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Evaluating Engineering Properties of Marine Clay Soil at Malacca and Proposed Methods of Quality Enhancement

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ABSTRACT

Malacca City is located along the western coastline of Peninsular Malaysia and lays on a foundation of soft marine clay. In studying the soil properties of the state of Malacca, samples were taken at a depth of 2.5 meters from the ground surface, whereby the water level was encountered at 1.0-meter depth following the water level of the Malacca river. Soil testing was performed on the collected samples to identify geotechnical parameters as an indication of Malacca marine clay properties and were compared to the engineering parameters of South East Asia marine clays. As per the comparison, the laboratory results have shown that the Malacca marine clay was found to be following the average general trend of identical engineering properties for the other marine clays considered in this research paper. Water content was found to be 74.15%, liquid limit 75.3%, plastic limit 35%, plasticity index 41.55, compressibility index 3.780 m^2/yr compression index 0.948, swelling index 0.174, and preconsolidation stress 103.54 kPa, and specific gravity 2.60. Different types of soil improvement were also reviewed in terms of their limitations, required scale of application, cost, time, and environmental restrictions to find the most suitable method to improve the engineering properties of Malacca marine clay.

Key words : Clay, Geotechnical parameters, Malacca, Marine Clay, Soil improvement, Soil investigation.

1. INTRODUCTION

Marine clay is a type of soil that is very sensitive to imposed load, whereby any deformations resulted is significant. However, predicting the development of deformations and excess pore water pressure during the loading process is difficult to be achieved [1]. Therefore, it renders marine clay a problematic soil that affects their existing and proposed structure safety, stability, and sustainability, as well as resulting in ambiguous behavior. Marine clays are typically found in regions of the coastlines, shores of lakes, and banks of rivers, which can be translated to have very high water content compared to its liquid limit in some cases. Therefore, void ratio values are deemed as significant as it makes the soil compressibility extremely high to the extent unstable deformations are generated, especially under non-uniform loading stresses. Furthermore, a high groundwater table is commonly encountered in these areas, which displays a bulk density significantly bigger than their dry density. It will alter the stresses upon the utilities present in the soil, especially those that are subjected to uplift force and are under the repeated cycles of loading and unloading. In this scenario, both the utilities and soil inevitably fail together or separately, according to which that is weaker. These properties are common for marine clays, with the region of South Asia following the same trending and tendencies [2]–[4].

The main minerals that formulate the marine clay in South Asia are smectite, vermiculite, kaolinite, halloysite, and mica [4]–[11]. Each region possesses marine clay having different ratios of these minerals, which results in their different behavior due to these ratios. Smectite, in particular, is a common and sensitive mineral that functions to clarify the highwater content values for marine clays. Regardless of the types of minerals forming the marine clay, it becomes extremely grueling to engage in either establishing the new structures of the immersed tunnel of Hong Kong-Zhuhai-Macao-Bridge (HZMB) [12] and Shanghai metro station [13] or curing these structures after failure as significant as in the settlements of the Shanghai metro line [14].

In the context of Peninsular Malaysia, soil formation of its western coastline is characterized by the soft soil of peats, organic soils, and marine and riverine alluvium [15]. This coastal line is also occupied by Malacca, which is located about 120 km away to the south of Kuala Lumpur. It is an important port in South-Asia due to its attractive role for tourism as a historical city and port alike. The city lies on soft marine clay layers that affect the structures established on top of it, which is subsequently perceived as a challenge in proposing future structures.

Various methods were proposed to treat marine clay soils to enhance its characteristics. The void ratio was reduced by water content reduction [7], [16]–[19], while others add materials to increase soil shear strength [6], [8], [18], [20], [21].

2. MATERIALS AND METHODS

Samples were collected from Malacca city, whereby the location of the city is shown in Figure 1, detailing the soil formation for the Peninsular Malaysia [15]. It is found that soil is formed from Marine alluvium, which was derived from high grade metamorphic and sedimentary rocks. The sample was obtained at a depth of 2.5 meters from the ground surface of the Malacca riverbanks, whilst the water level was at 1.0 m depth from the ground surface. It was also observed that the roots of plants within the area are extended to about 1.0 m deep from the ground surface. During sample collection, the soil was initially very stiff before becoming loose after some time and as the water was squeezed out from the soil. It is observed that the color of the samples was dark grey and emanated a bad smell, indicative of the presence of organic matter. The samples were kept in a sealed bucket to maintain its initial condition before any tests can be conducted. Sieve analysis, hydrometer test, Atterberg limits, oedometer test, and specific gravity, and micromechanical testing, which is X-ray fluorescence XRF test, were conducted to investigate the physical, mechanical and microstructural characteristics of the samples taken.

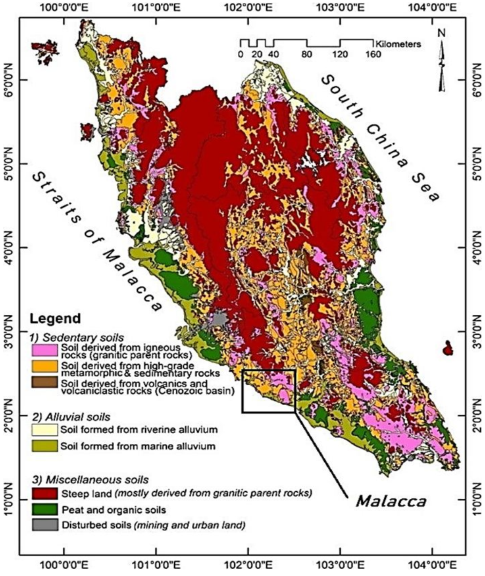

Figure 1: Malacca's location on the geological map for Peninsular Malaysia [15]

3. RESULTS

3.1 Soil Formation

Sieve analysis was applied to the samples according to the instructions of D422-63R98, ASTM [22], which indicated grain size distribution of 16.3% (gravel), 52.3% (sand), and 31.4% (fines), see Figure 2. The chart illustrates that the major of the soil's granular components to be about fine by 50%, directly revealing its hydraulic conductivity to be extremely low in the presence of 31.4% fines. The soil classification is characterized as SM silty sand soil, according to the Unified Soil Classification System (USCS) as per D2487-00, ASTM [23]. A hydrometer test, which was conducted according to the instructions of D422-63R98, ASTM [22] on the 31.4% fines showed that grain size distribution consists of 15.4% silt and 16% clay. Thus, major of the fines are clay by 50.95%. This is again depicted in Figure 2.

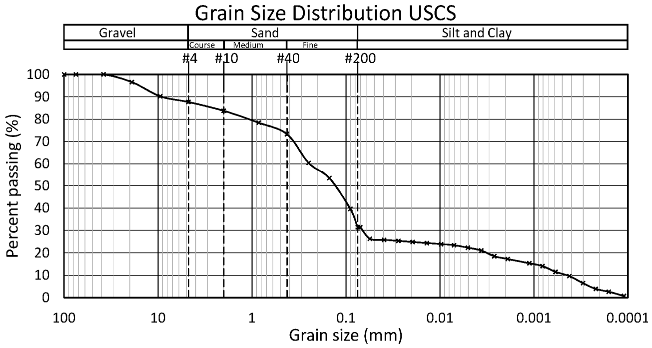

Figure 2: Full-grain size distribution for both coarse soil and fines for the samples collected

3.2 Fines Activity

The test to identify the Atterberg limits indicated a liquid limit of 63.66% and a plastic limit of 32.57%, see Table 1. The value of the plasticity index was very high by 31.10% in which the consistency index was −0.10, indicating that the soil behavior followed the liquid state and was very soft, according to Equation 1.

$$CI = w_{LL} - w_n / w_{LL} - w_{PL} \tag{1}$$

Such an explanation elucidated the soil instability seen during loading and the resultant huge deformations. According to the limits, the fines were classified as silt with high plasticity MH, or organic clays or organic silts OH as per the Casagrande plasticity chart shown in Figure 3.

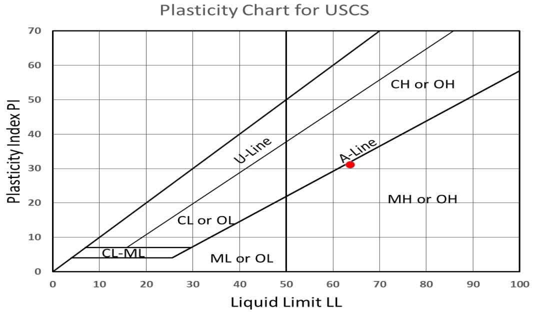

Figure 3: Fines classification using Atterberg limits as per USCS classification

The natural water content encountered was found to be 67%, which was higher than the liquid limit of the samples. It sufficiently explained the unstable behavior of the soil from Malacca City. Table 1 indicates that the Atterberg limits and natural water content w_n for Malacca soil follow the same tendency for southeast Asia marine clays.

Table 1. Natural water content, liquid limit, plastic limit, and plasticity index for previous and current research

Location	Country	w_n (%)	w_{LL} (%)	w_{PL} (%)	PI (%)	Source
Malacca	Malaysia	67	63.66	32.57	31.09	-
Bangkok	Thailand	38 – 92	68 – 102	28 – 39	38 – 64	[7]
Klang	Malaysia	59	63.66	49.66	14	[24]
Johor	Malaysia	59	41	22	19	[20]
Kalang	Malaysia	98 – 103	61.5 – 80	35 – 49	26.5 – 31	[8]
Changi	Singapore	10 – 88	38 – 95	13 – 31	20 – 67	[25]
UTHM	Malaysia	-	60.84	36.7	24.14	[17]
Changi	Singapore	10 – 88	50 – 95	18 – 30	30 – 67	[9]
Yarra Delta.	Australia	56.7 – 73.6	65 – 75	31 – 47	26 – 37	[6]
Changi East	Singapore	43 – 75	63 – 84	21 – 27	42 – 58	[26]
Pusan	South Korea	28 – 85	28 – 70	10 – 42	15 – 41	[27]
Mekong	Vietnam	60 – 95	60 – 80	30 – 40	30 – 40	[28]
Hong Kong	Hong Kong	34 – 90	34.7 – 76.5	16.6 – 45.2	18.1 – 31.1	[12]
Oita prefecture	Japan	126.2 – 141.3	-	-	-	[2]
-	-	41 – 120	34 – 122	14 – 41	13 – 92	[29]
Johor	Malaysia	45 – 100	55 – 102	20 – 42	35 – 63	[30]
Erzurum	Turkey	-	72	33	39	[31]
Sabak	Malaysia	80	79	31	48	[10]
Shanghai	China	32 – 55	33 – 43	19 – 22	13 – 21	[32]
Singapore	Singapore	20 – 74	35 – 113	16 – 44	19 – 83	[33]
Penang	Malaysia	-	47	28	19	[21]
Johor	Malaysia	-	58	23	35	[34]
Ariake	Japan	72 – 166	60 – 140	15 – 50	25 – 94	[4]
Bangkok	Thailand	42 – 135	78 – 142	17 - -75	25 – 125	[4]
-	Malaysia	25 – 110	50 – 120	20 – 35	30 – 85	[1]
Ashikari	Japan	90 – 150	68 – 115	26 – 41	28 – 75	[35]
Kelang	Malaysia	58 – 98	71 – 114	32 – 48	32 – 67	[5]
Batu Pahat	Malaysia	-	61	36	25	[36]
Klang	Malaysia	35 – 140	96 – 150	20 – 85	41 – 130	[37]
Ariake	Japan	90 – 150	65 – 130	40 – 100	25 – 45	[3]
Singapore	Singapore	50 – 60	65 – 80	40 – 60	20 – 25	[3]
Bangkok	Thailand	55 – 80	45 – 85	30 – 70	15 – 25	[3]
Osaka	Japan	36.6 – 69.1	82.4 – 100.4	32.7 – 37.8	46.7 – 62.6	[38]
Chinese Cities	China	18.4 – 80.1	28.36 – 86	6.53 – 48	6.92 – 55	[39]
Dalian City	China	46.6 – 63.7	28.6 – 49.2	16.1 – 30.7	12.5 – 18.7	[13]

Based on data analysis, the Malacca soil followed the soil parameters of South East Asia marine clays for locations in Malaysia like in Klang and Johor (Batu Pahat and UTHM), as well as in Singapore marine clays. Table 1 shows that the w_n range is between 10 - 166% and its average is 74.15%, whereas the liquid limit w_{LL} range is between 28 - 150% and its average is 75.3%, while the plastic limit w_{PL} range is between 6.53 - 100% and its average is 35%. Meanwhile, the plasticity index PI range is between 6.92 - 130, and its average is 41.55.

3.3 Soil Compressibility

One dimensional (1D) consolidation test was undertaken using an oedometer apparatus as per D-2435-96, ASTM (1996) instructions. Remolded samples were used where water content is equaled to the natural water content w_n and in the dimensions of 50mm (diameter) and 14.79 mm (height). The stresses applied for loading were 12.5, 25, 100, and 200 kPa, whereas unloading stresses were valued at 50 and 12.5 kPa. Results showed that the compression index, $C_{c,}$ and recompression (swelling) index, C_r were 0.2811 and 0.0576, respectively. From the relationship shown in Figure 4 between void ratio and vertical effective stress e – log P_c', the value of preconsolidation stress is determined to be equal to 42.17 kPa.

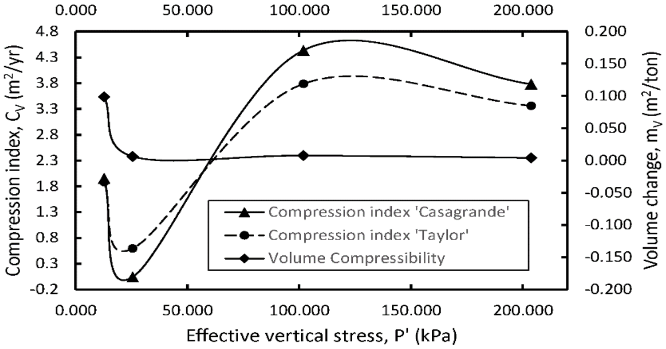

Figure 4: The relationship between vertical consolidation factor, $C_{v,}$ and coefficient of volume compressibility, mv with preconsolidation pressure P_c'.

Consolidation coefficient, C_v ranged from 1.952 to 4.435 m^2/yr. This is as shown in Figures 5 and 6. The coefficient of vertical consolidation C_v relationship with effective vertical stresses P_c' is not linear; it follows a power equation curve, as shown in Figure 6.

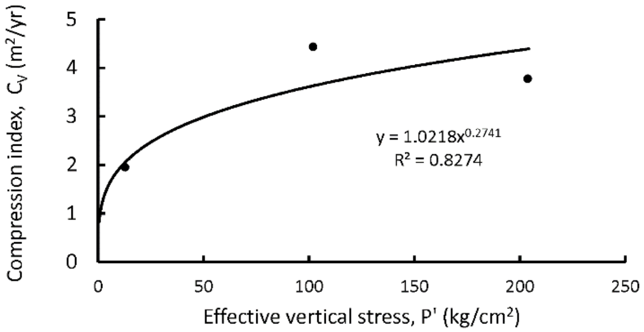

Figure 5: The relationship between the vertical coefficient of consolidation and the effective vertical stress

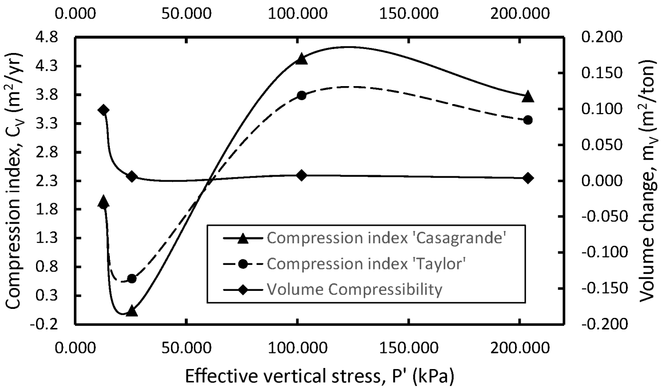

Figure 6: The relationship between vertical consolidation factor, C_{V}, and coefficient of volume compressibility, m_v with preconsolidation pressure P_c'.

A comparison of lab results obtained with other marine clays values, as displayed in Table 2 has revealed the following outcomes. The range of consolidation coefficient, C_v ranged from 0.15 - 25 m^2/yr and averaged at 3.780 m^2/yr, the compression index, C_c 0.08 - 2.25 and averaged at 0.948, the recompression index (swelling index) C_r 0.010 - 0.311 averaged 0.174, and yield (preconsolidation) stress P_c' 23 - 320 kPa and averaged at 103.54 kPa.

This showed that the Malacca marine clay values were within the average value for the other marine clays. Furthermore, the soil compressibility is a function of the Atterberg limits, and the results obtained are a reflection of the same results displayed in Section 3.2.

The water content for the tested samples was found to be equaled to 38.25%. The permeability of the soil was predicted using Equation 2 [40]. A graph drawn for the relationship between permeability k and void ratio e_o shows that the relationship is not linear, as seen in Figure 7.

$$k = C_V.m_v.\gamma_w \tag{2}$$

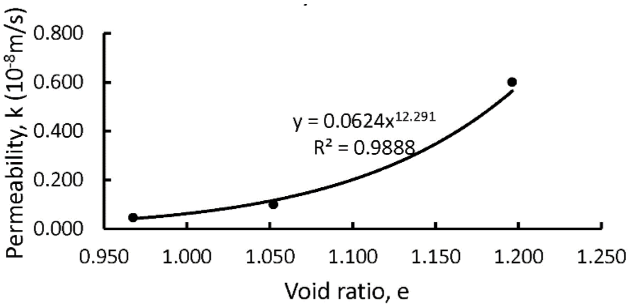

Figure 7: Relationship between permeability k and void ratio e_o.

Table 2: Natural water content, liquid limit, plastic limit, and plasticity index for previous and current research

Location	Country	P_c' (kPa)	C_c	C_r	C_v (m^2/yr)	Source
Malacca	Malaysia	42	0.281	0.0576	2.9	-
Changi	Singapore	60 – 250	0.2 – 1.7	0.08 – 0.2	0.47 – 4.5	[25]
Changi	Singapore	-	0.2 – 1.5	0.08 – 0.2	0.47 – 4.5	[9]
Ariake	Japan	-	-	-	3.65	[3]
Singapore	Singapore	-	-	-	1.095	[3]
Bangkok	Thailand	-	-	-	0.365	[3]
Yarra Delta.	Australia	38	0.594 – 1.352	-	-	[6]
Changi East	Singapore	42 – 205	0.45 – 1.4	-	-	[26]
Pusan	South Korea	23 – 230	-	-	-	[27]
Oita prefecture	Japan	42.1	-	-	-	[2]
Mekong	Vietnam	-	0.8 – 1.0	0.27 – 0.3	-	[28]
Hong Kong	Hong Kong	-	0.42 – 1.05	-	1.9 – 3.1	[12]
Johor	Malaysia	25 – 115	0.55 – 2.25	-	-	[30]
Sabak	Malaysia	-	0.614	0.169	0.93	[10]
-	Malaysia	30 – 110	0.9 – 2.2	0.01 – 0.2	0.95 – 6.94	[1]
Kelang	Malaysia	-	0.525 – 1.102	0.098 – 0.311	0.45 – 6.03	[5]
Chinese Cities	China	-	0.08 – 1.03	-	-	[39]
Klang	Malaysia	25 - 320	-	-	0.15 – 25	[37]

3.4 Specific Gravity and Density

Specific gravity for the samples was determined following D854-00R02, ASTM [41], where its value was found to be 2.57. Bulk density γ_{bulk} range and dry density γ_{dry} were subsequently determined by the values of 15.8 - 16.5 kN/m^3 and 9.44 - 9.88 kN/m^3, respectively .Collected data in Table 3 shows the range of specific gravity G_s, which is 2.13 - 2.80 and averaged at 2.60. The Malacca soil followed the same tendency, especially for the Batu Pahat marine clay range [8]. Moreover, the bulk density of the Malacca marine clay also followed the general tendency, despite the range found to be between 15.8 - 16.5 kN/m^3 and was relatively high compared to other ranges. This issue may be due to the fact that major of the previous research had not mentioned the level of samples taken, rendering it difficult to compare the data. Nevertheless, the value is not out of the range, as can be seen in Table 3.

Table 3. Bulk density and specific gravity for previous and current research

Location	Country	γ_{bulk} (kN/m^3)	G_s	Reference
Malacca	Malaysia	15.80 - 16.50	2.57	–
Bangkok	Thailand	14.80 - 17.20	2.64 - 2.68	[7]
Klang	Malaysia	-	2.39	[24]
Johor	Malaysia	-	2.52	[20]
Batu Pahat	Malaysia	14.00 - 16.00	2.55 - 2.67	[8]
Changi	Singapore	14.23 - 19.60	2.60 - 2.76	[25]
UTHM	Malaysia	-	2.60	[17]
Changi	Singapore	14.20 - 19.60	2.60 - 2.76	[9]
Yarra Delta.	Australia	15.00 - 16.00	2.40 - 2.61	[6]
Pusan	South Korea	14.80 - 18.50	2.63 - 2.73	[27]
Oita	Japan	13.10 - 15.40	2.13 - 2.65	[2]
-	-	-	2.63 - 2.80	[29]
Mekong	Vietnam	14.00 - 16.00	-	[28]
Hong Kong	Hong Kong	14.60 - 17.60	-	[12]
Sabak	Malaysia	14.74	2.35	[10]
Penang	Malaysia	-	2.42	[21]
Johor	Malaysia	14.00 - 17.50	-	[30]
Johor	Malaysia	16.00	-	[34]
-	Malaysia	14.00 - 17.00	2.52 - 2.72	[1]
Batu Pahat	Malaysia	-	2.60	[36]
Klang	Malaysia	14.42 - 15.48	-	[5]
Klang	Malaysia	12.70 - 18.80	-	[37]
Dalian City	China	16.80 - 18.50	-	[13]
Ariake	Japan	-	2.60 - 2.63	[3]
Singapore	Singapore	-	2.76 - 2.78	[3]
Bangkok	Thailand	-	2.72 - 2.75	[3]
Osaka	Japan	-	2.66 - 2.70	[38]
Erzurum	Turkey	-	2.62	[31]

3.5 Chemical Composition

For Malacca marine clay, chemical composition for a dry sample was identified using X-ray fluorescence XRF. The results of XRF is shown that SiO_2, Al_2O_3, Fe_2O_3, K_2O, SO_3, and MgO are the major chemical component of the clay by 56.23%, 22.81%, 11.29%, 2.82%, 1.92%, and 1.55%, respectively.

4. DISCUSSION

This paper serves as a comparison between studied marine clay and several types of marine clay samples taken from various South East Asian locations [1]–[10], [12], [13], [16], [17], [20], [21], [24]–[35], [37]–[39], [42]. Significant variations of the geotechnical parameters have been found for the same region, even if not of the same borehole. Such variation is due to the different conditions of partial soil deposition during the process of soil layer formation.

Despite these variations, the results have displayed a common tendency for their respective soil behavior: high values of void ratio, its range is 0.6 3.7 with average to 1.875. Furthermore, comparing the value of compression index C_c from the 1-D consolidation test has equaled to 0.281 across equations shown in Table 4 [43]–[46], which is a significant difference even in the case of the remolded clay equation [45]. Therefore, more readings are required to predict a relationship for compression index $C_{c,}$ and liquid limit w_{LL} or/and reduce the diversion with the curves formed by the equations in Table 5 [43]–[46].

Table 4. Compression index C_c for different equations

Equation	C_c	Source
$C_c = 0.009\ (w_{LL} - 10)$	0.483	[44]
$C_c = 0.005\ (w_{LL} + 71.8)$	0.677	[43]
$C_c = 0.007\ (w_{LL} - 10)$	0.376	[45]
$C_c = 0.0128w_{LL} - 0.008PI - 0.1423$	0.424	[46]

Similarly, parameters like water content w_n, liquid limit w_{LL}, plastic limit w_{PL}, plasticity index PI, coefficient of consolidation C_v , small values of permeability k and bulk density ɣbulk have been shown in Tables 1 and 2, and Figure 7 and Table 3, respectively. Some results have displayed odd values compared to the general tendencies seen for Arkine of Japan [2]–[4], Ashikari (Japan) [35], Oita Prefecture (Malaysia) [2], and Klang (Malaysia) [24]. Nevertheless, the value of liquid limit w_{LL} is found to be not less than 60% [3], [30], [35]; whereas the plastic limit w_{PL} is below 30% [9], [10], [17], [20], [21], [32], [34], [37]. Similarly, the natural water content wn is within the range of liquid limit if not higher [4], [5], [7], [10], [12], [16], [17], [20], [30], [32], [39].

Therefore, a comparison of the obtained soil parameters for Malacca marine clay with soil parameters of other works has revealed that the Malacca marine clay displays values that are within the range of clay parameters from Johor of Malaysia [30], [34], Kalang (Malaysia) [8], Changi (Singapore) [9],

[26], Bangkok (Thailand) [7], Pusan (South Korea) [27], and Yarra Delta (Australia) [6].

Due to the weakness and the random behavior of marine clay, it has to be treated before any construction work can be done. One of the major common solutions is soil stabilization by physical, chemical, or biological treatment, or a combination of two or more of them, see Table 5 .Each method is limited by specific restrictions that may match the case study which is based on the size of the project, required scale of application, cost, time, and environmental restrictions. Nevertheless, every method enhances the treated soil properties in varied ranges and/or focusing on different influencing factors.

Table 5 Categorized Comparison for different marine clay treatment methods

Type	**Treatment method**	**Disadvantages**	**Advantages**
Physical	Thermal treatment [7]	- Energy wasting - Limited conditions to be able for applying as surrounding temperature, moisture content, soil conductivity, etc.	- Enhances soil consolidation - Almost completed consolidation in period of 105 days
	Electro-kinetic stabilization [17]	- - New method that needs more experiments and data to get better estimation for requirements and its effect - Electric energy consuming increases for large zones to cover - Disturb pH, mineralogy and minerals inside soil texture because of force migration due to electric potential effect	- Significantly increased strength especially in the vicinity of the cathode - Electroosmosis process increases soil pore water pressure that increased soil shear strength
	Vacuum preloading [16]	- Takes long time to get the targeted strength; one year to rise strength from 4 kPa to 50 kPa	- Improves bearing capacity about 10 times - Reduces water content 3 times
Chemical	RBT (recycled blended tiles) [20]	- Very hard to apply in large scale because of mixing process limitation - For required strength a required RBT sizes are needed that could make uncertainties in shear strength due to mistakes in preparation of the mixture	- Decreases liquid limit, plastic limit and plasticity index - Significantly increase in maximum dry density and decrease in OMC
	Treated coir fibers [8]	- Hard to apply in large scale because of mixing process limitation - For required strength a required coir fibers sizes are needed that could make uncertainties in shear strength due to mistakes in preparation of the mixture	- Enhances strength and mechanical behavior, depending on fiber content and curing time - Fiber inclusion significantly increased tensile strength
	Nanomaterial additions [21]	- Hard to apply in large scale because of mixing process limitation - For required strength a required nanomaterial additions sizes are needed that could make uncertainties in shear strength due to mistakes in preparation of the mixture	- Liquid limit, plastic limit, plasticity index, and linear shrinkage decreased - Increase in compressive strength
	Cement mixing [6]	- Underestimation of the stiffness using external strain measurements	- UC strength increase with increasing amount of cement content
Biological	Biomass Silica [34]	- Increased plastic limits with Biomass Silica increase	- Decreased liquid limit with Biomass Silica increase - Biomass Silica is stabilizing agent

Combined	Electro-Osmotic Chemical Treatment Using $CaCl_2$ Solution [13]	- Electric energy consuming increases for large zones to cover and increases with the increase of the concentration of the injected $CaCl_2$ solution - For more efficiency consuming more $CaCl_2$ is required to increase the dewatering - Disturb pH, mineralogy and minerals inside soil texture because of force migration due to electric potential effect	- Speeds dewatering and the dewatering efficiency - Improved bearing capacities of soils in four tests
	Sand compacted piles [12]	- Upheaval soil clearly removed during installation with a high replacement area ratio	- Improved soil strength and settlements significantly decreased - During construction period most of settlement occurred

5. CONCLUSION

The laboratory tests conducted indicated that the marine clay samples collected from Malacca to be classified as silty sand, according to the USCS. The geotechnical parameters obtained include: liquid limit (63.66%), natural water content (67%), plastic limit (32.57%), compression index C_c (0.281), recompression (swelling) index C_r (0.0576), coefficient of vertical consolidation C_v (0.043 - 4.435 m^2/yr), specific gravity G_s (2.57), bulk density γbulk (15.8 - 16.5 kN/m^2), dry density γ_{dry} (9.46 - 9.88 kN/m2), permeability for fines only was k (6.3 x 10^{-9} to 6.0 x 10^{-7} m/yr), and preconsolidation stress Pc' 42.17 kPa. SiO_2, Al_2O_3 and Fe_2O_3 were found to be main compounds of Malacca marine clay by 56.23%, 22.81% and 11.29% respectively.

Based on the obtained results and comparison made with marine clay from previous research, Malacca marine clay was found to be following the same tendencies and behavior of other marine clays, which indicates the applicability of some of the proposed methods of treatment. However, each treatment method possessed their own respective limitation that may match the case study based on the size of the project, required scale of application, cost, time, and environmental restrictions. Its void ratio was also displayed to be very high, which is indicative of a high probability for failure and significant deformations under loading in the future. However, the values obtained from the tests were insufficient in estimating equations that describe the tendency of the parameters or to allow a comparison with other equations. Therefore, more readings are required in the future to encapsulate more sample behavior.

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