

A comparative study of soil-water characteristic curves for compacted lateritic soil – bacillus *coagulans* mixtures

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Abstract. A comparative study of soil-water characteristic curves (SWCCs) for compacted lateritic soil – *Bacillus coagulans* (*B. coagulans*) mixtures for municipal solid waste (MSW) application was studied. Soil treatment was performed at approximately about one-third pore volume of the microbes (i.e., *B. coagulans*) for suspension densities of 0, 1.5×10^8 , 6.0×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, correspondingly. Soil specimens were prepared at optimum moisture content (OMC) of British Standard light (BSL) compaction energy. Cementation reagent was applied on the compacted soil and permitted to penetrate until partial saturation was achieved. A set-up of pressure plate extractor was employed to measure the volumetric water content, θ (VWC) in the laboratory for varying matric suctions with a minimum of 10 kPa up to a maximum of 1,500 kPa. The unsaturated hydraulic conductivity (UHC) and VWC were assessed using Brooks - Corey (BC) and Fredlund - Xing (FX) models. Largely, BC and FX models overrated the VWC. Also, the VWC decreased with higher matric suction for the two models considered and the laboratory measured values. The UHC predicted for matric suctions of 500 and 1,500 kPa initially decreased for *B. coagulans* suspension density up to 1.2×10^9 cells/ml for BC and FX models, with the exception of a few cases, but thereafter increased with increase in microbial density. For FX model at 1,500 kPa, UHC values of 2.42×10^{-9} , 2.02×10^{-9} , 9.31×10^{-10} , 8.09×10^{-10} , 1.29×10^{-9} and 2.27×10^{-9} m/s were recorded at 0, 1.5×10^8 , 6.0×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. In the case of BC model, values of 2.26×10^{-17} , 1.41×10^{-14} , 2.2×10^{-14} , 4.6×10^{-19} , 3.25×10^{-17} and 2.45×10^{-14} m/s were recorded at 0, 1.5×10^8 , 6.0×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. Thus, the FX model met the design maximum hydraulic conductivity value of 1×10^{-9} m/s requirement for MSW system when lateritic soil was treated with *B. coagulans* suspension density of 1.2×10^9 cells/ml, while the BC model satisfied the requirement for all the microbial densities considered and it is recommended for modelling of UHC of lateritic soil admixed with *B. coagulans* for MSW containment application.

Keywords: *Bacillus coagulans*, Brooks - Corey model, Fredlund -Xing model, Lateritic soil, Unsaturated hydraulic conductivity, Volumetric water content.

1 Introduction

The study of soil-water behaviour prior to unsaturated studies is vital especially for waste containment purposes. Compacted soil used for liners and covers in waste containment facilities are frequently unsaturated in the field. Rainfall and other moisture sources do not all the time fully saturate the liners and covers system as they flow. Thus, it is needful to examine the unsaturated flow that represent the actual field condition. Chiu and Shackelford [1] as well as Wang and Benson [2] reported that modelling of flow and transportation mechanism requires an adequate understanding of their unsaturated hydraulic properties. Khire *et al.*, [3] reported that earthen landfill covers are generally unsaturated in the field and therefore require unsaturated studies. Unsaturated hydraulic conductivity (UHC) is obtained by using soil-water characteristics curve (SWCC), which correlates matric suction (Ψ) with volumetric water content, θ (VWC).

Researchers [4-8] recommended a less difficult approach for assessing the hydrology of soil covers compacted in the field based on UHC. The basic idea is

established on the fact that covers are mostly not fully saturated in the field after rainfall and need to be studied in that state. Also, the limited amount of rainfall in the tropical region that includes Nigeria underscores the need for actual field studies. Thus, the design of covers for landfill systems are centred on the UHC. However, in the past it was difficult to calculate the soil hydraulic performance at unsaturated phase using the empirical approach [9]. These practices encompass the application of hydraulic conductivity of saturated soil and the SWCCs. The idea of using mathematical correlations was the best approach with the aid of SWCC to forecast a new hydraulic conductivity. The hypothetical bases for the UHC used are dependent entirely on SWCCs.

Studies reported in the literature [10-12] showed that some compacted soil liners do not meet the requirement for landfill use in their natural form and need to be improved using industrial additives like cement, bitumen and lime which are relatively expensive and are not friendly to the eco-system. The use of agro-industrial wastes that exhibit pozzolanic properties are also not eco-friendly. Therefore, a sustainable mechanism that is friendly to the eco-system termed microbial-induced calcite precipitation (MICP) is desirable.

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MICP is a process that encompasses carbonates production as by-product of microbial metabolic or enzyme activities of bacterial species (*Bacillus coagulans*). The technique entails a cementation procedure that harnesses natural subsurface soils using urea hydrolysis to induce calcite precipitation [13-18]. The calcite precipitate stiffens the soil and reduces its hydraulic properties. Several promising results have been recorded using the method for different engineering applications [12]. This work assesses the SWCCs and UHC of modified lateritic soil - *Bacillus coagulans* using BC and FX models.

1.1 Background of the study

Unsaturated relationship in terms of water flows in soils was suggested by Fredlund *et al.*, [9]. For an unsaturated soil, the hydraulic conductivity (k) is a variable. Also, so many elements have definite impact on k comprising of VWC among many. Fredlund *et al.*, [9] suggested that soil suction, which affects the properties of soil in unsaturated state, be defined as the matric suction or total suction of the soil. The authors also suggested that unsaturated soils permeability function be utilised to denote the relationship between the soil suction and the permeability coefficient. Conversely, it is worthy of note that the permeability coefficient for a defined soil suction, $k(\psi)$, is linked to the saturated permeability coefficient, k_s , of the saturated soil. Thus, relative coefficient of permeability, $k_r(\psi)$, is determined using the expression:

$$K_r(\psi) = \frac{k(\psi)}{k_s} \quad (1)$$

In this study, k_s was obtained from a falling head permeability test, while UHC was determined from model predictions that relate k_s and UHC using SWCCs. However, results forecast from dissimilar models are usually inconsistent. Such differences occur because it is extremely challenging to describe the UHC of soils since it is time reliant, variable and time consuming.

The Brooks - Corey model [19], k_r relative to SWCC parameters is expressed as:

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

where λ and ψ_a are described as pore size distribution index and air entry pressure in that order.

The Leong and Rahardjo [20] model for relative hydraulic conductivity forecasting, with respect to SWCC fit parameters is expressed as [21]:

$$K_r = \frac{1}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^c} \quad (3)$$

θ can be functional in its normalized form sometimes referred to relative degree of saturation, s as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

Where: Θ =The normalized θ or relative degree of saturation, θ_s =The saturated θ ; θ_r =The residual θ . Typical SWCC parameters are displayed in Figure 1

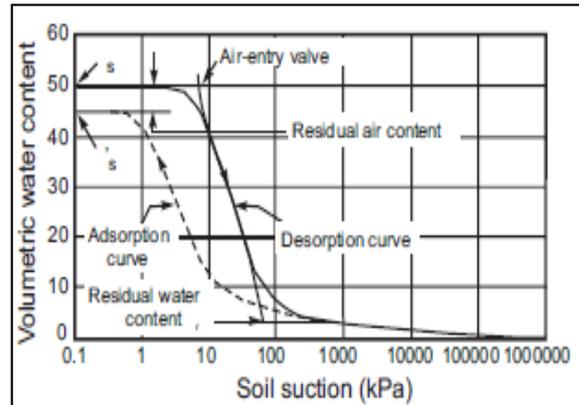


Figure 1: A typical SWCC , Source: [22]

Soils sizes affect the shape of SWCCs; thus grading of the soil plays a vital part in the understanding of flow of water in soil for containment application and in unsaturated soil studies. Soils with bigger unit sizes usually display a SWCC skewing to the left-hand of the curve accompanied by a drop in air-entry suction head, less residual water content, less saturated water content values [8]. Miller *et al.*, [8], Alavijeh *et al.*, [23] as well as Tamer *et al.*, [24] described the SWCCs as being hysteretic, having bounding curves which explains the desorption as well as the sorption practises. Nevertheless, normal technique used is to manage only the desorption curve because of experimental problems connected with sorption curve measurement as defined by Tinjum *et al.*, [25]. This curve is linked to desorption progressions only.

The Brooks and Corey [19] model for volumetric water content is expressed as:

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_a}{\psi} \right)^\lambda \quad (5)$$

The optimized parameters include θ_r , ψ_a and λ .

The Fredlund and Xing [22] model for volumetric water content is defined as

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^c} \quad (6)$$

But, θ_r is negligible and can be overlooked. Consequently, equation (6) becomes equation (7):

$$\frac{\theta_w}{\theta_s} = \frac{1}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^c} \quad (7)$$

a , b and c are the optimized parameters.

2 Materials and methods

2.1 Materials

2.1.1 Soil sample

Disturbed sample of lateritic soil was collected from Anambra state, Nigeria at 0.5 m depth and placed in poly sacks.

2.1.2 Microorganism

B. coagulans was used for the study and was classified as ATCC 8038 [26]. The microbes were isolated from the lateritic soil using serial dilution method.

2.1.3 Cementation reagent

Cementation reagent composed of 3 g Nutrient broth, 20 g urea, 10 g NH₄Cl, 2.12 g of NaHCO₃ and 2.8 g CaCl₂ per 1000 cm³ of distilled water [27]. was used in the study.

2.2 Methods

2.2.1 Index properties

Index tests were performed on untreated and treated soil as outlined in BS 1377 [28] and BS1924 [29] respectively.

2.2.2 Preparation of soil samples

Soil was mixed with *B. coagulans* at the varying suspension density of the microbes (i.e., 0, 1.5×10⁸, 6.0×10⁸, 1.2×10⁹, 1.8×10⁹ and 2.4×10⁹ cells/ml), prior to compaction; with about one-third of the volume of pore containing microbes [30]. Specimens were prepared with moulding water content (MWC) of -2, 0, and +2 % relative to optimum moisture content (OMC) and compacted with British Standard light (BSL) (or standard Proctor) energy. Cementation reagent was applied to saturate the compacted soil. After treatment, a 50 mm diameter and 50 mm height cylindrical core was used to obtain specimens from the compacted soil in the mould. The cored specimens were immersed in a water tank to enable them get saturation via capillary action. Thereafter the saturated specimens were tested in a pressure plate extractor.

2.2.3 Pressure application

The method adopted for the test using the pressure membrane apparatus (pressure plate extractor) is outlined in ASTM D3152-72 [31]. Pressures of 0, 10, 30, 100, 500, 1,000 and 1,500 kPa were applied on the saturated specimens. Pressure was applied (i.e., first from 0 –1,500 kPa), the arrangement is permitted to ditch out all the water till no drop of water was seen at the outlet. The specimens were then detached, weighed and again re-arranged before they were subjected to pressure greater than the previous. The process was repeated for pressures up to the highest pressure value of 1,500 kPa considered.

Thereafter, the specimens were removed from the equipment and oven-dried to determine the moisture content which was equal to their final gravimetric water content. The test was performed for each lateritic soil - *B. coagulans* mixture.

3 Results and discussion

3.1 Index properties

Preliminary investigations performed on the natural properties of the soil showed that the soil is fine-grained, having reddish brown colour with a natural moisture content of 11.3 %.. A more summary of the properties of the natural lateritic soil is given in Table 1.

Table 1. Properties of the natural lateritic soil

Property	Quantity
Percentage Passing No. 200 Sieve	35.4
Natural Moisture Content, %	11.3
Liquid Limit, %	37.5
Plastic Limit, %	19.3
Plasticity Index, %	18.2
Specific Gravity	2.62
AASHTO Classification	A-4(2)
USCS	SC
Maximum Dry Density, Mg/m ³	1.83
Optimum Moisture Content, %	15.3
Colour	Reddish brown
Dominant Clay Mineral	Kaolinite

3.2 Impact of microbial density on SWCC model parameters

The variation of Brooks - Corey air entry suction value ψ_a and pore-size distribution factor λ with microbial density is revealed in Table 2. The air entry (ψ_a) values (i.e., 18, 25, 87, 29, 20 and 28 kPa) increased and subsequently decreased with increase in *B. coagulans* suspension density (i.e., from 0 to 2.4×10⁹ cells/ml in that order). The initial increase may be related with the reduction in the volume of voids within the soil mass. Rowshanbakhta *et al.*, [30] reported that air entry value is inversely interrelated to the void ratio within the soil structure. Microbial hydrolyses of urea which manufactured dissolved ammonium, inorganic carbon, as well as carbon dioxide (CO₂) led to the build-up of insoluble carbonate (CaCO₃) which may have blocked the micro pores within the soil mass [30, 32]. In the case of pore size distribution factor λ , a general trend of increase (i.e., 0.739, 0.304, 0.633, 1.150, 0.698 and 0.301) was observed with higher microbial suspension density (i.e., 0 to 2.4×10⁹ cells/ml in that order). The overall assessment of these parameters show that the soil treated with *B. coagulans* suspension density of 2.4×10⁹ cells/ml relatively recorded the lower values, which is an indicator of improvement in the soil properties by the reduction in the pores spaces within the soil skeleton.

For the Fredlund-Xing model, SWCC parameter *a* (i.e., connected to inverse of air entry value and spaces caused by the pores inside the soil matrix), parameter *b* (slope factor) and parameter *c* (shape factor) with microbial density is presented in Table 2. Results largely showed an increase in parameters *a* (i.e., 46, 245, 260, 53, 54, and 280) and *b* (i.e., 0.049, 0.135, 0.216, 0.076, 0.074, and 0.092) values with increase in *B. coagulans* suspension density up to 2.4×10^9 cells/ml. Parameter *b* that governs the slope of SWCCs increased with increase in microbial density, however, parameter *c* (i.e., 5.621, 0.089, 2.786, 4.013, 2.672 and 0.928) which is related to residual water content decreased with higher microbial density. The increase in matric suction could probably be due to domination of smaller-pores in the soil matrix at higher MWC, and thus a decrease in *c* value. This is in agreement with findings reported by Fredlund and Xing [22] and Fredlund *et al.*, [33].

Table 2. Brooks - Corey (ψ_a and λ) and Fredlund-Xing (*a*, *b* and *c*) SWCC parameters with microbial density

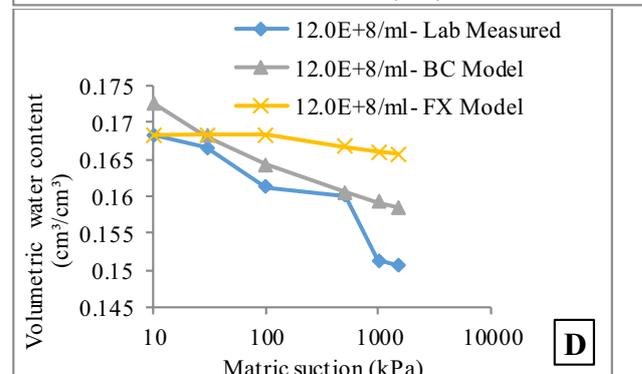
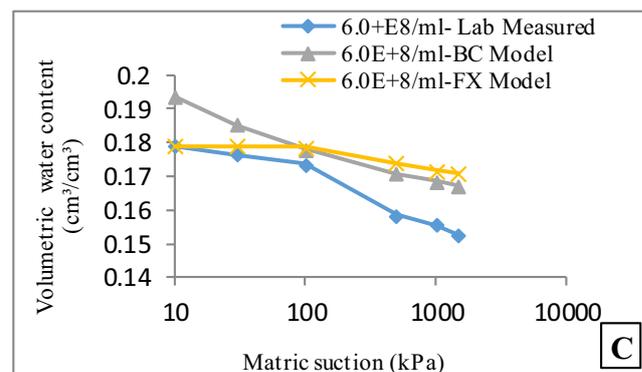
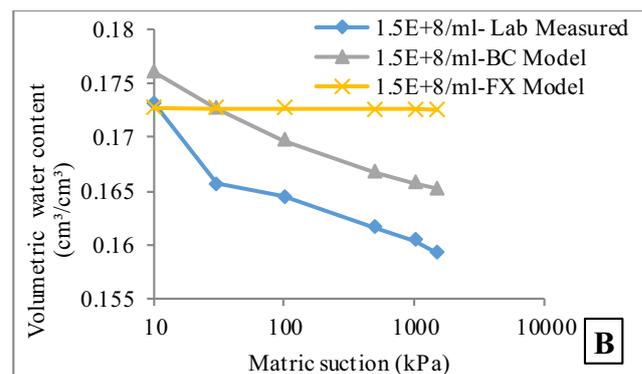
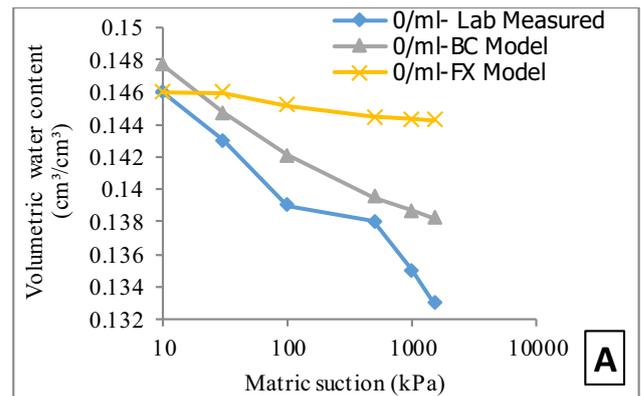
<i>B. coagulans</i> suspension density cells/ml	Brooks-Corey model parameters		Fredlund -Xing's model parameters		
	Air Entry pressure ψ_a (kPa)	Pore-size distribution index, λ	Parameters		
			<i>a</i>	<i>b</i>	<i>c</i>
0	18	0.739	46	0.049	5.621
1.5×10^8	25	0.304	245	0.135	0.089
6.0×10^8	87	0.633	260	0.216	2.786
1.2×10^9	29	1.150	53	0.076	4.013
1.8×10^9	20	0.698	54	0.074	2.672
2.4×10^9	28	0.301	280	0.092	0.928

3.3 A comparative result of SWCC

A comparative result of SWCC for measured values and the predicted ones using BC and FX models are displayed in Figures 2a-f. Generally, it was noticed that with increase in matric suction from 10 – 1,500 kPa, the VWC decreased gradually for the models and the measured results. For the natural soil, the VWC laboratory measured values of 0.146, 0.143, 0.139, 0.138, 0.135 and 0.133 were obtained for matric suctions of 10 – 1,500 kPa. BC model recorded 0.1476, 0.1447, 0.142, 0.140, 0.139 and 0.138 for matric suctions of 10 – 1,500 kPa. In the case of FX model, values of 0.1460, 0.1459, 0.1452, 0.1444, 0.1443 and 0.1442 were obtained for matric suctions of 10 – 1,500 kPa. Similar pattern was observed for all microbial densities used in the study.

Furthermore, the models overestimated the VWC with greater values than the measured results. However, the BC model overestimated the VWC at lesser matric suction over FX model for the microbial densities considered. With an increase in matric suction beginning from 30 up to 1,500 kPa, FX model overestimated the VWC over the BC model. Although, the residual VWC (θ_r) did not follow the usual path of over and under approximation when likened to the measured SWCC values as stated in

past research works i.e., [1,8,25,34-36], a decrease in VWC was observed with increase in matric suction.



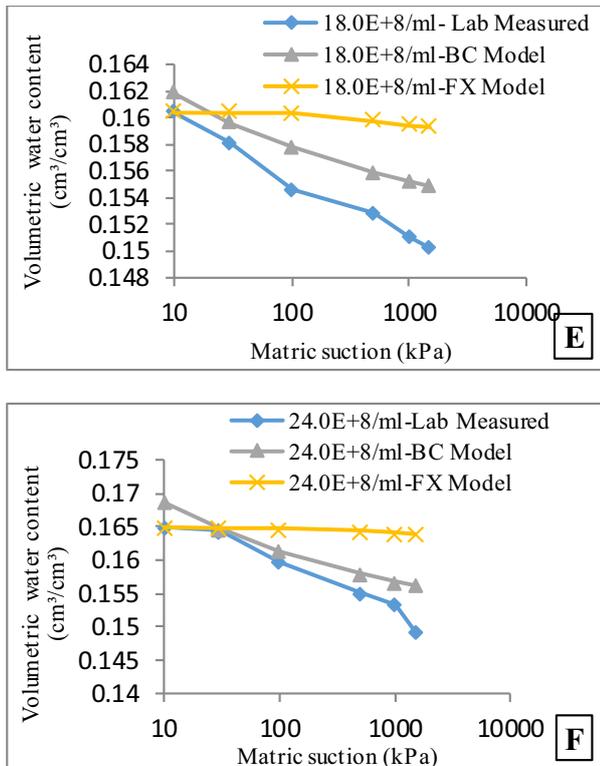


Figure 2. Measured and modelled SWCCs for varying microbial density (A) 0 cells/ml (B) 1.5×10^8 cells/ml (C) 6.0×10^8 cells/ml (D) 1.2×10^9 cells/ml (E) 1.8×10^9 cells/ml (F) 2.4×10^9 cells/ml.

3.4 Impact of microbial density on unsaturated hydraulic conductivity (UHC)

The variations of unsaturated hydraulic conductivity (UHC) with *B. coagulans* suspension density for samples prepared at OMC and compacted with BSL energy predicted using BC and FX models for matric suction of 500 and 1500 kPa is shown in Figure 3. The UHC predicted for matric suction of 500 and 1,500 kPa initially decreased from 0 up to 1.2×10^9 cells/ml for both BC and FX models with the exception of a few cases and thereafter increased with increase in microbial density. For BC model at 1,500 kPa, UHC values of 2.26×10^{-17} , 1.41×10^{-14} , 2.2×10^{-14} , 4.6×10^{-19} , 3.25×10^{-17} and 2.45×10^{-14} m/s were recorded at *B. coagulans* suspension density of 0, 1.5×10^8 , 6.0×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. In the case of FX model, at 1,500 kPa, UHC values of 2.42×10^{-9} , 2.02×10^{-9} , 9.31×10^{-10} , 8.09×10^{-10} , 1.29×10^{-9} and 2.27×10^{-9} m/s were recorded at 0, 1.5×10^8 , 6.0×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml in that order. As microbial density increased, formation of more calcites as product of MICP process may possibly be the reason for the decrease in UHC value. Also, soil particles binding and the clogging of openings in the soil skeleton as calcite are formed to fill such spaces led to lessening of the UHC. Abo-El-Enein *et al.*, [37], Muthukkumaran and Bettadapura [38], Chi *et al.*, [17] reported similar results.

The FX model satisfied the design maximum hydraulic conductivity value of 1×10^{-9} m/s for waste containment system for *B. coagulans* suspension density of 1.2×10^9 cells/ml treatment of lateritic soil, while BC model which met the requirement at all the microbial suspension

densities considered is recommended for use in modelling the UHC of the modified soil. The recorded finding shows that BC model has a more promising outcome in determining UHC in the field than FX model. Thus, these results should be carefully applied under field conditions in order to achieve the desired output. Also, adequate microbial density as achieved in the laboratory should be used in the field to achieve the target UHC values as specified in the literature.

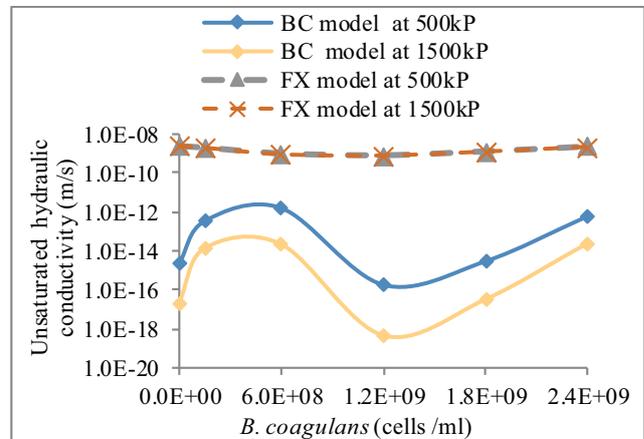


Figure 3. Plot of UHC with microbial density/ml based on Brooks-Corey (BC) and Fredlund-Xing (FX) models at 500 and 1500 kPa matric suction.

4 Conclusion

A comparative study of SWCCs for compacted lateritic soil - *B. coagulans* mixtures was carried out. Based on the laboratory and model outputs, the following conclusions can be made:

1. Generally, BC and FX models overestimate the volumetric water content (VWC). Also, the VWC reduced with higher matric suction for the measured and modelled values.
2. The unsaturated hydraulic conductivity (UHC) predicted for matric suction of 500 and 1,500 kPa initially decreased from 0 up to 1.2×10^9 cells/ml for both FX and BC model with the exception of a few cases and thereafter increased with increase in microbial suspension density.
3. For FX model at 1,500 kPa, UHC values of 2.42×10^{-9} and 2.27×10^{-9} m/s were recorded at *B. coagulans* suspension densities of 0 and 2.4×10^9 cells/ml, respectively. In the case of BC model, values of 2.26×10^{-17} and 2.45×10^{-14} m/s were recorded at 0 and 2.4×10^9 cells/ml.
4. The FX model satisfies the design maximum hydraulic conductivity value of 1×10^{-9} m/s for waste containment system at *B. coagulans* suspension density of 1.2×10^9 cells/ml, while the BC model met the requirement at all for all *B. coagulans* suspension density considered and therefore it is recommended for modelling the UHC of the modified lateritic soil for municipal solid waste containment application.

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