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Some factors affecting clay dispersion and aggregate stability in selected soils of Nigeria**

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Abstract. Using 22 soil samples from Nigeria, comprising Alfisols, Entisols, Inceptisols, Ultisols and Vertisols with 77- 676 g kg^{-1} clay, we studied the effect of various treatments on clay dispersion. Aggregate stability was evaluated by the aggregated clay (AC) index, *ie* clay in calgon minus clay in H_2O. Treatments with H_2O_2 to remove organic matter (OM) showed only slightly increased clay dispersion in some soils, but it increased clay dispersion in others. Organic matter also showed low correlation with AC. Greater amount of clay was dispersed following soil treatment with sodium dithionite-citrate-bicarbonate (DCB) than with acid NH_4 – oxalate (Ox). Treatment with either Na-bicarbonate (B), Na-citrate (C) or Na-citrate plus Na-bicarbonate (CB) produced clay amounts comparable to those obtained with the DCB treatment but extracted only 0.06 to 2.11% of Fe_D and 0.24 to 19.2% of Al_D. Generally, there were no significant correlations between the amount of dispersed clay and the contents of Fe and Al obtained from soil treatments with either B, C or CB extractants. Consequently, Fe_D explained only 22.8% and Al_D about 58.4% of variation in aggregated clay, *ie* DCB-clay minus H_2O-clay. This suggests that the bicarbonate and citrate anions increased clay dispersion even when little or no Fe and Al was removed. That can be interpreted in such a way that any aggregation effect of Fe and Al oxides cannot be eliminated only by totally extracting them but also by removing their interaction with clay and silt particles.

Keywords: aggregate stability, aggregated clay, chemical extractants, tropics, water-dispersible clay.

INTRODUCTION

Aggregates of many soils disintegrate rapidly under the impact of raindrops. This is followed by physicochemical dispersion of clay particles within the aggregates. The dispersed clays may form a surface seal or move down the soil profile where they clog water-conducting pores. Either of these processes restricts rapid infiltration of water into and/or lowers saturated hydraulic conductivity within the soil profile. The result of this is surface runoff and erosion (Dong *et al*., 1983; Goldberg *et al*., 1988; Mbagwu and Piccolo, 2004; Miller and Baharuddin, 1986; Shainberg *et al*., 1987; Yousaf *et al*., 1987). It is for these reasons that identification of dispersive soils and factors that influence their stability have received serious attention, especially in arid and semi arid zones that have high concentrations of salts and Na^+ (Levy *et al*., 1993) and in hard-setting soils (Breuer and Schwertmann, 1998; Rengasamy *et al*., 1984), whereas Oxisols and Ultisols of the tropics are generally regarded as better aggregated.

Among the factors that affect soil aggregation are pH (Suarez *et al*., 1984), clay minerals (Nwadialo and Mbagwu, 1991; Oster *et al*., 1980), exchangeable Na^+ (Shainberg and Letey, 1984), type and concentration of electrolytes (Miller, 1987; Rengasamy *et al*., 1984; Yousaf *et al*., 1987), organic matter (Dong *et al*., 1983; Mbagwu, 1989), and Fe and Al oxides (Ajmone-Marsan and Torrent, 1989; Cambier and Picot, 1988; Colombo and Torrent, 1991; Goldberg *et al*., 1988).

There still is, however, controversy concerning the roles of these soil constituents in clay dispersion. For example, whereas Gerard (1987) reported increased clay aggregation and percent water-stable aggregates due to increased soil organic matter (SOM), others (Mbagwu *et al*., 1993; Visser and Caillier, 1988) observed increased clay dispersion following additions of humic substances to soils. Gu and Donner (1993) suggested that in soils with trace to low concentrations of polyvalent cations (Fe, Al, Ca, Mg), the

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negatively charged humic and clay particles repel each other (and hence disperse). Also, whereas Oades (1984), Goldberg *et al*. (1988) and Colombo and Torrent (1991) reported increased clay aggregation due to high concentrations of Fe and Al in soils, others (Adesodun *et al*., 2004; Bartoli *et al*., 1988; 1991; Borggaard, 1983; Deshpande *et al*., 1968) showed that aggregate stability in water was independent of Fe and Al contents but dependent on SOM level. These conflicting results may be related, among others, to the different methods used to extract and quantify the aggregating agents.

As regards which Fe fraction is the most effective as a clay-aggregating agent, conclusive results have not been reported yet. Colombo and Torrent (1991) reported that crystalline Fe oxide (Fe_{D-Ox}) is more important than Fe_{Ox} in aggregating clay in some Terra Rosas from southern Spain. However, Goldberg *et al*., (1988) observed that Fe_{D-Ox}, Fe_{Ox}, Al_{D-Ox} and Al_{Ox} play important roles in aggregate stability of some arid zone soils in Isreal. El-Swaify and Emerson (1975) reported that Al_{Ox} was more effective than Fe_{Ox} in maintaining the stability of soil aggregates. However, Hsu (1977), who found a poor correlation between Fe_D and Al_D and aggregation, suggested that this does not necessarily imply that they do not have any effect on aggregate stability because their differences in crystallinity and particle size had not been taken into account. In synthetic work, ferrihydrite was more effective in aggregating silt particles of a loess Alfisol than goethite (Schwertmann and Schahabi, 1970).

As can be seen from the above, the epicenter of most of these studies is the temperate region. Pinheiro-Dick and Schwertmann (1996) recently reported that some tropical soils from Brazil and Cameron dispersed effectively under treatment with Na-citrate or Na-bicarbonate without removing substantial amounts of Fe, implying that Fe is not aggregating the clay. In this study we determined the extent of dispersion of 22 soil samples from Nigeria following treatments with H_2O_2, Na-pyrophosphate, NH_4-oxalate, Na-bicarbonate, Na-citrate and Na-dithionite, alone and in various combinations. The objective was to relate clay dispersion of these soils to OM and the fractions of Fe and Al. Aggregate stability was assessed by the aggregated clay (AC) index.

MATERIALS AND METHODS

Soils

The 22 soil samples were collected from the A, B or C horizons of profiles from different parts of Nigeria (Fig. 1), covering the main soil orders (Alfisols, Entisols, Inceptisols, Ultisols and Oxisols), parent materials (basement complex, shale deposits, sedimentary rocks, loess materials, and false-bedded sandstones) and land use/vegetation in Nigeria. The samples were air-dried and sieved to separate the 1-2 mm dry aggregates on which all the determinations were made.

The particle sizes – coarse sand (630-2000 μm), fine sand (100-630 μm), very fine sand (63-100 μm), silt (2-63 μm) and clay (< 2 μm), were measured by the standard pipette method following dispersion with sodium pyrophosphate (PP). Organic carbon (OC) was determined by loss of weight on dry combustion using an induction furnace (CSA 302, Leybold-Heraeus), and pH was measured in 0.01 M $CaCl_2$. Exchangeable cations were leached with 1 M ammonium acetate solution. The Ca and Mg in the leachate were determined by AAS, and Na and K were determined by flame photometer. Exchangeable Al (Al_{Ex}) was measured in 1 M KCl extracts by AAS. Cation exchange capacity (CEC) was determined by NH_4^+ saturation followed by displacement and titration of NH_3 collected in boric acid.

Soil dispersion treatments and clay determination

In each of the dispersion treatments, 10 g of the 1-2 mm dry aggregates were used (Alekseeva *et al*., 1995). These treatments included pure mechanical shaking in distilled water which served as the control, removal of SOM with 30% H_2O_2, shaking for 16 h with pH 9.5 solution of each of DCB, Na-citrate, (C) alone, Na-bicarbonate (B) alone, or Na-citrate + bicarbonate (CB) or with pH 3 NH_4-oxalate for 2 h in the dark (Schwertmann, 1964). To evaluate the contribution of Al_{Ex} to clay dispersion, the oxalate treatment was done before and after the removal of Al_{Ex} with 1 M KCl.

After chemical dispersion, each sample was centrifuged and the supernatant liquid collected for measurement of Fe and Al (where appropriate) using AAS (Perkin-Elmer 420 spectrometer), then washed three times with ethanol and once with acetone before air-drying. The levels of Fe and Al in these washings were below detection. These air-dried and the H_2O_2-treated samples were redispersed in 200 ml of deionized water in 250 ml plastic bottles, shaken for 16 h, poured into 1 litre sedimentation cylinders, brought to mark with deionized water and turned end-over-end five times before allowing them to stand for 8 h. Thereafter, the clay fraction was determined by the pipette method.

RESULTS AND DISCUSSION

The morphological information about the locations and other site information, as well as soil physical properties, is shown in Table 1. Some of the chemical properties of the soils are given in Table 2. The amounts of Fe and Al extracted by the various treatments are shown in Tables 3 and 4, respectively. The order is almost identical for both metals (M): $M_B < M_C \sim M_{CB} < M_{Ox} < M_D$. This indicates some close association of the two metals in these soils. It is well known that Al substitutes Fe in crystalline Fe oxides, which is extracted together with Fe by DCB because citrate forms stable complexes with both of them. In fact the Al-substitution calculated from $Al_{D-Ox}/(Al_{D-Ox}+Fe_{D-Ox})$ ranged from 0.0 to 0.18, which is well within the usual range. This means that Al_{D-Ox} derives essentially from structural Al in Fe oxides, goethite and heamatite.

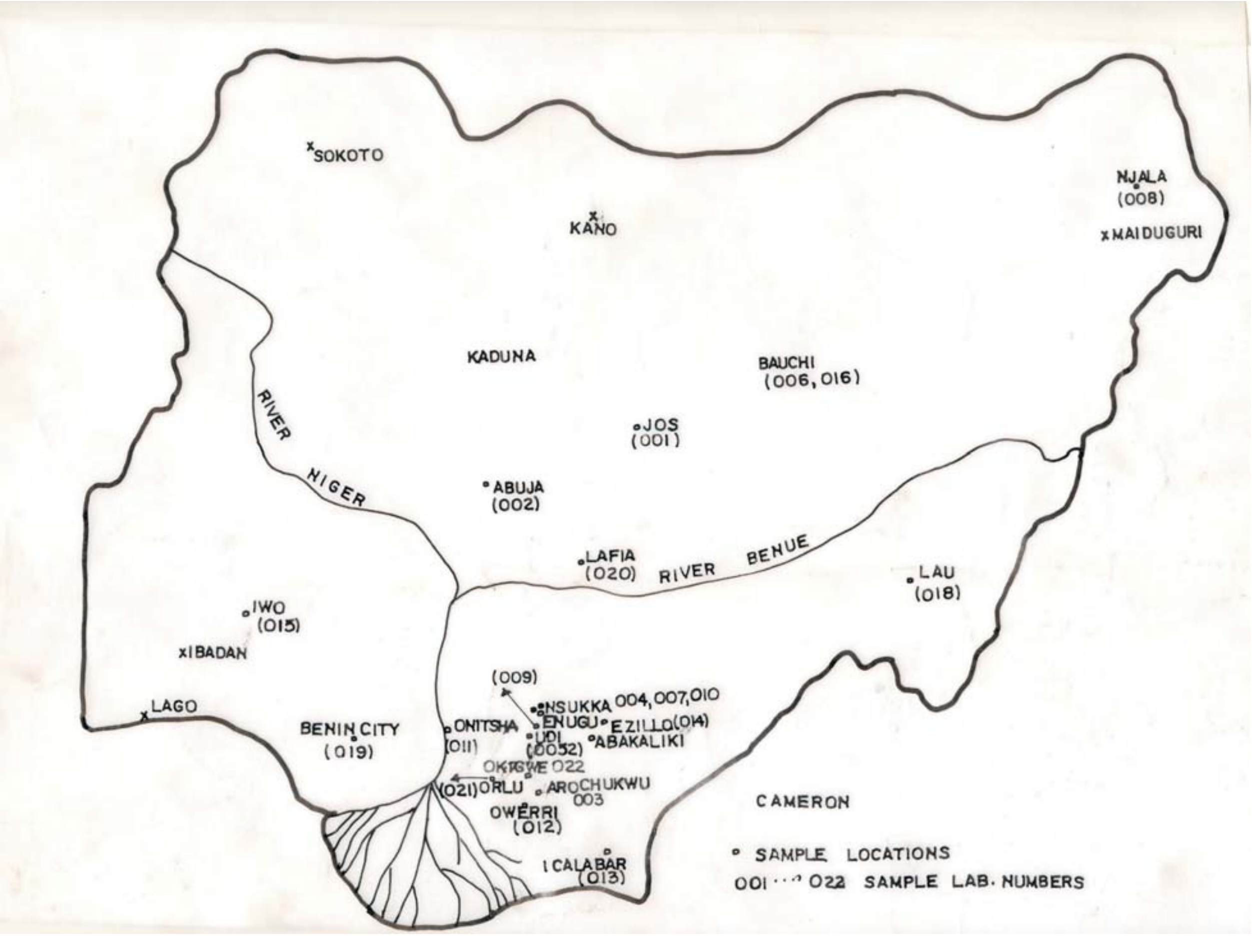

Fig. 1. Places of soil sampling, Nigeria.

The average clay values obtained after treatment with the various dispersants followed the order, $H_2O < H_2O_2 <$ Ox < B < PP < C = CB = DCB (Table 5). The highest variability was obtained in clay dispersed by Ox, followed by H_2O treatment, and the lowest with DCB. In six of the soils (Entisol, 1, Ultisols, 3, 4 and 9 and Vertisols, 5 and 18), clay dispersion decreased after H_2O_2 treatment. This indicates that OM enhances clay dispersion in these soils. These are mainly Vertisols, which contain expanding clay minerals, and Ultisols and Entisols, which do not contain such minerals. In the rest of the soils, the opposite was true, which shows the positive role of OM in aggregating the clay particles. These are soil Orders like Ultisols, Entisols, Alfisols and Inceptisols, which contain mainly non-expanding clay minerals. However, considering the fact that the correlation (r) between aggregated clay and OM content of these soils is low (0.342), the contribution of OM to the stability of clay particles is minimal here.

The DCB, which extracted the highest amount of Fe and Al, also produced the highest amount of dispersed clay and can be used as a reference (Table 6). The clay yield is higher in all the soils than in the standard PP treatment. However, C and CB – which showed essentially the same clay yield – extracted only about 2% of Fe_D and 9-19% of Al_D. Oxalate, which dispersed 71% of total clay on the average, extracted only 7% of Fe_D and the bicarbonate which dispersed 83% of total clay extracted only 0.06% of Fe_D.

The correlation between clay yield and the various fractions of Fe and Al are generally poor (Table 7), which agrees with the study of Pinheiro-Dick and Schertmann (1996). The best correlations were obtained for the Al_{Ox} and Al_D ($p = 0.001$) and the reason for this appears to indicate that – in these soils – Al is more important as a clay binding agent than Fe, even though they are likely to be different fractions of Al. It can hardly be explained by gibbsite (if present), because gibbsite does not dissolve in the oxalate, nor could it be Al_{Ex} because after its exclusion the correlation is still high. Although the combination of Al with Fe in the correlation statistics lowers the ‘r’ values somewhat, we still believe that most of the Al_D is extracted with Fe_D in Fe oxides.

T a b l e 1. Chosen properties of the soils investigated

Location	Soil	Depth (cm)	Clay	Silt	VFS	FS	CS	TS	pH (0.01 M $CaCl_2$)	ESP	OC	CEC (Cmol kg^{-1})	Munsell colour (Dry)
			(%)							(%)			
Jos	Entisol	0-10	54.9	38.0	1.9	4.8	0.4	7.1	5.4	1.09	2.26	23.0	7.5YR 4/6
Abuja	Inceptisol	0-20	16.0	36.3	11.3	34.0	2.4	47.7	4.6	2.43	2.00	11.5	2.5Y5/2
Arochukwu	Entisol	0-30	31.5	27.5	9.7	30.1	1.2	41.0	3.9	0.52	2.22	33.0	10YR5/6
Ekwegbe	Ultisol	10-30	41.1	6.0	3.1	43.3	6.5	52.9	4.4	2.62	0.71	6.5	7.5YR 6/8
Udi	Ultisol	100-150	14.8	6.8	7.4	68.0	3.0	78.4	4.2	4.57	0.12	3.5	5YR6/8
Bauchi 1	Vertisol	0-10	36.3	29.4	5.3	22.7	6.3	34.3	6.6	1.38	1.29	29.0	2.5Y6 /210YR7 /8
Nsukka 1	Entisol	0-5	52.5	19.7	9.0	17.2	1.6	27.8	3.7	1.08	5.00	18.5	5YR4 /8
Njala	Alfisol	0-10	17.5	39.5	5.2	30.8	7.0	43.0	4.8	1.63	1.02	13.5	2.5Y6/4
Emene	Ultisol	5-15	37.0	24.0	10.2	27.8	1.0	39.0	3.4	2.00	0.66	7.5	10YR7 /8
Nsukka 2	Ultisol	0-20	25.9	4.9	3.6	60.6	5.0	69.2	3.4	1.76	2.33	8.5	5YR4/ 8
Atani	Entisol	0-20	33.3	61.4	2.4	2.6	0.3	5.3	4.0	1.80	3.53	25.0	2.5Y6/4
Owerri	Ultisol	0-20	10.4	3.6	1.3	70.2	14.5	86.0	4.1	4.86	1.14	3.5	10YR4 /6
Calabar	Ultisol	0-15	18.0	5.3	1.3	52.9	22.5	76.7	4.0	2.43	1.83	7.0	10YR5 /4
Ezilo	Inceptisol	0-20	8.4	52.3	32.4	6.4	0.5	39.3	4.4	2.23	0.88	6.5	10YR7 /6
Iwo	Alfisol	0-20	22.9	13.8	6.1	54.0	3.2	63.3	5.4	2.62	0.86	6.5	7.5YR 6/6
Bauchi 2	Alfisol	0-10	16.1	28.0	8.7	36.5	10.7	55.9	5.7	8.80	2.05	11.0	10YR5 /3
Abakiliki	Ultisol	0-10	14.7	49.5	12.7	15.9	7.2	35.8	4.4	3.00	2.09	10.0	7.5YR 6/4
Lau	Vertisol	0-15	58.2	25.4	3.7	10.8	1.9	16.4	6.1	2.08	1.26	36.5	2.5Y5/7
Benin City	Ultisol	0-15	16.8	3.4	1.2	68.9	9.7	79.8	4.2	3.18	3.33	8.5	7.5TR 4/6
Lafia	Alfisol	0-10	5.2	13.2	7.6	64.0	10.0	81.6	5.2	4.00	0.71	4.5	10YR5 /4
Orlu	Ultisol	10-30	31.3	1.7	3.5	55.5	8.0	67.0	3.9	7.17	0.86	6.0	5YR5/8
Okigwe	Vertisol	0-20	63.2	12.4	7.1	11.9	5.4	24.4	5.8	0.77	4.65	44.0	2.5Y5/2

VFS – very fine sand, FS – fine sand, CS – coarse sand, TS – total sand; ESP – exchangeable sodium percentage, OC – organic carbon, CEC – cation exchange capacity.

Table 2. Exchangeable cations and exchangeable acidity of the soils

Location	Exchangeable cations (Cmol kg^{-1})					Exch. acidity (Cmol kg^{-1})
	Al	Ca	Mg	Na	K	
Jos	BD*	5.8	5.5	0.25	0.43	0.8
Abuja	BD	4.0	2.2	0.28	0.70	0.8
Arochukwu	24.0	0.7	0.8	0.17	0.29	26.0
Ekwegbe	2.8	0.3	BD	0.17	0.08	2.8
Udi	2.0	0.3	BD	0.16	0.06	2.0
Bauchi 1	BD	19.3	5.8	0.40	0.27	0.4
Nsukka 1	3.2	1.9	1.7	0.20	0.33	3.2
Njala	BD	7.0	3.4	0.22	0.25	0.4
Emene	4.8	0.5	3.4	0.15	0.12	5.2
Nsukka 2	4.0	0.3	BD	0.15	0.09	4.8
Atani	3.6	4.6	5.6	0.45	0.52	5.2
Owerri	1.6	0.6	0.8	0.17	0.12	2.0
Calabar	2.8	0.5	BD	0.17	0.06	2.8
Ezilo	2.4	1.3	1.6	0.21	0.19	2.8
Iwo	BD	1.8	1.2	0.17	0.19	0.6
Bauchi 2	BD	6.0	2.5	0.22	0.63	0.4
Abakiliki	0.8	1.8	1.1	0.30	0.39	1.2
Lau	BD	16.7	16.0	0.76	0.43	0.6
Benin City	BD	0.9	0.9	0.27	0.29	1.2
Lafia	BD	1.0	1.0	0.18	0.08	0.4
Orlu	3.2	0.3	BD	0.43	0.08	4.0
Okigwe	BD	31.2	7.0	0.34	0.39	0.4

*Below detection (assumed to be zero).

Table 3. Concentrations of Fe extracted from 1-2 mm aggregates with different dissolution procedures

Location	Fe_B	Fe_C	Fe_{CB}	Fe_{Ox}	Fe_D	Fe_{Ox}/Fe_D
	(mg kg^{-1})			(g kg^{-1})		
Jos	2.8	291	235	3.16	45.24	0.07
Abuja	38.0	1147	1078	0.43	3.76	0.11
Arochukwu	6.5	1129	856	3.46	13.95	0.25
Ekwegbe	2.0	151	105	0.22	15.51	0.01
Udi	0.9	28	8	0.05	1.36	0.04
Bauchi 1	2.8	116	72	1.04	8.19	0.13
Nsukka 1	65.6	1199	1439	1.64	109.32	0.02
Njala	6.9	133	132	0.97	2.94	0.33
Emene	0.9	186	96	0.78	53.12	0.02
Nsukka 2	41.5	710	601	1.47	26.41	0.06
Atani	35.9	1444	1792	6.79	13.80	0.49
Owerri	11.2	256	253	0.37	4.33	0.09
Calabar	22.6	902	851	1.35	4.38	0.31
Ezilo	5.8	342	327	1.81	9.34	0.19
Iwo	2.2	168	137	0.46	12.14	0.07
Bauchi 2	4.1	116	105	0.46	2.94	0.16
Abakiliki	11.9	325	378	1.00	101.74	0.01
Lau	1.4	133	119	0.12	1.86	0.06
Benin City	22.0	448	350	0.92	15.32	0.06
Lafia	5.0	116	58	0.16	2.02	0.08
Orlu	5.0	360	290	0.56	14.55	0.09
Okigwe	7.4	186	253	2.27	46.17	0.37

B – sodium bicarbonate, C – sodium citrate, CB – sodium citrate + sodium bicarbonate, Ox – sodium oxalate, D – Na-dithionite-citrate-bicarbonate.

Table 4. Concentrations of Al (mg kg^{-1}) extracted from 1-2 mm aggregates with different dissolution procedures

Location	Al_B	Al_{Ex}	Al_C	Al_{CB}	Al_{Ox}	Al_D	Al in Fe oxide*
Jos	0.8	16.2	97.2	518.9	1769	4753	0.066
Abuja	BD	3.6	BD	105.7	347	355	0.002
Arochukwu	16.5	412.3	840.6	958.0	1613	3756	0.170
Ekwegbe	BD	47.6	345.0	596.4	876	2976	0.121
Udi	0.8	28.8	BD	105.7	74	246	0.116
Bauchi 1	BD	BD	BD	105.7	456	562	0.015
Nsukka 1	20.5	1231.0	1832.0	2507.0	2544	9768	0.063
Njala	BD	3.6	BD	54.0	290	355	0.032
Emene	BD	116.8	97.2	312.3	622	3685	0.055
Nsukka 2	24.6	98.0	221.1	467.3	933	1969	0.040
Atani	2.1	79.1	97.2	699.7	798	1162	0.049
Owerri	6.0	24.9	BD	234.8	396	1228	0.174
Calabar	0.99	60.2	345.0	570.6	611	1260	0.177
Ezilo	2.1	60.2	BD	260.1	557	1566	0.118
Iwo	0.8	BD	97.2	157.3	483	1282	0.066
Bauchi 2	0.8	3.6	BD	54.0	263	399	0.052
Abakiliki	4.7	41.4	97.2	51.9	544	626	0.001
Lau	0.8	3.6	BD	183.2	709	812	0.056
Benin City	20.5	28.8	221.1	493.1	1011	1991	0.064
Lafia	2.1	BD	BD	54.0	157	224	0.035
Orlu	3.4	106.6	BD	467.3	585	1696	0.074
Okigwe	0.8	2496.0	BD	260.6	1053	4392	0.071

*Al substitution in Fe oxides, Al_{Ex}– exchangable Al, the other explanations as in Table 3.

Table 5. Amount of clay dispersed (%) following different dissolution procedures

Location	H_2O	H_2O_2	Ox	B	C	CB	DCB	PP
Jos	12.3	11.7	50.5	46.8	63.6	62.0	63.8	54.9
Abuja	8.1	12.9	9.7	14.4	18.1	17.4	18.7	16.0
Arochukwu	15.7	27.5	24.9	31.6	36.0	35.0	6.0	31.5
Ekwegbe	9.1	8.6	39.0	42.4	45.5	44.3	47.8	41.1
Udi	2.5	1.0	11.4	12.8	15.3	16.4	16.8	14.8
Bauchi 1	24.1	16.3	34.8	40.3	44.2	42.5	46.9	36.3
Nsukka 1	13.1	16.3	44..1	39.8	58.9	57.9	61.8	52.5
Njala	11.2	14.3	11.3	16.6	20.0	18.7	23.8	17.5
Emene	8.6	6.6	34.9	39.5	43.2	42.5	44.2	37.0
Nsukka 2	11.3	22.6	20.8	25.4	30.3	27.0	27.3	25.9
Atani	13.8	24.6	22.6	30.8	38.3	38.5	41.2	33.3
Owerri	6.9	9.6	5.8	7.5	10.6	12.1	14.5	10.4
Calabar	12.4	14.5	12.9	15.4	16.2	19.6	20.0	18.0
Ezilo	2.7	5.6	3.6	7.1	11.4	11.2	11.7	8.4
Iwo	19.2	21.6	19.2	23.9	27.3	26.6	27.4	22.9
Bauchi 2	9.0	10.6	8.8	13.9	16.6	16.0	16.5	16.1
Abakiliki	8.9	14.6	8.5	13.6	16.7	17.2	18.3	14.7
Lau	38.2	31.5	54.9	60.6	60.0	60.5	60.7	58.2
Benin City	8.2	15.8	9.2	15.9	18.7	16.6	18.7	16.8
Lafia	4.8	5.9	4.9	5.1	7.6	7.3	7.7	5.2
Orlu	18.1	27.9	25.7	29.0	31.6	31.1	31.6	31.3
Okigwe	37.1	44.7	56.9	65.7	66.8	64.1	67.5	63.2

DCB – sodium dithionite-citrate-bicarbonate, PP – sodium pyrophosphate, the other explanations as in Table 3.

Table 6. Relative clay dispersed and concentrations of Fe and Al extracted by different dissolution procedures (DCB = 1)

Extractant	H_2O	H_2O_2	Ox	B	C	CB	PP
Dispersed clay %	0.41	0.51	0.71	0.83	0.96	0.95	0.86
Extracted Fe (%)	-	-	0.07	< 0.01	0.02	0.02	ND[1]
Extracted Al (%)	-	-	0.35	< 0.01	0.09	0.19	ND

[1]ND – not determined, the other explanations as in Table 3.

Table 7. Correlation (r) between various Fe and Al fractions and the amount of clay dispersed by various extractions corrected for water-dispersible clay

Fe									
Fraction	Fe_B	Fe_C	Fe_{CB}	Fe_{Ox}	Fe_D	$(Fe=Al)_D$	$(Fe+Al)_{Ox}$	$(Fe+Al)_{D-Ox}$	Fe_{D-Ox}
r	-0.183	0.152	0.213	0.156	0.478	0.590	0.500	0.498	0.460
SL	ns	ns	ns	ns	*	**	*	*	
Al									
Fraction	Al_B	Al_C	Al_{CB}	Al_{Ox}	Al_D	Al_{D-Ox}	Al_{Ox}-Al_{Ex}		
r	-0.042	0.175	0.583	0.671	0.764	0.713	0.769		
SL	ns	ns	*	**	***	***	***		

*Significant at P=0.05, **significant at P=0.01, ***significant at P = 0.001, ns – not significant, SL – significant level.

The observation that Na-bicarbonate and Na-citrate, which removed only small amounts of Fe and Al, dispersed > 85% of the total clay confirms the results of Pinheiro-Dick and Schwertmann (1996) who attributed this to surface charge modification by specific adsorption of these anions by both the Fe oxides and by the edge surface of clay minerals. Shanmuganathan and Oades (1983) proposed that this increased dispersion was due to charge reversal of the positively charged mineral sites. This adsorption of anions will also increase the net negative charge on the clay particle, resulting in a more extended diffuse double layer, a condition that favours clay dispersion.

The closeness between the mean values of amount of clay dispersed by citrate and citrate-bicarbonate (31.7 vs. 31.1% or 96 vs. 95% of the clay dispersed by DCB, Table 5) shows very clearly that, when mixed with bicarbonate, citrate is the main dispersing agent (Table 5). We did not measure either citrate or bicarbonate adsorption on these soils, but Nagarajah *et al*. (1970), Inskeep (1989) and Zhang *et al*. (1985) reported citrate sorption by synthetic hematite, goethite, kaolinite and gibbsite (for a review see Cornell and Schwertmann, 1996). The high dispersive effect of bicarbonate (Table 5) could also be explained by possible adsorption of bicarbonate which, according to Nagarajah *et al*. (1970) and Kafkaki *et al*. (1988), has strong affinity for Fe and Al oxides.

CONCLUSIONS

1. Aluminium more than Fe oxides act as aggregating agents in these soils.
2. They cannot be removed by extraction only, but also by modifying their surface charge and thereby eliminating their interaction with the silt and clay particles.
3. Organic matter (OM) aggregated most of the soils but acted as disaggregating agents in a few others.

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