Unsaturated hydraulic conductivity of compacted bio-cemented lateritic soil in municipal solid waste containment application

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Abstract. Most engineering infrastructures, including municipal solid waste containment facilities, are situated in unsaturated zone. The use of chemical additives for soil improvement has been linked to the adverse environmental issues being experienced globally. Research into more sustainable methods of soil improvement has led to the discovery of a novel and innovative method known as microbial induced calcite precipitation (MICP). Lateritic soil was treated with stepped Sporosarcina *pasteurii* (S. *pasteurii*) suspension density up to 2.40 x 10^9 cells/ml at moulding water content (MWC) -2, 0 and +2 % relative to optimum moisture content (OMC) before compaction using Reduced British Standard light (RBSL), British Standard light (BSL), West African Standard (WAS) or *Intermediate* and British Standard heavy (BSH) energies. Compacted specimens were saturated with cementation reagent in three cycles with $1/3^{rd}$ pore volume at 6 hours' interval to induce calcite precipitation at an ambient laboratory temperature of 24 ± 2^oC. The soil-water characteristics curves (SWCC) of the specimens were determined using pressure plate extractor over a pressure range of 10-1500 kPa. Unsaturated hydraulic conductivity values were predicted for the S. *pasteurii* suspension densities considered using Brooks-Corey, van Genuchten as well as Fredlund and Xing curve fitting prediction models. Results show that the unsaturated hydraulic conductivity values of specimens prepared at lower, MWC relative to OMC were generally higher than at higher MWC regardless of compactive efforts and S. *pasteurii* suspension densities considered. The Brooks-Corey model gave the best predicted unsaturated hydraulic conductivity values which fit the requirements for waste containment facilities over the matric suction range and *S. pasteurii* suspension densities considered, than the van Genuchten and Fredlund – Xing, when compared with measured values.

Keywords : Lateritic soil, Pore volume, Sporosarcina *pasteurii*. Suspension density, Unsaturated soils.

1 Introduction

Geotechnical engineering technology and practice as reported in the literature was developed in the temperate climate where the soils are mostly saturated. Therefore, it was much easier and fruitful to direct a substantial research interest towards problems involving saturated soils with positive pore-water pressure (Fredlund and Rahardjo, 1993b) [1]. The assumptions made in the design of liners and waste containment facilities is that throughout the lifespan of the facility, it will remain saturated. However, during the inactive (closure) stage the soil is not totally saturated because most, if not all, engineering facilities are located within the unsaturated zones (known as the vadose zone) of the soil.

The study of unsaturated soils is an essential tool for the analysis of soil behaviour because the soils used in engineering construction are unsaturated (Fredlund and Rahardjo, 1993a) [2]. Although unsaturated soil has received much attention of researchers in the field of geotechnical engineering, the use or application of unsaturated soil mechanics is not only inexhaustible but still lags behind up-to-date knowledge (Chin *et al*., 2010) [3]. According to Tao *et al*. (2017) [4], more than 60% of the countries of the world are suffering the engineering harm brought about by unsaturated soils, as such the study of unsaturated soil behavior targeted for engineering use is not only of theoretically significance but also of practical importance. In the studies of unsaturated soil, much emphasis was placed on the flow of water in the soil, however, the constitutive equations developed which have become generally accepted in geotechnical engineering consist of the following : volume change, shear strength, as well as flow in the unsaturated soil (Fredlund and Rahardjo, 1993a) [2]. Some of the key difficulties that exist in the measurement of the properties of unsaturated soils include unsaturated soil laboratory tests being time-consuming and expensive, problems linked with the measurement of negative pore-water pressure *in situ* in unsaturated soil, the training of technical personnel to handle the test, etc. (Phoon *et al.*, 2008 ; 2010 [5-6] ; Mahmood and Kareem, 2010 [7] and Wang *et al.* 2015) [8].

The use of chemical additives as a conventional method of soil improvement has been a common practice for over a century. However, the use of these chemicals, except sodium silicate, has been questioned because of the negative environmental issues associated with them. Research into more sustainable methods of soil improvement has brought about the discovery of a new technique called Microbial Induced Calcite Precipitation (MICP). The aim of this study was the enhancement of the engineering properties of a deficient lateritic soil to be used in waste containment facilities using MICP approach. The targeted objectives include the

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determination of the soil - water characteristic curves (SWCCs) of lateritic soil treated with different *S. pasteurii* suspension densities, moulding water content and compactive efforts. Also, Brooks-Corey (1964) [9], van Genuchten (1980) [10] and Fredlund and Xing (1994) [11] curve fitting models were used to predict volumetric water content and unsaturated hydraulic conductivity of the treated soil in relation to the measured laboratory values.

1.1 Soil-Water Characteristics Curve

Soil-water characteristics curve (SWCC) was originally developed in the agriculture science. It is a plot that is used for the determination of the soil to store water at varied suction pressures (Mahmood and Kareem, 2010) [7]. Osinubi and Amadi (2010) [12], reported that SWCC is a plot that demonstrate the ability of soil to hold or release water when subjected to varying suction pressure. It also represents the association existing between soil water content at different suction pressure (Elkady *et al.*, 2017) [13]. SWCC has played an important role in the use of unsaturated soil mechanics in geotechnical engineering practice ; Zapata *et al.*, (2000) [14]. The curve is one of the earliest indirect methods used in the study of unsaturated soil that has shown some level of success because it is possible to approximate most unsaturated soil properties from saturated soil parameters and the SWCC (Fredlund and Rahadjo, 1993b; Chin *et al.*, 2010; Braudeau *et al.* 2014 ; Rahimi *et al.* 2015; Alsherif *et al.* 2015 and Li *et al.* 2017) [1;3 ;15 ;16 ;17 and 18]. A SWCC is a basis to regulate other important properties of soil such as unsaturated permeability and shear strength (Tao *et al.* 2017; Fredlund and Xing, 1994; Vanapalli *et al.*, 1996 and Bo and Yulong, 2016). [4 ;11 ;19 and 20]. Fredlund and Rahardjo (1993a)[1] reported that fine grain soils have greater air entry pressure (ψ_a), while those with broader collection of pore sizes (well graded) display more variations in matric suction with water content. For over five decades, several empirical equations were proposed to model SWCC with many of them having common and intersecting parameters.

2 Materials and Methods

2.1 Materials

2.1.1 *Soil* :

The lateritic soil used in this research was obtained from a site located in Abagana community of Anambra state, Nigeria (Latitude 6°10'15" N and Longitude 6°58'10" E). The method used was the disturbed sampling at a depth range of 0.5 m and 3.0 m.

2.1.2 *Bacteria* :

The bacteria used in this research is *Sporosarcina pasteurii,* an organism frequently found in soil. It is Gram-positive, urease positive, spore-forming and rod-shaped bacteria that was isolated and cultured from the soil sample.

2.2 Methods

2.2.1 Bacteria *culture/growth medium* :

The method used to identify the bacteria is the conventional method described by Cheesbrough (2006) [21]. Bacteria was cultured in an Ammonium-Yeast Extract media as delineated in Mortensen *et al.* (2011) and Feng *et al.* (2014) [22 and 23]. The organism was isolated from soil and inoculated on media with this composition viz : (20 g yeast extract, 10 g ammonium chloride, 2 g urea and 0.1g nickel in 1 litre distilled water) and NaOH was used to adjust the pH of the media to 9.0. The media was autoclaved at 121°C per 1.1 kg pressure for 15 minutes. 1 gram each of the soil samples were inoculated on each of the culture bottle and incubated at 37°C for 24-48 hours to facilitate proper characterization i.e. isolation and identification.

2.2.2 Bacteria *cell density* :

The bacteria suspension was varied in stepped density of 0, 4.0, and 8.0 McFarland Standards, equal to 0 /ml, 1.20 x 10^9 /ml and 2.40 x 10^9 cells/ml. A maximum one-third (1/3rd) of the pore volume of organisms was mixed with the soil as recommended by Rowshanbakht *et al.* (2016) [24]. Pore volumes were determined for all the compactive efforts employed in the study.

2.2.3 *Sample preparation*:

3000 g of the crumbled and air-dried soil sample sieved through BS No.4 sieve (4.76 mm opening) was mixed rigorously with 1/3rd of its pore volume as the bacterial suspension density using moulding water contents in the range of -2 % and +2 % relative to optimum moisture content. The treated soil samples were cured for 12 hours in a securely closed plastic bags at 24 ± 2°C to facilitate better distribution and attachment of the bacteria onto the soil before compaction with the energy level considered. The compacted samples were flooded with the cementating reagent under gravity in three circles with 2/3rd of their pore volumes cementation mixture the same as those used in Dejong *et al.* (2006) [25] to initiate the MICP process. A stainless steel pipe having an internal raduis of 25 mm and effective height of 50 mm was used in coring the seventy-two (72) specimens from the compacted soil and wrapped with polyethene sheets 24 hours after the third cycle. The cored specimens were later saturated by capillary action in a water tank for 3 weeks. Full saturation was confirmed only when water was observed to have risen to the top of the treated samples.

2.2.4 *Application of pressure on the pressure plate extractor*:

The fully saturated specimen was placed on a porous stone that only permit the movement of water through the pore inside the chamber of the pressure plate extractor. Controlled air from a compressor was used to apply pressure of 10, 500 and 1500 kPa, respectively, on the specimens until water stopped dripping from an outlet on the pressure plate extractor. The application of pressure on the specimens was carried for about 10 weeks, the whole process from sample preparation to the application

of the pressure lasted for about 3 months. The equipment was dismantled after the test, while the specimens were placed in an oven to determine the final water content. The volumetric water content was calculated from the water contents for each pressure applied and the data was used to plot the soil-water characteristic curves (SWCCs).

2.2.5 Model equations

A lot of models for the prediction of SWCCs have been used (Chin *et al.*, 2010 ; Miller *et al.*, 2002) [3 ;26] however, an extensive review of the subject matter by Leong and Rahardjo (1997) [27] showed that the Brooks - Corey (1964), van Genuchten (1980) [9,10] as well as Fredlund and Xing (1994) [11], are frequently used by researchers. Therefore, the three models expressed in equations (1) – (4) were considered in this study.
The Brooks - Corey Model [9] is expressed as:

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

and

$$\Theta = 1 \ and \ \theta = \theta_s \quad when \ \psi < \psi_a \tag{2}$$

Where: Θ = normalized dimensionless volumetric water content
$(\psi_a) = Air \ Entry \ Suction \ or \ Bubbling \ Pressure$
$\psi = suction \ point$
λ = the pore-size distribution index (Corey, 1994)[28]; which is related to the distribution of pores in the soil sample and can be deduced from the slope of SWCC van Genuchten (1980) model [10] is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{\frac{1}{1 + (p\psi)^n}\right\}^m \tag{3}$$

Fredlund and Xing (1994) [11] model is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left\{ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c} \tag{4}$$

Where: *a, b, c* are the different soil fitting parameters described by Leong and Rahardjo (1997) [27] and *m, n* and *p* are three soil fitting parameters described by van Genuchten (1980) [10] who also reported the relationship between **m** and **n** as:

$$m = \left(1 + \frac{1}{n}\right) \tag{5}$$

to attain a bounded form expression for hydraulic conductivity however that was found to decrease the flexibility of the model. Therefore, the parameters *m* and *n* should be used as obtained without using the relationship specified above to get precise predictive results. *p* is the turning point of the curve, which is associated to the air-entry suction. *n* occurs at regulated volumetric water content of 0.5, which controls the slope of SWCC about the pivot point such that as *n* increases the portion of the curve amid ψ_a and the knee (the point of inflexion) of SWCC becomes steeper (Miller *et al.*, 2002) [26].

2.2.6 Prediction of unsaturated hydraulic conductivity

The calculation of unsaturated hydraulic conductivity using the models is linked to the measured saturated hydraulic conductivity with several parameters obtained from the SWCC. The prediction is established on the following relationship:

$$k_r = \frac{k}{k_{sat}} \tag{6}$$

Where : k_r is a relative hydraulic conductivity ; **k** is unsaturated hydraulic conductivity of the soil and **k** $_{sat}$ is the saturated hydraulic conductivity of the soil determined in the laboratory. From Brooks-Corey (1964) model, [9] k_r in relation to the SWCC parameters is given as:

$$K_r = \begin{cases} 1 & ; \ \psi \leq \psi_a \\ \left(\frac{\psi_a}{\psi}\right)^{2+a\lambda} & ; \ \psi_a > \psi \end{cases} \tag{7}$$

From the van Genuchten (1980) model, [10] k_r in relation to the SWCC fitting parameters is given as:

$$k_r = \frac{\{1 - (\alpha\psi)^{n-1}[1 + (\alpha\psi)^n]^{-m}\}^2}{[1 + (p\psi)^n]^{m/2}} \tag{8}$$

Where *m, n* and *p* are as described in SWCC.
Also, from Fredlund and Xing (1994) model, [11] k_r in relation to the SWCC fitting parameters is given as:

$$K_r = \frac{1}{\left\{ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c} \tag{9}$$

Where: ψ = suction point; *a, b and c* are three different soil fitting parameters described by Leong and Rahardjo (1997) [27].
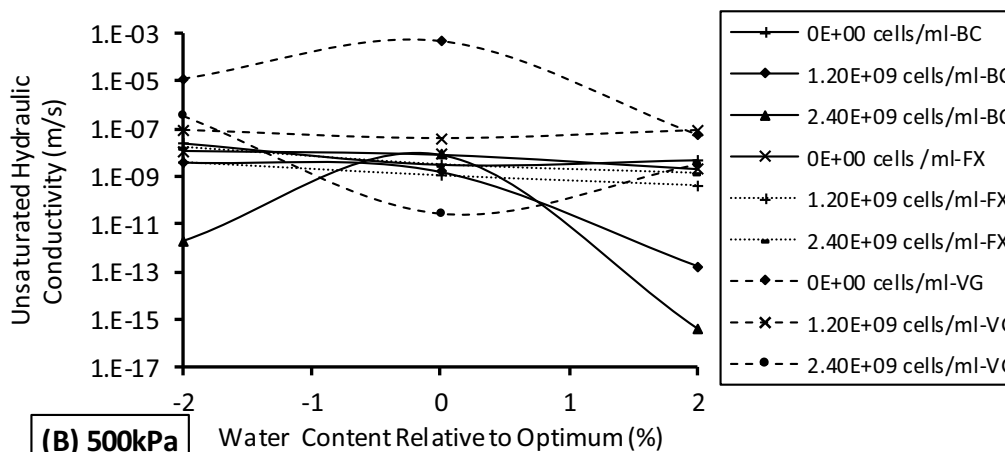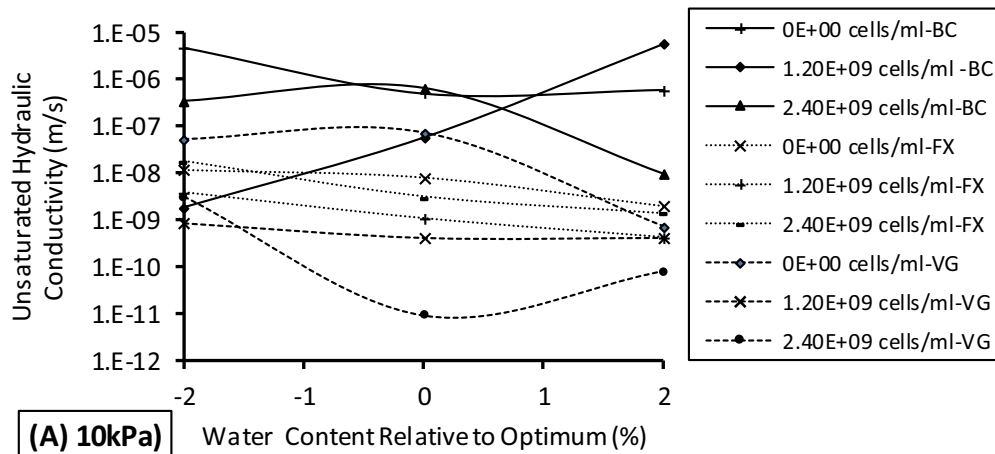
3 RESULTS AND DISCUSSION

3.1 Unsaturated hydraulic conductivity

3.1.1 Effect of moulding water content relative to optimum :

The changes recorded in the unsaturated hydraulic conductivity with moulding water content relative to optimum at matric suctions of 10, 500 and 1,500 kPa for Brooks-Corey (BC), van Genuchten (VG) and Fredlund-Xing (FX) models is shown in Figs. 1a-c. Generally, unsaturated hydraulic conductivity predicted, reduced with increasing moulding water content irrespective of the compactive effort and *S. pasteurii* suspension density used. It was observed that at 10 kPa suction, the [9] Brooks – Corey model recorded higher predicted unsaturated hydraulic conductivity ; which ranged between 4.70×10^{-6} m/s at 0 cells/ml treated at -2 % dry of OMC to 9.75×10^{-9} m/s at 2.40×10^9 cells/ml treated at 2% wet of OMC. [10] van Genuchten model recorded values in the range of 9.12×10^{-12} m/s at 2.40×10^9 cells/ml treated at OMC to 7.35×10^{-8} m/s at 0 cells/ml also treated at

OMC. Furhtermore, [11] Fredlund-Xing models recorded values that ranged between 1.16×10^{-8} m/s at -2% dry of OMC and 1.97×10^{-9} m/s at +2% wet of OMC for 0 cells/ml treated at OMC, lower values ranging between 3.92×10^{-9} m/s and 4.33×10^{-10} m/s were recorded at 1.20×10^{9} cells/ml. Furthermore, at 10 kPa suction pressure, the compacted treated soil was still saturated and did not exhibit unsaturated behaviour; when the suction pressure was increased to 500 kPa, the unsaturated behaviour increased. The Brooks – Corey [9] model recorded the lowest predicted unsaturated hydraulic conductivity in the range of 4.07×10^{-16} m/s at 2.40×10^{9} cells/ml treated at +2 % wet of OMC to 4.66×10^{-9} m/s at 0.0 cells/ml treated at +2 % wet of OMC. The next lower prediction was recorded by [10] van Genuchten model in the range of 2.67×10^{-11} m/s at 2.40×10^{9} cells/ml treated at OMC to 4.66×10^{-4} m/s at 0.0 cells/ml treated at OMC. Similarly, the Fredlund-Xing [11] model recorded relatively higher values which ranged between 1.15×10^{-8} m/s for 0 cells/ml at -2% dry of OMC and 4.18×10^{-10} m/s for 2.40×10^{9} cells/ml treated at +2% wet of OMC. As the suction was increased to 1500 kPa, Brooks – Corey [9] model recorded similar but much lower results compared to those recorded at 500 kPa, in the range of 3.44×10^{-18} m/s at 2.40×10^{9} cells/ml treated at +2 % wet of OMC to 2.12×10^{-7} m/s at 1.20×10^{9} cells/ml treated at -2 % dry of OMC. Similarly, van Genuchten [10] model recorded predited values in the range of 1.42×10^{-11} m/s at 2.40×10^{9} cells/ml compacted at OMC to 5.07×10^{-3} m/s at 0 cells/ml

Compacted at OMC. At the same suction pressure, the Fredlund-Xing [11] model recorded relatively higher values which ranged from 4.05×10^{-10} m/s at 1.20×10^{9} cells/ml compacted at +2 % wet of OMC to 1.67×10^{-8} m/s at 2.40×10^{9} cells/ml compacted at -2 % dry of OMC. At matric suction pressures of 500 kPa and 1,500 kPa, relatively the [10 and 11] model predictions were higher compared to the Brooks-Corey [9] model. From the results presented, all the models at varying suction pressure recorded unsaturated hydraulic conductivity lower than the maximum permisible value of 1.0×10^{-9} m/s, however, the Brooks-Corey model [9] recorded much lower prediction of unsaturated hydraulic conductivity at higher suction pressure compared to the other two prediction models, this condition is commonly found in arid/semi-arid regions like Nigeria. The results obtained of this study are similar to those reported by Osinubi and Eberemu, (2010); Osinubi and Bello, (2011) and Osinubi *et al.* (2015) [29-31] for soils treated with using different additives.

(A) 10kPa) Water Content Relative to Optimum (%)

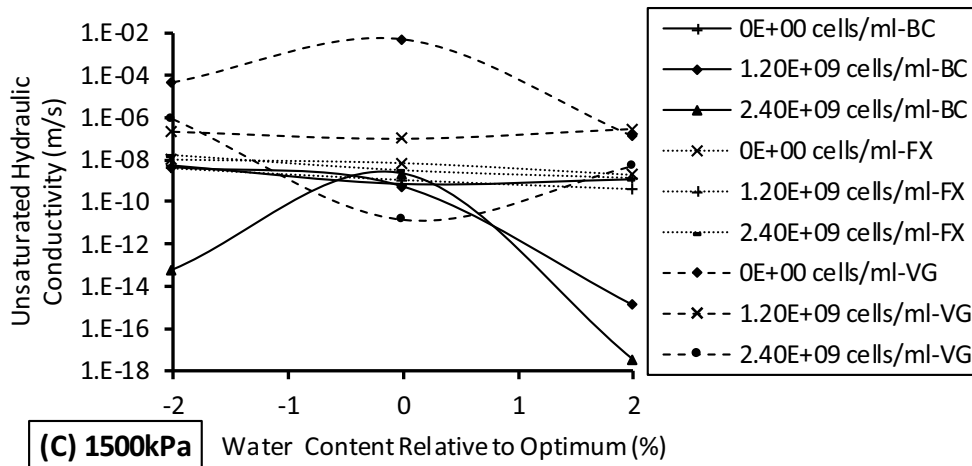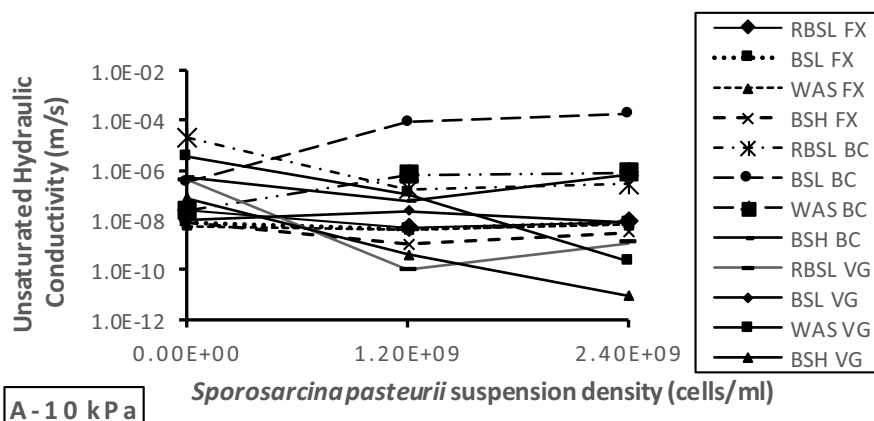

(B) 500kPa Water Content Relative to Optimum (%)

Fig.1 Variation of unsaturated hydraulic conductivity for lateritic soil compacted at optimum moisture content with water content relative to optimum based on Brooks-Corey (BC), Fredlund-Xing (FX) and van Genuchten (VG) models at varying *S. pasteurii* suspension density for matric suction:(A) 10 kPa (B) 500 kPa (C) 1500 kPa

3.1.2 *Effect of Sporosarcina pasteurii suspension density*

The effect of *S. pasteurii* suspension density on the unsaturated hydraulic conductivity of specimens treated at OMC and compacted with RBSL, BSL, WAS and BSH energy is presented in Figs.2a-c. At lower matric suction (i.e., 10 kPa) when the soil was still in its saturated state; Brooks-Corey (1964) [9] model recorded higher predicted values than the other two models. The range of values were between 2.37×10^{-8} m/s at 0 cells/ml to 1.80×10^{-4} m/s at 2.40×10^9 cells/ml. These predicted values did not satisfy the maximum permissible regulatory value of 1.0×10^{-9} m/s. The van Genuchten (1980) [10] model recorded values in the range of 9.12×10^{-12} m/s at 2.40×10^9 cells/ml to 3.52×10^{-6} m/s at 0.0 cells/ml, there was a general decrease in the predicted hydraulic conductivity values with increase in *S. pasteurii* suspension density. The Fredlund-Xing (1994) [11] model on the other hand recorded values in between [9 and 11] models, the predicted hydraulic conductivity values slightly decreased with increase in *S. pasteurii* suspension density. At 500 kPa matric suction the van Genuchten [10] model showed higher predicted

Unsaturated hydraulic conductivity values in the range of 2.77 m/s at 0 cells/ml to 2.67×10^{-11} m/s at 2.40×10^9 cells/ml, only treatment at 2.40×10^9 cells/ml using BSH compactive effort met the regulatory value of 1.0×10^{-9} m/s for this model. The Brooks-Corey [9] model recorded the least predicted unsaturated hydraulic conductivity in the range of 8.67×10^{-9} m/s at 0 cells/ml to 1.56×10^{-12} m/s at 2.40×10^9 cells/ml. On the other hand, the Fredlund-Xing [11] model predicted unsaturated hydraulic conductivity values that are between the values predicted by [9 and 10] models. Similarly, at 1500 kPa matric suction, van Genuchten [10] model recorded higher unsaturated hydraulic conductivity values, in the range of 1.23×10^2 m/s at 0 cells/ml to 1.42×10^{-11} m/s at 2.40×10^9 cells/ml; while the Brooks-Corey [9] model recorded the least predicted unsaturated hydraulic conductivity in the range of 3.11×10^{-9} m/s at 0 cells/ml to 3.27×10^{-14} m/s at 2.40×10^9 cells/ml. As previously reported, [11] model recorded values that are in between the range predicted by [9 and 10] models respectively. Osinubi *et al*. (2015) [31] reported similar results.

B-500 kPa

Sporosarcina pasteurii suspension density (cells/ml)

C 1500 kPa

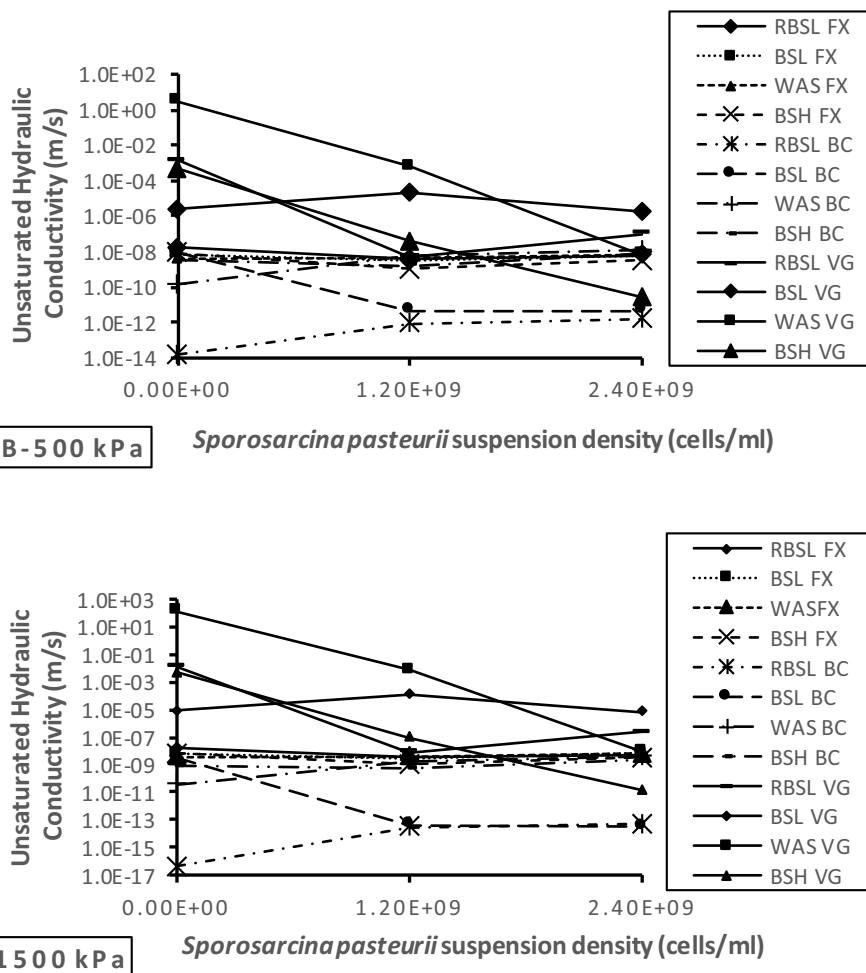*Sporosarcina pasteurii* suspension density (cells/ml)

Fig.2 Variation of unsaturated hydraulic conductivity of lateritic soil - *S. pasteurii* mixture compacted at optimum moisture content based on Brooks-Corey (BC), van Genuchten (VG), and Fredlund-Xing (FX) models for matric suctions : (A) 10 kPa (B) 500 kPa and (C) 1500 kPa.

3.1.3 *Effect of compactive effort*

The changes recorded due to compactive effort on the unsaturated hydraulic conductivity predicted by Brooks-Corey [9] model for varying *S. pasteurii* suspension density is presented in Fig.3a-c. The range of matric suction used in the study is between 10 kPa -1500 kPa, the highest and lowest values of the predicted unsaturated hydraulic conducvity recorded within these pressure range is discussed. It was generally observed that there was a linear decrease in the unsaturated hydraulic conductivity with increase in matric suction. For the natural soil at 10 kPa the highest hydraulic conductivity value of 2.04×10^{-5} m/s was recorded using RBSL compactive effort, while the lowest value recorded was 2.37×10^{-8} m/s using WAS compactive effort, at 1500 kPa. The highest value recorded was 3.12×10^{-9} m/s using BSL while the lowest value recorded was 4.47×10^{-17} m/s using RBSL compactive effort.

At 1500 kPa, the highest value recorded was 1.73×10^{-9} m/s using WAS while the lowest value recorded was 2.60×10^{-14} m/s

For soil specimen treated at 10 kPa suction, the highest hydraulic conductivity value of 1.67×10^{-3} m/s was recorded using WAS ; while the lowest value recorded was 2.40×10^{-7} m/s using RBSL compactive effort. At 1500 kPa, the highest value recorded was 7.10×10^{-14} m/s using RBSL while the lowest value recorded was 3.33×10^{-15} m/s using BSH compactive effort. For soil specimen treated with 1.20×10^{9} cells/ml, at 10 kPa suction ; the highest hydraulic conductivity value of 7.89×10^{-5} m/s was recorded using BSL, while the lowest value recorded was 5.75×10^{-8} m/s using BSH compactive effort. At 1500 kPa the highest value recorded was 1.71×10^{-9} m/s using WAS while the lowest value recorded was 3.05×10^{-14} m/s using RBSL compactive effort. Similarly, for soils specimen treated at 10 kPa suction, the highest hydraulic conductivity value of 6.11×10^{-4} m/s was recorded using BSL, while the lowest value recorded was 1.66×10^{-7} m/s using RBSL compactive effort. At 1500 kPa, the highest value recorded was 4.23×10^{-14} m/s using BSH while the

lowest value recorded was 7.75×10^{-21} m/s using WAS compactive effort. Furthermore, for soils specimen treated with 2.40×10^{9} cells/ml, at 10 kPa suction, the highest hydraulic conductivity value of 1.80×10^{-4} m/s was recorded using BSL, while the lowest value recorded was 2.83×10^{-7} m/s using RBSL compactive effort. At 1500 kPa, the highest value recorded was 3.91×10^{-9} m/s using WAS while the lowest value recorded was 3.27×10^{-14} m/s using BSL compactive effort. From the results presented, it can generally be concluded that RBSL compactive effort recorded the least predicted unsaturated hydraulic conductivity values

except at WAS compactive effort which recorded the least predicted unsaturated hydraulic conductivity values. The observed trend could probably be due to the precipitation of calcite within the pores of specimens prepared at lower compactive effort (especially the RBSL), resulted in a lower prediction of unsaturated hydraulic conductivity values.
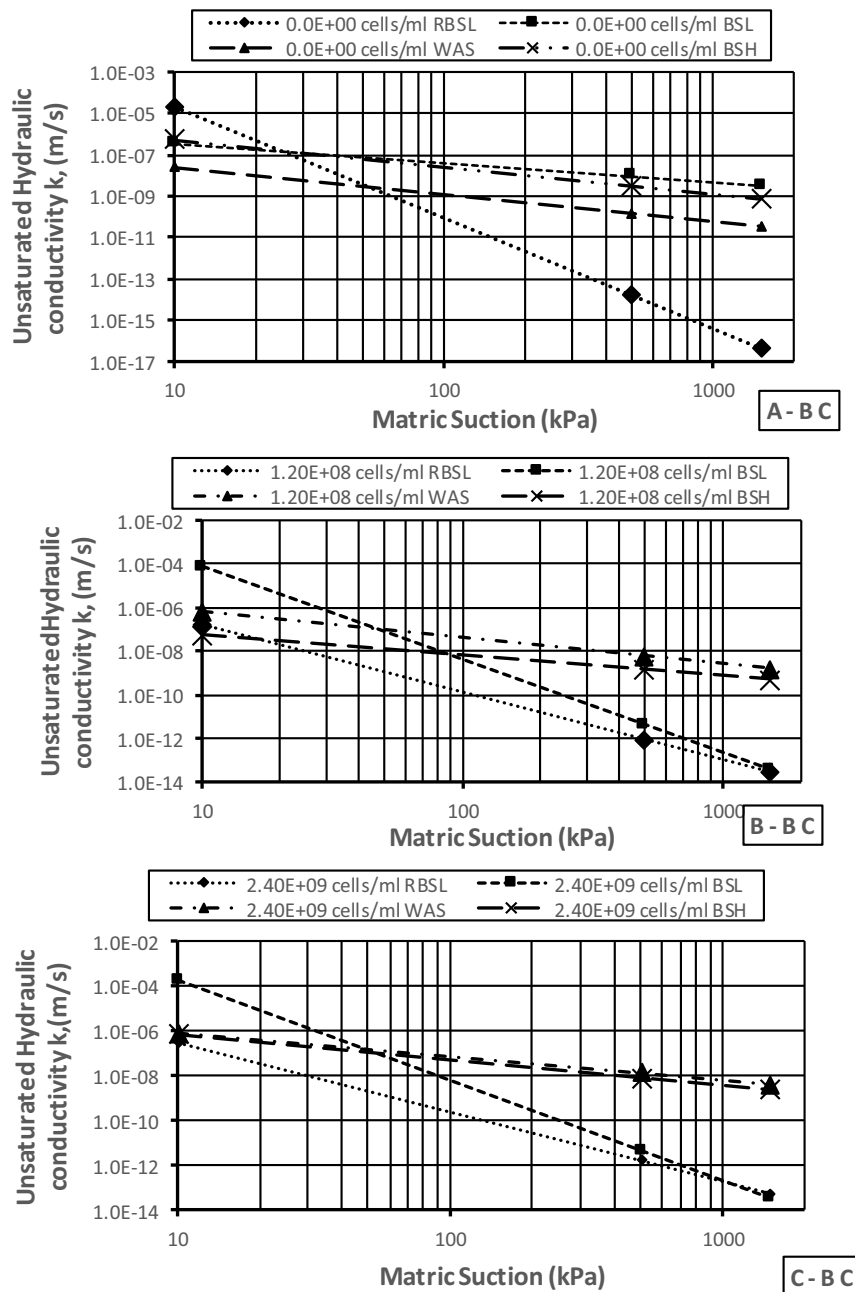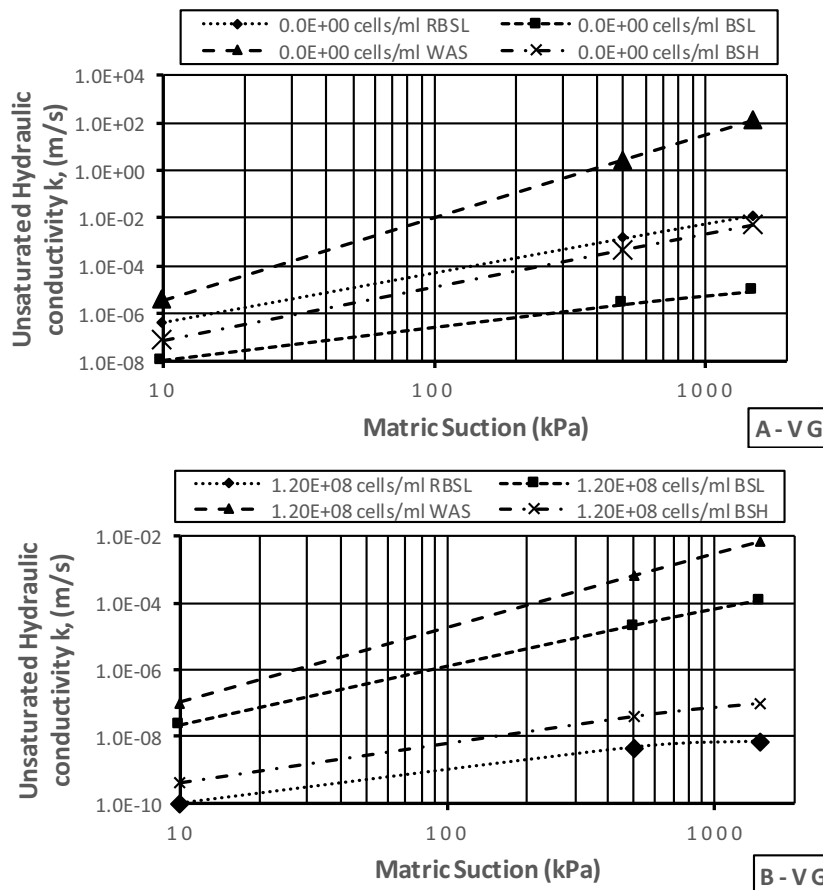

Fig.3 Variation of unsaturated hydraulic conductivity of lateritic soil prepared at optimum moisture content with matric suction based on Brooks - Corey (BC) model for *S. pasteurii* suspension density: (A) 0 cells/ml, (B) 1.20×10^{9} cells/ml and (C) 2.40×10^{9} cells/ml.

The changes due to effect of compactive effort on the predicted unsaturated hydraulic conductivity using van Genuchten [10] model for varying *S. pasteurii* suspension density is presented in Fig. 4a-c. In contrast to the predicted values obtained using [9] model, there was a linear increase in the unsaturated hydraulic conductivity values with increasing matric suction. As previously discussed, at 10 kPa suction for the natural soil, the highest value was 3.52×10^{-6} m/s using WAS, while the lowest value recorded was 1.08×10^{-8} m/s using BSL compactive effort, at 1500 kPa, 1.24×10^{2} m/s was recorded as the highest value using WAS and 8.21×10^{-6} m/s as the lowest using BSL compactive effort. At 10 kPa, the highest and lowest unsaturated hydraulic conductivity values were 3.13×10^{-8} m/s and 4.40×10^{-10} using BSL and RBSL compactive efforts respectively, while at 1500 kPa, the highest and lowest values are 1.25×10^{-4} m/s and 7.93×10^{-8} m/s using BSL and RBSL compactive efforts separately. At 10 kPa, the highest and lowest values were 2.90×10^{-8} m/s and 3.48×10^{-9} m/s, using RBSL and WAS compactive efforts respectively. At 1500

kPa suction, the highest and lowest values were 8.29×10^{-5} m/s and 2.23×10^{-6} m/s using RBSL and WAS compactive efforts respectively. Similar results were recorded for soil specimen treated with 1.20×10^{9} and 2.40×10^{9} cells/ml at both 10 and 1500 kPa matric suction. In all the various suspension densities used in the study, only treated soils at *S. pasteurii* of 1.20×10^{9} cells/ml satisfied the regulatory hydraulic conductivity requirement of 1.0×10^{-9} m/s using RBSL compactive effort at 10 kPa matric suction and at 2.40×10^{9} cells/ml both at 10 and 1500 kPa matric suction using BSH compactive effort. The prediction from this model would not be suitable for application since the the soil at matric suction of 10 kPa at which the hydraulic conductivity requirements were met is still saturated as such could not give true unsaturated properties of the treated soil. From the presented results, it can be concluded that van Genuchten [10] model is not appropriate for the predictions of unsaturated hydraulic conductivity of a soil classified according to AASHTO [32], as an A-4-3 soil treated with *S. pasteurii* using MICP approach.
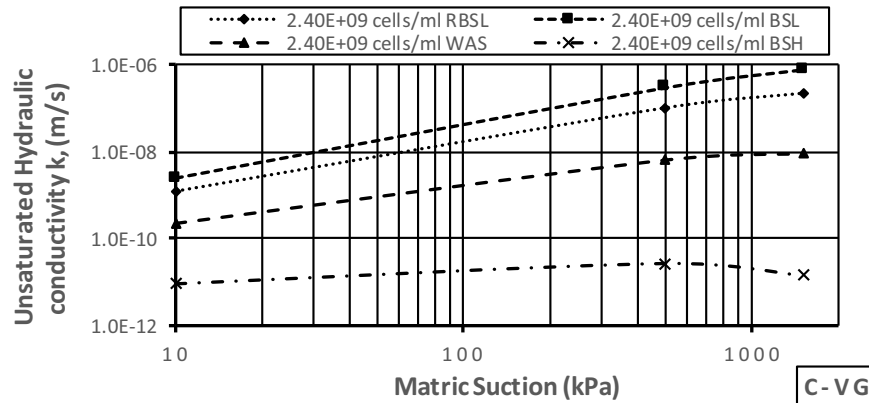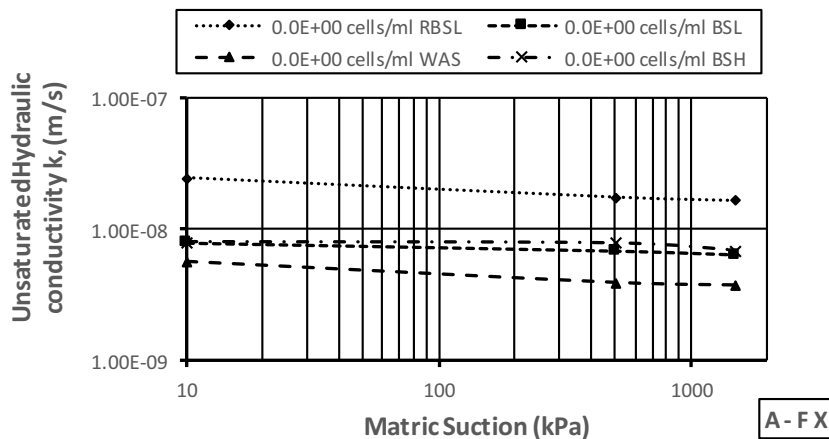
Fig.4 Variation of unsaturated hydraulic conductivity of lateritic soil compacted at optimum moisture content with matric suction based on van Genuchten (VG) model for *S. pasteurii* suspension density : (A) 0 cells/ml, (B) 1.20×10^9 cells/ml and (C) 2.40×10^9 cells/ml.

The variation in the unsaturated hydraulic conductivity predicted using Fredlund-Xing [11] model for varying *S. pasteurii* suspension density due to compactive effort is presented in Figs. 5a-c. A gradual decrease in the predicted unsaturated hydraulic conductivity values was recorded with increasing matric suction. The values predicted using the Fredlund-Xing model are similar to those obtained using the Brooks-Corey [9] model that showed more substantial reduction with increasing matric suction. The values predicted by the two models are at variance with the values recorded for [10] model that under predicted the unsaturated hydraulic conductivity values and as well recorded an increase in the predicted unsaturated hydraulic conductivity values with increase in matric suction. Furthermore, the effect of changes in compactive effort on the predicted values was not significant for all the treated specimens except for Figs. 5b. This has not satisfied the maximum regulatory hydraulic conductivity value of

$1.0x10^{-9}$ m/s. Comparatively, from Figs. 3a-c - 5a-c; all the treatment options used, the predicted values met the regulatory hydraulic conductivity value of $1.0x10^{-9}$ m/s at higher matric suction which displayed unsaturated hydraulic properties. In Figs. 4a-c out of the various *S. pasteurii* suspension densities used in the study, only soils treated with *S. pasteurii* of $1.20x10^9$ cells/ml met the regulatory hydraulic conductivity requirement of $1.0x10^{-9}$ m/s using RBSL compactive effort at 10 kPa matric suction and at $2.40x10^9$ cells/ml both at 10 and 1500 kPa matric suction using BSH compactive effort. From the results presented, the prediction model by Brooks-Corey model [9] predicted values that better represent the unsaturated hydraulic properties of the treated soil than the van Genuchten [10] model, which over predicted the unsaturated hydraulic conductivity.
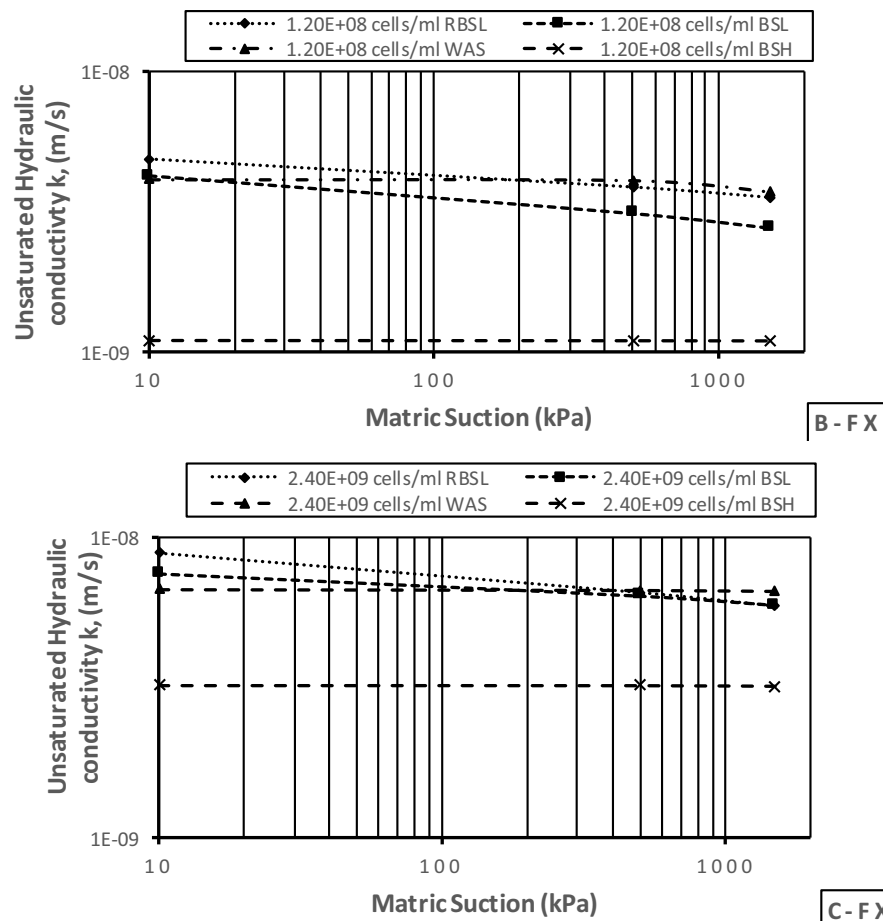
Fig.5 Variation of unsaturated hydraulic conductivity of lateritic soil prepared at optimum moisture content with matric suction based on Fredlund and Xing (FX) model for *S. pasteurii* suspension density : (A) 0 cells/ml (B) 1.20×10^9 cells/ml and (C) 2.40×10^9 cells/ml.

4 CONCLUDING REMARKS

From the results of the study conducted on the unsaturated hydraulic conductivity of lateritic soil treated with varying *S. pasteurii* suspension density and compacted with RBSL, BSL, WAS and BSH at moulding water content from -2 % to +2 % relative to optimum moisture content, the following concluding remarks can be made : Although the other two prediction models gave good results, the Brooks-Corey model gave the best prediction of unsaturated hydraulic conductivity values which fit the requirements for waste containment facilities over the matric suction range and *S. pasteurii* suspension densities considered.

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