

Hydrophobicity of Soils Formed over Different Lithologies

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ABSTRACT

Using a free survey technique and special analytical methods, wettability of soils derived from different parent materials in central Southeastern Nigeria were investigated in 2005. Resulting soil data were subjected to Analysis of Variance (ANOVA) using PROC Mix-model of SAS, and some soil properties were regressed to identify leading predictors of soil hydrophobicity in the study area. Soil hydrophobicity varied among the soil groups and horizons ($p < 0.05$) in response to differences in soil properties. Soil moisture, organic matter, clay, sand, sodium saturation were good predictors of soil hydrophobicity in soils of the study site although at varying levels of prediction and parameter combinations. Accuracy of predictions was very high. Further studies involving detailed sampling, increasing parameter combinations and geostatistical analysis should improve the quality of models used to study soil hydrophobicity in the study area.

Keywords: Modelling, wettability, parent materials, soil water, tropical soil

INTRODUCTION

The existence of water repellent soils has been known for many years. It is a phenomenon that occurs in different soils worldwide. It is also reported that under certain conditions, all soils may display water repellency (Doerr *et al.* 2000) although a majority of soils show low levels of hydrophobicity (Hallett *et al.* 2001). Soil hydrophobicity has a significant impact on soil hydraulic properties and water movement (Bauter *et al.* 1998) as low levels of soil water repellence encourage infiltration in such soils (Hallett *et al.* 2004). Soil hydrophobicity exhibits both temporal variability (Dekker *et al.* 2001; Buczko *et al.* 2002; Buczko *et al.* 2005) and spatial heterogeneity at different scales (Gerke *et al.* 2001). Non-uniform water repellency was observed in different soils under diverse vegetation types (Dekker *et al.* 2001), land use (Hallett *et al.* 2004) or lignitic mine soils (Gerke *et al.* 2001).

Soil hydrophobicity is controlled by microbial type abundance and activity (Grundmann and Debouzie 2000; White *et al.* 2000), initial soil moisture (Doerr *et al.* 2000) nutrient levels (Hallett and Young 1999) and chemistry of exudates (Czarnes *et al.* 2001). Soil organic matter (SOM) influences soil hydrophobicity as it is a mixture of hydrophilic and hydrophobic functional groups (Ellerbrock *et al.* 1999; Ellerbrock *et al.* 2005). However, organic carbon was found to be weakly correlated with higher water repellency (Scott 2000) and subcritical soil water repellency had a significant impact on the protection of SOM against microbial

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decomposition (Goebel *et al.* 2005).

Investigations on variable hydrophobicity of soils under natural conditions are important because it can induce unstable wetting fronts and preferential flow (Ritsema *et al.* 1998) and erratic water content distributions within the topsoil layers (Dekker *et al.* 1999). Water repellency has implications on root water uptake and leaching of agrochemicals (Doerr *et al.* 2000), aggregate stability (Zhang and Hartge 1992) and erosion (Clothier *et al.* 2001). It is this variability that has led to some investigations by scholars on sub-critical hydrophobicity (Goebel *et al.* 2005; Lamparter *et al.* (2006), using different techniques (Letey *et al.* 2000; Bachmann *et al.* 2003). This is because flow phenomena induced by water repellency are compounded, influencing other factors such as hydraulic parameter distribution of roots, surface micro-topography and macropores which can promote preferential flow and heterogeneous water content distributions. Little attempt has been made to assess variability in hydrophobicity of soils derived from different parent materials in South-eastern Nigeria. Based on the above, the major objective of this study was to quantify potential hydrophobicity of the soils of South-eastern Nigeria with varying lithosequential origin.

MATERIALS AND METHODS

Central Southeastern Nigeria lies between latitudes (04°40'.460" and 07°00'.50".010, N) and longitudes 6°40' 15".460 and 8°15' 10".200 E and was chosen for the study. Six major geological materials from which soils were derived in the area include Alluvium, Coastal Plain Sands, Falsebedded Sandstones, Lower Coal Measures, Shale and Upper Coal Measures. It is characterised by heavy rainfall in early and late periods of the year, which ranges from 1800 to 2500 mm a year. Mean annual temperature ranges from 26 - 29°C and is uniform throughout the year with slight variations. Soils of the area have been classified, ranging from Inceptisols to Ultisols (Onweremadu 2006). Rainforest is the predominant vegetation with a variety of plants including African walnut (*Lovoa klaineana*), gmelina (*Gmelina arborea*), oil palm (*Elaeis guineensis*), goat weed (*Ageratum conyzoides*), spear grass (*Imperata cylindrica*), cashew (*Anarcadium occidentale*), rattle box (*Crotalaria retusa*), cassava (*Manihot esculenta*) and yam (*Dioscorea* species). Low input farming, subsistence hunting, mining, cottage industrial activities and gathering from the rich rainforests are the main socio-economic activities.

Field Studies

Field surveys were conducted prior to a reconnaissance visit to the site in 2005. Guided by the geological map of the study area, a free survey was used in locating soil profile pits. Five profile pits were dug and described according to the procedure of FAO (1998) on six identified soil groups namely soils formed on Alluvium, Coastal Plain Sands, Falsebedded Sandstones, Lower Coal Measures, Shale and Upper Coal Measures. A total of 30 profile pits, from which 150 soil samples were collected, formed the basis for the study. Soil samples were taken by pressing 100 cm³ steel cylinders into the undisturbed profile pits at the midpoints between horizon boundaries. Soil samples were air-dried, gently crushed and sieved using a 2-mm sieve.

Laboratory Analyses

Particle size distribution was determined by hydrometer method (Gee and Qr 2002). Soil water holding capacity was determined on the undisturbed sample as the difference of water content at 0.03 - MPa determined by pressure plate, and at - 1.5 MPa determined by pressure membrane (Dane and Hopmans 2002). Soil pH was estimated electrometrically using 1:2.5 soil to water ratio (Hendershol *et al.* 1993). Total soil carbon was measured by elemental analysis (CNS 2000, LECO Ltd, Monchengladbach, Germany). Exchangeable cations were determined using Inductively Coupled Plasma Atomic Emission Spectrometer (ICP AES) (Integra XMP, GBC, Arlington Heights, IL). Saturations of basic cations (VCa, VMg, VK and VNa) were computed as the exchangeable basic cation divided by cation exchange capacity then multiplied by 100 percent. Percentage was converted to g kg^{-1} by multiplying by a factor of 10.

The sieved soil samples from different soil groups were sequentially extracted. Five grams of soil were mixed with 0.05 dm^3 of de-ionized water (Nierop and Buurman 1998). This mixture was shaken for 24 h using roller mixer (SRTZ Steward Scientific, United Kingdom) at room temperature. Solid residues were separated by centrifuging at $1400 \times g$ for 35 min. The solution was filtered through a 0.45 mm membrane filter (Schleicher and Schuell, Dassel, Germany). This represented the water extraction SOM/W) while the second step, the sodium pyrophosphate (SQM/PY) extraction was mixed with 0.05 dm^3 of 0.1 M $\text{Na}_2\text{P}_2\text{O}_7$ solution in de-ionized water (Ellerbrock *et al.* 1999) and shaken at room temperature for 6 h. The solid residue was separated by centrifuging at $1400 \times g$ for 35 min and filtered using 0.45 mm membrane filter. The remaining solution was adjusted with 1 M hydrochloric acid to pH 2, in order to enhance the precipitation of SOM (PY). Precipitation lasted for 12 h and this was followed by centrifuging the mixture at $1400 \times g$ for 30 min. Water and sodium pyrophosphate extracts were washed free of salts by using a dialysis membrane with a pore size of 2.5 to 4 nanometres and freeze-dried.

Soil organic matter fractions were determined by infra-red analysis using a BioRad FTS 135 (BioRad Corp., Hercules, CA) while absorption spectra was obtained by KBr technique (Celi *et al.* 1997) The A/B ratios in the Fourier-Transform spectra were calculated using BioRad WINIREZ (BioRad Corn, Krefeld, Germany) computer software. Soil wettability was assessed by the capillary rise method (CRM) (Goebel *et al.* 2004). Contact angle measurements were done on a thin layer of soil material fixed on a double-sided adhesive tape (TESA, type 55733, Beiersdorf Hamburg, Germany).

Statistical Analysis

Soil data were subjected to analysis of variance (ANOVA) using PROC Mix-model of SAS (Little *et al.* 1996). Means were separated using standard error of the difference (S.E.D.) at 5% Level of probability. Multiple stepwise regression using SAS Version 5 (SAS Institute, Cary NC) was done to identify the variance associated with the best fitting linear combination of variables while Root Mean Square Error (RMSE) and Bias were used to evaluate accuracy of prediction and

model estimation status, respectively (Moldrup *et al.* 2004).

The equations are given below:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad \dots \quad (1)$$

where RMSE = root mean square error

d_i = difference between the predicted and the measured values

n = number of sets of values used

$$\text{Bias} = \frac{1}{n} \sum_{i=1}^n d_i \quad \dots \quad (2)$$

where d_i and n are defined in equation 1 above.

RESULTS AND DISCUSSION

Soil Properties

Physical and chemical properties of the studied soils are shown in Tables 1 and 2, respectively. Soils were generally sandy in the study site with soils derived from Shale being least sandy while soils formed over Upper Coal Measures were the least clayey. There were significant differences ($p < 0.0001$) in the distribution of particle sizes among soil groups and horizons. The same trend was observed in the distribution of water holding capacity (WHC) among soil groups and horizons. Shale-derived soils had highest value of WHC (655.6 g kg^{-1}). Variation in moisture contents of soil is attributable to differences in parent materials. Saturations of calcium (Ca) and magnesium (Mg) differed significantly ($p < 0.0001$) among soil groups and horizons. The distribution of potassium (K) and sodium (Na) saturations also differed significantly among soil groups ($p < 0.05$) and horizons ($p < 0.0001$). Similar trends were observed in the distribution of soil pH and soil organic matter (SOM). These variabilities in chemical properties are possibly due to differences in parent materials, land use and land use history as well as micro-climatic differences. Some researchers (Asadu and Enete 1997; Akamigbo 2001; Nnaji *et al.* 2002) have attributed the above reasons as possible causes of differences in physicochemical properties of soil in the study area.

Hydrophobicity

Contact angles (CA) and heights of absorption bands A related to B bands are shown in Table 3, indicating that only soil derived from Shale ($CA=99^\circ$) and Lower Coal Measures ($CA=91^\circ$) are hydrophobic while hydrophobicity was also recorded in argillic horizons (Bt_1 , Bt_2 and Bt_3) having 92° , 94° and 93° , respectively. This conclusion was made since Goebel *et al.* (2004) defined hydrophobic soils as those having a contact angle of 90° or more. It was also found that CA increased as moisture content of soil groups increased. These results are consistent with the

TABLE 1
Selected physical properties of studied soils

Treatment	Sand	Silt	Clay	WHC
	g kg^{-1}			
Parent materials (p)				
Alluvium	808.4	42.0	149.6	215.2
Coastal Plain Sands	693.2	73.2	233.6	249.2
Falsebedded Sandstones	744.0	72.8	183.2	314.8
Lower Coal Measures	485.6	201.6	312.8	507.6
Shale	376.8	131.2	492.0	655.6
Upper Coal Measures	835.2	31.6	133.2	195.6
SED (p =0.05)	32.8	25.2	45.8	23.3
Horizon (H)				
A	714.0	107.0	179.0	278.0
AB	703.7	87.3	209.0	315.0
Bt ₁	632.7	90.3	277.0	388.0
Bt ₂	606.3	86.7	307.0	417.0
Bt ₃	629.3	89.0	281.7	383.0
SED (p 0.05)	15.6	7.1	12.3	14.5
Parent material (p)	<0.0001*	<0.0001	<0.0001	<0.0001
Horizon (H)	<0.0001	0.0271	<0.0001	<0.0001
P X H	<0.0001	<0.0006	<0.0001	<0.0001

WHC = water-holding capacity

* p = values

TABLE 2
Selected chemical properties of studied soils

Treatment	VCa	VMg	Vk	VNa	SOM	pH (1:2.5)
	g kg^{-1}					
Parent materials (p)						
Alluvium	224.3	89.5	14.3	13.4	15.8	4.7
Coastal Plain Sands	277.4	126.6	19.9	9.9	12.7	4.8
Falsebedded Sandstones	217.1	84.3	24.4	11.6	11.0	4.1
Lower Coal Measures	202.3	103.6	47.3	12.5	15.3	4.4
Shale	268.6	31.8	13.0	3.3	16.2	4.7
Upper Coal Measures	214.1	65.6	13.1	4.6	7.6	4.4
SED (p =0.05)	33.7	14.2	4.7	4.4	1.0	0.8
Horizon (H)						
A	217.5	88.0	22.8	11.0	25.8	4.6
AB	165.3	55.8	16.6	4.7	16.8	4.4
Bt ₁	211.6	80.2	24.9	9.3	11.2	4.5
Bt ₂	261.6	103.3	25.3	11.4	7.4	4.6
Bt ₃	313.8	90.5	20.3	9.6	4.2	4.6
SED (p = 0.05)	16.5	7.5	2.5	2.1	0.7	0.3
Parent material (p)	<0.0001*	<0.0001	<0.05	<0.05	<0.0001	<0.0001
Horizon (H)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
P XII	<0.0001	<0.0001	<0.05	<0.05	<0.0001	<0.0001

VCa = calcium saturation; VMg = magnesium saturation; VK = potassium saturation; VNa = sodium saturation; SCM soil organic matter.

* p = values

TABLE 3
 Contact angles and heights of absorption bands A related to B bands using Fourier-Transform
 Infra-red analysis of organic matter of water and sodium pyrophosphate soluble fractions of soil
 samples (n = 150) (Mean values)

	CA (o)	SOM (W) A/B	SOM (PY) A/B
Parent Material (p)			
Alluvium	63	0.16430	0.28705
Coastal Plain Sands	54	0.15824	0.29608
Falsebedded Sandstones	77	0.14896	0.27716
Lower Coal measures	91	0.15618	0.34227
Shale	99	0.17208	0.35218
Upper Coal Measures	57	0.14254	0.24112
SED (p =0.05)	6	0.08	0.12
Horizon (H)			
A	69	0.16723	0.36116
AB	86	0.14892	0.22662
Bt ₁	92	0.14986	0.23434
Bt ₂	94	0.12222	0.20424
Bt ₃	93	0.9898	0.19625
SED (p =0.05)	2	0.03	0.04
Parent material (P)	<0.0001*	<0.0001	<0.0001
Horizon (H)	<0.0001	<0.05	<0.0001
PXH	<0.0001	<0.05	<0.0001

CA = contact angle; SOM (W) = soil organic matter water soluble; SOM (PY) = soil organic matter pyrophosphate soluble fractions

* p = values

TABLE 4
Pedotransfer functions relating contact angle and some properties in the study site

Parent Material	Regression equations	R ²	RMSE	Bias
Alluvium	CA = 43.118 - 19.06 WHC + 5.22 OM + 39.77 - 11.14 VNa	0.38	1.61	+0.01
Coastal Plain Sands	CA = 58.216 + 7.11 OM + 46.11 Clay - 49.11 Sand	0.70	1.71	+0.0001
Falsebedded	CA = 49.111 - 79.21 WHC + 66.11 Clay - 22.11 OM	0.86	0.08	+0.0001
Lower Coal Measures	CA = 71.211 - 81.11 WHC + 68.22 Clay + 19.12 OM	0.79	0.11	-0.003
Shale	CA = 88 - 232 - 94.13 WHC + 77.11 Clay + 33.44 OM	0.96	0.02	-0.001
Upper Coal Measures	CA = 35.216 - 49.21 WHC + 6.55 Clay + 13.21 OM - 89.11 Sand	0.94	1.21	+0.006

findings of de Jonge *et al.* (1999) who found that several soil samples were not water repellent at low water contents. Strong hydrophobic experienced in soils of Shale and Lower Coal Measures imply little or no infiltration, and this could build up runoff water that would detach, transport and deposit easily erodible soils away from their origin. Results also showed that sandy soil groups had the least CA implying higher infiltration values, thereby circumventing a build-up of erosive runoff water. Values of water soluble SOM [(SOM (W))] were less than sodium pyrophosphate SOM [(SOM (PY))] in all soil groups and horizons (Table 3). Generally CA increased with depth and this could be in response to SOM and clay contents. Increased SOM reduced CA values while the reverse was the case when CA related with clay. Relationships between soil hydrophobicity with some soil properties using CA as an indicator are shown in Table 4. Water holding capacity, clay and organic matter contents were good predictors of CA in soils formed over Shale, Falsebedded Sandstone and Lower Coal Measures while WHC, clay, organic matter and sand had good relationship with soils of Upper Coal Measures and Coastal Plain Sands. Yet, in alluvial soils, WHC, organic matter, clay and VNa dominated influence on CA. However, the best predictions were made in Shale-derived soils and the least in alluvial soils, implying that there are other un-assessed principal components in the determination of soil hydrophobicity in alluvial soils. The accuracy of predictions are shown in Table 4, indicating low values of Root Mean Square Error (RMSE) and Bias, suggesting that the independent variables used in the modelling increased certainty of predictions with very little under-estimation and over-estimation which varied with soil group. Finally, there is need for more investigations involving detailed soil sampling, more parameters and geostatistical tools.

CONCLUSION

Results of this study indicated WHC, clay and organic matter as good predictors of CA in soils formed over shale, while WHC, clay, organic matter and sand in the parent materials of upper coal measures and coastal plain sands, and, for alluvial soils, the good predictors of CA are WHC, organic matter and Na saturation. However, best predictions of soil hydrophobicity were made in shale derived soil and least in alluvial soils. From this study, it is recommended that more studies need to be carried out involving detailed soil sampling, inclusion of more parameters and geostatistical tools to increase the certainty of soil hydrophobicity predictions.

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