

USING SATURATION WATER PERCENTAGE DATA TO PREDICT MECHANICAL COMPOSITION OF SOILS

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A b s t r a c t. One hundred and sixty-six soil samples representing eleven textural classes and having wide variations in organic matter (OM) contents and other physico-chemical properties were collected from different locations in southeastern Nigeria to study the relationship between mechanical composition and saturation water percentage (SP). The objective was to develop a prediction model for silt+clay (SC) and clay (C) contents of these soils using their SP values. The magnitude of the correlation coefficients (r) between SC or C and SP was dependent on the amount of organic matter (OM) present in the soils. For soils with $\leq 1.00\%$ OM, the correlation (r) between SC and SP was 0.9659 ($p \leq 0.001$) and that between C and SP was 0.9539 ($p \leq 0.001$). For soils with $\geq 2.00\%$ OM, the ' r ' values were generally low, varying between 0.5320 and 0.2665 for SC and 0.6008 and 0.3000 for C. The best-fit regression models for predicting SC and C were developed with soils having $\leq 1.00\%$ OM. An independent data set from 25 soil samples collected from other parts of the study area was used to test the predictive ability of the best-fit models. These models predicted SC and C accurately in soils having between 0.28 and 1.10 % OM, but poorly in soils having between 1.31 and 3.91 % OM. These results show that the use of saturation water percentage to predict the mechanical composition of soils is most reliable for soils with low ($\leq 1.00\%$) OM contents.

K e y w o r d s: soil mechanical composition, prediction, saturation water percentage

INTRODUCTION

Information on the distributions of the sand, silt and clay particles of soils (also known as mechanical composition) is needed

for assessing soil workability, ease of water movement into a soil, and resistance of soil aggregates to externally applied forces. In engineering geology and soil mechanics, this information is useful in evaluating the shrinkage and Atterberg limits of soils, and in predicting potential differential settlements in foundations. Also, many soil characteristics that influence crop growth and yield (such as water retention and release, cation exchange capacity and proneness to waterlogging, or rapid loss of water beyond the root zone) are influenced by particle size distribution. The magnitude of structural changes (associated with cyclic freezing and thawing, or wetting and drying) is influenced by soil texture, being more on the clayey than sandy soils. Many users of soils, therefore, need a rapid method of estimating the mechanical composition of soils. There are several methods available for estimating soil's mechanical composition. A soil surveyor estimates it in the field by the feel method, whereby a moist soil sample is rubbed between the thumb and the fore-finger and the smooth or gritty feel noted. In this method the soil texture is estimated from the relative amounts of sand, silt, clay and organic matter which display unique physical characteristics as they are rubbed [11,12,]. Hodgson

et al. [5] tried to estimate soil texture by combining laboratory determinations with hand texturing. According to Akamigbo [1], however, field texturing is not a very reliable method, being more accurate for coarse-textured soils and less accurate for fine-textured soils and soils containing large amounts of very small iron concretions that could impart the gritty feel associated with sand particles [18].

In the laboratory, mechanical composition is determined by the hydrometer or pipette method following deflocculation of the particles with a chemical dispersant. Even though this method is accurate if complete dispersion is achieved, it is relatively costly, labourious, time-consuming and cumbersome and, therefore, not ideal in situations where quick information on soil texture is required [15,16].

Many researchers [4,7-10,13,16,17] have developed empirical models for estimating soil water retention and available water from mechanical composition. These studies imply that it is also possible to estimate mechanical composition from its relationship with water retained at various matric potentials. Dahiya *et al.* [2] found very high correlations between the silt and clay (SC) and the clay (C) contents of 466 soil samples from the Indogangetic alluvial plains of northern India, and the natural logarithm of their saturation water percentage (SP). They proposed the following empirical models for estimating the silt and clay contents from which the sand content can be derived as $100 - (\text{silt} + \text{clay})$:

$$SC = 68.10 (\ln SP) - 213.74 \quad (r^2 = 0.982) \quad (1)$$

$$C = 38.40 (\ln SP) - 122.30 \quad (r^2 = 0.955). \quad (2)$$

Implicit in the above equations is that only the fine earth fractions influence the amount of water held at saturation. But it is also known that the amount of organic matter present, as well as the type and concentration of the dominant clay minerals, influence saturation percentage. It is our view that the very high positive correlation between the silt+clay, or the clay contents and SP obtained by Dahiya *et al.* [2], is due to the very low OM contents

(0.17-1.21 %) of the soils they used.

Therefore, regression models of the types shown in Eqs. (1) and (2) cannot be used for extrapolation purposes beyond locations similar to those where the measurements were taken. Local calibrations of such predictive empirical models are needed for a rapid and reliable estimation of the mechanical composition of soils. The objective of this research is to attempt an estimation of the mechanical composition of some Nigerian soils (with a wide range in OM contents and dominated by kaolinite, Fe and Al oxides) from their saturation water percentages (SP).

MATERIALS AND METHODS

In this study 166 soil samples (data set No. 1) were used. They were collected from the A, B and C horizons of profiles located in different parts of SE Nigeria. The soils of this area are mainly Ultisols (90 %) and few Entisols and Inceptisols (10 %). The vegetation is superhumid rainforest in the south, which gradually changes to derived savannah in the north (a more open-wooded vegetation). Average monthly temperature is 22-23 °C and annual rainfall varies from 2680 mm in the south to 1550 mm in the north. The parent materials consist of shales, sandstones, basement complex rocks and alluvial deposits. Kaolinite is the dominant clay mineral in these soils with traces of illite, smectite, vermiculite and mica. Iron and aluminium oxides (in particular haemetite and gibbsite) are also abundant in the subsoils [6]. The sand contents of the soils used varied from 14 to 98 %, silt, from 1 to 70 %, and clay, from 2 to 86 %. Soil pH in water ranged from 4.1 to 7.5, Fe oxides from 0.14 to 10.93 %, Al oxides, from 0.022 to 0.475 % and OM, from 0.12 to 10.05 %. The textural classes of these soils are given in Table 1.

All soil samples were air-dried in a greenhouse (at about 25 °C) and sieved through a 2 mm mesh. This <2 mm fraction was used for mechanical analysis by the hydrometer method [3]. The particles determined were sand (2.00-0.20 mm), silt (0.20-0.002 mm) and clay (<0.002 mm). A modified form of the Richards

Table 1. Distribution of textural classes of the soils used

| S/No. | Textural class | No. of soils represented | Percent distribution | Range in SP values (%) | Mean | CV (%) |
|-------|-----------------|--------------------------|----------------------|------------------------|------|--------|
| 1 | Loamy sand | 19 | 11.5 | 17.8-43.3 | 33.0 | 15.8 |
| 2 | Sandy loam | 29 | 17.5 | 19.0-58.2 | 36.2 | 18.8 |
| 3 | Sandy clay loam | 24 | 14.5 | 26.1-50.0 | 39.2 | 13.8 |
| 4 | Silt loam | 9 | 5.4 | 26.7-43.5 | 33.7 | 17.5 |
| 5 | Clay | 14 | 8.4 | 42.0-74.2 | 57.0 | 18.1 |
| 6 | Loam | 11 | 6.6 | 39.3-49.9 | 44.5 | 5.6 |
| 7 | Clay loam | 7 | 4.2 | 28.4-47.6 | 39.4 | 19.3 |
| 8 | Silty clay | 3 | 1.8 | 30.5-40.2 | 35.4 | 13.7 |
| 9 | Silty clay loam | 5 | 3.0 | 34.7-49.8 | 42.3 | 18.0 |
| 10 | Sand | 40 | 24.1 | 21.3-35.8 | 30.1 | 11.6 |
| 11 | Sandy clay | 5 | 3.0 | 45.4-55.0 | 50.2 | 9.6 |
| Total | | 166 | 100.0 | - | - | - |

saturation paste method [14] was used to determine the saturation water percentage (SP). In this method ceramic crucibles (each of 80 cm³ capacity) with a perforated base were used. The inner base of the crucible was covered with a circular cut-out filter paper to prevent loss of soil through the perforations. Duplicate determinations were made per sample. Portions of the <2 mm air-dry soil samples were transferred into the crucible until it was 1/4 full. The soil was consolidated by tapping the crucible gently on the work-bench. This process continued until the crucible was about 4/5 full. The crucible was then transferred into a basin and distilled water added into the basin up to a depth of 3 cm (i.e., about 1/2 the height of the crucible). It was allowed to stand in the basin for the soil to absorb water by capillarity through the porous base of the crucible. Water absorption continued until the exposed soil surface glistened as it reflected light, indicating that saturation point had been reached. For all soils this point was reached after 24 h of contact with water.

The crucibles were then removed from the basin and the outside wiped dry. After obtaining the mass of the crucible and saturated soil, it was dried in the oven for 24 h at 105 °C. Thereafter the mass of the crucible+dry soil was recorded. Saturation water percentage (SP) was calculated as follows:

$$SP = 100 \left[\frac{M_{(\theta)} + M_{(sa)} - M_{(so)}}{M_{(so)}} \right] \quad (3)$$

where

$$M_{(so)} = 100 \left[\frac{M_{(sa)}}{(100 + \theta_{(r)})} \right] \quad (4)$$

In Eqs. (3) and (4) $\theta_{(r)}$ is the residual (air-dry) moisture percentage (%), $M_{(\theta)}$ is mass of water absorbed (g), $M_{(sa)}$ is mass of air-dry soil (g) and $M_{(so)}$ is mass of oven-dry soil (g).

The accuracy of this modified method (SPm) relative to the conventional Richards [14] technique (SPr) was checked on 33 soil samples (data set No. 2) covering all the 11 textural classes (shown in Table 1) by regressing SPm on SPr. The following relationship was established:

$$SPr = 1.02 (SPm) - 0.003,$$

$$(r = 0.9998; P \leq 0.001). \quad (5)$$

Since the intercept in Eq. (5) is not significantly different from zero, the slope is not different from 1 and the correlation coefficient (r) is very high, it is concluded that our modified method is as good as the Richard's technique. This method has the advantage of being simple, straight-forward, and fast and the values are less dependent on the operator. To evaluate the

possible influence of OM on SP, the thirty three air-dry, 2 mm sieved samples were treated with 30 % hydrogen peroxide to remove OM. After washing off excess H_2O_2 with distilled water and air-drying, they were used to determine particle size distribution and SP with exactly the same procedures as reported for the other 166 samples. Regression analysis of percent silt+clay and clay contents on SP were carried out with data from the peroxide treated and untreated samples and also for the following ranges of OM contents (%): <1.00, 1.00-2.00, 2.00-3.00, 3.00-4.00 and >4.00. The best-fit regression models were tested on 25 independent experimental data set (No. 3) whose characteristics are summarized in Table 2.

$$SP = 25.05 + 15.57 (OM), (r^2 = 37.1 \%) \quad (8)$$

Equation (8) shows that OM is contributing a substantial part of the variance in SP of the soils. Indeed as can be seen from Table 3, as the OM increases its positive contribution to SP it becomes statistically more significant. However, it is in soils with >2.0 % OM that the contribution of OM to SP is significant. Below this range OM has virtually little contribution to SP, accounting for only 1.4 to 4.4 % of the total variance in SP. Given that 48 % of the 166 soil samples used had >2.0 % OM, it is reasonable to conclude that the low r^2 values of Eqs. (6) and (7) are due to the contribution of OM to SP which was not accounted for in these models.

Table 2. Statistical summary of the pertinent properties of the test soils

| Property (%) | Range | Mean | SD | CV (%) |
|----------------------------------|-----------|------|------|--------|
| Saturation water percentage (SP) | 19.0-74.8 | 45.2 | 13.1 | 28.9 |
| Organic matter (OM) | 0.28-3.91 | 1.36 | 0.93 | 68.1 |
| Sand (SD) | 16-96 | 49.9 | 23.2 | 46.5 |
| Silt (S) | 2-70 | 32.3 | 19.4 | 60.0 |
| Clay (C) | 2-64 | 18.6 | 15.4 | 82.9 |
| Silt+clay (SC) | 4-82 | 45.9 | 26.4 | 57.6 |

RESULTS AND DISCUSSION

With the 166 soil samples (data set No. 1), the best-fit regression models obtained between silt+clay (SC) and SP and between clay (C) and SP are:

$$SC = -32.64 + 1.67 (SP), (r^2 = 43.0 \%) \quad (6)$$

$$C = -28.84 + 1.22 (SP), (r^2 = 58.9 \%) \quad (7)$$

Even though these r^2 values are significant at $p \leq 0.001$, the magnitude of variance in SC or in C accounted for by SP alone is not much. The models leave between 41.1 %, and 57.0 % of variance in silt+clay and clay unaccounted for. This is not in agreement with the results of Dahiya *et al.* [2]. When the OM contents of these soils were regressed on SP, the following equation was obtained:

With data set No. 2. in which OM contents were removed by peroxidate treatment prior to determining particle size distribution and SP, the following best-fit regression models were obtained:

$$SC = -28.40 + 1.75 (SP); (r^2 = 97.8 \%) \quad (9)$$

$$C = -15.89 + 1.47 (SP); (r^2 = 98.2 \%) \quad (10)$$

The r^2 values in Eqs. (9) and (10) are close to those obtained by Dahiya *et al.* [2] shown in Eqs. (1) and (2). This confirms our speculation that it is only in soils with low OM contents that the SP can be used to predict accurately their mechanical composition. This argument is further supported by data shown in Table 4. Here highly significant correlations between SP and either silt+clay or clay were obtained

Table 3. Correlations between organic matter (OM),% and saturation percentage (SP), % for different ranges of OM levels

| Ranges in OM levels (%) | No. of soils | Correlation coeff. (r) | Significance level ¹ |
|-------------------------|--------------|------------------------|---------------------------------|
| <1.00 | 45 | 0.118 | NS |
| 1.00-2.00 | 41 | 0.210 | NS |
| 2.00-3.00 | 31 | 0.601 | * |
| 3.00-4.00 | 23 | 0.783 | * |
| >4.00 | 26 | 0.856 | ** |
| 0.12-10.5 | 166 | 0.629 | ** |

(All ranges included)

¹*significant at p≤0.01; **significant at p≤0.001; NS- not significant.

for soils with <1.00 % and 1.00-2.00 % OM contents. For soils with >2.00 % OM, the variance in silt+clay or clay accounted for by SP alone was generally low and not of much significance in physical terms.

For the 45 soil samples with OM contents ≤1.00 % (Table 4), the following best-fit regression models were obtained between their mechanical composition and SP:

$$SC = -35.15 + 1.61 (SP); (r^2 = 93.3 \%) \quad (11)$$

$$C = -31.58 + 1.19 (SP); (r^2 = 91.0 \%). \quad (12)$$

Table 4. Summary of regressions between silt+clay (SC) and clay (C) contents of soils and their saturation water percentages (SP) for different ranges of organic matter (OM) levels

| Range of OM levels (%) | No. of soils | Regression equations | Coefficients of determination (r ²) (%) | Significance level ¹ |
|-------------------------------------|--------------|----------------------|---|---------------------------------|
| <1.00 | 45 | SC=-35.15+1.61(SP) | 93.3 | ** |
| | | C=-31.58+1.19(SP) | 91.0 | ** |
| 1.00-2.00 | 41 | SC=-48.19+2.28(SP) | 75.9 | ** |
| | | C=-47.85+1.90(SP) | 81.8 | ** |
| 2.00-3.00 | 31 | SC=-25.63+1.51(SP) | 28.3 | * |
| | | C=-20.80+1.07(SP) | 36.1 | * |
| 3.00-4.00 | 23 | SC=-32.52+1.77(SP) | 11.4 | NS |
| | | C=-42.95+1.59(SP) | 14.8 | NS |
| >4.00 | 26 | SC=-27.73+0.70(SP) | 7.1 | NS |
| | | C=-33.43+1.30(SP) | 9.0 | NS |
| 0.12-10.05 (All ranges included) | 166 | SC=-32.64+1.67(SP) | 43.0 | ** |
| | | C=-28.84+1.22(SP) | 58.9 | ** |

¹*significant at p ≤0.05; **significant at p ≤0.001; NS - not significant.

The predictive ability of Eqs. (11) and (12) was tested with the 25 test soils (data set No. 3) whose pertinent properties were given in Table 2. A comparison between measured and predicted silt+clay and clay, shown in Figs 1 and 2, indicate that it is only in soils having ≤1.10 % OM that SP predicted accurately either the silt+clay or the clay contents of these soils.

As can be seen from Table 5, it is only within the OM range of 0.28-1.10 % that the intercept of the regression equation between predicted and measured silt+clay, or clay, is closest to zero, and the slope and coefficient of correlation (r) are closest to unity. Two other conditions imposed on the estimator errors to express the goodness of fit of the estimations of Eqs. (11) and (12) are: (i) the mean absolute

error (MAB), i.e., $\sum_{i=1}^n \{Abs(\text{predicted value} - \text{measured value})\} / N$ and, (ii) the composite

residual sum of squares (CRSS), i.e., $\sum_{i=1}^n (\text{predicted value} - \text{measured value})^2$. The smaller the values of MAB and CRSS, the better the prediction of the model. From Table 5,

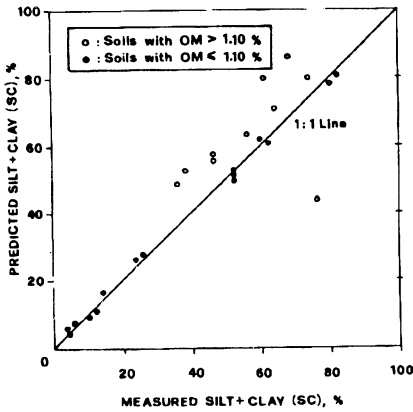


Fig. 1 Measured versus predicted silt-clay (SC), % in test soils of varying organic matter (OM) contents.

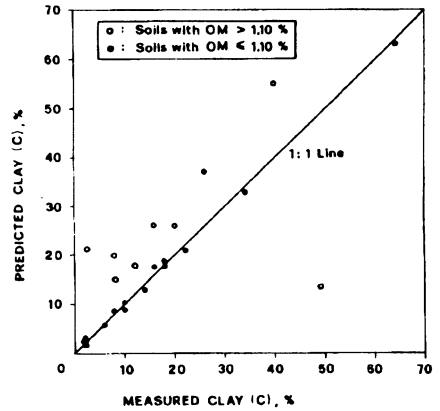


Fig. 2 Measured versus predicted clay (C), % in test soils of varying organic matter (OM) contents.

Table 5. Statistical parameters for comparing predicted (Y) and measured (X) silt+clay and clay contents of 25 test soils

| Parameter (%) | Range in OM values (%) | No. of soils | Intercept α | Slope β | Correlation coeff. (r) | MAB ¹ | CRSS ² |
|----------------|------------------------|--------------|--------------------|---------------|------------------------|------------------|-------------------|
| Silt+clay (SC) | 0.28-3.91 | 25 | 5.08 | 0.92 | 0.925 | 6.332 | 2535.33 |
| | 0.28-1.10 | 15 | 0.83 | 0.98 | 0.999 | 1.120 | 22.140 |
| | 1.31-3.91 | 10 | 42.14 | 0.38 | 0.421 | 14.150 | 2513.39 |
| Clay (C) | 0.28-3.91 | 25 | 5.26 | 0.80 | 0.794 | 5.944 | 2475.68 |
| | 0.28-1.10 | 15 | 0.46 | 0.97 | 0.998 | 0.544 | 16.18 |
| | 1.31-3.91 | 10 | 15.72 | 0.42 | 0.432 | 5.400 | 2459.50 |

¹MAB - mean absolute error = $\sum_{i=1}^n \{Abs(\text{predicted value} - \text{measured values})\}/N$;

²CRSS - composite residual sum of squares = $\sum_{i=1}^n (\text{predicted value} - \text{measured values})^2$.

these values were smallest in the 0.28-1.10 % OM range. This further confirms that the use of SP to predict the mechanical composition of soils is most reliable for soils with low (≤ 1.0 %) OM contents.

CONCLUSIONS

Our results indicate that in soils low in OM (≤ 1.0 %) there is a good possibility to predict their silt+clay (SC) and their clay (C) contents from their saturation water percentages (SP), which is a more-easily determinable property. The use of these equations for such soils:

$$SC = -35.15 + 1.61 (SP)$$

and

$$C = -31.58 + 1.19 (SP)$$

will give the best estimates of their silt+clay and clay contents. In soils having ≥ 2.00 % OM, the use of their SP to predict their mechanical composition is not reliable because of the highly significant positive contribution of OM to the saturation water content within this range of OM levels.

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