COMPRESSIBILITY BEHAVIOUR OF LATERITE SOIL TREATED WITH LIME UNDER SATURATED AND UNSATURATED CONDITIONS

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DEDICATION

This thesis is dedicated to the people I love, who have supported me throughout my journey to achieve my dreams. Thank you for making me see this adventure through to the end.

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ABSTRACT

In Malaysia, laterite soil is commonly employed as construction materials for roads, buildings, slopes and foundations as it is widely available. Besides, their nature as high durable soil makes them abundantly used in all geotechnical construction. However, some laterite soil is problematic due to its high clay content. Moreover, the climate conditions (annual flood and dry season) cause changes in soil suction in the unsaturated layer above the groundwater level, affecting the geotechnical structure performance. Therefore, quicklime (CaO) is used as a soil stabiliser with various percentages to enhance the strength and compressibility of natural soil, consequently extending the structure's life span and functionality. This research aims to evaluate the strength and compressibility of lime-treated laterite, under saturated and unsaturated conditions. However, the main focus is more on soil compressibility behaviour. The optimum lime content and curing period are determined by the Unconfined Compressive Test (UCT), following the Malaysian Public Work Department (MPWD) for soil strength requirement on the stabilised subgrade. The strength of lime-treated soil had achieved the required minimum of 800 kPa at 5% lime content seven days curing period, denoted as 5%L7D sample. Next, based on California Bearing Ratio (CBR) testing, lime helps increase soil strength in unsaturated conditions but requires more curing time to build resilience to withstand the saturated conditions, which is inconvenient for real-world construction. The soil compressibility was tested via a conventional oedometer (saturated) and a suction-controlled oedometer under the axis-translation technique (unsaturated). In saturated conditions, the compressibility of laterite changes from high to moderate compressibility upon lime treatment. In unsaturated conditions, the effect of cementation bonding and suction is noticeable. The compressibility of laterite changes from high to low compressibility with increasing suction. According to the loading-collapse (LC) curve result, the suction effect was depicted by higher yield strength with higher matric suction. However, the effect of bonding showed a reduction in yield strength with increasing matric suction, which opposed the empirical concept proposed by Alonso *et al.* (1994). It was concluded that the effectiveness of lime is low in dry conditions (high matric suction).

ABSTRAK

Di Malaysia, penggunaan tanah laterit adalah mudah untuk didapati dan biasanya digunakan sebagai bahan untuk asas pembinaan jalan raya, bangunan, dan cerun. Selain itu, sifat tanah laterit yang sangat tahan lama menjadikan ia kerap digunakan dalam semua jenis pembinaan geoteknikal. Namun, sesetengah tanah laterit dianggap bermasalah kerana kandungan tanah liat yang tinggi. Tambahan, disebabkan oleh keadaan cuaca yang tidak menentu (banjir dan kemarau) yang mengakibatkan perubahan dalam sedutan tanah pada lapisan tidak tepu yang terletak di atas aras air bawah tanah sekaligus menjejaskan struktur geoteknikal. Oleh hal yang demikian, kapur atau kalsium oksida (CaO) digunakan untuk menstabilkan struktur tanah pada kadar peratusan yang berbeza-beza untuk meningkatkan kekuatan tanah sedia ada dan kebolehupayaan untuk pemampatan dan secara tidak langsung memanjangkan jangka hayat, struktur dan fungsinya. Maka, tujuan penyelidikan ini dijalankan adalah untuk menilai kekuatan dan kemampatan tanah laterit yang telah dirawat oleh kapur untuk kedua-duanya sekali, tanah bersifat tepu dan tidak tepu. Tetapi fokus utamanya adalah pada sifat kemampatan tanah. Ujian Kuat Tekan Bebas (UCT) menentukan tempoh pengawetan dan kadar kandungan optimum kapur, seterusnya diikuti oleh ujian kekuatan tanah pada kestabilan subgred dari Jabatan Kerja Raya. Kekuatan tanah yang telah dirawat dengan kapur dianggap telah mencapai keperluan minimum pada 800 kPa selari dengan kandungan 5% kapur hasil tujuh hari tempoh pengawetan yang diwakili sebagai sampel 5%L7D. Seterusnya, berdasarkan ujian Nisbah Galas California (CBR), kapur membantu meningkatkan kekuatan tanah dalam kandungan tidak tepu tetapi memerlukan proses pengawetan yang kerap untuk membina ketahanan untuk bertahan dalam kandungan tepu, di mana ia sangat tidak sesuai diaplikasikan dalam situasi kerja pembinaan yang sebenar. Kemampatan tanah telah dianalisis menggunakan odometer konvensional (tepu) dan odometer penyedutan terkawal di bawah teknik terjemahan paksi (tidak tepu). Dalam keadaan tepu, kemampatan tanah laterit boleh berubah daripada tinggi kepada sederhana sejajar dengan rawatan kapur yang diberikan. Manakala dalam keadaan tidak tepu, kesan ikatan simen dan sedutan adalah jelas terpapar. Kemampatan laterit berubah daripada tinggi ke rendah dengan peningkatan sedutan. Mengikut keputusan lengkungan pemuatan-runtuh (LC), kesan sedutan ditakrifkan sebagai tinggi hasil kekuatannya selari dengan matrik sedutan yang tinggi. Walau bagaimanapun, kesan ikatan telah menunjukkan penurunan dalam hasil kekuatannya sekiranya matrik sedutannya meningkat sekaligus menyangkal konsep empirikal yang diusulkan oleh Alonso et al. (1994). Sebagai rumusan, keberkesanan kapur adalah rendah sekiranya berada dalam keadaan kering (matrik sedutan yang tinggi).

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LIST OF ABBREVIATIONS

1D	-	One dimensional
3D	-	Three dimensional
ADVDPC	-	Advanced pressure volume controller
ASTM	-	American Society of Testing Materials
BBM	-	Barcelona basic model
BLA	-	Bamboo leaf ash
BS	-	British Standard
CAH	-	Calcium aluminium hydrate
CASH	-	Calcium aluminate silicate hydrate
CBR	-	California Bearing Ratio
CL	-	Low plasticity clay
cps	-	Counts per second
CRS	-	Constant rate strain
CSH	-	Calcium silicate hydrate
EDX	-	Energy dispersive x-ray
FESEM	-	Field emission scanning electron microscope
HAEV	-	High air entry value
ICC	-	Initial consumption cement
ICL	-	Initial Consumption Lime
LC	-	Loading-Collapse
LL	-	Liquid limit
LVDT	-	Linear variable displacement transducer
MCC	-	Modified cam-clay
MDD	-	Maximum dry density
MH	-	Sandy elastic silt
MPWD	-	Malaysian Public Work Department
OMC	-	Optimum moisture content
PEG	-	Polyethylene glycol
PI	-	Plasticity index
PL	-	Plastic limit

PSD	-	Particle size distribution
RHA	-	Rice husk ash
SC	-	Clayey sand
SEM	-	Scanning electron microscopy
SWCC	-	Soil-water characteristic curve
UCS	-	Uncofined compressive strength
UCT	-	Unconfined compressive test
UIRL	-	University Industry Research Laboratory
USCS	-	Unified Soil Classification System
USM	-	Universiti Sains Malaysia
UTM	-	Universiti Teknologi Malaysia
XRD	-	X-ray dispersive
XRF	-	X-ray fluorescence

LIST OF SYMBOLS

Al_2O_3	-	Aluminium oxide
Ca^{2+}	-	Calcium ion
$Ca(OH)_2$	-	Hydrated lime
E_{50}	-	Secant modulus
Fe_2O_3	-	Iron oxide
H_2O	-	Water
OH^-	-	Hydroxyl ion
SiO_2	-	Silicon oxide
c_c	-	Compression index
c_s	-	Swelling index
c_v	-	Coefficient of consolidation
e_f	-	Final void ratio
e_i	-	Initial void ratio
m_v	-	Coefficient of volume compressibility
p_c	-	Yield stress
q_{50}	-	Half compressive strength peak
u_a	-	Air pressure
$u_a - u_w$	-	Matric suction
u_w	-	Water pressure
w_{opt}	-	Optimum moisture content
δ_{ij}	-	Kronecker's delta
ε_{50}	-	Strain at q_{50}
ρ_{dmax}	-	Maximum dry density
σ	-	Effective stress
σ'	-	Net stress
σ_{ij}	-	Total stress
Δe	-	Difference in void ratio
$\Delta p_{c\,e}$	-	Yield stress of uncemented soil at zero suction
$\Delta p_{c\,st}$	-	Difference of suction effect

$\Delta p_{c\ suc+st}$	-	Difference of bonding effect
$p_{c\ treated}$	-	Yield stress of treated sample
$p_{c\ untreated}$	-	Yield stress of untreated sample
µm	-	Micro-metre
Al	-	Aluminium
Ca	-	Calcium
CaO	-	Calcium oxide
Co-kα	-	Cobalt laminas
eV	-	Electron volt
Fe	-	Iron
g	-	gram
kg	-	kilogram
kJ	-	Kilo-joule
kN	-	Kilo-newton
kPa	-	Kilopascal
m	-	metre
min	-	Minute
mm	-	Millimetre
nm	-	Nano-metre
°C	-	Degree celcius
P	-	Phosphorus
pH	-	Percentage of hydrogen
Pt	-	Platinum
s	-	Suction
Si	-	Silicon
S-S	-	Silica-sesquioxide ratio

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CHAPTER 1

INTRODUCTION

1.1 Background

Residual soils can be found in most countries, especially in the tropics. In Malaysia, laterite soil is a common type of residual soil that is abundant due to the hot and humid climate changes. Laterite soils are usually used as backfill materials for road constructions, foundations, and slopes since they are abundant in widespread areas (Ogundipe and Adekanmi, 2019). However, these soils have distinct properties in different areas and even between vertical layers, depending on parent material, weather, terrain, vegetation, and age (Fookes, 1990). The strength of laterite soil is related to the composition of the soil. Severe chemical weathering causes silicate minerals in laterites to decompose into predominant clay minerals, kaolinite, and some montmorillonite and illite. These clay particles cause potential swelling behaviour and reduce soil strength (Dumbleton, 1963), which induces soil collapsibility (Kassim e*t al*., 2005; Latifi *et al*., 2013; Rashid *et al*., 2017).

Laterites are naturally strong due to their high cohesion and internal friction angle (Fish, 1971), but they are not as strong as rocks. In addition, laterite soils are collapsible soils that collapse upon wetting due to their porous and unsaturated nature (Silveira and Rodrigues, 2020). According to Uday (2014), dry laterites are durable. They can be utilised as bricks for construction, but they showed high collapse potential when wet because the soil particles become soft and break up. Many cases are reported on soil collapse after heavy rainfall and flooding that causes structures such as road foundations, buildings, slopes, pavements, and retaining walls to be reconstructed. As a result, the government has to allocate billions of ringgits to rebuild the damaged properties every year. Such incidents are a waste of money, and the lives of civilians are also at stake.

Therefore, soil stabilisation method is introduced in the construction. This is because, soil stabilisation is one of the methods to improve the engineering properties of soil by strengthening the soil using stabilisers such as lime and cement. In this research, soil stabilisation by lime is used. Thus, studying the compressibility behaviour of saturated and unsaturated laterite soil treated with lime is essential to predict the behaviour of untreated laterite and lime-treated laterite soil.

1.2 Problem Statement

Moisture-induced strain is common in so-called collapsible soils, characterised by an unstable structure (Dudley, 1970). When soil is saturated, the soil suction is lost. However, dry soil exerts high suction between soil particles. The collapse behaviour of soil is attributed to the structure of the soil, matric suction, and external load (Uday, 2014). For laterite soil, the groundwater surface is generally deep, and usually, evapotranspiration exceeds infiltration due to climatic conditions and thick vegetation, causing the soils above the groundwater to become unsaturated (Rao and Revanasiddappa, 2002; Aziz *et al.*, 2006; Huat *et al.*, 2007b). Because of the capillary feature, this state produces apparent cohesiveness. The capillary between the soil particles causes surface tension in the water film, resulting in a negative pore water pressure known as matric suction. Due to moisture, suction is reduced immediately after rain, causing the residual soil strength to deteriorate. Several authors reported that the collapse phenomenon is predicted in these circumstances (Aziz *et al.*, 2006; Huat *et al.*, 2008a). Soil collapses cause settlements, which can result in fissures in walls, floors, and concrete buildings (Silveira and Rodrigues, 2020).

Thus, intense weathering in Malaysia is associated with alternate high temperatures and heavy rainfalls throughout the year, resulting in an in-depth profile of laterite soil that is usually more than 30 m deep (Far *et al.*, 2013; Kholghifard, 2014). This deep soil profile is abundant and beneficial for engineering projects as fill materials for slopes, road constructions, and residential development (Huat *et al.*, 2008a). Laterite soil has highly durable (Fish, 1971), but some have poor engineering properties (Kassim *et al.*, 2005; Latifi *et al.*, 2013, Rashid *et al.*, 2017) due to swelling clays content such as montmorillonite, kaolinite, and illite that impose potential swelling behaviour and reduce soil strength (Dumbleton, 1963).

Then, another problem with laterite soil arises from the high annual rainfall. During the rainy season, the soil layer above the groundwater surface is saturated with water and loses its capillary stresses, which causes a reduction in soil strength. Soils above this surface are unsaturated, and it gains strength through capillary stresses and soil particle cementation. Generally, low moisture content exerts high suction between soil particles while high moisture content causes low soil suction (Uday, 2014). Reduction of soil strength was due to increase of pore water pressure, causing reduction of effective stress. However, unsaturated laterite tends to collapse (loading-collapse) when wetting occur at higher mean net stress before yielding. Therefore, the soil will collapse, leading to infrastructural damage such as road damage, building collapse, and slope failure (Huat *et al.*, 2007a; Kholghifard, 2014). As a result, the government must spend considerable money to reinstate the damaged properties (Ghani *et al.*, 2016). Figure 1.1 shows road failure due to soil collapse after heavy rainfall and flooding. Another example of soil collapse is the well-known tragedy of the Highland Towers in 1993 due to several days of continuous rain (Kazmi *et al.*, 2017). The most common landslide events occur in Cameron Highland because the area is prone to excessive precipitation throughout the year (Maturidi *et al.*, 2020).

Figure 1.1 Images of soil collapse after rainfall a) at Kg Bukit Sekencong Road, Kedah (Ismail and Ghani, 2017) and b) Jemaluang-Mersing Road, Johor (Astro AWANI, 2018).

Hence, the application of lime in soil stabilisation was implemented in this study, because they were introduced thousands of years ago (McDowell, 1959) and is more common in several developed countries such as China, Sweden, Japan and the United States (Association, 1990). Lime is commercially used as engineering and building materials and a chemical substance for raw materials. It originates from crushed or pulverised limestone composed of calcium carbonate. In addition, lime exists in other forms, such as quicklime and hydrated lime (Afolayan, 2017). According to Chan and Lau (1973), Malaysia is rich in limestone, making it easier to find and cost-effective. However, cement is the most common stabiliser for soil treatment in Malaysia. It is often used in construction projects (Kamaruddin et al., 2012) since cement production in this country is significant (produced over 20 million tons per year) (Madlool et al., 2011). Unfortunately, cement manufacture has had a negative impact on the environment, as it generates a significant amount of carbon dioxide gases (Taha *et al.*, 2013; Gao *et al.*, 2015). Hence, this study focuses on lime as a stabiliser to improve soil properties.

1.3 Study Objectives

This study evaluates the compressibility behaviour of lime-treated laterite soil subjected to saturated and unsaturated conditions. Several objectives are proposed as follows to achieve the aim:

1. To determine the basic properties of laterite soil, untreated and treated with lime.
2. To evaluate the strength and compressibility characteristics of untreated and lime-treated laterite soil under saturated and unsaturated conditions.
3. To determine the microstructural characteristics of untreated and lime-treated laterite soil.
4. To evaluate the empirical theory of the coupling effect of suction and cementation bonding of the lime-treated soil in the Loading-Collapse (LC) curve.

1.4 Scope of Research

This study is focused on determining the compressibility characteristics of laterite soil treated with lime in saturated and unsaturated conditions under constant suction. The soil used in this research was a reddish laterite soil obtained at a depth of about 1.0 m below the ground surface within Universiti Teknologi Malaysia (UTM), Skudai.

Both undisturbed and compacted soil samples were prepared according to BS EN ISO 17892 and BS 1377-4:1990 (BSI, 1990). The disturbed samples treated and untreated were utilised to determine soil properties such as physical, chemical and engineering characteristics. The initial Consumption Lime (ICL) test is performed to study the minimum percentage of lime required for soil performance. The ICL test is conducted according to ASTM D6276 – 19 (ASTM, 2006). Based on the ICL test, the range of lime used in this study was determined. The maximum dry density (MDD) and optimum moisture content (OMC) of untreated and treated samples were determined by the Modified Proctor compaction. To determine the optimum-lime content and curing period sample throughout this research, the Unconfined Compressive Test (UCT) is conducted. The strength of lime-treated soil shall achieve a minimum of 800 kPa to be used as optimum lime content and curing period based on Malaysian Public Work Department (MPWD) specification (JKRM, 2019). Next, the California Bearing (CBR) and consolidation tests shall proceed based on the result of the UCT.

CBR test was performed under soaked and unsoaked conditions. The soaked CBR samples were subjected to various curing periods (3, 7, 14 and 28 days). Next, a consolidation test consisting of a conventional oedometer and a suction-controlled oedometer were conducted to measure the compressibility behaviour of soil under saturated and unsaturated conditions. This was done via a suction-controlled oedometer (fabricated by Kholghifard (2014)) that was modified based on the axis translation technique. The suction-controlled oedometer was conducted with incremental vertical stress under constant suction (i.e., 20 and 400 kPa).

Several microstructural analyses such as Field Emission Scanning Electron Microscope (FESEM), Energy Dispersive X-ray (EDX), X-ray Diffraction (XRD), and X-ray Fluorescence (XRF) were employed to assess the variation in microstructural properties.

1.5 Research Significance

Unsaturated analysis has been carried out on natural laterite soil (Vilar and Rodrigues, 2011; Benatti *et al.*, 2011; Kholghifard, 2014; Kholghifard and Ahmad, 2021). Several researchers have also studied the effect of stabilisers on unsaturated clayey soils on various engineering parameters. Arroyo *et al.* (2013) measured the compressibility of silty sand under constant water content with varying loads. Djelloul *et al.* (2017) utilised an oedometer under a constant suction test but focused more on hydraulic conductivity. Furthermore, Yu *et al.* (2019) studied the effect of cement on the stress and strain of silty sand.

Meanwhile, Soleimani-Fard *et al.* (2022) used a new testing device called the Biaxial device to study the shear strength of the soil. Although researchers studied the compressibility of unsaturated lime-treated soil (Mavroulidou *et al.*, 2013; Haeri *et al.*, 2019), clayey soils were more concerned. Hence, there is a lack of studies on the compressibility of lime-treated laterite in unsaturated condition. Moreover, a previous researcher from UTM, Skudai, Kholghifard (2014), has studied the compressibility behaviour of untreated natural laterite soil subjected to constant suction. Therefore, it is essential to predict the behaviour of unsaturated treated laterite soil for comparison purposes and also looking at the bonding effect in saturated and unsaturated laterite.

Hence, this study extends the study for the framework of unsaturated laterite soil in UTM, which was pioneered by Kholghifard (2014) by using lime as the stabiliser in the researcher's work through evaluation of the following properties:

1. Basic properties behaviour of untreated and treated laterite soil.
2. Strength and compressibility behaviour and characteristics in saturated and unsaturated conditions.
3. Microstructural behaviour of lime-treated laterite.
4. Verification of effect of cementation in saturated and unsaturated conditions through strength and compressibility via controlled suction conditions.

1.6 Organisation of Thesis

Chapter 1 describes the problems related to laterite soils and the collapse behaviour of soil under unsaturated conditions. Furthermore, the objectives, scope, and significance of this research and the organisation of thesis outlines are presented in this chapter.

The literature review is presented in Chapter 2. The study describes the characteristics and problems of laterite soil related to saturated and unsaturated conditions. General knowledge on soil stabilisation, lime stabilisation and the engineering properties of lime-stabilised laterite soil is also discussed. This chapter also presents past studies' consolidation parameters of lime-treated soil in saturated and unsaturated conditions. The following sub-chapter discusses various experimental methods' mineralogy and microstructural characteristics of both treated and untreated laterite soils. The last part of this chapter reviews the empirical concept of the Loading-Collapse (LC) curve of unsaturated soil.

Chapter 3 explains the research methodology thoroughly. Basic properties of untreated and treated laterite soil were conducted according to BS EN ISO 17892 and BS 1377-4:1990 (BSI, 1990). The percentage of lime used is determined by the ICL test proposed by Eades and Grim (1966). The optimum lime content and curing period are determined by achieving a minimum of 800 kPa of Unconfined Compressive Strength (UCS) values based on Malaysian Public Work Department (MPWD) specifications (JKRM, 2019). Then, the obtained UCS results then proceeded with the CBR and consolidation tests. The central part of this research is the consolidation tests which consisted of a conventional oedometer (saturated condition) and suction-controlled oedometer (unsaturated condition). Lastly, microstructural analyses were performed as outlined by the American Society of Testing Materials (ASTM). The microstructural studies on both untreated and lime-treated soil (under optimum lime content and curing days) explains the soil behaviour from other testing in this research.

Chapter 4 discusses the result and discussion on the engineering properties of both untreated and lime-treated laterite soil. The selection of optimum lime content and curing period is determined through the UCS test based on the compressive strength values. Besides, the results of soaked and unsoaked CBR is also included. The main part of this research is the consolidation parameters of lime-treated laterite under saturated and unsaturated conditions. Microstructural analyses were also discussed to identify the effect of lime on soil microstructure based on its optimum lime content and curing period. Lastly, the obtained LC curve trend on the untreated and lime-treated samples is discussed and correlated with the empirical concept Alonso *et al.* (1990) proposed.

Chapter 5 concludes the results of this research and the recommendations for future research.

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