COMPRESSIBILITY BEHAVIOUR OF NIBONG TEBAL CLAY TREATED WITH CEMENT-CALTITE STABILIZER

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SCHOOL OF CIVIL ENGINEERING
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COMPRESSIBILITY BEHAVIOUR OF NIBONG TEBAL CLAY TREATED WITH CEMENT-CALTITE STABILIZER

By

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ABSTRAK

Lempung marin sering menyebabkan masalah penenggelaman tanah yang teruk. Penstabilan lempung marin adalah penting untuk mengelakkan masalah ini. Penyelidikan ini bertujuan untuk mengkaji sifat indeks geoteknik lempung Nibong Tebal, menentukan tingkah laku mampatan lempung Nibong Tebal yang dirawat dengan penstabil simen dan Caltite melalui ujian kebolehmampatan satu dimensi, dan menilai keberkesanan penstabil simen dan Caltite dengan membandingkan prestasi lempung Nibong Tebal yang tidak dirawat dan dirawat. Pengumpulan lempung Nibong Tebal telah dijalankan di Kampus Kejuruteraan USM. Beberapa sifat geotekniknya telah dikaji, termasuk kandungan lembapan, taburan saiz zarah, had Atterberg, dan graviti spesifik. Kebolehmampatan bagi lempung Nibong Tebal yang tidak terganggu dan lempung yang dirawat dengan simen dan Caltite ditentukan melalui ujian kebolehmampatan satu dimensi. Didapati bahawa lempung tersebut merupakan lempung berkeplastikan tinggi dengan indeks keplastikan 32%. Lempung tersebut mempunyai kadar kelembapan yang tinggi sebanyak 112.12% dan terdiri sepenuhnya daripada kelodak dan lempung. Indeks mampatan (C_c), pekali kebolehmampatan isipadu (m_v), dan pekali pengukuhan (C_v) untuk lempung tidak terganggu masing-masing adalah 1.27, 0.8m^2/MN hingga 5m^2/MN, dan 0.43m^2/tahun hingga 3.9m^2/tahun. C_c dan m_v yang tinggi serta C_v yang rendah menunjukkan bahawa kebolehmampatan lempung tersebut sangat tinggi. Kebolehmampatan lempung dikurangkan setelah dirawat dengan 10% simen. Pengurangan kebolehmampatannya lebih ketara apabila dirawat dengan 10% simen+10% Caltite. C_c dan m_v masing-masing telah diturunkan kepada 0.10 dan 0.01m^2/MN hingga 0.35 m^2/MN. C_v telah dinaikkan kepada 38.5m^2/tahun hingga 472.1 m^2/tahun. Rawatan semen-Caltite adalah kaedah yang lebih berkesan untuk mengurangkan kebolehmampatan lempung marin berbanding dengan rawatan semen.

ABSTRACT

Marine clay is a problematic soil that will cause severe settlement problem. Thus, the stabilization of marine clay is important. This research is aimed to determine the geotechnical index properties of Nibong Tebal clay, to determine the compressibility behaviour of Nibong Tebal clay treated with cement and Caltite stabilizer through one-dimensional consolidation test, and to evaluate the effectiveness of the cement and Caltite stabilizer by comparing the performance of untreated and treated Nibong Tebal clay. The Nibong Tebal clay was collected at USM Engineering Campus. Its geotechnical properties were studied, including moisture content, particle size distribution, Atterberg limit, and specific gravity. The compressibility of the undisturbed clay and the clay treated with cement and Caltite were determined through one-dimensional consolidation test. It was found that the clay is a high plasticity clay with plasticity index of 32%. It has high moisture content of 112.12% and is fully made up of silt and clay. The compression index (C_c), coefficient of volume compressibility (m_v), and coefficient of consolidation (C_v) of the undisturbed clay is 1.27, 0.8m^2/MN to 5m^2/MN, and 0.43m^2/year to 3.9m^2/year, respectively. The high C_c, high m_v and low C_v showed that it is very compressible. The compressibility of the clay reduced after treated with 10% cement. The improvement was more significant when it was treated with 10% cement+10% Caltite. The C_c and m_v were reduced to 0.10 and 0.01m^2/MN to 0.35m^2/MN, respectively. The C_v was increased to 38.5m^2/year to 472.1m^2/year. Hence, the cement-Caltite treatment is more effective than the cement-treatment in reducing the compressibility of marine clay.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Marine clay is a type of fine-grained soil that is commonly seen along the coastal region of Peninsular Malaysia. It is made up of silt, clay, and sand where usually the proportion of silt and clay is 78% or more while the proportion of sand is 12% or less. Other contents of the clay are minerals such as montmorillonite, kaolinite, illite, quartz, feldspar (Ahmad and Harahap, 2016). It has a low bearing capacity due to its highly compressible behaviour and low permeability with high susceptibility to water. For marine clay in Malaysia and South East Asia, the moisture content in the clay can range from 10% to 160% while the plasticity index (PI) can range from 10% to 80%, showing that the clay is very susceptible to water (Ramamoorthy, 2007).

Stability and settlement are always the main problems that will be encountered when engineers are dealing with soft soil like marine clay, for example to use the soil as a subgrade for roads, to excavate the soil, to build embankment or to construct buildings on the soil, etc. Serious settlement can be induced by problems of compressibility of the clay which occurred when there is a change in volume in the soil, especially when the external loads increase or is imposed for a prolonged time (Lat et al., 2018). In order to resolve this issue, stabilization of marine clay has been widely investigated using different additives including lime, recycled blended ceramic tiles, biomass silica, bentonite, granular inclusion, etc.

Most of the stabilization of marine clay is achieved by introducing cementitious compound in the clay, which are the calcium silicate hydrate (C-S-H), calcium aluminate hydrates (C-A-H) and calcium hydroxide (CH) produced through the hydration of calcium silicates. Some of the stabilization are achieved by filling up the voids in the clay particles with fines. Cement and lime are commonly used stabilizers which provides bonding between the clay particles and reduce the moisture surrounding the clay particles during hydration process (Jawad et al., 2014). However, it does not repel water and cannot prevent additional water attack.

Hydrophilicity, hydrophobicity, and superhydrophobicity are the attributes showing the wettability or the affinity of a surface towards water. It can be determined by the contact angle of static water with the surface. Hydrophilic surface is attracted to water where the contact angle of static water is less than 90°. Hydrophobic surface repels water with contact angle of static water is equal to 90°. Superhydrophobic surface is achieved when the contact angle is more than 150° (Law, 2014).

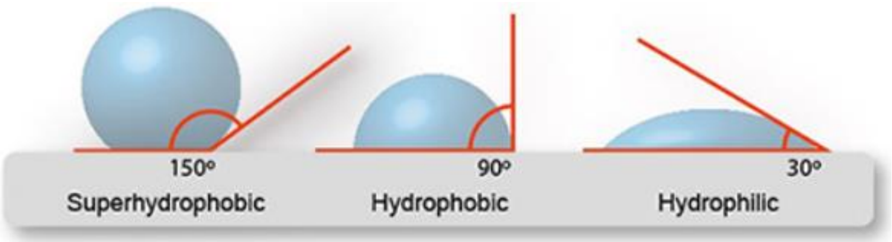


Figure 1.1: Hydrophilicity, hydrophobicity, and superhydrophobicity (Hydrophobic Coatings: Select the Ideal Dispensing Method and Equipment, n.d.)

The aim of this study is to stabilize the Nibong Tebal marine clay by reducing its compressibility through the addition of cement and introducing the hydrophobic attribute to the marine clay to prevent the penetration of water and chemical attack. Long-term stability of the clay is desired in order to achieve a longer service life of building structures built on the clay or infrastructures constructed underground in clay soil.

1.2 Problem Statement

Many researches have been done on the stabilization of marine clay using lime and cement (eg., Anggraini et al., 2017; Saleh et al., 2019; Gubran and Chan, 2020; Zidan, 2020). However, after a certain period of time, the clay is still susceptible to problems caused by changes in moisture content. Research was carried out by Cuisinier and Deneele (2008) to evaluate the long-term efficiency of lime-treatment on the swelling and shrinkage behaviour of clay. The results show that the efficiency of lime treatment tends to decrease with time and the swelling potential of the soil increased. Lime is brittle in nature and cracking may easily occur. Thus, lime-treated clay is vulnerable to moisture and chemical attack. Its compressibility even increases in the presence of sulphate salt, as sulphate ions can cause the formation of ettringite in lime, which disintegrate the cementitious compound in the soil. This indicated that the swelling of marine clay due to water penetration can still occur and lead to the settlement problems. Therefore, hydrophobic attribute is desired to avoid the degradation of lime-treated marine clay caused by water seepage. Caltite is a polymer that is used in concrete to achieve waterproof and to prevent the diffusion of moisture with dissolved salts which may cause corrosion in concrete. In this research, the geotechnical characteristics of the Nibong Tebal marine clay will be evaluated so that improvement can be made on the soil. The effect of the addition of cement and Caltite to the compressibility of the marine clay will be studied. The effectiveness of these additives to achieve long-term effective stability in marine clay will be evaluated.

1.3 Objectives

The objectives of the study are:

i. To determine the geotechnical index properties of the Nibong Tebal clay.

ii. To determine the compressibility behaviour of the Nibong Tebal clay treated with cement and Caltite using one-dimensional consolidation test.

iii. To evaluate the effectiveness of the cement and Caltite stabilizer by comparing the performance of untreated and treated Nibong Tebal clay.

1.4 Scope of Study

The physical properties of the Nibong Tebal marine clay that will be identified are the moisture content, Atterberg limit, specific gravity, and particle size distribution. The compressibility behaviour of the undisturbed Nibong Tebal marine clay and the remolded Nibong Tebal marine clay with treatment are observed for further analysis in terms of consolidation parameters, including void ratio, compression index, coefficient of volume compressibility, and coefficient of consolidation. Comparison will be carried out for the undisturbed natural clay, clay treated with cement, and clay treated with cement-Caltite to evaluate the effectiveness of the stabilizer.

1.5 Significance of Study

This research studies the stabilization and improvement of engineering performance of the Nibong Tebal marine clay by adding cement and Caltite to reduce its compressibility. The addition of cement will enhance the compressive strength of the Nibong Tebal marine clay while the addition of Caltite will provide a hydrophobic property to the marine clay. The cementitious compound produced by the cement is able to stabilize the clay after 28 days of curing period and hence, the compressibility of the clay can be reduced. Caltite can repel water with the activation by cement. Therefore, it prevents the swelling of clay due to the penetration of water particles. This can avoid the settlement of the marine clay even after a long period of time as the clay can remain stable without the attack of water and chemical.

The stabilization of marine clay using cement-Caltite is potential to be applied in lime column in the future. Lime column has been widely used in clay stabilization with deep soil mixing method. It can be expected that the long-term stability provided by the cement-Caltite will improve the engineering properties and reduce the problems encountered with the current lime column.

1.6 Dissertation Outline

Chapter 1 contains the background of the research project, problem statement, objectives, scope of study, and significance of study. Chapter 2 highlights the literature review which are related to the research, mostly on the characterization and stabilization of marine clay. Chapter 3 explains the research methodology which includes the sample collection, the design of experiments, and the theory for analysis. Chapter 4 analyses the results from the laboratory works and presents discussions on the results. Chapter 5 concludes the findings of this research and suggests recommendations for future study. The chapters included in the dissertation are listed as below.

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: Methodology

Chapter 4: Results and Discussion

Chapter 5: Conclusions and Recommendations

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Marine clay is a soil type that is extremely soft and sensitive with flat and featureless surface. It is usually deposited along the offshore land, low area, and coastal corridors. Due to its high proportion of silt and clay, its engineering properties are very poor. It has always been known as a soil type with huge settlement and low unconfined compressive strength of 25 to 50kPa (Ali and Al-Samaraee, 2013). The instability of the marine clay can lead to uncertainty in its geotechnical performance, bringing much difficulties to engineers when dealing with it.

The stabilization of marine clay has always been a target of research using various types of additives to handle with its highly expansive attribute. With soil stabilization, the structure of the soil will be modified to achieve the properties that is suitable for construction purposes (Attoh-Okine, 1995). There are some traditional stabilizers such as lime and cement, and some non-traditional stabilizer using recycled materials such as biomass silica.

This chapter discusses the previous researches pertaining to the characteristics and properties of marine clay in Malaysia and around the world. Their problematic attributes are similar, but their physical properties can be very different when it is expressed in quantitative form (Oh and Chai, 2006). The treatment that has been made to marine clay using different materials will also be presented in this chapter to have an overview regarding how marine clay can be stabilized.

2.2 Marine Clay

Marine clay is a product formed from quaternary erosion which is commonly deposited at water bodies such as rivers, water reservoirs such as channels, as well as harbours. It is slurry in nature due to the presence of high natural water content in marine clay. Some common attributes exhibited by marine clay includes its flat and featureless surface, severe settlement and unstable behaviour. With small loading, failure could be induced in the soil. Also, the clay has an expansive behaviour that is undesirable for engineering purpose such as unsuitable to act as a foundation (Mohammed Al-Bared and Marto, 2017). Since marine clay is prone to be affected by natural moisture, it expands when the moisture increases, and shrinks when the moisture is reduced (Pakir et al., 2015). This leads to many uncertainties in the properties of marine clay, therefore it is being studied in many researches.

2.2.1 Marine Clay in Other Countries

The study on engineering characteristics and performance of marine clay has been conducted in many countries. This section highlights several researches conducted on the geotechnical properties and consolidation behaviour of marine clay in Asia countries including Thailand, Singapore, and India.

2.2.1(a) Bangkok Clay

Bangkok clay is a type of marine clay with greyish or greenish-grey colour. The mineral consists of montmorillonite, kaolinite, and illite. According to the research by Teerachaikulpanich and Phupat (2003) on Bangkok clay taken at 10m depth through 25 boreholes in lower central plain of Thailand, the natural moisture content of Bangkok clay taken ranges from 40% to 90% with unit weight of 14 to 16kN/m^3. The formation of the marine clay was due to the changes of sea-level during the Holocene epochs, causing rapid sedimentation at the Chao Phraya River. Its liquid limit is between 30 to 60% while plastic limit is 15 to 30% and the plasticity index is 0 to 4%. The unconfined compressive strength is less than 50kN/m^3, showing that the clay is very soft.

Horpibulsuk et al. (2011) collected the Bangkok clay sample at 2 to 3m depth at where the groundwater table was only at 1m depth. The natural moisture content is 76% and the specific gravity is 2.66. With liquid limit 80% and plastic limit 29%, the plasticity index is 51% and the clay is classified as high plasticity clay (CH). The free swell ratio is 1.2, showing a low swelling potential. The marine clay contains 39% silt, 61% clay and no sand. Another consolidation test by Horpibulsuk et al. (2007) shows that the void ratio of remolded Bangkok clay is less than undisturbed Bangkok clay even at very high effective vertical stresses, and the void ratio of the disturbed stiff clay is higher than the undisturbed stiff clay, as shown in Figure 2.1. This tells that the stiff clay is stable in an overconsolidated state, while Bangkok clay is stable in a metastable state due to the structure of “card-house” arrangement of Bangkok clay particles.

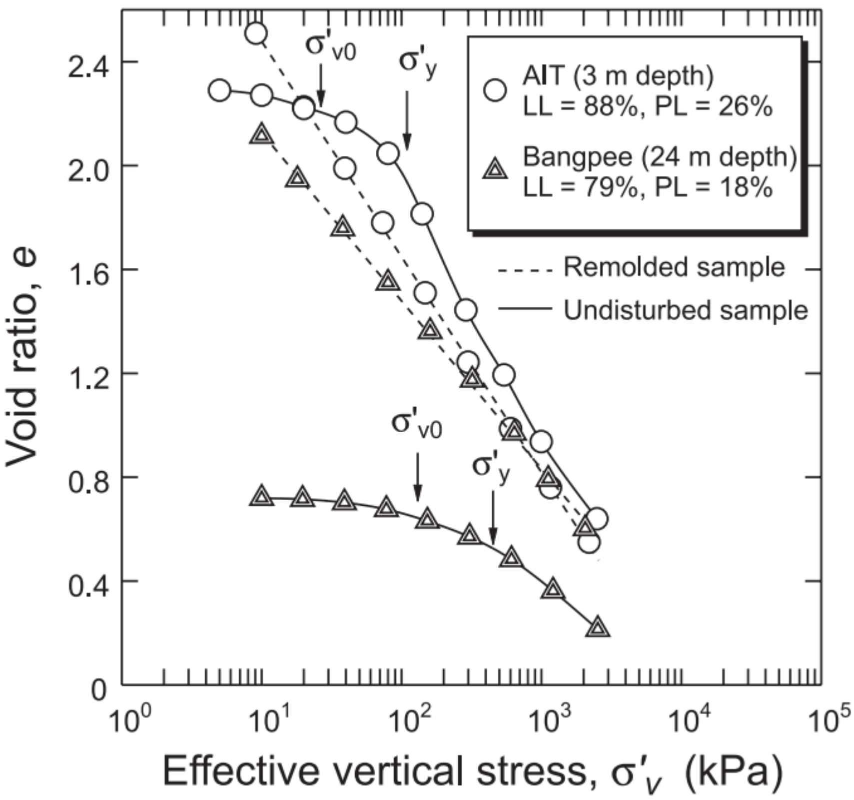


Figure 2.1: Compression behaviour of Bangkok Clay and stiff clay (Horpibulsuk et al., 2007)

2.2.1(b) Singapore Marine Clay

A research on Singapore marine clay at Changi area was carried out by Bo et al. (2015). The marine clay taken from was in a form of 3-layers sandwich, at which the top layer was a soft clay, the sandwiched layer was an intermediate stiff clay, while the bottom layer was a marine clay stiffer than the top layer. The intermediate layer was actually the desiccated crust due to change of sea level, thus it consisted of sandy silt or sandy clay. The top layer marine clay can be found at a depth of 20m to 30m below the seabed while the bottom layer can be found at 30m to 50m below the seabed.

Similar to the Bangkok clay, the structure of the Singapore marine clay is in "card-house" arrangement. The minerals contained in Singapore marine clay is predominantly kaolinite and smectite with mica, and some chlorite in small amount.

Some organic deposits and sand can also be found in the marine clay. The top and bottom layers of marine clay are brownish blue in colour, while the intermediate stiff clay is reddish in colour, indicating that the clay has undergone oxidation as the change of sea level had exposed the seabed in the past.

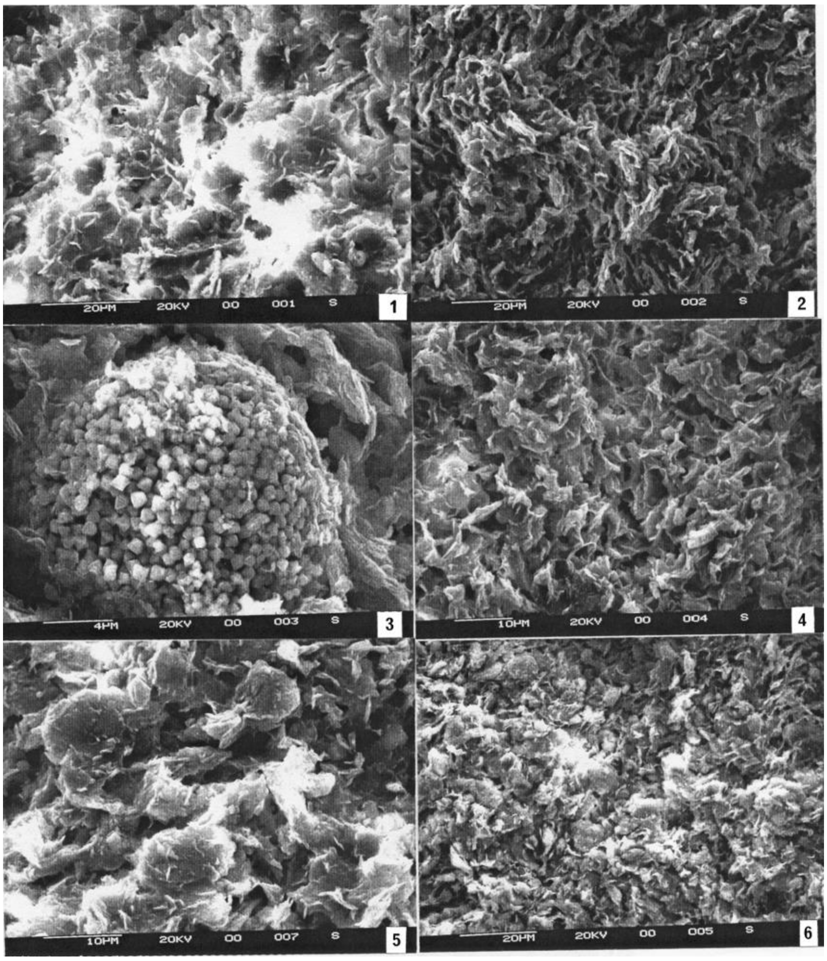


Figure 2.2: SEM photomicrographs of Singapore marine clay showing "card-house" structure (Bo et al., 2015)

Due to higher kaolinite composition, Singapore marine clay is mostly inactive clay and has a lower liquid limit and activity compared to Bangkok clay. The moisture content of the top layer marine clay is 70 to 88% while for the bottom layer is 40–60%. The liquid limit of the top layer is 80 to 95% and plastic limit is 20 to 28%. The liquid limit of the bottom layer is 65 to 90% and plastic limit is 20 to 30%. The water content of the intermediate stiff clay is 10 to 35%. Its liquid limit is 50% and plastic limit is 18 to 20%.

The undrained shear strength of the marine clay is very low, which is 10 to 30kPa for the top soft layer, and gradually increases to 30 to 60kPa for the bottom layer. The marine clay has a sensitivity of 3 to 8, showing that it is unfavourable for construction. Looking at its compressibility, the coefficient of consolidation due to vertical flow (C_v) of the top layer is 0.47 to 0.6 m^2/year and the coefficient of consolidation due to horizontal flow (C_h) is 2 to 3 m^2/year. The C_v of the intermediate stiff layer is 1 to 4.5 m^2/year and the C_h is 5 to 10 m^2/year. The C_v of the bottom layer is 0.8 to 1.5 m^2/year and the C_h is 3 to 5 m^2/year.

2.2.1(c) Cochin Marine Clay

The history of the Cochin marine clay can be traced back to 2500 years ago, the sea level rose up to high ranges of Western Ghats, thus the Western Ghats and the current coastal line were submerged below the sea. Due to volcanic activity, the land was uplifted again with some parts still submerged below the sea level. The Greater Cochin is located at the uplifted coastal line (Jose et al., 1988).

Sandeep and Reshma (2014) conducted a study on the consolidation behaviour of Cochin marine clay taken from Panampilly Nagar. Some physical properties of the clay were determined as well. The clay content is 40% and its shrinkage limit is 10%. The clay has a liquid limit of 79% and a plastic limit of 20%, resulting in a plasticity index of 59%. Therefore, the clay can be classified as high plasticity clay (CH). Through Standard Proctor Test, it was found that the maximum dry density of the clay is 12.94kN/m^3, with optimum moisture content of 33%.

Conventional incremental loading consolidation test was carried out for both undisturbed and remolded Cochin marine clay. The remolded sample is the air-dried clay passing through sieve size 425µm. The effective stress applied ranged from 4.9kPa to 313.81kPa. For the clay at 3m depth, the C_v ranged from 0.024 - 0.081×10^{-2} cm^2/min (or 0.013 to 0.043m^2/year). For the clay at 4m depth, the C_v ranged from 0.033 - 0.116×10^{-2} cm^2/min (or 0.017 to 0.061m^2/year). For the clay at 5m depth, the C_v ranged from 0.038 – 1.981×10^{-2} cm^2/min (or 0.02 to 1.04m^2/year). With the increase of the depth and the applied stress, the coefficient of compressibility (a_v) reduces.

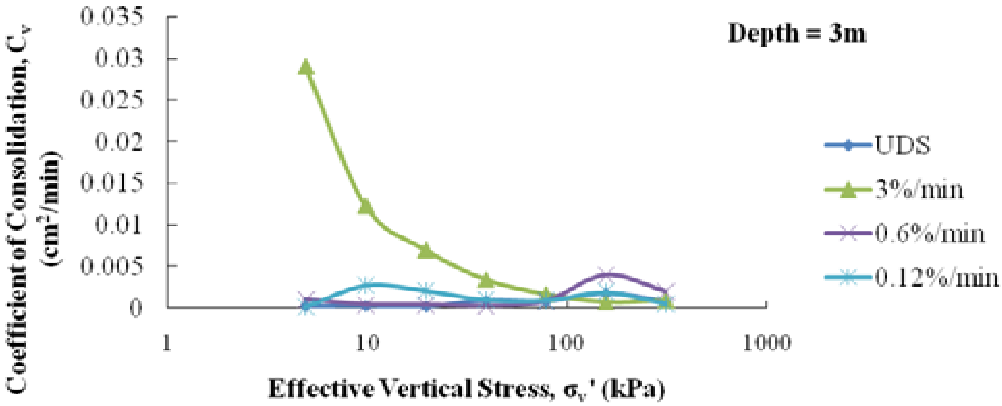


Figure 2.3: C_v versus effective vertical stress at 3m depth (Sandeep and Reshma, 2014)

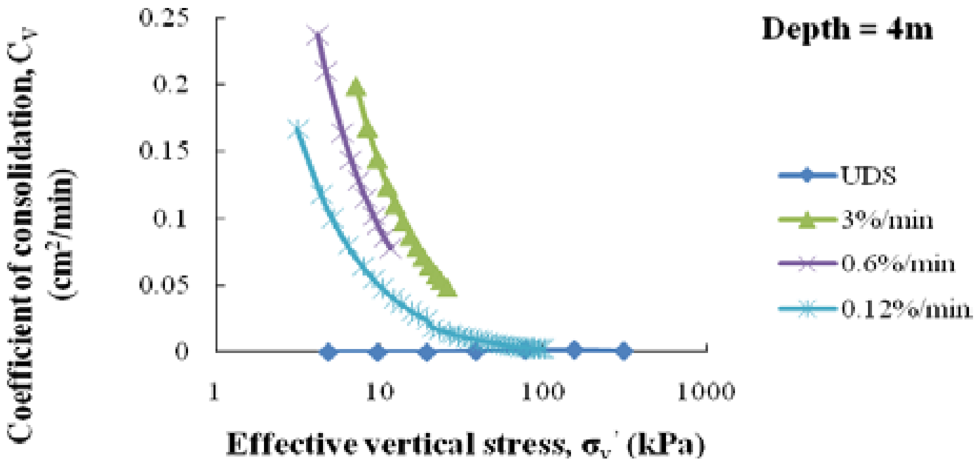


Figure 2.4: C_v versus effective vertical stress at 4m depth (Sandeep and Reshma, 2014)

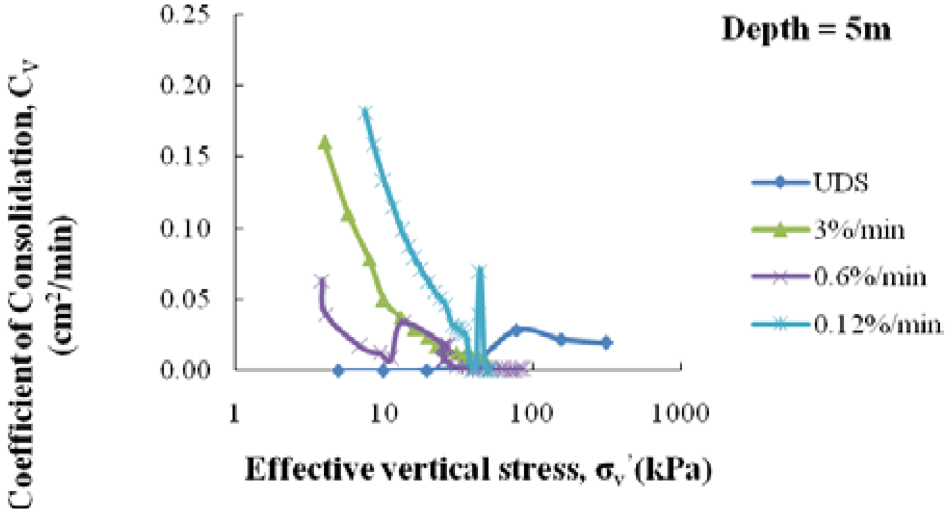


Figure 2.5: C_v versus effective vertical stress at 5m depth (Sandeep and Reshma, 2014)

Compared to the Singapore marine clay, the C_v of the Cochin marine clay is lower. Jose et al. (1988) also conducted test on the consolidation behaviour of the Cochin marine clay. At depth of 1.5m, the C_v of the undisturbed sample from Nettoor is 0.378 to 0.429 m^2/year and for the remolded is around 0.30 m^2/year. At depth of 2.0m, the C_v of the undisturbed sample is 0.293 to 0.505 m^2/year and for the remolded is 0.224 to 0.394 m^2/year.

2.2.2 Marine Clay in Malaysia

Marine clay is commonly found in Malaysia and its engineering properties has been widely investigated. This section highlights several researches conducted on the geotechnical properties and compressibility of marine clay at different regions in Malaysia including Pulau Pinang, Selangor, Johor, and Sarawak. Figure below shows the distribution of marine clay in Malaysia.

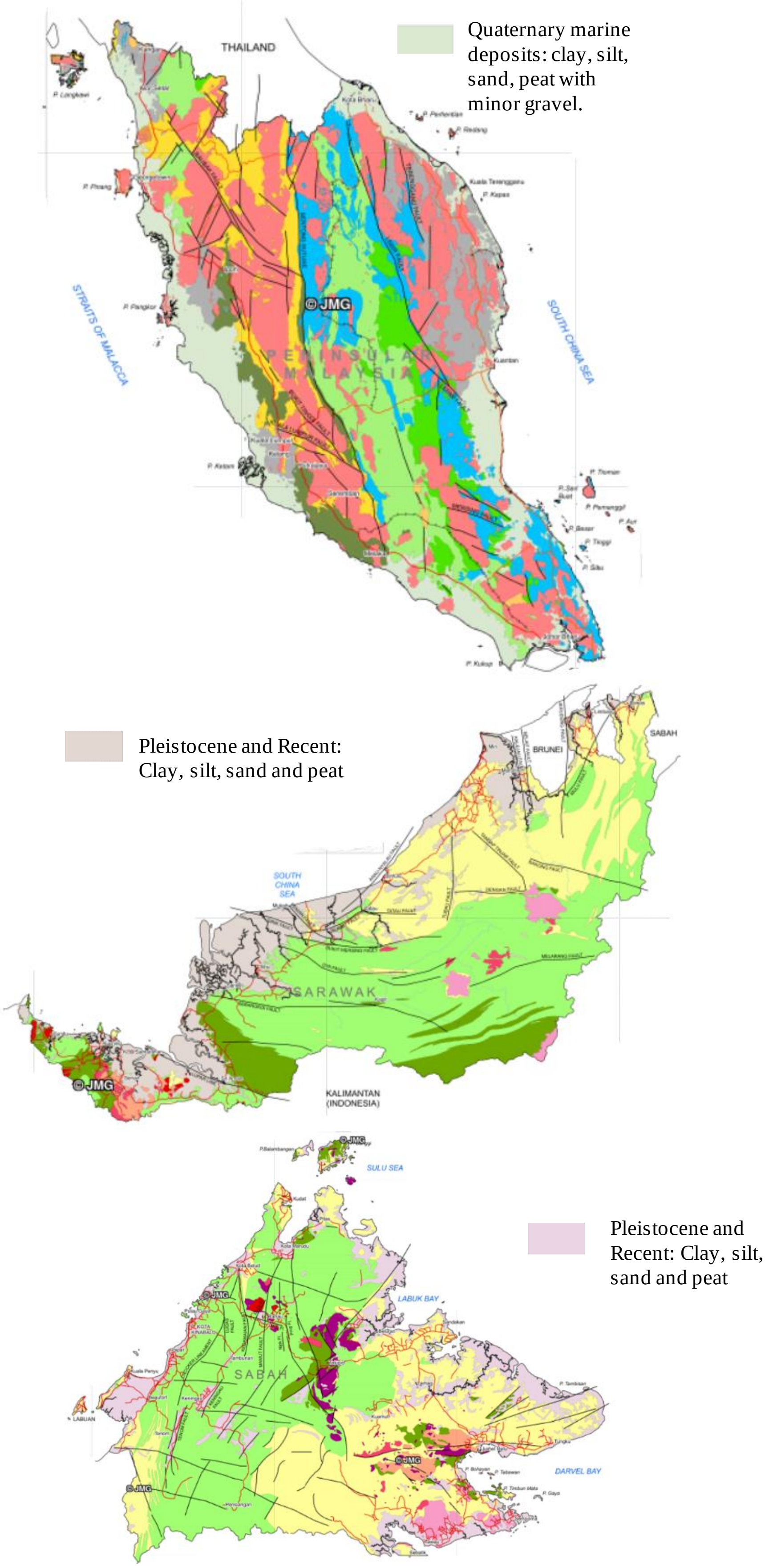


Figure 2.6: Distribution of marine clay in Malaysia (Jabatan Mineral dan Geosains Malaysia, 2019)

2.2.2(a) Tanjung Tokong Marine Clay

According to the study by Hassan et al. (2018), Penang island is formed from the deposits during the Quaternary Period. The deposits are composed of very soft to firm silty clay and silty sand, which can reach until 20 to 30m deep. There are many factors affecting the attributes of the soft alluvial deposits such as the type of parent rock, stratigraphy, erosion, consolidation, and changes of sea level. According to the subsurface investigation, the Tanjung Tokong marine clay, which located at the northeast region of Penang island consists of upper and lower layers of marine clay, similar to the Singapore marine clay. The top layer of clay is very soft while the bottom layer is stiffer than the top layer. Between these two layers, there is a layer of 2 to 8m thick of intermediate stiff clay, which is the desiccated crust caused by the change of sea level.

The major mineral content of the clay is kaolinite/chlorite which is up to 50% of the total mineral content, while another 30% is kaolinite/illinite, and the remaining 20% is smectite. The high amount of smectite can result in high liquid limit compared to the original water content. The researcher suggested that greater amount of kaolinite/chlorite can lead to less impact of the swelling and compression activity, hence the use of traditional pre-fabricated vertical drain might be sufficient to achieve the expected performance of the clay for construction.

The activity of the Tanjung Tokong marine clay can be classified under normal activity with an index of 0.96. Its sensitivity is 2 to 4, which is a medium sensitivity. Based on the OCR values, half of it are under consolidated while another half is overconsolidated. The clay has its compression ratio between 0.1 to 0.4. As the natural moisture content, liquid limit and void ratio increases, the compression index (C_c) increases. As the depth goes deeper, the undrained shear strength gets higher.

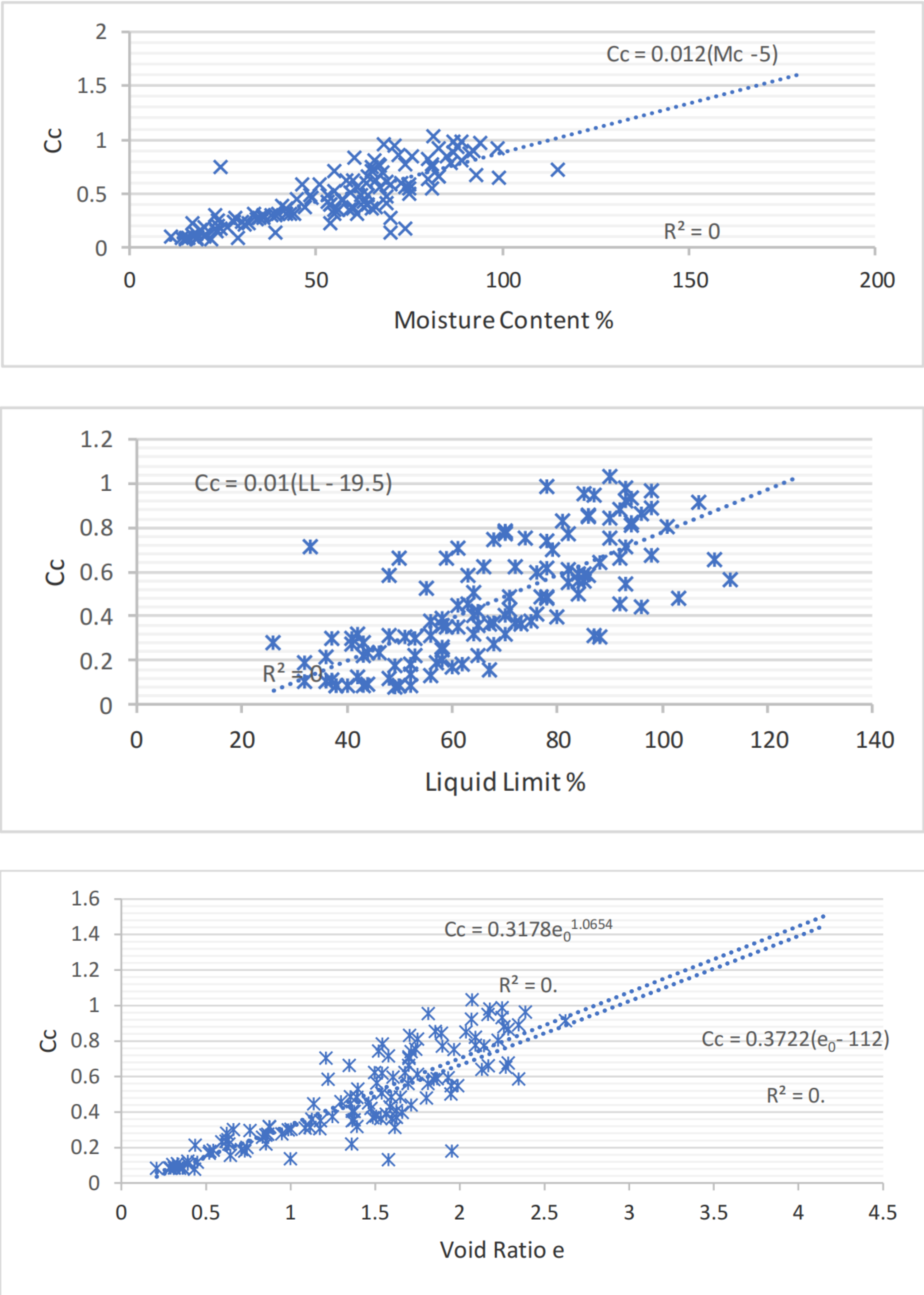


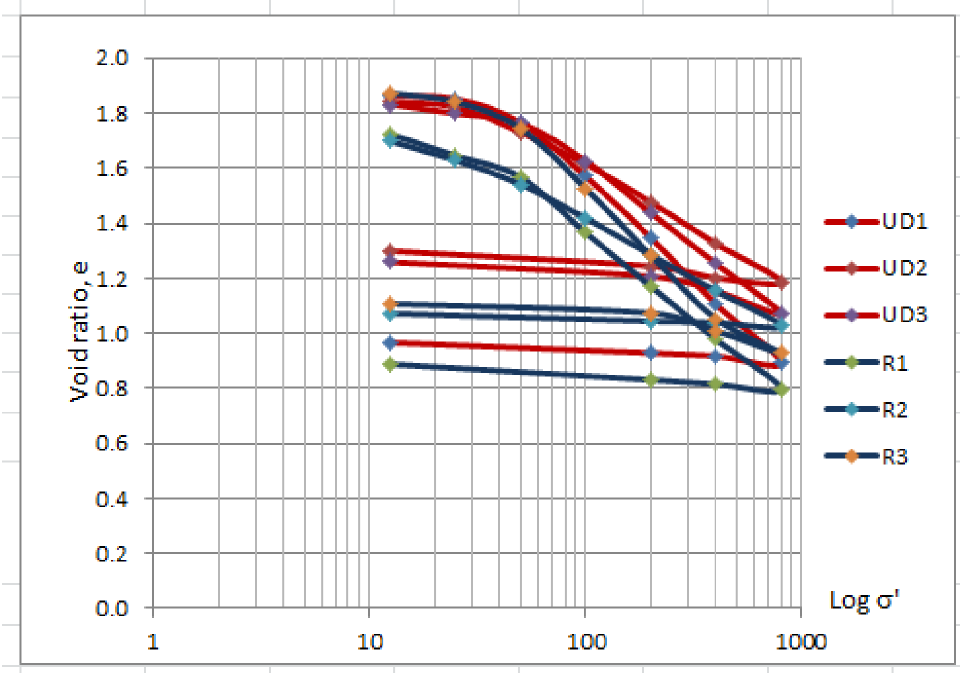
Figure 2.7: C_c versus moisture content, liquid limit, and void ratio (Hassan et al., 2018)

2.2.2(b) Sabak Bernam Marine Clay

The study on the Sabak Bernam marine clay from Sungai Besar of Sabak Bernam in Selangor is carried out by Lat et al. in 2018. With a distance of 2km from the coastal region of Malacca Straits, the clay is an alluvium deposit of the late marine and riverine alluvium. The grey colour clay has a large proportion of clay content. Due to the montmorillonite content, the clay has high cation exchange capacity and specific surface area which make it an active clay. Therefore, the sorption capacity of the clay is high.

The natural water content of the Sabak Bernam marine clay is 80%. It has a specific gravity of 2.352 and a bulk density of 1.474Mg/mm^3, while its dry density is 0.819Mg/mm^3. With liquid limit 79% and plastic limit 31%, the plasticity index is 48%, thus it is a clay with very high plasticity (CV). The linear shrinkage of the clay is 17%. The Sabak Bernam marine clay contains clay and silt with no sand. The values shown by the physical properties of the clay are within the range of physical properties of marine clays in other countries.

From the oedometer one-dimensional consolidation test, the e-log σ' curve is plotted. The compression index (C_c) can be determined from the gradient of the graph at the linear portion. The result shows that the average compression index of the Sabak Bernam marine clay is 0.614, which is similar to the C_c values found using equations developed by other researches such as Terzaghi and Peck. The preconsolidation pressure, P_c of the clay is 60kPa. The $C_c/(1+e_o)$ is 0.213 and the volume of compressibility (m_v) is 0.571m^2/MN which shows that the normally consolidated clay is highly compressible. The coefficient of permeability (k) of 1.68×10^{-10}m/s shows that the clay has a poor drainage. The C_v of the clay is 1.8mm^2/min or 0.93m^2/year.



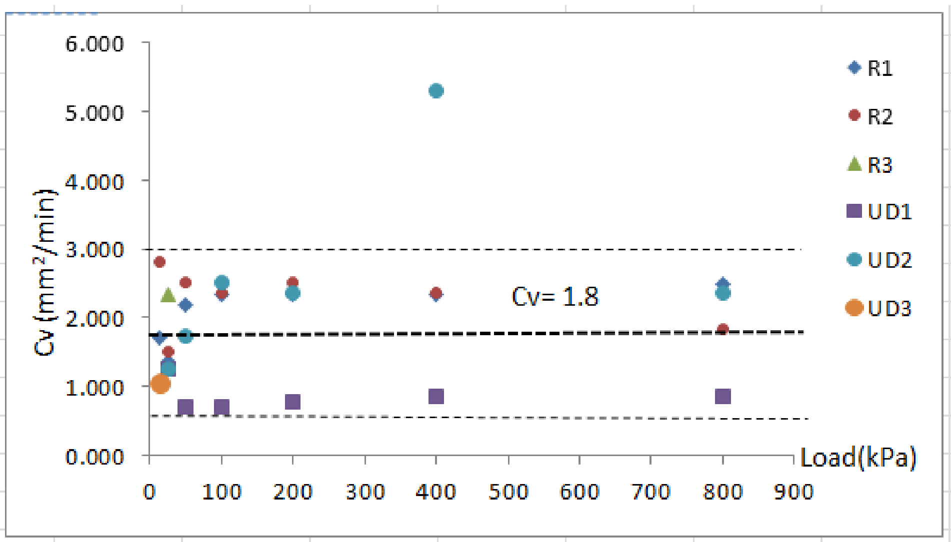


Figure 2.8: The compression curve and C_v of Sabak Bernam marine clay (Lat et al., 2018)

2.2.2(c) Batu Pahat Marine Clay

The study on geochemistry characteristics of Batu Pahat marine clay is conducted by Saleh et al. in 2019. The marine clay was collected at a depth of 1.5m inside the campus of Universtiti Tun Hussein Onn Malaysia (UTHM) in Parit Raja, Batu Pahat, Johor. It is a flat area with plenty of water, and the water flow is slow at an infiltration rate of 11.3mm/hour.

The Batu Pahat marine clay has a high natural water content of 67%. Its liquid limit is 65% and plastic limit is 26%, therefore it is classified as high plasticity clay with a plasticity index of 39%. Through Standard Proctor Test, it is found that the optimum moisture content of the clay is 25% while the maximum dry density is 1440kg/m^3. From the result of the particle size distribution test, more than 98% of the particles is finer than 65µm. Only 0.08% of particles is larger than 2mm and 1.24% of particles is between 2mm to 63µm. Among the 98%, 58% of particles is between 63µm to 1µm, and the remaining is finer than 1µm.

The chemical ions content in the Batu Pahat marine clay is determined as well. The concentration of sulphate ion is 6071mg/l, chloride ion is 287mg/l, nitrate ion is 22mg/l, and carbonate is less than 1mg/l. The low pH of 3.25 is due to the presence of sulphate ion and chloride ion. If the marine clay is stabilized with cementitious compound, sulphate ion can also cause the formation of ettringite (calcium sulphoaluminate hydrate) which will disintegrate the cementitious compound as shown in the chemical equation 2.1 and 2.2 and Figure 2.9.

Calcium aluminate hydrate + Calcium hydroxide + Sulphate ion + water → Calcium sulphoaluminate hydrate

$$C_3A \cdot CS \cdot H_{18} + 2CH + 2S + 12H \rightarrow C_3A \cdot 3CS \cdot H_{32} \tag{2.1}$$

$$C_3A \cdot CS \cdot H_{18} + 2CH + 3S + 11H \rightarrow C_3A \cdot 3CS \cdot H_{32} \tag{2.2}$$

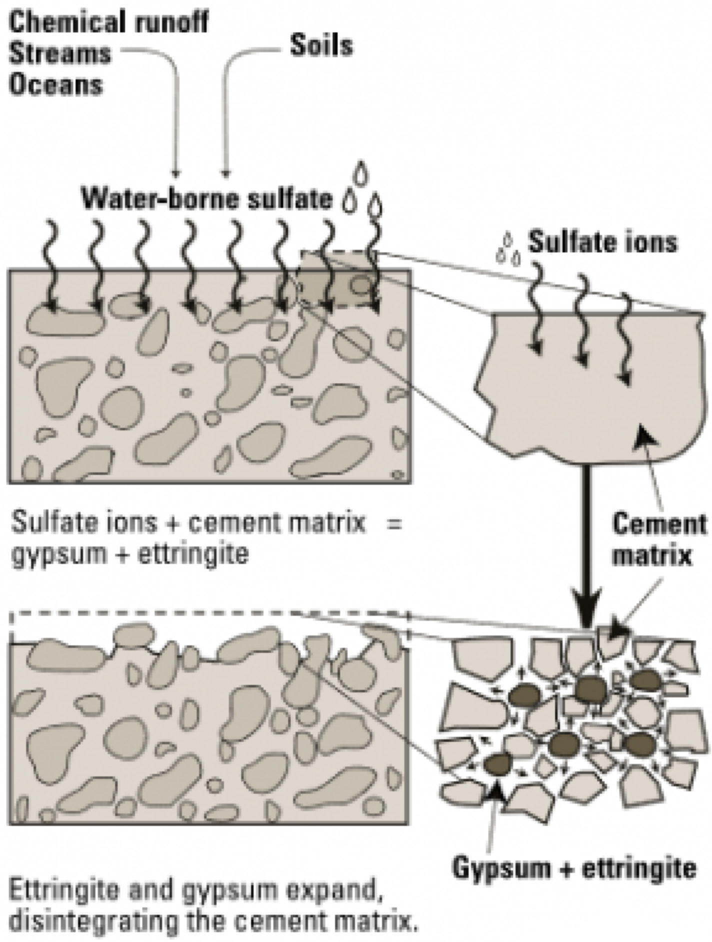


Figure 2.9: Sulphate causes the formation of ettringite (Emmons, 1994)

Thus, the penetration of sulphate ion into the marine clay stabilized with cementitious compound should be prevented by ensuring it is waterproof as water may contain soluble sulphate ions.

2.2.2(d) Marine Clay from Southeast Coast and Sarawak

Ahmad and Harahap (2016) studied on the compression behaviour of marine clays from several locations in Malaysia, including Duyung at southeast coast of Peninsular Malaysia, and Semantan and Serendah in Sarawak. Each samples were taken at different depth, from 2.2m to 27.6m. According to the particle size distribution curve, the silt content of Semantan marine clay ranges from 35% to 63% and clay content ranges from 25% to 60%. The silt content of Duyung marine clay is 47% while clay content is 46%. For Serendah marine clay, the silt content is 53% while clay content is 42%. The percentage of sand for the marine clays are 12% or less while their natural water content ranges from 24.2% to 65.2%. The plasticity of the clays are similar, with plastic limit at 27% to 36%, liquid limit at 50% to 66%, resulting in plasticity index at around 18% to 35%, where most of the samples at 22 to 27%. From the e-log σ' curve, the preconsolidation pressure is between 200 to 500kPa. The range of compression index of the marine clays is 0.177 to 0.797 while the range of swelling index is 0.133 to 0.066. Most of the Semantan marine clay samples have their compression index at 0.5 to 0.6, with only one sample at 0.177. This is because the sample is collected at depth of 27.6m, therefore it is already compacted by the overburden pressure.

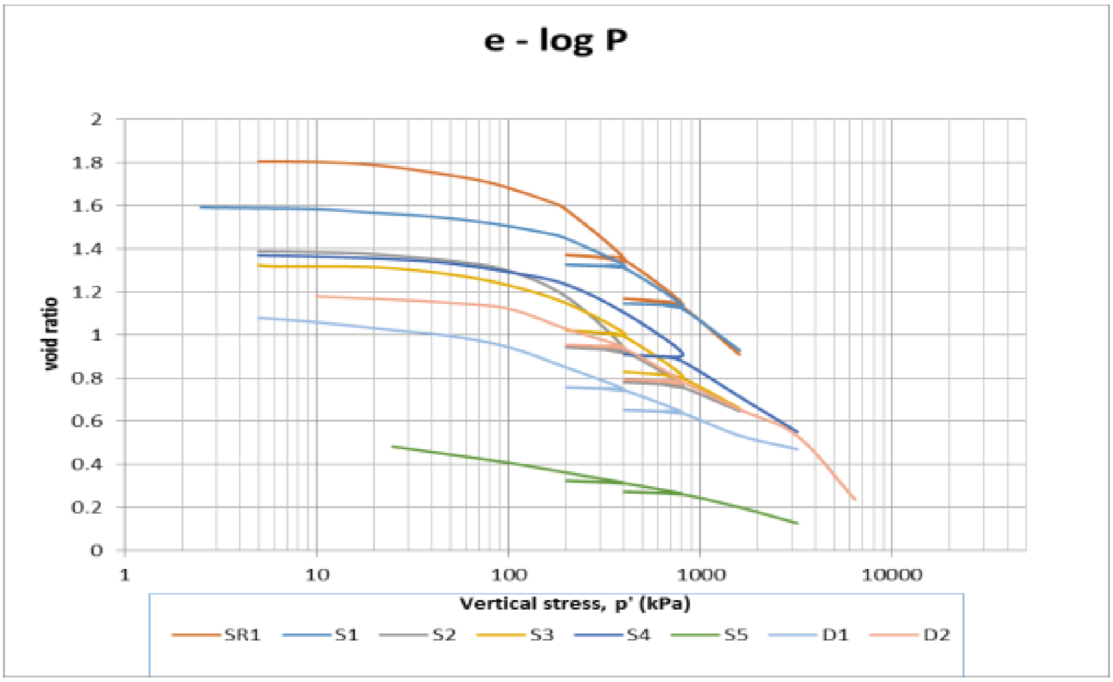


Figure 2.10: e-log σ' curve of marine clay from Sarawak and Duyung (Ahmad and Harahap, 2016)

2.2.2(e) Summary of Index Properties of Marine Clay in Malaysia

Table 2.1: Summary of Geotechnical Index Properties of Marine Clay in Malaysia

Reference	Location	Particle size distribution (%)			Natural moisture content (%)	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index
		Sand	Silt	Clay					
(Ramamoorthy, 2007)	Sg. Petani	-	-	-	15 – 112	-	37 – 39	15 – 44	20 – 62
	Butterwoth	-	-	-	22 – 101	-	19 – 126	23 – 56	13 – 49
	Klang	-	-	-	34 – 89	-	28 – 150	22 – 47	20 – 81
(Rahman et al., 2013)	Malaysia	19	57	24	56	2.6	72	42	30
(Marto et al., 2014)	Johor	-	-	-	60	2.6	58	23	35
(Yunus et al., 2015)	Johor	-	-	-	59	2.6	58	36	22
(Shahri and Chan, 2015)	Perak	18	4	78	166	2.6	96	35	61
	Melaka	12	20	68	146	2.6	59	31	28
	Kelantan	25	15	60	92	2.4	37	26	11
	Johor	20	54	26	122	2.4	46	36	10
(Hassan et al., 2018)	Tanjung Tokong	-	-	-	20 – 160	-	10 – 40	-	30 – 70
(Lat et al., 2018)	Sabak Bernam	10	60	30	80	2.352	79	31	48
(Saleh et al., 2019)	Batu Pahat	2	58	40	67	-	65	26	39
(Ahmad and Harahap, 2016)	Sarawak	12	63	25	24.2 – 65.2	2.4 – 2.66	56	33	23
	Sarawak	8	52	40			55	30	25
	Sarawak	5	47	48			54	31	23
	Sarawak	5	35	60			55	36	19
	Duyung	7	46	47			51	28	23
(Gubran and Chan, 2020)	Kuala Perlis	-	52	48	149	-	118	57	61
(Johan and Ming, 2018)	Kuala Perlis	1	38	61	218.07	2.68	66.5	55.8	10.69

2.3 Stabilization of Marine Clay

As the land use has become more and more saturated, the utilization of available land is a must and the unsuitability of land due to poor engineering performance should be overcame (Anggraini et al., 2017). Different types of marine clay exhibit different behaviour. Therefore, the marine clay must be treated with suitable stabilizer to avoid the settlement problem from occurring or to minimize the settlement (Saad et al., 2018).

2.3.1 Traditional Stabilizer

Cement and lime are the traditional stabilizers that have been commonly used in the real practice of marine clay stabilization due to its proven effectiveness (Mohammed Al-Bared and Marto, 2017). This section highlights several researches conducted on the stabilization of marine clay in terms of compressibility using cement and lime.

2.3.1(a) Cement

A study on the cement stabilized soft clay was carried out by Zidan (2020) to observe the improvement on the consolidation characteristics of two types of soft clay. The clay was collected from the Upper Egypt which consists of fully clay and silt content. The plasticity index of the clay is 57% and 10% respectively while liquid limit is 92% and 33% respectively. The clays were treated with 5%, 10%, and 15% of cement and undergone under one dimensional consolidation test. According to the e-log σ' curve, the behaviour of the cement-treated clay is similar to overconsolidated clay before the yield stress is achieved, while after reaching the yield stress, the behaviour is similar to a normally consolidated clay. The higher the percentage of cement added, the higher the yield strength of the treated clay. The engineering performance of the clay is greatly improved through the stabilization using cement. As the percentage of cement increases, the compressibility of the clay reduces. Without the addition of cement, the C_c of the clay type 1 is 2.83 and it is improved to 0.255, 0.231, and 0.209 with the addition of 5%, 10%, and 15% of cement respectively. The compression indexes are improved for more than 90%. For the clay type 2, without the addition of cement, the C_c of the clay is 0.28 and it is improved to 0.245, 0.237, and 0.176 with the addition of 5%, 10%, and 15% of cement respectively. The compression indexes are improved for 12% to 37%. The swelling index C_s of clay type 1 is improved from 0.0345 to 0.0332, 0.0289, and 0.0251 with the addition of 5%, 10%, and 15% of cement respectively, which is 4% to 27% of reduction. For clay type 2, the C_s is improved from 0.0162 to 0.0147, 0.0137, and 0.0117 with the addition of 5%, 10%, and 15% of cement respectively, which is 9% to 28% of reduction. Cement stabilization is a suitable and effective method for cohesive soil which contains high percentage of fine particles. The reaction between silt particles and cement particles is favourable for the pozzolanic reaction, which produces calcium content that bonds the particles together. Thus, the stiffness and strength of the clay increases and its compressibility reduces.

Table 2.2: Summary of consolidation result (Zidan, 2020)

Specimen	Clay 1				Clay 2			
	0% cement	5% cement	10% cement	15% cement	0% cement	5% cement	10% cement	15% cement
C_c	2.83	0.255	0.231	0.209	0.28	0.245	0.237	0.176
C_s	0.0345	0.0332	0.0289	0.0251	0.0162	0.0147	0.013	0.0117