MEASUREMENT AND ESTIMATION OF SOIL WATER CHARACTERISTIC CURVE FOR FOUR UNSATURATED TROPICAL SOILS

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Abstract: Infrastructures are mostly built on unsaturated soil in the tropical region such as Nigeria, yet soil investigations and designs are based on saturated soil mechanics owing to difficulties associated with soil suction measurements using direct methods such as pressure plate extractor, triaxial testing equipment for testing unsaturated soil, etc. Soil water characteristic curve is an important parameter for estimating unsaturated soil property function. This research considered an indirect method (filter paper) of laboratory soil suction measurement (which is relatively simple, fast and inexpensive) and predictive correlation equations for estimating soil water characteristic curve from index properties of soil for four unsaturated tropical soils of Nigeria, three predictive correlation equations were used in this research namely; Navid *et al* model (2012), Zapata *et al* model (2000) and Witczak model (2006), the soil water characteristic curve constant parameters computed from these models were fitted through either Van Genuchten model (1980) or Fredlund & Xing model (1994). Results of air entry values of soils from experimental work and predictive correlation equations were in close range which indicated that in spite of the difficulties experienced in performing laboratory suction test, the predictive correlation equations such as the ones used in this research were found to be proper for estimating soil water characteristic curve.
Keywords: Soil water characteristic curve; matric suction; tropical soils; filter paper method; and predictive correlation models

1. INTRODUCTION

Unsaturated soils are commonly found in many parts of the World, especially at shallow depths from the surface and in arid and semi-arid areas where the natural ground water table typically is at a greater depth [13]. In other cases, soils are usually compacted and used in many civil engineering works, such as roads, embankments, earth dams, backfills and hydraulic barriers. Compacted soils are invariably unsaturated at the time of placement and possess negative pore-water pressure or suction. The presence of air and water within the pore spaces between the soil particles generates capillarity effects that create suction where the pore water pressure is negative, provided that pore air pressure is zero [22]. Swelling clays, collapsible soils and residual soils are all examples of unsaturated soils encountered in engineering practice. These soils are often referred to as 'problematic soils'. Common to all of these soils is their negative pore-water pressures which play an important role in their mechanical behaviour and also make them difficult to test in the laboratory [13].

Soil suction can simply be defined as the unit attractive force of the soil for water [24]. The measurement of soil suction in engineering practice is very important for the application of the theory and practice behind unsaturated soil mechanics. Soil suction is one of the most important stress variables describing the behaviour of the unsaturated soils. In many cases, the soils are mostly unsaturated and behave quite differently from that predicted by saturated soil mechanics theory. Soil suction and positive pore water pressure are two similar important parameters in regard to describing the behaviour of unsaturated and saturated soils respectively [18]. Suction is a function of soil structure and soil water content. The relationship between soil suction (matric suction or total suction) and water content (or degree of saturation or volumetric water content) is termed as soil-water characteristic curve (SWCC) and it is a crucial tool to predict and interpret the behaviour and response of unsaturated soils [13]. The measurement of soil suction is therefore a prerequisite for understanding the behaviour of unsaturated soils and can be measured through direct and indirect methods. Tensiometer, suction probe, and null-type axis translation device are the commonly used techniques for direct measurement of matric suctions ([27]; [28]; [32].) These devices employ the axis-translation technique [15] and require a separation between water and air phases, usually by using a ceramic disk with high air-entry value. Indirect suction measurement methods measure the moisture equilibrium condition of the soil instead of suction [5]. Several of the available techniques can be used to measure soil suction indirectly; these include the use of psychrometers, chilled-mirror potentiometer, thermal and electrical conductivity sensors, and the filter paper technique.

The soil – water characteristics curve (SWCC) defines the relationship between (pore water suction) matric suctions (ψ) and water content [gravimetric (w) or volumetric (θ) or degree of saturation (S)] [30]. The soil – water characteristics can be described as a measure of the water holding capacity (i.e storage capacity) of the soil as the water content changes when subjected to various values of suction. The *soil – water characteristics* is a conceptual and interpretative tool through which the behaviour of unsaturated soils can be understood. As the soil moves from the saturated state to drier states (unsaturated states), the distribution of the soil, water and air phases change as the stress state changes. The relationships between these phases take on different forms and influence the engineering properties of unsaturated soils ([11]; [10];

[31].). The shape of the SWCC is a function of the soil type. Soils with smaller pores have higher air entry pressure (ψa). Soils with wider ranges of pore sizes exhibit greater changes in matric suction with water content ([17]; [13]. [12].). The SWCCs of compacted clay soils depend on the compaction water content, compactive effort and plasticity index [30]. Several models have been used to describe the SWCC, commonly used one includes the [13]. [34]; [13]; [9]. and these were reviewed by [20]. Approaches for the determination of soil water characteristic curve can be classified broadly into two, experimental laboratory measurement of soil suction versus water content (may be conducted through direct and indirect tests) and predictive correlation equation models which were mostly formulated from grain size distribution and soil index properties such as plasticity index, percent passing sieve no. 200 and group index. Numerous models can be found in the literature. Such equations basically consist of two or three constant evaluated by making use of either suction laboratory results in various water contents or statistical relations based on other soil properties. According to existing difficulties in evaluation of these curves experimentally and noticeable variability, the estimation of such parameters has widely been used by many researchers.

The filter paper method was developed by soil scientists and agronomists for measuring soil suction (For example, [16]; [8]; [1]). In geotechnical engineering fields, many researchers have also used the technique as a routine method for suction measurement (For example, [23]; [6]; [23] [7]; [18]; [29]; [20]). The advantages of filter paper method are the ability to measure matric and total suctions, and are considered to be an inexpensive, reasonably accurate, and technically simple method that can measure a wide range of soil suction. The working principle behind the filter paper method is that the filter paper will come to equilibrium with the soil either through vapour flow or liquid flow, and at equilibrium suction value of the filter paper and the soil will be the same. If the filter paper is allowed to absorb water through vapour flow (no contact between the filter paper and soil), then only total suction is measured. However, if the filter paper is allowed to absorb water through fluid flow (contact between the filter paper and soil), then only matric suction is measured [5]. Whatman No. 42 is the most commonly used type of filter paper. [19] stated that the consistency between the calibration curves obtained using different techniques and by different authors are greater by using Whatman No. 42 than Schleicher and Schuell No 589. The filter paper method is highly dependent on the performance (and speed) of the operator and calibration curves used. [25] suggested that the adopted conditions and testing procedures for calibrating the filter paper should be similar to the actual soil suction measurements.

Even though constitutive relationships that utilize the concepts of unsaturated soils have been proposed for the classic areas of interest to geotechnical engineers, the application or implementation into engineering practice has been rather slow. One of the reasons for the delay in the application of unsaturated soil mechanics in practice is with no doubt the time required for the determination of the SWCC in the laboratory, and also the specialized equipment and training needed. An alternative way to determine the SWCC via laboratory testing, is a method that estimates or derives the SWCC based on well-known soil index properties [14].

Several attempts have been made to estimate the SWCC based on grain-size distribution (GSD) and well-known index properties such as Plasticity Index. Also, several approaches have been used to solve the problem including three major approaches [36].

1) Statistical estimation of water contents/degree of saturation at selected matric suction values, which was the method adopted in this research.
2) Correlation of soil properties with the fitting parameters of the SWCC function by means of nonlinear regression analysis.
3) Estimation of the SWCC using a physics-based conceptual model.

Furthermore, three different models to estimate the soil water characteristic curve from soil index properties were utilized in this research. The first model [26] is based on the correlation of soil properties with the fitting parameters of the soil water characteristic curve analytical function proposed by [34], the second and third model ([36] and [35]) are based on the correlation of soil properties with the fitting parameters of the soil water characteristic curve analytical function proposed by [9]. Therefore, this research will measure and estimate SWCC using filter paper method and predictional equation models and compare the results obtained from the two methods for some tropical soils of Nigeria using lateritic soil, bentonite, fine sand and kaolinite as case studies.

2. MATERIALS AND METHODS

— Soils tested

Laterite and sand soil samples were collected from certain locations in the Federal University of Technology, Akure (FUTA), bentonite and kaolin clay were obtained commercially, these four soils were used for analysis, basic soil property tests such as particle density, grain size distribution, hydrometer analysis, Atterberg limits and compaction tests were performed on the soil samples to determine their index properties and for soil classification. Also, chemical test (CEC) was performed on the soil samples as well.

— Suction and soil water characteristic curve

Soil suctions were measured in the laboratory using an indirect measurement technique, the filter paper method, the procedure of which was adequately outlined in ASTM D5289 – 03 2010. Also soil water characteristics curves were estimated for the four soils using different predictive correlation equations and different curve fitting mathematical models ([34] and [9]).

Filter paper tests

Material finer than the No. 10 sieve was pulverized and moisture conditioned for compaction directly in a split mould 7.5 cm inner diameter, two different types and sizes of Whatman filter paper were selected for use, Whatman No. 41 filter paper (7cm diameter) was selected for use as protectives for Whatman No. 42 filter paper (5.5 cm) in this study. In addition, pre-existing calibration curves (ASTM D5289 – 03) were readily used for determining the matric suction.

Three sheets of filter paper were required to determine the matric suction of the compacted material. Two filter paper discs that served as protection against soil contamination were placed above and below the one piece of filter paper that was used to determine the matric suction of the material tested.

The three filter papers were sandwiched between the two compacted soil samples and taped with electrical tape to ensure good contact between the compacted specimen and the filter paper. The prepared test specimens were then taken and transferred to glass jars which were closed and sealed with electrical tape to maintain a constant moisture condition. The glass jars were placed in a constant temperature container at a temperature of 27°C to keep temperature flunctuations at ±1°C and allowed to come to equilibrium over a seven (7) day period. After the seven-day equilibrium period, appropriate numbers of moisture tins were labelled, cleaned free of dust, and the mass determined using a balance with 0.0001 g accuracy. This mass was selected as the cold tare (tc) mass.

The equilibrated specimen was carefully removed from the glass jar, the two halves separated, and the middle filter paper rapidly (within a few seconds) removed using laboratory forceps and placed into the moisture tin. The top was immediately placed on top of the tin to prevent moisture from escaping the tin. The mass of the wet filter paper and moisture tin was quickly determined and referred to as the cold tare plus wet filter paper (M1). The top of each tin was removed halfway and the moisture tin placed into an oven for a 24-hour period. After 24 hours, the oven was opened and the lid was placed back on top of the moisture tin and allowed to come to equilibrium conditions in the oven for approximately five (5) minutes. The moisture tin was removed and placed onto an aluminium block to allow for rapid heat dissipation (The tin was allowed to stay on the aluminium block for approximately thirty seconds (30) seconds). Each tin was placed onto the scale immediately after the cooling process, and the mass of the hot tare plus dry filter paper (M2) was determined. Finally, the dry filter paper was removed from the tin and the mass of the empty tin was determined as the hot tare (Th).

The water content of the filter paper was obtained and the material's matric suction determined through the use of calibration curves and models provided by ASTM D5289 – 03, Depending on the value obtained as the filter paper water content), matric suction were evaluated (for w less than 45.3% equation (1) was used and for w greater than 45.3%, equation (2) was used) using either of the equations 1 & 2:

$$\text{Log}_{10}\,(\text{suction}) = 5.327 - 0.0779\,(w) \tag{1}$$

$$\text{Log}_{10}\,(\text{suction}) = 2.412 - 0.0135\,(w) \tag{2}$$

where w = filter paper water contents in %.

Gravimetric water contents of each soil specimens were determined and plotted against corresponding calculated matric suction values to obtain soil water characteristic curves for the four soil samples used in this study.

Predictive correlation equation models

Correlation equation models were formulated by different researchers (such as [26]; [36]; [35]; to mention a few) from index properties of soil such as plasticity index, percent passing sieve no. 200, particle size distribution curve and group index for fast determination of some parameters of soil water characteristic curve owing to the difficulties encountered in suction measurement laboratories, wide variability in test results, longer duration and high cost associated with using experimental procedures. The correlation equations used in this research were formulated based on weighted plasticity index (plasticity index × percent passing sieve no. 200) of soil for plastic soils and particle diameter at specified percent finer for non – plastic soils. The constant parameters of each correlation equations are associated with certain parameters of soil water characteristic curve (a_f = air entry value of soil, b_f = associated with the curve slope and c_f = residual condition of soil), these constant parameters were used with either Van Genuchten model (1980) or Fredlund & Xing model (1994) to compute degree of saturation of soil at assumed suction values.

» Navid *et al.* (2012) Correlation Equations

The correlation equations by navid *et al.* (2012) model were based on weighted plasticity index of soil and fitting Van Genuchten model (shown in equation 6), the correlation equations are illustrated in equation 3 – 5. Curve fitting constant parameters were computed through these set of equations.

$$a = 0.0015(wPI)^3 + 0.1028(wPI)^2 + 0.5871(wPI) + 11.813 \tag{3}$$

$$b = 0.00011(wPI)^2 - 0.01358(wPI) + 1.76987 \quad (4)$$

$$c = -5 \times 10^{-6}(wPI)^2 - 0.00014(wPI) + 0.14745 \quad (5)$$

where the wPI parameter in equations (3) – (5) is defined as:

$$wPI = \text{percent passing sieve No.200} \times PI(\%)$$

neglecting the residual water content at high matric suctions compared with the water content of soil, basic equation proposed by [34] can be rewritten as:

$$S = \frac{1}{\left[1+\left(\frac{\psi}{a}\right)^b\right]^c} \quad (6)$$

where S = degree of saturation (%), Ψ = matric suction (kPa), a, b and c are curve fitting parameters defined above.

» Zapata *et al* (2000) Correlation Equations

The correlation equations by Zapata *et al* (2000) were formulated based on soil weighted plasticity index for plastic soils and particle diameter at 60% finer (D_{60}) for non – plastic soils, the constant parameters computed through the sets of correlation equations were fitted through Fredlund & Xing model (1994) to obtain degree of saturation values at assumed suction values. The equations proposed by Zapata for plastic soils are illustrated by equations 7 – 10,

$$a_f = \frac{0.00364(wPI)^3 + 4(wPI) + 11}{6.895} \quad (7)$$

$$\frac{b_f}{c_f} = -2.313(wPI)^{0.14} + 5 \quad (8)$$

$$c_f = 0.0514(wPI)^{0.465} + 0.5 \quad (9)$$

$$\frac{h_r}{a_f} = 32.44e^{0.0186(wPI)} \quad (10)$$

For non – plastic soil, the following equations are proposed by Zapata;

$$a_f = \frac{0.8627\,(D_{60})^{-0.751}}{6.895} \quad (11)$$

$$\dot{b}_f = 7.5 \quad (12)$$

$$c_f = 0.1772\ln(D_{60}) + 0.7734 \quad (13)$$

$$\frac{h_r}{a_f} = \frac{1}{D_{60} + 9.7e^{-4}} \quad (14)$$

where a_f, b_f, c_f and h_r are soil water characteristic curve fitting parameters.

» Witczak (2006) Correlation Equations

Like the two previous models, witczak model was also formulated based on weighted plasticity index for plastic soil and particle diameter at different specified percent finer for non–plastic soil, the proposed correlation equations for computing curve fitting constant parameters (Fredlund & Xing) by Witczak for plastic soil is illustrated below,

$$a_f = 32.835\{\ln(wPI)\} + 32.438 \quad (15)$$

$$b_f = 1.4221\,(wPI)^{-0.3185} \quad (16)$$

$$c_f = -0.2154\{\ln(wPI)\} + 0.7145 \quad (17)$$

$$h_{rf} = 500 \quad (18)$$

As stated for the two previous models, the degree of saturation values were estimated at assumed suction values and computed constant parameters from the equations illustrated above. Fredlund and Xing model (1994) is illustrated below by equation 19.

$$S(\%) = \frac{\theta_w}{\theta_s} = \left[1 - \frac{\ln\left(1+\frac{\Psi}{h_r}\right)}{\ln\left(1+\frac{1{,}000{,}000}{h_r}\right)}\right]\left[\frac{1}{\left[\ln\left[e+\left(\frac{\Psi}{a_f}\right)^{b_f}\right]\right]^{c_f}}\right] \quad (19)$$

where: S = degree of saturation (%), θ_s is the saturated water content, ψ is the soil suction (kPa), e is the natural number (e = 2.71828), (θ_r) is the soil suction (kPa) corresponding to the residual water content, and a_f, b_f and c_f are curve fitting parameters.

3. RESULTS AND ANALYSIS

— Geotechnical Index Test Results

The results of basic index properties of soils are summarized in Table 1. Specific gravity results ranged between 2.34 – 2.7, bentonite had the lowest value while laterite had the highest value at 2.7, according to AASHTO classification, kaolin and bentonite were classified as A – 7 – 6, laterite was classified as A – 6, sandy soil was classified as A – 3 while according to USCS laterite and kaolin were classified as lean clay, sandy soil was classified as well graded sand and bentonite was classified as CH (high plasticity clay). The percent passing sieve no. 200 for laterite, sand, bentonite and kaolin were 50%, 0.18%, 91.3% and 82% respectively.

Table 1: Index Properties of the Soil Samples

Properties	Soil Samples			
	Sand	Laterite	Kaolin	Bentonite
Specific gravity	2.65	2.7	2.50	2.34
Liquid limit, %	0	36	41	110
Plastic limit, %	0	22	26	85
Plasticity index, %	0	14	15	25
% Passing BS No. 4 sieve	100	96.4	100	100
% Passing BS No. 10 sieve	99.63	85.2	100	100
% Passing BS No. 40 sieve	43.74	68.4	100	100
% Passing BS No. 200 sieve	0.18	50	82	91.3
AASHTO classification	A – 3	A-6	A-7-6	A-7-6
USCS classification	SW	CL	CL	CH
Group index	0	6	13	16
CEC (meq/100g)	6.72	11.2	14.0	44.8

— Filter paper tests result

Filter paper tests (contact method) were conducted according to the procedure spelt out in ASTM D5289 – 03, 8 – 10 specimens were prepared for each soil at different water contents using the optimum water content of soil as guide, the water contents were varied at 2%, some were compacted wet of optimum and some dry of optimum depending on their water holding ability. For example sand specimens were compacted at 4% - 18% water contents while bentonite specimens were prepared at a much higher water contents (20% - 38%). After obtaining filter paper water content, calibration curve for Whatman 42 filter paper found in the literature (ASTM D5289 - 03) was used to determine the matric suctions of soil specimens. The results of gravimetric moisture contents and matric suctions obtained for the four soils used in the study are summarized in Table 2.

Table 2: Gravimetric Moisture Contents vs Matric Suctions of the Soils

Gravimetric moisture contents (%)				Matric suction (kPa)			
Sand	Laterite	Kaolin	Bentonite	Sand	Laterite	Kaolin	Bentonite
2.2	10.3	11.3	8	18.6	64	65	879
4.3	11.3	14.2	15	3.1	46.8	48.6	631
5.9	13.2	18	19	1.7	30	36	530
6.8	15.4	20.8	25	1.64	15.8	31	412
8.3	16.1	23	28	1.6	0.06	28	360
11.3		25	33	1.7		24.7	245
12.8		26.5	34.6	1.6		20	150
13.4		28	35.3	1.3		12	25
13.8		29		0.6		7	

It was observed that matric suctions of each of the soils decreased with increasing water contents, also, bentonite specimens had the highest values of matric suction compared to other soil specimens even at nearly equal water contents. It was shown that at 25% water content, bentonite had a matric suction of 412 kPa while kaolin had a matric suction of 24.7 kPa, Sand at 11.3% water content had a matric suction of 1.7 kPa whereas kaolin and laterite had a matric suction of 65 kPa and 46.8 kPa respectively, thus soils which have granular structures have lower matric suction and the amount of clay fractions in fine grained soils greatly influenced their matric suction values.

Soil water characteristics curves for the four soils are shown in Figures 1(a) – (d), it was observed that sandy soil with granular structure and lowest amount of fines passing sieve no. 200 had very low air entry value and residual suction, laterite, though granular in structure but contains appreciable fine materials (about 50% passing sieve no 200) and kaolin clay had air entry values of 13.3kPa and 21kPa respectively, this close values may be attributed to inexpansive nature of kaolin clay and also kaolinite is the major clay mineral found in laterite. Bentonite had the highest air entry value at 260 kPa of the four soils used in the study, this may be due to its high plasticity and its expansive nature, thus it was observed that the higher the soil plasticity index, the higher the air entry value of the soil. Furthermore, the slopes of the soil water characteristic curves varied in steepness, spectrum and wideness which is an indication of their differing water retention abilities.

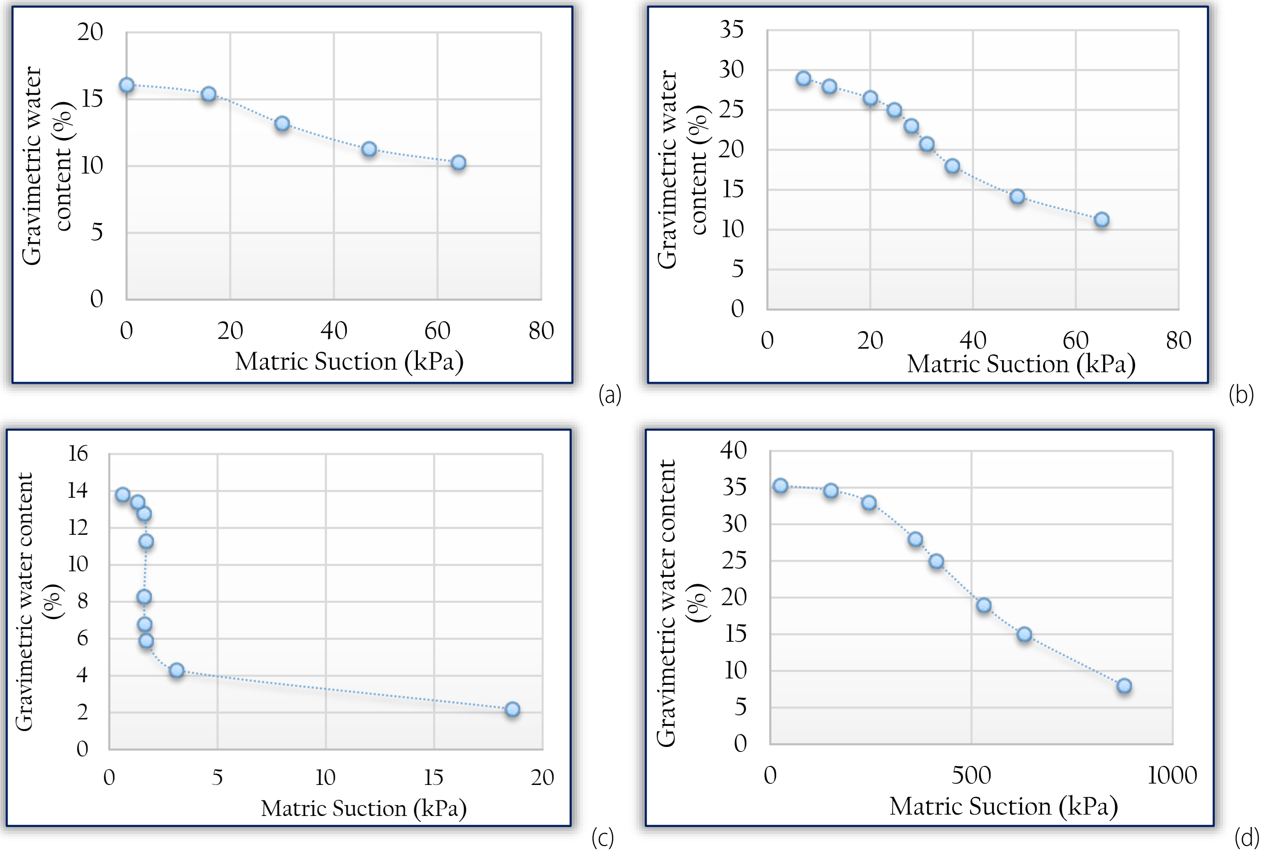


Figure 1(a): Experimental Plot of SWCC for Laterite. (b): Experimental Plot of SWCC for Kaolin. (c): Experimental Plot of SWCC for Sand. (d): Experimental Plot of SWCC for Bentonite.

— Predictive Correlation Equation Models

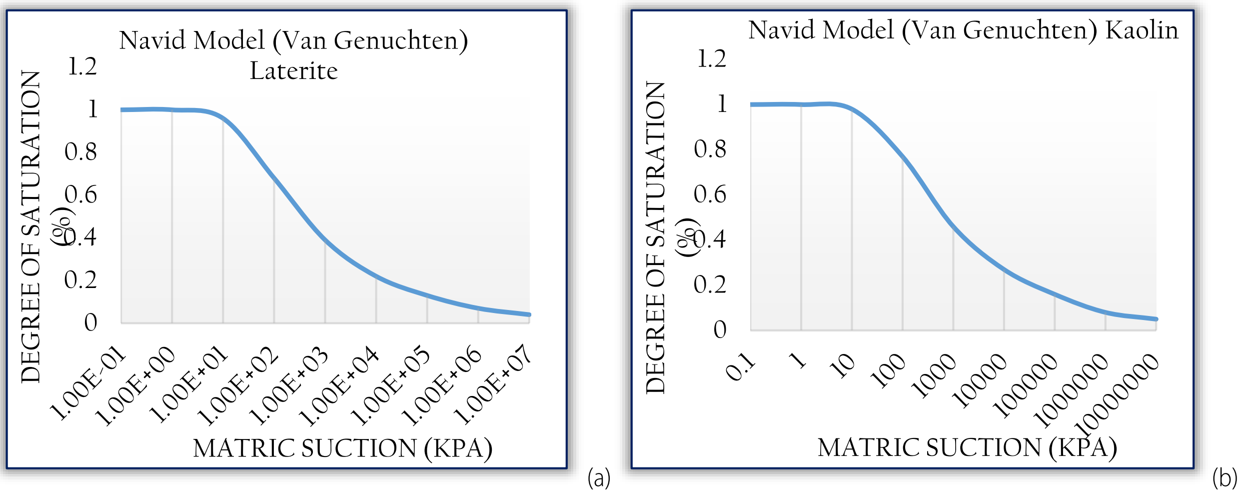
Navid *et al* (2012)

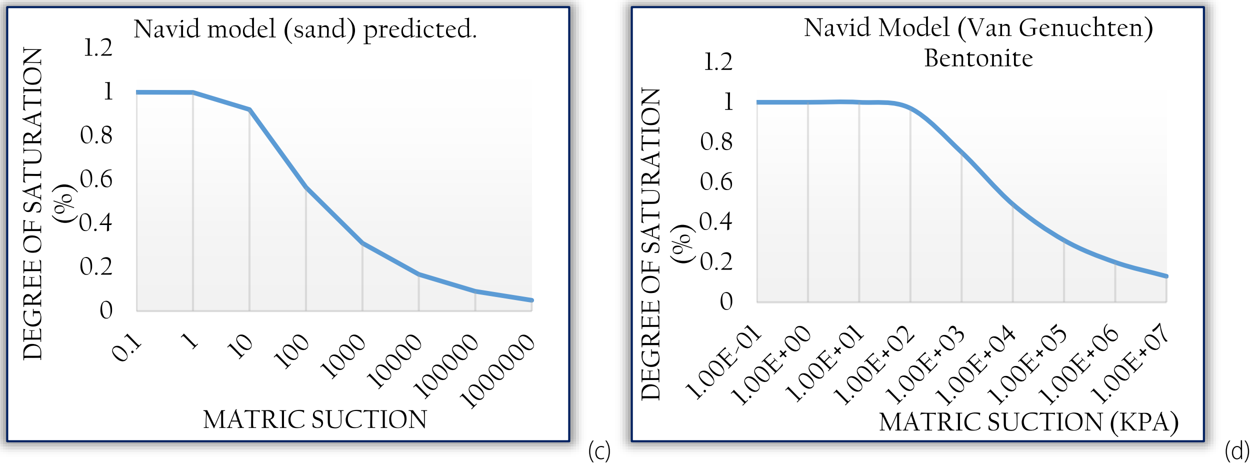
Navid *et al* (2012) developed correlation equations for predicting SWCC parameters based on weighted plasticity index of soils using Van Genuchten model for curve fitting constant parameters, Soil characteristics and Van Genuchten equation parameters which were computed with the proposed correlation equations are shown in Table 3a.

Table 3a: Soil Characteristics and Van Genuchten Constant Parameters.

Soil Type	Van-Genuchten constant parameters			Passing sieve no 200 (W)	Plasticity index (%PI)	Weighted plasticity index (wPI)
	a	b	c			
Laterite	21.5	1.68	0.146	0.50	14	7.0
Kaolin	37.4	1.62	0.145	0.82	15	12.3
Bentonite	243	1.42	0.136	0.91	25	36.5
Sand	11.8	1.77	0.147	0.27	0	0

Suction/ degree of saturation pair of values were plotted to obtain soil water characteristic curves for the four soils. Figures 2(a) – (d) show the soil water characteristic curves for the four soils.





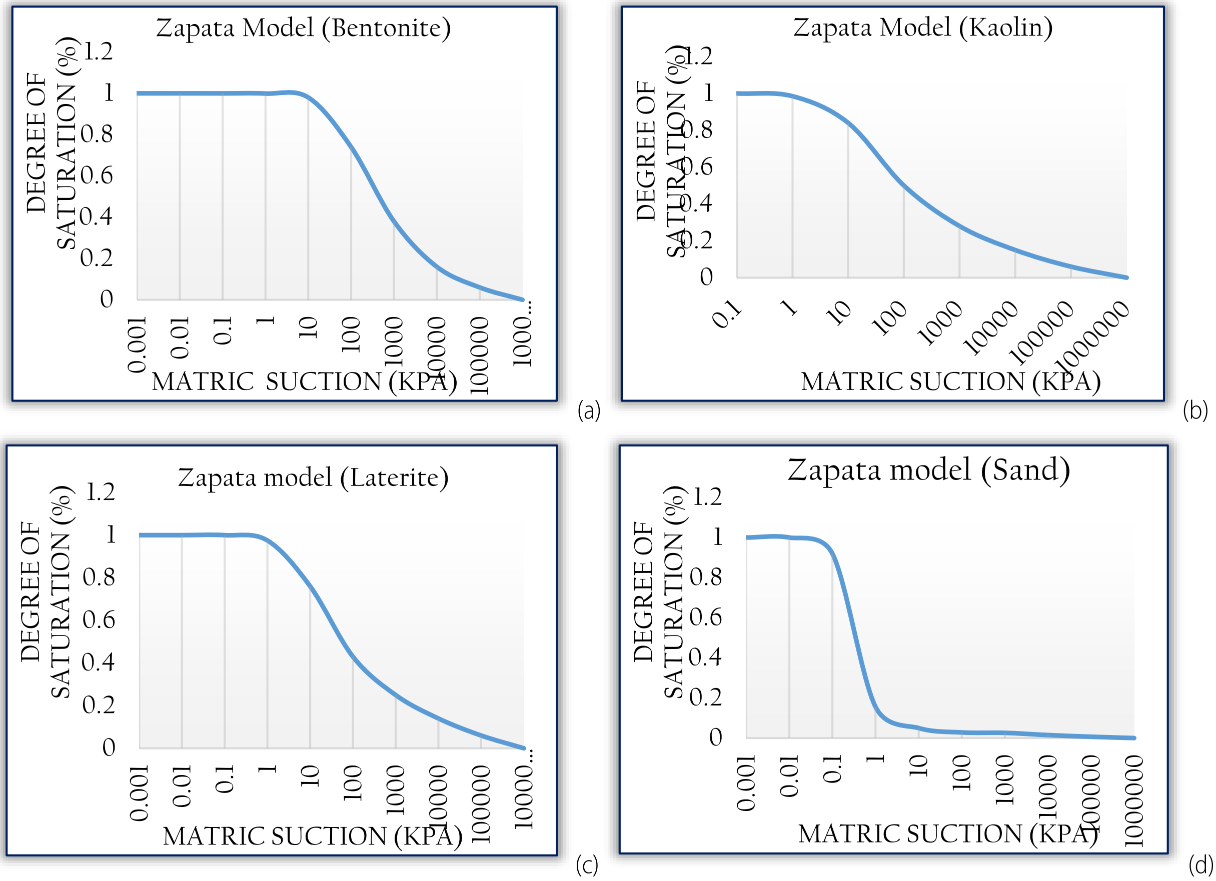
Figures 2(a): SWCC for Laterite (Predicted) (b): SWCC for Kaolin (Predicted)
(c): SWCC for Sand (Predicted). (d): SWCC for Bentonite (Predicted)

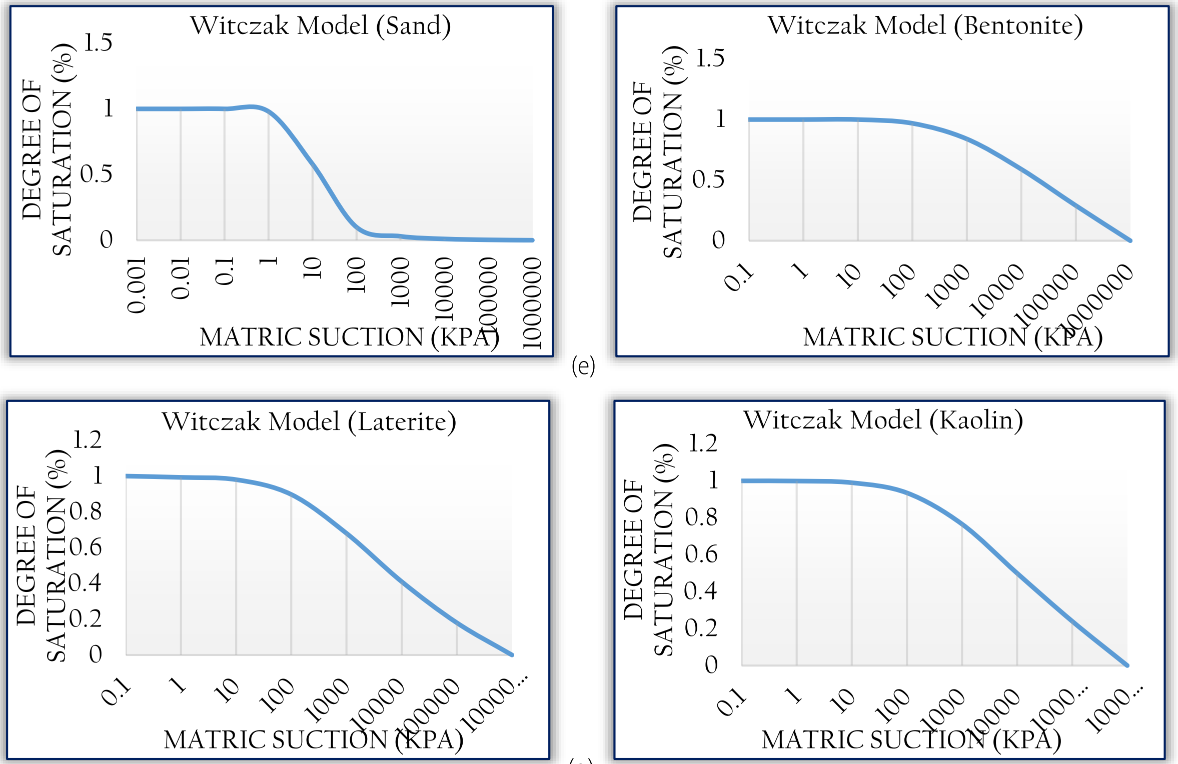
Zapata *et al* (2000) and Witczak (2006) models

Both models were formulated with the index properties of soil such as Atterberg limits (liquid limit, plastic limit and plasticity index) and percentage passing sieve no. 200, Fredlund & Xing model equation parameters were computed from the proposed correlation equations for both models. Curve fitting parameters for both models were estimated by using weighted plasticity index (wPI) of soils for plastic soils and particle diameter of the soil at some specified percent finer for non – plastic soils. Soils index properties and Fredlund & Xing contant parameters estimated from both correlation equations are presented in Table 3b. Figures 3(a) – (h) show SWCC for the soils and for both correlation equation models.

Table 3b: Soil Index Properties and Fredlund &Xing Model Estimated Constant Parameters

Soil Type	Zapata *et al* (2000) model Constant parameters				Witczak (2006) model Constant parameters				Soil index properties		
	a_f	b_f	c_f	h_{rf}	a_f	b_f	c_f	h_{rf}	P_{200} (W)	PI (%)	wPI (%)
Laterite	6.0	1.23	0.63	222	96.3	0.76	0.3	500	0.50	14	7.0
Kaolin	11.1	1.15	0.67	453	115	0.64	0.17	500	0.82	15	12.3
Bentonite	113.2	0.91	0.77	64	150	0.45	0.03	500	0.91	25	36.5
Sand	0.18	7.5	0.68	0.23	8.3	1.6	1.59	100	0.27	0	0





Figures 3(a) - (h): Zapata Model (a): SWCC for Bentonite (Predicted) (b): SWCC for Kaolin (Predicted) (c): SWCC for Laterite (Predicted). (d): SWCC for Sand (Predicted); Witczak Model (e): SWCC for Sand (Predicted) (f): SWCC for Bentonite (Predicted) (g): SWCC for Laterite (Predicted). (h): SWCC for Kaolin (Predicted).

— Discussions on the Predictive Models used for Obtaining SWCC

The air entry values obtained from the predictive models for all the soils are presented in Table 4, the three models based their correlation equations on index properties of soil such as percent passing sieve no. 200, plasticity index and particle size distribution of soil. Precisely, the correlation equations were built mainly on weighted plasticity index (wPI) for plastic soils and particle diameter of soils at some stated percent finer, yet there exists wide differences in the air entry values obtained, the air entry values obtained from [26] model were the highest for all the soils whereas the air entry values obtained from [36] model were the lowest for all the soils. The air entry values obtained from Witczak model were very high for soils of low plasticity index (laterite, PI = 14 and kaolin, PI = 15) but compare moderately with Zapata (2000) model for high plasticity soil (bentonite, PI = 25) and Navid (2012) model for non – plastic soil (sand, PI = 0).

Table 4: Summary of Air Entry Values of all the Soils and Correlation Equations used in this Study

Soil Type	Navid *et al* (2012) model	Zapata *et al* (2000) model	Witczak (2006) model
	Air entry value (kPa)	Air entry value (kPa)	Air entry value (kPa)
Sand	11.8	0.18	8.3
Laterite	21.5	6.0	96.3
Kaolin	37.4	11.1	115
Bentonite	243	113.2	150

Combined soil water characteristic curves for each model are illustrated in Figures 4(a) – (c). The combined soil water characteristic curves obtained for the soils tested in this study are in conformity with the curves obtained and published by [26] and [36]. Furthermore, the degree of saturation values obtained at assumed suction values for Van Genuchten model decreased gradually for all the soils up to a suction of 10000kPa although at higher suctions it deviated slightly from theoretical and experimental proven fact that at a suction of 10^6kPa, the degree of saturation for any soil is 0%.

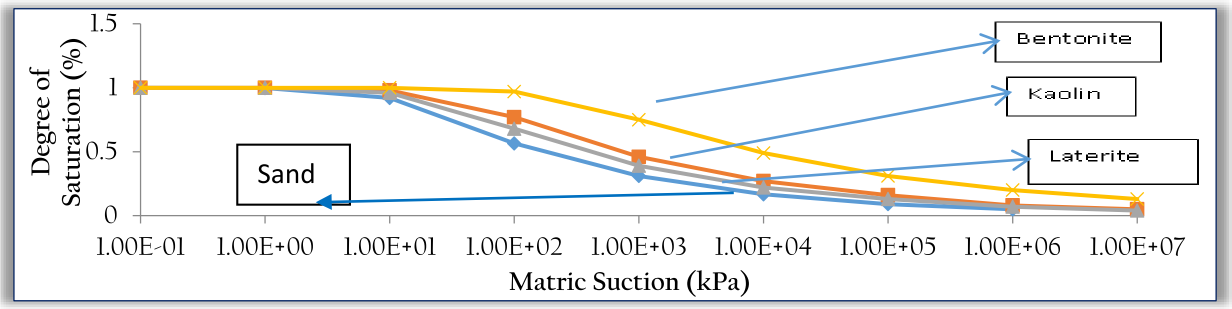


Figure 4(a): Combined plot of soil water characteristic curves for the soils used in this study [Navid Model (Combined) Predicted]

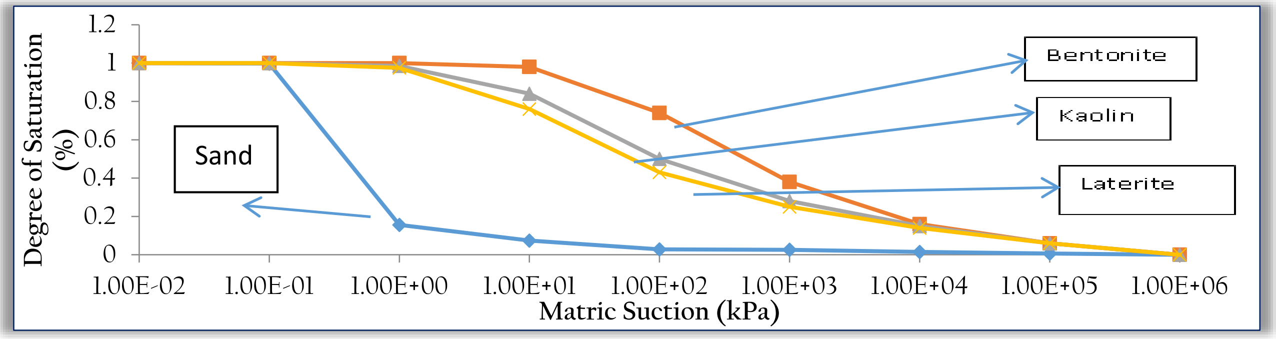


Figure 4(b): Combined plot of soil water characteristic curves for the soils used in this study [Zapata Model (Combined) Predicted]

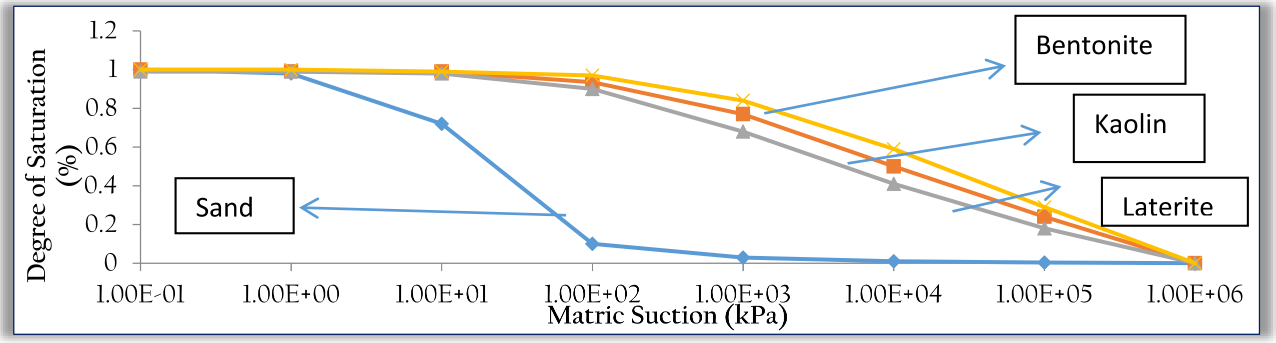


Figure 4(c): Combined plot of soil water characteristic curves for the soils used in this study [Witczak Model (Combined) Predicted]

— Comparison of Experimental and Predicted Results

The air entry values obtained from experimental work, although filter paper method was used in the study (an indirect soil suction measurement method) compared favourably well with those estimated from predictive models but with slight variations as illustrated in Table 5, the results obtained from [26] model were the closest to experimental results for all the plastic soils. [36] model also provided good results for plastic soils of moderate plasticity index (laterite and kaolin) and non – plastic soil (sand) used in the study. Wide variations were observed from [35] model results obtained to those of experimental work for laterite and kaolin (PI = 14% and 15% respectively) but performed slightly better than [36] model for bentonite (although with higher fine fractions). Overall, better results were obtained from [26] model and [34] model than [36] model and [35] model for the plastic soils used in the study whereas results obtained from [36] model was the best for the non – plastic soil (sand) compared with the results obtained experimentally in the study.

Table 5: Summary of Air Entry Values of all the Soils from Experimental and Predictive Methods.

Soil Type	Experimental Work	Navid *et al* (2012) model	Zapata *et al* (2000) model	Witczak (2006) model
	Air entry value (kPa)	Air entry value (kPa)	Air entry value (kPa)	Air entry value (kPa)
Sand	1.34	11.8	0.18	8.3
Laterite	13.3	21.5	6.0	96.3
Kaolin	21.0	37.4	11.1	115
Bentonite	260	243	113.2	150

4. CONCLUSIONS

The main results concluded from this research are listed below:

— Results obtained from the experimental work showed that for any soil, matric suction decreased with an increase in soil water contents.

— The experimental plot of soil water characteristic curves for some tropical soils used in this research showed that the lower the fines in the soil or the more permeable the soil structure, the lower is its water retention capacity.

— Results obtained from the experimental work also showed that air entry values of soils were enhanced with the amount of clay fractions contained in the soil (the higher the weighted plasticity index of soil, the higher the air entry value).

— Results of air entry values of soils from experimental work and predictive correlation equations were in close range which indicated that in spite of the difficulties experienced in performing laboratory suction tests and the variability during tests, the predictive correlation equations such as the ones used in this research would be proper for estimating soil water characteristic curve.

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