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ENGINEERING CHARACTERISTICS OF COMPACTED LATERITE SOIL AS HYDRAULIC BARRIER IN WASTE CONTAINMENT APPLICATION

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Abstract

The primary objective of hydraulic barriers in containment facilities is to prevent migration of leachate directly into the underlying subsurface during both the active disposal period and the post-closure period. Liner system is, therefore, one of the most important elements of a modern sanitary landfill. In order to achieve an effective soil lining system, a minimum criterion of 30% fines content is required to fulfil the hydraulic conductivity requirement of $\leq 1 \times 10^{-9}$ m/s as specified by most regulatory agencies and researchers. Studies reveal that at this percentage, laterite soils are vulnerable to leachate permeation, which will contaminate the groundwater. Therefore, this research aims to determine the effects of gradation on engineering properties of laterite soil with respect to hydraulic conductivity, volumetric shrinkage strain, and unconfined compressive strength. In order to satisfy the regulatory requirements of soil liner, tests were carried out on natural soil (30% fines) and two reconstituted soil samples (40% fines and 50% fines). The effects of fines content that is required to provide the recommended criteria of $\leq 1 \times 10^{-9}$ m/s hydraulic conductivity, $\leq 4\%$ volumetric shrinkage and ≥ 200 kN/m^2 unconfined compressive strength at their permissible limits were plotted. The overall acceptable zone was obtained at moulding water contents ranged between 24-28% for 50% fines content. Based on the laboratory experimental results, a minimum fines content of 50% must be achieved to fulfil the engineering characteristics requirements to prevent groundwater contamination in tropical laterite soil.

Keywords: Groundwater protection, Hydraulic barrier, Hydraulic conductivity, Unconfined compressive strength, Volumetric shrinkage.

1. Introduction

The rapid increase in population and vast industrialization have resulted in a significant increase in waste generation. Waste can be defined as any material that is discarded, abandoned, or is not of any direct economic value to its owner and thus constituting environmental liability [1]. This waste is mostly disposed-off in landfills. One of the main principal sources contributing to the release of leachates in the environment is the municipal solid waste (MSW) in landfill facilities. These leachates permeate the underlying groundwater aquifer and affect the livelihood of the ecosystem [2, 3]. Currently, there are many uncontrolled landfills in many parts of the world, and these landfills often lack the necessary anti-fouling barrier systems with leachate levels very high up to 10 m or more [4]. Consequently, the linear system has been designed to prevent landfill leachate from entering the groundwater [5]. Liners and covers are widely used to line landfills and waste impoundments, to cap new waste disposal units, and to close old waste disposal sites [6].

In order to minimize the environmental pollution caused by mankind, numerous scientific studies such as storing, transformation, and annihilation of wastes are practised. However, the most economical and composed is the impermeable nature of sanitary landfills with respect to underground and surface waters for solid waste disposal [7]. Hydraulic barriers usually refer to liners and covers used in sanitary landfill play the role in preventing/impeding fluid flow and attenuating contaminants. These hydraulics barrier's structural integrity must be ensured by adopting all the necessary and adequate criteria in their construction [8].

The regulations set by each country for the minimum recommended criteria for landfill bottom liners vary. Most environmental protection agencies in developed countries like the USA, UK, and most European countries recommend hydraulic conductivity (k) values for landfill liners to $k \leq 1 \times 10^{-9}$ m/s [9-11]. Likewise, the criteria set by most researchers and regulatory agencies specified a hydraulic conductivity value of $k \leq 1 \times 10^{-9}$ m/s, a volumetric shrinkage value of $\leq 4\%$, and a value of ≥ 200 kN/m^2 shear strength for hydraulic barrier systems [12, 13].

The establishment of waste disposal sites requires the use of soils with suitable geotechnical characteristics to ensure adequate engineering design with safe conditions in place [14]. In the construction of 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 [15]. The fines content in coarse soils is carefully considered because the fines determine the composition and type of soil and affect certain soil properties such as permeability, particle friction and cohesion [16].

Compacted fine-grained soils are famous as buffer material for waste repositories due to their auspicious self-sealing abilities. The swelling potential of compacted fine-grained soils is required to fill voids and fractures, and provide low hydraulic conductivity to achieve an impermeable zone around the landfill [17]. Fine particles have been shown to control the engineering performance of lateritic soils [18]. Lateritic soil can be effective as hydraulic barrier material in waste containment systems if it contains significant quantities of fines that permits the soil in its compacted state to yield low hydraulic conductivity values [15]. However, the percentage of fines might be different between the tropical and temperate soils due to variation in climate, weathering and morphology [19].

There have been noticeable important dissimilarities between tropical soils from the more ordinary soils of moderate climates [20]. The mode of formation and mineralogical composition of parent rocks caused variation in cohesion and compressibility characteristics of tropical soils. Rock weathering in tropical areas is very rigorous that can be described by fast disintegration of feldspars as well as ferromagnesian raw materials, the displacement of bases including Na_2O, K_2O, and MgO and silica, and the absorption of aluminium and iron oxides [21]. This processes, which include leakage of silica and decomposition of iron and aluminium oxides are called lateralization [22].

There is no information in the 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 [23]. Most regulatory agencies and researchers usually specify minimum criteria of 30% fines content to be used in the design of compacted soil liners in order to achieve hydraulic conductivity requirement of 1×10^{-9} m/s and lower, whereas laterite soils contradict the minimum criteria. Literature reveals that at this percentage requirement, laterite soils are vulnerable to leachate permeation, which can contaminate the groundwater and affects the whole ecosystem. Consequently, this research determines the effects of gradation especially relating to fines content on engineering properties of laterite soil with respect to hydraulic conductivity, volumetric shrinkage, and shear strength for waste containment application systems (sanitary landfill liners and covers).

2. Material and Methods

The material used in this study is laterite soil, where its reconstitution and the methods followed in testing are presented in this section.

2.1. Natural and reconstituted soil material

The natural laterite soil sample used in this study was collected from the hilly area near the Faculty of Electrical Engineering at a depth of about 1 m under the ground. The area is located at latitude 1º33'39"N and longitude 103º38'44"E, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia.

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

- Laterite soil on its natural state with 30% fines, 40% sand and 30% gravel contents by weight of dry soil denoted as $L1$.
- Reconstituted laterite soil mixtures of 40% fines, 40% sand and 20% gravel contents by weight of dry soil denoted as $L2$.
- Reconstituted laterite soil mixtures of 50% fines, 40% sand and 10% gravel contents by weight of dry soil denoted as $L3$.

These gradations with respect to percentage fines were selected based on the following considerations: First, the higher the fines content the lower the hydraulic conductivity [15]. Likewise, laterite soils with less than 50% fines content might not be used as a liner or hydraulic barriers because their hydraulic conductivities are less than the minimum requirement of 1×10^{-9} m/s [23, 24].

Hence, reconstituted soil with fines contents less than 50% is used in this study for validation. Second, an adequate amount of sand will result in volumetric shrinkage of less than or equal to 4% and low potential for desiccation cracks [23]. Third, the percentage of gravel content should be ≤ 30% because a high amount of gravel leads to high hydraulic conductivity [13, 15].

2.2. Soil compaction method

In this study, the British Standard light (BSL) compaction equivalent to the Standard Proctor compaction in accordance with the BS1377;1990 was used as a baseline. The compaction tests were performed to obtain the relationships between the dry density and the moisture content of the soils. This test was carried out on all three different gradations, i.e., $L1$, $L2$, and $L3$.

About 2 kg of dried natural soil sample ($L1$) that passed the 4.75 mm BS test sieve was thoroughly mixed with water. Then the soil was put inside a plastic bag for at least 24 hours to allow proper distribution of moisture. The soil was then compacted in 3 equal layers, where each layer was given 27 blows of the 2.5 kg rammer falling freely through a height of 300 mm.

At the end of compaction, the extension collar was removed, and the top of the soil trimmed off by means of a straight edge. The weight of the mould and the compacted soil was determined. The compacted soil was quickly extruded from the mould and a representative sample was taken for moisture content determination.

The entire process was repeated at least four times within which, the optimum moisture content (OMC) and maximum dry density (MDD) were determined by plotting a graph of dry density versus moisture content. Similar procedures were performed on the reconstituted soils $L2$ and $L3$. The OMC value of each soil gradation would be used as the reference in preparing samples for permeability tests.

2.3. Hydraulic conductivity method

The rigid wall permeameter under falling head condition was used to measure the hydraulic conductivity for fine-grained soil samples [25]. Soil samples were compacted using the BSL at different gradations ($L1$, $L2$, and $L3$) and at different moulding water contents of -4 %, -2 %, 0 % (OMC), +2 % and +4 %.

Note that the OMC values were previously obtained from compaction tests. Then the samples were soaked for a minimum period of 48 hours until no air bubbles were obviously observed to allow for full saturation inside a water tank. Thereafter, each sample was connected to distilled water through a standpipe.

Distance covered by the distilled water in the standpipe was recorded with respect to time. This procedure was repeated at various moisture contents for $L1$, $L2$, and $L3$ and the coefficient of permeability (k) was calculated. The coefficient of permeability was calculated from Eq. (1).

$$k = 2.3\frac{aL}{At}\log_{10}\frac{h_1}{h_2} \quad (1)$$

2.4. Volumetric shrinkage method

Volumetric shrinkage is the decrease in soil volume expressed as a percentage of the initial soil volume when the moisture content is decreased from a given value to the shrinkage limit [26]. Air-dried soil at various gradations were compacted in accordance with the procedures outlined in the BS 1377: Part 4: 1990 at different moisture contents with respect to the optimum moisture content.

Then the samples were extruded out of the cylindrical mould and placed on a laboratory bench (with plastic at the bottom) at a uniformly constant temperature of 26 ± 2ºC for 30 days to dry naturally. A vernier calliper accurate to 0.05 mm was used to take daily measurements of the diameters and heights for each sample. Volumetric shrinkage strain was computed by using the average diameters and heights as expressed in Eq. (2) [27-29].

$$VSS = \frac{(V_0 - V_d)}{V_0}\, 100\% \tag{2}$$

2.5. Shear strength method

The maximum value of the compressive force per unit area, which the specimen can sustain is referred to as the unconfined compressive strength (UCS) of the soil [30]. The laterite soil samples were compacted according to the BSL procedures.

Each soil specimen with the size of 38 mm in diameter and 76 mm high was extruded from the compaction mould using steel mould of that size. The procedures for the UCS are summarized following the BS 1377: Part 7: 1990. The specimen was placed centrally on the pedestal of the UCS machine between the upper and the lower platens.

Adjustment of the axial deformation was done such that the rate of axial strain does not exceed 2% per minute of the soil specimen length. Then, compression was applied to the specimen at the selected rate and the readings of the force-measuring device and the axial deformation gauges were recorded at regular intervals.

The test was continued until the maximum value of the axial stress has been passed or the axial strain reached 20% of the soil specimen diameter. The whole specimen was removed from the apparatus. The unconfined compressive strength was computed using Eq. (3).

$$UCS = RC_r \frac{\left(1 - \left(\frac{L_1}{L_0}\right)\right)}{100\, A_0} \tag{3}$$

3. Results and Discussion

3.1. Physical properties

Results of the laboratory tests carried out to determine the physical properties and compaction characteristics of natural laterite soil are shown in Table 1. The particle size distribution curves of the natural and reconstituted laterite soils are shown in Fig. 1. The Atterberg limits results revealed a liquid limit of 76.0 %, plastic limit of 42.0 %, and a plasticity index of 34%. Based on these data, the natural laterite soil is classified as very high plasticity sandy silt with gravel (MV) according to the British Standard (BS) classification.

Table 1. Physical properties of laterite.

Property	Value
Specific gravity	2.70
% Fines	30.0
% Sand	40.0
% Gravel	30.0
OMC, %	30.0
MDD, Mg/m^3	1.35
Liquid limit, %	76.0
Plastic limit, %	42.0
Plasticity index, %	34.0
BS classification	MV

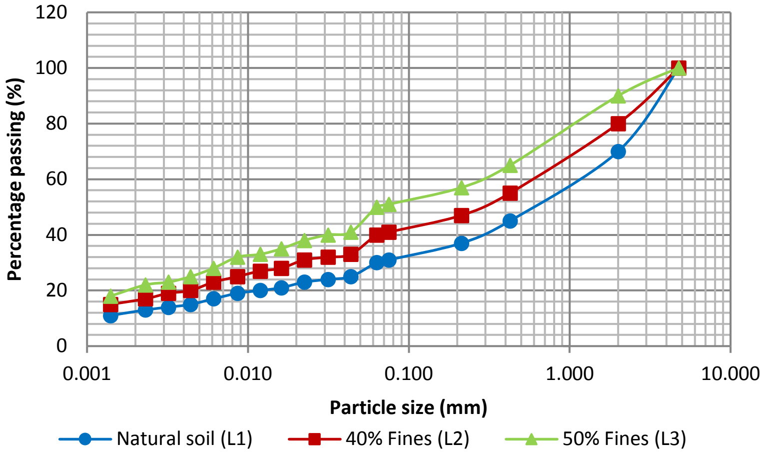

Fig. 1. Particle size distribution curves for the natural and reconstituted laterite soils.

3.2. Compaction characteristics

The effect of gradation on MDD and OMC of the laterite soil mixtures is shown in Fig. 2. The MDD generally increased with increasing fines content. This could be due to the fines filling the voids of the soil mixture.

As the air voids are squeezed out under the load of the rammer, the finer particles of the soil replaced the air and became denser. On mixing with 30%, 40% and 50% fines content at OMC, the values of the MDD increased to 1.35, 1.42 and 1.43 Mg/m^3, respectively.

This is consistent with Guerrero [31], who demonstrated that the addition of fine content produced an increment in the maximum dry density in all of the four different types of soils experimented. On the other hand, the OMC decreased with increasing fines content.

The OMC reduced to 30%, 29% and 28% for *L*1, *L*2 and *L*3, respectively, probably due to the soil-water interaction. According to Head [32], there are five categories of water on and surrounding the soil:

- Water of hydration within the crystal structure that is chemically bonded to the soil.
- Adsorbed water is held by powerful electrical forces of attraction, which normally cannot be removed by oven drying at 110º.
- Hygroscopic water, which can be removed by oven drying, but not by air drying.
- Capillary water is held by surface tension and generally removable by air drying.
- Gravitational water can flow under its own weight.

The water of hydration adsorbed and hygroscopic water that cannot be removed by air drying could be responsible for the lower moisture contents with increasing fines content. Since fines have larger surface area than coarse soil, the amount of water already stored by the fines is higher, and the fines will automatically require less water to attain the OMC, as the laterite soil used in this research was air-dried.

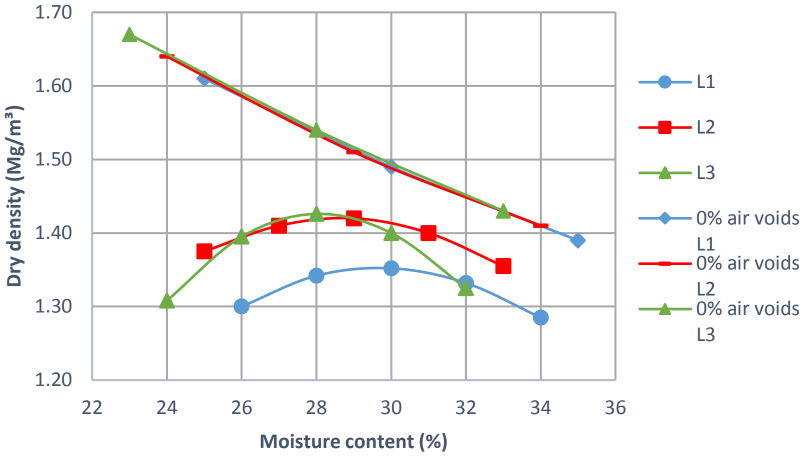

Fig. 2. Dry density of natural and reconstituted laterite soils versus moisture content.

3.3. Hydraulic conductivity

The influence of hydraulic conductivity is explained with respect to the effects of moulding water content. There is a general decrease in hydraulic conductivity with increase in moulding water content regardless of the soil gradations as shown in Fig. 3. The hydraulic conductivity at the OMC decreased from 2.5×10^{-6} to 2.44×10^{-9}m/s with 30% to 50% fines, respectively. Similarly, on the wet side of the OMC the hydraulic conductivity value decreased from 1.55×10^{-7} to 1.02×10^{-9}m/s with 30 % to 50 %, fines respectively.

The decrease in the hydraulic conductivity is attributed to the larger degree of dispersion in the soil structure with higher moisture content due to expansion of double layer and an increased inter-particles repulsion, which permits the particles to slide more easily past one another into a more oriented state of packing together.

According to Holtz et al. [33], at the same compactive effort, as the water content increases, the soil fabric becomes increasingly oriented. Fine-grained soils at dry of optimum are always flocculated, whereas at wet of optimum are more oriented or dispersed. Thus, on the wet side of the OMC, the hydraulic conductivity decreases more because of the adsorbed water surrounding the fine-grained soil particles is not free to move, and reduces the effective pore space available for the passage of water [34].

Results show that the reconstituted laterite soil with 50 % fines content (*L*3) used in this study attained within the range of maximum regulatory hydraulic conductivity value of 1×10^{-9} m/s.

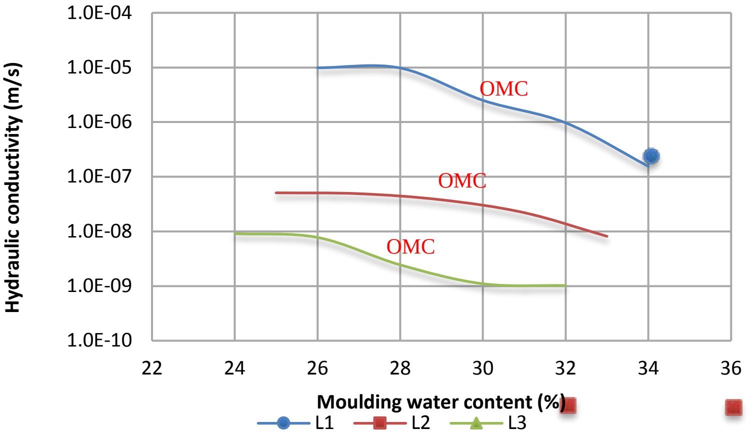

Fig. 3. Variation of hydraulic conductivity of natural and reconstituted laterite soils with moulding water content.

3.4. Volumetric shrinkage

The influence of volumetric shrinkage of compacted laterite soil is explained with respect to the effects of moulding water content. The graphical representation in Fig. 4 indicates that volumetric shrinkage strain (VSS) increases with higher moulding water content, and this research observation is consistent with the results of [29, 35, 36].

Compacted soil specimens at higher moulding water content shrink more when dry because drying shrinkage in fine-grained soils depends on particle movement due to pore water tension developed by capillary menisci [27, 29, 36]. When saturated soil is allowed to dry, a meniscus develops in each void at the soil surface. Formation of such a meniscus causes tension in the soil-water leading to a compression in the soil structure and consequent reduction in the volume. The tension in material with small pores is very large, owing to the capillary pressure essentially pulling the particles together.

The smaller the meniscus, the larger the capillary tension and the larger the intergranular contact stress between the particles [33]. Equally, volumetric shrinkage is proportional to the volume of water leaving the pore spaces of compacted soil samples [37]. Thus, *L*1, *L*2 and *L*3 samples compacted at higher moulding water contents (wet of optimum) have more water in their void spaces, which lead to higher shrinkage on drying [38]. The variation in volumetric shrinkage strain at different moulding water contents is shown in Fig. 4.

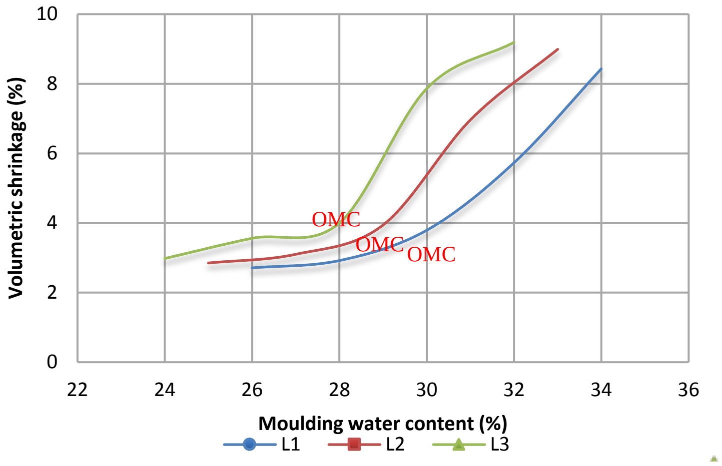

Fig. 4. Volumetric shrinkage versus moulding water content.

3.5. Unconfined compressive strength

The influence of unconfined compressive strength of compacted laterite soil is explained with respect to the effects of moulding water content. The unconfined compressive strength (UCS) of compacted soil depends on the moisture content as well as the density [39]. The variation of UCS values with moulding water content is shown in Fig. 5.

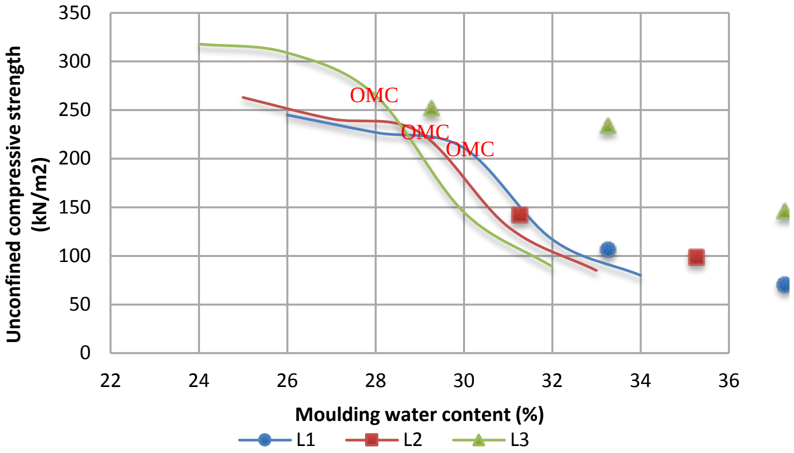

Fig. 5. Variation of unconfined compressive strength with moulding water content.

In agreement based on findings of Osinubi et al. [40] and Amadi et al. [41], the UCS values decreased with increased in moulding water content. Such phenomena regardless of the soil gradation took place because the soil fabrics were increasingly lubricated thus leading to a reduction in the shearing resistance due to loss in cohesion between soil particles [42]. Another reason could be due to the plastic nature of the laterite soil used. According to Daniel [13], one should be cautious about using highly plastic soils (soils with plasticity indices > 30 - 40%) because these materials are very sticky when the soil is wet. Additionally, soils with high plasticity index when in contact with water can cause a reduction in strength of compacted soil liners due to ductility [43]. The ductility of compacted soil liner increases and the strength decreases alongside the increase in water content. For instance, the percentage of strain at failure for the natural laterite soil compacted at -4%, -2%, OMC, +2% and +4% water contents were 3.91%, 5.44%, 7.56%, 10.04% and 11.13%, respectively.

Based on study by Husin et al. [44], six different sedimentary soils revealed that 5% addition of moisture content can cause decrease (loss) in shear strength up to 75% compared to its optimum moisture content, and up to 145% increase (gain) in shear strength with 5% decrease in moisture content relative to optimum. The lubricating occurs when the surface of the clay particles is wetted, causing the mobility of the absorbing film to increase.

Furthermore, a decrease in water content results in a decrease in the radius of a meniscus, which in turn results in an increase of contact pressure and decrease in the void ratio of the soil with a corresponding increase in shear strength [26]. Thus, $L3$ with higher fines content yielded higher UCS values on the dry side of the OMC than $L1$ and $L2$ because the soil fabrics are a stack more closely together with stronger bonding as a result in a decrease in the radius of the meniscus.

3.6. Acceptable zones

A critical step in the design of a compacted soil liner is the determination of the range of acceptable water content and dry unit weight of the soil. In contemporary geoenvironmental practice, soil barriers are compacted within this definite range of water content and dry unit weight. This requirement is principally needed to attain a minimum dry unit weight for factors controlling the performance of compacted soil liners especially the hydraulic conductivity [45]. An acceptable zone is obtained by relating the dry density with moulding water content for each of the three design parameters at their permissible limits, i.e., $k \leq 1 \times 10^{-9}$ m/s, VSS $\leq$ 4%, and UCS $\geq$ 200 kN/m^2. The compaction plane was reached by using the average density values from k, UCS and VSS test specimens [42, 46].

Table 2 presents the acceptable ranges of moulding water contents at various fines contents for $L1$, $L2$, and $L3$. Samples $L1$ and $L2$ failed to meet the hydraulic conductivity requirement but met the shear strength and volumetric shrinkage requirements. Therefore, $L1$ and $L2$ are not fit to be used as hydraulic barriers. Only samples of $L3$ satisfy the k, VSS and UCS acceptable ranges of moulding water contents. Figures 6 to 8 show acceptable zones of $L3$ for hydraulic conductivity, shear strength, and volumetric shrinkage respectively. The hatched zones indicate portions on the compaction plane showing the limits based on different criteria for the acceptable zones. Furthermore, after an acceptable zone was defined for each of the three design parameters, they are superimposition to obtain the overall acceptable zone as shown in Fig. 9. The overall acceptable zone was achieved at moulding water contents ranged between 24-28% and dry densities ranged between 1.31-1.43 Mg/m^3.

Soils with inadequate fines typically have too little silt- and clay-sized material to produce suitably low hydraulic conductivity [47]. Data from Benson et al. [48], suggest that a minimum of 50% fines might be an appropriate requirement for many soils. According to Daniel and Koerner [47], field inspectors should check the soil to make sure the percentage of fines meets or exceeds the minimum stated in the construction specifications and should be particularly watchful for soils with less than 50% fines.

Table 2. Acceptable ranges of moulding water contents.

Engineering criteria	**Fines content (%)**		
	30 (*L*1)	40 (*L*2)	50 (*L*3)
	Moulding water content range (%)		
***K* (m/s)**	-	-	24 - 32
***VSS* (%)**	26 - 30	25 - 29	24 - 28
***UCS* (kN/m^2)**	26 - 30	25 - 29	24 - 28
OAR			24 - 28

OAR – Overall Acceptable Range

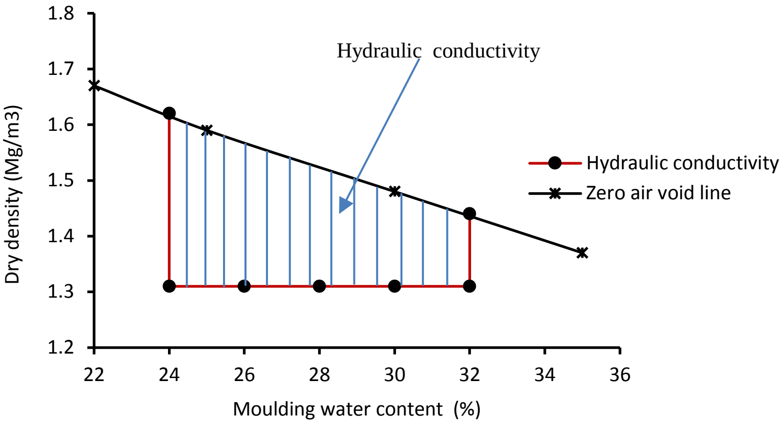

Fig. 6. Acceptable zone for hydraulic conductivity at 50% fines content (*L*3).

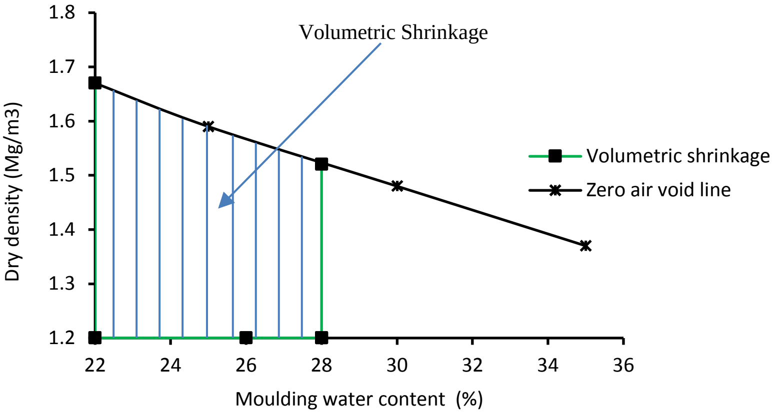

Fig. 7. Acceptable zone for volumetric shrinkage at 50% fines content (*L*3).

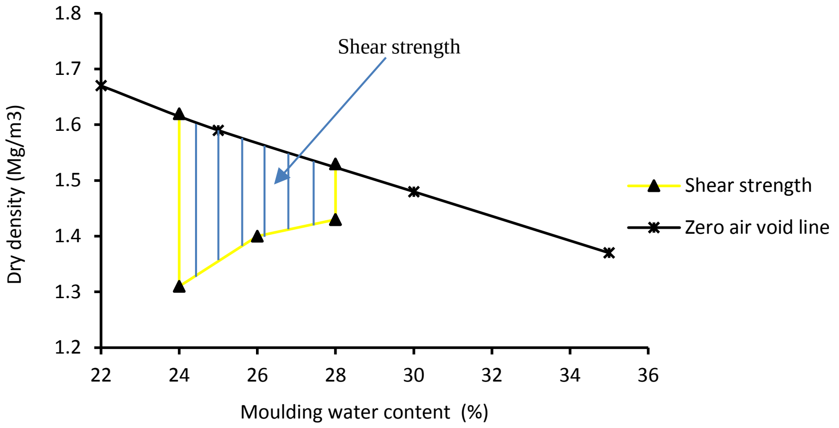

Fig. 8. Acceptable zone for shear strength at 50% fines content (*L*3).

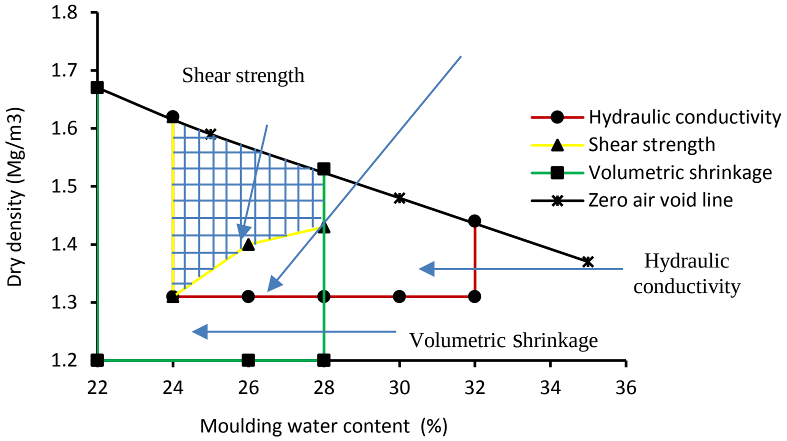

Fig. 9. Overall acceptable zone at 50% fines content (*L*3).

4. Conclusions

Laboratory tests were carried out on laterite soil to assess its suitability at different gradations with respect to fines content for use as liners and covers in waste containment systems. Specimens were prepared at moulding water contents -4, -2, 0, +2 and +4% of the optimum moisture content. The laterite soil was classified as very high plasticity sandy silt with gravel (MV) according to British Standard (BS) classification. Generally, OMC and MDD decreased and increased respectively, with higher fines content. The effects of fines content that is required to provide the recommended engineering criteria of ≤ 1 × 10^{-9} m/s hydraulic conductivity, ≤ 4% volumetric shrinkage and ≥ 200 kN/m^2 unconfined compressive strength at their permissible limits were plotted. Thus, the overall acceptable zone was obtained, which shows that laterite soil with 50% fines content (*L*3) should be prepared at moulding water contents in the range of 24-28% and dry densities ranged between

1.31-1.43 Mg/m^3. Also, the laterite soil should be compacted according to BSL method so as to be effectively used as a hydraulic barrier. Therefore, an investigation is strongly recommended for laterite soils having fines content lower than 50% before using them in waste containment applications because they might not provide the required engineering characteristics.

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Nomenclatures

A	Cross-sectional area of sample, m^2
A_0	Initial cross-sectional area, m^2
a	Area of the standpipe, m^2
C_r	Calibration of load ring
h_1	Initial height of water in standpipe, m
h_2	Final height of water in standpipe, m
k	Coefficient of permeability, m/s
L	Length of sample, m
L_0	Initial length of specimen, m
L_1	Final length of specimen, m
MDD	Maximum dry density, Mg/m^3
OMC	Optimum moisture content, %
R	Load ring reading, kN
t	Time required to get head drop, s
UCS	Unconfined compressive strength, kN/m^2
V_0	Volume of wet sample, m^3
V_d	Volume of dry sample, m^3
VSS	Volumetric shrinkage strain, %

Abbreviations

BSL	British Standard Light
OAR	Overall Acceptable Zone

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