EFFECTS OF ORDINARY PORTLAND CEMENT ON THE SOIL-WATER CHARACTERISTICS CURVE OF LATERITIC SOIL

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Abstract

The lateritic soil, abundant in tropical and sub-tropical countries, is a common construction material used for various purposes, such as constructing transportation infrastructures, landfills, and other earthworks. The residual lateritic soil is usually located in the vadose zone (unsaturated zone) situated above the water table. Therefore, this paper investigates untreated and cement-treated lateritic soil behaviour in terms of Soil Water Characteristics Curve (SWCC), a key topic in unsaturated soil mechanics. The soil sampling was performed from Universiti Teknologi Malaysia campus, Johor Bahru, and then the collected soil was tested in the laboratory. The 3%, 6%, 9%, and 12% ordinary Portland cement (OPC) according to the dry soil weight were utilized, and then the necessary basic tests, compaction tests, and pressure plate tests were performed. The obtained data points from pressure plate extractor equipment were fitted using Fredlund and Xing and van Genuchten models. The results exposed that the used soil is plastic silt (MH) and A7-5 according to the Unified soil classification System (USCS) and AASHTO, respectively. The Maximum Dry Density (MDD) increased from 1.39 g/cm^3 for untreated to 1.419 g/cm^3, 1.447g/cm^3, 1.46g/cm^3, and 1.479g/cm^3 for 3%, 6%, 9%, and 12% cement, respectively. Similarly, the Optimum Water Content (OMC) increased from 28% to 29.5, 30, 30.5, and 31% by adding 3, 6, 9, and 12% cement, respectively. Regarding the obtained SWCC results, the Air Entry Value (AEV) increased with the increasing cement content. Overall, the results revealed that the water holding capacity of lateritic soil increases with increasing cement content.

Keywords: **Lateritic soil, SWCC, ordinary portland cement (OPC), unsaturated zone, AEV**

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Introduction

The unsaturated soil mechanic is of great importance, particularly for the infrastructure and earthwork above the water table, such as shallow foundations, embankments, landfills, dams, and slopes. The SWCC of the using material is the cornerstone in applying unsaturated soil mechanics (Lins *et al*., 2009). The soil-water characteristic curve (SWCC) shows the relationship between the degree of saturation, gravimetric water content, and volumetric water content (Yang *et al*., 2008). Therefore, the SWCC is a key issue in unsaturated soil mechanics whereby the unsaturated hydraulic conductivity and unsaturated shear strength can be calculated (Osinubi and Amadi, 2010; Fredlund *et al*., 2011). In the same way, to model the water flow in the soil, two parameters, namely hydraulic conductivity and SWCC, are necessary (Gofar and Rahardjo, 2017; Fredlund, 2019).

Varying methods such as axis translation technique, osmotic technique, vapour technique, and filter paper can be employed to obtain the SWCC curve. Besides, the centrifuge method is another method that has been effectively used for compacted and fine-grained soil (Khanzode *et al*., 1999), while the dew point technique was employed for the SWCC of road subgrade made of Class C fly ash stabilized-silt and clay (Wen *et al*., 2015). The reliability and consistency of the axis translation technique, osmotic technique, and vapour technique have been proven for application in compacted silty sand (Ng *et al*., 2015). The axis translation technique proposed by HIlf (1956) is commonly applied in triaxial, shear box, Oedometer, and pressure plate extractor equipment to measure the matric suction. However, the total suction consists of matric suction and osmotic suction, but the matric suction is often considered in civil engineering because it has a considerable share in unsaturated soil characteristics (Vanapalli *et al*., 1996). Numerous studies have been conducted previously regarding the soil-water characteristic curves of different soils (Huang *et al*., 2009; Miguel and Vilar, 2009; Elkady *et al*., 2015; Han *et al*., 2017; Yamusa *et al*., 2018; Azmi *et al*., 2019). Yamusa *et al*. (2018) found the relationship between volumetric water content and matric suction for a particular residual tropical soil for landfill application using the pressure plate extractor. Regarding their study, the fine grain content increase resulted in increasing the residual tropical soil's water retention capacity. Besides, the filter paper test results for five fine-grain subgrade soil revealed that the plasticity index and clay content increase the water retention capacity (Han *et al*., 2017). The increase of Air Entry Value (AEV), the main feature in SWCC, was found with growing clay content (Huang *et al*., 2009; Elkady *et al*., 2015).

Similarly, the air entry value was also increased by filling the macropores of sand caused by increasing the concentration of urea-calcium chloride solution (Chen *et al*., 2021). The influence of lime on SWCC also unveiled that AEV rises with the increasing percentage of lime (Jiang *et al*., 2019; Li *et al*., 2020). Besides, the AEV for wet of optimum moisture content is higher than that of dry of OMC (Elkady *et al*., 2015). Unlike most researches conducted for SWCC using pressure plate, Thu *et al*. (2007) used the unsaturated triaxial cell to find the SWCC of compacted silt. Their research results showed the increase of air entry value (AEV) with confining pressure development. The SWCC properties of two Brazil's residual granite soils having saprolitic and lateritic nature were studied using the filter paper method in undisturbed and disturbed conditions (Heidemann *et al*., 2016). Their research results disclosed that the lateritic soil has a higher suction level than saprolitic soil; the suction level increased for disturbed specimens due to pores' change and developed clay clusters size upon compaction. The homogeneity of the SWCC curve of a lateritic soil at different depths in Brazil was highlighted in the research by (Miguel and Vilar, 2009).

Regarding their results, the SWCC curves for the lateritic soil obtained from different depths showed a homogeneous shape for all the samples. Similarly, the SWCC of two compacted and two slurred soil specimens were investigated; and the authors proposed a water retention model based on the obtained results (Tarantino, 2009). The influence of 15%, 17.5%, 20%, and 22.5% para rubber biopolymer on particular sand in Thailand has been investigated in terms of SWCC (Lukjan *et al*., 2020). The filter paper method results reported increased water holding capacity and AEV with rising para rubber biopolymer content, while the hydraulic conductivity decreased. Cement has been used in 2%, 4%, and 6% to treat a particular natural loam soil in Algeria (Tewfik *et al*., 2020). The AEV and gravimetric water content or degree of saturation were raised with increasing cement percentage regarding their results.

Overall, varying empirical models have been used for the calculation of the SWCC of soil. Statistical estimation, correlation of basic soil properties with the fitting parameters, physico-empirical modelling, and artificial intelligence are the main four empirical predictive models for calculating the SWCC (Johari *et al*., 2006). Among these four methods, the second one is applied commonly. For instance, Brooks and Corey (1964) and van Genuchten (1980) models have been used for SWCC of untreated and Bagasse ash treated lateritic soil in Nigeria (Osinubi and Eberemu, 2010). The Fredlund and van Genuchten (1980) and Fredlund and Xing (1994) models were applied by Azmi *et al*. (2019) for particular mining sand in Malaysia. According to their results, the van Genuchten (1980) and Fredlund and Xing (1994) models were reliable for fitting mining sand data obtained using a pressure plate extractor.

On the other hand, the modified van Genuchten and modified Brooks-Corey model's effectiveness and reliability demonstrated the SWCC of compacted biochar and rapeseed mixed-loam and sandy loam (Garg *et al*., 2020). However, lateritic soil's water retention characteristics have been studied relatively vastly, as mentioned earlier, but the research of SWCC of cement-treated lateritic soil is not sufficient. Therefore, this research explores the influence of Ordinary Portland Cement on the SWCC of lateritic soil, particularly on the AEV. Besides, the Fredlund and Xing (1994), modified van Genuchten (1980) and Fredlund and Xing (1994) models were employed on the results obtained from the pressure plate extractor.

Soil Water Characteristic Curve

The soil-water characteristic curve defines the relationship between water content and matric suction. The soil-water characteristic curve is divided into three segments: boundary effect or capillary saturation zone, transition or funicular zone, and residual saturation zone, as shown in Figure 1 (Vanapalli *et al*., 1996). The water content is dominant in the boundary effect zone, but it continues up to the air entry value, where the air starts to enter the pores and replace the water content. Once the residual saturation zone starts, the moisture content movement happens mostly in vapour form (Sillers *et al*., 2001). The SWCC of soil can be applied for varying purposes. For instance, the unsaturated shear strength of soil, which is a crucial parameter in designing all civil engineering infrastructures, can be controlled and estimated according to the SWCC curve (Oh *et al*., 2012). Similarly, Vanapalli and Oh (2010) proposed a model that predicts the modulus of elasticity for both coarse and fine grain soil, according to SWCC. Furthermore, the SWCC of soil is one of the key input data in numerical modelling of unsaturated slope stability analysis (Roshan *et al*., 2021).

Varying factors such as soil texture and mineralogy, amount, size, and distribution of pores affect soil's SWCC properties (Vanapalli *et al*., 1999; Miguel and Vilar, 2009). In this context, Fredlund and Zhang (2017) explored the influence of initial conditions on the SWCC. The air-entry value (AEV) and residual water content are the main parameters that characterize soil's SWCC behaviour. The suction in which the air breakthrough into the soil pores happens is called AEV, while the residual water content is the point where the disconnection of pore water starts, as shown in Figure 1.

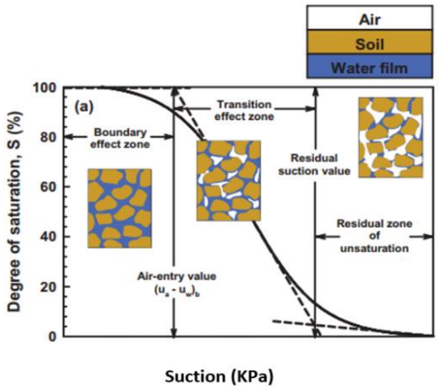

Figure 1. A typical SWCC (Oh and Vanapalli, 2011)

The SWCC experimental points obtained in the laboratory can be fitted using mathematical models. Among the proposed models the Equation 1, which was proposed by Fredlund and Xing (1994) and containing three fitting parameters, a, n, and m, is flexible (Sillers *et al*., 2001) and produces the best fitting (Leong *et al*., 2001).

$$\theta(\psi)=\frac{\theta_s}{[\ln(e+(\frac{\psi}{a})^n)]^m} \quad (1)$$

Where the, $\theta(\psi)$ is volumetric water content as a function of suction, ψ is suction, e = 2.718 is the Euler digit. The a is a fitting parameter describing the inflection point suction value. The n parameter is connected to the desaturation zone changing rate. Finally, the SWCC asymmetry is related to the m parameter. In civil engineering practices, mostly matric suction (u_a-u_w) is considered instead of total suction (ψ). A correction factor shown in Equation 2 has been proposed for Equation 1 to fit the water content equal to zero when the suction reaches 1,000,000 KPa (Fredlund, 2000).

$$C(\psi) = [1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{\ln(1 + \frac{1000000}{\psi_r})}] \quad (2)$$

Where the, $C(\psi)$ is the correction factor due to suction, ψ is suction, and ψ_r is the residual suction.

Other than Fredlund and Xing (1994), the model proposed by Van Genuchten (1980) (see Equation 3) is also used on a significant scale worldwide.

$$\theta(\psi) = \frac{\theta_s}{[1 + (\alpha \times \psi)^n]^m} \quad (3)$$

Where $\theta(\psi)$ is volumetric water content due to the suction α is the inverse of air entry value, n and m are factors relating to the shape of the SWCC curve. The correlation between the n and m parameter for the Genuchten (1980) model is depicted in Equation 4.

$$m = 1 - \frac{1}{n} \quad (4)$$

Materials

The lateritic soil used in this study was sampled from Universiti Teknologi Malaysia in Johor Bahru, Malaysia. The transported soil in the lab was tested using coupled methods of sieving and laser diffraction analyser for particle size distribution, cone penetration method for limit equilibrium, Casagrande method (threading of soil) for plastic limit, standard compaction for Maximum Dry Density (MDD), and Optimum Moisture Content (OMC), Compression test for Unconfined Compressive Strength (UCS), and finally the Pressure Plate test for SWCC properties of the desired specimens. According to the obtained results, the soil is categorized as plastic silt (MH) and A-7-5 according to the Unified Soil Classification System (USCS) and AASHTO method, respectively, containing 69.67% fine grains and 30.33% coarse grains, which is consistent with the results of (Kassim *et al.*, 2012). Overall, Table 1 summarizes all primary necessary test results, while Figure 2 depicts the Particle Size Destruction (PSD) for the soil and Ordinary Portland Cement (OPC) used in this study. A study by Wahab *et al.* (2021a) contains further information about the soil and cement utilized in this investigation.

Table 1. Primary tests results

Properties	Symbol	Value
Liquid limit %	L_l	70.3
Plastic limit %	Pl	42
Plasticity index %	Pi	28.3
Gravel %	-	12.79
Sand %	-	17.54
Silt %	-	61.26
Clay %	-	8.41
Soil classification:		
USCS		MH
AASHTO		A-7-5
Specific gravity	G_S	2.74
Dry unit weight: (KN/m^3)	γ	13.64
Unconfined Compressive Strength (UCS) (kPa)	qu	200.75
Undrained Shear Strength: (kPa)	Su	100.38

Table 2. Compaction results

Cement (%)	MDD (g/cm^3)	OMC (%)
0	1.39	28
3	1.419	29.5
6	1.447	30
9	1.46	30.5
12	1.479	31

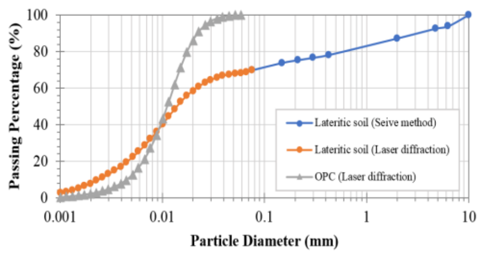

Figure 2. Particle size distribution (PSD)

The standard compaction test was carried out to obtain the compaction curve of untreated and cement treated specimens. The compaction test results for the untreated soil and treated soil with 3%, 6%, 9%, and 12% of cement are tabulated in Table 2.

Methods

Pressure Plate Extractor

The principle of pressure plate extractor is based on the axis translation technique. The test was performed using the pressure plate procedure, according to ASTM D 2325-68 standard (Yang *et al.*, 2008). The samples for determining the SWCC can be prepared in three methods: slurry, compacted, and undisturbed (Fredlund and Zhang, 2017). In this research, the specimens were compacted according to MDD and OMC in rings having 50 mm diameter and 20 mm height in the same size used by (Miguel and Vilar, 2009). The influence of ring size on the pressure plate results is negligible; therefore, a small size circular ring was selected to reduce the equalization time (Wang *et al*., 2015). The varying MDD and OMC were employed to prepare specimens since the cement content increases the MDD and OMC of untreated soil (Wahab *et al*., 2021b). After compaction of the calculated amount of soil inside the rings, the rings were kept in a thermostatically moisture-controlled chamber for seven days. The temperature and humidity of the chamber were set at 25°C and about 100%, respectively. The initial degree of saturation in compacted specimens usually ranges from 70% to 85% (Fredlund and Zhang, 2017). Therefore, the cured specimens were then saturated before starting the test. The test was started upon saturation of the compacted specimens. In the drying path adopted in this research, the air pressure range was 1KPa -850 KPa. The specimens

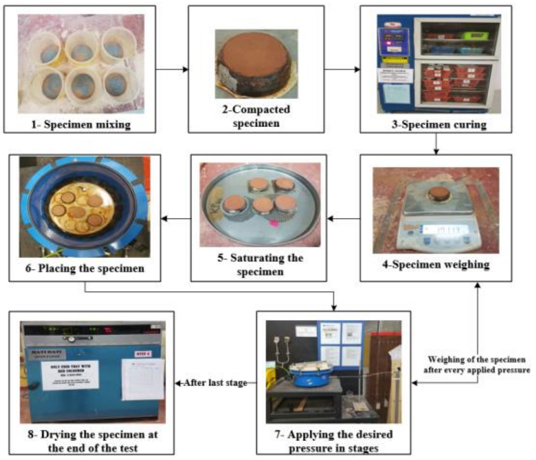

Figure 3. Stages of pressure plate test

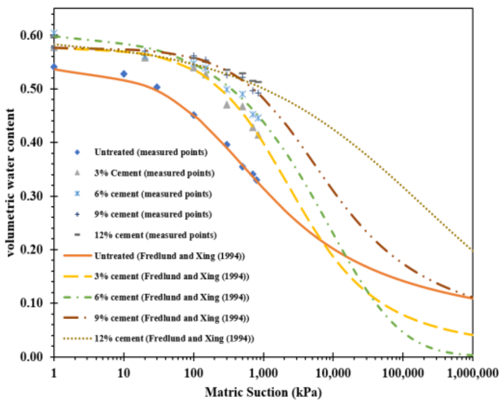

Figure 4. SWCC, according to measured and Fredlund Xing (1994) model

were weighed after the suction equalization in every stage of pressure increasing. Finally, at the end of the test, the specimens were put in an oven to be dried and accordingly, the moisture content was back-calculated for every applied air pressure. The procedure of doing the pressure plate test is portrayed in Figure 3, step by step.

Results and Discussions

The experimental data obtained using a pressure plate extractor is tabulated in Tables 3 and 4 for untreated and 3%, 6%, 9%, and 12% cement-treated

Table 3. Obtained experimental data points for untreated lateritic soil

Matric suction (kPa)	Volumetric water content
	Untreated
1	0.541
10	0.528
30	0.503
100	0.451
300	0.396
500	0.355
700	0.340
800	0.329

Table 4. Obtained experimental data points for cement-stabilized lateritic soil

Matric suction (kPa)	Volumetric water content			
	3% C	6% C	9% C	12% C
1	0.578	0.604	0.577	0.596
20	0.558	0.561	0.570	0.563
100	0.540	0.548	0.561	0.558
150	0.527	0.539	0.554	0.551
300	0.471	0.499	0.526	0.535
500	0.467	0.490	0.522	0.529
700	0.429	0.452	0.497	0.515
850	0.414	0.446	0.492	0.513

Table 5. Fredlund and Xing (1994) fitting parameters

Cement content (%)	a (kPa)	m	n	θs
0 (untreated)	160	0.87	0.71	0.54
3	1350.9	1.63	0.77	0.57
6	103582	9.60	0.50	0.60
9	2067.9	1.04	0.78	0.57
12	618300	3.62	0.30	0.59

Table 6. van Genuchten (1980) fitting parameters

Cement content (%)	α	m	n	θs
0 (untreated)	0.021	0.14	1.16	0.54
3	0.005	0.16	1.19	0.57
6	0.008	0.11	1.13	0.60
9	0.004	0.10	1.11	0.57
12	0.049	0.035	1.03	0.59

specimens, respectively. The obtained experimental data were then used in SWRC-Fit software to determine the fitting parameters for van Genuchten (1980) and Fredlund and Xing (1994) models. The fitting parameters obtained for van Genuchten (1980) and Fredlund and Xing (1994) models are illustrated in Tables 5 and 6, respectively.

The experimental data were fitted using the Fredlund and Xing (1994) model according to Equation 1. The fitted curves are in a desirable agreement with experimental data for both untreated and treated soil, as illustrated in Figure 4. In Figure 4, unlike the SWCC of particular mining sand used in the research by Azmi *et al*. (2019), the residual portion is situated in an extensive suction range. This issue can be attributed to the type of soil in such that for fine-grain soil like clay and treated soil, the residual suction is more than that of coarse soil. Therefore, the residual suction can probably equal to 1,500 KPa for most of the soils (Fredlund, 2000). Thus, in this research, 1,500 KPa was considered for the residual suction to find the correction factor according to Equation 2. The calculated correction factor was then multiplied to Equation 1 to fit the SWCC for the zero-water content in 1,000,000 KPa suction. Thus, after applying the correction factor, the changing of Figure 4 can be seen in Figure 5. Having considered the idea that the zero water content will be obtained with 1,000,000 KPa and the residual suction of almost all types of soil is equal to 1,500 KPa (Fredlund, 2000), the modified Fredlund and Xing (1994) (Figure 5) is more suggestable compared to the Fredlund and Xing (1994) model (Figure 4), and van Genuchten (1980) model (Figure 6).

The air entry value (AEV) increased with an increase in cement, as shown in Figures 4, 5, and 6. This phenomenon is ascribed to the size of soil pores (Chen *et al*., 2021) decreased with cement content. The results obtained for the AEV trend are consistent with that of in the research by (Hoyos *et al*., 2007). However, unlike the result revealed in the research by Hoyos *et al.* (2007), the soil's volumetric water content in the current research increased by enhancement in cement percentage. This discrepancy is because of OMC and MDD values; varying OMC and MDD were used in this research according to the cement content shown in Table 2. Whereas in the study by Hoyos *et al.* (2007), the untreated OMC and MDD have also been applied for treated specimens. Thus, the higher the initial or moulding water content, the higher the volumetric water content expected in SWCC. Figure 7 represents the AEV with respect to cement content, which was obtained based on Figure 5. Regarding the results obtained, the untreated soil air entry value is 25 KPa, then it increases to 185 KPa, 270 KPa, 330 KPa, and 490 KPa for 3%, 6%, 9%, 12% cement, respectively. This inclination is attributed to the small pores caused by adding of cement. Ng and Pang (2000) found that the initial dry density, initial water content, soil structure, drying and wetting history, and stress history affect the SWCC. Hence, in this study, the increment trend of AEV with cement dosage addition can be related to compaction (MDD and OMC) and changed soil structures caused by cement content. The overall results obtained in this paper are consistent with the

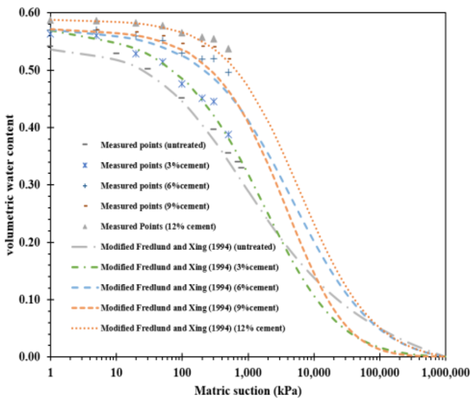

Figure 5. **SWCC according to measured points and modified Fredlund and Xing (1994) model**

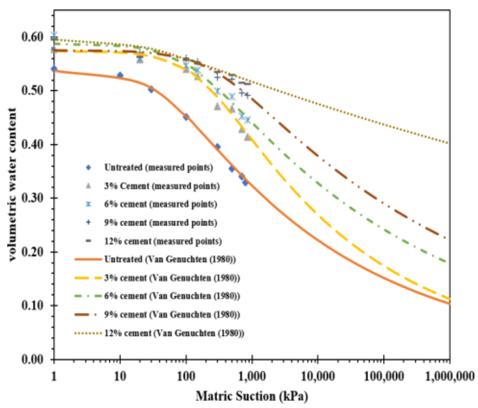

Figure 6. **SWCC according to measured points and van Genuchten (1980) model**

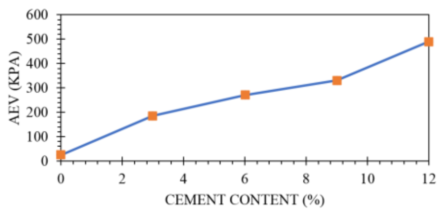

Figure 7. **Air entry value with respect to ordinary Portland cement content**

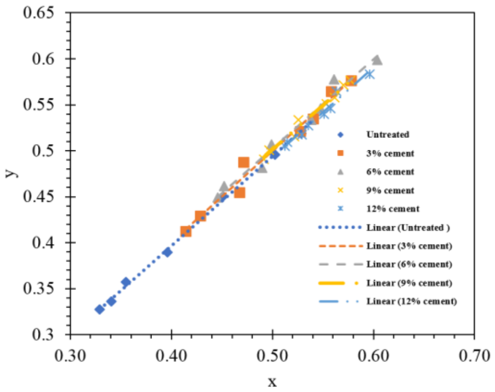

Figure 8. **Comparison of measured (x) and calculated or predicted (y) volumetric water content according to Fredlund and Xing (1994) model**

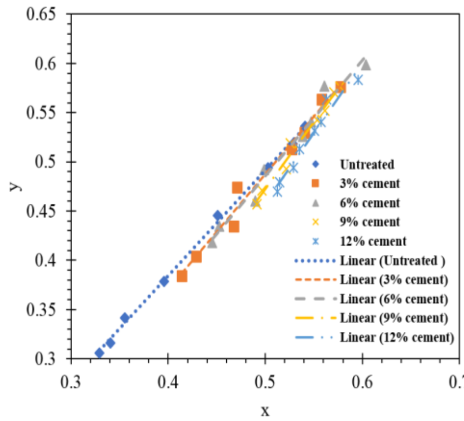

Figure 9. **Comparison of measured (x) and calculated or predicted (y) volumetric water content according to modified Fredlund and Xing (1994) model**

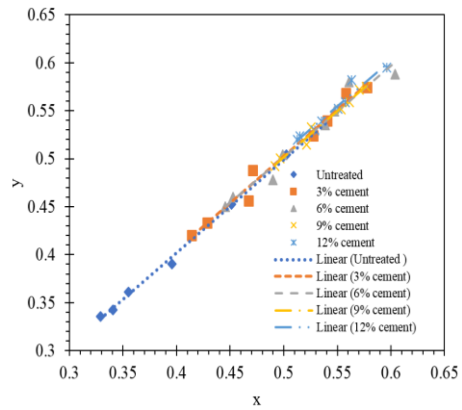

Figure 10. **Comparison of measured (x) and calculated or predicted (y) volumetric water content according to van Genuchten (1980) model**

previously performed researches (Jiang *et al*., 2019; Lukjan *et al*., 2020; Tewfik *et al*., 2020).

The regression analysis of Fredlund and Xing (1994), modified van Genuchten (1980) and Fredlund and Xing (1994) models are portrayed in Figures 8, 9, and 10, respectively. An acceptable agreement between measured and calculated (predicted) volumetric water content can be seen in Figures 8, 9, and 10. Similar to the results obtained by Wen *et al*. (2015) it was found that the van-Genuchten (1980) and Fredlund and Xing (1994) models, along with the modified Fredlund and Xing (1994) model, can fit the experimental points suitably. For more details, the linear regression equations are tabulated in Tables 7, 8, and 9 according to Figures 8, 9, and 10, respectively. R^2 criteria can evaluate the reliability of obtained linear regression equations. Overall, all three models are effective and reliable for all the desired cement content since the R^2 value is above 0.95, as shown in Tables 7, 8, and 9. R^2 = 1 value for untreated soil in Tables 7, 8, and 9 indicate the closeness of measured experimental data point to fitting models. Therefore, regarding the R^2 value, it is perceived that the untreated soil can desirably be fitted using all three models, even with the limited number of measured points at low suctions. The lowest R^2 value is 0.95, 0.96, 0.96 for van Genuchten in 12% cement, van Genuchten in 6% cement, and modified Fredlund and Xing in 12% cement, respectively. Thus, additional experimental points in high suction value are suggested for treated soils, particularly for high cement percentages for the effective fitting of measured points. This issue can be attributed to the high residual suction of cement-treated specimens.

Conclusions

This paper provides relatively comprehensive information about the influence of cement on the lateritic soil in terms of SWCC. The experimental data of SWCC was determined using the pressure plate extractor method in the drying path. Then the experimental data were fitted by Fredlund and Xing (1994), modified van Genuchten (1980) and Fredlund and Xing (1994) mathematical models. Overall, the following conclusion can be drawn from the results of this research:

1. Overall, the SWCC of lateritic soil meliorates by using ordinary portland cement (OPC). Therefore, the cement-treated lateritic soil can be employed as a construction material for road and railway construction, landfill cover, embankment, and slope stability.

Table 7. Linear regression equations according to Figure 8

cement (%)	Fredlund and Xing (1994)	
	Equation	R^2
0 (untreated)	y = 0.9742x + 0.0069	1.00
3	y = 0.9955x + 0.0018	0.98
6	y = 0.9696x + 0.0178	0.98
9	y = 0.9661x + 0.0182	0.98
12	y = 0.9847x	1.00

x = measured volumetric water content; y = calculated or predicted volumetric water content

Table 8. Linear regression equations according to Figure 9

cement (%)	Modified Fredlund and Xing (1994)	
	Equation	R^2
0 (untreated)	y = 1.0744x - 0.0456	1.00
3	y = 1.1721x - 0.0989	0.98
6	y = 1.1789x - 0.104	0.97
9	y = 1.3543x - 0.2048	0.98
12	y = 1.4156x - 0.2494	0.96

x = measured volumetric water content; y = calculated or predicted volumetric water content

Table 9. Linear regression equations according to Figure 10

cement (%)	van Genuchten (1980)	
	Equation	R^2
0 (untreated)	y = 0.9718x + 0.0129	1.00
3	y = 0.9724x + 0.016	0.98
6	y = 0.9485x + 0.0276	0.96
9	y = 0.9645x + 0.019	0.98
12	y = 0.9602x + 0.0266	0.95

x = measured volumetric water content; y = calculated or predicted volumetric water content

2. The SWCC results obtained in this study can be applied to calculate unsaturated hydraulic conductivity, shear strength, and numerical modelling of unsaturated lateritic and cement-treated lateritic soil.
3. The volumetric water content increased with the addition of cement content. Thus, the SWCC of stabilized specimens is situated above the untreated specimen, indicating more water content for treated lateritic soil in the same suction.
4. The air entry value (AEV) increased from 25 kPa for untreated to 185, 270, 330, and 490 kPa for 3%, 6%, 9%, and 12% cement, respectively. Thus, this issue indicates that the water infiltration and flow can be delayed and prevented when lateritic soil is stabilized by cement.
5. The increasing trend of AEV with the raise in cement content is attributed to the decreased pores size. Thus, the more the cement content, the more energy or matric suction needed to start water removal from soil pores.

The van Genuchten (1980), Fredlund and Xing (1994), and modified Fredlund and Xing (1994) were used for fitting of experimental data. All three models fitted the unsaturated lateritic soil effectively, as can be perceived from $R^2 = 1$. However, a few extra points at the hi gh suction level are suggested for better results, particularly for cement-treated soil. These supplementary points at high suction can be obtained using filter paper or other methods.

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