Stability of aggregates of some weathered soils in south-eastern Nigeria in relation to their geochemical properties

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The stability of some highly weathered soils of the tropics is controlled by their organo-mineral substances. Highly weathered soils from 10 different locations were sampled from their A and B horizons to determine their aggregate stability. The objective of the study was to determine the aggregate stability of the soils and their relationships with geochemical constituents. The major geochemical elements of the soils are quartz and kaolinite, SiO_2, Al_2O_3 and Fe_2O_3, while the dithionite extractable Fe and Al was greater than their corresponding oxalate and pyrophosphate forms. The mean-weight diameter from dried aggregates (MWD_d) and their corresponding wet mean-weight diameter (MWD_w) were related significantly (r = 0.64*). The dithionite extracted Al and Fe or the crystalline forms of these elements were outstanding in the stability of the aggregates. However, this did not diminish the influence of SOC reduced to third order level in the stability of the soils. The influence of SOC in these soils, however, indirectly manifested on the role of Fe_p and Al_p in the aggregation of these soils. The crystalline Fe and Al sesquioxides were very prominent in the aggregation and stability of these soils.

1. Introduction

In highly weathered, deep, well drained soils often characterized by soil degradation resulting to gullies, interrills and rill erosion due to frequent high intensity rainfall, study of the stability of soil aggregates is very important. This is because of the obvious soil break-down and detachment associated with poor aggregation due to low or absence of aggregating agents. Previous studies (Yang and Wander 1998; Zhang and Horn 2001; Igwe 2003, 2005; Darboux and Le Bissonnais 2007) have all tried to discuss the relationships between soil structural stability and erodibility of the soils. They all observed that soils with weak aggregate stability erode faster than those with high aggregate stability values. Le Bissonnais (1996) proposed that mean-weight diameter (MWD) could be applied to predict the potential erodibility of the soil. However, other indices have been used effectively to measure aggregate stability in soils such as the use of water-stable aggregates (WSA) proposed by Kemper and Rosenau (1986), state of aggregation (AS and SA) (Topp *et al.* 1997). According to Six *et al.* (2000), aggregate stability is used as an indicator of soil structure. Soil aggregation therefore results from the rearrangement of particles, flocculation and cementation (Duiker *et al.* 2003). However, improper land use results in breakdown of soil aggregates. Levy and Miller

(1997) showed that breakdown of unstable aggregates results in pore collapse and produces finer and more-easily transportable particles and microaggregates.

There are many studies on the mechanisms and binding of soil aggregates that make them stable. Harris *et al.* (1966) discussed these agents ranging from organic matter, soil micro organisms, abiotic agents, soil chemical and mineralogical properties. Recently, there has been generated interest on the study of soil organic matter in the aggregation of soils (Six *et al.* 2000, 2004; Zotarelli *et al.* 2005). In tropics with low soil organic matter contents, many researchers (Koutika *et al.* 1997; Spaccini *et al.* 2001, 2002; Igwe and Nwokocha 2006) have tried to investigate the role of low organic matter in the stability of soil aggregates. Igwe *et al.* (1995) reported that the soil organic matter they studied had no effect in the aggregation of the soil but the free Fe oxides was shown to be responsible for soil aggregation.

The superior role of cation exchange capacity (CEC) and oxides of total elements over soil organic matter in the aggregation and stability of tropical ultisol was demonstrated by Zhang and Horn (2001). In some Nigerian soils, Igwe *et al.* (1995) and Igwe and Stahr (2004) confirmed the effectiveness of Fe and Mn oxides in the stability of soil aggregates. Six *et al.* (2004) emphasised that the aggregating role of oxides was mainly at the micro aggregate level rather than at macro- and meso-aggregate levels. Duiker *et al.* (2003), however, argued that it was the poorly crystalline Fe oxide that was responsible for aggregation because of its strong relationship with soil organic carbon. Again, the positive role of Ca and Mg ions in the soil as aggregating agents have been highlighted recently (Dontsova and Norton 2001; Yilmaz *et al.* 2005). The studies showed that Ca^{2+} ions were more effective than Mg^{2+} ions in the aggregation of clays.

Soils studied are deep, extensively weathered but succumb to landslide, gullying, rill and interrill erosion during heavy rainfalls. The tropical ultisols and perhaps inceptisols are known to be well aggregated, yet these soils are the worst scenery of soil erosion in south-eastern Nigeria. The relative contributions of the secondary elements resulting from weathering to the stability of these typical tropical soils are unknown, yet information on floodplain and some temperate soils are abound in literature (Duiker *et al.* 2003; Igwe and Stahr 2004). The study of the relationships between the geochemical characteristics of the soils may help to explain the weakness of some of these soils and their susceptibility to soil erosion in the form of rill, interrill and gullies during intensive tropical rainfall. The contributions of Fe and Al oxides in the stability of these soils are not well elucidated. The objectives of this study were:

- to determine the dry-(DSA) and water-stable aggregates (WSA) of these soils,
- to determine the clay mineralogy and their geochemical properties, and
- to relate the soil geochemical properties such as Fe and Al oxides to the stability of the aggregates.

The aim is to provide basic information for the stability of the soils especially when being manipulated for agronomic and engineering purposes.

2. Materials and methods

2.1 *Description of the area*

The area is located between longitudes $6°57'$ and $9°05'$E; latitudes $5°50'$ and $6°52'$N. Rainfall of 1600–2000 mm occurs annually from April to November in bimodal distribution with peaks in July and September and with a very high intensity. The winter is very dry with 'harmattan' wind while the summer is wet. The mean monthly temperatures vary between 25° and 32°C with the mean monthly temperature in summer differing from the mean monthly winter temperature by not more than 5°C. The natural vegetation is mainly derived savannah, with some relicts of rainforest distributed in patches (Jungerius 1964). Orajaka (1975) showed that the underlying geological materials are Sandstone Formations and Shale of varying formations. The general description of the physical environment is shown in table 1.

2.2 *Field study*

Ten soils located on two major geological formations (Sandstones and Shales) were sampled (table 1). These soils form the major soil groups in south-eastern Nigeria and are mainly the representatives of major soil groups. These soils are extensively weathered with low organic matter content due to active mineralization resulting from high temperature regime. In the absence of the effect of soil organic matter which aggregates the soils, the alternative aggregating agents should be the product of weathering. The soils are often severely leached and over-used due to cultivation of arable crops and are highly weathered. Soil samples were taken from A and B-horizons in 10 locations making it a total of 20 soil samples. In all 10 locations, samples were taken from areas that have been on fallow for more than 5 years and have not received any fertilizer amendment within the same period. Soil samples were air-dried, sieved

Table 1. *Site characteristics and soil classification according to USDA Soil Taxonomy.*

Location	Coordinates	*Soil classification	Texture	Relief	Geological formation
Nanka	6°57′E; 6°03′N	Typic Paleustult	S, SC	Undulated and dissected	Sand stones of sedimentary origin
Awkuzu	6°59′E; 6°11′N	Rhodic Paleustult	SCL	Undulated and dissected	Sand stones of sedimentary origin
Okigwe	7°21′E; 5°50′N	Oxic Paleustult	SL	Hilly	Sand stones of sedimentary origin
Nkpologu	7°21′E; 6°52′N	Oxic Paleustult	SCL	Flat/Hilly	False bedded sandstones (Ajali formation)
Abakaliki	8°07′E; 6°19′N	Typic Haplustult	SL, CL	Flat	Asu River Group (Shale)
Enugu	7°34′E; 6°28′N	Typic Haplustult	SCL	Flat	Awgu/Ndeabo Shale
Ugwuoba	7°07′E; 6°23′N	Typic Dystrustept	C	Flat almost	Imo Clay Shale
Yahe	8°55′E; 6°24′N	Typic Paleustult	SCL	Plain	Ezeaku Shale
Ogoja I	9°05′E; 6°24′N	Typic Dystrustept	SL, SCL	Undulated and dissected	Ezeaku Shale
Ogoja II	9°00′E; 6°24′N	Typic Dystrustept	SL, SC	Undulated and dissected	Ezeaku Shale

*According to Soil Survey Staff (1999), S = sand, SCL = sandy clay loam, SL = sandy loam, CL = clay loam, C = clay, SC = sandy clay. Two textures in the same location means textures for A and B-horizons, while single texture indicates uniform nomenclature for the two horizons.

through a 2 mm mesh and analysed as described below. Samples that were used for bulk density and aggregate stability determinations were collected with cylindrical cores in an undisturbed form and preserved for various analyses. All analyses were determined in triplicates to allow reproducibility of results.

2.3 *Laboratory methods*

Particle size distribution of <2 mm fractions was measured by the hydrometer method as described by Gee and Bauder (1986). Soil bulk density was measured by the core method (Blake and Hartge 1986). Soil pH was measured in a 1:2.5 soil: KCl ratio using the pH meter method. The soil organic carbon was determined by the Walkley–Black method described by Nelson and Sommers (1982). Exchangeable cations were determined by the method of Thomas (1982). Dithionite-citrate-bicarbonate extractable Fe and Al (represented as Fe_{di} and Al_{di}) were measured as described by Mehra and Jackson (1960), pyrophosphate Fe and Al (Fe_p and Al_p) by methods of Agriculture Canada (1984) and oxalate extractable Fe and Al (represented as Fe_{ox} and Al_{ox}) by the McKeague and Day (1966) method.

Clay minerals were determined by X-ray diffractometry (XRD) with a Siemens D500 diffractometer, using Ni-filtered $CuK\alpha$-radiation after various pretreatments. The geochemical composition of the total elements in the fine-earth fractions (<2.00 mm soil fraction) was determined using Siemens SRS 200 X-ray

fluorescence (XRF) equipment. Total Fe and Al obtained through this determination were represented as Fe_2O_3 (Fe_t) and Al_2O_3 (Al_t), respectively.

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 2.00, 1.00, 0.50, and 0.25 mm mesh size and pre-soaked for 30 min in deionised 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 transferred into beakers, dried in the oven at 60°C until steady weight was achieved. The percentage ratio of the aggregates in each sieve represents the water-stable aggregates (WSA) of size classes: >2.00, 2.00–1.00, 1.00–0.50, 0.50–0.25 and <0.25 mm.

To obtain the 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 WSA determination but under a dry condition. Aggregate stability in both determinations was measured by the following equations after correction for sand:

(a) as the mean-weight diameter (MWD) of stable aggregates as equation;

$$\text{MWD} = \sum X_i W_i \qquad (1)$$

where X_i is the mean diameter of the ith sieve size and W_i is the proportion of the total aggregates in the ith fraction. The higher the MWD values, higher the proportion of macroaggregates in the sample and therefore better stability.

(b) State of aggregation

$$SA = (WSA > 0.5mm - Wt \text{ of sand})$$
$$/(Wt \text{ of soil})100 \qquad (2)$$

(c) Aggregate stability

$$AS = (WSA > 0.5 \text{ mm} - Wt \text{ of sand})$$
$$/(Wt \text{ of soil} - Wt \text{ of sand})100 \qquad (3)$$

where Wt is the mass of sand or mass of soil sample.

To assess the susceptibility of these soils which disintegrate upon contact with water, the potential structural deformation index (PSDI) was calculated for the soils using the method of Mbagwu and Bazzoffi (1989) as follows:

$$PSDI = [1 - (MWD_w/MWD_d)]100 \qquad (4)$$

where MWD_w is the mean-weight diameter by wet sieving and MWD_d is the mean-weight diameter by dry sieving.

2.4 *Data analysis*

The interrelations between the wet and dry stable aggregate indices were determined through a correlation matrix using the SYSTAT 9 statistical software (SPSS 1999) package. Also, the relationships between the aggregate stability indices at

Table 2. *Summary of soil physico-chemical properties.*

Soil property	Minimum	Maximum	Mean	CV%
Clay g kg^{-1}	70	470	254	43
Silt g kg^{-1}	30	430	161	68
Sand g kg^{-1}	260	900	585	3
SOC g kg^{-1}	1.10	26.3	7.30	19
pH KCl	3.80	6.1	4.40	13
CEC cmol kg^{-1}	7.35	22.17	12.00	34
Fe$_{di}$ g kg^{-1}	3.29	56.48	23.36	63
Al$_{di}$ g kg^{-1}	0.46	5.71	2.34	60
Fe$_{ox}$ g kg^{-1}	0.01	5.01	2.34	56
Al$_{ox}$ g kg^{-1}	0.08	1.53	0.76	54
Fe$_p$ g kg^{-1}	0.00	1.07	0.13	176
Al$_p$ g kg^{-1}	0.09	1.44	0.43	74
MgO%	0.15	1.27	0.43	79
Al$_2$O$_3$%	2.53	20.32	10.48	54
SiO$_2$%	60.02	91.49	78.93	13
K$_2$O%	0.03	0.97	0.30	100
CaO%	0.01	0.56	0.11	109
TiO$_2$%	0.29	3.07	1.05	69
Fe$_2$O$_3$%	1.02	10.49	4.43	62
ZrO$_2$%	0.03	0.15	0.08	38
Fe$_{di}$/Clay	0.01	0.80	0.13	127
Fe$_{di}$/Fe$_2$O$_3$	2.91	6.74	5.22	16
Fe$_{ox}$/Fe$_{di}$	0.00	0.15	0.03	133
Fe$_{di}$-Fe$_{ox}$	3.28	56.22	22.51	64
SiO$_2$/Al$_2$O$_3$	3.00	35.82	11.63	83
SiO$_2$/(Al$_2$O$_{3+}$ Fe$_2$O$_3$)	1.97	24.76	8.20	82
(CaO + MgO)/Al$_2$O$_3$	0.02	0.11	0.06	48
Kaolinite	+++			
Illite	+			
Vermiculite	+			
Smectite	(+)			

SOC: soil organic carbon; Fe$_{di}$, Al$_{di}$: dithionite-extractable Fe and Al; Fe$_{ox}$, Al$_{ox:}$ oxalate-extractable Fe and Al; Fe$_p$, Al$_p$: pyrophosphate Fe and Al; CEC: cation exchange capacity; MgO: magnesium oxide, SiO$_2$: silicon oxide; K$_2$O: potassium oxide; CaO: calcium oxide; TiO$_2$: titanium oxide; ZrO$_2$: zirconium oxide; + + +: abundant; +: few; (+): trace; CV: coefficient of variation in %.

both dry and wet states and soil properties were determined in a correlation matrix. Principal Component Analysis (PCA) was also used to reduce the unwieldy factors which affect the stability of aggregates to few orthogonal components.

3. Results

3.1 *Soil and geochemical characteristics*

The soils used for this study were mainly Ultisols apart from soils from Ugwuoba and Ogoja I and II that are inceptisols (table 1). The soil organic carbon (SOC) content and CEC are low while the soil pH in KCl was from 3.8 to 6.1 (table 2). Table 2 also shows the minimum, maximum and mean values of the dithionite, oxalate and pyrophosphate extractable Fe and Al. Quartz and kaolinite minerals remained the most abundant minerals, often being up to 90% in some soils. Illites and vermiculites are low in the soils while traces of smectites were found only in Enugu and Ugwuoba soils.

The ratios of Fe_{di} and clay were calculated and their other corresponding forms to determine their activities in soil processes and soil formations. Fe_{di}/clay ranged between 0.01 and 0.80, while an average of 5.22 was obtained for Fe_{di}/Fe_t. Fe_{ox}/Fe_{di} which is an index of crystallinity and amorphous form had an average value of 0.03 while an average of 22.51 gkg^{-1} was obtained when Fe_{ox} was subtracted from Fe_{di} ($Fe_{di}-Fe_{ox}$) (table 2). Table 3 shows the bulk density measurements for the soils. The values ranged between 1.26 and 1.66 Mgm^{-3} with an average value of 1.43 Mgm^{-3}.

3.2 *Soil aggregate stability*

DSA and WSA distributions are shown in figure 1. In the DSA, the aggregate sizes >2.00 mm dominated the other aggregate sizes except Okigwe, Nanka A, Nkpologu B, Awkuzu B and Yahe B soils. In Awkuzu, Okigwe, Nkpologu and Yahe soils, the aggregate sizes >2.00 mm were very low.

The mean-weight diameter of dry stable aggregates (MWD_d) ranges from 0.65–2.77 mm with mean value of 1.79 mm. Also, mean-weight diameter of wet stable aggregates (MWD_w) was from 0.26–2.07 mm and a mean of 1.15 mm. The PSDI for the soils was low to high (table 3). The PSDI values were between 1 and 82% with a mean of 33% and a coefficient of variation of 70%. Most soils have PSDI below 65%. Higher values of PSDI implies high tendency of the aggregates

Table 3. *Bulk density and aggregate stability indices of the soils.*

Location/horizon	BD ($Mg\ m^{-3}$)	MWD_d (mm)	MWD_w (mm)	PSDI (%)	SA (%)	AS (%)
Nanka A	1.66	1.28	1.02	20	31.96	43.47
B	1.34	1.41	1.15	18	14.74	14.74
Awkuzu A	1.55	1.54	0.55	64	42.80	54.48
B	1.45	0.65	0.60	8	20.28	25.00
Okigwe A	1.55	0.79	0.52	34	28.80	36.04
B	1.52	0.66	0.53	20	17.40	23.09
Nkpologu A	1.44	1.97	0.77	61	68.16	82.84
B	1.39	0.89	0.74	17	34.68	39.59
Abakaliki A	1.46	2.58	1.76	32	17.92	29.03
B	1.32	2.62	1.70	35	16.00	26.39
Enugu A	1.37	1.65	1.63	1	54.52	55.27
B	1.35	2.77	1.03	63	20.64	26.07
Ugwuoba A	1.27	2.71	1.61	41	66.52	66.92
B	1.26	2.66	0.92	65	42.72	46.84
Yahe A	1.42	1.52	0.26	83	49.08	52.62
B	1.37	0.66	0.48	27	35.00	38.79
Ogoja I A	1.51	2.57	1.95	24	37.92	67.04
B	1.41	2.32	1.91	18	18.32	39.52
Ogoja II A	1.52	2.26	2.07	8	35.80	58.49
B	1.35	2.35	1.79	24	32.16	50.34
Mean	1.43	1.79	1.15	33	34.27	41.83
CV%	7	44	51	70	47	46

BD: bulk density; MWD_d: mean-weight diameter dry; MWD_w: mean-weight diameter wet; PSDI: potential structural deformation index; SA: state of aggregation; AS: aggregate stability; CV: coefficient of variation.
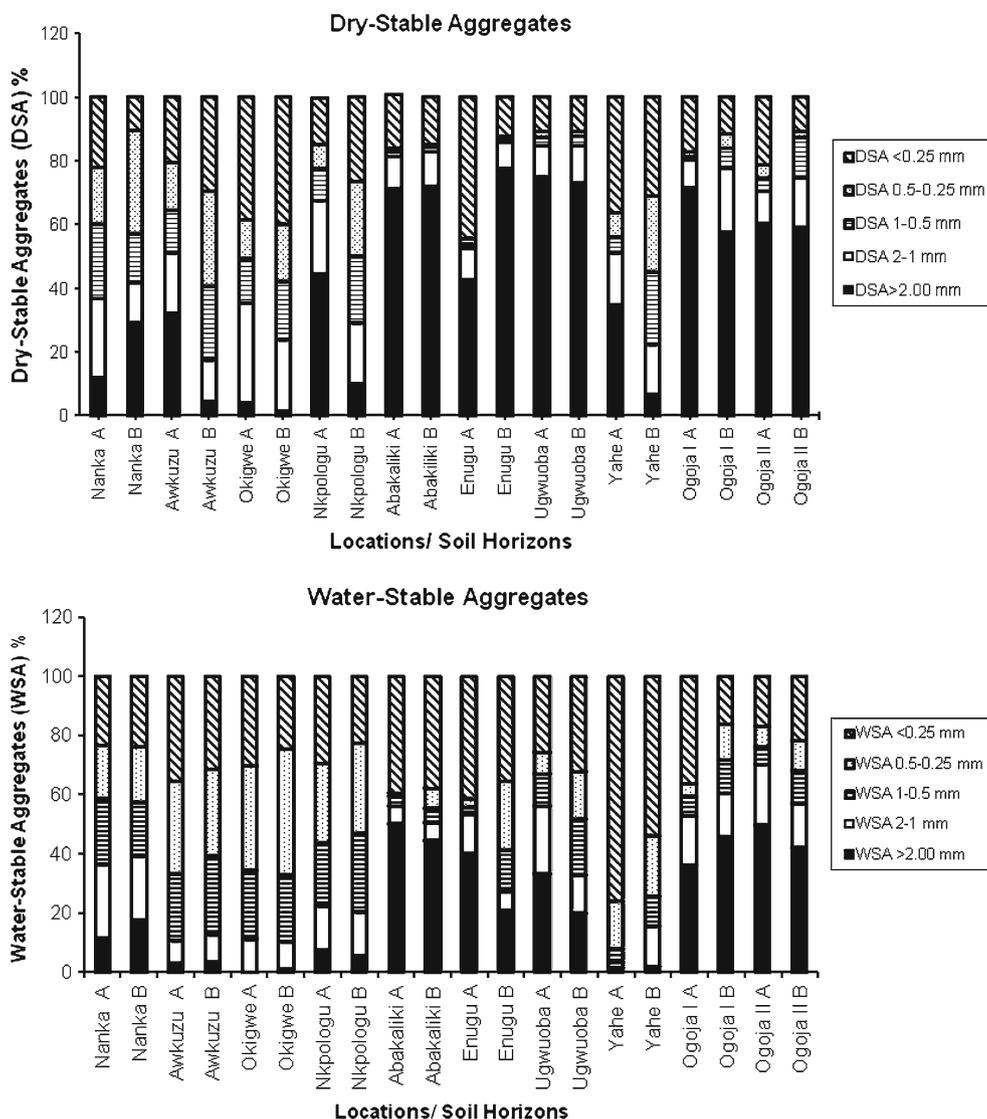
Figure 1. Dry-stable aggregates (DSA) and water-stable aggregates (WSA) for the soils.

to disintegrate easily upon wetting. The SA was from 14.74–68.16% while AS was between 14.74 and 82.84% with a mean of 41.83%.

3.3 *Interrelationships between aggregate stability, soil properties and geochemical properties*

The soil bulk density negatively correlated with MWD_d, clay content and silt + clay contents. Also, MWD_d related positively with MWD_w and clay + silt contents of the soil. SA also showed a significant positive relationship with AS. Clay contents related positively and significantly with clay + silt contents (table 4).

The soil bulk density had negative significant relationship with CEC, Fe_{di}, Al_{di}, Al_{ox}, Al_p, K_2O, MgO, Al_2O_3, TiO_2, Fe_2O_3 and Fe_{di}–Fe_{ox}. Also there were significant positive relationships

between SiO_2, SiO_2/Al_2O_3, $SiO_2/Al_2O_3 + Fe_2O_3$ and bulk density. Both MWD_d and MWD_w had some levels of positive relationships with SOC and the geochemical properties (table 5). The MWD_d and MWD_w on their own significantly correlated positively with SOC, CEC, Fe_{di}, Al_{di}, Fe_{ox}, Al_{ox}, Fe_p, MgO, K_2O, CaO and Fe_2O_3. In addition, MWD_d correlated positively with Al_p and TiO_2 while it negatively correlated with SiO_2, Fe_{di}/Fe_t and $SiO_2/(Al_2O_3 + Fe_2O_3)$. SiO_2 and Fe_{di}–Fe_{ox} correlated negatively with MWD_w. The various forms of relationships between geochemical properties and the two forms of MWD are shown. Both SA and AS correlated significantly with SOC while only SA positively correlated with Fe_p. The levels of significant positive and negative correlations between clay contents and silt + clay contents with the soil geochemical properties are shown in table 5.

Table 4. *Correlation coefficients for the linear relationships among aggregate stability indices and particle sizes.*

	BD	MWD$_d$	MWD$_w$	PSDI	SA	AS	Clay	Silt + clay
BD	–							
MWD$_d$	−0.50*	–						
MWD$_w$	−0.18	0.64**	–					
PSDI	−0.17	0.43	−0.34	–				
SA	0.02	0.16	−0.12	0.32	–			
AS	0.25	0.15	0.25	0.02	0.75**	–		
Clay	−0.96**	0.42	0.17	0.07	0.02	−0.25	–	
Silt + clay	−0.94**	0.51*	0.14	0.20	0.07	−0.20	0.88**	–

*$P < 0.05$; **$P < 0.01$; BD: bulk density; MWD$_d$: mean-weight diameter dry; MWDw: mean-weight diameter wet; PSDI: potential structural deformation index; SA: state of aggregation; AS: aggregate stability.

Table 5. *Correlation coefficients for the linear relationships between aggregate stability indices bulk density, clay, silt and soil properties.*

	BD	MWD$_d$	MWD$_w$	PSDI	SA	AS	Clay	Silt + clay
SOC g kg^{-1}	−0.05	0.52*	0.46*	0.17	0.57**	0.69**	−0.001	0.15
CEC cmol kg^{-1}	−0.65**	0.75**	0.64**	0.09	0.16	0.10	0.61**	0.58**
Fe$_{di}$ g kg^{-1}	−0.47*	0.44*	0.48*	−0.03	−0.02	0.01	0.58**	0.30
Al$_{di}$ g kg^{-1}	−0.57**	0.61**	0.57**	0.09	−0.06	−0.01	0.61**	0.41
Fe$_{ox}$ g kg^{-1}	−0.34	0.44*	0.46*	−0.06	0.16	0.09	0.33	0.37
Al$_{ox}$ g kg^{-1}	−0.65**	0.64**	0.53*	0.03	0.18	0.11	0.71**	0.53*
Fe$_p$ g kg^{-1}	−0.15	0.62**	0.44*	0.29	0.45*	0.41	0.05	0.26
Al$_p$ g kg^{-1}	−0.58**	0.58**	0.35	0.23	0.27	0.17	0.64**	0.47*
MgO%	−0.76**	0.83**	0.66**	0.11	0.10	0.02	0.72**	0.71**
Al$_2$O$_3$%	−0.70**	0.34	0.35	−0.09	−0.16	−0.21	0.79**	0.50*
SiO$_2$%	0.64**	−0.48*	−0.48*	0.03	0.05	0.07	−0.74**	−0.45*
K$_2$O%	−0.62**	0.82**	0.65**	0.22	0.14	0.16	0.53*	0.63**
CaO%	−0.43	0.79**	0.76**	0.07	0.27	0.33	0.38	0.41
TiO%	−0.76**	0.57**	0.28	0.15	0.04	−0.13	0.81**	0.74**
Fe$_2$O$_3$%	−0.49*	0.53*	0.55*	0.01	−0.02	0.02	0.58**	0.32
ZrO$_2$%	−0.21	0.40	0.27	0.07	0.13	0.14	0.10	0.45*
Fe$_{di}$/Fe$_t$	0.12	−0.45*	−0.38	−0.09	−0.20	−0.32	0.12	−0.19
Fe$_{ox}$/Fe$_{di}$	0.02	0.26	0.16	0.08	0.18	0.03	−0.08	0.08
Fe$_{di}$−Fe$_{ox}$	−0.47*	0.40	0.46*	−0.05	−0.04	−0.02	0.58**	0.28
SiO$_2$/Al$_2$O$_3$	0.68**	−0.38	−0.41	0.10	0.13	0.16	−0.76**	−0.46*
SiO$_2$/(Al$_2$O$_3$+Fe$_t$)	0.65**	−0.48*	−0.50*	0.06	0.08	0.10	−0.74**	−0.46*

*$P < 0.05$; **$P < 0.01$. See tables 2–4 for explanation of abbreviations.

Table 6 indicates that WSA >2.00 mm correlated positively with SOC, CEC, Al$_{di}$, Fe$_{ox}$, Al$_{ox}$, Fe$_p$, MgO, K$_2$O, CaO, Fe$_{di}$/clay and (CaO+ MgO)/Al$_2$O$_3$ while negatively correlated significantly with SiO$_2$. WSA sizes >2.00 mm correlated with Fe$_2$O$_3$, Al$_{di}$/clay and SiO$_2$/(Al$_2$O$_3$ + Fe$_2$O$_3$). WSA sizes between 2.00 and 1.00 mm positively related with Fe$_{di}$/clay, but WSA sizes between 1.00 and 0.50 mm negatively correlated significantly with SOC, CEC, Fe$_p$, MgO, K$_2$O, CaO, ZrO$_2$ and (CaO + MgO) + Al$_2$O$_3$. However, WSA 1.00–0.50 positively correlated significantly with Fe$_{di}$/Fe$_2$O$_3$. The soil properties that correlated negatively with WSA sizes between 0.50 and 0.25 mm were SOC, CEC, Fe$_{ox}$, Fe$_p$, MgO, K$_2$O, CaO, ZrO$_2$ and (CaO + MgO)/Al$_2$O$_3$ while it had a significant correlation with Fe$_{di}$/Fe$_2$O$_3$. WSA <0.25 mm positively correlated significantly with SiO$_2$, ZrO$_2$, SiO$_2$/Al$_2$O$_3$ and SiO$_2$/(Al$_2$O$_3$+ Fe$_2$O$_3$) while it negatively correlated with Fe$_{di}$, Al$_2$O$_3$, Fe$_2$O$_3$, Fe$_{di}$−Fe$_{ox}$, Al$_{di}$/clay and Fe$_{di}$/clay. Al$_{di}$/clay correlated positively with WSA >2.00 mm.

Table 7 presents the PCA which reduced the 23 variables that were studied and among those that might influence soil aggregation to five

Table 6. *Correlation coefficients for the linear relationships between water-stable aggregates (WSA) and soil properties.*

	WSA >2.00 mm	WSA 2–1.00 mm	WSA 1–0.50 mm	WSA 0.50–0.25 mm	WSA <0.25 mm
SOC g kg^{-1}	0.49*	0.14	−0.62**	−0.63**	0.16
CEC cmol kg^{-1}	0.68**	0.14	−0.54*	−0.61**	−0.10
Fe$_{di}$ g kg^{-1}	0.43	0.37	0.12	−0.16	−0.50*
Al$_{di}$ g kg^{-1}	0.54*	0.29	−0.08	−0.32	−0.37
Fe$_{ox}$ g kg^{-1}	0.48*	0.32	−0.19	−0.49*	0.17
Al$_{ox}$ g kg^{-1}	0.54*	0.34	−0.13	−0.29	−0.37
Fe$_p$ g kg^{-1}	0.51*	0.10	−0.56*	−0.70**	0.28
Al$_p$ g kg^{-1}	0.32	0.28	−0.05	−0.18	−0.25
MgO%	0.71**	0.12	−0.48*	−0.62**	−0.05
Al$_2$O$_3$%	0.32	0.39	0.15	−0.02	−0.54*
SiO$_2$%	−0.45*	−0.39	−0.05	0.18	0.51*
K$_2$O%	0.73**	−0.06	−0.67**	−0.76**	0.20
CaO%	0.80**	0.24	−0.66**	−0.78**	−0.08
TiO%	0.41	0.09	−0.11	−0.20	−0.19
Fe$_2$O$_3$%	0.49*	0.34	0.01	−0.25	−0.45*
ZrO$_2$%	0.40	−0.30	−0.75**	−0.61**	0.59**
Fe$_{di}$/clay	0.51*	0.60**	0.02	−0.33	−0.53*
Fe$_{di}$/Fe$_2$O$_3$	−0.38	0.14	0.73**	0.56*	−0.24
Fe$_{ox}$/Fe$_{di}$	0.19	0.02	−0.10	−0.27	−0.23
Fe$_{di}$−Fe$_{ox}$	0.40	0.38	0.15	−0.12	−0.51*
Al$_{di}$/clay	0.59*	0.33	−0.13	−0.36	−0.45*
Al$_{di}$/Al$_{ox}$	0.26	0.21	0.11	−0.17	−0.32
SiO$_2$/Al$_2$O$_3$	−0.37	−0.41	−0.12	0.08	0.88**
SiO$_2$/(Al$_2$O$_3$+Fe$_2$O$_3$)	−0.47*	−0.40	−0.05	0.19	0.53*
(Ca + Mg)/Al$_2$O$_3$	0.48*	−0.06	−0.74**	−0.75**	0.35

*$P < 0.05$; **$P < 0.01$. Abbreviations are as in previous tables.

orthogonal components with eigenvalues greater than 1. The PCA has the capability of limiting the unwieldy factor to fewer components. The five components altogether explained 88.79% of the total variance within the variables. Component 1 explained 49.01% of the total variance and had positive significant loadings (±0.65) on Al$_{di}$, Fe$_{di}$−Fe$_{ox}$, Fe$_2$O$_3$, Fe$_{di}$, Al$_{ox}$, Al$_2$O$_3$, Al$_p$, MgO and K$_2$O but negative significant loadings on SiO$_2$, SiO$_2$/(Al$_2$O$_3$ + Fe$_2$O$_3$) and SiO$_2$/Al$_2$O$_3$. This first component described mainly the crystalline Al and Fe sesquioxides. Component 2 explained 18.95% of the total variance and loaded significantly on Fe$_{ox}$, Fe$_p$, Fe$_{ox}$/Fe$_{di}$, Fe$_{di}$/clay and TiO$_2$. These variables are mainly the amorphous and less crystalline Fe groups. Component 3 explained 11.02% of the total variance and loaded heavily on SOC and CaO. The underlying factor here is the organic matter. The fourth component explained 5.52% of the total variance and loaded significantly on (CaO+MgO)/Al$_2$O$_3$ ratio and Fe$_{di}$/Fe$_2$O$_3$. This component is mainly described as weatherable elements. Finally, component 5 explained only 4.27% of the total variance but loaded significantly on ZrO$_2$. The main elements that may be explaining

the variability in the MWD$_w$ index of AS are the variable that loaded highest in each component and are referred to as component defining variables (CDV). These CDV are Al$_{di}$, Fe$_{ox}$, SOC, (CaO + MgO)/Al$_2$O$_3$ and ZrO$_2$. These are mainly sesquioxides and resistant minerals in the soil.

4. Discussion

The role aggregate stability indices play in the estimation of soil erodibility by water has been highlighted (Bajracharya *et al.* 1992; Le Bissonnais 1996; Igwe 2003). They observed that soils with low MWD and with WSA occurring more on <0.25 mm aggregate ranges correlate highly with interrill and rill erosion in the field. Soils with high SA and AS did not disperse easily. The MWD, WSA and water-dispersible clay (WDC) have been used successfully in the prediction of potential soil erosion hazard by water in the tropics. However, the predictive ability of the whole indices may differ and not agree on the level of prediction. In our present study, the indices did not agree with the estimated values of the erodibility of the soil.

Table 7. *Principal component analysis of aggregate stability indices after varimax rotation using* MWD_w *component.*

Soil properties	Components				
	1	2	3	4	5
Al_{di}	0.950	0.169	0.097	0.043	0.061
$Fe_{di}-Fe_{ox}$	0.947	0.018	0.037	-0.127	-0.018
Fe_2O_3	0.944	0.122	0.137	-0.026	0.046
Fe_{di}	0.943	0.101	0.040	-0.119	-0.011
SiO_2	-0.913	-0.242	-0.123	0.085	0.180
Al_{ox}	0.872	0.263	0.304	0.085	-0.051
Al_2O_3	0.871	0.201	0.031	-0.221	-0.201
Al_p	0.852	0.115	0.022	0.302	-0.073
$SiO_2/(Al_2O_3+Fe_2O_3)$	-0.814	-0.134	-0.135	0.458	-0.150
SiO_2/Al_2O_3	-0.785	-0.125	-0.112	0.472	-0.105
MgO	0.732	0.503	-0.015	0.400	-0.035
K_2O	0.675	0.193	-0.004	0.447	0.429
CEC	0.616	0.200	0.581	0.363	-0.029
Fe_{ox}	0.238	0.932	0.028	0.060	0.059
Fe_p	0.138	0.925	0.182	0.110	0.012
Fe_{ox}/Fe_{di}	-0.080	0.862	0.033	0.081	0.338
$Fe_{di}/clay$	0.268	0.809	0.227	-0.051	-0.113
TiO_2	0.527	0.733	0.019	0.015	-0.108
SOC	-0.001	0.139	0.917	0.148	0.194
CaO	0.261	0.123	0.911	0.181	0.060
$(CaO + MgO)/Al_2O_3$	-0.093	0.270	0.393	0.801	0.276
Fe_{di}/Fe_2O_3	0.153	-0.007	-0.365	-0.684	-0.212
ZrO_2	-0.227	0.053	0.243	0.279	0.811
MWD_w	0.450	0.130	0.523	0.075	0.542
Eigenvalue	11.76	4.55	2.65	1.33	1.02
% Variance	49.01	18.95	11.02	5.52	4.27
% Cum. variance	49.01	67.97	79.00	84.52	88.79

See table 2 for explanation of abbreviations.

Bajracharya *et al.* (1992) in Ohio soils showed that the indices of aggregation did not agree on the extent of soil erosion even while using rainfall simulator. Also, Igwe (2003) observed that in spite of this weakness in the use of these indices, they can be applied reliably in formulating soil conservation strategies in the area. The MWD_w were medium to fine in size except Ogoja II A, perhaps showing the ease of transportation by water during rains and splash. High soil bulk density in soils always indicate soil compaction and soil structural deformation and an indication of some form of soil degradation. Also, high PSDI observed in the soils were attributed to cause high erodibility potential of these soils.

Tables 5–7 indicated that the geochemical properties, SOC and to some extent, CEC play very significant roles in the aggregation mechanism of these soils. Other elements that are associated with aggregate stability of the soils included MgO, SiO_2, K_2O, CaO and TiO_2. The SOC, CEC, Fe_{di}, Al_{di},

Fe_{ox}, Al_{ox}, Fe_p, Al_p, Fe_t and the ratio of Fe_{di}/Fe_t were all associated with aggregate stability of these soils. The ratio of $Si/(Al_t + Fe_t)$ and $Fe_{di}-Fe_{ox}$ were also linked to stable aggregate formation of the soils. These may be associated with the stage of weathering which is advanced, age of the pedological and lithological materials and other soil contemporary processes. In highly weathered tropical soils with a lot of sesquioxide minerals and resistant minerals left over after extensive leaching, the SOC is bound to be low. When SOC is low in the soil, its role as a very important aggregating agent becomes diminished. Goldberg *et al.* (1990) indicated that SOC could be an aggregating or disaggregating agent depending on the soil and other aggregating agents in the soil. Oades (1984) showed that when the Fe and Al oxides are high, they reduce the effect of SOC as aggregating agent. Igwe *et al.* (1995) remarked that the role of SOC as an aggregating agent is very much dependent on soil type. In our soils, different forms of Fe and

Al oxides are high (table 2) and thus masking the influence of SOC in the soil. The role of SOC as an aggregating agent in these soils has been reduced or may have been masked by high Fe and Al contents of these soils.

The results confirmed the superiority of Fe and Al oxide forms and their various combinations in the aggregation of highly weathered tropical soils. In the floodplain of southern Nigeria, Igwe and Stahr (2004) were able to isolate Mn oxide as influencing the soil aggregation in those soils. Igwe *et al.* (1995, 1999) indicated that in some soils of southeastern Nigeria, not among those in the current study, the sesquioxides were responsible for their aggregation. However, they were not able to separate these sesquioxides into Al, Fe or Mn oxides or even the other organo-metallic oxides responsible for the stability of soil aggregates. Our present study shows that the major soil aggregating agents among others in these soils were Al_{di} or the crystalline Al oxide, Fe_t, Fe_{di}, Al_{ox}, Al_t and Al_p. These do not suppress the contributory roles of other polyvalent ions in the stability of these soil aggregates. Duiker *et al.* (2003) remarked that it was Fe_{ox} that was responsible for the aggregation at macroaggregate level of the B horizons of their soils because of their low concentration and low range of SOC. This was contrary to the result of our present study. In our soils, Al_{di} was of moderate quantity while the crystalline Fe was high. Mbagwu and Schwertmann (2006) showed that in some other highly weathered soils, aluminium acted as aggregating agents more than Fe oxides. Very recently, Barthes *et al.* (2008) also showed that in some kaolinitic soils from tropical regions, water stable macroaggregation depended closely on Al_{di} which measures Al-substitution on crystalline hematite and goethite which in turn affects specific surface area. Alekseeva and Alekseev (1999) confirmed that the crystalline oxides play major role in the aggregation of soils. They do this by reacting with clay particles via electrostatic forces which is at optimum at pH 5.5 or there about. According to Amezketa (1999), polyvalent Al^{3+} and Fe^{3+} cations improve soil structure through cationic bridging and formation of organo-metallic compounds and gels. Oades and Waters (1991) emphasised that in acidic soils with low clay and SOC contents such as Oxisols, both Al^{3+} and Fe^{3+} control aggregation. Six *et al.* (2000) agreed that the interaction of Al and Fe oxides with kaolinite can synergistically promote aggregation with limited impact on SOC. The oxides and hydroxides of Al^{3+} can interact synergistically with SOC and dispersible clay to improve aggregation (Molina *et al.* 2001).

The role of Si in the aggregation of the soils was purely in negative form as it tend to weaken aggregation rather than stability of aggregates (tables 5–7). The low surface area of this element and their weak bonding forms may have contributed to their poor binding capacity. The high values of this element in the soils can be attributed to the age of the soils, geological/parent materials and other prevailing processes that contribute to the synthesis of quartz and other non-weatherable and inert materials in the soils. While Pinheiro-Dick and Schwertmann (1996) showed that in Oxisols and Inceptisols in Brazil, Si associated with acid oxalate extraction was acting as aggregating agent, this study only analysed the total form of Si. Igwe and Stahr (2004) in a flooded Inceptisol in south-eastern Nigeria indicated that SiO_2 had a linear relationship with WSA sizes 2.00–1.00 mm. Their role was merely that of a bridge between the polyvalent cations such as Fe or Al and SOC. Colombo and Torrent (1991) observed that these relationships between Si and aggregation indices was possible due to the formation of bridges between silica and either Fe or Al oxides and other particles such as clay and SOC.

The role of K_2O and MgO and to some extent CaO in the aggregation of these soils were minimal and were captured on tables 5, 6 and 7. These elements were not high in these soils, however, their limited presence and occurrence in the soils added to the overall stability of the soil aggregates. Earlier, Harris *et al.* (1966) and Edwards and Bremner (1967) recognised the importance of Ca and Mg in stabilisation of soil aggregates and proposed a linkage or bridge of C-P-OM-C; where C is clay, P is polyvalent cations (Al, Fe, Ca), OM is organic matter. We adopted this model to explain the mechanism and positions of the agents in the stability of the soils. Bronick and Lal (2005) remarked that bivalent Ca^{2+} and Mg^{2+} cations improve soil structure through cationic bridging with clay particles and SOC. The presumed contribution of MgO in these soils were from the total form, as the ones in the exchange sites of these soils appear to contribute little to the stability of these soils as shown by Igwe *et al.* (1999).

The studied soils were dominated by the presence of quartz and kaolinite minerals. Such soils are regarded as low activity clay soils and do not undergo swell-shrink process when submerged. Amezketa (1999) and Schulten and Leinweber (2000) indicated that kaolinite has a good flocculation capacity due to electrostatic charges between platelets and SOC. They concluded that aggregation was generally higher in 2:1 clays than in the 1:1 type. These soils were dominated by quartz and 1:1 clay minerals. The soils studied had, in addition to abundant kaolinite, Fe and Al sesquioxides minerals. These may explain the high stability potential of these soils. This study therefore highlights the dominant roles of Al_{di}, Fe_2O_3, Fe_{di}, Al_{ox},

Al_2O_3 and the Al_p in the aggregation and stability of most tropical soils low in native organic matter. The individual roles of MgO and K_2O are merely secondary in these soils and can only manifest if the rate of leaching and land use pressure are reduced.

5. Conclusions

The soils were deep highly weathered and often physically degraded. The major geochemical elements of the soils are SiO_2, Al_2O_3 and Fe_2O_3 while the dithionite extractable Fe and Al were greater than their corresponding oxalate and the pyrophosphate forms.

The dithionite extracted Al or the crystalline form and the corresponding Fe forms were very outstanding in the stability of the aggregates. However, this does not diminish the influential roles of SOC, other forms of Fe and Al oxides, MgO and CaO in the stability of the soils. The dominance of quartz and kaolinite clay mineral in the soils and their low shrink-swell characteristics may also be an advantage in the stability of the soils.

We therefore postulate that Al_{di}, Fe_2O_3, Fe_{di}, Al_{ox}, Al_2O_3 and the Al_p are the major forms of secondary elements responsible for the aggregation and stability of these tropical soils low in native organic matter while the roles of MgO and K_2O are merely secondary in these soils. The results obtained from this study could be extrapolated in the study of similar tropical soils with no basic information. This is imperative especially in the management of such soils for agronomic and engineering manipulations as in foundation and septic tank construction including canal development.

Acknowledgements

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