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USING SOIL WATER CHARACTERISTIC CURVE IN COMPUTING UNSATURATED HYDRAULIC CONDUCTIVITY OF COMPACTED TROPICAL SOIL

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ABSTRACT

Contaminants flow through compacted soil liners and coversare usually considered under saturated conditions during design stage. Whereas, the compacted soil barriers in reality are neither completely saturated nor completely dry, rather they are in an unsaturated state. Thus, unsaturated flow principles need to be properly simulated to determine the contaminant flow through compacted soil barriers in order to protect groundwater. Soil water characteristic curve (SWCC) which is the relationship between soil suction and water content is the main modeling parameter of unsaturated soil. This paper evaluates the SWCC data of a tropical laterite soil used as a liner material in sanitary landfill. The effect of gradation with respect to fines content on the dry of optimum, optimum and wet of optimum moisture contents on SWCC were investigated. Laboratory tests using pressure plate apparatus were conducted to determine the variation of volumetric water content with soil suction for a pressure range of 1 kPa to 1000 kPa. The experimental SWCC data were fit to the Brooks and Corey parametric equation to compute the unsaturated hydraulic conductivity. Based on the SWCC data, greater air entry suctions were obtained for specimens with higher fines contents when compacted wet of optimum moisture content and the water retention capacity increased with increase in fines content. Using the SWCC, the unsaturated hydraulic conductivities of the soil liner used in simulating leachate migration were computed.

Keywords: groundwater, sanitary landfill, tropical soil, soil water characteristic curve, unsaturated hydraulic conductivity.

1. INTRODUCTION

Preventing groundwater contamination from the most common method of solid waste disposal technique i.e. landfilling is by proving hydraulic barriers. These hydraulic barriers which are referred to as liners and covers in sanitary landfills helps in impeding contaminants migration. Thereby, securing the health of the living things and the environment around them. Designing hydraulic barriers in the laboratory involves assumption that the soil is in saturated state, while actually they are in unsaturated conditions (Amadi and Osinubi, 2016).

The general requirement guidelines for designing and siting solid waste landfills that it should be above water table i.e. unsaturated zones (Johnson *et al.*, 1981). Movement of water above water table usually occurs in the unsaturated state. The soil water exists under tension by capillary forces at less than atmospheric pressures. Soil physicists, agricultural engineers, and others have extensively studied the physics of unsaturated flow. Recently, the idea of unsaturated flow has become increasingly important to geoenvironmental engineers and hydrogeologists, especially regarding studies of the impact of waste disposal on groundwater (Johnson *et al.*, 1981).

Hydraulic barriers are exposed to different environmental conditions. The cover systems in contrast to the liner systems are exposed to unsaturated environmental condition where stresses are low and interaction with the atmosphere happens continuously (Benson, 2001). The hydrology of compacted soil covers should be proper evaluated based on the unsaturated hydraulic conductivity of the soil since in reality they are unsaturated in compacted state (Osinubi and Eberemu, 2010; Miller *et al.*, 2003).

Beside the occurrences of natural soil in unsaturated conditions, compacted soils are commonly found in an unsaturated conditions as well (Hezmi *et al.*, 2015). The common problems encountered in unsaturated compacted soils include heaving, deformation, low bearing capacity, and slope instability. Most of these problems are involve with mechanical characteristics and water retention characteristics. The water retention is ability of soil to store water which could be link to soil suction. Soil suction and water content are among the controlling parameters in geotechnical properties of soil involving shear strength, permeability and volume change (Hezmi *et al.*, 2015).

In numerical analysis associated with unsaturated zone in geotechnical and geoenvironmental problems, the importance of unsaturated soil properties is well recognized. To attain success in any numerical simulations of unsaturated hydraulic properties, there has to be a dependable and reliable input data in the soil-water characteristic curve. This SWCC defines the relationship between volumetric water content and matric suction (Phoon *et al.*, 2010). The ability or capacity of soil to store water and as well release the water when subjected to different suction is referred to as soil water characteristic curve. It plays a vital role in estimating and interpreting unsaturated soil property functions (Li *et al.*, 2014; Osinubi and Amadi, 2010). The matric suction in unsaturated soil mechanics it is most notably defined as the difference between the pore air pressure and pore water pressure (Mahmood and Kareem, 2010).

For modeling and other numerical purposes, it is often convenient to provide the water retention characteristics in functional form, in which equation is selected amongst the numerous mathematical equations commonly used to describe the water retention characteristics (Amadi and Osinubi, 2016). Several models have been used to describe the SWCC, commonly used models include Leong and Rahardjo (1997), *Fredlund et al*. (1994), Van Genuchten (1980) and Brooks and Corey (1964). The two most commonly models are the Brooks-Corey (BC) equation and van Genuchten (VG) equation (Moses, 2012; Eberemu, 2008). For the purpose of this work, the Brooks and Corey (1964)in Equation 1 for water retention was adopted to describe the unsaturated behaviour of the tested soil.

$$\Theta = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \left(\frac{\psi_a}{\psi}\right)^{\lambda} \tag{1}$$

Where, Θ is a normalized, dimensionless volumetric water content; θ , θ_r and θ_s are the water content, residual water content and saturated water content, respectively; ψ_a and λ are the air entry value and pore size distribution index respectively.

Water retention is defined as the soil water content at a given soil suction. Soil water at free energy state measured in terms of partial vapor pressure generally referred to as soil suction(Fredlund and Rahardjo, 1993). A water retention function is computed when the soil suctions are varied and the corresponding changes in soil water content are recorded. According to Fredlund (2002) and Jim (2001), soil water content is expressed on gravimetric or volumetric basis. Gravimetric water content (θ_g) is the mass of water (m_w) per mass of dry soil (m_s) expressed in Equation 2:

$$\theta_g = \frac{m_w}{m_s} \tag{2}$$

The water content obtained from the pressure plate test is the gravimetric water content. Then is converted to volumetric water content using Equation 3. Volumetric water content (θ_v) is the volume of water per volume of soil. Volume is the ratio of mass to density (ρ).

$$\theta_v = \frac{v_w}{v_s} = \frac{\theta_g * \rho_s}{\rho_w} \tag{3}$$

In order to understand the unsaturated behavioral characteristics of soils, the soil water characteristic curve (i.e. matric suction versus water content) plays a vital role (Osinubi and Amadi, 2010). In this paper, laterite soil was reconstituted to find the effect of fines content on the SWCC and to compute the unsaturated hydraulic conductivities. Three different gradations are investigated as each gradation will portray a different characteristic. As each soil has a unique chemical composition and pore-size distribution, the energy equilibrium conditions or the relation between water content and matric suction is unique (Lu, 2016). Therefore, accurate calculation of the SWCC is important for better prediction of performance (Miller *et al.*, 2003).

2. MATERIAL AND METHOD

2.1 Material

A red laterite soil with kaolinite as the dominant clay mineral was collected at a depth between 1m to 1.5m from a borrow pit in Universiti Teknologi Malaysia. It was reconstituted into three different gradations to investigate the effect of fines content on the SWCCs. The fines contents examined are 30%, 40%, and 50% denoted as L1, L2, and L3 respectively.

2.2 Method

2.2.1 Specimen preparation

L1, L2, and L3 specimens were prepared at moulding water contents relative to optimum i.e. 2% dry of optimum water content, optimum water content and 2% wet of optimum water content. The specimens were then compacted inside a mould using the British Standard light (BSL) compaction energy. The soil samples to be tested were subsequently cored from the compacted soil using a stainless-steel ring of dimension 50 mm and 20 mm with respect to diameter and height respectively. These cored samples were soaked for saturation and then subjected to pressure plate drying test. Measurements were made in triplicates for each sample and the average value is computed.

2.2.2 Pressure plate test

Using pressure plate apparatus, procedures were followed in accordance with ASTM-D3152-72 (1994) in determination of the soil water characteristic curve. The water-holding characteristics of the soil samples are determined using the pressure extractors. The water contents against matric suction pressures relationship are determined for the soil samples by evaluating the sample at different pressures. The determination described here is based on desorption procedure that used suction from 1, 10, 30, 100, 300, 500, 800 to 1000 kPa. To induce matric suction in the saturated soil specimens placed inside the pressure plate cell, pressure was applied to a predetermined value. The test continues until when the outflow stopped, indicating that specimens were in equilibrium with the applied matric suction. Thereafter, the specimens are removed from the pressure plate cell and the volumetric water contents evaluated. Thisin order to develop a soil water characteristic curve, the soil specimens were subjected to different pressures by repeating the procedure.

3. RESULTS AND DISCUSSIONS

3.1 Physical properties

The physical properties of laterite soil determined by standard laboratory procedures as prescribed in BSI (1990) are presented in Table-1.

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Table-1. Physical properties of tropical laterite soil.

Property	Value
Colour	Red
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

3.2 Soil water characteristic curves

The measured SWCC data were fitted with Brooks and Corey (BC) functions defined by equation (1). Figures 1, 2 and 3 show fitted curves for the various gradations prepared dry, wet and at optimum moisture content using BSL compactive effort.

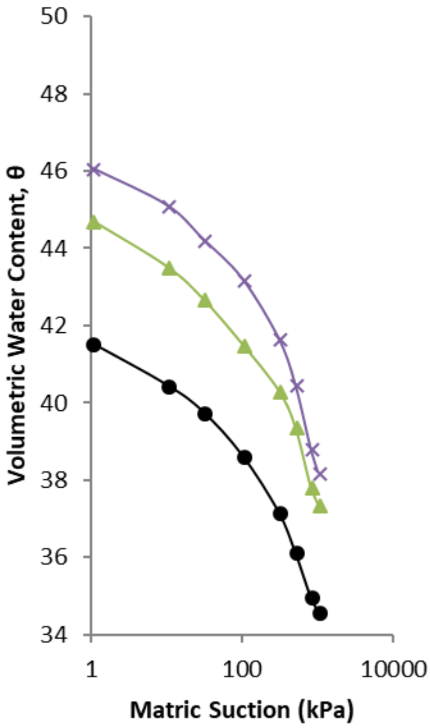

Figure-1. Fitted SWCCs based on BC functions for specimens compacted dry of optimum moisture content.

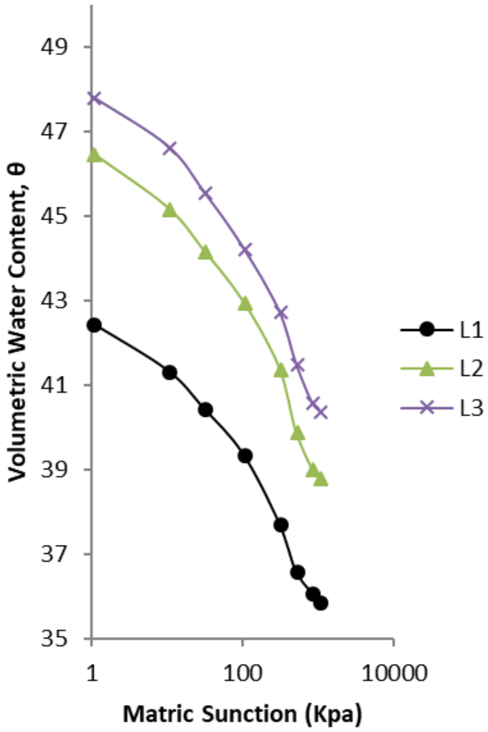

Figure-2. Fitted SWCCs based on BC functions for specimens compacted at optimum moisture content.

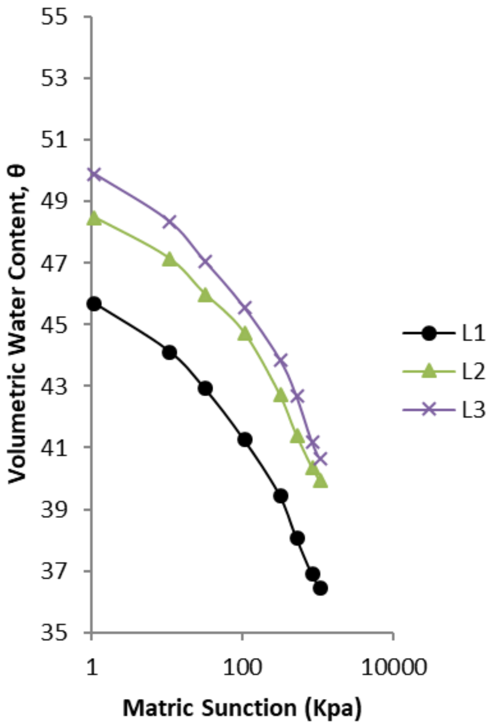

Figure-3. Fitted SWCCs based on BC functions for specimens compacted wet of optimum moisture content.

In the three gradations of compacted specimens, an observed trend is that the SWCCs plot in order of increasing fines content with specimens having higher fines content being above those with lower fines content.

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It was observed as the fines particle contents in the soil increase, the rate of de-saturation decreases. Generally, the volumetric water content increased with higher fines content. This was expected since the increase in fines increase the plasticity of the mixtures and therefore more water was retained at any given matric suction (Osinubi and Amadi, 2010). According to Miller et al. (2003), suction is inversely proportional to the water content in a soil. As the soil desaturates the suction normally increase. The increase in suction result in a typically high resistance to flow and increases in effective stress. The increase effective stress can cause desiccation cracking in the soil.
The size and spacing of soil particles determines the quantity of water that flows into the soil. According to Azmi et al. (2016), large pores in the soil increase the water infiltration. In coarse-grained soils, water moves easily into larger pores and the infiltration rate is higher than fine soils. On the other hand, fine-grained soils have larger surface area than coarse-grained soils which allow them to hold more water.

The principles of water retention in soils as it varies with suction was described by Amadi and Osinubi (2016); At very low suctions, it depends primarily on capillary surface tension effects, and hence on the pore size distribution and soil structure. At higher suction (lower moisture contents); water retention is increasingly due to adsorption which is influenced more by the texture and the specific surface of the material. Due to the greater number of fine pores and the larger adsorption, the laterite soil gradation containing higher fines (i.e. L3) typically have greater amount of water retained at a given matric suction than gradations with lower fines (i.e. L1 and L2). Similar results were observed by researchers such as Taha and Taha (2016), Amadi and Osinubi (2016) and Osinubi and Amadi (2010). Hence, for the range of fines contents used in this study, the SWCC of L3 specimens has greater ability to store water.

As stated by Kasim *et al.* (1999), most of residual soils have low air-entry value and therefore the soils have low suction values. As the suction value increases, the coefficient of permeability decreases. It is possible for a single soil to has a coefficient of permeability that ranges over 5 orders of magnitude when the suction value increases from 0 kPa to 100 kPa (Kasim et al., 1999). The soil water characteristic curve presents relationship between water content and pore water suction that describes one of the fundamental relationships of unsaturated behavior of soils (Aldaood *et al.*, 2013).

3.3 Unsaturated hydraulic conductivity

Due to natural variability in the field, it is quite difficult to get the measurement of unsaturated hydraulic conductivity; likewise, it is very expensive and time-consuming procedure. It is therefore mostly computed using models based on the SWCC parameters and the saturated hydraulic conductivity (Kasim *et al.*, 1999). The unsaturated hydraulic conductivity at any given soil suction (k_u) is the product of saturated hydraulic conductivity (k_s) and the relative hydraulic conductivity (k_r) given as (Moses, 2012; Eberemu, 2008; Fredlund et al., 1994):

$$k_r = \frac{k_u}{k_s} \tag{4}$$

$$k_r = \left(\frac{\psi}{\psi_a}\right)^{-\lambda} \quad \text{for} \quad \psi \geq \psi_a$$

$$k_r = 1 \quad \text{for} \quad \psi \leq \psi_a$$

Where ψ is the suction, ψ_a is the air entry value and λ is the empirical parameter representing the pore size distribution index. Fitting those parameters into BC equation, the unsaturated hydraulic conductivities were computed. The unsaturated hydraulic conductivity versus the fines content at different moisture contents is presented in Figure-4.

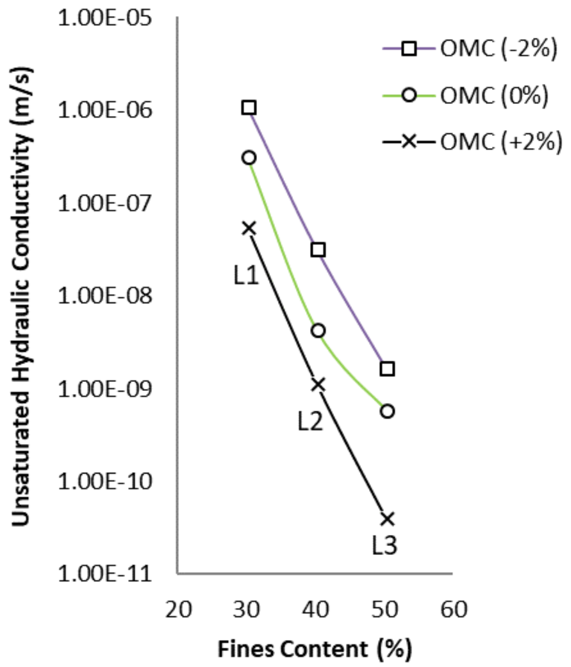

Figure-4. Unsaturated hydraulic conductivity versus fines content at dry of optimum, optimum, and wet of optimum moisture contents.

The unsaturated hydraulic conductivities at different fines content 30% (L1), 40% (L2) and 50% (L3) at dry of OMC are 1.13 x 10^{-6} m/s, 3.25 x 10^{-7} m/s, and 5.70 x 10^{-8} m/s; at OMC are 1.13 x 10^{-8} m/s, 4.50 x 10^{-9} m/s, and 1.01 x 10^{-9} m/s; at wet of OMC are 1.72 x 10^{-9} m/s, 6.15 x 10^{-10} m/s, and 4.23 x 10^{-11} m/s respectively. Unsaturated hydraulic conductivity decreases with increasing fines content, as well as with corresponding increase in moisture content. As the suction value increases, the coefficient of permeability decreases. The increase in fine particles content increases the water content of samples possibly due to greater adsorption of water by fine particles (Taha and Taha, 2016). Likewise, increase in soil density reduces the gravimetric water content in soil samples (Taha and Taha, 2016). Thus, due to the higher fines content in L3, the fines can fill the microvoids leading to increase in soil density which in turn leads to lower gravimetric water content. The results of this study revealed that the retention capacity increased with increase in fines content, similar to predictions made by other researchers (Amadi and Osinubi, 2016; Osinubi and Amadi, 2010; Kasim et al., 1999).

4. CONCLUSIONS

A tropical laterite soil at different fines content denoted as L1, L2 and L3 by dry weight of soil were prepared at different moisture contents i.e. dry (-2%), optimum (OMC) and wet (+2%) moisture contents and compacted using BSL. Specimens with higher fines content recorded higher air entry suction values on the wet side of optimum moisture contents than those with lower fines content based on the SWCC data. The measured SWCC of the specimens were fitted into Brooks and Corey function and the unsaturated hydraulic conductivities of the three different gradations of the soil were calculated. The gradation for L3 (with 50% fines) provides the best material to be used in the design of soil liner in sanitary landfill as it possesses the lowest unsaturated hydraulic conductivity of 4.23 x 10^{-11} m/s. The results of the study show that accurate values of the SWCCs for the various laterite soil gradations used as hydraulic barriers are essential in determining their unsaturated hydraulic conductivity properties which are employed in simulating leachate migration. Therefore, the study provides an understanding on the effects of varying soil gradation with respect to fines content on SWCC that can in turn be use in choosing a suitable grading material for geotechnical works.

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