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SUITABILITY OF SWCC MODELS FOR EVALUATING SELECTED RECONSTITUTED TROPICAL RESIDUAL SOILS

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ABSTRACT

Soil water characteristic curve (SWCC) is a very important property of unsaturated soil. This is due to the fact that several other soil properties can be related to it. Natural soil samples obtained from two locations in Benin City, Nigeria were reconstituted to simulate tropical soils' variability ranging from low plasticity configuration with fines content less than 30% to high plasticity tropical soils with fines content greater than 70%. The soil's matric potential was determined using the Filter Paper technique. The 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 values were used to determine the suitability of the models for predicting the SWCC of the selected reconstituted tropical soil. The models used were: Fredlund and Xing (1994); Van Genuchten (1980), Brooks and Corey (1964) and Kosugi (1996). It was seen that all four models can be used to predict tropical red earth SWCCs although some models perform better than others depending on the plasticity characteristics of the tropical soils. In whole, Brooks and Corey (1964) and Kosugi (1996) methods performed best across all plasticity ranges of tropical soil investigated.

1. INTRODUCTION

Soil-Water Characteristic Curve (SWCC) is a curve that describes the relationship between the amount of water in a soil and its suction. It can be viewed as a continuous sigmoid function which describes the water storage capacity of a soil as it is subjected to various soil suctions (Matlan, et al., 2014). Soil-Water Characteristic Curve (SWCC) is a very important property of unsaturated soil because other soil properties such as shear strength, permeability function, compressibility, modulli and fluid flow can be related to it (Zhai & Rahardjo, 2013; Houston, et al., 2006); Choudhury & Bharat, 2014). Different models have been developed in the field of SWCC over the last five decades and some of the notable ones include Brooks and Corey, 1964; van Genuchten, 1980; Fredlund and Xing, 1994; Kosugi, 1999; Omuto, 2009; Krishnapillai and Ravichandran, 2012. (Taban, et al., 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 =volumetric water 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 SWCC of various soils. It's among the most widely used model judged to be suitable for use for a wide range of both disturbed and undisturbed soils ranging from fine grained to coarse grained soils (Taban et al., 2018).
The van Genuchten model presents the relationship between the normalized water content and the suction as stated in equations 2a and 2b below:

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

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

Where S is the normalized water content (a dimensionless parameter), Θ is the volumetric water content, the indices r and s in θ_r and θ_s symbolize the residual and the saturated volumetric water contents respectively. Ψ is 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 distribution parameters. m on the other hand is related to the asymmetry of the model

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:

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

And θ is the volumetric water content, also the indices r and s in θ_r and θ_s symbolize the residual and the saturated volumetric water contents respectively, Ψ is the suction and ψ_b,is the air entry value while λ is the pore size distribution index. This model is relatively simple and thus widely used although the model doesn't provide a continuous mathematical function for the entire SWCC (Matlan et al., 2014)

Kosugi (1996)'s model

Kosugi (1996)'s models, the most recent model of the four models evaluated in this study is reported to be among the three commonly used models, the other two are the Brooks and Corey, 1964 and van Genuchten, 1980 (Mavimbela & Rensburg, 2012). The model was developed by applying a lognormal distribution law and its parameters are directly related to the soil pores radius distribution (Matlan, et al., 2014). Kosugi's model is expressed in Equations 5 and 6:

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

Where Q is 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 and σ are the fitting parameters. h_m is a capillary pressure head and is related to the median pore radius while σ is a dimensionless parameters related to the width of the pores radius distribution. The complementary error function present in the Kosugi's model introduces complexity into the equation thereby making its usage difficult (Matlan et al., 2014). It was however noted by Matlan et al., 2014 that Kosugi's model has greater flexibility than the other models owing to the fact that the model can be used to represent the soil water characteristic curve in both the wet and dry regions and for all soil types.

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 said that each equation appears to apply for a particular group of soils. It is therefore not irrational to evaluate any given soil against some selected popular SWCC models to determine which most closely describes its SWCC. It is for this reason that the aforementioned four models were chosen for the evaluation of selected tropical residual red earth water characteristic curve. More-so the most suitable model would be used in determining other geotechnical properties of tropical red earth soil such as shear strength and permeability function.

2. MATERIALS AND METHODS

The filter paper method of determination of SWCC in the laboratory was adopted in this study. This current study evaluates the SWCC of reconstituted tropical red soil using Whatman No. 42 filter paper to establish the soil water characteristic curve.

2.1 Sample Preparation

Red earth residual soils were obtained at shallow foundation location at depth ranging from 1.2m to 2.0m and separated into coarse fraction and fines (silt/clay fractions) using 75µm sieve aperture and they were thereafter marked as A and B subsamples respectively. A comprehensive description of the primary tropical residual red earth including the mineralogy was presented by Okovido & Obroku (2021b). To ensure the fraction coarser than 75 microns sieve devoid of silt/clay constituent, the soil was soaked in a solution containing 4% Sodium Hexametaphophate for 20 hours and was thereafter washed through the 75 microns sieve aperture. The subsamples were reconstituted back into one soil specimen by partial blending of coarse (sand) sub samples in 10 percent increments from 10% fines (90A+10B) 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. The characteristics of the reconstituted samples with respect to density and void ratio were presented in Okovido & Obroku, 2021a; Okovido & Obroku (2014). Other samples were prepared at water content less than optimum and also at water content greater than optimum in order to capture a broad range of the matric suction characteristics of the soil. All reconstituted soil samples were allowed to cure for a minimum of 20 hours. The cured samples were thereafter extruded and prepared for matric suction test.

2.2 Matric Suction Sample Preparation

The matric suction test was executed using the filter paper technique. The filter paper technique offers some advantages over the conventional methods and has been in use for several decades. The filter paper technique has also been accepted as a standard method of measuring soil potential (ASTM D5298-10, 2010). The procedures include placing a portion of the filter paper in-between two protective filter papers which are in contact with the soil sample in such a way that suction equilibrium is established between them. Although the filter paper and the soil have different water contents, they are subjected to the same matric potential (Lucas de Almeida et al., 2015). In this work Whatman No. 42 filter paper was used**.** Each matric suction test was performed on a sample of 42 mm diameter and 30 mm height. The samples were carefully extruded and cut to ensure that the surface is planar and smooth to enable a good contact surface between the filter papers and the soil. Each set of three filter papers (2 Nos protective filter papers with diameter 42 mm and 1 Nos. 38 mm diameter Whatman No. 42 filter paper) were placed between two soil samples. The central filter paper was made smaller in diameter to prevent soil samples from polluting the central filter paper. The joint was thereafter sealed with an electrical tape and the sealed sample placed in an airtight plastic container with the cover again sealed with the electrical tape to prevent moisture loss from the soil. The whole assembly was kept in a well-insulated container for suction equilibrium. After a period of three days to one week of suction equilibration, the assembly was opened and both the soil samples and the central filter paper were weighed with a 0.0001g precision balance. Weighing was carried out within 20 seconds to avoid possible evaporation. Finally, suction was calculated from the computed filter paper water content using the appropriate calibration curve which depends on the initial state of the filter paper, whether wet or dry. Matric suction values were computed using calibration equations stated below:

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

For $wc_{fp} < 45.26\%$

And

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

For $wc_{fp} > 45.26\%$

Each of the two segments can be expressed as

$$\log S = a(wc_{fp}) + b \quad (9)$$

Where S is suction in kPa, a is slope of the line, b is y intercept and wc_{fp} is gravimetric filter paper water content in %.

2.3 Evaluation Criteria

In the evaluation, three criteria were used for comparison and understanding the descriptive and predictive capabilities of the four models. This would enable one to know the model which most adequately describes the SWCC based on the plasticity.

The first criterion is the degree of curve match. The closer the difference between the predicted curve and the measured data the better the descriptive capability of the model. (Guan, et al., 2010). These can be evaluated using Average Relative Error (ARE) computed from equation (16) shown below:

$$ARE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100 \quad (10)$$

Where y_i is the actual value of *i*th data; $\hat{y}_i$ is the predicted value of the *i*th data; and N is the total number of data available.
In this study, agreement of predicted with actual will be patterned along the same line as those of (Guan et al., 2010) where "agreement" was defined as ARE value being smaller than or equal to 20%, and "discrepancy" was defined as ARE value being larger than 20%. These terms were used to identify the models with the best capacity to predict the SWCC of the selected tropical soils investigated in this study.

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

$$SSE = \sum_{i=1}^{N}\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2 \quad (11)$$

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

The last criterion used in the evaluation is the coefficient of determination, r^2. This evaluates 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. The sum of squares of the deviation from the mean, $\bar{y}$ in the y direction is given as $\sum_{i=1}^{N}\left(\frac{y_i - \bar{y}}{1}\right)^2$, the coefficient of determination is therefore the fraction of this sum of squares which is explained by the linear relation between $\hat{y}$ and x given by the regression of y on x. The coefficient is expressed as:

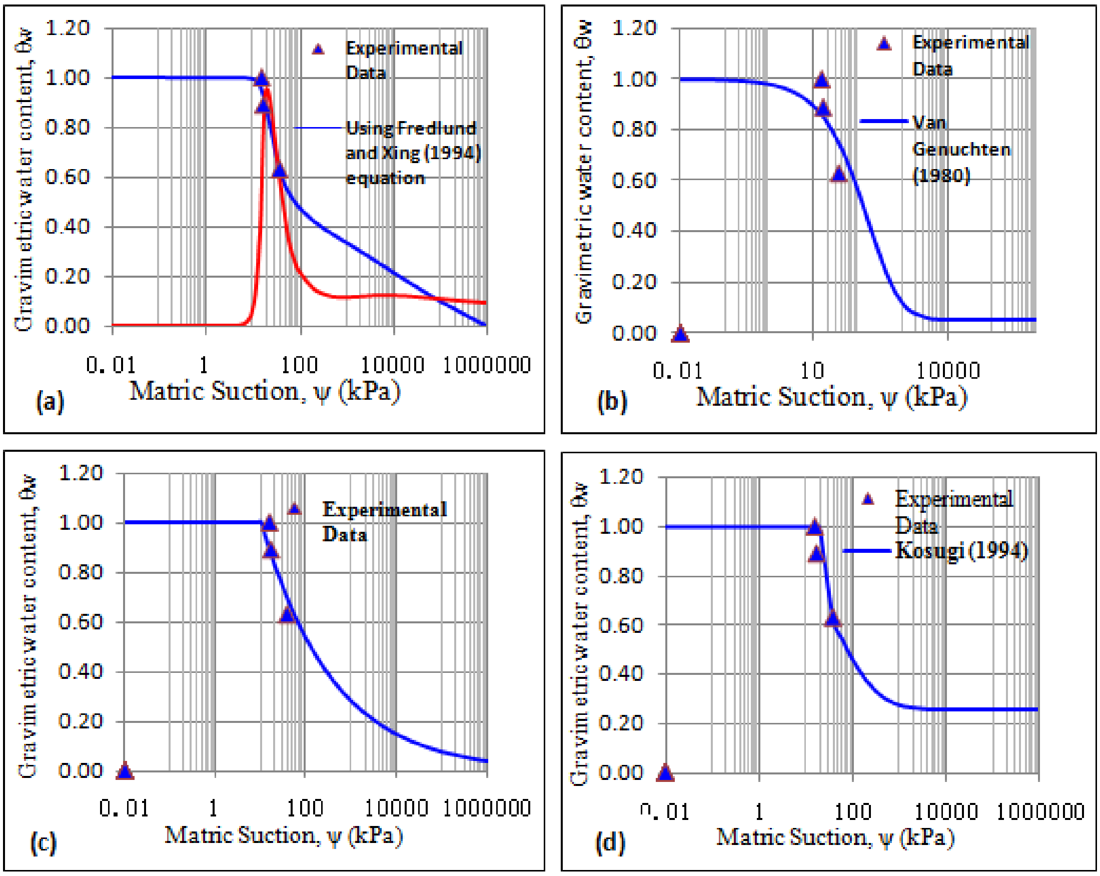
$$r^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \quad (12)$$

If the coefficient of determination becomes larger for the same algebraic forms, it indicates the relationship between the variables has become stronger. It should however be noted that a sizeable database of soil water characteristic curve data is required in order for ideal correlations to be drawn 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 a more rigorous testing scheme highlights the need for such. Recent researches also highlight the need for interpreting gravimetric soil water characteristics parameters in conjuction with shrinkage properties of the soil((Zhai, et al., 2020).

3. RESULTS AND DISCUSSION

3.1 Soil-Water Characteristics Curve of Reconstituted A-3 Tropical Red Earth Soil

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 Fredlund and Xing, 1994 (FX); Van Genuchten, 1980 (VG); Brooks and Corey, 1964 (BC) and Kosugi, 1996 (K) are presented in Figures 1a, 1b, 1c and 1d while the summary of the fitting parameters and evaluation data are presented in Table 1. As observed in Figure 1a, FX equation can be seen to adequately predict the SWCC of the soil as virtually all points were fitted into the equation with fitting parameters shown in Table 1. The experimental data points all lie along the equation's trend line showing a strong agreement between the model and experimental data. The actual magnitude of the relationship determined statistically is presented in Table 1.



Figures-1: SWCC of an A-3 Tropical Red Earth Soil Using (a) FX, (b) VG, (c) BC and (d) K-Model Respectively

Figure 1b shows the plot of gravimetric water content versus matric suction (SWCC) using VG model fitting the experimental data to the equation. The plot shows scattered points fairly close to the trend line of the VG model which is suggestive of the fact that the experimental data fairly match the VG model. This also shows that the VG model is suitable for predicting the SWCC of A-3 tropical red earth soil although the coefficient of determination which clearly shows the degree to which the prediction is in line with the experimental data is presented in Table 1. The BC model is presented in Figure 1c for the A-3 tropical SWCC. The fitting parameters, a, n and m resulting in the close match between experimental data and the predicting equation are shown in Table 1. Visual inspection of the plot shows that the equation can adequately predict the behaviour of the soil as the points lie close to the equation's trend line. The degree of agreement between the experimental data and the BC equation determined statistically is shown in Table 1. Kosugi (1994) model is presented in Figure 1d for the SWCC equation and the experimental data fitted into the equation. Visual inspection of the plot shows that the equation can adequately predict the behaviour of the soil as virtually all points lie close to the equation's trend line. The fitting parameters resulting in this close fit between experimental data and the equation are shown in Table 1. The strength of the correlation determined from statistical evaluation is also presented in Table 1.

Table 1: Summary of Models' Evaluation using MSSE, R^2 and ARE and Fitting Parameters for an A-3 Tropical Red Earth Soil

Model	a	n	m	R^2 (%)	MSSE (%)	ARE (%)
FX	18.012	5.497	0.326	94.21 (4)	0.16	3.33 [A]
VG	0.001	0.881	5.480	97.04 (3)	2.04	2.43 [A]
BC	10.000	0.277	0.000	98.96 (2)	0.80	0.93 [A]
K	1.000	2.967	1.711	99.30 (1)	0.51	0.48 [A]

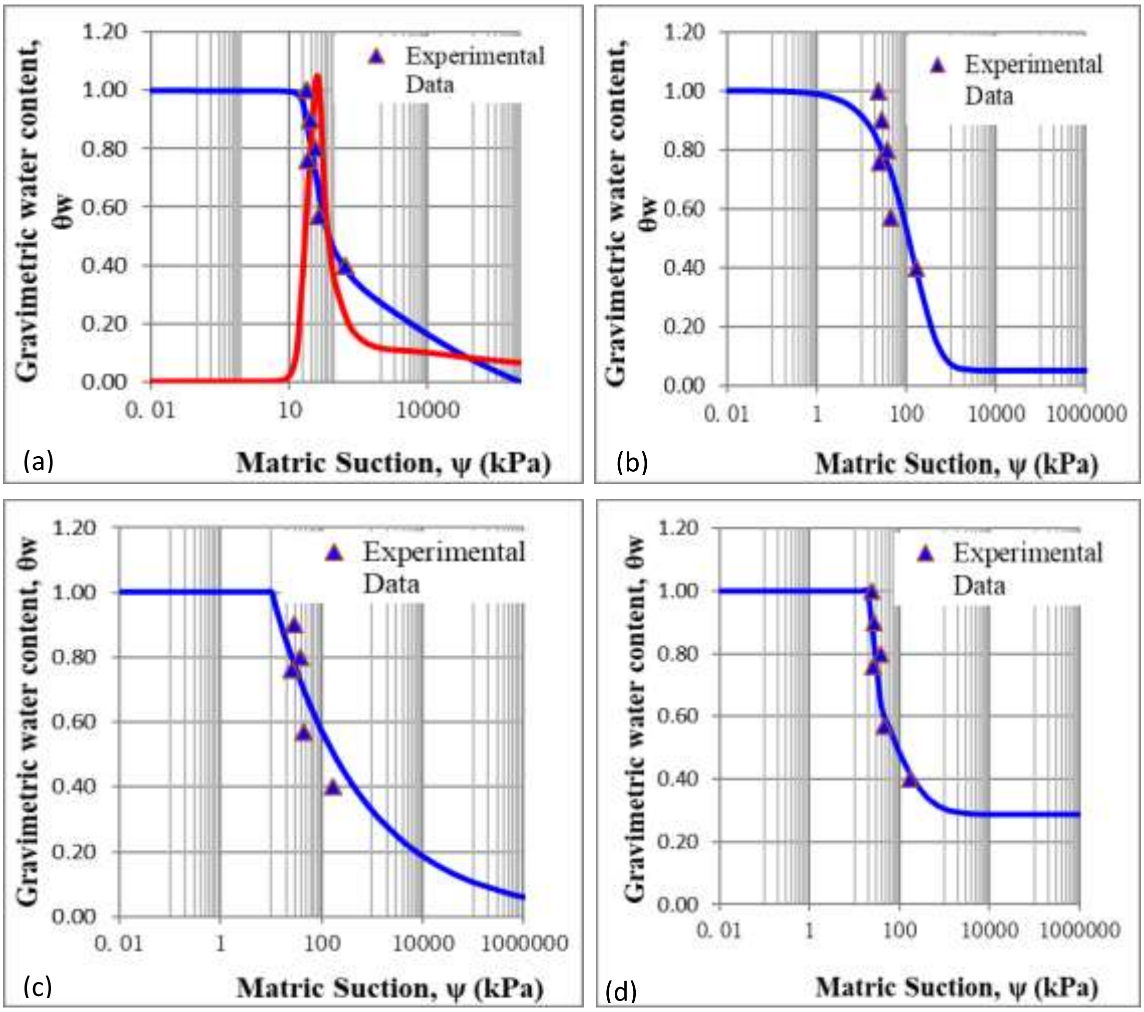
Note: MSSE value is between zero infinity, the smaller the value, the better the model's predicting capability. The value in parentheses at every row is the best-prediction ranking for models evaluated. Value of 1 indicates the best prediction for the data using the model. The letters [A] and [D] signifies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

As shown in Table 1, when considering reconstituted A-3 tropical soil, K model is the most suitable to be used in predicting the soils' WCC. The strength of the relationship between the predicted and experimental results is high as a coefficient of determination value of 0.993 was recorded, showing 99.3% of the variance in the model can be explained by the variance in the experimental results. This implies that only 0.7 percent of the data is unexplained (coefficient of alienation). The lower the MSSE value, the higher the predicting capability of the model. This is also low for the K model, with a value of 0.51. Using the average relative error (ARE) value, it can be seen that all models are significant in their ability to predict the SWCC of tropical red earth soil with varying plasticity. This conclusion is reached as all models have ARE values less than

4, where 20% is the upper boundary for significant relationship between models. This further indicates that the four equations are able to predict the SWCC of A-3 tropical red earth soils.

3.2 Soil water characteristics curve of an A-7-6 reconstituted tropical red earth

A-7-6 reconstituted tropical red earth, also classified as SC using USCS classification scheme 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 2a to 2d while the summary of the data are presented in Table 2. Figure 2a, FX equation can adequately predict the SWCC of the soil as virtually all points were fitted into the equation with the fitting parameters shown in Table 2. The experimental data points all lie along the equation's trend line showing a strong agreement between the model and experimental data. The actual strength of the relationship was determined statistically and the results presented in Table 2.



Figures-2: SWCC of an A-7-6 Tropical Red Earth Soil Using (a) FX, (b) VG, (c) BC and (d) K Models

Figure 2b shows VG model and the corresponding experimental data plotted using appropriate fitting parameters. The plot shows scattered points with some points lying relatively far away from the trend line of the VG model. This indicates that the experimental data fairly matches the VG model. This also shows that the VG model is fairly suitable for predicting the SWCC of an A-7-6 tropical red earth. The coefficient of determination which clearly shows the degree to which the prediction is in line with the experimental data is presented in Table 2. The BC model is presented in Figure 2c for the A-7-6 tropical red earth soil SWCC. The fitting parameters, a, n and m resulting in the relatively close alignment between experimental data and the predicting equation are shown in Table 2. Visual inspection of the plot shows that the equation can adequately predict the behaviour of the soil as the points lie close to the equation's trend line. The degree of agreement between the experimental data and the BC equation determined statistically is shown in Table 2.

Kosugi (1994) model is presented in Figure 2c for the SWCC equation of an A-7-6 tropical red earth soil and the experimental data fitted into the equation. Visual inspection of the plot shows that the equation is superbly able to predict the behaviour of the soil as virtually all points lie virtually along the equation's trend line. The fitting parameters resulting in this close fit between experimental data and the equation are shown in Table 2. The strength of the correlation which was determined from statistical evaluation is also presented in Table 2. As shown in Table 2, when considering A-7-6 (15) tropical red earth, VG model is the most suitable among the four models evaluated in predicting the soils' water characteristic curve. The strength of the relationship between the predicted and experimental results is high as a coefficient of determination value of 0.988 was recorded, showing 98.8% of the variance in the model can be explained by the variance in the experimental results.

Table 2: Summary of Models' Evaluation Using MSSE, R^2 and ARE and Fitting Parameters for an A-7-6 Tropical Red Earth Soil

Model	a	n	m	R^2 (%)	MSSE (%)	ARE (%)
FX	26.262	4.800	0.430	83.42(4)	1.18	9.49[A]
VG	0.001	0.760	2.480	98.88(1)	0.91	1.52[A]
BC	10.000	0.243	0.000	96.30(2)	3.03	3.27[A]
K	1.000	2.959	1.711	95.89(3)	2.65	2.58[A]

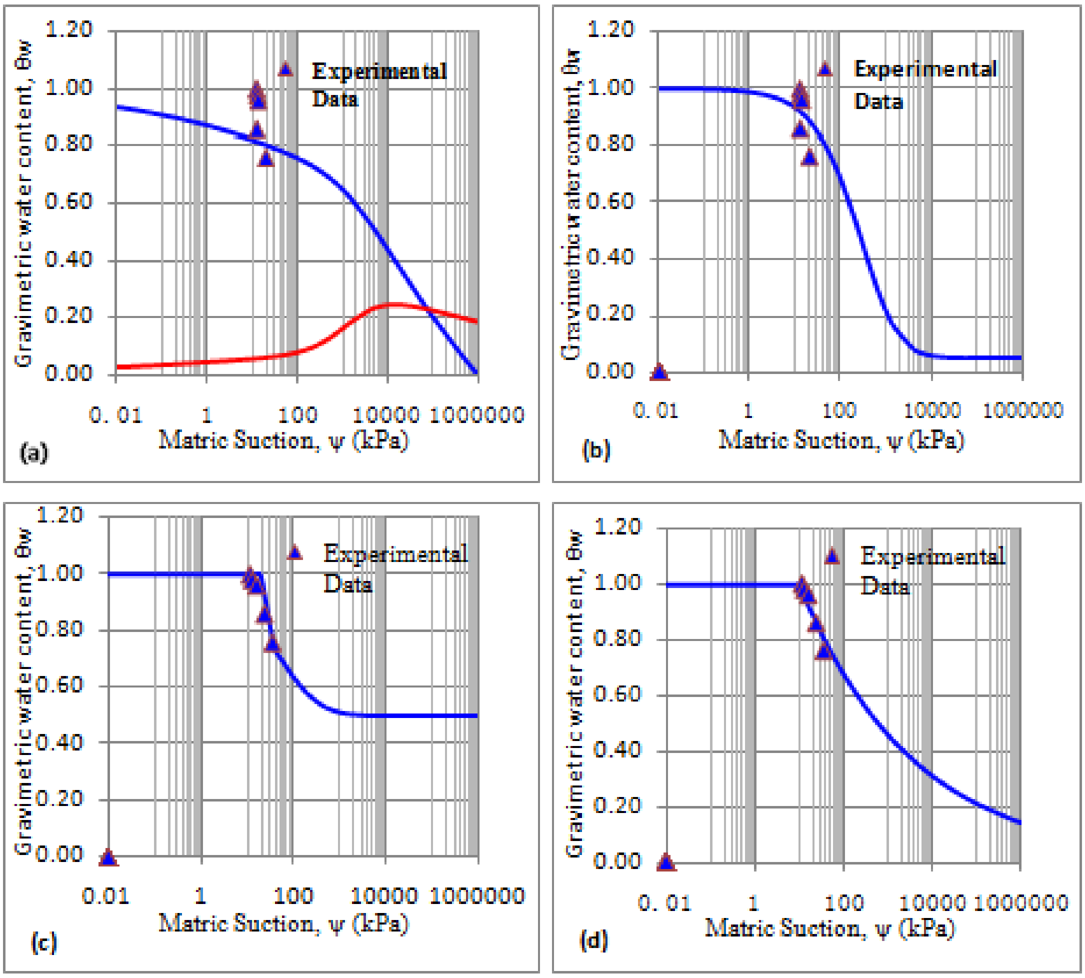
Note: MSSE value is between zero infinity, the smaller the value, the better the model's predicting capability. The value in parentheses at every row is the best-prediction ranking for models evaluated. Value of 1 indicates the best prediction for the data using the model. The letters [A] and [D] signifies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

The lower the MSSE value, the higher the predicting capability of the model. This again is the least with the VG model, supporting the ranking criterion used by the coefficient of determination. Using the average relative error (ARE) value, it can be seen that all models are significant in their ability to predict the SWCC of the A-7-6 (15) tropical red earth. This conclusion is reached as all models have ARE values less than 20%, indicating that the equations are able to predict the SWCC of an A-7-6 (15) tropical red earth soils.

3.3 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.

Figure 3a shows FX model and the corresponding experimental data points using fitting parameters. The plot shows scattered points fairly close although not in line with the trend line of the FX model which is suggestive of a fairly weak relationship between the experimental data and the FX equation.



Figures-3: SWCC of an A-7-5(20) Tropical Red Earth Soil Using (a) FX, (b) VG, (c) BC and (d) K Model

This also shows that the FX model is probably not suitable for predicting the SWCC of tropical red earth soil although the coefficient of determination will clearly show the degree to which the prediction is in line with the experimental data and this detail is presented in Table 3. The results from the SWCC using the four models of FX, VG, BC and K are presented in Figures 3a to 3d while the summary of the data are presented in Table 3.

Figure 3b shows VG model and the corresponding experimental data plotted using fitting parameters. The plot shows data points which are relatively close to the trend line of the VG model apparently suggestive of a strong relationship between the predicting equation and the model. This also shows that the VG model is fairly suitable for predicting the SWCC of A-7-5(20) tropical red earth soil. Statistical evaluation was performed to determine degree to which the model is in line with the experimental data and the results are presented in Table 3.

The BC model is presented in Figure 3c for the A-7-5 (20) tropical soil's water characteristic curve. The fitting parameters, a, n and m are shown in Table 5. Visual inspection of the plot shows that the equation can adequately predict the behaviour of the soil as the data points lie close to the equation's trend line. The fitting parameters are also shown in Table 5. The degree of agreement between the experimental data and the BC equation determined statistically is also shown in Table 3. Kosugi (1994) model is presented in Figure 3d for the SWCC equation and the experimental data fitted into the equation. Visual inspection of the plot shows that the equation can be relied upon for predicting the behaviour of A-7-5(20) tropical red earth for the as most of the experimental data points lie close to the equation's trend line. The fitting parameters resulting in this close fit between experimental data and the equation are shown in Table 3. The strength of the correlation which was determined from statistical evaluation is also presented in Table 3. As shown in Table 3, the SWCC of A-7-5 (20) tropical soils can best be predicted by the BC and the K models among all four models evaluated for predicting the soil's water characteristic curve.

Table 3: Summary of Models' Evaluation Using MSSE, R^2 and ARE and Fitting Parameters for A-7-5(20) Tropical Red Earth Soil

Model	a	n	m	R^2 (%)	MSSE (%)	ARE (%)
FX	33.548	0.180	0.821	-98.82(4)	0.82	11. 92[A]
VG	0.001	0.760	1.380	98.88(3)	0.91	1.52[A]
BC	10.000	0.170	0.000	99.81(1)	0.13	0.59[A]
K	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.

The coefficients of determination of both models were 99.81% and 99.24% respectively for the BC and the K models. Both models also have MSSE value of less than 1, indicating the high predicting capability of the models. Again, this is least with the BC models, supporting the ranking criterion used by the coefficient of determination. The coefficient of determination also shows there is relatively strong relationship between the VG model and the experimental data as its value was about 98. 9%. FX model however appears to be unrelated to the experimental data trend for a negative coefficient of determination was recorded. Using the average relative error (ARE) value, it can be seen that all models are significant in their ability to predict the SWCC of tropical red earth soil with high plasticity. This conclusion is reached as all models have ARE values less than 20%, although FX equation gave a negative r^2 value and interestingly FX model gave the highest value of ARE indicating a relatively weaker relationship. It can be concluded that the three equations with positive coefficient of determination can satisfactorily predict the SWCC of A-7-5(20) tropical soils using the corresponding fitting parameters presented in Ta**b**le 3.

4. 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 is the K-model which also had significant high values of r^2 across all classes of tropical soils investigated. The VG model came third on the list of general performance while FX model came last on the list. One interesting fact is that all models had ARE values significantly less than 20%, indicating agreement exist between the models and the experimental data.

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