, 2010)

From Figure 2.6, the findings showed that 20% cement had the highest strength after 7 days of curing. The strength of the cement-treated soil for 20% cement is around 1748 kPa. As curing period increases, the compressive strength of the stabilized marine clay soil increase.

Table 2.5: Summary of previous research related to cement as a stabilizing agent with different soil types in Malaysia

Reference	Soil type	Soil Location	Result
Wahab et al., 2021	Lateritic Soil	Universiti Teknologi Malaysia, Johor campus	For 7 days curing time, the untreated UCS of 200.74kPa improved to 391.35kPa, 1233.15kPa, 1737.52kPa and 1899.6kPa for 3%, 6%, 9% and 12% cement content.
Saeed et al., 2014	Kaolin Clay	Tapah, Perak	The cement-treated soil exhibited the trend of UCS increase with an increase in cement content from 5% to 10% of 716kPa and 1418kPa at 7 days curing

In Table 2.5, several studies have been done with different soil types for cement additives improvement in Malaysia. The result of unconfined compression strength analysis has been extracted from the previous research to look into the improvement on stabilization of different soil types with cement admixture.

2.5 Lime

Lime is a cost-effective method of soil stabilization. The amount of lime used in most soil stabilizers ranges from 5% to 10%. Rather than cementing via pozzolanic reaction, lime stabilization adds strength through cation exchange capacity. Lime stabilization is a pozzolanic reaction that happens when pozzolana minerals react with lime in the presence of water, resulting in the formation of cementitious compounds.

(Afrin, 2017). The addition of lime to a soil increases the plasticity limit while decreasing the plasticity index value (Puppala et al., 2015).

The stabilization of marine clay using cement and lime to enhance subgrade material is accessed in a research from Rivers State University in Nigeria. (Youdeowei et al., 2020). The types of stabilization used were mechanical and chemical. The percentage of lime by mass of soil used is 2 %, 5 %, 8 % and 11 %.

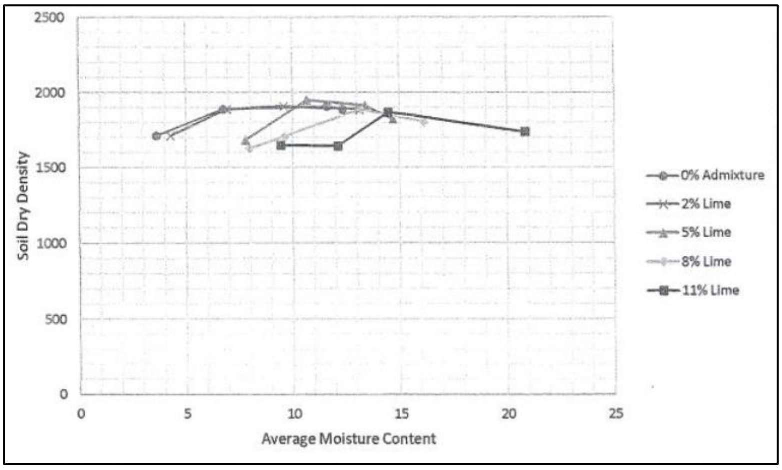

Figure 2.7: Graph of Dry Density against Average Moisture Content for Percentage Addition of Lime (Youdeowei et al., 2020)

From the Figure 2.7 above, the best result was obtained at 2 % lime with maximum dry density value 1960 kg/m^3 after which decreases to 1870 kg/m^3 at 11 % lime. The highest CBR values obtained are 5.07 % for the unsoaked and 10.46 % for the soaked CBR with 11% lime content. Lime stabilized at 11% for soaking CBR shown that lime may be utilized efficiently as a subgrade material for the construction of flexible pavements on rural roads with high traffic volumes.

Yunus et al. (2015) discussed on the compressibility properties and strength of lime-treated marine clay. Marine clay in Nusajaya's Iskandar Malaysia Region has required solutions for the development of buildings and highways. As a result, soil treatment with lime is recommended to raise the strength of unsuitable materials in order to satisfy building requirements for foundation and development of work. The hydrated lime proportions are 3%, 6%, and 9% to the untreated marine clay and were evaluated after 7 and 28 days of curing. When lime is added to marine clay soil, UCS test is performed to measure the maximum compressive strength. Table 2.6 shows a summary of results from unconfined compressive tests (UCS) at various time periods.

Table 2.6: Summary of UCS data at different curing period (Yunus et al., 2015)

Sample	UCS (kPa) 7 Days	UCS (kPa) 28 Days
Untreated	21	21
Marine clay + 3% of lime	138	144
Marine clay + 6% of lime	294	423
Marine clay + 9% of lime	379	517

After 28 days of curing, the strength of marine clay with 9% lime is 517 kPa, which has larger marine clay strength with 3 % and 6 % lime. When the strength of 9 % lime treated marine clay after 28 days is compared to the strength after 7 days, the strength of the marine clay is greater after 28 days. When the curing duration is increased to 28 days and the lime concentration stays constant at 3%, the soil strength rises dramatically to 144kPa. The strength steadily rises when additional lime concentration 6% is added. It has been shown that a 3% increase in strength is insignificant, indicating that the addition of 3% lime is ineffective for stabilizing marine clay. However, the strength increases dramatically with additions of 6% and

9% lime content. Between 7 and 28 days, the percentages of strength gained assessed for marine clay treated with 6% and 9% lime content are 30% and 27% respectively. Prior to analysis, increased lime concentrations may be used to stabilize the strength of marine clay. The experiment revealed that prolonging the curing duration enhances the strength of lime treated marine clay.

Venkateswarlu et al. (2014) discussed on different chemicals such as lime and cement were used as stabilizing materials in the experiment. The marine clay was collected from Kakinada, India. Soft marine clays are very sensitive to changes in stress system and moisture content. The percentage of lime used is 4%, 6%, 8%, 10% and 12%. From the compaction test, as percentage of lime increase, the optimum moisture content decrease while dry density increase.

Several studies have been done with different soil types for cement additives improvement in Malaysia from Table 2.7. The result of unconfined compression strength analysis has been extracted from the previous research to look into the improvement on stabilization of different soil types with cement admixture.

Table 2.7: Summary of previous research related to lime as a stabilizing agent with different soil types in Malaysia

Reference	Soil type	Soil Location	Result
Saeed et al., 2013	Brown Pure Kaolin	Tapah, Perak	Comparison to maximum UCS value of 10% lime, it can notice that 5% lime-treated soil specimens show an increased in UCS at early stages of curing time 7, 14 and 28 days. However, 10% lime cured samples showed increased about more than 9 times of original untreated strength after 200 days curing.
Saeed et al., 2012	Lateritic Clay contaminated by heavy metals	Balai Cerap, Universiti Teknologi Malaysia	Soil specimens treated by 5% and 10% for contaminated soil with copper. 10% lime for all percentages of copper has an obvious improvement in the UCS value when compared to 5% lime.

2.6 Microstructural changes of Marine Clay soil treated with Stabilizing Agents

The microstructural properties of the treated sample will be studied in order to analyze the chemical reaction and microstructure changes at the micro level. Material's physical and mechanical qualities are determined by its microstructure and composition. Microstructure measurements use size, shape, and relation between phase to define the quantity of each phase, distribution and composition.

In Bangkok, a study is being conducted to see of the addition of cement kiln dust and fly ash improves the UCS of soft clay compared to standard Portland cement (Yoobanpot et al., 2017). X-ray Diffraction (XRD) was utilized to analyze each reaction product, and a scanning electron microscope (SEM) was employed to observe changes in the microstructures of the stabilized clay after 3 days, 7 days, 28 days, and 90 days of curing. The clay was taken from 2 m to 6 m depth in Bangkok, Thailand. An X-Ray Fluorescence (XRF) analysis was used to determine the chemical composition of clay which indicated in Table 2.6. This reveals the clay's principal components to be SiO_2, Al_2O_3 and Fe_2O_3. A SEM micrograph of typical Portland cement particles revealed that they have sharp corners, an uneven surface, and are not homogeneous in shape as shown in Figure 2.8.

Table 2.8: Chemical composition of base clay and ordinary Portland cement (Yoobanpot et al., 2017)

Compound	**Base clay**	**OPC**
Silicon dioxide (SiO_2)	61.17	18.43
Alumina oxide (Al_2O)	21.64	4.95
Ferric oxide (Fe_2O_3)	9.32	3.29
Calcium oxide (CaO)	1.03	66.35
Magnesium oxide (MgO)	1.68	0.86
Sulphur trioxide (SO_3)	1.15	3.18
Potassium oxide (K_2O)	2.53	1.22
Na_2O + TiO_2 + other	0.57	0.15
Loss on ignition (percentage by mass)	0.91	1.57

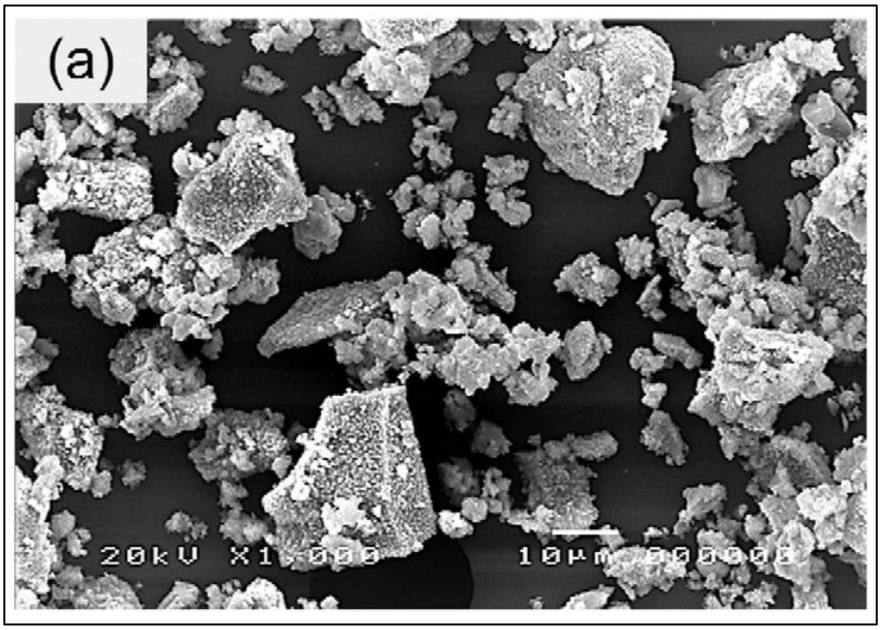

Figure 2.8: Scanning electron microscope for ordinary Portland cement (Yoobanpot et al., 2017)

The XRD patterns of 10% ordinary Portland cement at 3 days, 7 days, 28 days, and 90 days compared to base clay are shown from Figure 2.9. After 3 days of cement addition, new reflections of calcium silicate hydrate (CSH), calcium hydroxide (CH) and ettringite phases may be detected in stabilized clay. Furthermore, tricalcium silicate and dicalcium silicate were discovered to be generated by the remaining unhydrated reactant. According to the XRD pattern, CSH intensity grew fast at 3 days and 7 days, to 28 days and rises at 90 days, which is consistent with the curve of unconfined compressive strength development.

The reflections of new ettringite crystal that developed at 3 days, 7 days, 28 days, and 90 days also increased with time which is similar to how calcium silicate hydrate (CSH) increased. It should be noted that ettringite crystal is excellent for increasing strength. The lower intensity of product calcium hydroxide (CH) compared to calcium silicate hydrate (CSH) rises with time, whereas the tricalcium silicate (C_3S)

and dicalcium silicate (C_2S) tend to drop slightly with time. The intensities of C_3S and C_2S dropped with time as the hydration process progressed, resulting in greater quantities of CSH and CH products over the curing phase. Furthermore, reflection of montmorillonite of the basal clay reduced after three days of admixture with OPC. The decrease in reflection was especially evident on curing 7 days, 28 days, and 90 days. The XRD analysis results show that the large decrease in reflection of montmorillonite had an influence on modifying the clay mineralogy as a consequence of the formation of new CSH and ettringite.

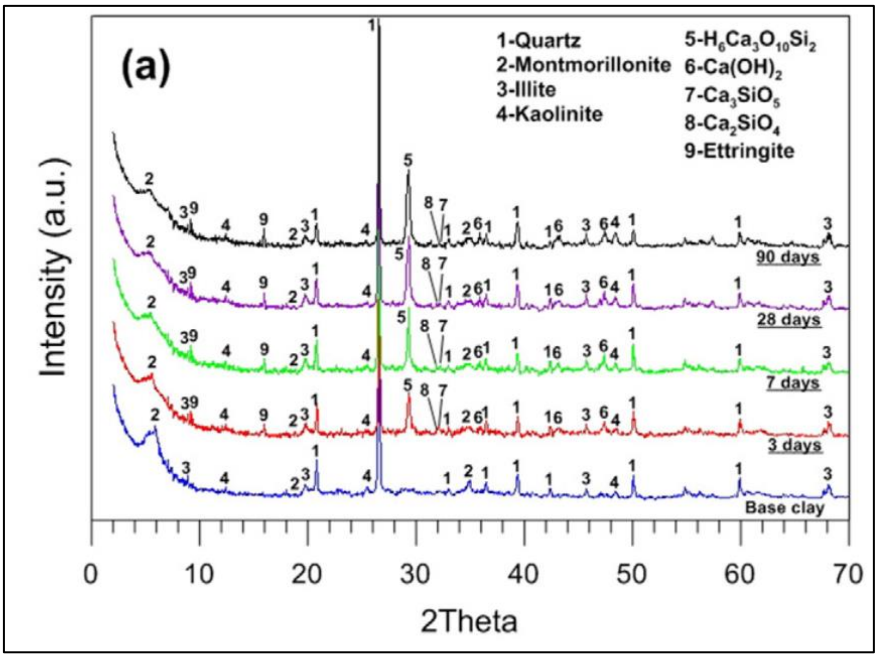

Figure 2.9: X-ray diffraction patterns of stabilized clay specimen with 10% ordinary Portland cement (Yoobanpot et al., 2017)

Scanning electron microscope (SEM) may be used to examine the microstructure of the clay after it has been enhanced by cementitious materials. After unconfined compressive strength test, the approach was utilized to examine the microstructure change of the stabilized clay. The microstructure of 10% OPC is presented in the figure below, which demonstrated that the major reaction of hydration products are calcium silicate hydrate (CSH) and ettringite, which was coated on the surface of clay in the phases of three and seven days, as validated by XRD analysis in Figure 2.10 and Figure 2.11 respectively. The CSH components, which are given in fabric form, were distributed over clay clusters and filled the pore between particles of clay, resulting in a denser clay structure. The ettringite crystal with needle-like shape developed between the clay and the CSH fabric, resulting in stiffer clay packed structure.

At day of 28, an extra amount of CSH and ettringite were constantly generated throughout a curing time to cover the surface of clay, stiffening the structure of clay and increasing the strength of clay as shown in Figure 2.12. For long period curing, such as 90 days, continuous intercrossing of clay particles with CSH and ettringite influenced the improved structure of clay becoming stronger, resulting in enhanced strength of clay through curing duration as shown in Figure 2.13. It was discovered that a change in the stabilized structure of clay corresponded to the results of the XRD analysis and the compressive strength test.