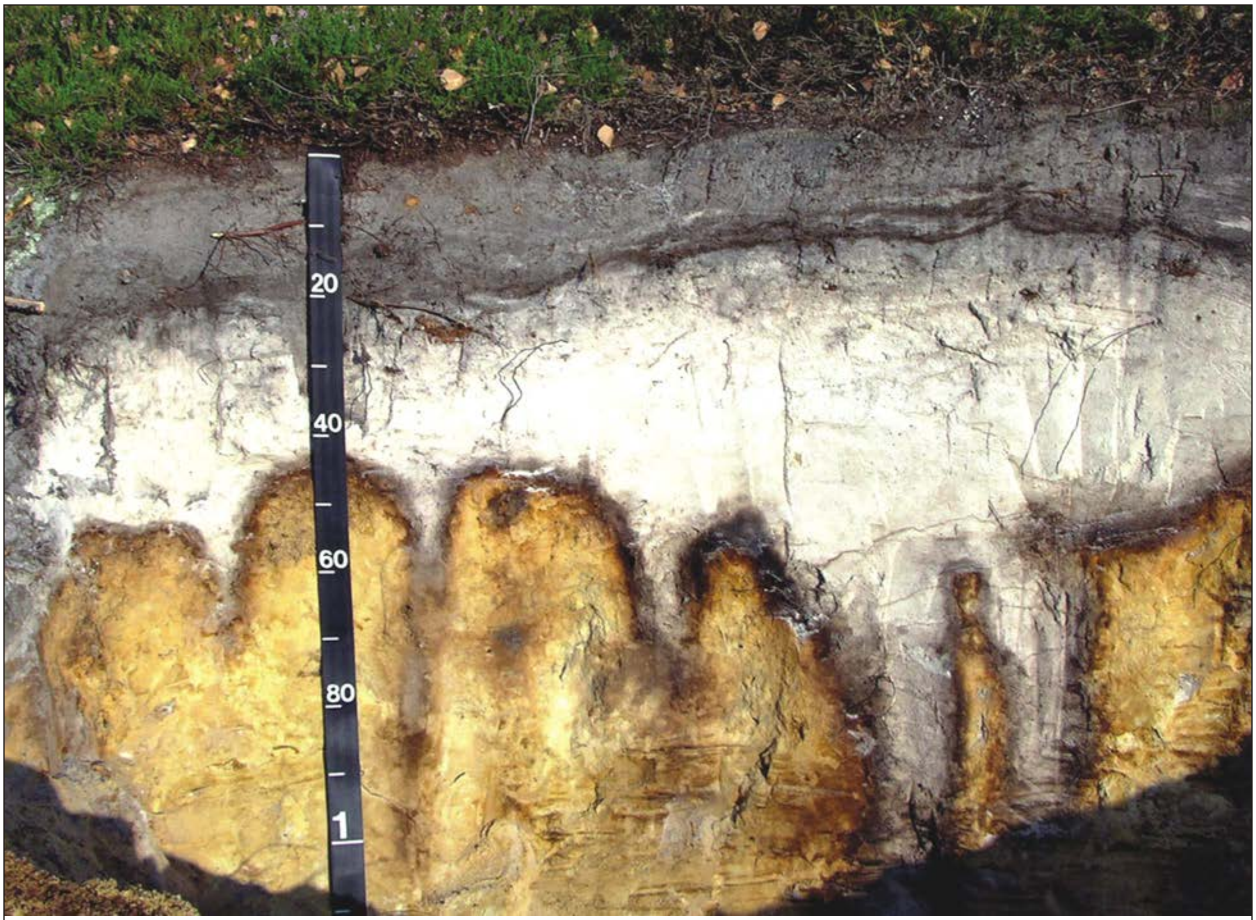

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Homomorphic Modelling of Shrinkage Properties of Soils of Southeastern Nigeria for Sustainable Land Use

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Abstract: Responsiveness of soils to volume change at all moisture statuses affect infrastructural development of soils. Volume Shrinkage (VS) was estimated from Coefficient of Linear Extensibility (COLE) values, using 150 soil samples from 30 soil profile pits in southeastern Nigeria. The objective of this study was to use soil properties related to shrinkage in predicting and monitoring volume changes in these soils in southeastern region of Nigeria. The value of liquid limit (26-30%) was higher than that of plastic limit (11-13%). Plasticity index was lower (16-17%) in the upper soil layer (0-40 cm) than in the lower horizons (41-80 cm layer) by 24%. Volume shrinkage value (11.20-11.80%) was least at the topmost horizon (0-40 cm depth) and increased to between 14-18% in the lower part of the profile (40-100 cm). Soils at all depths showed low to moderate shrink-swell properties having coefficient of linear extensibility of 0.036-0.057 cm cm^{-1} with middle layers showing higher shrink-swell characteristics. These results show moderate shrinkage (VS = 10-20) although intra-pedal variability was prominent. Multiple regression analysis showed good predictive ability ($R^2 = 0.76$): $p = 1.05$; $n = 150$) of Atterberg's limits, texture, bulk density and organic matter (OM) in determining shrinkage properties. Accuracy of prediction was defined by a low Root Mean Square Error (RMSE) value of 0.01 while the model overestimated slightly (bias±0.00001).

Key words: Homomorphic modelling, prediction, shrink-swell potential, soil properties, tropical soils

INTRODUCTION

Models of agro-ecological systems provide means of prediction beyond the bounds of experience or experimentation. Extrapolation may involve simulation of the expected behaviour for different climate and/or soil conditions, perhaps with alternative management or for a longer time scale than observed experimentally (Probert and Keating, 2000). Models in soil studies are used to collect data in a systematic manner, describe system or to predict relationships and behaviour in order to extend our knowledge of soils. They represent a series of approximations towards the truth. Soil landscape models provide descriptions of the gradually varying contiguity of soil properties in the landscape. Soil landscape models hypothesize that there is a close relationship between soil attributes and landscape position (Pennock *et al*., 1987; Irvin, 1996). Soil modelling is applied in pedogenesis (Hoosbeek and Bryant, 1994; Suarez and Goldberg, 1994) and the development of quantitative pedogenic process

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models have improved our understanding of pedogenic and geomorphic processes, especially with advances in geostatistics and computer power. Gertsev and Gertseva (2004) observed that homomorphic models are imperfect representation of reality in ecological models. Ecological models are classified into two, namely isomorphic and homomorphic models based on degree of complexity with the latter describing relationships in soil groups as a whole and not as individual phenomenon.

Shrinkage properties of soils guide in estimating the strength of soil resources in terms of its ability to sustain farm buildings, farm structures, farm road and general agricultural mechanization and engineering. Swelling and shrinking clay soils change in volume with water content changes. These volume changes depend on the amount and type of clay minerals and are characterized by their magnitude and geometry. They result in the occurrence of shrinkage cracks and surface subsidence (Cornelis *et al*., 2006; MacNabb and Boersma, 1996) and this influences sustained use of soils. Now, it is common to hear of cracked and collapsed agricultural and non-agricultural engineering structures in southern Nigeria hence Igwe (2003) called for the inclusion of shrink-swell potential of soils in soil survey reports.

In Southeastern Nigeria, soils are formed from six major parent materials, namely Coastal Plain Sands, Shale, Upper Coal Measures, Lower Coal Measures, False-bedded Sandstones and Alluvium. Although the pedogenic processes in the area may seem to be similar, wider variations in soils including volume shrinkage properties vary as a result of differences in parent materials of soils. For instance, soils having greater clay content may have greater shrinkage capacity, implying that sandy soils have lower shrinkage values.

A number of researchers (Igwe, 2003; Mbagwu and Abeh, 1998) have associated the soil moisture volume changes with shrink-swell phenomena to changes in water content, clay content, mineralogy and type of cation present on the soil exchange site, soil structure, organic matter, density, sesquioxides, overburden pressure and interactions among these properties. In addition to this, bulk density influences shrinkage behaviour of soils. Igwe (2003) postulated that soils in which montmorillonite was a major component had a wide range of COLE values, indicating that differences in clay content may be the primary factor controlling the degree of shrinkage. On the other hand, soils having equal amounts of kaolinite and montmorillonite behave like montmorillonitic soils. Although shrink-swell potential is recommended for inclusion in soil survey reports, this important parameter is absent in all existing survey reports for areas where very intensive agricultural operation is on-going in the study area. Thomas *et al*. (2000) showed that the shrink- swell potential in kaolinitic and mixed mineralogy soils and acid montmorillonitic soils is often more difficult to predict. Presently, no one method of soil analysis estimates shrink-swell potential accurately for all soils. Soil scientists recognize that shrink-swell behavior can best be predicted by examining a combination of physical, chemical and mineralogical soil properties. A protocol that integrates these properties and then establishes a shrink-swell model that can be extrapolated across the same or similar parent materials is needed.

The objective of this study was to use soil properties related to shrinkage [Plastic Index (PI), Total Clay (TC), Total Sand (TS), Organic Matter (OM) and Bulk Density (BD)] in predicting and monitoring volume changes (represented by Volume Shrinkage (VS)) in these soils in southeastern region of Nigeria.

An understanding of the relationship between soil properties and swell-shrink characteristics of soils will aid a priori prediction of the effects of these soil properties on building foundations, septic tank, subsurface absorption systems, roads, dams and other structures in contact with the soil. Structural damage to homes and agricultural structures (i.e., walls, irrigation channels and foundations) due to expansive soils is costly to repair and may be somewhat avoidable if soil properties, such as clay content and the Coefficient of Linear Extensibility (COLE), are investigated (Vaught *et al*., 2006).

MATERIALS AND METHODS

Description of Study Site

The study was conducted at the floodplains of *Otamiri* River in Federal University of Technology, Owerri in southeastern Nigeria during the 2004 rainy season. The area is located between latitudes 5°30′ and 6°00′N and longitudes 7°00′ and 7°30′E. Soils of the study site are derived from alluvial deposits and are below 50 m above sea level. The topography is almost flat having a slope gradient of between 0 and 2%. Six soil groups classified based on their parent material, namely Coastal Plain Sands, Alluvium, Shale, Lower Coal Measures, Upper Coal Measures and False-bedded Sandstones were identified at the site. The mean annual rainfall is 2250 mm with an annual temperature range of 26-29°C. The soil has isohyperthermic soil temperature regime (Anikwe *et al*., 2003).

Field Studies

A free survey method was used (observation points that are representative of the site are chosen by the surveyors based on personal judgment and experience) (Mulla and McBratney, 2000). Auger and core samples were collected from 150 pedogenic horizons of 30 soil profile pits dug at the site. Five profile pits were dug on each of the 6 soil groups classified based on their parent material, namely Coastal Plain Sands, Alluvium, Shale, Lower Coal Measures, Upper Coal Measures, False-bedded Sandstones. Core samples (for determining soil dry bulk density) were collected using open-faced coring tube (area, 19.5 cm^3 and height, 5 cm from Eijkelkamp Agrisearch Equipment) at the selected depths. Auger samples were collected at fixed depths of 0-20, 21-40, 41-60, 61-80 and 81-100 cm using a hand-pushed auger (Push Probe, 23 mm diameter). For auger samples visible roots, twigs and leaves were manually removed in the screen house and the samples air-dried at ambient temperature for 72 h and sieved (using 2 mm sieves). Core samples were analyzed and mean results from each depth used whereas the auger samples (collected from each depth) were mixed and composite sub-samples (from each depth) used for the analyses. All soil profile pits were geo-referenced using a Global Positioning System (GPS) (Garmin Ltd. Kansas, USA).

Laboratory Analyses

Particle size distribution of less than 2 mm fine earth fractions was measured by hydrometer method as described by Gee and Or (2002). Bulk density was estimated by the method of Grossman and Reinsch (2002). Atterberg's limits, namely Liquid Limit (LL) and Plastic Limit (PL) were estimated using Cassagrande method as described by Smith (1990). Plasticity Index (PI) was calculated as a difference between LL and PL.

The Coefficient of Linear Extensibility (COLE) being a measure of shrink-swell behaviour was calculated as follows using the method described by Foth (1984):

$$\text{COLE} = \text{Length of moist sample}/\text{Length of dry sample} - 1 \qquad (1)$$

Volumetric Shrinkage (VS) was calculated from COLE according to Schafer and Singer (1976) as follows:

$$\text{VS} = \{(\text{COLE} + 1)^3\} - 1\times 100 \qquad (2)$$

Total carbon was measured by combustion with an Elemental CNS analyzer (Elemental America, Inc. Mt. Laurel, NJ) according to the methods described by Nelson and Sommers (1996). Organic matter was estimated as total carbon content multiplied by a factor of 1.724.

Statistical Analyses

Soil data were subjected to Analysis of Variance (ANOVA) using the PROC mix-model of SAS (2000). Means were separated using Standard Error of the Difference (SED) at 5% level of probability. Multiple regression was used to calculate the variance associated with the best fitting linear combination of the variables according to the model below as proposed by Steel and Torrie (1980).

$$Y = a+b_1x_1+ b_2x_2+b_3x_3+ \ldots+ b_nx_n$$

where,

Y = Volume Shrinkage (VS) of soils
A = Intercept
bs = Slopes corresponding to the Xs
xs = Independent soil variables
n = Number of variables used in the model.

In order to evaluate average prediction uncertainty of the model, Root Mean Square Error (RMSE) was estimated.

$$\text{RMSE} = {}^{1}\!/_{n} \sum_{1=1} n\, di^2 \qquad (4)$$

where,

di = Difference between the predicted and measured values at a given level
n = Number in the data set.

The bias of the model was calculated to evaluate model overestimation or underestimation.

$$\text{Bias} = {}^{1}\!/_{n} \Sigma di \qquad (5)$$

Di is defined as in Eq. 4

RESULTS AND DISCUSSION

Particles Size Distribution

Intrinsic soil properties varied significantly with depth at 5% level of probability. Sand and clay-sized particles had higher values possibly due to the parent materials from which they were derived. Lower clay content (17%) was found in the upper 0-20 cm of the study soils. However, clay content increased at lower depths (21-100 cm) to 20-30%. Conversely, silt and sand content decreased with depth. The extent of shrinking and swelling is influenced by the amount and kind of clay in the soil (Table 1).

Table 1: Particle size distribution of soil at different depths

Depth (cm)	Clay (%)	Silt (%)	Total sand (%)
0-20	17.9±2.18	10.7±1.61	71.9±3.36
21-40	20.9±2.16	8.7±1.21	70.8±3.05
41-60	27.7±2.77	9.0±1.14	63.8±3.49
61-80	30.7±3.10	8.7±1.43	61.5±3.61
81-100	28.2±3.38	8.9±1.40	64.0±3.96
SED (p = 0.05)	1.23	0.71	1.27
Pr>F	<0.001	0.0271	<0.0001

Table 2a: Atterberg's limits, bulk density and COLE

Depth (cm)	LL (%)	PL (%)	PI (%)	OM (%)	BD (mg m^{-3})	COLE (cm cm^{-1})	VS
0-20	29.7±3.44	11.1±1.96	17.8±2.13	1.58±0.81	1.36±1.36	0.036±0.006	11.20±3.11
21-40	26.9±3.74	11.5±2.05	16.7±2.32	1.16±0.32	1.40±1.40	0.038±0.006	11.84±2.16
41-60	29.8±3.69	11.8±2.25	19.2±2.16	0.93±0.21	1.44±1.44	0.057±0.008	18.10±1.12
61-80	32.9±4.06	12.6±2.40	21.9±2.52	0.55±0.13	1.48±1.48	0.050±0.006	15.76±0.92
81-100	30.7±3.96	13.3±2.40	19.3±2.53	0.09±0.01	1.53±1.53	0.046±0.006	14.44±2.61
SED (p = 0.05)	1.32	0.76	1.08	0.16	0.03	0.005	0.17
Pr>F	0.0001	0.0316	0.0001	<0.0001	<0.0001	0.0002	<0.0001

Table 2b: Shrink-swell hazard ratings

Cole	VS	Rating
0.00-0.03	0-10	Slight
0.03-0.06	10-20	Moderate
0.06-0.09	20-30	Severe
>0.09	>30	Very severe

(Source: Schafer and Singer, 1976)

Table 3: Correlation coefficients of Volume Shrinkage (VS) and some soil properties

Factor correlated	Correlation coefficient (R)	Significance (p<0.05)
VS versus LL	0.59	<0.0001
VS versus PL	0.64	<0.0001
VS versus PI	0.50	<0.0001
VS versus clay	0.61	<0.0001
VS versus OM	0.47	<0.001
VS versus BD	0.01	NS

*: Significant-p<0.05, NS: Non Significant

Atterberg's Limits, Bulk Density and VS

Atterberg's limits present the values of liquid limit, plastic limit and plasticity index for the soils (Table 2a). The value of liquid limit (26-30%) was higher than that of plastic limit (11-13%). Plasticity index was lower (16-17%) in the upper soil layer (0-40 cm) than in the lower horizons (41-80 cm layer) by 24%. The value of bulk density was 1.36 mg m^{-3} at the upper horizons (0-20 cm). This increased to 1.40-1.58 mg m^{-3} in the lower part of the profile (21-100 cm). Similarly, volume shrinkage value (11.20-11.80%) was least at the topmost horizon (0-40 cm depth) and increased to between 14-18% in the lower part of the profile (40-100 cm). Conversely, soil organic matter with a value of 1.85% was higher at the upper horizon (0-20 cm) when compared with values of between 0.09-1.16% at the lower part of the profile (21-100 cm). Soils at all depths showed low to moderate shrink-swell properties (Table 2b) with middle layers showing higher shrink-swell characteristics. These results show that soils of the study area in their natural state exhibit shrink-swell potentials. Higher shrink-swell values at the middle layers of the soil profile may be attributable to high concentration of illuvial clays. Soil shrinkage has been related to a number of different soil properties. Some of these include clay percentage (De Jong *et al*., 1992) and organic carbon (Reeve *et al*., 1980). Of all the soil properties, soil clay content has most often been shown to be related to soil shrinkage potential. For example, Simon *et al*. (1987) showed that 42-71% of the variation of COLE could be explained by soil clay percentage. Other studies have indicated shrinkage indices such as COLE were more strongly related to the fine clay fraction (Dasog *et al*., 1988).

Relationship Between VS and Selected Soil Properties

The Volume Shrinkage (VS) showed positive significant correlation ($p<0.05$, n = 150) with Atterberg's limit, clay and OM. The highest correlation was found with plastic limit (R = 0.64) and clay (R = 0.61) while medium to low correlation was found between VS and liquid limit (R = 0.59), plastic index (R = 0.50) and organic matter (R = 0.47) (Table 3). Gray and Allbrook (2002) found no

Table 4: Volume shrinkage model attributes ($p<0.0001$)

Attribute	Value
R	0.87
R^2	0.76
$1-R^2$	0.24
Dependent mean	0.05
CV (%)	35.12
RMSE	0.01
BIAS	+0.00001

significant relationship between organic carbon and COLE. They concluded that there appears to be no consensus on the role of organic matter in soil shrinkage in soils. While Reeve *et al*. (1980) found a positive correlation between organic carbon and shrinkage in both topsoil and subsoil samples, the majority of studies have found no relationship with this soil property (Gray and Allbrook, 2002).

No significant relationship was found between soil bulk density and VS. Flowers and Lal (1999) found that field measurements of soil shrinkage did not show change in the total shrinkage volume due to the lack of changes in the soil bulk density. They found that field bulk density values ranged between 1.4 and 1.6 mg m^{-3} and no differences in shrinkage volume were found in this range. Igwe (2003) made similar findings in the floodplain soils along the banks of River Niger. Earlier, Mbagwu and Abeh (1998) and Thomas *et al*. (2000) found strong linear relationships between COLE and plastic limit. Therefore, it will be concluded that those Atterberg's limits and clay content contribute significantly to volume shrinkage and eventually shrink-swell hazards of soils of the area.

Modelling

Using five independent variables, namely, total clay, total sand, OM and BD, VS model was derived as follows:

$$VS = 0.190 + 0.040\ BD + 0.010\ OM - 0.001\ PI - 0.002\ \text{Total clay} - 0.003\ \text{Total Sand}.$$

These predictor variables were highly associated with VS ($R^2 = 0.76$; $p<0.0001$; $n = 150$). The prediction was highly accurate (RMSE = 0.01) with slight overestimation (bias = + 0.00001). These trends occur although soils were formed from different parent materials. These mean that the variables used in the model had direct relationship with VS and could be used to predict the swell-shrink behaviour of soils in the area of study (Table 4).

CONCLUSION

Soils of the study site exhibit varying degrees of volume shrinkage with depth. Generally, these soils showed moderate shrink-swell hazard rating although undisturbed soil samples were used in the analysis.

Volume Shrinkage (VS) showed strong relationship with Atterberg's limits and clay and as a consequence, these properties plus BD, texture and OM were used as predictors in VS modelling.

The volume shrinkage model resulted to a good prediction of load-bearing strength of soils at $p\leq 0.05$ with little $I-R^2$ value using 150 soil samples. This model will be useful in sustainable use of soils for engineering purposes, especially at planning stages of project implementation.

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