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Soil properties influencing water-dispersible clay and silt in an Ultisol in southern Nigeria**

C.A. Igwe* and O.N. Udegbunam

Department of Soil Science, University of Nigeria, Nsukka, Nigeria

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A b s t r a c t. Soil degradation such as soil erosion by water is directly linked to water-dispersible clay (WDC) in the soil. Ten locations in an Ultisol in southeastern Nigeria were sampled for analysis. In each locations 2 samples were collected *viz*; 0-20 and 20-40 cm depth. The aim was to measure the water-dispersible clay and silt and determine the easily measured soil properties that influence clay dispersion in the soils. The soils investigated are porous, high in soil bulk density and low available plant nutrient. Soils are all within the acid range in pH while the soil organic carbon (SOC) contents are low. The exchangeable Ca^{2+} and Mg^{2+} contents of the soils dominated the exchange complex. Values of WDC are between 60 and 120 g kg^{-1} with a mean value of 73 g kg^{-1}. Also water-dispersible silt (WDSi) ranged from 10-190 g kg^{-1} with a mean of 66.5 g kg^{-1}. These results indicate that pH, SOC, exchangeable Ca^{2+}, exchangeable acidity (EA), CEC, sodium adsorption ratio (SAR), the clay and silt contents of these soil are the soil factors that influence the water-dispersible properties of the soils. The modifications of the regular management procedures of the soils through the addition of soil organic matter will check the rate of WDC in the soils and that will accordingly check the high degradation rate of the soils.

K e y w o r d s: microaggregates, erodibility, clay-dispersion, soil organic carbon, sodium adsorption ratio

*Corresponding author's e-mail: charigwe1@hotmail.com

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INTRODUCTION

Soil erosion has been directly linked to the rate and volume of water-dispersible clay in a soil. Potential soil erosion in areas of very high rainfall has been estimated using water-dispersible clay and its indices (Amezketa *et al*., 1996; Igwe, 2001; 2003; 2005; Igwe and Agbatah, 2008; Calero *et al*., 2008). Clay and silt dispersion when soils are submerged in water affect a lot of soil physical and chemical properties such as shrink-swell for soils with very high clay contents, water-retention characteristics and hydraulic conductivity, water pollution, including crusting and sealing (Heathwaite *et al.*, 2005; Seta and Karathanasis, 1996). The fraction of clay that dispersed in water which is known as water-dispersible clay (WDC) has been shown by Kjaergaard *et al*. (2004) as an important property with respect to predicting soil erosion and colloid leaching.

The clay-dispersion ratio (CDR) derived from the clay contents, WDC and the dispersion ratio (DR) being an index from water-dispersible silt and clay and their corresponding total forms have also been successfully used to predict erosion by water. Igwe (2005) remarked that the clay-dispersion ratio and dispersion ratio were found to be good indices for predicting erodibility in some soils of southeastern Nigeria. Earlier, Igwe *et al*. (1995) observed that DR and CDR correlated very significantly with erodibility in the Universal Soil Loss Equation (USLE) model. The CDR and DR do not only relate significantly with soil erosion but other negative features in the soil such as high soil bulk density. Extensive break-down of soils leading to dispersion of the clay results to slaking and clogging of soil pores thereby reducing aeration and affecting a whole lot of metabolic process of soil micro and macro flora and fauna.

A wide range of soil properties can influence the rate at which the soil disperses. Igwe *et al*. (1995) concluded that organic carbon and Fe oxides control flocculation and deflocculation in the soil. Also, in a floodplain soil with hardsetting properties Igwe *et al*. (2006) noted that soil properties which have significant role in WDC formation are the oxides of Fe and Al including exchangeable cations. Panayiotopoulos *et al*. (2004) working on Greek soils indicated that sodium adsorption ratio (SAR) influenced the rate of clay dispersion. In an arid soil in Northern Nigeria, Igwe (2001) pointed out that apart from soil organic carbon, that exchangeable Na^+, exchangeable sodium percentage (ESP) and SAR were found to influence clay dispersion significantly. A number of works exists on clay dispersion in Nigeria but none had dwelt on the soil properties affecting WDC in highly weathered soils of southeastern Nigeria. The objectives of this study are to (i) determine the easily measured physico chemical properties, (ii) measure the water-dispersible clay and silt and (iii) determine the soil properties that influence clay dispersion in the soils.

MATERIALS AND METHODS

The study locations are between latitudes 6°44' and 6°55'N; longitudes 7°11' and 7°28'E. The climate is generally characterized by mean annual rainfall of about 1500 mm and mean evepotranspiration of 1558 mm. The vegetation is derived savanna (Igbozurike, 1975). The underlying geology is meanly weathered sandstones of Ajali formation on between 1-4% slope. The soils have been classified as Typic Paleustult (Soil Survey Staff, 2003). The soils are deep and coarse textured with very low cation exchange capacities especially at the controlled section of their profiles. Jungerius and Levelt (1964) indicated that kaolinite is the major clay mineral of the soils. The soil organic matter content is very low, where as leaching; including soil erosion by water remained the major problems of the soil.

Twenty soil samples from 0-20 and 20-40 cm depth were collected from 10 locations. These soils generally belong to soil order Ultisols (Akamigbo and Igwe, 1990). These soil samples were air dried, sieved through a 2-mm mesh and analyzed in triplicate as described below.

Particle size distribution of the less than 2-mm fine earth fractions was measured by the hydrometer method as described by Gee and Bauder (1986). The clay obtained from particle size analysis with chemical dispersant is regarded as total clay (TC), while clay and silt obtained after particle size analysis using deionised water only are the water-dispersible clay (WDC). Soil pH was measured in a 1:2.5 soil: 0.1 M KCl suspensions. The soil organic carbon was determined by the Walkley and Black method described by (Nelson and Sommers, 1982). Exchangeable cations were determined by the method of Thomas (1982). Exchangeable sodium percentage (ESP) was calculated using the following equation;

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

$$\text{SAR} = \text{Na}^+ / \sqrt{(\text{Ca} + \text{Mg}) / 2}\ . \quad (2)$$

The clay-dispersion indices were calculated as follows;

Dispersion ratio (DR)=(WDSi + WDC)/(Silt + Clay), (3)

Clay dispersion ratio (CDR) = WDC /Clay, (4)

Clay flocculation index (CFI) = (TC – WDC) /Clay. (5)

The higher the CDR and DR the more the ability of the soil to disperse while the higher the CFI the better aggregated the soil. The soil saturated hydraulic conductivity was measured using Klute and Dirksen method (1986). Soil bulk density was determined by the core method (Blake and Hartge, 1986). Total porosity (*Tp*) was obtained from bulk density (ρ_b) values with assumed particle density (ρ_s) of 2.65 Mg m^{-3} as follows,

$$\text{Porosity } (Tp) = 100\ (1 - \rho_b/\rho_s). \quad (6)$$

The soil moisture content at saturation was obtained by Klute (1986) method.

The method of Kemper and Rosenau (1986) was used to separate the water-stable aggregates (WSA). In this method 40 g of < 4.75 mm air-dried soils were put in the topmost of a nest of four sieves of 2, 1, 0.50, 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 s. After wet-sieving, the resistant soil materials on each sieve and the unstable (<0.25 mm) aggregates were quantitatively transferred into beakers, dried in the oven until steady weight is achieved. The percentage ratio of the aggregates in each sieve represents the water-stable aggregates (WSA) of size classes; <2, 2-1, 1-0.50, 0.50-0.25 and <0.25 mm. Aggregate stability was measured as the mean-weight diameter (MWD) of stable aggregates as equation:

$$MWD = \Sigma X_i W_i\ , \quad (7)$$

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, the higher proportion of macro-aggregates in the sample and therefore better stability:

Aggregate stability (AS) = (WSA - Mass of sand)/

Mass of sample - Mass of sand) 100. (8)

Data analysis was performed by correlation and regression analysis of water-dispersible clay indices and other soil properties using the SPSS.10 on Windows computer package. The significant levels of relationships are shown on a matrix.

T a b l e 1. Particle size distribution and textural classification

Soil No.	Clay	Silt	Sand	Textural class
	(g kg^{-1})			
1	70	80	850	S
2	170	80	750	SL
3	70	80	850	S
4	70	100	830	LS
5	70	40	890	S
6	112	58	830	LS
7	72	38	890	S
8	72	38	890	S
9	72	18	910	S
10	132	18	850	LS
11	112	38	850	LS
12	232	58	710	SCL
13	232	78	690	SL
14	272	78	650	SCL
15	112	38	850	LS
16	232	18	750	SCL
17	192	58	750	SL
18	372	78	550	SCL
19	232	138	630	SCL
20	372	178	450	SC
Mean	163.5	66	770.5	
CV %	61	62	16	
LSD $_{(0.05)}$	44.41	18	55	

RESULTS AND DISCUSSION

The particle size distributions of the soils are presented in Table 1. The textural class ranges from sand to sandy clay loam with sand particles dominating other fractions in the soils. Clay fraction is low with average value of 163.5 g kg^{-1} followed by silt fraction which is the least with an average value of 65 g kg^{-1} soil. Soils from this region are known for their very low silt fractions (Igwe, 2001; Igwe, 2004; Igwe *et al*., 1995). Soil bulk density varied in a wide range from 1.03 to 1.88 Mg m^{-3} with very low coefficient of variation of 14%. The total porosity of the soils is low which average moisture content of the soil at saturation is 36.31%. The saturated hydraulic conductivity of the soil is between 21.03-153.50 cm h^{-1} (Table 2). Table 3 presents the major chemical properties of the soils. Soils are all within the acid range while the soil organic carbon (SOC) contents are low. The

T a b l e 2. Chosen physical properties of the investigated soil

Property	Min	Max	Mean	CV %
Bulk density (Mg m^{-3})	1.03	1.88	1.57	14
Total porosity (%)	31.70	50.61	46.75	18
Moisture content at saturation (%)	26.09	51.01	36.31	30
K sat (cm h^{-1})	21.03	153.50	79.17	62.31

T a b l e 3. Chosen chemical properties of the investigated soil

Soil No.	pH_{H_2O}	pH_{KCl}	SOC (g kg^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	EA	CEC	ESP	SAR
				(cmol$_c$ kg^{-1})							
1	6.3	5.6	5.3	0.23	0.62	1.4	1.8	0.4	20.8	1.11	0.26
2	5.5	5.1	3.8	0.14	0.62	1.0	1.0	3.6	11.2	1.25	0.20
3	6.9	5.9	14.6	0.09	0.56	3.8	3.4	0.2	14.0	0.64	0.07
4	6.4	5.9	4.1	0.28	0.68	2.6	1.0	1.4	20.4	1.37	0.30
5	6.3	5.4	5.6	0.09	0.56	2.4	0.6	0.8	14.4	0.63	0.10
6	6.1	5.3	3.8	0.09	0.56	2.0	0.4	1.6	20.0	0.45	0.12
7	6.3	5.5	2.6	0.09	0.56	2.2	0.4	0.4	15.5	0.58	0.11
8	6.2	5.4	1.5	0.05	0.49	2.6	1.2	0.8	4.8	1.04	0.05
9	6.6	6.0	4.5	0.23	0.56	2.0	1.2	0.4	16.8	1.37	0.26
10	6.0	5.0	2.6	0.09	0.68	1.4	1.2	1.2	12.4	0.73	0.11
11	5.9	5.0	6.2	0.09	0.49	1.2	0.4	1.8	17.2	0.52	0.14
12	5.6	5.0	7.3	0.09	0.49	1.2	0.6	2.6	17.6	0.51	0.13
13	5.9	5.4	12.1	0.09	0.56	1.4	0.6	2.8	25.6	0.35	0.13
14	4.8	4.6	8.8	0.09	0.56	1.6	0.2	3.2	16.8	0.54	0.13
15	5.1	4.6	7.0	0.14	0.62	2.0	0.2	1.6	14.0	1.00	0.19
16	5.0	4.8	5.9	0.09	0.94	1.6	1.0	1.6	16.8	0.54	0.11
17	5.7	4.5	9.5	0.14	0.43	0.2	2.0	1.8	30.4	0.46	0.19
18	4.8	4.6	4.4	0.09	0.49	2.0	0.2	2.4	16.8	0.54	0.12
19	4.6	4.2	20.2	0.37	0.49	1.2	0.4	3.6	20.0	1.85	0.59
20	4.6	4.4	7.0	0.28	0.62	0.6	1.0	4.8	31.6	0.89	0.44

exchangeable Ca^{2+} and Mg^{2+} contents of the soils dominated the exchange complex. The exchangeable sodium percentage (ESP) and sodium adsorption ratios of the soils are low thus indicating the low content of exchangeable Na^{+} in the soils. These soils are leached due to the porous nature of the soils and the high rainfall regime of the zone.

Values of water-dispersible clay (WDC) are between 60 and 120 g kg^{-1} with a mean value of 73.00 g kg^{-1} and coefficient of variation (CV) of 22%. Also water-dispersible silt ranged from 10 to 190 g kg^{-1} with a mean of 66.50 g kg^{-1} and a CV of 62% (Table 4). The dispersion ratio are high with values ranging from 0.33-0.90, with an average of 0.68 and 25% CV. At the same time the clay dispersion ratio were also high with values of between 0.15 and 0.80 and 42% CV. Soils with high DR and CDR are known to be weak structurally and can easily erode. Many researchers have used these indices in predicting soil erosion by water (Bajracharya *et al*., 1992; Igwe, 2003; Igwe, 2005; Igwe *et al*., 1995). Bajracharya *et al*. (1992) recommended the use of WDC and CDR in predicting the relative ease of soil to erode in some Ohio soils in the United States of America. It has been successfully applied in some other Nigerian soils not related to the ones being studied presently.

The clay-flocculation index (CFI) is also another index that shows the ability of the soils to resist dispersion in water. The CFI of the soils are low and a direct inverse of CDR. CFI values range from 0.20-0.85 with average value of 0.45 and 51% coefficient of variation. The CFI also is a very good index for predicting soil erodibility and a good microaggregate index. Soils high in CFI are well aggregated and will not easily dispersed in water. Igwe *et al*. (1995) claimed that CFI ranked highest among other micro and macro aggregate indices in predicting potential soil loss in some soils of southeastern Nigeria.

The water-stable aggregate sizes (WSA) <0.25 mm are between 7.96 and 68.6%, an average 31.55% and 42% CV. The mean-weight diameter (MWD) is also between 0.47 and 1.90 mm, a mean of 0.80 mm and a CV of 51%. The aggregate stability (AS) of the soils ranges from 3.61 to 45.44% with an average value of 21.55% and 66% CV (Table 5). All these are indices of aggregation which control the breakdown of aggregates in water. Levy and Miller (1997) indicated that breakdown of unstable aggregates results in the collapse of soil pores and production of finer particles and microaggregates. According to Six *et al*. (2000) MWD is an index of aggregate stability that characterizes the structure of the whole soil by integrating the aggregate size class distribution into one number. MWD and WSA have some times correlated highly with water-dispersible clay and often used to predict soil erosion (Amezketa *et al*., 1996; Dexter and Czyż, 2000).

T a b l e 4. Water-dispersible clay and silt, dispersion ratio (DR), clay-dispersion ratio (CDR) and clay-flocculation index

Soil No.	WDC (g kg^{-1})	WDSi	DR	CDR	CFI
1	60	80	0.90	0.80	0.21
2	80	90	0.68	0.45	0.55
3	60	50	0.73	0.80	0.27
4	60	70	0.77	0.80	0.20
5	60	30	0.82	0.80	0.20
6	80	70	0.88	0.69	0.31
7	60	30	0.82	0.80	0.20
8	60	30	0.82	0.80	0.20
9	60	10	0.78	0.80	0.20
10	80	30	0.73	0.59	0.41
11	80	50	0.87	0.69	0.31
12	80	70	0.52	0.33	0.67
13	80	130	0.68	0.33	0.67
14	60	90	0.43	0.21	0.79
15	60	30	0.60	0.51	0.49
16	80	50	0.52	0.33	0.67
17	80	70	0.60	0.40	0.60
18	60	90	0.33	0.15	0.85
19	100	70	0.46	0.42	0.58
20	120	190	0.56	0.32	0.68
Mean	73.0	66.5	0.68	0.55	0.45
CV %	22	62	25	42	51
LSD $_{(0.05)}$	7.2	18.3	0.08	0.10	0.10

T a b l e 5. Water-stable aggregate <0.25 mm, mean-weight diameter (MWD) and aggregate stability (AS)

Soil No.	WSA <0.25 mm (%)	MWD (mm)	AS (%)
1	32.08	0.51	4.90
2	33.76	0.47	6.63
3	17.44	1.01	43.32
4	30.00	0.51	5.63
5	19.44	1.23	45.11
6	32.60	0.55	7.75
7	23.84	0.77	30.99
8	24.64	0.51	3.61
9	25.80	0.62	12.59
10	24.80	0.52	9.28
11	28.40	0.55	14.11
12	33.00	0.50	14.05
13	68.60	0.65	33.27
14	32.44	0.89	28.66
15	7.96	1.90	39.87
16	26.20	0.57	13.03
17	41.28	1.76	45.44
18	35.52	0.64	23.72
19	59.92	0.65	24.00
20	33.28	1.10	25.07
Mean	31.55	0.80	21.55
CV %	42	51	66
LSD$_{(0.05)}$	6.00	0.18	6.42

T a b l e 6. Correlation coefficients matrix of water-dispersible clay (WDC) factors and soil properties

	WDC	WDSi	DR	CDR	CFI	WSA <0.25 mm	MWD	AS
pH KCl	-0.58*	-0.38	0.72*	0.77*	-0.76*	-0.26	-0.35	-0.31
SOC	0.34	0.25	-0.50*	-0.29	0.48*	0.53*	0.52*	0.65*
Na^+	0.41	0.30	-0.11	0.03	-0.04	0.31	-0.01	-0.05
K^+	0.05	-0.02	-0.01	-0.03	0.02	-0.26	-0.17	-0.29
Ca^{2+}	-0.66*	-0.47*	0.30	0.56*	-0.53*	-0.68*	-0.10	-0.05
Mg^{2+}	-0.13	-0.07	0.26	0.36	-0.32	-0.17	0.11	-0.22
EA	0.74*	0.79*	-0.66*	-0.77*	0.76*	0.76*	0.01	0.11
CEC	0.56*	0.68*	0.21	-0.36	0.36	0.52*	0.29	0.11
ESP	0.09	-0.10	0.03	0.26	-0.27	0.07	-0.16	-0.40
SAR	0.59*	0.40	-0.25	-0.15	0.13	0.42	0.03	-0.13
Clay	0.58*	0.60*	-0.81*	-0.97*	0.95*	0.67*	0.13	0.12
Silt	0.20	0.81*	-0.32	-0.31	0.33	0.61*	0.04	0.08

Table 6 shows the correlation coefficient matrix of water-dispersible fraction indices and soil properties. Water-dispersible clay (WDC) negatively correlated significantly with pH in KCl and exchangeable Ca^{2+}. WDC also correlated positively and significantly with exchangeable acidity (EA), CEC, SAR and clay content of the soil, however, the regression analysis with WSA<0.25 mm indicate that WSA < 0.25 mm could only explain 22% of variation in WDC (Fig. 1). Water-dispersible silt (WDSi) negatively correlated significantly with exchangeable Ca^{2+} (r= -0.47), but it had significant positive correlation with EA, CEC, clay and silt contents. Also WSA<0.25 mm explained only 29% of the variation in WDSi (Fig. 2). It is only pH in KCl that positively correlated significantly with DR (r = 0.72) while negative significant correlations occurred between DR and the following soil properties; soil organic carbon (SOC), EA and clay content. The relationship between SOC and DR is expected. Although the SOC in the soils is low, it is expected that higher values of SOC in the soil will reduce the DR values and perhaps reduce the rate of microaggregate disintegration especially during tropical rainfalls.

Clay-dispersion ratio (CDR) as in DR is moderate to high. However, CDR positively correlated significantly with pH in KCl and exchangeable Ca^{2+} (r = 0.77 and 0.56, respectively), but negatively correlated significantly with EA (r = -0.77) and clay content (r = -0.97). At the same time WSA <0.25 mm could only explain 20% of the total variation in CDR and the relationship is a negative one (Fig. 3). The CFI negatively correlated significantly with pH in KCl (r = -0.76) and exchangeable Ca^{2+} (r = -0.53). CFI also correlated significantly and positively with SOC (r = 0.48), EA (r = 0. 76) and clay content (r = 0.95). Also 19% of CFI was explained

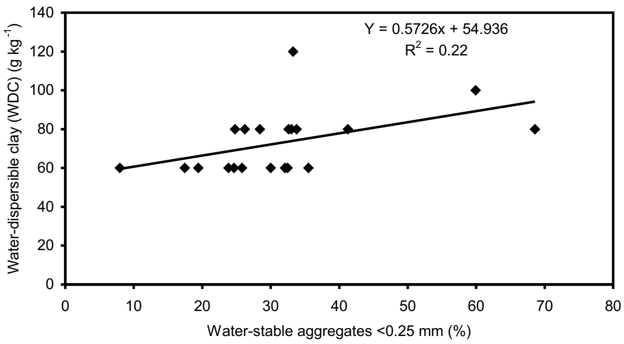

Fig. 1. Relationship between water-dispersible clay and WSA <0.25 mm.

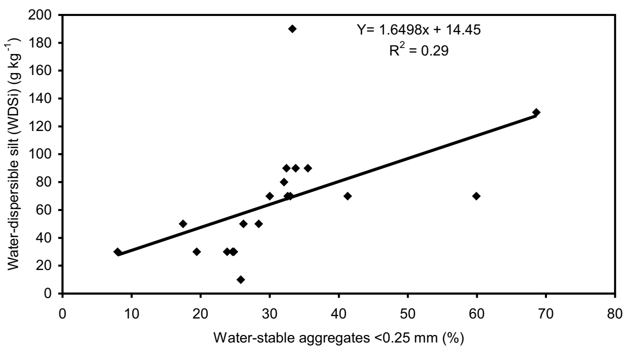

Fig. 2. Relationship between water-dispersible silt and WSA <0.25 mm.

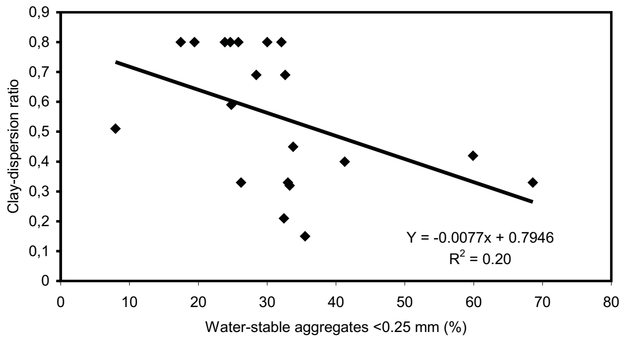

Fig. 3. Relationship between clay-dispersion ratio and WSA <0.25 mm.

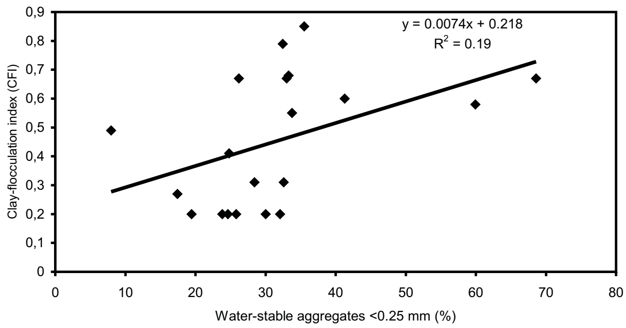

Fig. 4. Relationship between clay-flocculation index and WSA < 0.25 mm.

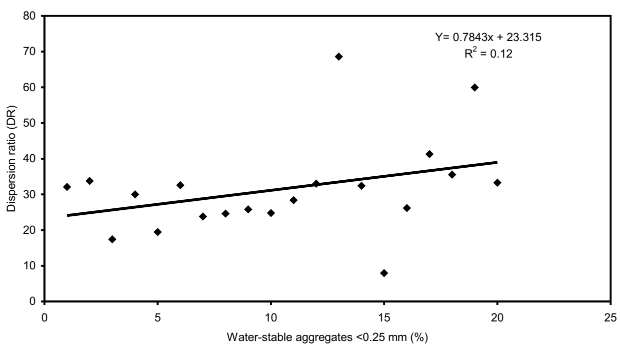

Fig. 5. Relationship between dispersion ratio and WSA < 0.25 mm.

by WSA <0.25 mm aggregate size (Fig. 4). Relationship between dispersion ratio and WSA < 0.25 mm is shown in Fig. 5. WSA size <0.25 mm correlated significantly and positively with SOC, EA, CEC, clay and silt contents correlated negatively with exchangeable Ca^{2+} (Table 6). The role of Ca^{2+} in the stability of these soils has been high-lighted recently (Dontsova and Norton, 2001; Yilmaz *et al*., 2005). They showed that Ca^{2+} ions were more effective than Mg^{2+} ions in the aggregation and stability of clays. Nonetheless, WSA <0.25 mm explained only about 12% variation in CDR. The mean-weight diameter (MWD) and aggregate stability (AS) correlated positively and significantly with SOC (r = 0.52, 0.65), respectively. This shows that SOC is a soil factor that contributes significantly in the aggregation of the soils. From these results we can infer the following; that pH, SOC, exchangeable Ca^{2+}, EA, CEC, SAR, the clay and silt contents of the soil are the soil factors that influence the water-dispersible properties of the soils.

CONCLUSIONS

1. The soils investigated indicate that the soils are moderate to high in soil bulk density and low available plant nutrient. Soils are all within the acid range while the soil organic carbon (SOC) contents are low. The exchangeable Ca^{2+} and Mg^{2+} contents of the soils dominated the exchange complex.

2. Water-dispersible clay (WDC) and water-dispersible silt (WDSi) are low to moderate. Low pH, SOC, Ca^{2+}, EA and CEC reduce the WDC while SAR, the low clay and silt contents of the soil are the soil factors that contribute to the low water-dispersible properties of the soils.

3. The modifications of the regular management procedures of the soils through organic matter incorporation will check the rate of WDC in the soils and that will in turn check the high degradation rate of the soils.

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