ABSTRACT: The knowledge of soil hydraulic properties and processes leads to better predictions of both agricultural and environmental impact. This research concentrates on hydraulic conductivity (K) as a function of soil water content and soil water sorptivity (Sw). The objective of this research is to determine, characterize and compare the relationship between measured and estimated (obtained by PTF) soil hydraulic properties in Ekiti State, forest vegetative zone of Nigeria. Measured hydraulic conductivity and sorptivity were determined by a steady-state flow using an infiltration device (mini-disk infiltrometer). Pedotransfer models (PTF) for point and parametric (van Genuchten’s parameters) estimation of hydraulic conductivity and soil sorptivity from basic soil properties such as bulk density (BD), water holding capacity (WHC), soil moisture content (MW), cation exchange capacity (CEC), organic matter content (OMC) and were developed and validated using multiple-linear regression method. K and Sw predicted by the PTF models was highly significant using only BD, MW and WHC (r=0.774** and 0.803**) while models developed using BD, MW, WHC, OMC and CEC increased significance level of the relation between predicted and measured values of Sw (r=0.808**). Equation (3) was the best model for predicting K with R = 0.774, RMSE = 0.55, MAE = 0.42 and RE = 21.67 respectively. These models are adequate enough to predict hydraulic conductivity and soil water sorptivity in areas of similar climate and soil types.

Keywords: pedotransfer, soil hydraulic properties, hydraulic conductivity, soil sorptivity, Ekiti State.

INTRODUCTION

Soil Hydraulic Properties are properties reflecting the ability of a soil to retain or transmit water and its dissolved constituents (Genuchten and Pachepsky, 2003). Soil hydraulic properties also define the relationship between soil moisture, hydraulic head and hydraulic conductivity (Gutman and Small, 2005), thus controlling how water moves through the soil. This water movement in the unsaturated zone, together with its water holding capacity is very important for assessing the water demand of the vegetation, as well as for recharge of the ground water storage (Kumar and Mittal, 2000). Soil hydraulic properties include hydraulic conductivity as a function of both soil water pressure and soil water content, and the soil moisture retention relationship (Hillel, 1998). This research concentrates on hydraulic conductivity as a function of soil water content and soil water sorptivity. Hydraulic conductivity (K), according to Kirkham, 2005 is defined as “the metres per day of water seeping into the soil under the pull of gravity or under a unit hydraulic gradient”. It is a measure of the soil’s ability to transmit water when submitted to a hydraulic gradient. Sorptivity (S), on the other hand as an integral property of the soil water diffusivity (White and Perroux, 1987), is the capacity of soil to ‘suck’ up water.

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and is dominated by the antecedent water content of the soil (Hallet, 2007). Philip (1957) in his well-known infiltration equation introduced the term sorptivity to describe the ability of soil to absorb water without reference to gravitational effects i.e. a measure of the ability of the soil to attract water by capillary action. In other words, sorptivity governs the early stage of the infiltration process (Bonsu, 1993). Both hydraulic conductivity and sorptivity are controlled by the shape, volume and tortuosity of pores in the soil.

Soil hydraulic properties affect the partitioning of rainfall and irrigation water into infiltration and runoff at the soil surface, available water in the soil root zone, the rate and amount of redistribution of water in a soil profile, and recharge to or capillary rise from the groundwater table, among many other processes in the unsaturated or vadose zone between the soil surface and the groundwater table (Genuchten and Pachepsky, 2003). They also play crucial role in the use of mathematical models for studying or predicting site-specific water flow and solute transport processes in the subsurface. This includes using models as tools for designing, testing, or implementing soil, water, and crop management practices that optimize water use efficiency and minimize soil and water pollution by agricultural and other contaminants (Genuchten and Pachepsky, 2003). In general, Soil hydraulic properties are important for modelling hydrological processes and related contamination transport (Xu et al., 2009). Despite this, information on soil hydraulic properties is lacking in the south western part of Nigeria. All of these indicated the importance and the need for proper characterization of the spatial variability of soil hydraulic properties particularly in south western part of Nigeria. The hydraulic conductivity and sorptivity of water in soil can be measured by both field and laboratory experiments. The field technique is known to be generally more reliable than laboratory techniques (Klute and Dirksen, 1986). Despite the progress made in measuring soil hydraulic properties directly, Soil information is still expensive to obtain both in the field, and also in the laboratory analysis of soil physical and chemical properties. Also Soil properties can be highly variable spatially and temporally and measuring these properties is time consuming and problematic. Therefore it is essential to derive relationships that link the basic soil properties to the functional soil properties that are more difficult to measure.

Recently, indirect estimation of these functional properties from widely available or more easily measured basic soil properties (sand (S), silt (Si), clay (C), bulk density (BD), and organic matter (OM)) using Pedotransfer functions (PTFs) has received considerable attention (Wosten et al., 1995; Minasny and McBratney, 2002; Minasny et al., 2004). Bouma (1989) coined the term pedotransfer function as translating data we have into what we need. PTF uses basic soil properties as input and yields hydraulic functions as output (Bouma, 1989). Pedotransfer models have been successfully used to predict some soil hydraulic properties (Pachepsky et al., 1996; deMacedo et al., 2002; Gülser, 2004; Gülser et al., 2007). Wosten et al. (2001) made an excellent review of PTFs. In the light of the above, the objective of this research is to determine, characterize and compare the relationship between measured and estimated (obtained by PTF) soil hydraulic properties in the forest vegetative zone of Nigeria.

**MATERIALS AND METHODS**

**Site description and sampling design**

**Site description**

The study was conducted in Ekiti State in the forest vegetative zone of Nigeria. Ekiti State is located between Longitude 4° 45’ to 5° 45’ East of the Greenwich Meridian and Latitudes 7° 15’ to 8° 5’ North of the Equator (EKSG, 2009). The State is 6,353 km² (2,453 sq ml). The State enjoys...
tropical climate with two distinct seasons. The rainy season is bimodal (April – October) and dry season (November – March). Ekiti State has a small temperature range; the temperature ranges are almost constant throughout the year (www.wikipedia.org). The temperature ranges between 21° and 28° with high humidity. The vegetation of Ekiti State is guinea forest with its attendant climate, flora and fauna. Ekiti State is located within the southern part of Nigeria which experiences heavy and abundant rainfall, the storms are usually conventional in making, due to the region proximity to the equatorial belt. The annual rainfall received in this region, is very high. Ekiti State has a total annual rainfall of about 1400 mm with a low co-efficient variation of about 30% during the rainfall peak months, and with an average of about 112 rainy days per annum (Adebayo, 1993).

Experimental procedure and Soil sampling
Field experiments were conducted from January to March, 2014 at 35 different locations in Ekiti State. Soil sampling and field experiments were conducted to determine the hydraulic conductivity and soil water sorptivity. Three sampling points were randomly selected per location and undisturbed soil samples were collected at depths up to 20 cm from the different locations. Topsoil samples were collected from each location, packed in plastic bags, and transferred to the laboratory. The samples were allowed to dry in the open air until reaching friability. Soil physical properties such as infiltration rate, moisture content, bulk density and total porosity were also determined.

Measurements
Mini disk infiltrometer
Hydraulic conductivity and water sorptivity
Measured Hydraulic conductivity and soil water sorptivity were determined by a steady-state flow using an infiltration device (mini-disk infiltrometer) provided by decagon devices. The minidisk infiltrometer (Decagon Devices, Inc., Pullman, WA) is a hand-held field instrument for rapidly assessing soil infiltration capacity. It was used to measure the soil hydraulic conductivity and water sorptivity. Suction rate of 2 cm per seconds was chosen for better accommodation of the infiltration measurement (Fasinmirin and Olorunfemi, 2012). The data collected were then used to calculate the water infiltration rates of the soil. The hydraulic conductivity of soil was then calculated using the method described by Zhang (1997).

The method requires measuring cumulative infiltration vs. time and fitting the results with the infiltration function

\[ I = C_1 t + C_2 \sqrt{t} \]  

(1)

where \( C_1 \) (m s\(^{-1}\)) and \( C_2 \) (m s\(^{-1/2}\)) are parameters. \( C_1 \) is related to hydraulic conductivity, and \( C_2 \) is the soil sorptivity.

The hydraulic conductivity of the soil (\( k \)) was then computed using the relationship in equation 3.2:

\[ K = \frac{C_1}{A} \]  

(2)

where \( C_1 \) is the slope of the curve of the cumulative infiltration vs. the square root of time, and \( A \) is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the infiltrometer disk. \( A \) is computed from:

\[ A = \frac{11.65(n^{0.41} - 1)\exp[2.92(n - 1.9)ah_0]}{(ar_0)^{0.91}} n \geq 1.9 \]  

(3)

\[ A = \frac{11.65(n^{0.31} - 1)\exp[7.5(n - 1.9)ah_0]}{(ar_0)^{0.91}} n < 1.9 \]  

(4)

Where \( n \) and \( a \) are the van Genuchten parameters for the soil, \( r_0 \) is the disk radius and \( h_0 \) is the suction at the disk surface.

Physical and chemical characterization of soils
The chemical properties tested for includes soil cation exchange capacity (CEC) and organic matter content (OMC) whereas the physical properties include soil particle size distribution, bulk density (BD), total porosity (PT), water
holding capacity (WHC) and soil moisture content (MW). The organic carbon was determined using the Walkley - Black wet oxidation procedure and the soil organic matter content was determined from the organic carbon (Nelson and Sommers, 1996). The cation exchange capacity (CEC) at pH 7.0 was determined following the procedure compiled and described by Reeuwijk (2002). The exchangeable potassium (K\(^{+}\)) and sodium (Na\(^{+}\)) was extracted with HCl solution and their levels determined by flame and exchangeable magnesium (Mg\(^{2+}\)) and calcium (Ca\(^{2+}\)) by atomic absorption spectrophotometer (Senjobi and Ogunkunle, 2010). The exchangeable magnesium and calcium by atomic absorption spectrophotometer (Senjobi and Ogunkunle, 2010). The total porosity (PT) was calculated from BD and PD using the equation developed by Danielson and Sutherland (1986). Soil particle sizes were determined using the Bouyoucos hydrometer method.

### Statistical analysis
The slope of the curve of the cumulative infiltration vs. the square root of time was determined using a Basic Microsoft Excel spreadsheet macro created by Decagon (Decagon Devices, 2007). Hydraulic conductivity and sorptivity were subjected to statistical analysis to determine the mean, standard deviation, coefficient of variation among soil samples from different locations. Descriptive statistics such as minimum and maximum value, arithmetic mean value, standard deviation (StDev), coefficient of variation (CV) were calculated to help in providing explanations and assessing the dispersion of the variables. Measure of Dispersion tells us about the variation of the data set. Shapiro-Wilk’s statistics was used to test the assumption of normality to determine whether the data follow a normal distribution. To predict the hydraulic conductivity (K) and sorptivity of soil (Sw), pedotransfer (PTF) models, which are multiple regression equations, among the soil properties were obtained using the Minitab 17 statistic program. Pedotransfer models (PTF) for point and parametric (van Genuchten’s parameters) estimation of hydraulic conductivity and soil sorptivity were developed from basic soil properties such as bulk density, total porosity, CEC, organic matter content and soil moisture content and validated using multiple-linear regression method.

Statistics such as Correlation Coefficient (R), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Relative Error (RE) were calculated using equation (4), (5), (6) and (7) respectively, where \( n \) represents the number of instances presented to the model and \( O_i \) and \( P_i \) represent measured and predicted, and \( O_{ave} \) and \( P_{ave} \) represent mean values of measured and predicted respectively.

\[
R = \frac{\sum_{i=1}^{n}(O_i - O_{ave})(P_i - P_{ave})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{ave})^2}(P_i - P_{ave})^2}
\]

(4)

\[
RMSE = \left[ \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n} \right]^{1/2}
\]

(5)

\[
MAE = \sum_{i=1}^{n} \left| \frac{P_i - O_i}{n} \right|
\]

(6)

\[
RE = \left( \frac{MAE}{O_{ave}} \right) \times 100
\]

(7)

### RESULTS AND DISCUSSION

#### Physical and chemical properties of sampled soils
Descriptive statistics of some physical and chemical properties of the soils used in this study are given in Table 1. Soil textural classes of the experimental sites were predominantly sandy clay loam and clay loam respectively. Table 1 shows the descriptive statistics of
Table 1 Descriptive statistics of physical and chemical properties of sampled soils

<table>
<thead>
<tr>
<th>Statistics/Soil Properties</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>MW</th>
<th>WHC</th>
<th>OMC</th>
<th>BD (g cm⁻³)</th>
<th>CEC (cmol+ kg⁻¹)</th>
<th>Sw (cm h⁻¹)</th>
<th>K (cm h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>24</td>
<td>4</td>
<td>20</td>
<td>1.68</td>
<td>29.27</td>
<td>1.52</td>
<td>1.12</td>
<td>3.43</td>
<td>18.36</td>
<td>0.54</td>
</tr>
<tr>
<td>Maximum</td>
<td>64</td>
<td>32</td>
<td>56</td>
<td>9.16</td>
<td>71.83</td>
<td>4.07</td>
<td>1.38</td>
<td>11.97</td>
<td>135.48</td>
<td>4.82</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>44.571</td>
<td>21.371</td>
<td>34.057</td>
<td>3.97</td>
<td>44.996</td>
<td>2.459</td>
<td>1.257</td>
<td>6.527</td>
<td>74.621</td>
<td>1.959</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.853</td>
<td>6.227</td>
<td>9.536</td>
<td>2.27</td>
<td>8.529</td>
<td>0.656</td>
<td>0.075</td>
<td>2.008</td>
<td>32.578</td>
<td>0.979</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.221</td>
<td>0.291</td>
<td>0.28</td>
<td>0.572</td>
<td>0.19</td>
<td>0.267</td>
<td>0.06</td>
<td>0.308</td>
<td>0.437</td>
<td>0.5</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.534</td>
<td>-0.731</td>
<td>0.465</td>
<td>0.987</td>
<td>1.28</td>
<td>0.652</td>
<td>0.109</td>
<td>0.774</td>
<td>0.068</td>
<td>0.972</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-0.313</td>
<td>0.514</td>
<td>-0.701</td>
<td>0.07</td>
<td>2.571</td>
<td>-0.063</td>
<td>-1.154</td>
<td>0.164</td>
<td>-1.063</td>
<td>1</td>
</tr>
<tr>
<td>Shapiro-Wilk Statistic</td>
<td>0.943</td>
<td>0.957</td>
<td>0.95</td>
<td>0.879</td>
<td>0.895</td>
<td>0.949</td>
<td>0.941</td>
<td>0.937</td>
<td>0.96</td>
<td>0.933</td>
</tr>
<tr>
<td>Shapiro-Wilk p-value</td>
<td>0.067</td>
<td>0.181</td>
<td>0.11</td>
<td>0.001</td>
<td>0.003</td>
<td>0.105</td>
<td>0.06</td>
<td>0.046</td>
<td>0.223</td>
<td>0.034</td>
</tr>
</tbody>
</table>
particle size distribution of the collected soil samples. The sampled soils generally had an average sand content of 44.57% with a standard deviation of 9.85. The coefficient of variation of the sand fractions is 0.22. The silt content is 21.4% on average, with the larger coefficient of variation (0.29). The clay content is 34.1% (± 6.22) on average, with a coefficient of variation (0.28).

Gravimetric soil moisture content ranged from 1.68% to 9.16% in all the 35 sites at the topsoil with a mean value of 3.97% ± 2.27 and coefficient of variation of 0.57. The water holding capacity (WHC) ranged from 29.27% to 71.83% for all soil samples in the 35 locations with an average value of 45%, standard deviation of 8.53 and coefficient of variation of 0.19.

The bulk density of soils in the 35 project sites ranged from 1.12 g cm$^{-3}$ to 1.38 g cm$^{-3}$ with a mean value of 1.26 g cm$^{-3}$ (± 0.08). Values for the bulk density at the experimental field are similar to those reported by Adekiya et al., 2011, and Fasinmirin and Olorunfemi, 2013. Soil organic matter comprises an accumulation of partially disintegrated and decomposed plant and animal residues and other organic compounds synthesized by the soil microbes as the decay occurs (Brady, 1990). The results of the soil organic matter (SOM) of all the different locations show that the percentage organic matter ranged from 1.52% to 4.07% with an average of 2.46% ± 0.66 (Table 1). The coefficient of variation of SOM is 0.27.

The minimum and maximum hydraulic conductivity values were 10.67 mm h$^{-1}$ and 0.54 cm h$^{-1}$ with a mean value of 4.82 cm h$^{-1}$. The coefficient of variation was 0.5 and the standard deviation was 0.98. Skewness coefficient of 0.97 for the K data at the distribution shows a moderately skewed distribution of the K data and the distribution is positively skewed. Further use of Shapiro–Wilk statistics with $p = 0.034$ shows that there is enough evidence to suggest that the data do not follow a normal distribution at 0.05 significant levels. Soil water sorptivity has a standard deviation (32.58) and coefficient of variation (0.44) indicating a considerable variability of sorptivity to water in the experimental field. Skewness coefficients (0.07) demonstrate that soil water sorptivity is approximately symmetric showing positive skewness. Meanwhile, kurtosis coefficients (-1.063) indicate a platykurtic behavior in their distribution. Further use of Shapiro–Wilk tests with $p = 0.22$ shows that there is enough evidence to suggest that the data follow a normal distribution at 0.05 significant levels.

**Prediction of Soil Hydraulic Properties using Pedotransfer Functions (PTF)**

Pedotransfer models have been successfully used to predict some soil hydraulic properties (Pachepsky et al., 1996; De Macedo et al., 2002; Gülser, 2004; Gülser et al., 2007). The knowledge of these soil hydraulic properties and processes leads to better predictions of both agricultural and environment impact. Soil hydraulic properties also define the relationship between soil moisture, hydraulic head and hydraulic conductivity, thus controlling how water moves through the soil.

The pedotransfer models showed that which were developed using some soil physical properties, to predict hydraulic conductivity and soil water sorptivity were statistically significant at 1% probability level (Table 2 and 3). In each case, pedotransfer models 1 and 4 were obtained from the combination of only bulk density (BD), moisture content (MW) and water holding capacity (WHC), models 2 and 5 were a product of the combination of bulk density (BD), moisture content (MW), water holding capacity (WHC), and organic matter content (OMC), while models 3 and 6 were obtained from the combination of bulk density (BD), moisture content (MW), water holding capacity (WHC), organic matter content (OMC) with cation exchange capacity (CEC).

Comparison of measured vs predicted values of hydraulic conductivity and soil water sorptivity
is presented in Figure 1 and 2 respectively. There was little increase in the correlation coefficient of the models when soil organic matter and cation exchange capacity were added. However, the overall prediction performance of the regression was enhanced when five soil physical properties i.e. BD, PT, CEC, SOM and MC were used together as revealed by the summary of statistics of the various equations of K and Sw (Table 4 and 5). Moreover, results from these models are adequate enough to predict hydraulic conductivity and soil water sorptivity by PTF, after the necessary steps of model calibration, evaluation and testing has been done, especially when hydraulic conductivity and soil water sorptivity parameters are not available in the study areas and in the south western part of Nigeria at large or areas of similar climate and soil types. Table 4 and 5 indicate the statistics of equations of hydraulic conductivity and soil water sorptivity mentioned above. The results showed

<table>
<thead>
<tr>
<th>S/N</th>
<th>Models</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K = 12.9 – 6.36BD – 0.0071MW – 0.0640WHC</td>
<td>0.774**</td>
</tr>
<tr>
<td>2</td>
<td>K = 13.1 – 6.50BD + 0.0029MW – 0.0720WHC + 0.119SOM</td>
<td>0.753**</td>
</tr>
<tr>
<td>3</td>
<td>K = 12.8 – 6.28BD - 0.0010MW – 0.0803WHC- 0.014SOM + 0.115CEC</td>
<td>0.774**</td>
</tr>
</tbody>
</table>

*significant at 1% probability level

Table 3: Pedotransfer models to predict soil water sorptivity (All samples)

<table>
<thead>
<tr>
<th>S/N</th>
<th>Models</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sw = – 78.3 + 150BD – 11.1MW – 0.194WHC</td>
<td>0.803**</td>
</tr>
<tr>
<td>2</td>
<td>Sw = –77.7 + 149BD – 11.0MW – 0.084WHC + 2.20SOM</td>
<td>0.804**</td>
</tr>
<tr>
<td>3</td>
<td>Sw = –74.6 + 146BD – 11.0MW + 0.218WHC + 3.97SOM – 1.58CEC</td>
<td>0.808**</td>
</tr>
</tbody>
</table>

*significant at 1% probability level

<table>
<thead>
<tr>
<th>Equation</th>
<th>Statistics</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>RMSE</td>
</tr>
<tr>
<td>1</td>
<td>0.774</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>0.753</td>
<td>0.58</td>
</tr>
<tr>
<td>3</td>
<td>0.774</td>
<td>0.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation</th>
<th>Statistics</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>RMSE</td>
</tr>
<tr>
<td>4</td>
<td>0.803</td>
<td>19.12</td>
</tr>
<tr>
<td>5</td>
<td>0.804</td>
<td>19.09</td>
</tr>
<tr>
<td>6</td>
<td>0.808</td>
<td>18.94</td>
</tr>
</tbody>
</table>

R is the Correlation Coefficient; RMSE is the Root Mean Square Error; MAE is Mean Absolute Error and RE is the Relative Error

Table 4: Summary of Statistics of Various Equations of Hydraulic Conductivity

Table 5: Summary of Statistics of Various Equations of Soil Water Sorptivity
Figure 1: Relationships between measured and predicted hydraulic conductivity using pedotransfer function (a) models 1, (b) model 2 and (c) model 3 in all sampled soils.

Figure 2: Relationships between measured and predicted soil water sorptivity using pedotransfer function (a) models 4, (b) model 5 and (c) model 6 in all sampled soils.
as per the table that equation (3) was the best model for predicting soil hydraulic conductivity (cm h$^{-1}$) with $R = 0.774$, RMSE = 0.55, MAE = 0.42 and RE = 21.67. Comparison of observed vs. predicted values of $K$ obtained from the equation (3) has been depicted in figure (1(c)) that indicates good match. Likewise, equation (6) comprising of model parameters (MW, BD, WHC, SOM AND CEC) was the best model for predicting water sorptivity (cm h$^{-1/2}$) with $R = 0.808$, RMSE = 18.94, MAE = 16.22 and RE = 21.74. Figure 2(c) equally indicated good match between the observed vs. predicted values of $Sw$ obtained from the equation (6).

**CONCLUSION**

This paper presented the evaluation and characterization of hydraulic conductivity and soil sorptivity to water in Ekiti State, south western part of Nigeria and, developed and validated pedotransfer (PTF) models for the prediction of hydraulic conductivity and soil sorptivity from basic soil properties using regression methods. Pedotransfer models were successfully used to predict some soil hydraulic properties. Pedotransfer models (PTF) for point and parametric (van Genuchten’s parameters) estimation of $K$ and $Sw$ from basic soil properties such as BD, PT, CEC, SOM and MC developed and validated using multiple-linear regression method are adequate enough to predict hydraulic conductivity and soil water sorptivity by PTF, after the necessary steps of model calibration, evaluation and testing has been done in areas of similar climate and soil properties. The overall prediction performance of the regression was enhanced when five soil physical properties i.e. BD, PT, CEC, SOM and MC were used together.

**REFERENCES**


