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Geotechnical Characterisation of Marine Clay As Potential Liner Material

(Pencirian Geoteknik Lempung Marin Sebagai Potensi Bahan Pelapik)

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ABSTRACT

Natural clay is commonly used as a liner material to contain landfill leachate from contaminating the environment. A key characteristic of liner material is its hydraulic conductivity. It is recommended that the hydraulic conductivity of the potential liner material should be of 1×10^{-9} m/s or less. This paper presents the geotechnical characteristics of marine clay that may be used as landfill liner material. The tests were consistency index, compaction behaviour, compressibility and hydraulic conductivity. The marine clay was dominated by finer fraction of silt and clay (78%-88%) followed by sand (12%-22%). The clay minerals commonly present were montmorillonite, kaolinite and illite as well as quartz as the non-clay mineral. The consistency index for the liquid limit, w_L and plastic limit, w_P were 56.6%-80.5% and 36%-45%, respectively. The plastic index, I_p of the marine clay samples ranged from 19% to 37%. The permeability test indicated that the hydraulic conductivity of the samples ranged between 1.10×10^{-9} and 2.44×10^{-9} m/s. The very low permeability showed by the marine clay can be related to the presence of high content of finer fraction. Compaction of marine clay samples resulted in maximum dry density, ρ_{dmax} that ranged between 1.5 and 1.6 g/cm^3 and optimum moisture content, w_{opt} that ranged between 18.2% and 25%. During the consolidation of the marine clay, the hydraulic conductivity decreased within the recommended permeability for landfill liners. This study showed that some geotechnical characteristics of the studied marine clay were in favour of being used as landfill liner material.

Keywords: Consistency index; landfill; liner; marine clay; shear strength

ABSTRAK

Lempung semula jadi sering digunakan sebagai bahan pelapik untuk menghalang pencemaran cecair larut resap tapak pelupusan ke persekitaran. Ciri utama bahan pelapik adalah sifat ketelapannya. Kekonduksian hidraulik yang disarankan bagi bahan berpotensi sebagai pelapik seharusnya 1×10^{-9} m/s atau kurang. Kertas ini menunjukkan ciri geoteknik lempung marin yang mungkin dapat digunakan sebagai bahan pelapik tapak pelupusan. Ujian yang dilakukan adalah indeks ketekalan, sifat pemadatan dan kekonduksian hidraulik. Lempung marin didominasi oleh fraksi halus bersaiz lodak dan lempung (78%-88%) diikuti oleh pasir (12%-22%). Mineral lempung yang sering hadir adalah monmorilonit, kaolinit dan ilit serta kuarza sebagai mineral bukan lempung. Indeks kekonsistensi bagi had cecair, w_L dan had plastik, w_p masing-masing adalah 56.6%-80.5% dan 36%-45%. Indeks keplastikan, I_P sampel lempung marin berjulat daripada 19 hingga 37%. Ujian ketelapan menunjukkan kekonduksian hidraulik sampel berjulat antara 1.10×10^{-9} dan 2.44×10^{-9} m/s. Nilai ketelapan yang sangat rendah yang ditunjukkan oleh lempung marin boleh dikaitkan dengan kehadiran kandungan fraksi halus yang tinggi. Pemadatan sampel lempung marin menghasilkan ketumpatan kering maksimum, ρ_{dmax} berjulat 1.5 - 1.6 g/cm^3 dan kandungan optimum lembapan, w_{opt} berjulat antara 18.2% dan 25%. Semasa pengukuhan lempung marin, kekonduksian hidraulik menurun dalam kebolehtelapan yang disyorkan bagi bahan pelapik tapak pelupusan. Kajian ini menunjukkan ciri geoteknik lempung marin yang dikaji memihak sebagai bahan pelapik tapak pelupusan.

Kata kunci: Indeks ketekalan; kekuatan ricih; lempung marin; pelapik; tapak pelupusan

INTRODUCTION

Rapid development has increased the quantity of solid waste that has to be safely disposed and handled by landfill operators at effective cost (Arasan & Yetimoglu 2006). The presence of heavy metals such as lead, cadmium, zinc, nickel and chromium are commonly associated with industrial waste and considered noxious to human health (Yong & Phadungchewit 1993). A common natural earth material such as clayey soil is widely used for containment of landfill leachate from migrating to the environment. Geosynthetic Clay Liner (GCL) is one of the advanced synthetic material that has been widely used in construction of impermeable liner material in modern landfills. The uncertainty of its

performance over a period and its expensive cost have made this product unfavourable (Arasan 2010). Finding natural earth materials can be an advantage economically to landfill operators as long as the material provides suitable characteristics (e.g. permeability, strength and shrinkage). However, these earth materials should comply with the recommended criteria to ensure their effectiveness as impermeable liners.

Marine clay is characterised by low permeability and has the capability in attenuation of inorganic contaminants. This sediment is mainly deposited along the coastal areas of Peninsular Malaysia. It is microcrystalline in nature and consists of clay minerals such as chlorite, montmorillonite, kaolinite and illite (Basack & Purkayastha 2009; Bjerrum 1973). Some common non-clay minerals are also present such as quartz and feldspar. It has been found that the strength and stiffness characteristics of marine clay deposits are subjected to wave induced cyclic stresses (Dias & Alves 2009; Hyde et al. 1993; Long & Menkiti 2007).

Previous studies showed that the properties of marine clay have advantages over the lateritic soils as permeable liners (Chalermyanont et al. 2008; Du & Hayashi 2004; Kamon & Katsumi 2001). Clay minerals have high metal absorption capability and are characterised by low hydraulic conductivity. The hydraulic conductivity of an effective liner material should be equal or less than 1×10^{-9} m/sec (Jones et al. 1993). The engineering behaviour of marine clay has been studied by many researchers (Chew et al. 2004; Chung et al. 2007; Rao et al. 2011; Suneel et al. 2008). Benson and Trast (1995) performed hydraulic conductivity tests on thirteen compacted clay samples under controlled conditions. They found that the k value decreased with an increase in clay content. In addition, compaction of clayey soils at initial saturation in excess of 85% could decrease the hydraulic conductivities down to 10^{-10} m/s. Itakura et al. (2005) examined the consistency limit and hydraulic conductivity of Londonderry Clay deposit for industrial liquid waste containment material.

This paper presents the geotechnical characteristics of marine clay that may be used as liner material to contain the migration of landfill leachate to the environment. The geotechnical characterisation conducted on the marine clay samples were consistency index, compaction behaviour, compressibility, hydraulic conductivity and shear strength.

Materials and Methods

Sample Collection and Preparation

The collection of the marine clay samples was performed at three locations along the coastal area of Kuala Muda, Kedah (Figure 1). At each station, three sub-samples were collected for sample replication. This soft marine clay deposit was developed under the shallow coastal saline water conditions. On-hand sample, marine clay found to be greenish or bluish in colour with fine stripes of organic matter. It was common to find a lot of small fragments of shells. The grey colour was possibly developed because of the oxidation of sulphur and iron in the clay as a result of being exposed to the atmosphere (Taha et al. 2000). The sample collection was performed using shallow open trench excavation (0.5 m depth from ground surface) approach during low tide. Undisturbed samples were taken for oedometer tests. A block sampler of 300 mm cubical with a 20° outside angle cutting edge was pushed vertically into the marine clay deposit and a scoop was carefully used to dig out the sample. Extreme precautions were imposed during sampling to keep the clay in its natural water conditions. Sufficient amount of disturbed marine clay samples, weighing about 30 kg for each station, was also taken from the same trench and then transferred for laboratory experiments. Undisturbed samples were used to determine the value of their natural compression index. Meanwhile, bulk samples were air-dried at room temperature for a week. Aggregates of dried samples were manually crushed by pestle and mortar to individual grain. The prepared samples were used to determine the mineralogical and geotechnical characteristics. The studied characteristics were particle size distribution, clay mineralogy, specific gravity, pH, consistency index, compaction behaviour, compression index and hydraulic conductivity.

Experimental Procedures

The technique adopted to determine the particle size distribution was dry-sieving and hydrometer (size passing sieve number 200) techniques. Identification of clay and non-clay minerals was determined by the X-ray diffraction (XRD) technique. A Philip X-ray diffractometer equipped with Ni-filtered CuKα radiation generated at 30 kV and 30 mA with a scan speed of $4°2\theta$ min^{-1} was used. Prior to analysis, samples had to be pulverized into powder state. In this study, the samples tested for X-ray diffraction had particle size of less than 2 μm. Quantitative estimation of clay minerals was carried out based on peak areas and peak height for non-clay minerals (Pierce & Siegel 1969). Determination of the specific gravity of the marine clay samples was established by using the pyknometer bottle technique. Consistency index is usually used to correlate the water contents of cohesive soil into empirical boundaries namely non-plastic, plastic and viscous liquid (Dias & Alves 2009). It is widely known as the Atterberg limits of liquid limit, w_L and plastic limit, w_P. Liquid limit is used to classify particular soil and to estimate its moisture content at which the shear strength is virtually zero. Liquid limit can be determined by using the Casagrande method where the V-groove cut in the soil paste is subjected to shallow drop of the cup. The plastic limit is determined by rolling the soil thread into a 3 mm diameter without crumbling. The plasticity, I_p index is defined as the difference between the liquid limit and the plastic limit.

FIGURE 1. The location of the sampling points for the marine clay

Soil with difference in I_p value tends to be clay, silt or non-plastic material. The ratio of the difference between natural water content, plastic limit and plasticity index is known as the liquidity index, I_L. The I_L value can be correlated to the shear strength of the soil (Dias & Alves 2009; Yilmaz 2000). As value I_L equal to 1.0, the soil achieves its liquid limit and becomes a plastic limit if I_L equal to 0. A reliable correlation between I_L value and degree of consolidation of clayey soil was presented by Rominger and Rutledge (1952) and Means and Parcher (1963). The values of the liquid limit and plasticity index of the marine clay samples were then plotted onto the Casagrande Chart. The chart is usually used to classify the soil based on its different behaviour. Compaction characteristic tests were performed using 2.5 kg standard proctor (also known BS Light). Sample was compacted in three equal layers using a rammer where each layer experienced 27 blows that were evenly distributed over the mould area. The maximum dry density, ρ_{dmax} and optimum moisture content, w_{opt} can be achieved from the compaction curve. Meanwhile, the permeability tests performed adopted a falling head permeameter method. The compression index, C_c of the samples was determined using the oedometer test. A further explanation of the methods applied for particle size distribution, specific gravity, consistency limits, 1-dimension compression, compaction and permeability tests for soil can be referred to the British Standard Institution 1377 (1990(a), 1990(b), 1990(c), 1990(d)) Parts 2, 4, 5 and 7.

RESULTS AND DISCUSSION

PARTICLE SIZE DISTRIBUTION AND MINERALOGY

The particle size distribution curves for the three clay samples collected at different locations with three replications for each sample are shown in Figure 2. These samples can be classified as clayey silt. The mean values for sand, silt and clay fractions are shown in Table 1. It shows that the marine clay samples are dominated by silt fraction (54.3%-58.3%) followed by clay fraction (23.7% – 29.7%). Sand fraction in marine clay samples ranged between 12% and 22%. The sand fraction at stations L1 and L2 showed a higher content, namely 19.2% and 22%, respectively. Shell fragments were also commonly found in the marine clay samples. The presence of higher silt and clay fractions is a characteristic of the typical muddy coastal beach of Kuala Muda, Kedah. An appreciable content of fines is desirable in soil that is to be used as the hydraulic barrier (Belloo 2012). Jones et al. (1993) cited that the suitable material for liners should contain clay of greater than 10%. EPA (1990) recommended that soils used as liner material should have at least 20% fines (fine silt and clay size particles) to achieve hydraulic conductivity values of or less than 1×10^{-7} m/s. It is difficult to achieve the recommended hydraulic conductivity for soil with less clayey content. Hydraulic conductivity usually decreases with the increase of the content of fine particles (Alamgir et al. 2005).

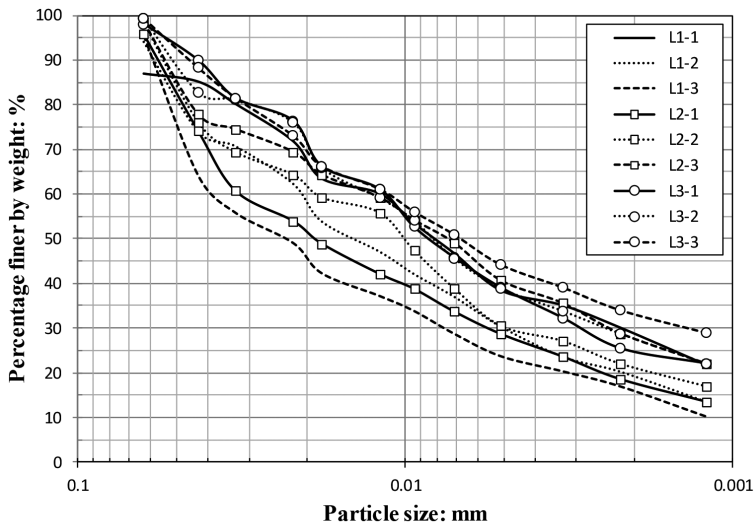


FIGURE 2. Particle distribution curves for the marine clay samples

TABLE 1. Summary of the marine clay characteristics

Material Properties	Sample No.			Mean
	L1	L2	L3	
Particle size distribution, %				
Sand	19.2	22.0	12.0	17.8
Silt	56.5	54.3	58.3	56.4
Clay	24.3	23.7	29.7	25.9
Fines fraction,	80.8	78.0	88.0	82.3
Organic cont., %	2.13	1.96	1.83	1.97
Natural moisture cont., *w%*	56.7	73.5	67.6	65.9
XRD Analysis†	Montmorillonite, kaolinite, illite, quartz, halite	Quartz, halite, montmorillonite, kaolinite	Montmorillonite, kaolinite, illite, quartz, halite	
Specific gravity, G_s	2.6	2.4	2.6	2.6
pH	7.7	7.7	7.6	7.7
CEC, *meq/100g*	25.24	25.82	27.09	26.05
Atterberg limit, %				
Liquid limit, w_L	72.0	70.0	79.0	73.0
Plastic limit, w_P	42.0	42.0	44.0	47.0
Plastic index, I_P	30.0	28.0	35.0	30.0
Liquidity index, I_L	0.5	1.3	0.7	0.8
Ratio w_P/w_L	0.6	0.6	0.4	0.5
Permeability, *k*: (x10^{-9}) m/s	1.10	2.44	1.77	1.77
Compaction test				
Max. dry density, ρ_{dmax}: g/cm^3	1.6	1.5	1.5	1.5
Opt. moisture content, w_{opt}: %	18.2	25.0	23.8	22.3
1-D Compression test				
Pre-consolidation stress, P_c'	65-58kPa	14-53kPa	60-59kPa	-
Compression index, C_c	0.576-0.611	1.674-1.032	0.849-0.900	-

† - in descending order of intensity value
σ_3 - applied confining pressure

X-ray diffraction (XRD) is a common technique used to determine mineral content in sediments. It is important to establish the types of minerals present in order to assess the behaviour of soil toward pollutants. Yong et al. (1998) mentioned that every mineral has particular surface and structure characteristics that determine its capability to confine heavy metals. Identification of mineral is based on the characteristics of diffraction when the photon X-ray is radiated to the samples. The results from the XRD analysis indicated that the studied clay samples were composed of montmorillonite, kaolinite and illite (Table 1). Each mineral has different mineral concentration as reflected from the intensity of the XRD. For sample L1, the presence of peak at 15.52 Å and 5.01 Å was identified as montmorillonite. Kaolinite was detected from the peak at 7.22 Å and 3.58 Å while illite at peak of 10.10 Å and 3.55 Å. Sample L2 indicated the presence of montmorillonite from the peak at 15.17 Å and 4.48 Å followed by kaolinite at peak of 7.17 Å and 3.57 Å. The presence of both minerals in L2 were lesser than the sample of L1. In sample L3, montmorillonite showed the strongest peak at 15.29 Å and 5.01 Å, followed by kaolinite at peak of 7.16 Å and 3.57 Å. Illite was detected at peak of 5.01 Å and 3.34 Å. Other minerals detected were quartz and halite. The ratio between plastic limit, w_P and liquid limit, w_L of the samples ranged between 0.4 and 0.6; these values typically reflect marine clay from around the world (Dias & Alves 2009; Sridharan et al. 2004).

SPECIFIC GRAVITY, PH AND ORGANIC MATTER

The mean value for specific gravity, G_s of the marine clay was 2.6 and no significant difference was found in the result of the test. The value of G_s ranged between 2.4 and 2.6 (Table 1). The pH test showed that the samples were slightly alkaline with values ranging from 7.6 to 7.7. Similarly, no clear difference was found from the samples collected at the three locations (Table 1). These values of G_s and pH were also similar to the marine clay deposit studied by Rao et al. (2009) and Tan et al. (2002). Loss on ignition value for organic content in marine clay samples was low, ranging from 1.83 to 2.13% with a mean value of less than 2%. It was also reported that the organic matter from Singapore marine clay is less than 1% (Ohtsubo et al. 2012). Tan et al. (2002) also stated that the organic content of marine clay composed of sedimentary deposit is around 3%, with moderate contents of kaolinite, illite, chloride and smectite.

ATTERBERG LIMITS AND PERMEABILITY TESTS

The values of the liquid limit, w_L and plastic limit, w_P are shown in Table 1. The w_L values ranged from 70 to 79% while the w_P values were between 42 and 44% with mean values of 73 and 43%, respectively. The values of each Atterberg limit are remarkably uniform. The plastic index, I_P ranged from 28 to 35 with a mean value of 30. The recommended materials for landfill liners are those clays that have w_L and I_P less than 90% and 65%, respectively, with clay fraction of greater than 10% (Jones et al. 1993). These criteria should be followed in order to avoid instability, deformation and compaction in earthworks (Department of Transport 1991).

According to Benson and Trast (1995), the liquid limit w_L and plastic limit w_P values are directly related to mineralogy and clay content. The presence of high content of clay, especially active clay minerals generally corresponds to a decrease in the size of microscale pores that subsequently lower the hydraulic conductivity of the soil. The liquidity index of the studied clay ranged from 0.5 to 1.3 with a mean value of 0.8. The mean value of I_L indicated that the studied clay fall within the cohesive soil deposit and can be categorised as normally consolidated clay based on the classification scheme introduced by Means and Parchers (1963).

The plotted results of I_P and w_L of all the clay sub-samples on the Cassagande Chart are shown in Figure 3. All samples lie below the A-line, representing silt with high to very high plasticity. It is clearly seen in Figure 3 that even though the samples collected from L2 and L3 are below the A-line, these samples are distributed slightly further up in comparison to the samples of L1. Jones et al. (1993) stated that such material that falls below the A-line is classified as material unsuitable as a liner. However, they also added that materials classified as silt based on plasticity can achieve the required low permeability if adequately compacted within an acceptable range of moisture content. Studies showed that compaction can decrease void ratio that resulted in low hydraulic conductivity of soils (Ahn & Jo 2009; Bagchi 2004; Kooistra & Tovey 1994).

The permeability of earth materials for liners should be investigated in order to establish their capability in confining or eliminating the movement of leachate from being seeped into the surrounding environment (Van Imple 1998). Murray et al. (1992) recommended that the permeability of a liner for high-technology landfill should be 1×10^{-9}m/s. The permeability of the studied clay was generally very low; it ranged from 1.10 to 2.44×10^{-9} ms^{-1} with a mean value of 1.77×10^{-9} m/s (Table 1). The low permeability value was due to the higher content of finer fraction of silt and clay. The low permeability values of the marine clay samples were within the requirement for liner material. The differences in the hydraulic conductivity were related to the different content of fine and clay minerals (Table 1). Higher content of finer fraction can be associated with high CEC value in marine clay (Chalermyanont et al. 2008). This resulted in a thicker double layer during hydration in which the capacity of the water flow path decreases, subsequently lowering the hydraulic conductivity (Mitchell 1993).

COMPACTION AND CONSOLIDATION TESTS

The purpose of compaction is to densify the soil mass by bringing down the air voids. Islam et al. (2008) presented results showing the effect of compaction on the hydraulic

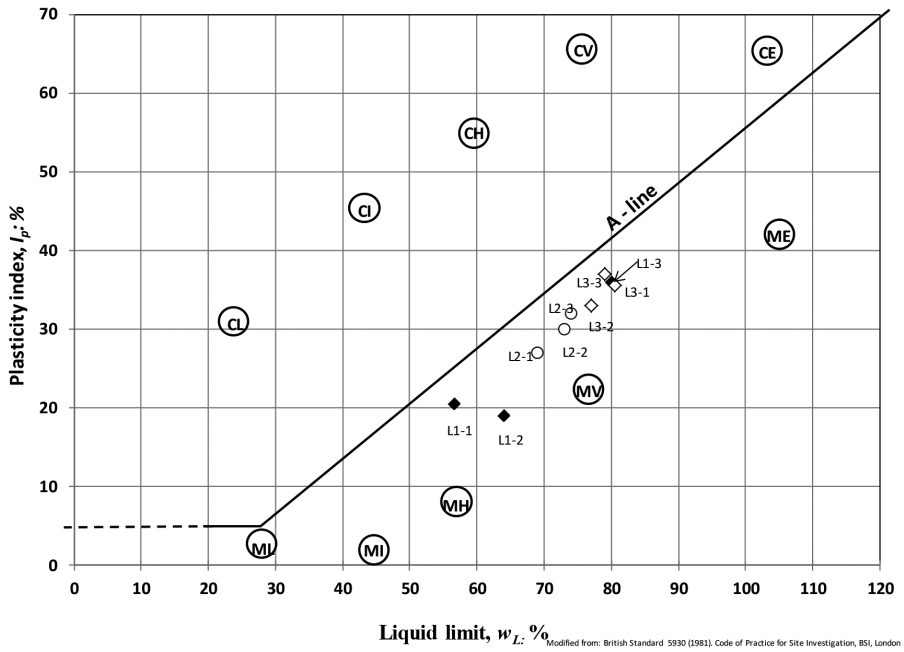


FIGURE 3. Plasticity chart for the marine clay samples

conductivity. In this study, compaction tests of 2.5 kg (BS Light) standard proctor compactive efforts were performed on the marine clay samples.

The results of the maximum dry density, ρ_{dmax} and optimum moisture content, w_{opt} are shown in Table 1. Figure 4 illustrates the compaction curves of the marine clay samples. The maximum dry density, ρ_{dmax} values ranged from 1.5 to 1.6 g/cm^3 with a mean value of 1.5 g/cm^3. Meanwhile, the values of optimum moisture content, w_{opt} ranged between 18.2% and 25% with a mean value of 22.3%. It can be seen from Figure 4 that the compaction curves for sample L1 is located above those of samples L2 and L3. Sample L1 achieved higher ρ_{dmax} at lower moisture content when compared with that of samples L2 and L3. The study carried out by Islam et al. (2008) on Khulna clay deposit indicated that the compacted soil at maximum dry density, ρ_{dmax} at 20% optimum moisture content, w_{opt} could achieve hydraulic conductivity close to 2.5×10^{-10} m/s.

The consolidation behaviour was studied using oedometer test. This test provides information related to the amount of loads that clay can withstand once the

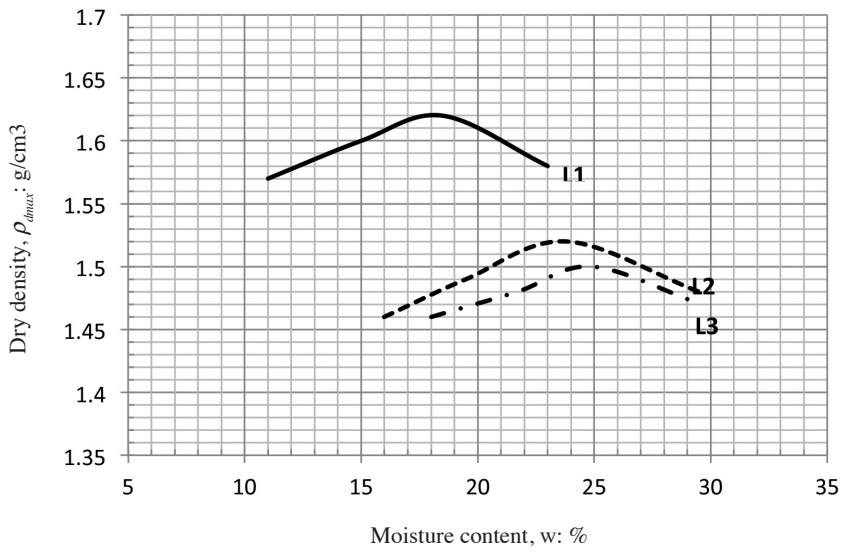
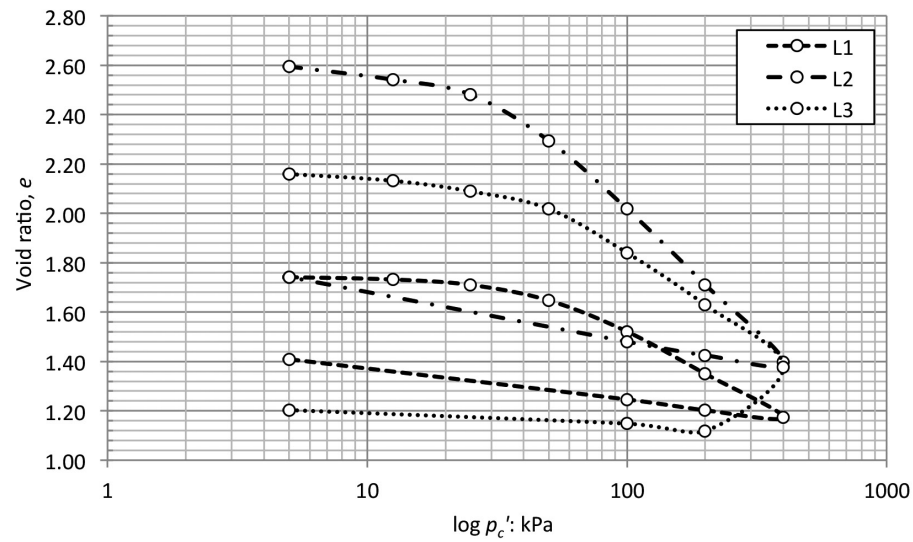


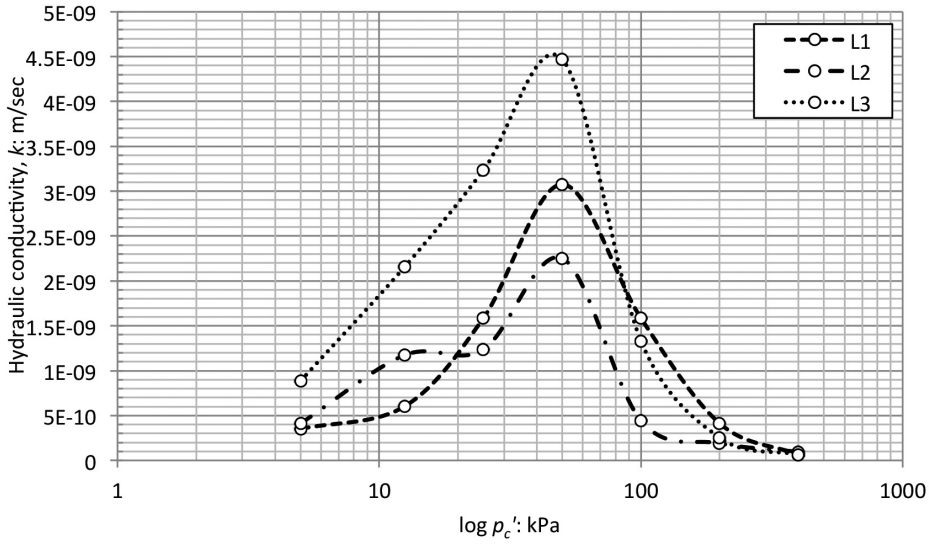
FIGURE 4. Compaction curves for the collected marine clay samples

liners are in operation. However, the overburden pressure was released during sampling that resulted in a lower value of maximum effective stress compared to the value of field condition. The 1-dimension consolidation tests were performed on the marine clay samples. The preconsolidation stress, p_c' is the effective stress that denotes the boundary between soft and stiff deformation response of soil to loading (Terghazi et al. 1996). The p_c' values were obtained from the void ratio; $e - log\ p_c'$ curves gave values ranging from 58-65kPa for sample L1, 14-53kPa for L2 and 60-59kPa for L3 (Table 1).

Figure 5(a) shows the consolidation curves for two clay samples in $e - log\ p_c'$ space. The consolidation curves of $e - log\ p_c'$ illustrated a slight concave upon reaching the virgin compression line. This typical behaviour was also reported by Taha et al. (2000). The C_c is described by the change of the void ratio, e and the change of the effective stress, σ' plotted to the log scale. It is clearly seen that the initial void ratio of L1 was lower than L2 and L3 (Figure 5(a)). The compression index, C_c values for samples L1, L2 and L3 ranged from 0.576 to 0.611, 1.674 to 1.032 and 0.849 to 0.900, respectively. The change in hydraulic conductivity during consolidation of the samples is shown in Figure 5(b). It indicated that the marine clay could achieve very low hydraulic conductivity value of equal or less than 10^{-10} m/s.



(a)



(b)

FIGURE 5. (a) Consolidation curves for marine clay samples plotted on $e - log\ p_c'$ space and (b) Hydraulic conductivity, k plotted against log p_c'

CONCLUSION

Geotechnical characterisation of marine clay deposit was investigated for possible use as liner material. The marine clay samples were classified as clayey silt with low organic content. The fraction of the finer ranged between 78% and 88%, indicating appreciable quantity of fines that are suitable for achieving the targeted low hydraulic conductivity for liners. The XRD analysis showed the presence of clay minerals of montmorillonite, kaolinite and illite. The liquid and plastic limit ranged from 70% to 79% and 42% and 44%, respectively. The plasticity index ranged from 28 to 35 and these values are within the recommended values for landfill liner materials. Based on the Cassagrande chart, all marine clay samples were classified as silt of high to very high plasticity. Even samples were categorised below A-line, the required permeability can be achieved if adequate compaction effort is applied. The marine clays presented very low permeability that ranged from 1.10 - 2.44 × 10^{-9} m/s which corresponded with higher content of finer fraction of silt and clay. Compaction of the marine clay samples achieved maximum dry density ranging from 1.5 - 1.6 g/cm3 with optimum moisture content that ranged from 18.2% - 25%. The hydraulic conductivity of the marine clays also dropped within the desired permeability of landfill liners during consolidation. The results of this study showed that the geotechnical characteristics of the studied marine clay can potentially be used as landfill liner material.

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