Available online at
http://journal.uitm.edu.my/ojs/index.php/BEJ

Built Environment Journal

e-ISSN: 2637-0395

Built Environment Journal 22(Special Issue) 2025, 1 – 14.

The Determination Strength of Marine Clay Stabilised with Quicklime

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ARTICLE INFO

Article history:
Received 1 November 2024
Revised 24 April 2025
Accepted 15 May 2025
Online first
Published 31 July 2025

Keywords:
Soil Stabilisation
Quicklime
Marine Clay
Unconfined Compressive Strength (U.C.S.)

DOI:
10.24191/bej.v22iSI.6466

ABSTRACT

Sub-grade or Soil stabilisation is a technique to increase the strength of the pavement layer by altering the chemical and mineral composition using chemical or non-chemical additives as the stabilising agents. Soil stabilisation using quicklime mixed with the existing subgrade/soil has been widely applied to the base or foundation in any construction by geotechnical engineers to improve or to develop desirable engineering properties for a particular construction. This paper investigates the effect of a chemical stabiliser, which is quicklime, on the strength of clay to act as a subgrade for the pavement layer. This current study focused on a series of laboratory tests consisting of initial tests on physical material characteristics of treated subgrade/soil and ungraded subgrade/soil. The analysis will focus on improving marine clay's strength while withstanding the load applied during the Unconfined Compressive Strength (U.C.S.) test. This paper also focuses on exploring the material characteristics of marine clay before and after being treated with quicklime.

INTRODUCTION

As a developing country, Peninsular Malaysia, with a total land area of 130,268 km2, is part of Sundaland, which encompasses the islands of Borneo, Java, and Sumatra, as well as the shallow oceans between them, from which several smaller islands arise (Van Bemmelen,1949). Separated into three parts of longitudinal belts, East, Central and West of Peninsular Malaysia, each belt has many different characteristics and geological evolution. The Western Belt's whole length, from the Kinta Valley to Malacca, comprises Palaeozoic rocks. The Kinta Valley is dominated by moderately thick limestones that range in age from

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Silurian to Permian and contain schists, amphibolite, conglomerates and other clastic as well as tiny serpentinite bodies. Rocks of Permian and Mesozoic largely coat central belts. Clay's undesirable properties include high plasticity, poverty in workability, difficult compaction and high swelling potential, which increase the construction cost and may be a significant problem for particular construction. Hence, an enhancing technique, which is stabilisation, is needed before construction can be made. Over the past years, road engineers have applied many revolutions and developments to improve the parameters of cohesive soils (Cai et al., 2006). Stabilisation of subgrade/soil can increase and improve soil shear strength and soil's durability, soil shear strength and soil's durability in the overall bearing capacity of subgrade/soil. In road construction for pavement layer, with the addition of a stabilising agent in clay the pavement's subgrade can be increased. Once the subgrade/soil was stabilised, the moisture content through water absorption and permeability can be reduced in dry clay cases, in conjunction with the reaction to shrinking of materials by moisture content and temperature changes. Due to the modification, the strength development after 28 rapidly increases in the curing period during the Unconfined Compression Test (U.C.T.), which is the effect of the reaction between lime and clay (Yunus et al.,2015).

LITERATURE REVIEW

Marine or Soft Clay

Increasing urbanisation, to achieve the target for the development of the country and the desperation to make money, many investors are taking a brave step on exploring new locations, which area at coastal areas, to build superstructures, construction of facilities for portsports and reclamation of land. Not only buildings but coastal areas also need to construct roads to connect states. In Malaysia, marine clay is usually very thick, about 30m and is typically found in coastal area. Untreated marine clay can be a problem for geotechnical engineers due to its poverty of strength to support any load or structure in the areas. Marine/soft clay behaviour, such as high compressibility, poor drainage characteristics and low shear strength and durability, causing a primary concern in the construction near the coastal area. Marine clay's undesirable behaviour is a highly compressible soil and illustrates a mild swelling mechanism with the presence of moisture (Ruan et al., 2020).

With the inhabitancy of water, marine clay will lose its strength and become as hard as brick when it becomes dry. As it dries, which is the situation when it loses moisture, a crack will happen and based on a few studies, the cracks will go worst, which is 250mm to 500mm (Surya Karteek, 2018). These misbehaviours are due to the existence of clay minerals and organic material content in triggering marine clay's reaction activities. Keeping marine clay well drained is challenging as these soils absorb water through capillary action. In addition, due to excellent surface permeability and capillary action, these soils can become very moist and wet until the early summer months (G.S Karteek, 2018). Soft soils have high plasticity indexes with respect to liquid limit, and their volume fluctuates dramatically with the changing water concentration. Based on (Zurairahetty et al., 2015), the behaviour limits of the marine clay are as follows.

Table 1. Index Properties of Marine or Soft Clay

Material Content	Marine/Soft Clay
Liquid Limit (%)	58
P.L. (%)	36
P.I. (%)	22
Specific gravity	2.62
Optimum Moisture Content (%)	21

https://doi.org/10.24191/bej.v22iSI.6466

Max. Dry Density (kg/m³)	1600
Organic content (%)	4.2

Source: Zurairahetty et al. (2015)

Quicklime

Quicklime or hydrated lime is a calcium-based stabiliser which has an influence the geotechnical and engineering properties and often used in civil engineering applications. Quicklime is a reasonably priced substance. A chemical derivative (calcium hydroxide, of which quicklime is the basic anhydride) are significant industrial compounds. Using various stabilisation techniques and quicklime as stabilising agents an improve the soil's strength and durability. Aside from that, while lime and cement can help with the engineering properties of soils, they can also have adverse effects on other soil properties (Singh & Vasaikar, 2015). In the presence of sulphate, for example, these additives may cause undesirable expansion (Behnood, 2018). The combination of stabilisation the method through the material's engineering process for the existing subgrade/soil and the binder agent has an impact on its properties. The selection of binder agent or cementitious materials process via soil characteristics analysis such as Particle Size Distribution (PSD) or Gradation (Sieve Analysis), chemical composition and mineralogy, Percentage of Plasticity Index, organic matter content, salt content, primarily sulphate, cation exchange capacity (C.E.C.), Lime Demand Test, specific surface area and others, all influencing the stabilisation effectiveness. In addition, the properties of stabilised soils can be affected by the type and duration of the curing condition, the construction method and quality, for example, the amount of compaction test (Eilmy et al., n.d.).

Lime is commonly used to improve subgrade soil performance by minimising volume change. Mixing with quicklime and subgrade/soil is crucial to achieve the desired results specified in the specifications. Lime also reduces soil fines by flocculating and aggregating clay particles (Little 1995). This increases the fraction of sand and silt particles in the grain size distribution (Basma and Tuncer 1991). Lime additionally reduces fine-grained soil swell potential (Kennedy et al. 1987). Soils with moisture content below optimal have a substantially greater swell potential than soils with above optimum (Sweeney et al. 1988). Soils with high montmorillonite content showed no reaction to an increase in strength via U.C.S. test. Therefore, some treatments for surface area for the cementitious chemicals have a substantial impact on the strength through mixing altogether with cement O.P.C. for strength and quicklime to reduce the moisture content.

Soil Stabilisation

Table 2. Various Additives for Stabilisation of Soil

Group	Binder Agent
Cementitious	Lime, fly ash, ground-granulated blast furnaced (GGBS), cement, kiln dust and silica fume.
Chemical	$CaCl_2$, KCl, Na_2SiO_3, $FeCl_3$, $Mg(OH)_2$, Na(OH), NaCl, $MgCl_2$, and $AlCl_3$
Non-Cementitious	Stone dust, quarry dust, aggregate waste, rock waste powder, crusher dust, granite sawdust and sand.

Source: Reddy & Tahasildar (2015)

Soil modification explains the process of altering chemical and physical characteristics in soils to achieve more strength and durability for construction purposes. When it comes to reaction to increase physical soil, such as shear strength and bearing capacity. Soil stabilisation is a process of applying measured compaction with the addition of a binder agent to generate a better soil characteristic that is required in the material's engineering properties. To achieve desired soil properties, a variety of existing

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technologies and materials are available to choose. An operational of soil stabilisation and selection material binder agent plus existing sub grades/soil, named as stabilisation method. The soil stabilisation method is more commonly method being used for marine/soft clay treatment to change the material characteristic to improve the strength and save time and cost. The cementitious, chemical additives and non-cementitious are all examples of the binder agents, according to Reddy & Tahasildar (2015).

Quicklime Treatment

Soil engineering qualities may be greatly improved by applying lime. Enhancement may be divided into two broad categories: soil modification and soil stabilisation (Mohammed Al-Bared & Marto, 2017). Quicklime able to enhance almost all fine-grained soils, although it has a greatest impact on clay soils with a moderate to high ductility. For the most part, modification happens primarily to the substitution of calcium cations provided by hydrolysed lime that is already present on the clay mineral's surface. Cementitious products are formed in high-pH environments when lime combines with clay minerals to generate hydrated lime. This reaction alters the clay mineral properties. Plasticity and swelling are decreased, moisture-holding capacity is lowered, and stability is increased.

This method of soil stabilisation involves mixing lime into the soil to increase its strength and resiliency (Babu & Poulose, 2008). The proportion of lime added/mixed into the existing soil varies depending on the characteristics of the native soil. The higher the plasticity, the more lime is required/usually mixed in. Quicklime is a naturally occurring material in nature. Although treating soil with lime is a popular method of soil stabilisation, it is most common on paved roads. Typically, treating unpaved roads with lime is prohibitive. Geographical regions frequently dictate whether or not it can be used to stabilise soil. The subgrade of pavement can be strengthened and stiffened by mixing/adding quicklime to existing subgrade/soil.

METHODOLOGY

The Soil Mechanics, Laboratory of the School of Civil Engineering, test was conducted to identify the fundamental properties of natural soil. There were determined that several initial tests were based on BS 1377: Part 2:1990, specifically for moisture content, specific gravity, particle size distribution, and Atterberg limit test. The soil's chemical content test (pH test was conducted using BS 1377: Part 3:1990 at the Environmental Laboratory of the School of Civil Engineering using a pH meter and its buffer solutions. Furthermore, the density compaction of the soil sample was identified through the Proctor Compaction test by BS 1377: Part 4:1990. Following the initial test for physical properties, a series of Unconfined Compressive Strength (U.C.S.) tests are conducted by BS 1377: Part 7:1990 to determine the improvement of material characteristics and the increased strength properties of soil sample before and after reinforced through mixing with different proportions of binder agents.

https://doi.org/10.24191/bej.v22iSI.6466

Fig. 1. Example Laboratory Test

Source: Authors (2025)

Study Area

The soil that was being used was marine clay. The soil was taken at a landfill area in Nibong Tebal, Pulau Pinang. Clayey soil was selected as the testing soil. It is regarded as problematic because it is particularly vulnerable to water logging because of its high mineral content, such as montmorillite, which causes structure settlement. The soil sample should be more than 30 kg for laboratory testing to conduct all the proposed testing.

Fig. 2. The Site Location of The Case Study

Source: Authors (2025)

The quicklime being used was obtained from RCI Lime Sdn. Bhd. The certificate and analysis for this quicklime powder are shown in Table 3.

Table 3. A Proportion of Quicklime Powder is Being Used

Parameters	Results	Test Method
Calcium Oxide, CaO (%)	90.62	MS 850: 2010
Magnesium Oxide, MgO (%)	2.41	MS 850: 2010
Insoluble Matter, Including Silicon Dioxide, SiO_2 (%)	0.36	MS 850: 2010
Ferric Oxide, Fe_2O_3 (%)	0.02	MS 850: 2010
Aluminium Oxide, Al_2O_3 (%)	0.25	MS 850: 2010
Passing 1 mm sieve (%)	100.00	ASTM C110

Source: Authors (2025)

Design Mix Process

The design mix process for this research is shown in Table 4 below. Usually, in the pavement layer, the normal range for lime stabilisation takes about 3% to 6% lime addition by mass of the dry soil (Zukri & Ghani, 2014). The specimens get stronger as the pH drops. Three percent of the lime stabilised with soil and quadrupled its strength, but more lime resulted in a more extended response with more strength (Eades et al., n.d.). The proposed mix design on the percentage of lime for this research is based on past researchers who conducted a study on soil stabilisation using quicklime/hydrated lime on clayey soil.

Table 4. Mix Design Used in This Study

Batch	Sample	Type of Laboratory Tests
Control sample	Natural Subgrade/Soil i.e. Marine Clay (100%)	• Moisture Content (MC) • Specific Gravity • Particle Size Distribution (PSD) • pH Test • Atterberg Limit Test • Proctor Compaction Test • Unconfined Compressive Strength (U.C.S.) test
1	Marine Clay + 3% lime	• Proctor Compaction test • Unconfined Compressive Strength (U.C.S.) test
2	Marine Clay + 6% lime	
3	Marine Clay + 9% lime	
4	Marine Clay + 12% lime	

Source: Authors (2025)

https://doi.org/10.24191/bej.v22iSI.6466

RESULTS AND DISCUSSION

Material Characteristic of Marine Clay

By measuring material characteristics via the moisture content, specific gravity, particle size distribution, and Atterberg limit test, the physical characteristics of natural soil are identified based on the British Soil Classification System. The subgrade/soil samples are categorised as clayey SILT of Intermediate Plasticity (CI) based on the physical characteristics tests that were performed. Information about the soil index characteristics (Refer to Table 5).

Table 5. Material Characteristic of Soil Sample

Soil Properties	Marine Clay (Nibong Tebal, Pulau Pinang)
Colour	Dark brown
Natural moisture content (%)	16.72
pH	3.302
Specific gravity (Mg/m_3)	2.605
Particle size distribution (%)	
Gravel	0.58
Sand	2.42
Silt	70.04
Clay	26.96
Plastic limit, P.L. (%)	15.76
Liquid limit, L.L. (%)	35.85
Plasticity index, P.I. (%)	20.09
Soil Classification	CI

Source: Authors (2025)

Atterberg Limit Test

Sub grade or soil subgrade is to deform without cracking or collapsing, known as plasticity. The lubricating effect of water films between adjacent particles is one of the primary properties of all cohesion soils. Soil engineering relies heavily on information about a soil's plasticity and standard limits tests established to measure it. The shear strength and compressibility of fine soils are greatly influenced by their plasticity and as a result, this property is used to classify soils. The Atterberg Limit is the point at which soilssoil behaves similarly to plastic when water is high. It determines the moisture content at which fine-grained clay and marine clay appear in four states: solid, semi-solid, plastic, and liquid. The Atterberg limits are used to measure fine-grained soil for critical water content. It has three limits, including shrinkage, plastic, and liquid.

https://doi.org/10.24191/bej.v22iSI.6466

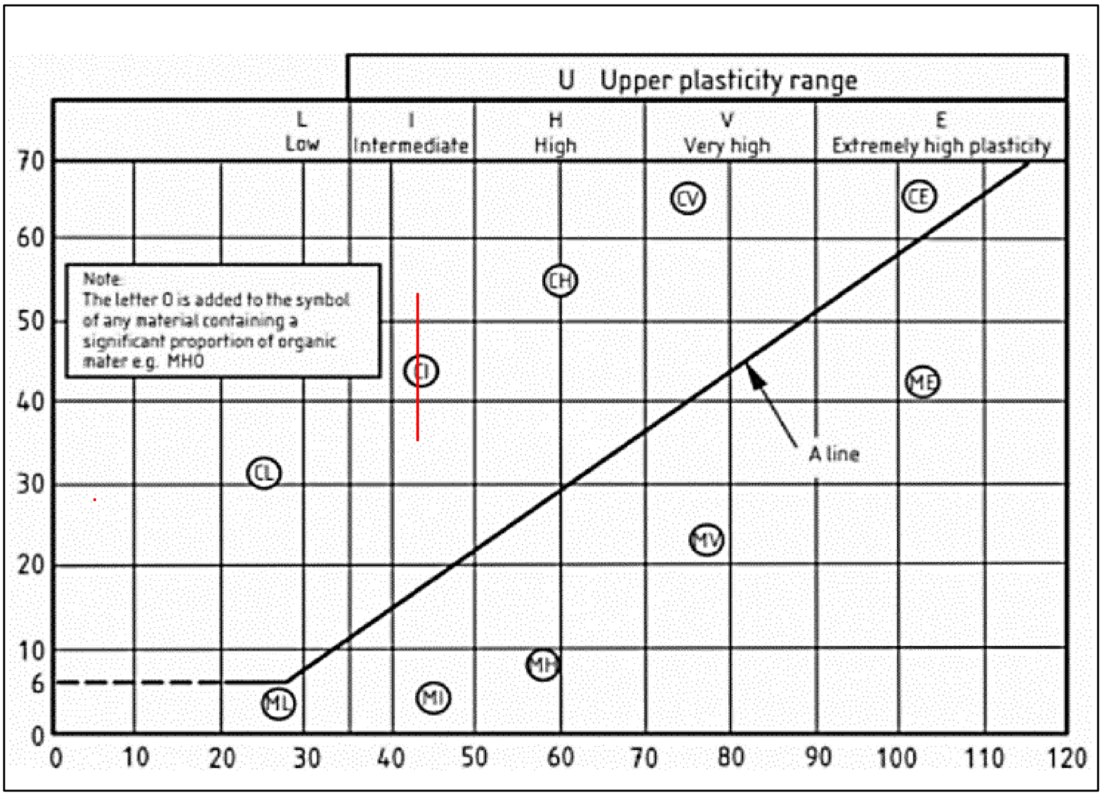

Fig. 3. Plasticity Chart of Marine Clay's Sample

Source: Authors (2025)

Table 6. Atterberg Limit of Soil Sample

Liquid Limit (L.L.)	35.85 %
Plastic Limit (P.L.)	15.76 %
Plasticity Index (P.I.)	20.07%
Soil classification	CI

Source: Authors (2025)

Proctor Compaction Test

The process of identifying soil density using an engineering process known as compaction. It causes the particles in the soil to rearrange themselves, leading to a decrease in the amount of space between them. When soil is compacted to a very high degree, there are relatively few voids existing in the soil, which may result in the soil having a more extensive unit weight. Because the soil in its natural state is only loosely connected, it needs to be compacted to increase its bearing capacity (Hussain & Dash, 2016). The compaction test has shown the relationship between the dry density and moisture content. A few compaction tests are done on both natural soil/marine clay and subgrade/soil that has been stabilised by adding quicklime in varying quantities, such as 3%, 6%, 9% and 12% by weight of dry soil.

Table 7. Optimum Moisture Content and Maximum Dry Density Soil Sample

Sample	O.M.C. (%)	M.D.D. (Mg/m^3)
Natural soil	55.8	1.129
Soil (Marine Clay) + 3% Quicklime	55.9	1.210
Soil (Marine Clay) + 6% Quicklime	50.83	1.266
Soil (Marine Clay) + 9% Quicklime	47.19	1.270
Soil (Marine Clay) + 12% Quicklime	40.23	1.347

Source: Authors (2025)

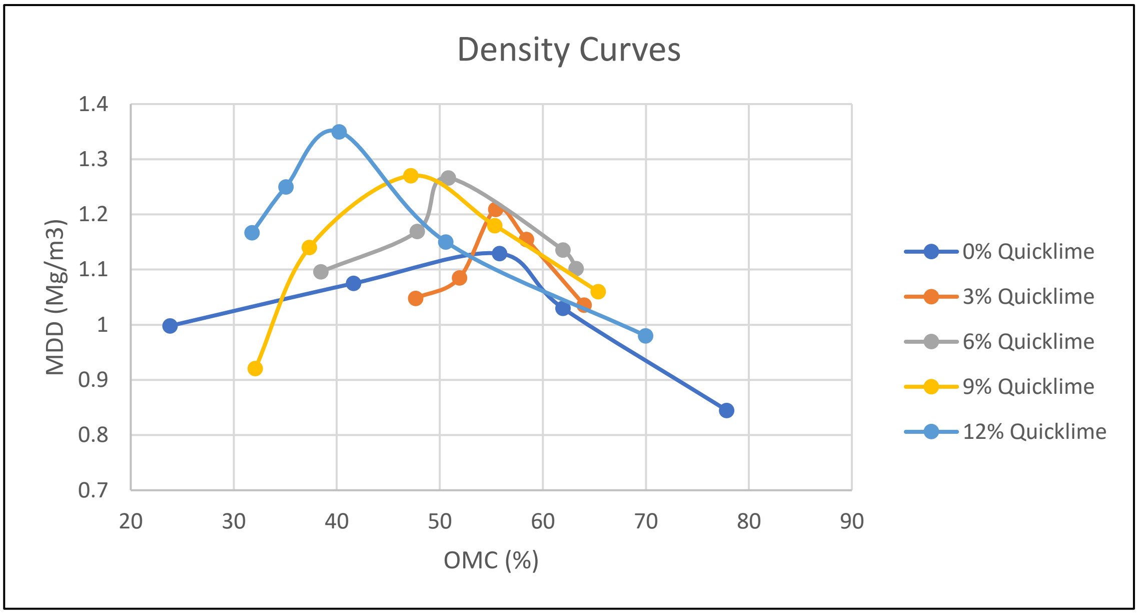

Fig. 4. Density Curves for Sub Grade/Soil Stabilised with Quicklime

Source: Authors (2025)

With an increase in the amount of quicklime from 0 per cent to 12 per cent by weight of the soil, the Maximum Dry Density (M.D.D.) increased from 1.129 Mg/m3 to 1.347Mg/m3, as indicated in the graph that refers to Figure 4. On the other hand, the results displayed to demonstrate that the Optimum Moisture Content (O.M.C.) gradually decreased from 55.8 per cent for natural soil to 40.23 per cent for soil stabilised with 12% quicklime. According to the findings, one conclusion that can be drawn is that the decrease in soil content, which relates to an increase of per cent in the amount of quicklime in the subgrades/soil, caused the increasing the subgrades/soil's dry density, as a result, the addition of lime had the effect of lessening the compacted soil's total mass and volume. In addition, lime treatment has resulted in flattening compaction curves, indicating the modification in density is due to changes in moisture content. In other words, the required density of subgrids/soil can be defined with lime treatment over a broad range of controlling moisture content.

Unconfined Compressive Strength (U.C.S.) Test

A test of the material's strength through the Unconfined Compression Strength Test (U.C.S.) is carried out to establish the maximum compressive strength of marine clay after lime has been added. The

https://doi.org/10.24191/bej.v22iSI.6466

unconfined compressive strength of subgrades/soil is defined as the maximum compressive force per unit area that a subgrade/soil sample can withstand. Figure 5 summarizes the results obtained from unconfined compressive tests (U.C.T.) conducted after 7 days of curing with varying lime content.

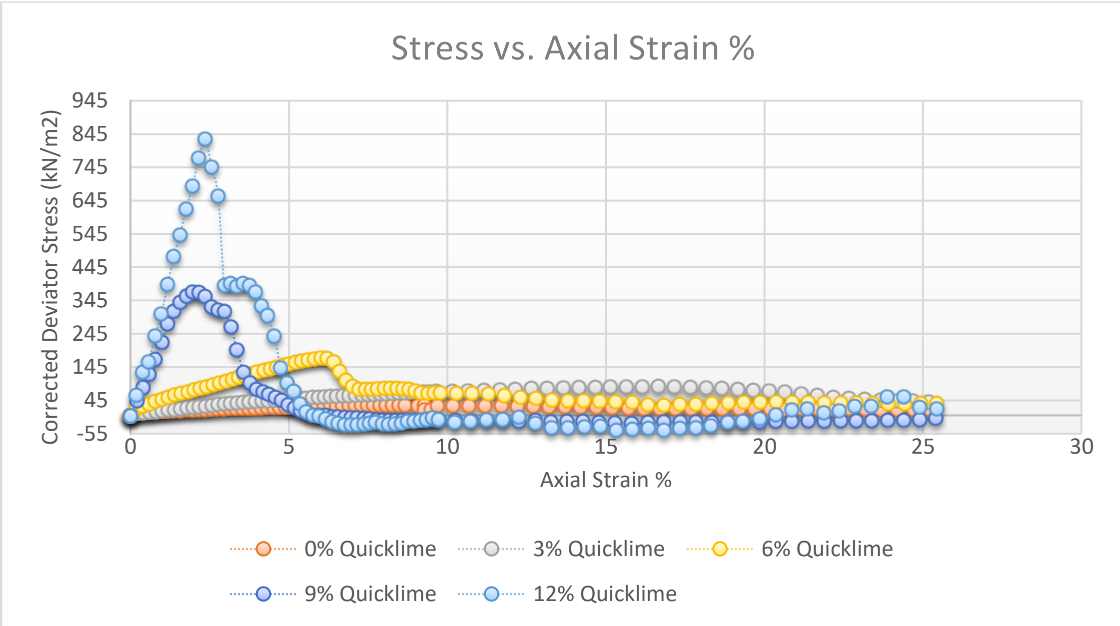

Fig. 5. Stress vs. Strain Curves of Soil Sample Added with Different Amounts of Quicklime

Source: Authors (2025)

The Unconfined Compressive Strength of the grade/soil sample is gradually increased after 7 days of curing time. After curing days, an increase strength can be seen as the soil material samples become harder. The small rise in strength between natural soils and the subgrade/soil added with 3% quicklime is due to an adaption of soil to stabiliser added. Furthermore, by increasing the percentages of quicklime, the Unconfined Compressive Strength test of marine clay is also reinforced. Figure 6 shown the curves obtained from plotting the stress and strain value of 0% , 3%, 6%, 9% and 12% of quicklime as the soil stabiliser. As can be seen each curve reach peak value of strength but start to drop at certain point due to brittle structure of soil sample. The duration of 7 days curing time, reducing the moisture content of sample and the sample will undergo brittle shear slip failure due to dry conditions of sample.

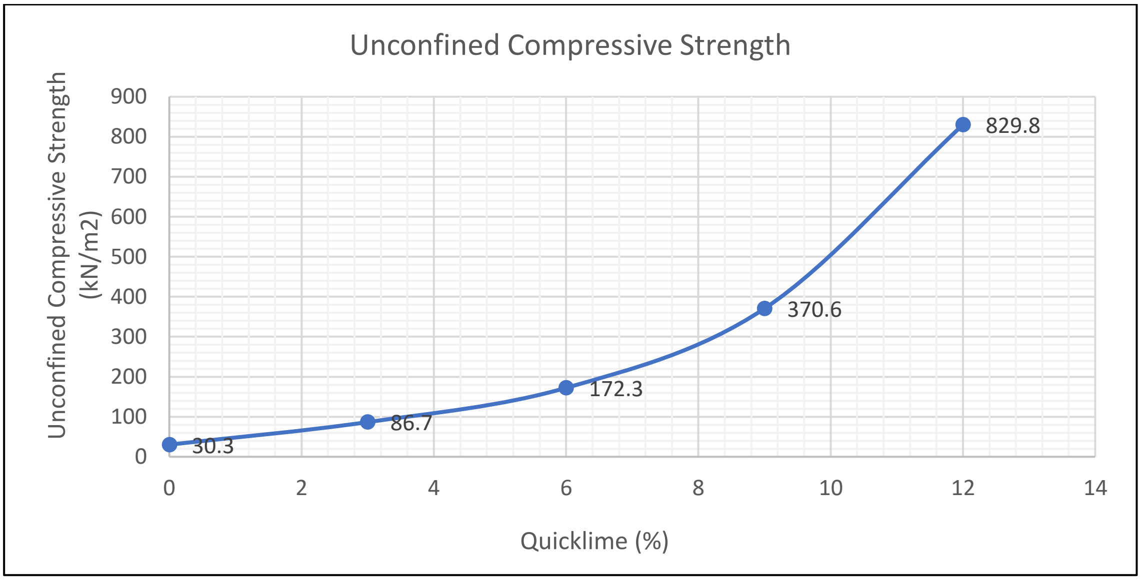

Fig. 6. Stress vs. Strain Curves of Soil Sample Added with Different Amount of Quicklime

Source: Authors (2025)

CONCLUSION

In this research study, the utilisation of lime as stabilising material in marine clay are investigated and analysed. The physical engineering test was prepared on the subgrade/soil before conducting the mechanical test on the marine clay. Based on the British Soil Classification System (BSCS) and the Plasticity Test, the samples of soil from the marine clay area are classified as clayey SILT with Intermediate Plasticity (CI). The reaction of mixing quicklime to a soil sample at different rates of 3%, 6%, 9% and 12% by weight of sub grade/soil caused the Maximum Dry Density (M.D.D.) increased while the Optimum Moisture Content (O.M.C.) is decreased. This is because the quicklime behaviour that absorb the moisture in soil through pozzolanic activities. With more lime, cations near negatively charged clay surfaces grow. This reaction imbalance in pore water causes osmosis. Charge on the clay surface prevents ion diffusion. Free water molecules diffuse towards the clay surface to equalise charge. In such a system, hydration and osmotic forces offset long-range attractive forces, and the overall force becomes repulsive (Mitchell and Soga, 2005). It separates clay particles, creating a scattered structure that allows particles to slide over each other during compaction. Other than that, through this laboratory testing, the strength of modified sub grade/soil is determined. Through a series of U.C.S. test, the strength of soil sample increased with the increasing percentages of lime content. The highest compressive strength obtained is 829.8 kPa when marine clay is added with 12% of quicklime. Soil stabilisation's treatment flattens compaction curves, increased density variation with gradually decreasing of moisture content. With soil treatment, soil density can be reached over a lower down a moisture content. Overall, it can be concluded that quicklime can be used for altering the problematic soil, this can be proved as the characteristic of soil such as strength increase gradually. The untreated soil shows significant changes when added with lime. This shows a big difference between the strength of soil sample before and after being treated.

Other than that, the output of this study is giving knowledge on the importance to treat soil before proceeding to construct a building and roadways. Soil stabilisation is necessary in soft soil so that they can act as strong foundation before any infrastructure and commuting ways can be built. This is to ensure no fatality and economy loss happened due to damage on the construction that have been built. This study may help any public and private sector which involved in developing new infrastructure at coastal areas. Furthermore, this study concentrated on building a strong foundation using marine clay as a material for subgrade's pavement. Thus, the result of this research can influence people on how to use natural resources towards reprocessing materials for soil treatment to create innovative and cost-effective solutions for the pavement's infrastructure demands. In this study, quicklime can be proven as a binder agent for soil stabilisation method that can treat marine clay to be a reliable base for any pavement's construction.

ACKNOWLEDGEMENTS

In the name of Allah S.W.T. the Most Gracious and the Most Merciful. All praise is due to Allah, who preserves and governs the whole world. The authors would like to express their sincere appreciation to all parties involved directly especially Warren Smith the Group of Director from Stabilised Pavements Australia or indirectly in the completion of this paper entitled The Determination Strength of Marine Clay Stabilised with Quicklime.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest associated with this research.

AUTHORS' CONTRIBUTIONS

Ghazali Ismail led the research project, coordinate data collection and contributed to the writing of the manuscript. Ismacahyadi Bagus Mohamed Jais assisted in data analysis and manuscript editing. Harris Ramli provided technical input and reviewed the structural and geotechnical aspects of the paper. Mohd Khairolden Ghani contributed to the discussion on lime stabilisation methods and shared industry relevant insights from CACTI-2 and CREAM for CIDB.

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