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Influence of soil properties on the aggregate stability of a highly degraded tropical soil in Eastern Nigeria

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A b s t r a c t. Soil structure of fragile ecosystems should be monitored frequently for soil pore rigidity and aggregate stability. We studied four soil profiles in Eastern Nigeria that are loose, porous, highly weathered and deep in order to characterize their aggregate water stability upon drying and wetting and their relationship with soil properties. Mean-weight diameter of dry aggregates (MWDd) was largely determined by dry-stable aggregates (DSA) between 1-0.25 mm while the mean-weight diameter of water-stable aggregates (MWDw) was dominated by water-stable aggregates (WSA) between 0.5 to <0.25 mm. The permeability rates for the soils indicated that most horizons were within the moderately rapid to very rapid class. The MWDd correlated significantly with saturated hydraulic conductivity (*Ks*) (r = 0.68). The MWDw correlated negatively with bulk density (r= -0.65). The potential structural deformation index (PSDI) for the soils indicates that soil moisture contents, particle size distribution, soil organic matter (SOM), *Ks*, bulk density and CEC were soil factors that influenced it. To maintain good soil structure thereby reducing soil degradation, long term fallows or other farming practices that ensure steady maintenance of SOM are recommended.

K e y w o r d s: potential structural deformation, soil organic matter, aggregates stability, permeability

INTRODUCTION

In a fragile ecosystem, characterized by severe gully, rill and inter-rill erosion like in eastern Nigeria, it becomes very important to monitor the stability of soil aggregates during transformation from forest to cultivated farm land use. Levy and Miller (1997) observed that breakdown of unstable aggregates results in pore collapse, which produces finer and more easily transportable particles and microaggregates. These particles and microaggregates are very important in such soil processes as infiltration, seal and crust formation, runoff and soil erosion, and subsequent deterioration of soil structure and plant drought stress. Zhang and Horn (2001), therefore, remarked that aggregate stability is an important property to explain, quantify, or to predict these processes or changes in some basic soil properties with respect to soil water erosion and soil sealing, and to propose restoration methods of degraded soils. Earlier, Igwe *et al.* (1995) used some aggregation indices including mean-weight diameter (MWD) and geometric-mean weight diameter (GMD) to assess potential soil loss in some soils of southeastern Nigeria.

Rampazzo *et al*. (1993) showed that soil structure is a dynamic soil property and is often influenced by soil properties. These soil properties can be chemical, physical, mineralogical and micromorphological in nature. Oades (1984) insisted that all organic compounds in soils are not responsible for aggregation. Different kinds of organic matter stabilize aggregates of different sizes and they may sometimes have no effect on aggregation of soils. Generally, aggregate stability depends on basic soil properties such as organic matter, clay and Fe and Al oxides contents. Koutika *et al.* (1997) remarked that soil organic matter losses in non-forest land use can be high and are diversely compensated by incorporation of crop residues in the humic materials. They insisted that soil physical properties such as aggregate stability and bulk density were often affected by change from forest to cultivated land use.

Soils within the sandstone geological materials are very fragile and severely degraded by erosion and leaching due to high rainfall. Most of the previous studies on the evaluation of stability of aggregates were mainly for topsoil, and were concerned with the farmers' different cultural practices (Igwe 2001; Spaccini *et al*., 2004). The objective of this paper therefore is (i) to characterize the aggregate stability

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of the soils at dry and water-stable states and (ii) to determine the relationships between the aggregate indices and laboratory determined soil properties. The aim was to have an insight to the natural state of the soil aggregate stability. This will provide information on the proper management of the soils.

MATERIALS AND METHODS

Field study and soils

The study area is located between latitudes 6°44' and 6°55'N; longitudes 7°11' and 7°28'E. Four soil profile pits (P1, P2, P3 and P4) used for this study were located in a highly degraded area of Nsukka in southeastern Nigeria. The soils were described and soil samples collected from different soil depths corresponding to the pedogenetic horizons. The pedogenetic soil horizons are natural layers parallel to the top layers formed as a result of soil development. The vegetation of the area is derived savanna (Igbozurike, 1975). The underlying geology is mainly weathered sandstone (Ajali Formation). The climate of the area is mainly humid tropical type with the mean annual precipitation of 1500 to 1600 mm. The rainy season is between the months of April and October every year. The land is mainly used for arable crop production while some of it is under tropical secondary forest with grasses dominating the trees.

The soils are classified as Typic Paleustult (Soil Survey Staff, 1998). They are deep, acid and low in plant available nutrient including the cation exchange capacity which is an index of plant nutrient reserve (Table 1). Jungerius (1964) observed that the soil organic matter content was very low, whereas leaching, including soil erosion by water, remains the major cause of degradation of these soils. The major silicate clay of the soil is kaolinite, quartz and gibbsite. The soil texture is coarse to medium with high soil bulk density (1.6-1.9 g cm^{-3}) and low soil porosity. All samples were collected in the dry season (January – February). These soil samples for routine chemical and particle size analysis were air dried, sieved through a 2 mm mesh and analyzed in triplicate as described below. However, the soil samples for water-stable aggregates (WSA) and the dry-stable aggregates (DSA) were not air dry but used as collected from the field as shown since their field moisture contents were almost at the permanent wilting point. These were in undisturbed forms and were not among those initially sieved with 2 mm sieve.

Laboratory methods

Particle size distribution of the less than 2 mm fine grain fractions was measured by the hydrometer method as described by Gee and Bauder (1986). Soil pH was determined in a 1:2.5 soil/deionized water suspensions. The soil saturated hydraulic conductivity was obtained using the Klute and Dirksen method (1986). Soil bulk density (BD) was measured by the core method (Blake and Hartge, 1986). The soil water content at different retention levels was determined by the Klute and Dirksen (1986) method, while the available water capacity was calculated as the difference between moisture retention at suctions 0.1 and 1.5 MPa *ie* field capacity (FC) and permanent wilting point (PWP). Permeability was derived using the classification system adopted by O'Neal (1952). He proposed a classification for categorizing *Ks* into permeability classes as follows:

Permeability Class	Ks (cm h^{-1})
Very slow	<0.125
Slow	0.125-0.5
Moderately slow	0.5-2
Moderate	2-6.25
Moderately rapid	6.25-12.5
Rapid	12.5-25
Very rapid	>25

The soil organic carbon was determined by the Walkley and Black method described by Nelson and Sommers (1982). Exchangeable cations and the cation exchange capacity (CEC) were determined by the method of Thomas (1982).

Exchangeable sodium percentage (ESP) was calculated using the following equation;

$$ESP = (\text{Exchangeable } Na^{+} / CEC) \times 100. \quad (1)$$

The method of Kemper and Rosenau (1986) was used to separate both dry-stable aggregates (DSA) and water-stable aggregates (WSA). In the WSA 40 g of <4.75 mm air-dried soils were put in the topmost of a nest of four sieves of 2, 1, 0.5, and 0.25 mm mesh size and pre-soaked for 30 min in deionized water. Thereafter, the nest of sieves and its contents were oscillated vertically in water 20 times using 4 cm amplitude at the rate of one oscillation per second. After wet-sieving, the resistant soil materials on each sieve and the unstable (<0.25 mm) aggregates were quantitatively transferred into beakers and dried in the oven until steady weight was achieved. The percentage ratio of the aggregates in each sieve represents the water-stable aggregates (WSA) of size classes; >2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm.

To obtain the dry-stable aggregates (DSA), the same procedure was adopted without the soil being soaked or immersed in water. Electrically-operated vibrator was used to simulate the shaking as in the water-stable aggregate determination, but under a dry condition. Aggregate stability in both determinations was measured as the mean-weight diameter (MWD) of stable aggregates:

$$MWD = \Sigma X_i W_i , \quad (2)$$

where: X_i is the mean diameter of the i*th* sieve size and W_i is the proportion of the total aggregates in the I*th* fraction.

T a b l e 1. Basic characteristics of the representative soil profiles

Profile No.	Depth (cm)	Particle size distribution ($g\ kg^{-1}$)			Textural class	pH_{H_2O}	ESP (%)	CEC ($cmol_c\ kg^{-1}$)	SOM ($g\ kg^{-1}$)
		Clay	Silt	Sand					
				Typic Paleustult (Cultivated land use)					
P1	0-20	220	60	720	SCL	4.4	5.1	1.76	14.4
	20-65	220	20	760	SCL	4.6	2.7	2.92	7.6
	65-100	200	40	760	SL	4.5	2.6	2.68	6.2
	100-135	240	40	720	SCL	4.9	2.9	2.40	15.8
	135-180	260	40	700	SCL	4.9	2.4	2.50	3.4
				Typic Paleustult (Cultivated land use)					
P2	0-23	220	40	740	SCL	4.4	2.0	3.50	10.4
	23-45	240	20	720	SCL	4.7	3.0	2.70	1.4
	45-80	200	40	760	SL	4.8	2.7	2.60	3.8
	80-120	240	20	740	SCL	5.0	2.9	2.80	4.1
	120-175	100	60	840	LS	4.8	1.6	4.50	1.4
				Typic Paleustult (Secondary forest land use)					
P3	0-18	140	40	820	SL	4.8	2.3	3.10	11.7
	18-40	140	40	820	SL	4.3	0.6	3.20	18.7
	40-70	200	40	760	SL	4.3	2.5	2.80	9.6
	70-120	240	20	740	SCL	4.5	2.9	2.40	4.1
	120-180	240	20	740	SCL	4.6	3.3	2.10	2.1
				Typic Paleustult (Secondary forest land use)					
P4	0-21	180	20	800	SL	4.6	2.5	3.20	13.8
	21-45	200	20	780	SL	4.5	3.1	2.60	9.6
	45-86	240	20	740	SCL	4.6	2.3	3.00	6.9
	86-120	220	60	720	SCL	4.7	3.3	1.80	3.4
	120-190	240	40	720	SCL	4.5	2.3	2.60	6.2

The higher the MWD values show the higher proportion of macroaggregates in the sample and therefore better stability.

To assess the susceptibility of these soils to disintegration upon contact with water, the potential structural deformation index (PSDI) was calculated for the soils as:

$$PSDI = [1- (MWDw / MWDd)\ 100]\ , \qquad (3)$$

where: MWDw – mean-weight diameter by wet sieving and MWDd – mean-weight diameter by dry sieving.

Data analysis

The interrelations between the wet and dry stable aggregate indices were determined through a correlation matrix using the SYSTAT 9 statistical program (SPSS 1999) computer package. Also the relationships between the macroaggregates stability indices at both dry and wet states and soil properties were determined in a correlation matrix.

RESULTS AND DISCUSSION

Dry-stable aggregates (DSA) and dry mean-weight diameter (MWDd)

The dry-stable aggregates (DSA) for the soils are presented in Table 2. The DSA sizes >2 mm ranged from 11.88 to 22.18%, while the 2-1 mm sizes were between 13.03 and 23.03%. The largest DSA aggregate sizes were found in sizes 1-0.5 mm with values of between 21.33 to 37.45% while in the 0.5-0.25 mm aggregate sizes were between 17.98 to 30.83%. The values for the <0.25 mm aggregate sizes were between 5.38 to 19.58% (Table 2). Mean-weight diameter for the DSA was from 0.88 to 1.87 mm (Table 2). In all these distributions, the aggregate sizes tended not to follow a definite trend in their distribution in the soil profile. However, as mentioned earlier, the larger aggregate sizes found in DSA between 1-0.5 mm and 0.5-0.25 mm indicated that the MWDd were to some extent determined by these aggregate sizes. Soils with larger

T a b l e 2. Dry-stable aggregates (DSA) distribution of the studied soil profiles

Profile No.	Depth (cm)	Dry-stable aggregates distributions (%) (dia in mm)					MWDd (mm)
		>2	2-1	1-0.5	0.5-0.25	<0.25	
				Typic Paleustult (Cultivated land use)			
P1	0-20	17.18	19.38	34.15	23.93	5.38	1.23
	20-65	13.48	13.45	30.43	30.83	11.88	1.04
	65-100	16.55	17.88	28.68	24.45	12.45	1.12
	100-135	14.28	20.68	24.68	26.55	10.83	1.11
	135-180	16.75	21.25	23.73	24.75	14.30	1.24
				Typic Paleustult (Cultivated land use)			
P2	0-23	16.80	16.65	35.43	25.03	6.30	1.19
	23-45	14.43	18.75	37.45	22.10	7.28	1.15
	45-80	15.83	18.63	27.15	26.38	12.10	1.16
	80-120	16.58	14.65	25.78	24.88	18.23	1.11
	120-175	11.88	15.55	25.33	27.58	19.58	0.88
				Typic Paleustult (Secondary forest land use)			
P3	0-18	19.40	16.93	21.33	23.35	12.90	1.23
	18-40	18.60	15.45	24.98	26.78	14.20	1.18
	40-70	14.48	19.73	32.70	23.18	12.33	1.14
	70-120	21.23	23.03	28.08	17.98	9.70	1.27
	120-180	17.63	19.38	24.05	23.65	15.20	1.20
				Typic Paleustult (Secondary forest land use)			
P4	0-21	18.45	17.33	26.00	24.00	14.23	1.20
	21-45	22.18	21.78	23.80	21.13	11.13	1.87
	45-86	17.50	18.88	25.50	23.33	14.80	1.19
	86-120	17.88	20.93	27.28	21.93	12.01	1.24
	120-190	20.85	13.03	23.80	23.98	18.35	1.22

aggregate classes controlling the MWD diameter are more stable than those of smaller aggregate classes and are not easily blown away in case of cyclone or severe wind condition.

Water-stable aggregates (WSA) and wet mean-weight diameter (MWDw)

The water-stable aggregates for the aggregate sizes determined are shown in Table 3. While the aggregate sizes >2 mm ranged from 0.05 to 5.35%, the aggregate sizes between 2-1 mm were from 2.28 to 11.88%. In the aggregate sizes between 1-0.5 mm, the values were from 13.13 to 28.48 and 16.23 to 36.85% for WSA sizes 0.5-0.25 mm. The water-unstable aggregates <0.25 mm recorded sizes of between 28.48 and 54.68 %. Unlike the DSA, the WSA sizes were more on the WSA sizes between 0.5-0.25 mm and <0.25 mm aggregate sizes. In general, the WSA classes favoured the aggregate classes <0.5 mm. This is in contrast to the findings of Igwe and Stahr (2004) who obtained values tilting towards bigger aggregates *ie* those >0.5 mm for floodplain soils with higher clay contents and more 2:1 silicate clay minerals than the soils of our present study. However, there are some similarities between these results and those of Igwe (2004) in similar soils that are deep and well drained. These soils are loose, with low clay content and low organic matter content due to leaching and high mineralization rate. The major clay minerals are the kaolinites, oxides and hydroxides of Fe and Al.

The wet mean-weight diameter (MWDw), in contrast to MWDd, was smaller with values of between 0.4 to 0.67 mm (Table 3). The difference between these two MWD indices explained the potential rate of structural deformation of the aggregates. It was used to explain or evaluate soil management systems and to estimate wind erosion (Zobeck *et al.*, 2003). These values tend to cluster about the mean of 0.45 mm and showing no trend in the distribution within individual soil profiles. These low values of MWDw could lead to quick dispersion of the soil in any rainfall, event leading to severe rill or inter-rill erosion. Although Igwe *et al.* (1995), Six *et al.* (2000), Igwe (2003) demonstrated that MWD does not predict well the potential of the soil to erode, yet it is known that finer aggregates flow easily when submerged by water. However, Amezketa *et al.* (1996) showed that the combined use of MWD in various forms and

T a b l e 3. Water-stable aggregates (WSA) distribution of the studied soil profiles

Profile No.	Depth (cm)	Water-stable aggregates distributions (%) (dia in mm)					MWDw (mm)
		>2	2-1	1-0.5	0.5-0.25	<0.25	
		Typic Paleustult (Cultivated land use)					
P1	0-20	0.88	2.78	15.33	28.63	52.40	0.43
	20-65	0.55	3.13	18.88	36.45	41.00	0.45
	65-100	0.95	3.45	15.28	26.50	53.83	0.43
	100-135	0.23	4.75	15.00	26.60	53.43	0.43
	135-180	0.08	2.75	15.55	27.88	53.55	0.40
		Typic Paleustult (Cultivated land use)					
P2	0-23	0.55	2.28	17.78	36.85	42.05	0.44
	23-45	0.15	2.45	17.20	32.73	47.55	0.41
	45-80	0.43	3.78	16.15	33.80	45.85	0.44
	80-120	0.63	3.30	14.35	28.95	52.53	0.42
	120-175	0.33	3.08	14.60	28.85	53.15	0.41
		Typic Paleustult (Secondary forest land use)					
P3	0-18	0.05	3.08	16.05	28.53	52.30	0.41
	18-40	0.05	11.88	28.48	31.13	28.48	0.58
	40-70	0.45	3.35	14.55	34.90	48.75	0.43
	70-120	0.46	3.40	14.65	25.88	54.68	0.47
	120-180	0.28	3.35	14.85	27.88	53.65	0.41
		Typic Paleustult (Secondary forest land use)					
P4	0-21	5.35	7.90	22.80	32.88	31.78	0.67
	21-45	0.13	3.06	13.13	31.38	52.35	0.42
	45-86	0.65	4.43	17.85	29.30	47.80	0.45
	86-120	0.88	5.08	17.30	27.83	48.93	0.46
	120-190	0.12	5.20	25.88	16.23	51.30	0.47

the soil slaking index can be useful in assessing soil erosive behaviour. Therefore, the combination of the MWDw of these soils and other soil slaking or dispersion properties may be used to estimate the potential danger of soil erosion by water on these soils.

Soil moisture content, bulk density, hydraulic conductivity and potential structural deformation index of the soils

The volumetric moisture content values for the soils are shown on Table 4. The moisture measured at 0.1 MPa and the assumed soil moisture at field capacity (FC) ranged from 25.38 to 37.75% while the moisture at 1.5 MPa, assumed to be the moisture at permanent wilting point (PWP), was between 11.75 and 14.81%. The available water capacity (AWC) of the soil was low and ranged between 13.17 and 24.47%. The soil bulk density was high with values ranging between 1.37 and 1.88 Mg m^{-3}. Igwe (2001) obtained such high bulk densities for top soils of similar soil units. The explanations for such high bulk density have been attributed to the coarse texture of the soil, low SOM content, and the close packing of the coarse grains of sand in the particle size due to structural deformation.

The hydraulic conductivity *Ks* for the soils was from 0.5 cm h^{-1} and in one case up to 101.8 cm h^{-1} (Table 4). The permeability classes of the soils based on the *Ks* data indicate that the soils were mainly moderate to rapid, and slow for one of the subsoils of P4 (Table 4). If we apply the O'Neal (1952) classification to the soils, it will be observed that the permeability is greater for the topsoils than for the subsoils. This is because in most cases the overburden forces are higher in the subsoil than in the topsoil, creating more micro than macro pores within the depth of the profiles. Also the clay content is higher in the subsoil than in the topsoil. All these may reduce the permeability of the soil.

The potential structural deformation index (PSDI) for the soils is high, with values of 44.17 and 77.54 % (Table 4). Mbagwu *et al*. (1991) indicated that the higher the values of PSDI the more the tendency of the aggregates to disintegrate upon wetting. Table 4 shows that P4 has the lowest PSDI in the topsoil and hence may resist deformation by water more than the other top soils from the other soil profiles. The reason may be due to higher CEC and soil organic matter (SOM) content of the topsoil of P4 (Table 1). The soil profile is located on an area that is presently covered with secondary forest and that explains the high SOM and better formation of aggregates in the topsoil of the profile.

T a b l e 4. Chosen physical characteristics and potential structural deformation index (PSDI) of the investigated soils

Profile No.	Depth (cm)	FC (%)	PWP (%)	AWC (%)	PSDI (%)	BD (Mg m^{-3})	*Ks* (cm h^{-1})	Permeability classification
				Typic Paleustult (Cultivated land use)				
P1	0-20	29.60	14.30	15.30	65.04	1.73	9.20	Mod. rapid
	20-65	29.33	14.30	15.03	56.73	1.73	9.00	Mod. rapid
	65-100	28.54	13.79	14.75	61.06	1.73	9.00	Mod. rapid
	100-135	30.12	14.81	15.31	61.26	1.80	4.20	Moderate
	135-180	30.12	14.81	15.31	67.74	1.80	4.80	Moderate
				Typic Paleustult (Cultivated land use)				
P2	0-23	29.33	14.30	15.03	63.02	1.82	32.60	Rapid
	23-45	29.33	14.30	15.03	64.35	1.78	4.80	Moderate
	45-80	28.54	13.79	14.75	62.07	1.88	4.10	Moderate
	80-120	29.33	14.30	15.03	62.16	1.88	5.10	Moderate
	120-175	27.10	11.75	15.35	53.41	1.80	0.60	Mod. slow
				Typic Paleustult (Secondary forest land use)				
P3	0-18	26.96	12.77	24.19	66.67	1.61	84.40	Very rapid
	18-40	26.96	12.77	14.19	50.85	1.61	25.50	Very rapid
	40-70	26.96	13.79	13.17	62.28	1.82	3.20	Moderate
	70-120	29.33	14.30	15.03	63.00	1.87	4.30	Moderate
	120-180	60.20	14.30	15.90	65.83	1.77	58.00	Very rapid
				Typic Paleustult (Secondary forest land use)				
P4	0-21	27.75	13.28	24.47	44.17	1.37	24.10	Rapid
	21-45	28.54	13.79	14.75	77.54	1.59	101.80	Very rapid
	45-86	29.33	14.30	15.03	62.18	1.58	4.90	Moderate
	86-120	29.33	14.30	15.03	62.90	1.76	1.40	Mod. slow
	120-190	25.38	11.75	13.63	61.48	1.81	0.50	Slow

Interrelationships between dry, wet aggregate indices and soil properties

The correlation coefficient matrix of dry and wet-stable aggregate indices is shown in Table 5. WSA sizes between 0.5-0.25 mm significantly correlated negatively with DSA sizes >2 and DSA <0.25 mm (r= -0.41 and -0.42). However, a significant positive correlation existed between WSA sizes 0.5-0.25 mm and DSA sizes 1-0.5 mm (r= 0.5). The negative relationship between WSA 0.5-0.25 mm and DSA >2 and <0.25 mm showed that, as DSA is increasing at those aggregate size fractions, the WSA was decreasing at 0.5-0.25 mm aggregate size fractions. The WSA <0.25 is positively correlated with DSA sizes between 2-1 mm, hence suggesting that more DSA 2-1 mm may indicate very high dispersion of aggregates when wetted and thus a high erodibility potential.

The soil properties measured correlated with both DSA and WSA at various levels (Table 6). The DSA sizes >2 mm significantly correlated positively with *Ks* while the same DSA sizes positively correlated with PWP and ESP. It then suggest that larger DSA >2 mm favours the *Ks* and PWP of the soils. It also significantly correlated negatively with CEC. DSA sizes 1-0.5 mm negatively correlated significantly with soil pH in water. The DSA 0.5-0.25 mm correlated positively with CEC indicating that the CEC was supporting the increase of the dry aggregate sizes at this range while DSA<0.25 mm correlated negatively with PWP and ESP. A positive significant correlation exist between CEC DSA<0.25 mm sizes (r=0.39) and also MWDd positively correlated significantly with *Ks* (r = 0.68). The soil chemical properties that contribute significantly to aggregate stability are pH, ESP and CEC. The soil pH and ESP are both indices of soil reaction and sodicity. Levy *et al.* (2003) have demonstrated the effect of sodicity and pH in aggregate breakdown, which may lead to slaking, crusting and other negative soil attributes over time. Also Greene *et al.* (2002) showed that CEC affects the stability of soil aggregates of some Australian hard-setting soils. These, however, were linked to the type and nature of soil mineralogy including the soil organic matter contents.

The properties that correlated significantly with WSA >2 mm are moisture content at field capacity (FC), available water capacity (AWC) and bulk density (Table 6). It has

T a b l e 5. Correlation coefficients between dry-stable aggregates (DSA) and water-stable aggregates (WSA) indices

Indices	Dry-stable aggregates (DSA) (mm)					MWDd (mm)
	>2	2-1	1-0.5	0.5-0.25	<0.25	
WSA >2 mm	0.07	-0.05	0.02	-0.03	0.04	-0.05
WSA 2-1 mm	0.24	-0.23	-0.31	0.16	0.27	-0.03
WSA 1-0.5 mm	0.23	-0.55	-0.11	0.25	0.22	-0.13
WSA 0.5-0.25 mm	-0.41*	0.02	0.50*	0.29	-0.42*	-0.04
WSA <0.25 mm	0.01	0.39*	-0.14	-0.36	0.05	0.10
MWDw	0.27	-0.20	-0.11	0.40	0.10	-0.01

*significant $p<0.05$.

been proved that variation in water contents of soils may increase aggregate stability while prolonged wetting or drying treatments may have positive effect on the formation of unstable macroaggregates (Daneef *et al*. 2001; Daneef *et al*. 2002). Also WSA sizes between 2-1 mm positively correlated significantly with coarse sand, total sand and soil organic matter (SOM), but negatively correlated with bulk density and ESP. The WSA size range of 1-0.5 mm negatively correlated with PWP, bulk density, pH in water and ESP. The WSA size <0.25 mm negatively correlated with coarse sand, total sand, and SOM, but correlated positively with bulk density (Table 6). The potential structural deformation index (PSDI) for the soils significantly correlated with clay, PWP, *Ks* and ESP. Also PSDI correlated negatively with total sand and CEC. In the whole of these relationships the controlling factors are clay, bulk density, CEC, SOM and moisture contents. In some other studies (Zhang and Horn, 2001; Igwe and Stahr, 2004) the role of clay content, SOM and CEC or the polyvalent cations have been demonstrated. Soil organic matter and the clay contents are low in these soils. In most areas of the sahalian region with low input agriculture, the temperature is high all year round leading to high SOM mineralization. In spite of this, SOM is still regarded as a major component of soil aggregation together with clay, iron and Al oxides. Some researchers (Six *et al*., 2000; Boix-Fayos *et al*., 2001; Denef *et al*., 2002) concluded that soils with high amount of 1:1 clay minerals have higher potential to form stable aggregates when SOM is low.

The nutrient cations are also low while the negative contribution of bulk density is manifested in these soils through their role in wet stability of the soils. The high bulk density of the soils is due mainly to soil structure degradation as a result of leaching and removal of fine particles due to erosion. Akamigbo and Igwe (1990) observed that the high bulk density of similar soils was due to structural failure and the collapse of the soil fabric reducing the natural pore spaces of the soil. Therefore, to restore good soil structure, these soils should be allowed to stay under forest as suggested by Igwe (2001) or under a long fallow period to build up the SOM and hence better aggregation. This system will not only improve the soil structure but also replenish the low nutrient supply of these soils.

CONCLUSIONS

1. The four soils investigated indicate that the soils are low in porosity, excessively drained, low in SOM and available plant nutrient.

2. Mean-weight diameter of the dry aggregates (MWDd) was largely determined by the DSA sizes between 1-0.5 and 0.5-0.25 mm. However, in the MWDw, the WSA sizes that were dominant were those aggregate sizes between 0.5-0.25 and <0.25 mm.

3. Higher bulk density obtained for the soils was linked to the coarse texture, low SOM content and poor structural set-up of the coarse particles. Also the higher permeability of the topsoils was due to the presence of larger pores in the topsoil more than in the subsoil.

4. The SOM content, bulk density, pH, and ESP were the soil characteristics that affect the water aggregate stability of these soils, while CEC, SOM, moisture content and particle size distribution appeared to be some of the soil properties controlling PSDI.

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T a b l e 6. Correlation coefficients for the linear relationships between dry-stable aggregates (DSA) and water-stable aggregates (WSA) indices

Soil property	DSA (mm) >2	DSA 2-1	DSA 1-0.5	DSA 0.5-0.25	DSA <0.25	MWDd (mm)	WSA (mm) >2	WSA 2-1	WSA 1-0.5	WSA 0.5-0.25	WSA <0.25	MWDw (mm)	PSDI (%)
Clay	0.14	0.32	0.22	-0.29	-0.27	0.18	-0.11	-0.34	-0.19	-0.19	0.32	-0.26	0.42*
Silt	-0.25	-0.02	0.06	0.19	-0.04	-0.28	-0.18	0.02	-0.01	-0.19	0.15	-0.16	-0.07
F. sand	-0.17	-0.20	0.06	0.21	0.10	-0.14	0.12	-0.16	-0.14	-0.07	0.15	-0.07	-0.08
C.sand	0.11	-0.08	-0.23	0.01	0.13	0.05	0.08	0.39*	0.25	0.23	-0.39*	0.31	-0.25
T. sand	-0.03	-0.34	-0.32	0.26	0.34	-0.09	0.20	0.38*	0.20	0.26	-0.39*	0.35	-0.44*
FC	0.16	0.10	-0.21	-0.11	-0.11	0.06	0.61*	0.04	-0.05	0.19	-0.19	0.35	-0.19
PWP	-0.12	0.57*	0.34	-0.16	-0.55*	0.15	-0.05	-0.35	-0.49*	0.34	0.18	-0.27	0.38*
AWC	0.20	-0.07	-0.31	-0.06	0.05	0.01	0.62*	0.15	0.10	0.09	-0.24	0.42*	-0.31
BD	-0.32	0.05	0.27	0.03	-0.05	-0.31	-0.63*	-0.50*	-0.39*	-0.16	0.54*	-0.65*	0.33
Ks	0.51*	0.13	-0.35	-0.22	-0.09	0.68*	-0.06	-0.05	-0.14	0.13	0.02	-0.06	0.44*
pH H_2O	-0.30	0.01	-0.39*	0.19	0.36	-0.24	-0.06	-0.29	-0.37*	-0.15	0.37	-0.33	0.08
ESP	0.07	0.42*	0.32	-0.32	-0.48*	0.25	0.07	-0.52*	-0.52*	-0.08	0.49*	-0.32	0.45*
CEC	-0.35	-0.51*	-0.07	0.41*	0.39*	-0.37	0.10	0.11	0.18	0.29	-0.32	0.16	-0.47*
SOM	0.14	-0.02	-0.21	0.23	-0.13	0.14	0.22	0.59*	0.36	0.10	-0.44*	0.48*	-0.27

*significant $p<0.05$. F. sand-fine sand; C. sand- coarse sand; T. sand- total sand.

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