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Original Article

A laboratory study on water transfer properties of unsaturated compacted lateritic soil – *bacillus coagulans* mixtures

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ABSTRACT

A study on soil water characteristic curves (SWCC) and unsaturated hydraulic conductivity (UHC) of lateritic soil–*Bacillus coagulans* mixes was done. Three well known models (i.e van Genuchten (VG), Brooks-Corey(BC) and Fredlund-Xing (FX)) were used to predict SWCC and UHC from laboratory test results. Soil samples for the test were admixed with *B. coagulans* at one-third (1/3) pore in step suspension densities of 0 to 2.4x10^{9}cells/ml. Soil samples were then compacted differently with Reduced British Standard light (RBSL), British Standard light(BSL),West African Standard (WAS) and British Standard heavy(BSH) compactive efforts. Cementitious reagent was injected into the compacted soil using gravity up until saturation was attained. Specimens after being compacted were then cored out from the mould using stainless steel cylindrical moulds. The specimens (i.e., inside the stainless steel cylindrical moulds) were then immersed in water chamber till the samples were completely saturated via capillary action and thereafter allowed to undergo a pressure plate drying(PPD) test. Matric suctions of 0, 10, 30, 100, 500, 1000 and 1500kPa, respectively, were used. Result of SWCCs show that with a rise in matric suction, the volumetric water content(θ) declined progressively for all the models (i.e van Genuchten (VG), Brooks-Corey(BC) and Fredlund-Xing(FX)) and the experimental measured values. The UHC slightly reduced with rise in *B.coagulans* suspension density for VG, BC and FX models. At 500 and 1500kPa matric suctions (MS), BC model documented the least UHC values and satisfied the regulatory lowest hydraulic conductivity value of 1.0×10^{-9}m/s for use in containment system. Thus, is suggested for modelling the UHC of lateritic soil−*B.coagulans* mixtures.

1. Introduction

The use of sanitary landfills to mitigate the environmental impact of disposed waste in the environment has been in existence for long [1]. One of the promising approaches is the application of compacted soil liners and cover systems as barrier materials in the construction of sanitary landfill to decrease the movement of unwanted chemical species called leachate from landfills and lessen their influence on ground water. The important principle regulating the performance of sanitary landfills relies profoundly on the hydraulic performance of the barrier system. Compacted soil liners are thick compacted layer of fine-grained soil constructed at the construction site established on the soil's compaction properties. Compacted soil liner could efficiently mitigate leachate movement by either the mechanism of advection or that of diffusion into the immediate environment in that way helps in reducing ground pollution [2-5]. However, certain compacted soil liners are not suitable for landfill practice in

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their natural formed thus, is essential to upgrade them by means of industrial produced additives like cement are quite costly and not responsive to eco-system. The practice of using pozzolanic materials with cementing properties from industrial and agro waste are also not responsive to eco-system.

Therefore, the need for a novel, environmentally welcoming and sustainable soil enhancement method that encompasses the utilization of soil micro-organisms (*B. coagulans*) to precipitate calcite is named microbial-induced calcite precipitation (MICP). MICP being a natural process were carbonates are produced as by product of microbial metabolic activities. The practice comprises a cementation technique were chemical reagent are used to influence urea hydrolysis and thus induce precipitation of calcite [6]. Thus, MICP is a desirable field in geotechnical engineering that comprises the practice of using microbial methods for soil improvement. This is a desirable technique for soil improvement for the reason that the calcite precipitation induced as a product of microbial activities is environmentally friendly. MICP process effectively improves soil by the practice of urea hydrolysis, in that way increasing strength and stiffness and also decreasing water permeability [7-10].

Compacted soil liner and covers are mostly unsaturated in the field, thus the need to measure their unsaturated properties is important. Measurement of UHC in the field is very costly and very monotonous due to the inconsistency of soil properties in the field, time spending and relatively high cost of equipment required for the test in the field. Therefore, because of the mentioned factors, several efforts was put in place by researchers to forecast using mathematical expressions the unsaturated soil permeability properties[11-18] in the laboratory. These processes utilise the SWCC and the corresponding soil saturated coefficient of permeability (k_s).

Study on SWCC for different applications has been reported in many literatures recently [16-19]. For instance, Isidro *et al.*, [18] carried out a study on collapsible soil in Peru. Findings from their studies show that a relation exists between the soil bearing capacity and the SWCC of the collapsible soil. Carnavale *et al.*, [17] reported on a resistivity study performed. They established a solid association amongst the soil resistivity values and suction of the soil. Thus, by resistivity measurement, the SWCC of a soil can be determined. This study is a build-up on the previously published conference paper by Osinubi *et al.*, [19]. A more comparative study using varying energy levels for three models was conducted.

1.1 Background Study

A study on the coefficient of permeability (k) by Fredlund *et al.*, [20] and Arezoo *et al.*, [13] for unsaturated soil shows that k is usually not a constant. There are several factors or parameters that influence k which include the volumetric water content θ, which is equally defined by the soil suction (ψ). ψ is a principal stress state parameter that has impact on the performance of unsaturated soils(USs). According to Fredlund *et al.*, [20], who proposed that the word permeability function for USs could be made use of to signify the association between the k and ψ. Where k at whichever soil suction, k(ψ), is referred to the saturated coefficient of permeability (k_s), Thus k_r (ψ) defined as the relative coefficient of permeability expressed as:

$$k_r(\psi) = \frac{k(\psi)}{k_s} \tag{1}$$

The ($k_r(\psi)$ or $k_r(\theta)$), is defined as scalar function, while k_s, is determine via laboratory study using falling head permeability test. Not like the k_s, The UHC is derived from developed numerical models which connect the k_s with the numerous variables derived from SWCC. Conversely, inconsistency usually occurs amid results projected from diverse models, this is due to its difficulty to define the UHC of soil as it is dependent on time, time wasting and at variation.

Established by van Genucheten model [21], relative hydraulic conductivity comparative to SWCC appropriate parameters is defined by:

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

m, n and p are terms in SWCC.

Established by Brooks-Corey model [22], relative hydraulic conductivity relative to SWCC parameters is set as:

$$K_r = \begin{cases} 1 & ; \ \psi \le \psi_a \\ \left(\dfrac{\psi_a}{\psi}\right)^{2+3\lambda} & ; \ \psi_a > \psi \end{cases} \tag{3}$$

Leong and Rahardjo [23] proposed a method for estimation of K_r in connection to SWCC appropriate parameters stated as[24]:

$$K_r = \frac{1}{\left\{ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c} \tag{4}$$

and

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5}$$

Where:

Θ= relative degree of saturation, θs = saturated θ, θr= the residual θ.

A representative SWCC curve shows affiliation between water content and pore water suction as given in Fig. 1.

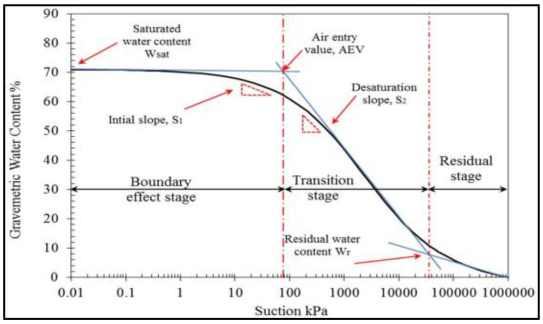

Fig. 1. A typical plot SWCC [14]

Numerous equations have been recommended to denote SWCC. Commonly applied models comprise the BC, VG, and FX equations. The Brooks and Corey [22] model is denoted as:

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_a}{\psi}\right)^{\lambda} \tag{6}$$

Thus **θr , ψ_a** and **λ** are the optimized factors and **λ**= pore-size distribution index, connected to the gradient of the curve.

van Genuchten [21] defined his model as:

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + \left(\frac{\psi}{\propto}\right)^n\right]^m} \tag{7}$$

the optimised factors include **θr ,∝, n** and **m**. as described in [23].

The Fredlund and Xing [11]model is denoted as:

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left\{Ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c} \tag{8}$$

It is presumed that θ_r is negligible. Therefore equation (8) becomes equation (9):

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

Thus, optimized factors are a, b and c [25].

2. Materials and Methods

2.1 Materials

2.1.1 Soil sample

Soil was acquired from Anambra state. Disturbed sample was collected. Sample after collection, was dried, crushed and sieved over a standard sieve with aperture size 4.76mm (BS No. 4 sieve) prior to geotechnical testing.

2.1.2 Microorganism

Bacillus *coagulans,* a urease positive bacterial was utilised for the study, categorized ATCC 8038[26].

2.1.3 Cementation reagent

20 g of urea, 10 g of NH_4Cl, 2.8 g $CaCl_2$, 3g of Nutrient broth and 2.12 g of $NaHCO_3$ was the Cementitious reagent used as proposed in literatures[27-28].

2.1.4 Bacteria solution

The solution used for microbe inoculation is as described by Osinubi *et al.,* [28].

2.2 Methods

2.2.1 Bacterium Specie Isolation

Serial dilution method was adopted for the isolation of microbes in the soil as stated in Osinubi *et al.,* [19]. The process continues for higher dilutions required. Storage of the isolates was done at 4°C.

2.2.2 The Culture medium and growth conditions

The method used was in agreement with that defined by Stocks-Fischer *et al*., [27].

2.2.3 Unsaturated hydraulic conductivity

Specimens for the test were admixed before being compacted with a proportion of liquid *B. coagulans* solution at a relative one-third (1/3) pore volume (i.e based on the suggestion of Rowshanbakhta *et al*., [29] for 0, 1.5 x10^8, 6 x10^8, 1.2 x10^9, 1.8 x10^9 and 2.4 x10^9/ml, suspension densities respectively. Specimens were mix at optimum moisture content (OMC) and compacted with the respective energies that were considered for the process. Cementation reagent was added to the compacted specimen and was permit to flow by gravity to a point that saturation was attained. The procedure was carried out in three cycles at 6 hours interval. Then a stainless steel cylindrical moulds were used to cure the specimens. The specimens (i.e., inside the stainless steel cylindrical moulds) were then immersed in water basin till the specimens were completely soaked in water via capillary action (for about 3 weeks) before subjecting to PPD test. Application of pressure was done as suggested in literature [30]. Specimens after being saturated were lay open to pressure of 0 to 1500 kPa, individually. At every one pressure applied (first from 0 up to 1500kPa), the system is permitted to ditch out entirely the water at that applied pressure till definitely no water drip was witnessed at the corresponding outlet. The specimens were after that detached, weighed and put back over again for the succeeding application of pressure. The pressure is further raise and the process reiterated to the determined pressure of 1500 kPa. For each succeeding application of pressure, the setup was checked carefully for any pressure leakages that might affect the result. These processes were carried out with all caution to avoid accident and erroneous results. After maximum pressure application; specimens were oven dry to determine their final gravimetric water content. Test process is shown in Fig. 2-4.

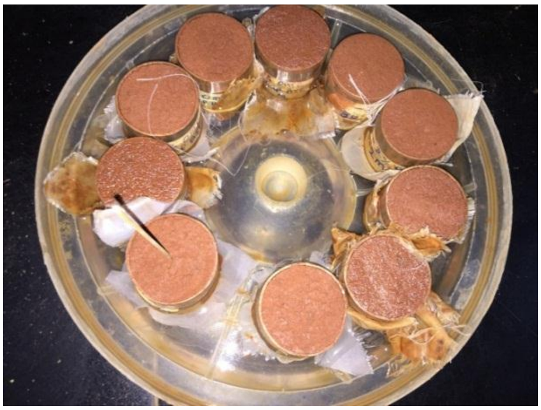

Fig. 2 Soil specimens being saturated in a water bathe before setting up in pressure plate cell.

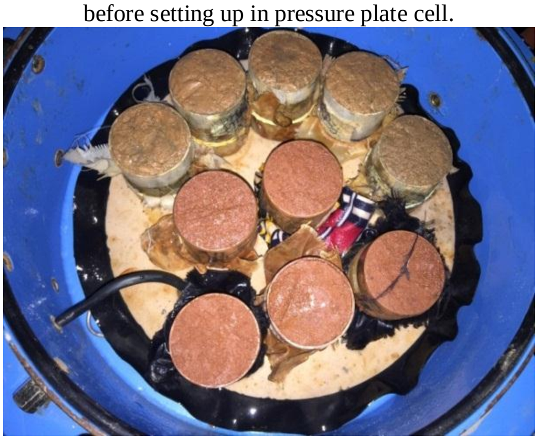

Fig. 3 Soil specimens in the pressure plate cell

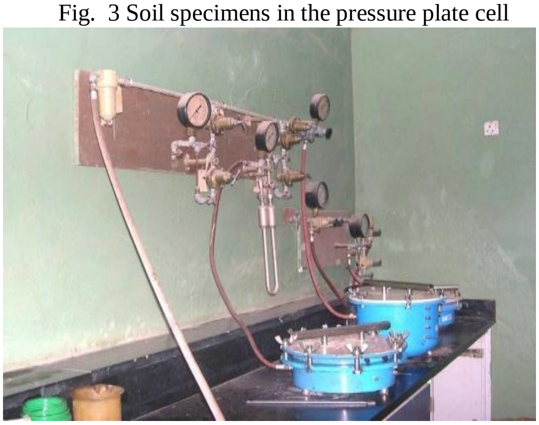

Fig. 4 Pressure plate extractor setup in the laboratory

3. Results and Discussion

3.1 Prediction of SWCC

SWCC for laboratory experimental results and the corresponding projected values using VG, BC and FX models are shown in Figs. 5a-f. Equations (7– 9) were applied to model the SWCCs for the models and compared with the laboratory experimental values. According to the recorded results, VG model overestimated θ at lesser matric suction (shown with higher values above the other values) over laboratory measured as well as BC and FX models for all the bacteria suspension density deliberated. However, as the matric increased beyond 30kPa, FX model overestimated θ values. Values of 0.1460, 0.14599, 0.1452, 0.1444, 0.1443 and 0.1442 were documented for FX model at matric suction of 10 up to 1500kPa in that order. In the case of lab measured θ values, 0.145, 0.143, 0.139, 0.138, 0.135 and 0.133 were noted for variable matric suctions of 10 up to 1500kPa in that order. Similar trend were noted with varying microbial density and compaction energies. In general, with increment in the matric suction (i.e., 10, to 1500 kPa), θ declined progressively for all the models and the laboratory experimental values. With increment in metric suction starting from 30 upto 1500kPa, FX model overestimated the θ over VG and BC models. The VG and BC models slightly over-estimated the θ above the laboratory experimental values. However, it was observed that θ_r did follow neither the pattern of over nor under estimation when related to the laboratory experimental SWCC results as stated by researchers [19, 25, 31-34].

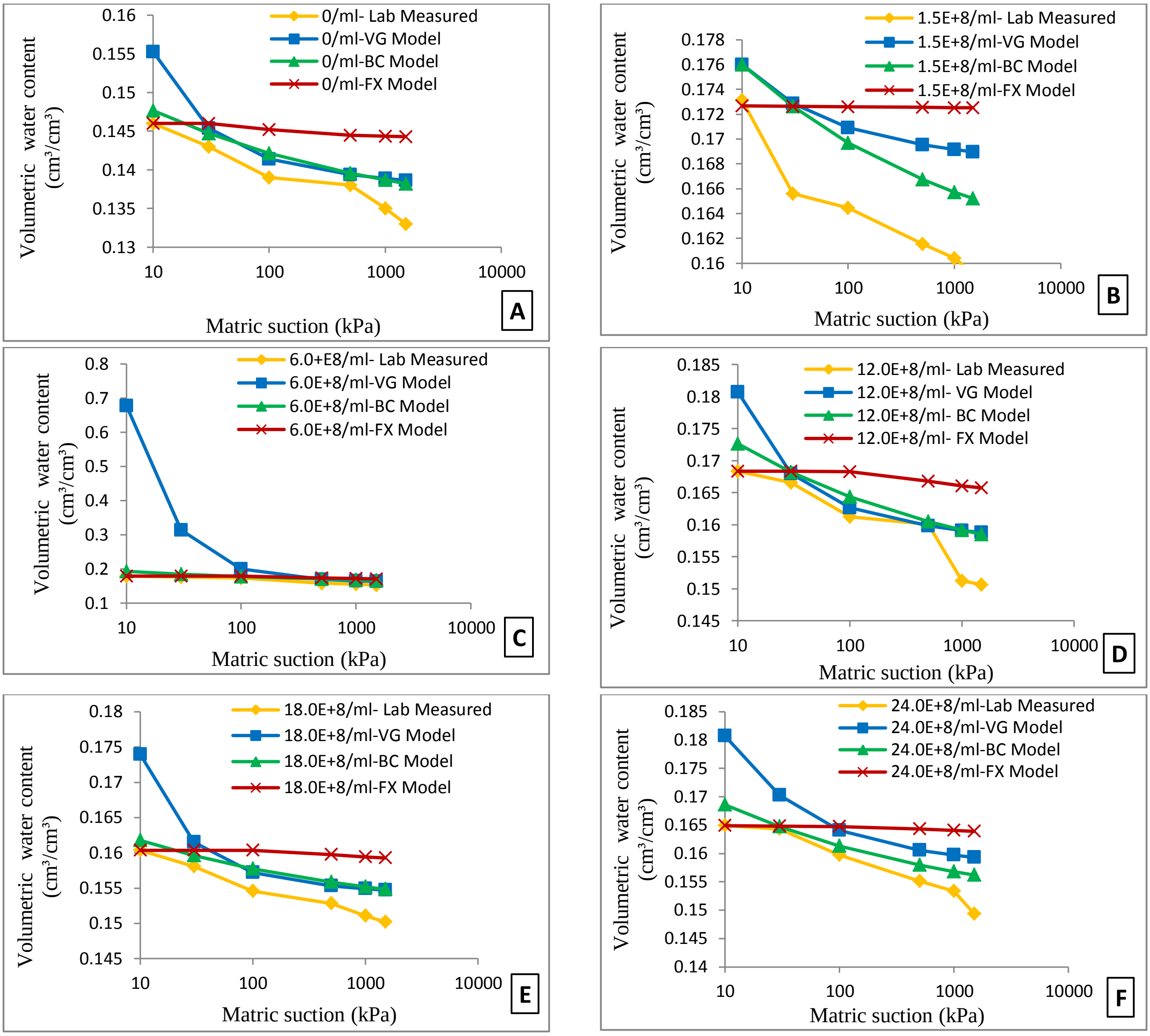

Fig 5a-f: Laboratory experimental values and modelled SWCCs for *B. coagulans* suspension density at OMC: (A) 0/ml (B) 1.5 x 10^8/ml (C) 6 x 10^8/ml (D) 1.2 x 10^9/ml (E) 1.8 x 10^9/ml and (F) 2.4 x10^9/ml (BSL compaction).

3.2 Effect of Microbial density on UHC

The distinction in UHC with Microbial density for sampls mix at OMC and compacted with respective energies as projected using VG, BC and FX models at 10, 500 and 1500 kPa suctions are given in Fig 6a-c. In general, a fluctuating trend in UHC was noticed with rise in microbial density. The fluctuating results of UHC could be attributed the soil-water characteristics parameters use in predicting the UHC. As the suspension density of *B. coagulans* increased it is supposed that additional calcites were manufactured which bound the soil elements together and the blockage of pores openings within the soil matrix. The rearrangement of the soil grain and the packaging of the soil particles with the formation of clods of bigger particles could be responsible for the variations in the hydraulic performance of the treated soil. Isidro *et al.*, [18] established a relation between the soil grain structure and the SWCC for collapsible soil. They reported in their findings that the soil density and its corresponding grain size have significant influence on the SWCC of the collapsible soil examined. Related behaviour was described by Abo-El-Enein *et al.*, [35] and Osinubi *et al.*, [28], who reported that calcite produced by bacteria implements the action of binding the sand elements together. BC model prediction noted higher values at 10 kPa than VG and FX models. With increment in matric suction to 500 and 1500 kPa, respectively, VG model gave higher values followed by FX model.

At 500 and 1500kPa matric suctions BC model documented the least k values and satisfy the regulatory least k value of 1.0×10^{-9}m/s for use in containment system. Generally, results demonstrated that compactive effort has minimal consequence on the UHC of the treated soil. This because no specific trend was established on the UHC changes with compactive effort. However, field application cannot underestimate the packaging effect of the compacted soil with increment in the compaction energy. Thus, it implies that the recorded variations in UHC is basically due to calcite formation and not due to packaging effect of the compaction rammer. Field application implies that care should be taken on the application of the microbes and the cementation reagent as these factors significantly influence the calcite formation in the soil structure in order to achieve optimal results.

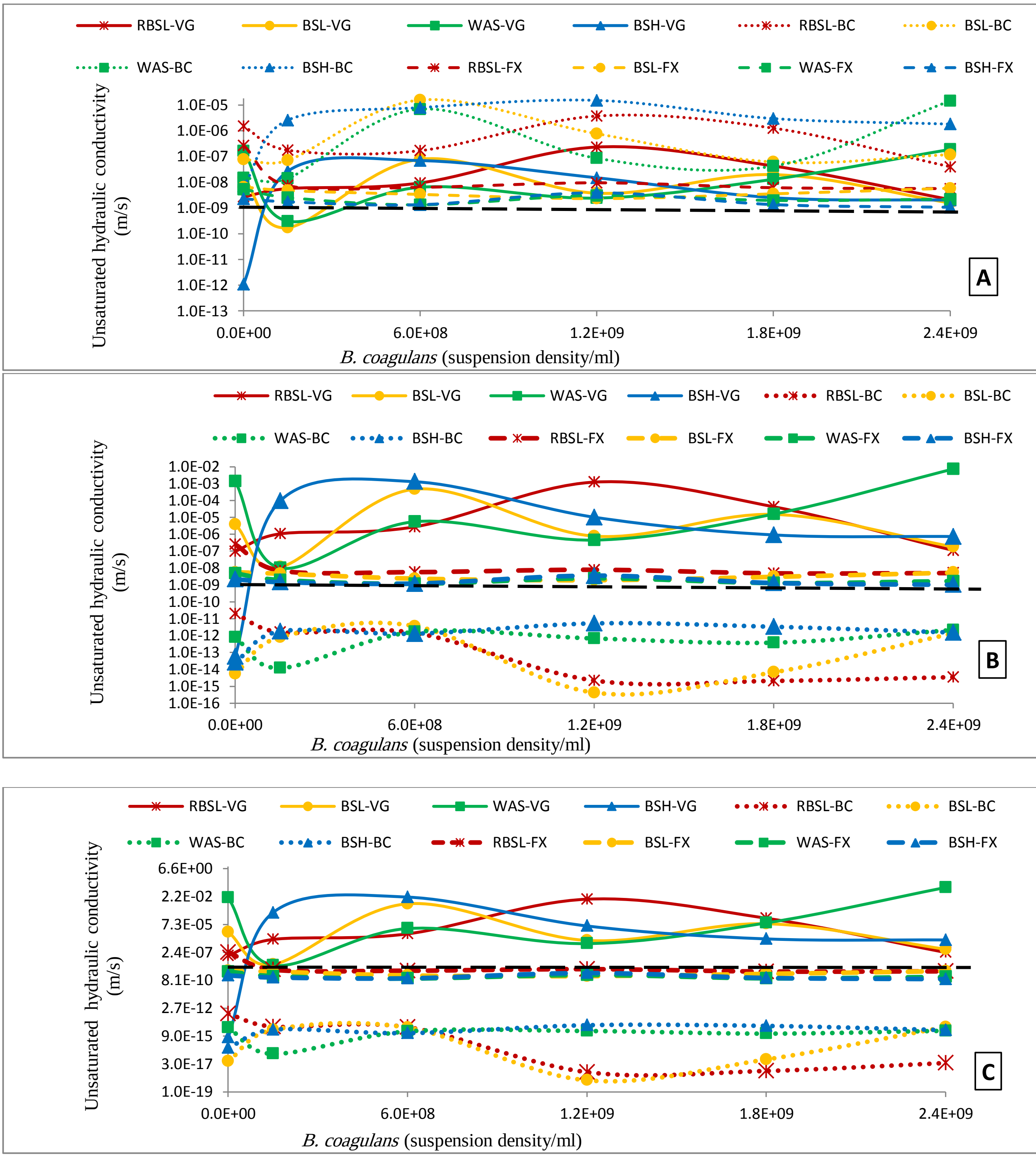

Fig. 6. Variation of UHC with *B. coagulans* suspension;VG, BC and FX models for (A) 10 (B) 500 (C) 1500 kPa at optimum moisture content

3.3 Impact of compactive effort on UHC

The UHC of soil with microbial density for different energies as predicted using VG, BC and FX models at OMC are presented in Figs 7a and b, Figs 8a and b, Figs 9a and b, for matric suctions of 10, 30, 100, 500, 1000 and 1500 kPa respectively. UHC generally increased with increase in matric suction from 0 upto 1500kPa for VG model only. Similar behaviour was observed by Oluremi [36]. The increase with increase in the matric suction could be attributed to the soil-water characteristics parameters use in predicting the UHC. In the case of BC and FX models, reverse is the case were the values reduced linearly with rise in the matric suction from 0 upto 1500kPa (see Figs 8 and 9). UHC values significantly decrease when predicted using BC model while a marginal drop in the UHC values was documented in the case of FX model. With respective to the effect of compactive effort, VG model recorded the highest UHC values with WAS compactive effort, while RBSL, BSL and BSH recorded variable results. No specific pattern was recognized for the effect of compactive effort on the UHC as projected using BC model. In the case of FX model prediction, UHC values decreased with increasing compaction energy (i.e RBSL<BSL<WAS<BSH). In general, field application cannot underestimate the packaging effect of the compacted soil with increment in the compaction energy. During field application, the use of sheep foot rollers that gives maximum kneading effect will be an added advantage in achieving desired results, as it gives better compacted density for fines grain materials when compared with other rollers types.

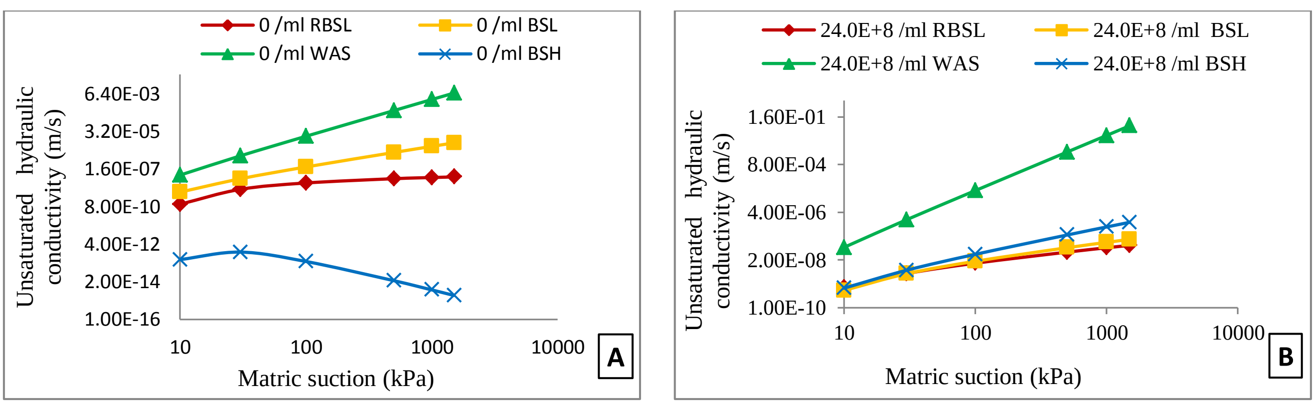

Fig. 7: Plot of UHC with matric suction for VG model for (A) 0/ml and (B) 2.4 x10^9/ml of *B. coagulans* at optimum moisture content.

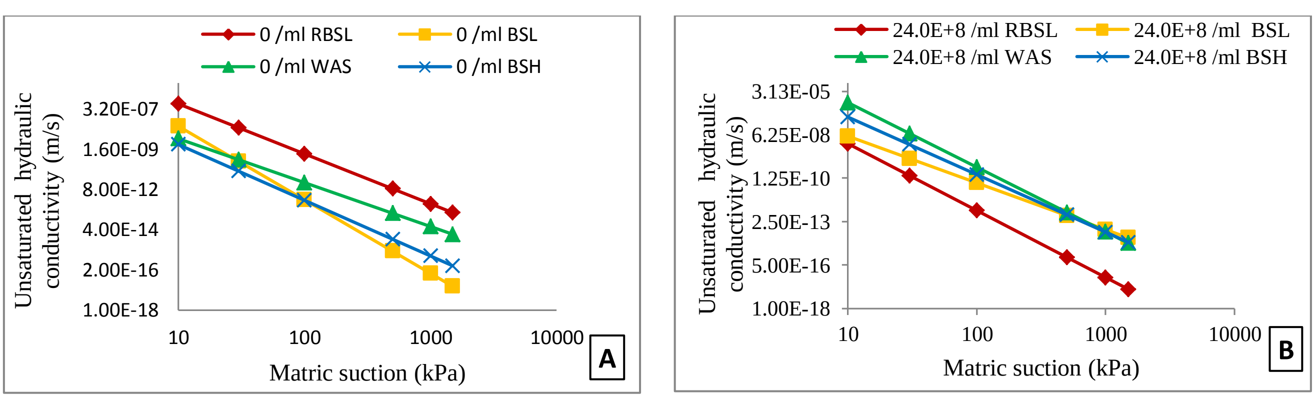

Fig. 8 Plot of UHC with matric suction based on BC model for (A) 0/ml and (B) 2.4 x10^9/ml of *B. coagulans* at optimum moisture content

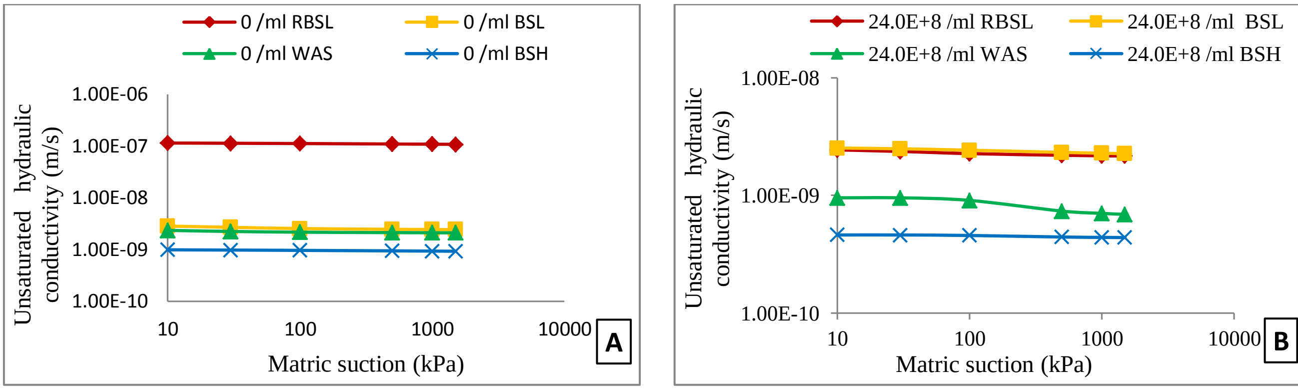

Fig. 9 Plot of UHC with matric suction based on FX model for (A) 0/ml and (B) 2.4 x10^9/ml of *B. coagulans* at optimum moisture content.

4. Conclusion

In accordance with the study done, the resulting closes can be drawn, thus

1. Volumetric water content (θ) declined with rise in matric suction (i.e., 10, 30, 100, 500 and 1500 kPa). All the models used (i.e VG, BC and FX models) overestimated the VWC above the laboratory experimental values.

2. The UHC marginally decreased with increased microbial density for VG, BC and FX models. At 500 and 1500kPa matric suctions BC model note down the lowest k values and satisfied the regulatory least k value of 1.0×10^{-9}m/s for use in containment system.

3. for containment system. During field application, care should be taken on the application of the microbes and the cementation reagent more than the compactive effort as these factors significantly influence the formation of calcite within the soil structure in order to achieve optimal results.

Conflict of Interest

The authors declare that they have no conflict of interest

References

1. Abdulghader AH. Hydraulic Performance of Compacted Clay Liners Under Simulated Landfill Conditions. Unpublished M.Sc Thesis.Ottawa-Carleton *Institute of Civil and Environmental Engineering*. 2014
2. Bostwick LE. Laboratory study of geosynthetic clay liner shrinkage when subjected to wet/dry cycles. M.Sc. thesis, ueen's Univ., ingston, ON, Canada. 2009.
3. Rowe RK.. Systems engineering: the design and operation of municipal solid waste landfills to minimize contamination of groundwater, *Geosynthetics International*, 2011. 18(6), p. 391–404.
4. Yohanna P, Thomas SI, Adrian OE. Kolawole JO. Diffusion study of municipal solid waste contaminants in compacted lateritic soil treated with bacillus coagulans. Third International Symposium on Coupled Phenomena in Environmental Geotechnics.Tokyo University, Japan. 20-22 October, 2021. *Japanese Geotechnical Society Special Publication*. https://doi.org/10.3208/jgssp.v09.cpeg038, 343-350. 2021.
5. Marcin KW, Witol S, Anna, MP. Clays of Different Plasticity as Materials for Landfill Liners in Rural Systems of Sustainable Waste Management. Sustainability, 2018, 10, 2489; Doi:10.3390/su10072489.
6. DeJong JT, Fritzges MB. Nu¨sslein K. Microbial induced cementation to control sand response to undrained shear. *ASCE J. Geotech. Geoenviron. Engng,* 2006. 132, (11); 1381–1392.
7. Whiffin VS, van Paassen, L.A., Harkes, M.P. Microbial carbonate precipitation as a soil improvement technique, Geomicrobiol J. , . 2007, 24 (5) 417–423.
8. Harkes, M.P., van Paassen, L.A., Booster JL., Whiffin VS, van. Loosdrecht MC. Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement, *Ecol. Eng*., 2010; 36, 112–117.
9. Burbank MB, Weaver TJ, Lewis R, Williams T, Williams B, Crawford R. Geotechnical Tests of Sand Following Bio-induced Calcite Precipitation Catalyzed by Indigenous Bacteria, *Journal of Geotechnical and Geoenvironmental Engineering*. 2012, 139 (6) 928–936.

10. Chi L, De Y, Shihui L, Tuanjie, Z, Siriguleng B, Yu, G and Lin, L. Improvement of Geomechanical Properties of Bio-remediated Aeolian Sand, *Geomicrobiology Journal*, DOI: 10.1080/01490451.2017.1338798, 2017.
11. Fredlund D. G.and Xing A. Equations for the Soil-Water Characteristic Curve. *Canadian Geotechnical Journal*, 1994, 31(4): 521–532. DOI:10.1139/t94-061.
12. Luckner L, Van Genuchten MT, Nielsen DR. A consistent set of parametric models for the two ‐ phase flow of immiscible fluids in the subsurface. *Water Resources Research*. 1989;25(10):2187-2193.
13. Rahimi A, Rahardjo H, Leong EC. Effect of range of soil–water characteristic curve measurements on estimation of permeability function. *Engineering Geology*. 2015;185:96-104.
14. Al-Mahbashi AM, Elkady TY, Alrefeai TO. Soil water characteristic curve and improvement in lime treated expansive soil. *Geomechanics and Engineering*. 2015;8(5):687-706. DOI: http://dx.doi.org/10.12989/gae.2015.8.5.687
15. Dolinar B. Prediction of the soil-water characteristic curve based on the specific surface area of fine-grained soils. Bulletin of Engineering Geology and the Environment. 2015;74(3):697-703. DOI 10.1007/s10064-014-0664-y.
16. de Souza CT, Alves LH. Evaluation of installation procedures of volumetric water content and matric potential probes: fundamentals for obtaining field and laboratory accordance. InMATEC Web of Conferences 2021 (Vol. 337, p. 01009). EDP Sciences. https://doi.org/10.1051/matecconf/202133701009, 2021a
17. de Souza Carnavale T, de Campos Viana AC, de Magalhães PM, de Campos TM. Soil-water resistivity curve of a tropical soil. InMATEC Web of Conferences 2021 (Vol. 337, p. 01011). EDP Sciences. https://doi.org/10.1051/matecconf/202133701011, 2021b
18. Isidro M, Trejo P, López M. Soil water characteristic curve parameters of collapsible sand in Lambayeque, Peru. InMATEC Web of Conferences 2021 (Vol. 337, p. 01005). EDP Sciences. https://doi.org/10.1051/matecconf/202133701005. 2021.
19. Osinubi KJ, Yohanna P, Eberemu AO, Ijimdiya TS. A comparative study of soil-water characteristic curves for compacted lateritic soil–bacillus coagulans mixtures. InMATEC Web of Conferences 2021 (Vol. 337). EDP Sciences. https://doi.org/10.1051/matecconf/202133701001, 2021.
20. Fredlund DG, Xing A, Huang S. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal. 1994;31(4):533-546.
21. Van Genuchten MT. A closed ‐ form equation for predicting the hydraulic conductivity of unsaturated soils. Soil science society of America journal. 1980;44(5):892-898.
22. Brooks RH. Corey AT. Hydraulic properties of porous media. Colorado State University, Hydrology Paper NO. 3, Fort Collins, Colorado. 1964.
23. Leong EC, Rahardjo H. Review of soil-water characteristic curve equations. *Journal of geotechnical and geoenvironmental engineering*. 1997;123(12):1106-1117.
24. Gui M., Wu C. Lu, C. Comparison of Two Water Storage Functions of Soil on Porewater Pressure of Earth-Filled Dam under Changing Environment. Proceedings of the 28th International Association for Automation and Robotics in Construction, ISARC , Seoul Korea, 2011;534-543. http://www.iaarc.org/publications/fulltext/S15-7.pdf
25. Miller CJ, Yesiller N, Yaldo K, Merayyan S. Impact of soil type and compaction conditions on soil water characteristic. *Journal of Geotechnical and Geoenvironmental Engineering*. 2002 Sep;128(9):733-742.
26. ATCC, American Type Culture Collection P.O Box 1549 Manassas, VA 20108 USA. http://www.atcc.org. 2013.
27. Stocks-Fischer S, Galinat JK, Bang SS. Microbiological precipitation of CaCO3. Soil Biology and Biochemistry. 1999;31(11):1563-1571.
28. Osinubi KJ, Eberemu AO, Ijimdiya TS, Yohanna P. Interaction of landfill leachate with compacted lateritic soil treated with bacillus coagulans using microbial-induced calcite precipitation approach. Journal of Hazardous, Toxic, and Radioactive Waste. 2020;24(1):04019024. DOI: 10.1061/(ASCE)HZ.2153-5515.0000465.
29. Rowshanbakht K, Khamehchiyan M, Sajedi RH, Nikudel MR. Effect of injected bacterial suspension volume and relative density on carbonate precipitation resulting from microbial treatment. *Ecological engineering*. 2016;89:49-55. https://doi.org/10.1016/j.ecoleng.2016.01.010.
30. ASTM . Standard test method for capillary moisture relationships for fine-textured soils by pressure membrane apparatus' Designation: D 3152-72. West Conshohocken, Pa. 1994.
31. Tinjum JM, Benson CH, Blotz LR. Soil-water characteristic curves for compacted clays. *Journal of geotechnical and geoenvironmental engineering.* 1997;123(11):1060-1069.
32. Chiu TF, Shackelford CD. Unsaturated hydraulic conductivity of compacted sand-kaolin mixtures. *Journal of Geotechnical and Geoenvironmental Engineering*. 1998;124(2):160-170.
33. Eberemu OA. Evaluation of Compacted Bagasse Ash Treated Lateritic Soil as Hydraulic Barriers in Waste Containment Systems. Unpublished Ph.D. dissertation submitted to the Department of Civil Engineering, Ahmadu Bello University, Zaria. 2008.
34. Osim AR. Compacted Cement Kiln Dust Treated Black Cotton Soil as Suitable Liner and Cover Material in Waste Containment Facilities. Unpublished Ph.D Thesis. Department of Civil Engineering Ahmadu Bello University Zaria. 2017.
35. Abo-El-Enein SA, Ali AH, Talkhan FN, Abdel-Gawwad HA. Utilization of microbial induced calcite precipitation for sand

consolidation and mortar crack remediation. *HBRC Journal*. 2012;8(3):185-192.
36. Oluremi JR. Evaluation of Waste Wood Ash Treated Lateritic Soil For Use In Municipal Solid Waste Containment Application. Unpublished Ph.D Thesis. Department of Civil Engineering Ahmadu Bello University Zaria, 2015.

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