 https://doi.org/10.1051/e3sconf/20183401005

Effects of fines content on hydraulic conductivity and morphology of laterite soil as hydraulic barrier

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Abstract. Laterite soil was investigated to find out the effects of fines content and to identify the micro-structural and molecular characteristics to evaluate its potentiality as a compacted soil landfill liner material. Tests were carried out on natural soil and reconstituted soil by dry weight of soil samples to determine the physical and engineering properties of the soil. All tests were carried out on the samples by adopting the British Standard 1377:1990. The possible mechanisms that contributed to the clay mineralogy were analyzed using spectroscopic and microscopic techniques such as field emission scanning electron microscopy (FESEM), energy-dispersive X-ray (EDX) and X-ray diffractometry (XRD). The laterite soil was found to contain kaolinite as the major clay minerals. A minimum of 50% fines content of laterite soil met the required result for hydraulic barriers in waste containment facilities.

1 Introduction

The vast increase in population associated with rapid development in industrial and agricultural production, more waste is being produced regularly. This waste is mostly disposed of in landfills. In order to minimize the environmental pollution caused by mankind, numerous scientific studies such as storing, transformation, and annihilation of wastes. But the most economical and the most confident is the impermeable nature of sanitary landfills, with respect to underground and surface waters for solid waste disposal [1]. Hydraulic barriers usually refer to liners and covers used for waste containment structures in engineered sanitary landfill design play the role in preventing/impeding fluid flow and attenuating inorganic contaminants. These hydraulics barrier's structural integrity must be ensured by adopting all the necessary and adequate criteria in their construction [2].

The minimum recommended criteria for sanitary landfill liners varies upon regulations set by different countries. The environmental protection agencies in developed countries, like the USA, UK, and most European countries recommended hydraulic conductivity (k)

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of $k \leq 1 \times 10^{-9}$ m/s values for sanitary landfill liners [3]. The criteria set by most researches and regulatory agencies specified a hydraulic conductivity value of $k \leq 1 \times 10^{-9}$ m/s, a volumetric shrinkage value of ≤ 4%, and a value of ≥ 200 kN/m^2 shear strength are required for hydraulic barrier systems [4-11]. This paper focused on the hydraulic conductivity criteria.

In constructing compacted soil liners for sanitary landfills, the most common materials used are fine-grained soils because of their relative economy and availability, and good engineering properties when compacted [12]. Though, the morphology, which relates to the structural pattern and mineral formation of soils are controlled by the fines particles. The reason FESEM, EDX and XRD were carried out to examine the minerology of the laterite soil. There is no information in published literature on the minimum percentage of fines required to be adopted in the design of compacted laterite soils as landfill liners and covers in waste containment applications [4]. Therefore, there is need to find the minimum gradation with respect to fines content that can satisfy the hydraulic conductivity criteria used in hydraulic barriers.

2 Materials and methods

2.1 Natural Soil and Reconstituted Soil

In this study, the natural laterite soil sample used was collected from the hilly area near the Faculty of Electrical Engineering at 1 - 1.5 m below the ground. Located on latitude 1º33'39"N and longitude 103º38'44"E, Skudai campus of Universiti Teknologi Malaysia (UTM).

The reconstitution of the laterite soil used in this study was air-dried and then passed through BS 4.75mm aperture sieve to remove oversized gravel. The laterite soil was then sieved into three different grades i.e. fines (<0.063 mm), sand (0.063 mm to 2.00 mm) and gravel (>2.00 mm to ≤4.75 mm). The following gradation of laterite soil specimen were investigated:

Natural laterite soil sample with 30% fines, 40% sand and 30% gravel.

For the reconstituted laterite soil;

(i) 40% fines, 40% sand and 20% gravel.

(ii) 50% fines, 40% sand and 10% gravel.

2.2 Morphological and Mineralogical Composition

Field emission scanning electron microscopy (FESEM) technique was used to examine the morphology and microstructural properties of the laterite soil fabric. Likewise, providing information on the size, shape, and the state of orientation and aggregation of soil particles [13]. This was used in conjunction with Energy Dispersive X-Ray Spectroscopy (EDX), which is a chemical microanalysis method to determine the elements present in the sample. The FESEM and EDX sample preparation is described as follows. Dry sample was prepared and placed on aluminum stub, and to prevent charging effect as well as loss of resolution it was then covered with carbon tape and coated with platinum using a vacuum sputter. Crossbeam 340 machine was used to analyze the sample connected to a computer as shown in Fig. 1. Moreover, X-ray diffraction (XRD) technique is primarily used to identify and characterize compounds based on their diffraction pattern. SmartLab X-ray diffractometer machine was used to analyze the sample connected to a computer as shown in Fig. 2.

Fig. 1. Crossbeam 340.

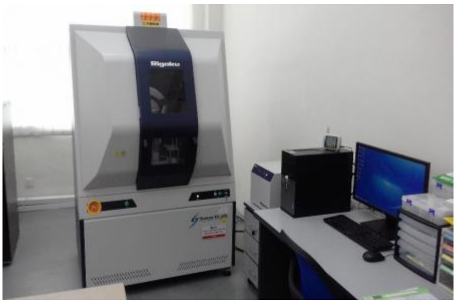


Fig. 2. SmartLab X-ray Diffractometer.

2.3 Hydraulic Conductivity

Rigid wall permeameter under falling head condition was used to measure the hydraulic conductivity as recommended by [14]. Soil samples were compacted using the BSL at 30%, 40% and 50% fines contents by varying the moulding water contents at -4%, -2%, 0%, +2% and +4% of the optimum moisture content (OMC). Then the samples were soaked for a minimum period of 48 hours until no air bubbles are obviously observed to allow for full saturation inside a water tank. Then connected to distilled water through a standpipe. Readings of time and distance covered by distilled water in the standpipe were recorded and permeability (k) calculated. Tests were repeated for different gradation at various moisture contents.

3 Results and Discussion

3.1 Index properties

British Standards (BS) [15] was followed in all the laboratory tests carried out to determine the index properties and particle size distribution of the soil as shown in Table 1 and Fig. 3 respectively. From the particle size distribution shown in Fig. 3, the natural laterite soil contains 30% fines, whereas the reconstituted laterite soils contain 40% fines and 50% fines. Furthermore, Atterberg limits results revealed a liquid limit of 76%, plastic limit of 42%, and plasticity index of 34%. Based on these data, the laterite soil is classified according to the BS as sandy silt with gravel of very high plasticity (MV). Generally, low hydraulic conductivity is attained from soils with high liquid limit [16] recommended that the liquid limit of a liner material should be ≥ 20%. Though, clay soils with too high liquid limit (LL) are more susceptible to desiccation cracking [12].

Table 1. Index properties of laterite soil.

Property	Value
Natural Moisture Content, %	34
Specific Gravity	2.7
% Passing BS 63µm sieve	30
OMC, %	30
MDD, Mg/m3	1.35
Liquid Limit, %	76
Plastic Limit, %	42
Plasticity Index, %	34
BS Classification	MV

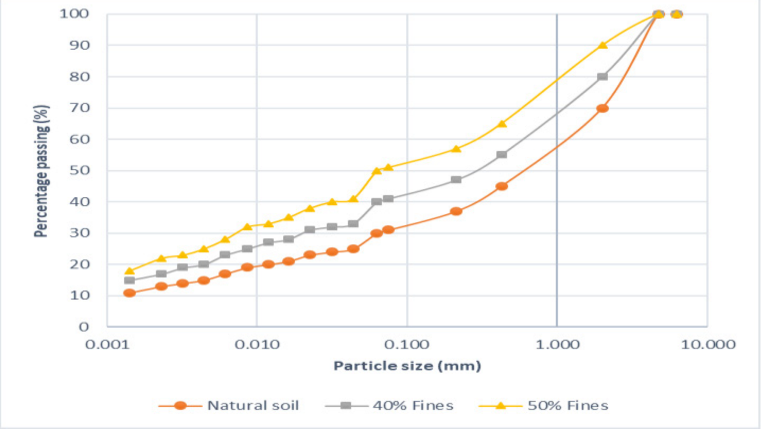


Fig. 3. Particle Size Distribution Curves.

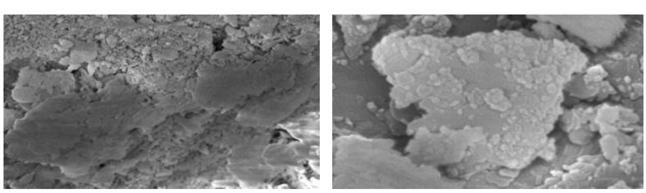
3.2 Morphological and Mineralogical Composition

FESEM technique was used to examine the morphology and microstructural properties of the laterite soil fabric. From the FESEM micrograph shown in Fig. 4 (a & b), there are presence of kaolinite flakes in the soil fabric. This was used in conjunction with EDX which is a chemical microanalysis method to determine the elements present in the sample. Moreover, EDX spectrum in Fig. 5 shows the present of element of oxygen, iron, aluminum, and silica. The oxide composition of the soil as given in Table 2 revealed the sample to be a laterite soil [17-19]. Laterite soil is whose ratio of iron oxide to aluminum oxide is less than 1.33 [20]. As shown in Fig. 4, the neatly arranged book-like kaolinite particles with free oxides present in the soil, and Kaolinitic and Halloysitic Flakes are the major feature of the natural soil in agreement with [21] and [22] respectively. According to [23] the free iron oxides in soils usually have special electrochemical properties, relatively great surface energy, and a strong ability to adsorb, and hence provide structural cementation in the soil. When free iron oxides exist in soil, there is an increase in strength, and a corresponding decrease in swelling-shrinkage capacity. It was observed that the sesquioxide ratio is 1.14 with very high concentrations of Fe_2O_3, Al_2O_3 and SiO_2 of 35.53%, 31.1 and 25.46 respectively, while CO_2 has relatively low concentrations of 7.91%.

X-ray diffraction (XRD) technique is primarily used to identify and characterize compounds based on their diffraction pattern. As a popular fundamental investigation technique, XRD is easy to use and can give a wide range of instantly interpretable data on soil minerals [13, 19]. The XRD quantitative analysis result and pattern that determined the clay mineralogy of the laterite soil was found to contain kaolinite as the major predominant mineral with some mixtures of gibbsite, goethite and cristobalite as presented in Table 3 and Fig. 6 respectively. According to [24] kaolinite clay mineral has the least affinity for water among the clay minerals will usually exhibit moderate shrinkage and swelling on drying and on wetting respectively. It is to mention that the type and quantity of clay minerals present in a soil can make a tremendous influence on the soil behavior when exposed to different environmental conditions [25]. Thus, an investigation method combining macro- and micro-analysis allows one to deeply understand the mechanical properties of clay soils [26]. The quantitative analysis of XRD in Table 3 revealed that the kaolinite clay mineral has the major portion of the laterite soil with 69.5%, 20.4% gibbsite, 6.5% cristobalite and 3.6% goethite.

Table 2. Oxide composition of laterite soil.

Property	Value (%)
SiO_2	25.46
Al_2O_3	31.10
Fe_2O_3	35.53
CO_2	7.91



(a) (b)

Fig. 4. (a) and (b) Showing Micrograph using FESEM at: 10,000 and 50,000 Magnification.

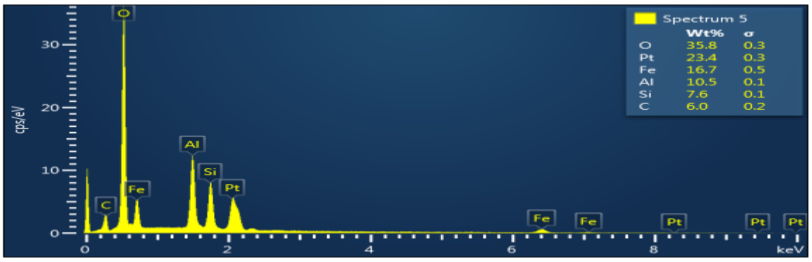


Fig. 5. EDX Spectrum.

Table 3. XRD quantitative analysis.

Property	Value (%)
Kaolinite	69.5
Gibbsite	20.4
Goethite	3.6
Cristobalite	6.5

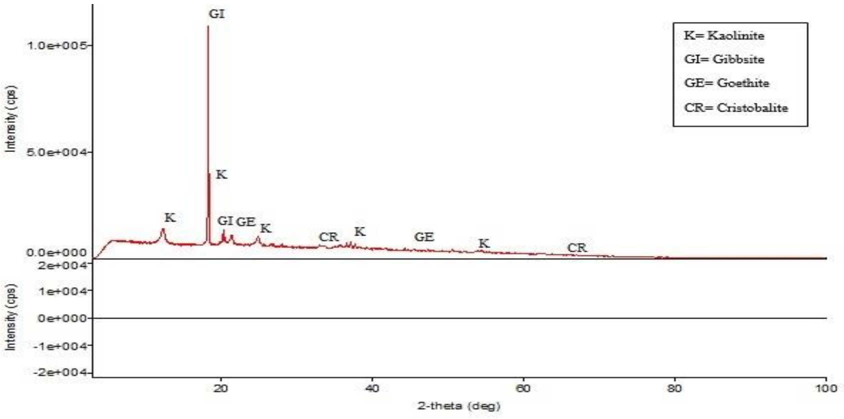


Fig. 6. XRD pattern.

3.3 Hydraulic Conductivity

The effect of fines content on low hydraulic conductivity is expected to be attained when the soil is well graded, and the clay fraction governs the hydraulic behaviour of the soil matrix [27]. The fines in a soil have a higher impermeabilizing effect if they are well distributed so they can most effectively plug voids among the larger particles. Mechanical mixing distributes fines and breaks down some of the soil aggregates thereby supplying fines for void-plugging and destroying large voids [28]. There is a general decrease in hydraulic conductivity with higher fines content as shown in Fig. 7. Hydraulic conductivity of 30%, 40% and 50% fines decreased to 2.5×10^{-6}, 3.78×10^{-8} and 2.44×10^{-9}m/s respectively on OMC. Similarly, hydraulic conductivity of 30%, 40% and 50% fines decrease to 1.55×10^{-7}, 8.13×10^{-9} and 1.02×10^{-9}m/s respectively on the wet sides of optimum. Unlike

OMC and wet of OMC, hydraulic conductivity of 30%, 40% and 50% fines decrease to 9.87x10^{-6}, 5.08x10^{-8} and 9.1x10^{-9}m/s respectively on the dry side of OMC. The hydraulic conductivity differs with about one order of magnitude with respect to fines content. The maximum regulatory hydraulic conductivity value of 10^{-9}m/s was attained at 50% fines content for the laterite soil investigated. More pronounced result at the 50% fines content is obtained on the wet side of OMC. This indicates that higher moulding moisture contents results to lower hydraulic conductivity.

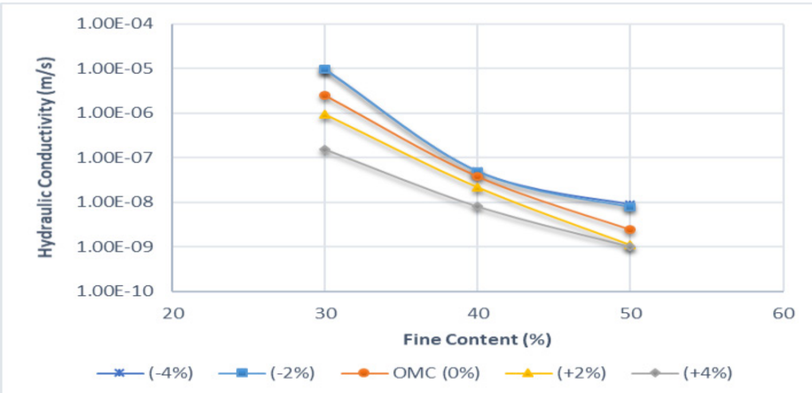


Fig. 7. Hydraulic Conductivity Versus Fines Content.

4 Conclusions

This research technically analyzed the effects of fines content and morphological features of laterite soil as liner in waste containment facilities. The spectroscopic and microscopic techniques revealed the laterite soil to contain kaolinite as the major predominant clay mineral. Hydraulic conductivity decreases with higher fines content. The permeability coefficient of the soil at 50% fines content gives the recommended value of 1×10^{-9} m/s. Percentage of fines content lower than 50% did not meet the hydraulic conductivity requirement. The studied laterite soil is suitable for use as soil liner when contains up to 50% fines content.

The authors thankfully acknowledge the monetary supports provided by the Ministry of Education (MOE) through Universiti Teknologi Malaysia (UTM) under the Fundamental Research Grant Scheme (FRGS – VOT NO 4f885).

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