DOI: https://dx.doi.org/10.4314/gjass.v23i1.5

GLOBAL JOURNAL OF AGRICULTURAL SCIENCES VOL. 23, 2024: 49-60
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AGGREGATE STABILITY AND THE INFLUENCE OF SODIUM CHLORIDE ON DISPERSION OF SANDY CLAY LOAM SOILS IN SOUTHEASTERN NIGERIA

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(Received 22 March 2024; Revision Accepted 9 May 2024)

ABSTRACT

Soil dispersion is an important process that should be considered in irrigation and ferti-irrigation of agricultural soils. Triplicate topsoil samples from five different locations in southeastern Nigeria were characterized and examined for aggregate stability and clay dispersion potential by leaching with different NaCl concentrations. The results showed that the soils were mainly sandy clay loam (SCL), slightly acid to neutral pH and low in soil organic carbon (SOC), total nitrogen, and exchangeable cations. The soils had lower proportions of > 1.00 mm water-stable aggregates (WSA) compared to the higher proportions of < 1.00 mm WSA. Percent aggregate stability (AS) of the soils averaged 36.25 % and was significantly positively correlated with SOC (r = 0.55*) and Na^+ content (r = 0.58*). Furthermore, Na^+ correlated positively with the 1.00-2.00 mm WSA (r = 0.67*), but negatively with the < 0.25 mm WSA fraction (r = -0.68**), while the opposite was true for the correlation of clay and these WSA fractions (r = -0.57*; 0.60*, respectively), indicating the minor role of clay in aggregate formation. The soils were less dispersible in water than in NaCl solutions, resulting in a higher clay content, which increased with increasing NaCl concentration. However, the clay dispersion ratio of the soils was moderately low and showed a decreasing trend with increasing NaCl concentration, and indicating the NaCl dispersion potential at the lowest 25 S m^{-1}. Thus, the clay dispersion potential of Na^+ at ≤ 50 S m^{-1} relates to the reduced stability of < 0.25 mm microaggregates, while the clay flocculation potential of Na^+ at ≥ 75 S m^{-1} accounts for the 1.00-2.00 mm macro aggregation and aggregate stability of the soils. Therefore, the structural stability of SCL soils in the humid tropics depends on SOC and Na^+ content, including the dispersive and flocculative influence of Na^+ on clay minerals.

KEYWORDS: Clay dispersion, clay flocculation, clay dispersion ratio, water-stable aggregates, aggregate stability, macroaggregates, microaggregates, exchangeable sodium.

INTRODUCTION

Clayey soils have unique properties that affect nutrient availability, water retention, aggregate stability and crop productivity. Clayey soils are characterized by their high plasticity, low permeability, and high nutrient retention capacity (Abdu *et al*., 2016). The aggregate stability of the clayey soils in water is an important factor affecting water infiltration, soil dispersion and soil erosion.

The aggregates of many soils disintegrate rapidly under the influence of raindrops. This is followed by a physiochemical dispersion of clay particles within the aggregates. The dispersed clay particles may form a surface seal or move downwards in the soil profile, where they clog the water-conducting pores (Igwe, 2003). Both processes restricts rapid infiltration of water into the soil and/or lowers the saturated hydraulic conductivity in the soil profile, leading to surface run-off and erosion

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(Mbagwu and Abeh, 2000).

Soil aggregation is affected by pH, clay minerals, exchangeable Na^+, type and concentration of electrolytes, organic matter (OM), and Fe and Al oxides (Mbagwu and Abeh, 2000). However, in tropical weathered soils, clay and oxides of Fe and Al are the most important and well-known aggregate stabilizing agents (Igwe *et al*., 2013) compared to SOM, which plays a partial role in aggregate formation in highly weathered soils (Six *et al*., 1999; Denef *et al*., 2002; Okolo *et al*., 2020). In these soils, the dominance of 1:1 clay mineral (e.g., kaolinite) and their electrostatic interaction with other aggregating agents (such as Fe_2O_3 and Al_2O_3 and SOM) can also contribute to either aggregate formation or soil dispersion (Jungerius and Levelt, 1964; Denef *et al*., 2002; Igwe *et al*., 2005). Dispersive soils are clay soils that usually have a high content of Na^+ in their adsorption cations (Abbaslou *et al*., 2020). When a saline (Na) soil comes into contact with rainwater, the water molecules between the clay platelets cause the clay to dislodge and the platelets to break away from the soil aggregate, resulting in dispersion phenomenon (Singh *et al*., 2018). Abbaslou *et al*. (2020) reported that soil dispersion is directly related to the diffuse double layer and electrostatic forces, while the strength parameters of soil mainly depend on cementation and binding of soil particles together. Nasser and James (2008) showed that the degree of flocculation of kaolinite-NaCl dispersions changes significantly with ionic strength and pH. Accordingly, at low ionic strength, an increase in pH results in a collapse of the floc structure and an increase in ionic strength results in weak, randomly structured flocs.

Based on the relative dispersivity and flocculation capacity of exchangeable bases (Na, K, Mg and Ca), Rengasamy *et al*. (2016) proposed the concept of "net dispersive charge" for determining the clay dispersivity of a soil. Igwe and Okebalama (2006) used the clay dispersion ratio indices to show that different concentrations of KCl rather than NaCl significantly affect clay dispersion. Although NaCl can cause dispersion in soil (Ward and Carter, 2004), Abbaslou *et al*. (2020) found that the dispersion potential of clays in Na^+ is related to a decrease in cation exchange capacity (CEC), specific surface area, and plastic index. Clay dispersion depends on several soil properties, such as soil texture, soil pH, ionic strength, sodium adsorption ratio, electrical conductivity, clay type, organic matter content, ratio of chloride ions to charge of sulfate ions in the soil water and the ratio of the charge of Na^+ to the sum of the charges of Na^+ and Ca^{2+} in the soil water (Prior *et al*., 1992; Guarnieri *et al*., 2005; Nasser and James, 2008).

Dispersive soils are problematic soils that exhibit high deflocculation in water, low erosion resistance and low permeability, resulting in serious problems in soil structure (aggregate stabilization), pore collapse, reduced infiltration rate and increased surface water runoff (Abbaslou *et al*., 2016; Umesh *et al*., 2011; Singh *et al*., 2018).

Soil structure, particularly the amount and stability of aggregates, is critical for soil water and nutrient management. Therefore, it is important to investigate these functions, especially in soils prone to clay dispersion and aggregate collapse. The disintegration of clay aggregates and mobilisation of OM is typical of saline soils. Although most soils in the humid tropics are highly leached and currently non-saline, careless or continuous use of contaminated wastewater from sewage and industrial byproducts to irrigate agriculture soils could lead to soil salinization (Igwe and Okebalama, 2006; Joshi *et al*., 2000). Irrigation with nutrient-rich wastewater helps farmers to increase their yield potential and reduce the cost of additional fertilizers. Chhonkar *et al*. (2000) reported a significant increase in Na^+ and available N, P and K following the use of industrial wastewater for irrigation of soils. However, irrigation with untreated wastewater leads to salinization and deterioration of the soil structure due to high concentrations of Na, heavy metals and trace elements, which has a negative impact on the soil and plants (Hussain *et al*. 2002).

The dispersion of clays in soils has been linked to the quality of irrigation water (Chaudhari 2001; Gharaibeh *et al*., 2016; Yan *et al*., 2023). Wastewater irrigation serves as a potential source of nutrients for agriculture, but can pose significant ecological risks to soils, plants, water, animals and humans (McCornick *et al*. 2004; Chauhan *et al*., 2020). Due to the presence of chloride and Na in irrigation water and wastewater, parameters related to NaCl have been used to study the effects of Na^+ and electrical conductivity (EC) of soil solution on the CDR of soils (Igwe and Okebalama, 2006; Yan *et al*., 2023). The deleterious effects of NaCl on clay dispersion have been shown to be greater in heavier soils (Prior *et al*., 1992). Other studies have characterised and identified some dispersive soils regardless of differences in soil textural (Nasser and James, 2008, Abbaslou *et al*., 2020; Umesh *et al*., 2011). Information about the stability of soil structure as influenced by Na^+ concentrations, can be useful for farmers and agricultural experts to make informed decisions on irrigation water quality and ferti-irrigation practices to combat low crop productivity and soil degradation. We investigated five clayey-textured soils in some parts of the southern eastern part of Nigeria with the aim of characterizing their physiochemical properties, describing their aggregate stability and the effect of different NaCl ions concentrations on clay dispersion.

MATERIALS AND METHODS

Location of study

Five locations within the South-eastern Nigeria were considered in this study. The respective locations are: Okigwe in Imo State, and Udi, Obollo-afor, Obukpa, and Awgu, in Enugu State. The study area lies between latitudes 5°49' and 6°54' N and longitudes 7°21' and 7°28' E, and are characterized by a distinct wet and dry season. The wet season usually lasts from April to October, with peak rainfall occurring between June and September. The dry season spans from November to March. The average annual rainfall and temperature are between 1600-1800 mm and 26-28 °C, respectively. The geology of the locations consists mainly shale and weathered sandstone (Igwe and Okebalama, 2006), while the topographic characteristics comprise flat plains, undulating terrains, and isolated hills, displaying gentle and slightly steeper slopes. The study area falls within the tropical rainforest (Okigwe) and the derived savanna zone (Udi, Obollo-afor, Obukpa and Awgu). The local farmers cultivate a variety of crops including cassava (*Manihot esculenta*), yam (*Dioscorea spp.*), maize (*Zea mays*), and vegetables such as okra (*Abelmoschus esculentus*) and pumpkin (*Cucurbita spp.*) and fluted pumpkin (*Telfairia occidentalis*) (Odiong and Nwosu, 2019; Onyekwelu *et al*., 2020). These crops serve as essential sources of food and income for the local population and also contribute to the local economy and food security.

Soil sampling and laboratory analysis

At each of the five locations, topsoil samples (0-30 cm) were randomly taken at 3 different points with a spade and core samplers from agricultural fallow lands that had not been cultivated for about 3 years. This was to ensure that the soils were not under recent agricultural fertilization influence. The bulk soil samples were air-dried under laboratory condition, divided into two parts and sieved through a 2.00 mm and 4.75 mm mesh. The samples were then analyzed in triplicate according to the standard laboratory procedures described below.

Particle size analysis

Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986) both in 0.1 N NaOH chemical dispersant (for total clay content) and in deionised water (for water-dispersible clay, WDC). The bulk density was determined by the core method and calculated using the formula in equation 1, while the total porosity was determined by equation 2.

$$\text{Bulk density} = \frac{\text{Dry soil weight (g)}}{\text{Volume of soil core (cm}^3)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\text{Soil porosity} = 1 - \frac{\text{Bulk density(g cm}^3)}{\text{particle density (g cm}^3)} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Soil aggregate size separation was performed on the 4.75 mm sieved soils by wet sieving method (Cambardella and Elliot 1994). A nest of four sieves (2 mm, 1 mm, 0.5 mm, 0.25 mm) were used to obtain five fractions of water-stable aggregates (WSA); > 2.00 mm, 1.00–2.00 mm, 0.50–1.00 mm, 0.25–0.50 mm, and < 0.25 mm. These fractions were weighed and expressed in a percentage (%) of the initial sample weight (equation 2). The MWD of the water-stable aggregate fractions was also calculated as shown in equation 3.

$$\text{WSA (\%)} = \frac{\text{Mi}}{\text{weight of soil (g)}} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\text{MWD} = \sum_{i=1}^{n} \text{XiWi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where, WSA = water-stable aggregate of each size fraction,
Mi = weight of each aggregate size fraction (g),
MWD = mean weight diameter of aggregates (mm),
Xi = mean diameter of each size fraction (mm), and
Wi = proportion of the total sample weight occurring in the corresponding size fraction.

The soil pH was measured in 1:2.5 suspension of soil in distilled water using a pH metre. The soil EC was measured in a 1:5 w/v soil to water suspension using an EC meter. Soil organic carbon (OC) was determined by the Walkley-Black wet oxidation method (Nelson and Sommers, 1983), while OM was obtained by multiplying the % OC with the conventional van Bemmelen factor of 1.724. Total nitrogen was by the Kjeldahl distillation method (Bremner, 1996). Soil available phosphorus was assessed by Bray II bicarbonate extraction method (Olsen and Sommers, 1982). The exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were extracted in ammonium acetate pH 7 (Thomas, 1982) and measured by the flame photometer (for Na^+ and K^+), and the complexometric EDTA titration (for Ca^{2+} and Mg^{2+}). The exchangeable acidity (H^+ and Al^{3+}) were determined using extracts from 1 N KCl (McLean, 1982). The cation exchange capacity (CEC) was determined by the NH_4OAC method. The treatment of soils NaCl solution was employed to simulate and assess the effect of saline-alkali (Na) irrigation water. The soils were weighed into a filter-fitted funnel and leached with NaCl solutions at 0, 25, 50, 75, 100 S m^{-1} electrical conductivity (EC). The clay dispersion ratio (CDR) was calculated as follows:

$$\text{Clay dispersion ratio (CDR)} = \frac{\text{WDC}}{\text{Clay obtained from NaCl treatment}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where, WDC = water dispersible clay.

$$\text{Clay dispersion index (CDI)} = \frac{\text{WDC}}{\text{Total clay}} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Statistical analysis

Descriptive statistics (means and coefficient of variation, CV) were performed on the collected data to compare the treatment means. According to Wilding *et al*. (1994), a CV of < 15 % = low variation, 15 to ≤ 35 % = moderate variation, and > 35 % = high variation. In addition, the data were subjected to one-way analysis of variance in CRD using GenStat (11th edition) for PC/Windows. The test for the significance of treatment means was at 5 % probability, while the mean separation was by least significant difference (LSD). Correlation analysis was carried out to evaluate the degree of relationship between soil physiochemical properties and aggregate stability indices.

RESULTS

Physical properties of the soils

The particle size distribution of the soils (Table 1) showed a predominance of sand (64 %) and a low content of silt (10 %). These soil separates, including the clay content (26 %) were statistically similar across the locations. Accordingly, the soils were mainly sandy clay loam in texture. The bulk density and the total porosity of the soils averaged 1.58 g cm^{-3} with a CV of 0.42 %, and 39.32 % with a CV of 10.41 %, respectively.

Table 1: Soil particle size distribution and some physical properties of the study locations

LOCATION	Clay	Silt	Sand	Textural class	Bulk density ($g\ cm^{-3}$)	Soil porosity (%)
	---------------- (%) ----------------					
OBOLLO	27.90	10.00	62.10	SCL	1.62	38.87
OBUKPA	25.87	11.33	62.80	SCL	1.54	41.89
AWGU	22.53	8.67	68.80	SCL	1.79	32.45
OKIGWE	27.87	9.33	62.80	SCL	1.57	40.76
UDI	27.17	9.33	63.50	SCL	1.52	42.64
MEAN	26.27	9.73	64.00		1.58	39.32
CV (%)	18.84	29.95	8.74		0.42	10.42

SCL = sandy clay loam; CV = coefficient of variation

Chemical properties of the soils

Some selected chemical properties of the soils presented in Table 2 showed that the soils had a pH range of 6.40 to 6.90, with a mean of 6.71. The soils had a low content of SOC, TN and exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, H^{+}, Al^{3+}), and a percentage base saturation of between 21 to 35 %. The CEC of the soils averaged 6.48 $cmol_c\ kg^{-1}$ with a CV of 15.16 %, indicating little variation.

Table 2: Chemical properties of the soils of the study locations

Location	pH H_2O	SOC (%)	Total N (g kg^{-1})	Avail. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	Na^+	K^+	Al^{3+}	H^+	CEC	BS (%)
					------------------------------- ($cmol_c$ kg^{-1}) -------------------------------							
Obollo	6.80	0.31	0.05	0.12	0.67	0.67	0.06	0.17	0.45	1.15	6.27	29.00
Obukpa	6.40	0.26	0.04	0.08	1.07	0.40	0.03	0.09	0.40	2.01	5.87	35.00
Awgu	6.90	0.46	0.07	0.10	0.60	0.87	0.50	0.06	0.47	1.48	6.40	32.00
Okigwe	6.83	0.36	0.05	0.08	1.07	0.40	0.60	0.12	0.44	0.40	7.60	21.00
Udi	6.60	0.27	0.02	0.08	0.47	0.73	0.37	0.10	0.40	1.66	6.27	31.00
Mean	6.71	0.33	0.05	0.09	0.77	0.61	0.05	0.11	1.34	0.43	6.48	29.60
CV (%)	4.52	39.84	39.49	19.44	44.65	65.76	54.29	42.62	45.56	7.21	15.16	17.81

SOC = soil organic carbon; CEC = cation exchange capacity; BS = base saturation; CV = coefficient of variation;
LSD = least significant difference at 5 % probability level.

Aggregate stability of the soils in water

In general, the proportions of > 1.00 mm WSA were lower than the proportions of < 1.00 mm WSA (Table 3). There was greater variation (CV of > 40 %) in the > 1.00 mm water-stable macro-aggregates compared to the other aggregate size fractions (< 1.00 mm), which had a CV of ≤ 33.41 %. As such, the proportion of the > 2.00 mm water-stable aggregates in the Obukpa, Awgu and Okigwe soils was relatively high, while the Udi soil had the least. The < 0.25 mm clay and silt fraction ranged from 19.15 to 27.52 % with a CV of 33.41 %. On average, the soils had a mean weight diameter of 1.00 and a percentage aggregate stability (AS) between 24.10 and 44.50 % with an average of 36.25 %.

Table 3: Aggregate size distribution and aggregate stability of the soils of the study locations

	Water-stable aggregates (mm)						
Location	> 2.00	1.00-2.00	0.05-1.00	0.25-0.05	< 0.25	MWD	Aggregate stability
	------------------------------- (%) -------------------------------						(%)
Obollor	11.71	19.88	20.44	28.83	19.15	1.31	43.33
Obukpa	15.76	10.67	18.63	31.11	23.84	0.97	33.60
Awgu	15.43	17.40	23.24	19.73	24.20	1.06	44.50
Okigwe	15.65	13.67	19.09	24.07	27.52	0.65	24.10
Udi	3.25	12.11	28.17	32.25	24.21	1.00	35.70
Mean	12.36	14.74	21.92	27.20	23.78	1.00	36.25
CV (%)	77.86	40.33	32.33	26.23	33.41	40.48	38.91

MWD = mean weight diameter; CV = coefficient of variation

Soil dispersion with sodium chloride treatment

The effect of deionized water and the different concentrations of NaCl solution on the dispersion of the soils (Table 3) resulted in mean values of 6.77 % clay with deionized water, and 15.48, 16.77, 17.97, and 19.74 % clay content with NaCl at 25, 50, 75 and 100 S m^{-1} EC, respectively. Obviously, the comparatively high values of the clay content obtained with the NaCl treatment increased correspondingly with increased salt concentrations. The NaCl treatments had CV values ranging from 16.0 to 26.5, while the deionized water treatment had a CV of 7.0.

The clay dispersion ratio (CDR) of the soils (Table 4) ranged from 0.31 to 0.56, and showed a decreasing trend with increasing concentration of NaCl treatment. Accordingly, the highest mean CDR of the soils was obtained at 25 S m^{-1} while the least CDR was achieved at 100 S m^{-1}. Although there were no significant differences in the treatment means, the CV for the NaCl dispersed soils at 25 S m^{-1} was 23.65 %, while that at 50, 75 and 100 S m^{-1} was about 18.52 %.

Table 4: Effect of sodium chloride treatment on clay dispersion of the soils of the study locations

		NaCl treatment (S m^{-1})			
Location	Deionized H_2O	25	50	75	100
	-------------------------------- Clay content (%) --------------------------------				
Obollor	6.33	14.67	15.00	16.33	17.72
Obukpa	7.17	16.08	17.67	18.83	22.50
Awgu	6.83	12.30	14.83	16.17	18.50
Okigwe	6.50	19.17	20.00	20.67	21.67
Udi	7.00	15.18	16.33	17.83	18.33
Mean	6.77	15.48	16.77	17.97	19.74
CV (%)	17.41	21.59	18.03	19.21	17.76

CV = coefficient of variation

Table 5: Clay dispersion ratio of the soils relative to sodium chloride treatments

	NaCl treatment (S m^{-1})			
Location	25	50	75	100
Obollor	0.45	0.43	0.39	0.36
Obukpa	0.45	0.40	0.39	0.33
Awgu	0.56	0.46	0.42	0.37
Okigwe	0.34	0.33	0.32	0.31
Udi	0.47	0.43	0.39	0.39
Mean	0.45	0.41	0.38	0.35
CV (%)	23.65	18.73	18.00	18.83

CV = coefficient of variation

Table 6: Correlation coefficient (*r*) of some soil properties and water-stable aggregates and aggregate stability index

Dependent variable	Water stable aggregates (mm)					Aggregate stability
	> 2.00	1.00-2.00	0.50-1.00	0.25-0.50	< 0.25	
	-- *r* --					
Clay	-0.18	-0.57*	-0.01	0.04	0.60*	-0.49
Silt	-0.22	-0.06	0.14	0.19	0.02	-0.23
Soil pH	-0.20	0.02	´0.16	-0.19	0.25	-0.14
SOC	0.42	0.53*	-0.05	-0.63*	-0.27	0.55*
Ca	0.46	-0.12	-0.34	-0.13	-0.04	0.19
Mg	-0.23	0.43	0.19	0.20	-0.38	0.13
Na	0.24	0.68**	0.12	-0.23	-0.68**	0.58*
K	0.29	0.19	-0.48	-0.08	-0.02	0.16

Relationship between some soil properties and aggregate stability indices of the soils

The correlation between some soil physiochemical properties and water-stable aggregates indicated that clay content correlated significantly with 1.00-2.00 mm (*r* = -0.57*) and < 0.25 mm WSA (*r* = 0.60*) (Table 6). The SOC showed a negative correlation with the 0.25-0.05 WSA (*r* = -0.63*) and a positive relationship with the 1.00-2.00 mm WSA (*r* = 0.53*) and the AS (*r* = 0.55*). The soil exchangeable Na^+ also correlated positively with the AS (*r* = 0.58*) and the 1.00 - 2.00 mm WSA (*r* = 0.67**), but had a negative correlation with the < 0.25 mm WSA fraction (*r* = -0.68**).

DISCUSSION

The study soils had a particle size distribution that is typical of highly weathered soils within the transition zone of the tropical rainforest and the derived savanna (Igwe *et al*., 2013; Okebalama *et al*., 2017). All the soils contained similar amounts of the primary soil separates. The clay content of the soil (27 %) is quite substantial and can affect the dispersion/flocculation processes. The low silt content of the soils has been similarly reported in Igwe *et al*. (1995) and Okebalama *et al*. (2022). The comparatively high total sand content could be due to sandstone parent material of sedimentary origin (Akamigbo and Asadu, 1983). Even though the sand content is not directly vital for clay dispersion however, it can define soil porosity, in addition to the aeration status of the soil, and therefore influence water movement via infiltration and surface runoff. Accordingly, these soils with about 1.58 g cm^{-3} bulk density and 39 % porosity could be characterized as having a good drainage.

The chemical characteristics of the soils indicate a slightly acid to neutral pH status and a low content of SOC and TN, including the exchangeable cations. Similar results were reported for most soils in southeastern Nigeria (Igwe and Okebalama, 2006; Igwe and Agbatah, 2008), except for the higher soil pH. The near neutral pH value of the soils, attributable to the low concentrations of Al^{3+} and H^+, suggests that continuous irrigation with saline water could lead to salt deposition in soils with low buffering capacity. The low levels of the major nutrients is an indication that the soils were depleted of nutrients and probably might not meet the nutritional needs of crops unless co-opting soil fertility management measures. The high temperature and rainfall regime in the region contribute to high SOM mineralization, severe leaching and erosion/runoff due to landscape aspect. All these phenomena result in loss of SOC and leaching of nutrients, both of which are known to participate in soil aggregate formation. This suggests that the low OM content, which is a consequence of the sand texture, may affect soil aggregation.

The lower proportions of > 1.00 mm WSA indicate a high aggregate stability of > 1.00 mm in water, which is consistent with the reports of Boix-Fayos *et al*. (2001) and Okebalama *et al*. (2022). This observation could be due to the non-aggregating role of clay and the low SOM content of the soils. It is surprising that clay had a negative correlation with the macroaggregates, which contradicts the report that clay is one of the most important aggregate stabilizing agents in tropical weathered soils (Igwe *et al*., 2013). The positive relationship between clay and the < 0.25 mm WSA shows the minor role of clay in aggregate formation in the soils. However, the correlation of the SOC content with the 1.00-2.00 WSA, < 0.25 mm WSA and the AS indicates the contribution of SOC to the formation and stability of macroaggregates through the aggregation of the 0.25-0.50 mm WSA.

Hence, the higher the SOC content, the higher the structural stability of the soils. Also, the soil Na^+ had a direct relationship with the AS and the 1.00-2.00 mm WSA, but correlated negatively with the < 0.25 mm WSA. Exchangeable Na has the ability to aggregate or disperse the soil, depending on its threshold concentration, net dispersive charge, and the ratio in which it occurs with other aggregating agents in the soil (Igwe and Okebalama, 2006; Nasser and James, 2008); Rengasamy *et al*., 2016). In this study, our results show that increasing the Na^+ concentration increases the stability of the 1.00-2.00 mm macroaggregates, but decreases that of < 0.25 mm microaggregates, which includes silt and clay. The lower stability of this aggregate fraction due to increased Na^+ indicates a higher dispersivity of clay. This result indirectly confirms the increasing effect of Na^+ treatment on clay dispersion of the soils (Table 4). Compared to the other soils, the Udi soil had a very high > 2.00 mm aggregate instability in water. The increase in the proportion of the < 0.50 mm micro-aggregates resulted from the disintegration of > 1.00 mm macro-aggregates possibly due to the effect of the low SOM content of the soil (Igwe and Udegbunam, 2008). Acid soil pH and low content of SOC are known to negatively affect the contribution of soil microbes in macro-aggregate formation (Six *et al*., 1999; Castro Filho *et al*., 2002). The higher stability of the micro-aggregates compared to the macro-aggregates suggests that the Udi soils were less dispersive in water. This claim is supported by the low WDC (6.77 %) and CDI (26.68 %), indicating less dispersivity and higher micro-aggregate stability, respectively (Igwe *et al*., 2009; Zhu *et al*., 2018).

The dispersion of the soils with deionized water and different NaCl conductivity levels showed that the clay content produced was higher in the NaCl-dispersed soils than in the water-dispersed soils. The progressive increase in clay yield of these soils due to increased concentrations of NaCl solution suggests that a further increase in salinity would lead to a correspondingly higher clay yield. However, the average clay dispersion ratio (CDR) of the soils of < 0.50 at different NaCl concentrations was moderately low, indicating a lower dispersivity of the soils. The higher the CDR of the soil, the greater the soil dispersivity (Igwe and Agbatah, 2008). A high soil CDR can lead to clogging of pores, reduced saturated hydraulic conductivity, and the formation of surface seal (Igwe and Agbatah, 2008). In our study, the CDR values corroborate the aforementioned moderate porosity of the soils, which influences both air and water movement.

On the other hand, the CDR values of the soils, which showed a decreasing trend with increasing NaCl concentration, demonstrated that the dispersion problem due to NaCl was reached at a lower concentration of 25 S m^{-1}. Abbaslou *et al*. (2020) found that dispersive soils leached easily in water with low salt concentrations, despite the high concentration of Na^+ at their cation adsorption sites. Igwe and Okebalama (2006) reported that the dispersion caused by NaCl ions was reached at 100 S m^{-1}, resulting in the highest clay dispersion ratio (CDR). However, the lower CDR values of < 0.40 as a result of NaCl treatment at 75 and 100 S m^{-1} indicates clay flocculation with increased ionic strength of the NaCl solution. So at higher Na^+ concentrations, flocculation instead of dispersion of clay particles in the studied soils could therefore occur. Obviously, at lower ionic strength of NaCl (< 50 S m^{-1}), dispersion of clay minerals predominates, leading to the collapse of < 0.25 mm microaggregates, while an increase in ionic strength (> 50 S m^{-1}) leads to flocculation of clays into stable structured medium macroaggregates (1.00-2.00 mm). With this study, a better understanding of the correlation between Na^+ and the WSA fractions (1.00-2.00 mm and < 0.25 mm), including the AS of the soils, was established. Thus, it is evident that in these SCL soils, the dispersion of clay minerals depends not only on the charge of the counter ions, but also on the ionic strength. The dual role of Na^+ in the formation and stabilization of macroaggregates and in the dispersion of clay minerals and the collapse of microaggregates in the studied soils has thus been clarified. Dispersive soils have poor physical properties such as reduced porosity, infiltration rate and air and water movement, which in turn limit crop production (Abbaslou *et al*., 2016; Rengasamy *et al*., 2016; Singh *et al*., 2018). The structural stability of highly weathered soils of southeastern Nigeria is a function of SOM and Na^+ content and the influence of the latter on the dispersion and flocculation of clay minerals. These results should guide farmers in the study areas and in areas with similar soil texture on the use of irrigation water containing Na salts and fertigation with wastewater.

CONCLUSIONS

The studied soils were predominantly sandy clay loam (SCL), slightly acid to neutral, and low in organic matter and nutrient reserve. The microaggregates of the soils were largely stable, while the > 1.00 mm large macroaggregates were very unstable in water and could lead to reduced water permeability and increased erosion and runoff. The soils were less dispersible in water than in NaCl solutions, and the resulting clay content increased with increasing NaCl concentration. However, the clay dispersion ratio as influenced by NaCl ions decreased with increasing salt concentration, indicating dispersion of clay at 25 and 50 S m^{-1} and flocculation of clay at 75 S m^{-1} and above. In these SCL soils, the dispersion of clay minerals depends not only on the charge of Na ions, but also on the ionic strength.

The correlation analysis confirms the dual contributions of Na^+ to clay flocculation, leading to macroaggregate stability, or to clay dispersion, leading to microaggregate collapse. Overall, structural stability in SCL soils of the humid tropics is a function of SOM and Na^+ content as well as the dispersion and flocculation power of Na^+ on clay minerals.

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