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Evaluation of Four SWCCs Models' Flexibility for Selected Reconstituted Tropical Red Earth Soils

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ABSTRACT

Soil water characteristic curve (SWCC)is asignificant property of unsaturated soil which includes tropical redearth soil. Thisis due to the fact that other soils' properties whichinclude shear strength,permeability function and compressibility can berelated to it.Selected reconstituted tropical red soil samples were prepared to simulate tropical soils characteristics with plasticity properties ranging fromlow to high configuration. The soil's matric potential was obtained from the filter paper technique. Gravimetric water content was utilized in the computation of the SWCC. Four models were used to estimate the SWCCs of the soils investigated and MSSR, ARE, and R^2 valueswere utilized in the determination of the order of suitability of the models' capability to predicting the SWCCs. The models utilizedwere: Fredlund and Xing (1994); Van Genuchten (1980), Brooks and Corey (1964) and Kosugi (1996). It was observed that some models perform better for certain class of tropical red earth andthe implication is that by simplyidentifying the fines content of a tropical soil, the class of the soil can be inferred and ultimately the SWCC can be predicted using the most suitable model for the particular class of tropical red earth.

Keywords: *Tropical soil, SWCC, matric suction, filter paper*

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I. INTRODUCTION

Soil-WaterCharacteristic Curve (SWCC) is acurve that showsthe relationship between the water content in asoil and its suction.Italso can be seen asacontinuous sigmoidfunction which describes the water storage capacity of asoil asitissubjected to various soil suctions (Matlan, Mukhlisin, & Taha, 2014).SWCCis avery significantproperty of unsaturated soil because other soil propertiessuch asshearstrength,permeability function, compressibility, modulli and fluid flow can berelated to it (Zhai & Rahardjo, 2013); (Houston, Dye, Zapata, Perera, & Harraz, 2006); (Choudhury & Bharat, 2014).

Different models have been developed in the field SWCCover the last five decades and some of the most commonly used ones include Brooks and Corey (1964), van Genuchten(1980),Fredlundand Xing (1994),Kosugi((1999),Omuto(2009),Krishnapillaiand Ravichandran(2012. (Taban, Sadeghi, & Rowshanzamir, 2018).

Fredlund and Xing (1994)'s equation

Fredlund and Xing (1994)'s equation with the correction factor C(Ψ) can be expressed as shown in equation 1.

$$\theta = C(\Psi)\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} = \left[1-\frac{\ln\left(1+\frac{\psi}{C_r}\right)}{\ln\left(1+\frac{10^6}{C_r}\right)}\right]\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} \quad (1)$$

Where
θ =Volumetricwater content; θ_s =saturated volumetric water content
a, n, m: are fitting parameters
C_r =Parameter related to residual suction, often assigned a value of 1500

Van Genuchten(1980) model

Van Genuchten(1980)SWCC model is widely used for the description of the SWCCof various soils.It's among the most widely used model observed to be suitable for use for a wide range ofboth disturbed and undisturbed soils ranging from fine grained to coarse grained soils (Taban, Sadeghi, & Rowshanzamir, 2018).
The vanGenuchtenmodel presents the relationship between the normalizedwater content and suction asstated in equation 2 below:

$$S = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)} = \frac{1}{[1+(a\psi)^n]^m}, \quad (2)$$

Where $m = 1 - \frac{1}{n}$ (2b)

Where Sis the normalized water content (adimensionless parameter)

Θis the volumetric water content,the indices rand sin θ_r and θ_s symbolize the residual and the saturated volumetric water contents respectively Ψis the suction (unit is kPa),while "a"and "n"are the model fitting parameters. Parameters "a" is related to the air entry value while "n" is the value related to the pores size distributionparameters mis the value related to the asymmetry of the model (Taban, Sadeghi, & Rowshanzamir, 2018).

Brooks and Corey (1964) model

Brooks and Corey (1964) equation is the form of power law relationship and it's expressed as:

$$\Theta = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \quad (3)$$

Where :

Θ is the normalized water content which is expressed as:

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

Where θis the volumetric water content, also the indices rand sin θ_r and θ_s symbolize the residual and the saturated volumetric water contents respectively,Ψis the suction and ψ_b,is the air entry value while λis the poresize distribution index.This model is relatively simple and thus widely used although the model doesn't provide acontinuous mathematical function for the entire SWCC (Matlan, Mukhlisin, & Taha, 2014)

Kosugi(1996)'smodel

Kosugi(1996)'s models,the most recent model of the four models evaluated in this study is reported to beamong the threecommonly used models, the other two are the Brooks and Corey(1964) and van Genuchten(1980).(Mavimbela & Rensburg, 2012).The model was developed by applying alognormaldistribution lawand its parameters are directly related to the soil pores radius distribution(Matlan, Mukhlisin, & Taha, 2014).Kosugi's model is expressed asstated below:

$$\Theta = Q\left[\frac{\ln \psi / h_m}{\sigma}\right] \quad (5)$$

WhereQis related to the complementary error function (erfc),and it's defined as

$$Q(\chi) = erfc\frac{\left(\frac{x}{\sqrt{2}}\right)}{2} \quad (6)$$

Where h_m andσ are the fitting parameters.h_m .is acapillary pressure head andis relatedto the median pore radius while σ is adimensionlessparameters related to the width of the pores radius distribution.

While commenting on the theoretical basis of the shape of the soil-water characteristic curve, (Fredlund & Xing, 1994), stated that the equations proposed in the research literature are empirical in nature. He further opined that each equation appears to apply for a particular group of soils. It istherefore reasonable to evaluate anygiven soil against some selected popular SWCCmodels to determine which most closely describes its WCC.Itis for this reason that the four models were chosen for the evaluation of selected tropical residual redearth SWCC.The existence of a suitable template for easy determination of the SWCC from basic index tests would spur researchers and practitioners to harness the numerous benefits of utilizing SWCCs in their routine geotechnical assessments of the soil.

II. MATERIALS AND METHODS

The filter paper method of determination of SWCCin the laboratory was adopted in this study owing to its simplicity and adaptability to a wide range of suction values.WhatmanNo.42filter paper was utilized in the study.

Sample Preparation

Red earth residual soils were obtained and separated into coarse fraction and fines (silt/clay fractions) using 75µm sieve aperture and they were marked as A and B subsamples respectively. The subsamples were reconstituted back into one soil specimen by partial blending of coarse (sand) sub samples in 10percent incrementsfrom 10%(90A+10B)fines to 100%fines(0A+100B). Each fraction was reconstituted at roughly the OMC and the reconstituted specimen subjected to soil water characteristics curve evaluation using filter paper method.Other samples were prepared atwater content less than optimum and also at water content greater than optimum in order to capture a broad range of the matricsuction characteristicsof the soil. Allreconstituted soil samples were allowed to curefor aminimum of20hours.Thecured samples were thereafter extruded and prepared for matricsuction test .

MatricSuction Sample Preparation

The matricsuction test was executed using the filter paper technique. The procedures includeplacing aportion of the filter paper in-between two protective filter papers which are in contact with the soil sample in such away that suction equilibrium is established between them. Although the filter paper and the soil have different water content, they're subjected to the same matricpotential (Lucas de Almeida, Teixeira, Filho, Raimundo , & Raimundo, 2015).In this work WhatmanNo.42 filter paper was used**.**

Each matricsuction test was performed ona sample of 42 mmdiameter and 30mm height the samples were carefully extruded and cut to ensure that the surface is planar and smooth to enable agood contact surface between the filter papers and the soil. Each set of three filter papers (2 Nosprotective filter papers with diameter 42 mm and 1 Nos. 38mmdiameter Whatman No.42filter paper)were placed between two soil samples.The choice of the central filter paper being made smaller in diameter is to prevent soil samples from polluting the central filter paper.The joint was thereafter sealed with anelectrical tape and the sealed sample placed in anairtight plastic container with the cover again sealed with the electrical tapeto prevent moisture loss from the soil.The whole assembly was kept in awell-insulatedcontainer for suction equilibrium.Afteraminimum of threedays of suction equilibration,the assembly was opened and both the soil samples and the central filter paper were weighed with a0.0001g precision balance.Weighing was carried out within 20seconds to avoid possible evaporation.Finally suction was calculated from the computed filter paper water content using the appropriate calibration curve depending onthe initial state of the filter paper,whether wet ordry.

Matric suction values were computed using calibration equations provided by(Kim, Prezzi, & Salgado , 2017)**.** The equations adopted in this study are stated below:

$$\log_{10} S = 5.327 - 0.0779(wc_{fp}) \qquad (7)$$

For $wc_{fp} < 45.26\%$

And

$$\log_{10} S = 2.412 - 0.0135(wc_{fp}) \qquad (8)$$

For $wc_{fp} > 45.26\%$

Evaluation Criteria

In the evaluation, three criteria were used for comparison and understanding the descriptive and predictive capabilities of the four models. The first criterion is the degree of curve match. Thecloser the difference between the predicted curve and the measured data the better the descriptive capability of the model.(Guan, Rahardjo, & Choon, 2010).These can beevaluated using Average Relative Error (ARE) computed from equation (9) shown below:

$$ARE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_i - \widehat{y_i}}{y_i}\right| \times 100 \qquad (9)$$

Where $y_i$isthe actual value of *i*thdata;$\widehat{y_i}$is the predicted value of the *i*thdata;and Nis the total number of data available.

In this reportagreement of predicted with actual will be fashioned along the same line as those of (Guan, Rahardjo, & Choon, 2010)where "agreement" was defined as ARE being smaller than orequalto 20%,and "discrepancy" was defined as ARE being larger than 20%.

The second criterion used in this study is the normalized sumof square error (SSE_{norm}). In this evaluation, the smaller the valueof$SSE_{norm}$the better the predictive capability of the model. The$SSE_{norm}$is defined as:

$$SSE = \sum_{i=1}^{N}\left(\frac{y_i - \widehat{y_i}}{y_i}\right)^2 \qquad (10)$$

The parameters needed were obtained using minimization algorithm for SSE_{norm}, which implies least number of parameters in the equationsbeing able to provide the minimum SSE_{norm}(MSSE) for all selected data sets also known as the residual error.

The third criterion is the coefficient of determination, r^2. This is the percentage of variance in one variable that is accounted for by the variance in the other variable. It's the square of the correlation coefficient.Thesumof squares of the deviation from the mean, $\bar{y}$ in the ydirectionisgivenas$\sum_{i=1}^{N}\left(\frac{y_i - \bar{y}}{1}\right)^2$the coefficient of determination is therefore the fraction of this sumof squares which is explained bythe linear relation between $\hat{y}$and xgiven bythe regression of y on x. thus the coefficient is given bytheratioof$\sum_{i=1}^{N}\left(\frac{y_i - \widehat{y_i}}{1}\right)^2to\sum_{i=1}^{N}\left(\frac{y_i - \bar{y}}{1}\right)^2$.i.e.

$$r^2 = 1 - \frac{\sum(y_i - \widehat{y_i})^2}{\sum(y_i - \bar{y})^2} \qquad (11)$$

If the coefficient of determination becomes larger for the same algebraic forms, it indicates the relationship between the variables has become stronger.

III. RESULTS

Soil-water characteristics curve of a reconstituted A-3 tropical red earth

Reconstituted A-3 tropical earth was investigated to determine the matric suction at different gravimetric water content. The results gotten from the SWCC using the four models of FX, VG, BC and K are presented in Figures 1 to 4. The performance of the models is shown in Table 1.

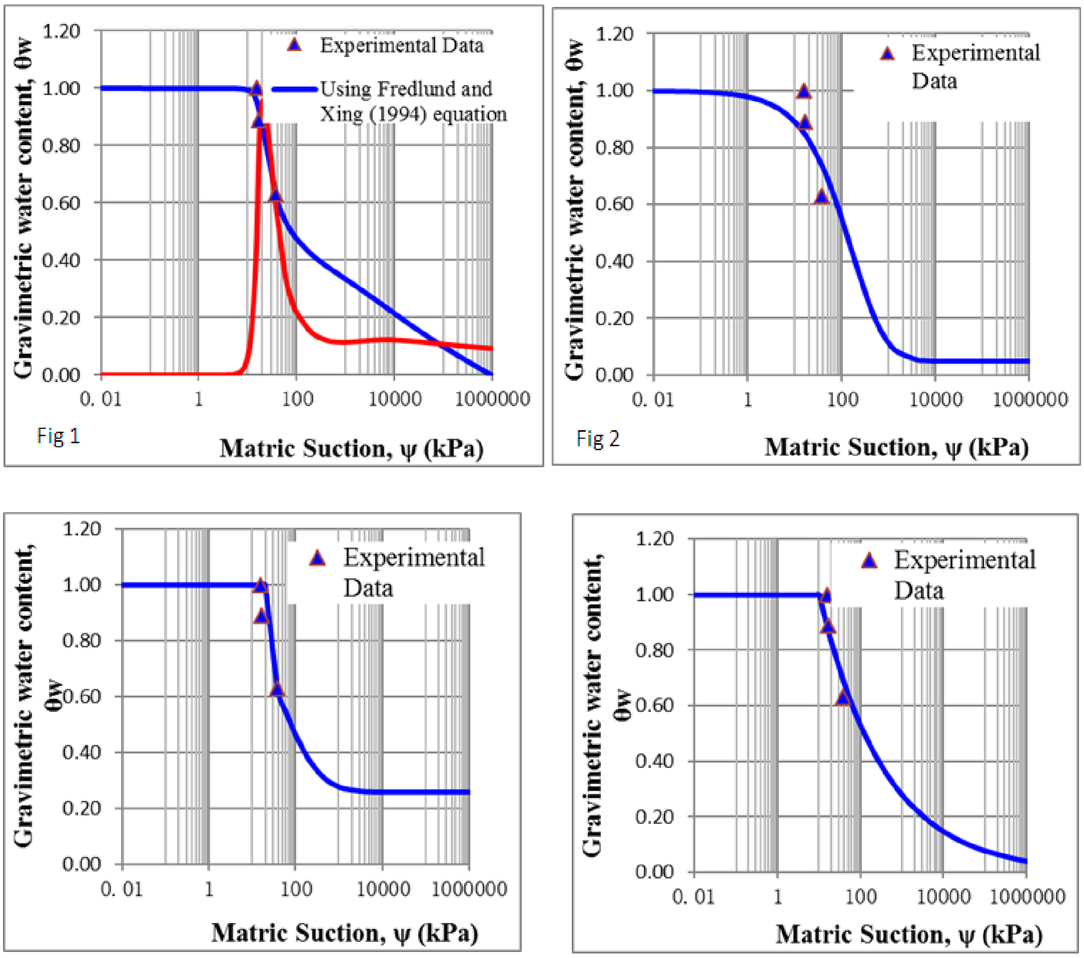
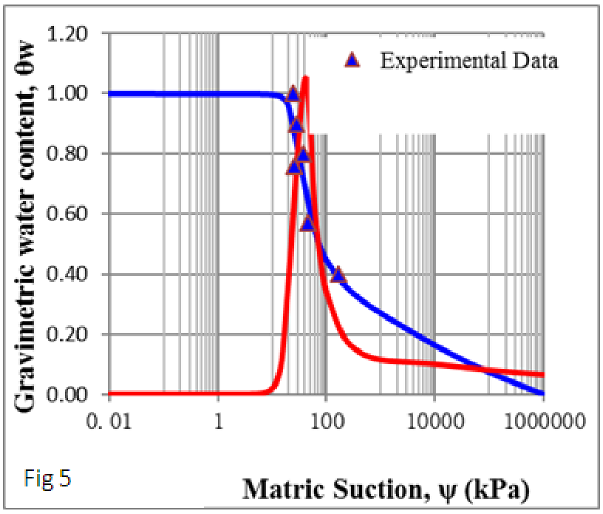
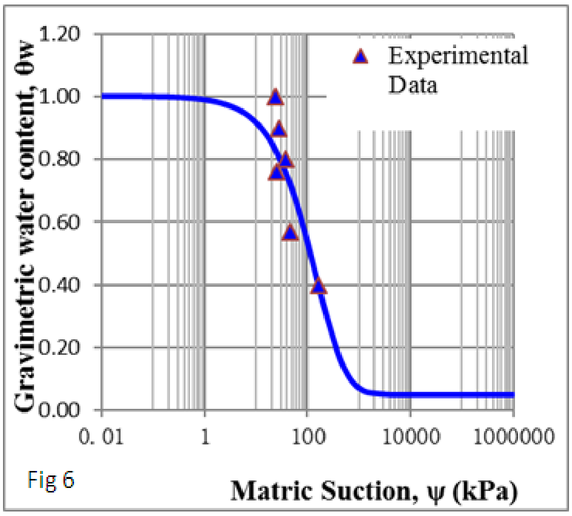


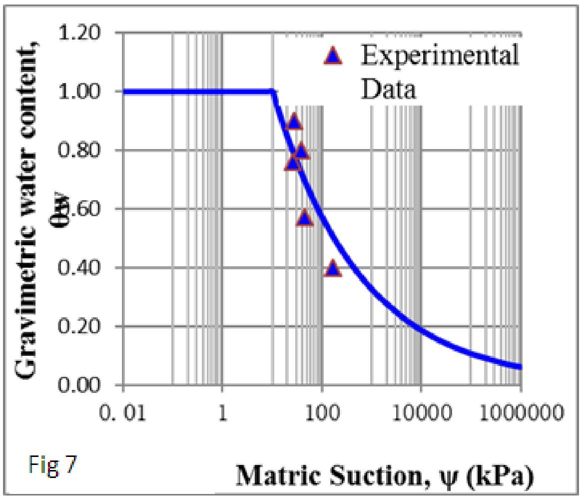
Figure 1-4: .SWCC of anA-3 tropical red earth soil using FX, VG, BC and K model respectively

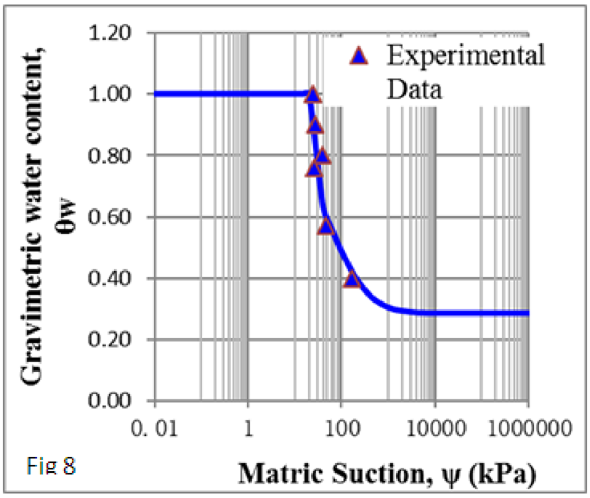
Soil water characteristics curve of an A-7-6 reconstituted tropicalred earth

A-7-6 reconstituted tropical red earth, also classified as SC using USCS classification was evaluated for matric suction using gravimetric water content. The results gotten from the SWCC using the four models of FX, VG, BC and K are presented in Figures 5 to 8 while the summary of the data are presented in Tables 1.







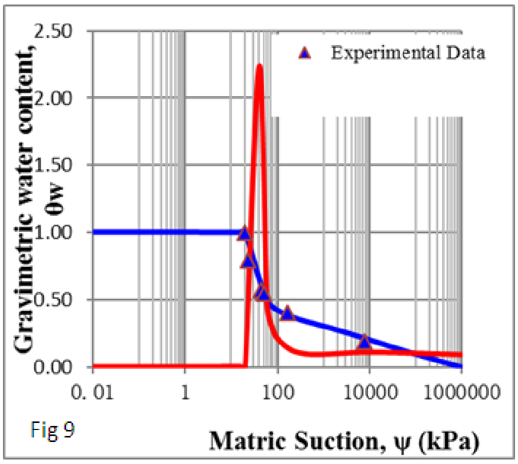


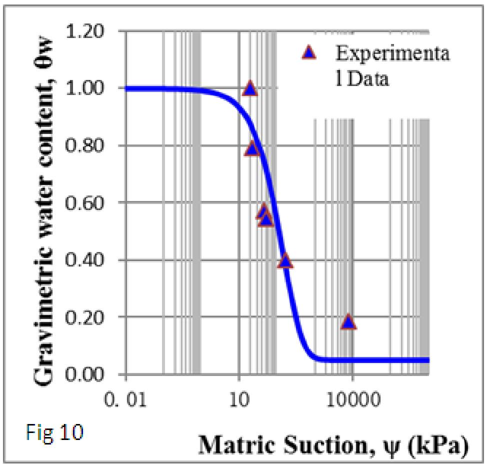
Figures5-8.SWCC of an A-7-6 tropical red earth using FX, VG, BC and K models respectively

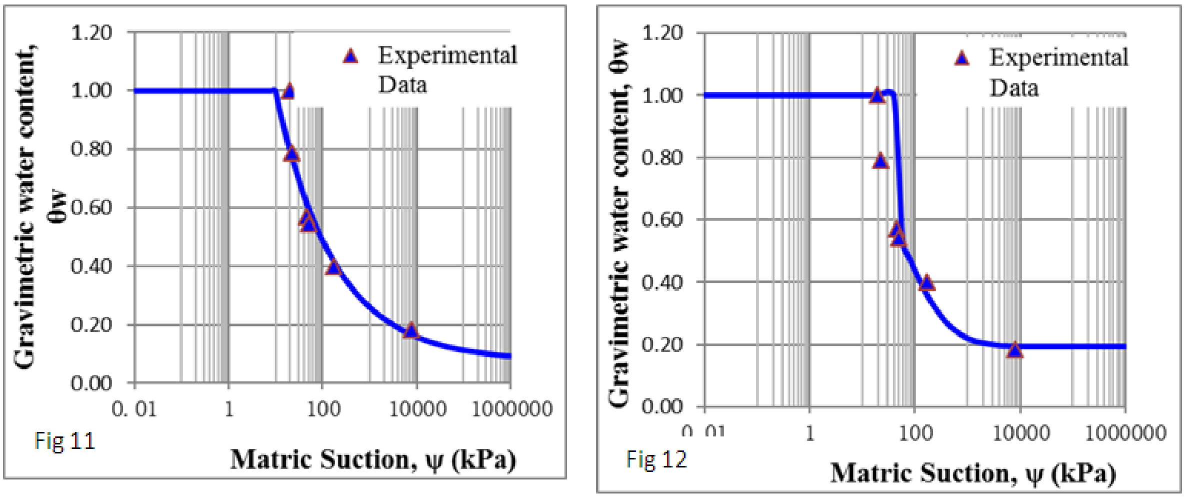
Soil water characteristics curve of an A-7-5(5) tropical red earth soil

The results gotten for samples of the A-7-5(5) tropical red earth soil using the chosen four equations proposed for determining SWCC of various soils are presented in Figures 9to 12 while the summary of the results are shown in Tables 1-4..

Figure 9.SWCC of an the A-7-5(5) tropical red earth soil using FX-model



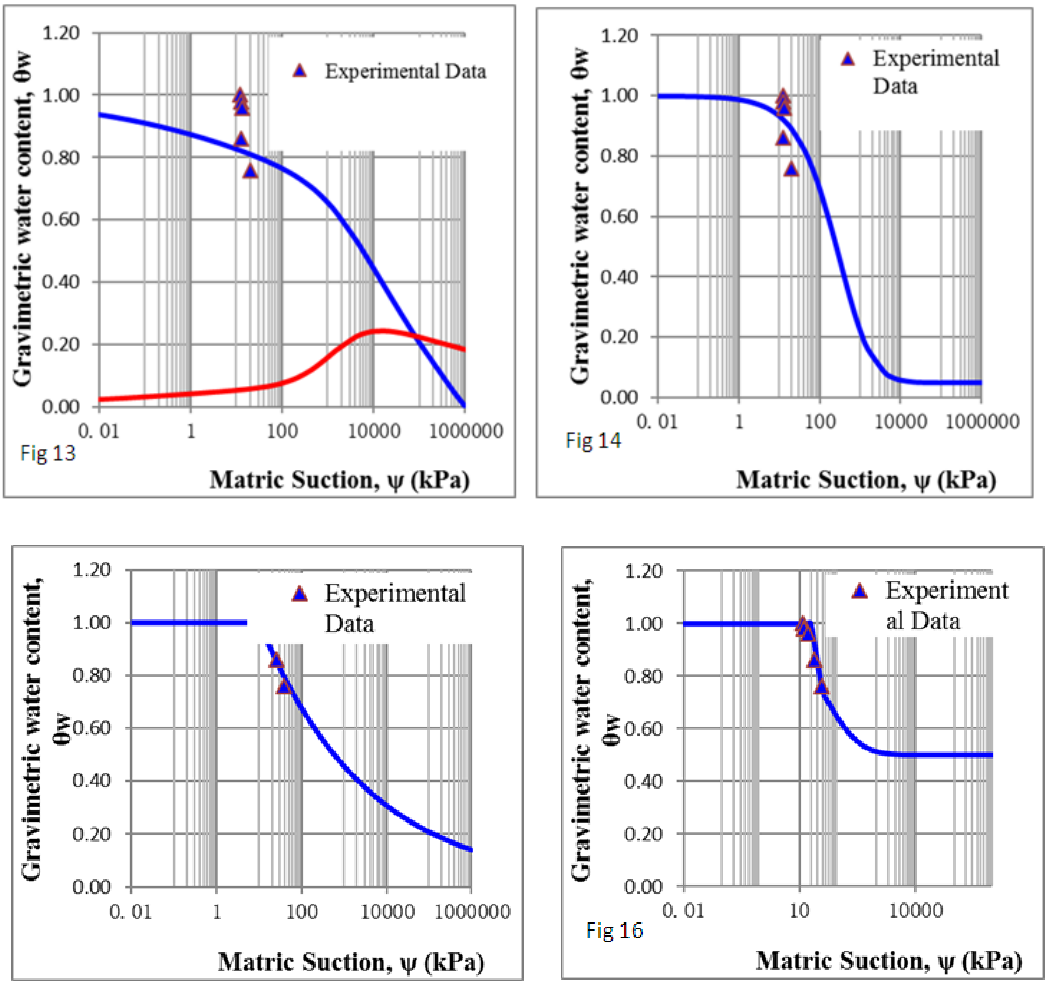




Figures 9-12.SWCC of an the A-7-5(5) tropical red earth soil using FX, VG, BC and K models respectively

Soil water characteristic curve of reconstituted A-7-5(20) tropical red earth soil

Reconstituted A-7-5(20) tropical soil is examined to determine its water characteristic curve. The results gotten from the SWCC using the four models of FX, VG, BC and K are presented in Figures 13 to 16 while the summary of the data are presented in Table 1.



Figures 13-16.SWCC of A-7-5(20) tropical red earth soil using FX, VG, BC and K models respectively

Determination of Models' Suitability for Selected Tropical Red Earth Soils

In order to determine the flexibility of the four models evaluated in this study to adequately predict the SWCC of selected classes of tropical soils cutting across low to high plasticity properties of the soils,Table1 were prepared. The ranking on each table section provides a quick guide to the type of soil most suitable for evaluation using the given model.

Table 1. Summary of models' fitting parameters for selected tropical red earth soils

Soil Class	a	n	m	R^2 (%)	MSSE (%)	ARE (%)
			Fredlund and Xing			
A-3	18.012	5.497	0.326	94.21 (1)	0.16	3.33[A]
A-7-5(5)	34.459	44.658	0.222	89.21(2)	1.57	8.26[A]
A-7-6(15)	26.262	4.761	0.430	83.42 (3)	1.18	9.49[A]
A-7-5(20)	33.548	50	0.206	-91.96 (4)	2.52	10.70[A]
			Van Genuchten			
A-7-5(5)	0.001	0.981	6.58	93.84(4)	12.82	5.64[A]
A-3	0.001	0.881	5.48	97.04 (3)	2.04	2.43 [A]
A-7-6(15)	0.001	0.760	2.48	98.88(1)	0.91	1.52[A]
A-7-5(20)	0.001	0.760	1.380	98.88(2)	0.91	1.52[A]
			Brooks and Corey			
A-7-5(5)	10.000	0.349	0	97.37(3)	1.18	1. 98[A]
A-3	10.000	0.277	0	98.96(4)	0.80	0.93[A]
A-7-6(15)	10.000	0.243	0	96.30(4)	3.03	3.27[A]
A-7-5(20)	10.000	0.170	0	99.81(1)	0.13	0.59[A]
			Kosugi			
A-7-5(5)	1.049	2.868	1.761	97.28(3)	1.60	1.42[A]
A-3	1.000	2.967	1.711	99.30(1)	0.51%	0.48[A]
A-7-6(15)	1.000	2.959	1.711	95.89(4)	2.65	2.58[A]
A-7-5(20)	1.000	2.966	1.711	99.24(2)	0.58	0.85[A]

Note: MSSE value is between zero infinity, the smaller the value, the better the model's predicting capability. The value in parentheses at every row is the best-prediction ranking for models evaluated. Value of 1 indicates the best prediction for the data using the model. The letters [A] and [D] signifies "agreement" and "discrepancy", respectively.

As shown in the first section of Table 1, FX model performs best with predicting the SWCC of an A-3 tropical red earth soil with a coefficient of determination of about 94%.A-7-5(5) tropical red earth soil came second in the ranking with a coefficient of determination of slightly under90%. A-7-6(15) reconstituted tropical soil came third in the ranking of soils suitable for SWCC determination using FX equation. A-7-5(20) reconstituted tropical soil however gave a negative coefficient of determination apparently indicating the data are not explained by the FX model indicating none suitability of FXmodel for predicting the SWCCof the soil.

Table 1 also shows the summary of Van Genuchten model fitting parameters for selected tropical red earth soils. Thesuitability of VGmodel for predicting the soil water characteristic curve of selected tropical soils with varying plasticity characteristic is shown in the table.VG model performs best with predicting the SWCC of A-7-6(15) and A-7-5(20) tropical red earth soilswithr^2value of almost 99%. A-3 tropical red earth soil came third in the ranking with a coefficient of determination of about 97%. A-7-5(5) came last in the ranking of the soilswith a coefficient of determination of slightly above 94%. Itis noteworthy however that across allthe soils' variations the coefficient of determination is over 94%, anindication of the relative strongcorrelationbetween the experimental data and the VGmodel.Itcan therefore beconcluded that the VGmodelcan beusedfor predicting the SWCCof virtually all classes of tropical soils with a relativestrong conviction in the results to be obtained using the model. Thesignificanceofthe relationship is further confirmed bytheAREvalue,all of which are under 6% much less than the 20% criterion of significance of any correlation.

Also found in Table 1 is the summary of Brooks and Corey model fitting parameters for selected tropical red earth soilsthe BCmodeland its suitability for predicting the SWCCacross a broad range of plasticity characteristics of tropical red earth soil ranging from low to high plasticity. With the fitting parameters stated in Table 1, the model performs wonderfully well in predicting the SWCCof virtually allthevarious classes of tropical soils investigated.A-7-5(20) and A-3-soils have high coefficient of determination of over 98%, thus rank top in the list.A-7-5(5) tropical red earth with coefficient of determination of approximately 97% came third on the ranking. A-7-6(15) reconstituted tropical soil came last in the ranking of the soils although its coefficient of determination is also high with a value of approximately 96% indicating the reliability of BC model to predicting the SWCC of tropical soils with different values of fines content reflecting in different plasticity behaviour.

Kosugi's model and its predicting capability for various classes of tropical soil according to their plasticity are further presented in Table 1. At a glance through the coefficient of determination column it can be seen that the model is suitable for predicting the SWCC of virtually all the groups of the tropical soils irrespective of the fines content or plasticity characteristics.This conclusion was reached as the coefficient of determination range from roughly 96 to 99%. A-3 tropical red earth soil ranked first in the list implying it's the most suitable soil for the model's predicting capability,for the coefficient of determination obtained for it was over 99%. A-7-5(20) tropical red earth soil came second also with coefficient of determination of over 99%.A-7-5(5) tropical soil came third with over 97% coefficient of determination while A-7-6(15) ranked last in the list although its coefficient of determination is also high with a value of approximately 96%, thus indicating the capability of the K model to also predictthe SWCC of tropical soils irrespective of its plasticity properties or fines content.

Proposed Easy Template for Utilising SWCC In Routine Engineering Procedures

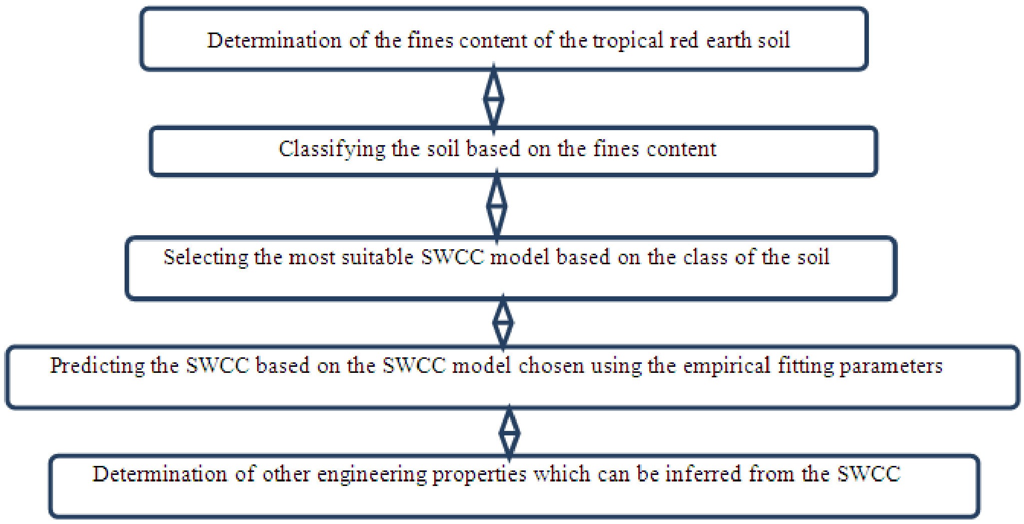


Figure 17 Flow chart for utilising SWCC in tropical red soils in routine engineering procedures

Armed with the information in Table 1, it becomes rational to propose an attractive yet easy template for incorporating SWCC determination into routine geotechnical engineering laboratory procedure. Beginning with the identification of the fines content of the tropical red earth soil other index properties of the soil can be predicted and the soil classified. Using the information on Table 1, the appropriate SWCC parameters can be selected and the SWCC determined. Following the choice of the SWCC, other engineering properties of the soil can thereafter be determined as illustrated in the flow chart shown in Figure 17.

IV. CONCLUSION

In conclusion it can be said that of the four models evaluated in this study viz: Fredlund and Xing (1994); Van Genuchten (1980), Brooks and Corey (1964) and Kosugi (1996),the BC model performed best with the estimation of the SWCC of tropical red earth soils irrespective of the fines content or plasticity characteristics as the least coefficient of determination recorded was over 96%. Closely following the BC model was the K-model which also had significant high values of r^2across all clases of tropical soils investigated. The VG model came third on the list of general performance while FX model came last on the list. Generally, all models had ARE values significantly less than 20%, indicating agreement exist between the models and the expermental data. FX model performed fairly with various classes of tropical soils except with that of high plasticity characteristics(A-7-5(20)) where the results indicated no correlation between experimental data and the model.Itshould however benoted that asizeable database of soil water characteristic curve data is required in order for ideal correlations to bedrawn between the fitted model parameters and the soil properties under consideration(Sillers & Fredlund, 2001) . This implies that the results presented and evaluated are open for further refinement should amorerigorous testing scheme highlights the need for such. Recent researches also highlight the need for interpreting gravimetric soil water characteristic parameters in conjuction with shrinkage properties of the soil((Zhai, Rahardjo, Satyanaga, Dai, & Zhuang, 2020)

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