Permeability Investigation of Compacted Bentonite-Treated Lateritic Soil Liner Using a Consolidation Test

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Abstract. *A traditional permeability (k) test has two main limitations: 1) the test is time consuming (requiring more than 20 days to complete) and 2) material with a very low k value (< 10^{-9} m/s) cannot be investigated (for example, a constant head test). Therefore, this research introduced an alternative test method using the results of a consolidation test, which measure k values of 10^{-11} m/s of a compacted lateritic soil-bentonite mixture, and takes only about 7 days to complete the test. The laboratory test results indicated that the k values of the compacted soils were reduced by adding bentonite and that by using a bentonite content of more than 4%, the mixed soils could be used as a compacted clay liner material with a k value less than 10^{-9} m/s. The effect of cation concentration substantially increased the k values due to the collapse in the thickness of the diffuse double layer. The study results showed that a consolidometer test can be precise in measuring the k value of the compacted clay liner. Moreover, it is important to note that with the bentonite-treated, lateritic soil liner, care is necessary to consider the effect of cations, so the test should be applied considering cations and not only using deionized water, especially in salt-affected areas such as Northeastern Thailand. This research could be a guideline for laboratory investigation of the k value for the evaluation of compacted clay materials.*

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1. Introduction

A compacted clay liner (CCL) has several functions such as use in landfill to isolate wastes or for water storage in arid areas. Generally, the CCL design involves an impervious layer with a permeability (*k*) value of less than 10^{-9} m/s, about 0.75 to 1.00 m in thickness [1]. Moreover, the prominent benefits of using a CCL are its low cost and the fact that local aggregate such as lateritic soil can be utilized [2-3]. Lateritic soil is a tropical residual soil commonly found in Northeastern Thailand [4-5]. Even through the *k* values of CCL made from lateritic soil can meet the required level (<10^{-9} m/s), sometime the *k* value of CCL-lateritic soil may be lower than the defined value. Thus, the barriers properties of compacted lateritic soil liner must be improved and one effective method is to mix it with a swelling clay mineral such as bentonite [6-8]. Bentonite can absorb a lot of water as well as having a very low *k* value (<10^{-11} m/s) [9].

Sodium (Na^+) bentonite has been widely used in CCLs compared to other types of bentonite [10]. Generally, the *k* value is investigated using a standard permeability test [7], but such a test is not appropriate for a very low *k* value of less than 1.17×10^{-9} m/s as reported by Pakjarean [7]; furthermore, this test is time consuming (requiring about 24 days to complete) [7]. However, few researches have paid any attention to this issue.

Another problem in Northeastern Thailand is that the soil is salt-affected due to salt bearing rocks [11]. Consequently, as the seasons change, salts in the groundwater moves up and accumulate on the soil surface during the dry season, only to be leached down with rainfall during the rainy season [12], which can be produce a saline solution. Thus, not only agricultural uses are heavily impacted, but also the physicochemical properties for engineering applications can be also altered by the saline effect [13-14]. However, while literature reviews have extensively studied the agricultural point of view [11-12] [15-16], there has not been any broad investigation of the effect of saline solutions on the barrier properties of compacted soil liners made from the lateritic soil.

Due to these limitations, this research aimed to investigate the *k* value of a compacted bentonite-treated lateritic soil liner using an alternative method to determine the *k* value under different overburden pressures through a series of consolidation tests. In addition, the effect of the saline solution on the *k* value was also evaluated by using NaCl solutions with concentrations of 0.3 M and 0.6 M.

This research should provide useful information for a laboratory investigation of CCL material under different surcharge loads and cation concentrations.

2. Materials and Methods

2.1 Materials

An earth auger was used to sample lateritic soil from a borrow pit on the Kasetsart University Chalermphrakiat Sakon Nakhon Province campus, Sakon Nakhon, Thailand at a depth of about 2-3 meters. The coarse soil particles were removed by passing the soil sample through a No. 40 sieve, after which the soil sample was air-dried for 3-4 days. The measured initial water content of the lateritic soil was about 5-8%. The lateritic soil was composed of 20% fine-grained particles and 80% sand, with no gravel particles. The liquid limit (LL) and plastic limit (PL) were 38.00% and 23.30%, respectively. The lateritic soil was classified as clayey sand (SC). The specific gravity (G_s) of the lateritic soil was 2.70.

The bentonite used in this study was the sodium type and was purchased from Wee-Rin Chemical Partnership Company. The initial water content was about 10%. The bentonite contained a fines content of 68%, with the remainder being sand. The LL and PL were 504.4% and 48.1%, respectively. The bentonite was classified as high plasticity clay (CH). The bentonite had a G_s value of 2.89. The current study used bentonite contents of 2%, 4%, 8% and 16% by dry weight of lateritic soil.

Sodium chloride (NaCl) solutions were prepared at two different concentrations of 0.6 M and 0.3 M. It should be noted that 0.6 M NaCl can be considered as an aggressive liquid, in which the cation concentration is similar to that of sea water [18]. Deionized water was used as a control liquid to compare the effect of the saline solution on the soil properties.

2.2 Methods

A series of compaction tests was conducted following ASTM D698 in a 100 mm diameter mold using the standard proctor method. The void ratio (e) of the compacted soil was calculated using Equation 1:

$$e = \frac{\gamma_w \cdot G_s}{\gamma_d} - 1 \quad (1)$$

where γ_w is the unit weight of water (9.81 kN/m^3). γ_d is the dry unit weight of compacted soil and G_s is the specific gravity of the compacted soil.

The permeability (k) values were calculated from the test results from the consolidation test (ASTM D2435) using the Eq. 2[17]:

$$k = c_v m_v \gamma_w \quad (2)$$

where c_v is the coefficient of consolidation determined by Taylor method, m_v is the coefficient of volume change, and γ_w is the unit weight of water.

The air-dried lateritic soil was mixed with the liquids (deionized water, 0.3 M NaCl or 0.6 M NaCl) using a mechanical mixer. The amount of water was about 1.2 times the LL. Then, the mixed slurry was wrapped and cured for 24 h. After that, the slurry was pre-consolidated in the consolidation ring under a vertical stress of 20 kPa for 24 h. It should be noted that the pre-consolidation pressure was obtained using trial and error to successfully form a sample. Subsequently, the pre-consolidated sample was trimmed to 20 mm in height. Then, the specimen was installed in the consolidation test apparatus. After applying the vertical pressure (σ_v'), the settlement elapsed time was recorded until the specimen had achieved a steady state for each σ_v'value (for 24 h). The test was carried out using σ_v' in the range 10-320 kPa, by doubling the stress for each subsequent step.

3. Results of Physical Properties and Compaction Test

The results of G_s values increase with increasing in bentonite content. For the result of Atterberg limits, the LL and PL of the soils trend to increase with increasing in bentonite content. This is because the bentonite has higher capacity to absorb water compare to that of the lateritic soil.

	Bentonite content (%)			
Properties	2	4	8	16
Specific gravity, G_s	2.72	2.75	2.79	2.82
Liquid limit, LL (%)	47.8	50.1	56.2	66.5
Plastic limit, PL (%)	26.3	26.7	27.7	30.3

Table 1 Soil physical properties

The results of the compaction test are shown in Fig. 1 and indicated that

- the maximum dry density ($\gamma_{d,\ max}$) decreased with increasing bentonite content, while the optimum water content (OWC) increased with increasing bentonite content.
- The ordinary compacted lateritic soil had the highest $\gamma_{d,\ max}$ of 16.97 kN/m^3 with an OWC of 17.46%, which is a reasonable value for a compacted lateritic soil based on the literature [19].
- The $\gamma_{d,\ max}$ values decreased to 16.76 kN/m3, 16.19 kN/m^3, 15.79 kN/m^3 and 15.13 kN/m^3 with increasing OWC values of 18.10%, 18.76%, 19.72% and 20.82%, respectively, and bentonite contents of 2%, 4%, 8% and 16%, respectively.

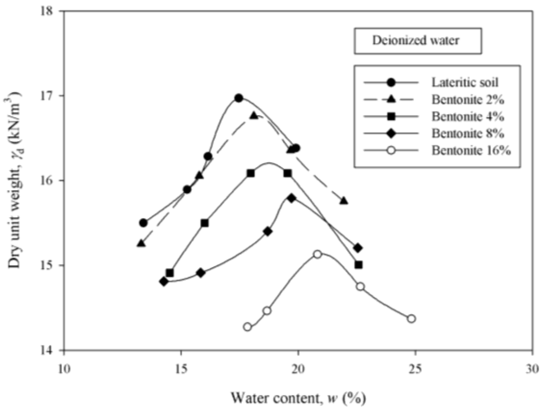

Fig. 1: Compaction test results

4. Test results of permeability

Fig. 2 shows the relationships between permeability (k) on a log scale and the void ratio (e). It was clear that the k value decreased linearly with an increasing e value, where the e value decreased due to the increasing overburden pressure. At the same e value, it was clear that the k value tended to decrease with increasing bentonite content. This can be explained by the bentonite having a thicker diffuse double layer (DDL) capable of holding more water compared to the lateritic soil.

The results of the calculated e and k values under the $\gamma_{d,\ max}$ conditions are reported in Table 2. The results indicated that the e value increased with increasing bentonite content. This reflected that the soil had greater spaces (voids) to hold water as a result of adding the bentonite.

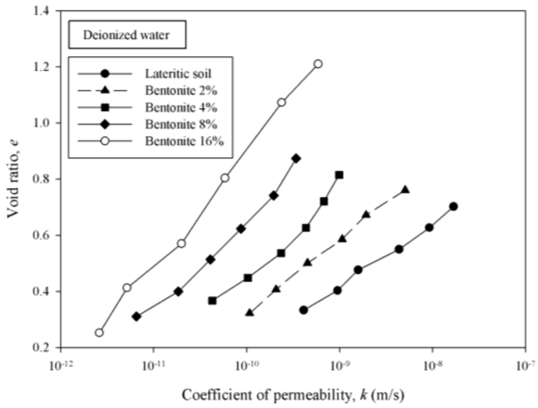

Fig. 2: Plot of k (log) versus e value

Considering the k value under the $\gamma_{d,\ max}$ condition, the test results show that the values of $k_{\gamma d,\ max}$ had the same tendency as the k values reported in Fig. 2, with the $k_{\gamma d,\ max}$ values decrease with an increasing in the bentonite content. Based on the test results in Table 2, a bentonite content of more than 4% could produce k values less than 10^{-9} m/s, indicating that such material could be used in compacted clay liner applications. This study selected a bentonite content of 4% as a representative case to further investigate the effect of a saline solution.

	Bentonite content (%)				
Properties	0	2	4	8	16
$e_{\gamma d,\ max}$	0.56	0.59	0.67	0.73	0.83
$k_{\gamma d,\ max}$ (m/s)	6.8×10^{-8}	3.7×10^{-9}	4.7×10^{-10}	6.2×10^{-11}	1.5×10^{-11}

Table 2 Calculated e and k values under $\gamma_{d,\ max}$ conditions

The results of k in the literature were used for comparison to validate the results from using the alternative test method. The plot of k versus e for the compacted ordinary lateritic soil was compared with the results reported by Chaiyasat [20], as shown in Fig. 3. The test k results in the current study were comparable with the results reported in the literature. Moreover, the suggested method required less time than the conventional test and was easier to perform as only a single soil sample was required to determine the k value for different values of surcharge load.

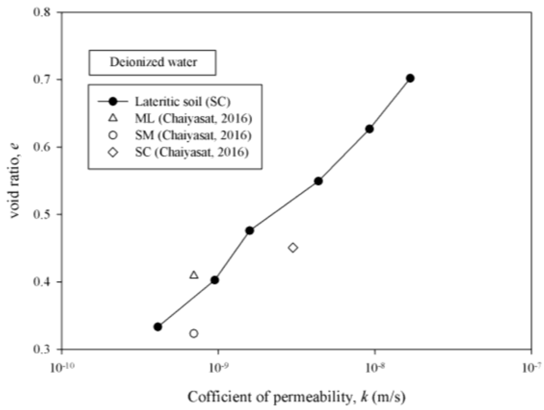

Fig. 3: Comparison of test results with data from literature

5. Effect of Saline Solutions on Soil Properties

The test results of LL and PL clearly showed that the plastic consistency of the soil was substantially affected by the cation concentration (Table 3). As the cation concentration increased, the values of LL and PL tended to decrease because the soils particles lost water holding capacity due to collapse in the thickness of the DDL [21].

	NaCl solution concentrations (M)	
Property	0.3	0.6
Liquid limit, LL (%)	29.35	22.94
Plastic limit, PL (%)	13.8	10.5

Table 3 Results of LL and PL for 4% bentonite mixed lateritic soil with NaCl solutions

In the compaction test as shown in Fig. 4, increasing the cation concentration decreased the OWC, resulting in increased $\gamma_{d,\ max}$. These results were consistent with those for LL and PL as reported in Table 3.

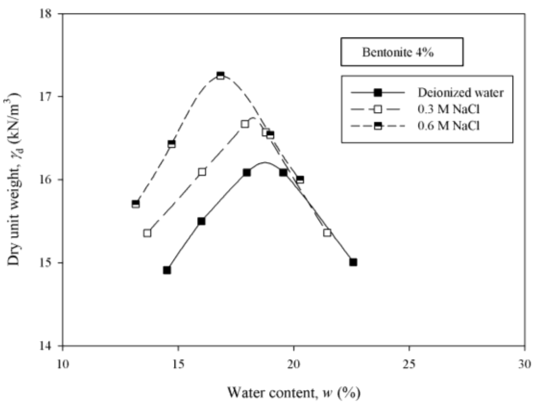

Fig. 4: Effect of NaCl solution on compaction characteristics

Fig. 5 shows the relationship between the k and e for soil samples permeated with different liquids. For the same e value, the k value increased with increasing cation concentration. The calculated results of $e_{\gamma d,\ max}$ and $k_{\gamma d,\ max}$ of the soil samples permeated with 0.3 M and 0.6 M NaCl solution are reported in Table 4.

	NaCl solution concentration (M)	
Property	0.3	0.6
$e_{\gamma d,\ max}$	0.62	0.56
$k_{\gamma d,\ max}$ (m/s)	5.7×10^{-9}	2.2×10^{-8}

Table 4 Results of k with NaCl solutions under maximum dry density conditions

The $e_{\gamma d,\ max}$ value indicated that the water holding capacity of the soil was reduced perhaps because the higher cation concentration can be exchanged with a counterion in the d-spacing between the soil particles, resulting in decreased thickness of the DDL [21]. Comparison of the $k_{\gamma d,\ max}$ values in the three different permeated liquids, indicated that the compacted soil interacting with the NaCl solutions produced a k value higher than for the defined values of materials for the CCL. Therefore, it is important to note that cations can have a large impact on the barrier properties of the soil. To design a proper CCL for containment of a liquid in a salt-affected area, testing should be undertaken using saline solutions where previously only deionized water was used.

6. Conclusions

This research investigated the barrier properties of compacted lateritic soil by mixing with sodium bentonite, and the permeability (k) was used to evaluate clay liner materials through a series of consolidation tests. In addition, the effect of NaCl solutions on soil properties was investigated and discussed. Based on the test results, the following conclusions can be drawn.

Bentonite causes major alterations in the physical, engineering and hydraulic properties of the mixed soils due to bentonite having a higher water absorption capacity than lateritic soil. The liquid limit (LL), plastic limit (PL) and optimum water content (OWC) of the compacted soils tended to increase with increasing bentonite content, while the maximum dry density ($\gamma_{d,\ max}$) values decreased.

For the same void ratio (e), the permeability (k) of the compacted soils tended to reduce with increasing bentonite content. Considering $k_{\gamma d,\ max}$ with the maximum dry density, the soil mixed with a bentonite content of more than 4% had $k_{\gamma d,\ max}$ values lower than that of the minimum requirement for compacted clay liner materials (< 10^{-9} m/s).

The NaCl solutions had a large impact on the soil properties. The LL and PL decreased with increasing cation concentration because of the decreased thickness of the diffuse double layer of the soil particles. The cation concentrations also affected the compaction characteristics as the OWC of the compacted soil decreased with increasing cation concentration, while $\gamma_{d,\ max}$ tended to increase. Considering $e_{\gamma d,\ max}$, the k value substantially increased with increasing cation concentration.

Based on the test results in this study, it is reported that a consolidometer test can be precise in measuring the k value of the compacted clay liner, and it is suggested that a saline solution should be investigated for CCL materials that previously have only been tested using deionized water, especially in salt-affected area such as Northeastern Thailand.

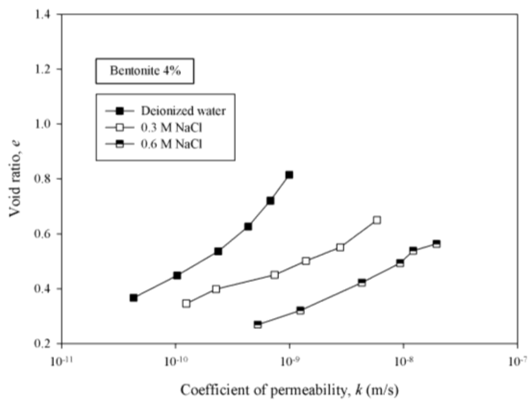

Fig. 5: Effect of NaCl solutions on k value

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