Effects of organic matter and calcium on soil structural stability

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Summary

The cationic bridging effect of the calcium ion (Ca^{2+}) and the flocculating ability of clay and organic matter are crucial in the formation and stability of soil aggregates. They are therefore likely to influence the soil's saturated hydraulic conductivity (K_s). We tested the individual effects of these factors on aggregate stability and related hydraulic properties, and studied the influence of clay mineralogy also. Samples from the surface (0–10 cm) of three contrasting soils in Trinidad were used. The soils were treated with three levels of Ca^{2+} and three levels of organic matter in a $3 \times 3 \times 3$ factorial design and incubated for 14 days. Both aggregate stability and saturated hydraulic conductivity were influenced by all factor combinations. Interactions between soil type and Ca^{2+} revealed the importance of polyvalent cations in aggregate stability of soils with low activity minerals. The influence of organic matter varied with quantity; the more there was, the more stable the soil became, particularly in the soil containing little clay. Clay dispersion and slaking of expanding minerals occurred even with large additions of Ca^{2+} and organic matter, emphasizing the overall influence of mineralogy in determining the response of soils to stability treatments.

Introduction

Stable aggregates are crucial for the maintenance of adequate pore space for infiltration and water storage in soil. Aggregate stability expresses the soil's resistance to the destructive actions of wetting, raindrop impact and cultivation. Hence, the extent to which soil aggregates succumb to disruption depends on the strength of cohesive forces holding the particles together and the magnitude of disruptive forces in operation (Mbagwu & Bazzoffi, 1998). Normally, when disruptive forces overcome cohesive ones, aggregates disintegrate, hydraulic conductivity and infiltration rate decrease, run-off increases, and the likelihood of soil degradation through erosion becomes imminent. Knowledge of binding factors that confer cohesive strength to the soil aggregates to maintain structural integrity under continuous wetting and raindrop impact is therefore important, particularly in the humid tropics.

Rapid soil wetting and raindrop impact are the most important disruptive mechanisms that modify the number, shape, continuity and size distribution of pores, as well as the strength and stability of the soil (Mbagwu & Auerswald, 1999). The main processes by which soil aggregates are disrupted under rain are slaking, which is the disruption of aggregates due to the forces exerted by compressed air entrapped during rewetting, differential swelling of clays, mechanical dispersion due to the kinetic energy of raindrops, and physicochemical dispersion (Le Bissonnais, 1996).

Nemati *et al*. (2000) found that rapid wetting was the dominant agent causing aggregates to disintegrate when the soil was initially dry, but that on tension pre-wetting, the kinetic energy of the raindrops became almost equally important. In the Caribbean, the agents of disintegration are very active. The rainfall of the region ranges from 1270 mm to as much as 7600 mm per year, and the rain intensities can exceed 127 mm $hour^{-1}$ (Gumbs, 1982). Under these conditions, the soil is highly susceptible to structural breakdown, with the attendant run-off and erosion. Also, the preponderance of soils of medium to heavy textures, with little organic matter and little free iron oxides, could accentuate the ills of the structural instability of the surface (Ahmad & Roblins, 1971). Ahmad & Roblins (1971) showed that the susceptibility of the River Estate Series in Trinidad to crust formation was as a result of weak structure associated with little organic matter (< 1.5%) and less than 8% free iron oxide. In this region therefore, the major challenge is to achieve and maintain an open aggregated structure to ensure adequate water movement and infiltration, and sustain it under continued wetting and raindrop impact.

Clay, along with polyvalent cations, can act as a cementing material that holds particles together in aggregates and protects aggregates against disruptive forces. Therefore, increasing the content of cementing materials results in increasing aggregate stability. Chan & Heenan (1999) emphasized that increased aggregate stability in limed soils resulted from the formation of strong bonds involving Ca^{2+} bridges. Alternatively though, under fast wetting, an increase in clay content in the aggregate could also increase the extent of differential swelling and the volume of entrapped air that, in turn, increases aggregate slaking (Mbagwu & Auerswald, 1999).

In addition to clay content, clay mineralogy has a substantial effect on aggregate stability and dispersion. Smectitic soils are the most dispersive and kaolinitic soils the least. The stability of soils dominated by 1:1 clays is attributed mainly to the binding capacity of the minerals themselves (Oades & Waters, 1991), whereas polyvalent metal–organic complexes that form bridges between the negatively charged clay platelets are the main factors in aggregate stability of soils predominated by 2:1 clays (Six *et al.*, 2000).

Soil organic matter binds primary particles in the aggregates, physically and chemically, and this in turn, increases the stability of the aggregates and limits their breakdown during wetting (Sullivan, 1990). The mechanism of action involves two processes explained in detail by Chenu *et al.* (2000) and Zaher *et al.* (2005). Most studies so far have focused on the sole effects of organic matter or clay content on aggregate stability, with minimum research into the interaction effects of these properties. Strong links have been established between aggregate stability and clay and organic matter. Nevertheless, the variations in reported relations between aggregate stability and clay or organic matter content suggest that aggregate stability cannot be inferred solely from clay content or organic matter content. Thus, assessment of aggregate stability can be obtained only from the knowledge of a range of soil properties (clay, organic matter, base saturation and oxides content), which are all linked by their representation of binding processes in the soil (Idowu, 2003). We hypothesized that there are interactions between clay, Ca^{2+}, organic matter content and aggregate stability, and that these interactions are influenced mainly by clay mineralogy. We tested our hypothesis experimentally and report our findings below.

Materials and methods

Soils

Our experiments were carried out on the topsoil (0–10 cm) of three agricultural soil series in Trinidad, air-dried and ground to pass a 2-mm sieve. We chose the soils to give a range of clay content, clay mineralogy and organic matter content. The other factors affecting aggregation, such as exchangeable sodium percentage (ESP) and sesquioxide content, are generally small in Trinidadian soils. Soil mineralogy and other properties are presented in Table 1. All analyses were done by standard methods. Particle-size distribution was determined by the hydrometer method (Gee & Bauder, 1986). The pH was determined in a soil to water ratio of 1:1. Organic carbon content of the soils was assessed by the wet oxidation method of Walkley and Black described by Nelson & Sommers (1996). Cation exchange capacity (CEC) was determined by the unbuffered salt-extraction method described by Sumner & Miller (1996). Exchangeable sodium percentage (ESP) was mathematically derived from the sodium concentrations and CEC.

Incubation

We investigated experimentally the main effects of Ca^{2+} and organic matter on Bejucal, Non-Pariel and Piarco soil series and their interactions. Cured manure (sieved to pass a 2-mm mesh) was added at three rates (0, 4 and 12% mass of dry soil) and thoroughly mixed with the dry soil. Calcium as $Ca(Cl)_2$ was added in aqueous solution at concentrations of 0, 0.05, and 1.0 M, providing 0, 0.67 and 13.4 cmol Ca^{2+} kg^{-1} soil. The mixtures were then placed in pots. All treatment combinations were replicated twice, giving 54 experimental units in total. The pots were wetted to 80% water-holding capacity, sealed within polyethylene bags and left to incubate for 14 days. At the end of the incubation the soil mixtures were air-dried and crushed to pass a 2-mm sieve for the following analyses.

Aggregate stability

The aggregate stability of the 1–2 mm size fraction of the samples was determined by wet sieving. A single sieve apparatus with a stroke of 1.3 cm and a frequency of about 34 cycles minute^{-1}

Table 1 Physical and chemical properties of soils

Soil	Mineralogy	pH	Coarse sand (0.25–2 mm)	Fine sand (0.05–0.25 mm)	Clay	Organic carbon	CEC	Ca^{2+}	BS[a]	ESP[b]
			/%				/cmol$^+$ kg^{-1}		/%	
Bejucal	Very-fine, mixed	4.3	0.9	8.1	82.3	1.6	30.7	13.9	73	1.7
Non-Pareil	Clayey, kaolinitic	4.1	5.2	7.3	65.8	1.3	15.8	3.1	49	3.0
Piarco	Sandy, kaolinitic	4.2	51.4	15.6	14.8	1.2	6.1	2.7	69	3.9

[a]BS, base saturation determined as: $100 \times [Na^+ + K^+ + Ca^{2+} + Mg^{2+}]/CEC$.

[b]ESP, exchangeable sodium percentage determined as: $100 \times [Na^+]/CEC$.

was used. Prior to wet sieving in deionized water through a 0.25-mm sieve, 4 g of air-dried aggregates were immersed in deionized water and allowed to stand for 10 minutes. Thereafter, the sieving commenced and continued for 15 minutes. The materials that passed through the sieve (unstable aggregates) were dried at 105°C for 48 hours. Sand particles > 0.25 mm were separated from the material remaining on the sieve (stable aggregates) by dispersion with 0.02 M NaOH and the stable material passing through during dispersion was oven-dried. Aggregate stability was calculated as the mass of stable aggregates divided by the total aggregate (stable + unstable) mass, and expressed as the percentage of water-stable aggregates (sand free basis):

$$WSA = \{M_s/(M_s + M_u)\} \times 100, \qquad (1)$$

where M_s is mass of stable aggregates, and M_u is mass of unstable aggregates.

Saturated hydraulic conductivity (K_s)

The saturated hydraulic conductivity, K_s, was determined in 98-cm^3 columns by the constant head method, as described by Reynolds & Elrick (2002). Each column was uniformly packed with 1–2 mm air-dried aggregates, which were then wetted to saturation by gradual upward wetting with water under zero pressure. After saturation, the columns were placed in a constant head device (I.C.W. laboratory permeameter). Once an outflow was observed, the time taken for the outflow solution to reach a predetermined volume in a burette was taken. Saturated hydraulic conductivity (K_s, cm hour^{-1}) was calculated as follows

$$K_s = VL/At(\Delta H), \qquad (2)$$

where V is volume of outflow solution collected in the burette (cm^3), L is length of the soil column (cm), A is the cross-sectional area of the column (cm^2), t is time taken to obtain a predetermined volume of outflow in burette (hours), and ΔH is change in the head of water (cm).

Statistical analysis

Analysis of variance (ANOVA) was used to determine significance of treatments and their interaction for WSA and K_s. Where effects were significant, least significant differences (LSD) were used to discriminate among means.

Results and discussion

Aggregate stability

The analysis showed significant differences for the effects of main treatments and their interactions on water stable aggregates. The results indicated non-linear effects with increasing

levels of factors, which excluded trend analysis, although obvious observations were identified. Results are presented in two and three-way interaction tables, which also display main treatment effects.

Increasing Ca^{2+} content resulted in greater percentages of water stable aggregates for Piarco and Non-Pareil, whilst enhancing aggregate dispersion in Bejucal (Table 2). This observation is contrary to the reported ability of Ca^{2+} to inhibit clay dispersion and disruption of aggregates by replacing primarily Na$^+$ and sometimes Mg^{2+} in clay aggregates (Armstrong & Tanton, 1992). The increased disaggregation with Ca^{2+} treatment in Bejucal can be attributed to the addition of Ca^{2+} to a soil with an initially large inherent Ca^{2+} content (13.87 cmol kg^{-1}). This addition increased the potential of swelling-induced disaggregation. These cations have large hydrated radii, which enlarge the basal spacing of the minerals, leading to increased swelling and instability (Gouveia & Eudoxie, 2002). The short incubation exacerbated the dispersion effect noticed with Ca^{2+} (Baldock *et al.*, 1994). The Ca^{2+} bridging process is a dominant factor for the long-term positive effect of Ca^{2+} addition on soil structural stability (Six *et al.*, 2004).

Increasing quantity of Ca^{2+} resulted in a significant decline in soil pH (data not shown). Brady & Weil (2002) explain this phenomenon through the displacement of acidic cations from the exchange complex into solution. The attendant loss of these polyvalent cations also contributed to the destabilization seen in Bejucal.

Piarco showed the greatest difference in the state of aggregation as expressed by WSA, a difference of 15.7% between the control and the maximum Ca^{2+} treatment. Increasing Ca^{2+} content resulted in greater stability. Piarco, dominated by non-expanding minerals, also had the largest exchangeable sodium percentage (ESP) among the three soils (Table 1). Therefore, the profound effects of Ca^{2+} in inhibiting dispersion of kaolinitic clay and the associated disruption of aggregates

Table 2 Percentage water-stable aggregates for three soils treated at three Ca^{2+} levels

| Soil type | Ca^{2+} concentration/M | | | |
	0	0.05	1	Soil mean[b]
Bejucal	56.1[a]	50.4	44.7	50.4
Non-Pareil	71.6	75.4	73.1	73.4
Piarco	39.5	48.0	55.2	47.6
Ca^{2+} Mean[c]	55.7	57.9	57.7	
	Soil	Ca^{2+}	Soil × Ca^{2+}	
LSD	1.5	1.5	2.6[d]	

[a]Values represent the means of replicated treatments across all organic matter levels.
[b]Main effect of soil on percentage water-stable aggregates.
[c]Main effect of Ca^{2+} on percentage water stable aggregates.
[d]LSD$_{95}$ for the interaction between soil and Ca^{2+} concentration.

by replacing Na^+ must have taken place and, thus, significantly added to the aggregate stability of the soil.

Aggregate stability increased with increasing clay content among the soils (Table 2). All three soils were significantly ($P < 0.0001$) different with decreasing stability in the order: Non-Pareil > Bejucal > Piarco. Our study clearly demonstrates that this positive effect of clay on aggregation depends largely on clay mineralogy, particularly at large clay contents.

The comparable aggregate stability of Bejucal, the soil with the largest clay content but dominated by smectites, with Piarco, a soil with little clay dominated by kaolinite, is explained from the expanding nature of smectites. During wetting, the interparticle cementing forces in aggregates of Bejucal would have been undermined as a result of swelling, causing aggregates to succumb to disruption. This was further augmented by addition of Ca^{2+}. Aggregate stability increases with increase in clay content in soils dominated by non-expanding, crystalline clays, such as kaolinite, which are less dispersive, but the stability of a soil with large amounts of clay dominated by swelling minerals, could be as small as or even smaller than that of a soil with little clay of the kaolinitic type. Similarly, Yilmaz *et al*. (2005) reported best structural stability in soils containing the most kaolinite and weakest in those with large smectite contents. The practical implication of this is that soils should be wetted slowly if they contain many swelling minerals.

Organic matter affects aggregation by increasing interparticle cohesion within the aggregates, reducing increase in pressure by retarding water entry, decreasing the potential at the wetting front and reducing the hydraulic conductivity of the aggregate (Zaher *et al*., 2005). The 4% organic matter treatment resulted in a significant reduction in WSA, whilst the larger treatment increased aggregate stability to 60.5% (Table 3). While organic matter improved the structure of the coarse-textured soil, an inconsequential influence was observed on the soils rich in clay, especially those dominated by smectites. Bejucal showed non-significant variation with increasing organic matter content, whilst the largest application resulted in a significant positive increase in percentage of WSA for Non-Pareil.

In assessing the state of aggregation as a result of the combined Ca^{2+} and organic matter treatments on the soil types, we found that dispersion intensified with increasing level of combination of Ca^{2+} with organic matter only in Bejucal (Table 4). Combinations of the additives strengthened aggregation in the two kaolinitic soils, in some instances even more than the factors individually. The presumed influence of organic matter on stability in Non-Pareil is shown to be truly an effect of the Ca^{2+}, the organic matter probably not having had sufficient time to react with the clay in the soils. It is worth noting therefore that addition of Ca^{2+} with organic matter will create temporary disaggregation in Bejucal and other such soils. Care should be taken, then, in bringing these soils immediately under cultivation after treating the soil with Ca^{2+} or organic amendments or both, but awaiting long-term improvement of aggregation through the Ca^{2+} bridging effect, and stabilization.

Saturated hydraulic conductivity

As expected, K_s for Non-Pareil (largest percentage WSA) was significantly ($P < 0.0001$) greater than that for both Piarco and Bejucal (Table 5). A large amount of fine clay with dispersive and swellable montmorillonitic and vermiculitic minerals, which characterize Bejucal coupled with effects of Ca^{2+}, blocked water-conducting pores, thereby significantly diminishing K_s. On the other hand, the large clay in the Non-Pareil soil is dominated by kaolinite, which is less dispersive and non-expanding. Therefore, in the Non-Pareil soil, the disintegration of aggregates to finer particles and expansion during wetting, which are essential for blocking pores, were almost entirely eliminated, resulting in very large K_s values. Kaolinite comprises about 70% of the crystalline clays of the topsoil in Non-Pareil (Agbu *et al*., 1990) and about 76% in Piarco (William, 1970). Hence, the significantly greater K_s of Non-Pareil over Piarco may be a consequence of enhanced aggregation from the larger amount of clay in the former, along with greater responsiveness to soil amendments (Table 2).

In our study, we found that clay mineralogy, instead of texture, was the dominant factor influencing K_s. Therefore, in soils

Table 3 Percentage water-stable aggregates for three soils treated at three levels of organic matter (OM)

Soil type	Organic matter/%		
	0	4	12
Bejucal	50.8	48.9	51.4
Non-Pareil	72.4	72.3	75.4
Piarco	46.6	41.4	54.7
OM mean	56.6	54.2	60.5
	OM	Soil × OM	
LSD	1.5	2.6	

Table 4 Percentage water-stable aggregates for three soils treated at three levels of organic matter and three of Ca^{2+}

Soil type	Organic matter/%	Ca^{2+} concentration M		
		0	0.05	1
Bejucal	0	60.3	45.8	46.3
	4	58.0	46.4	42.4
	12	49.9	59.1	45.4
Non-Pareil	0	70.7	76.1	70.3
	4	73.4	75.1	68.3
	12	70.6	74.9	80.8
Piarco	0	39.9	47.7	52.2
	4	34.7	42.6	47.0
	12	43.9	53.8	66.3
LSD	4.5			

Table 5 Saturated hydraulic conductivity for three soils treated at three levels of Ca^{2+}

| Soil type | Ca^{2+} concentration/M | | | |
| | 0 | 0.05 | 1 | Soil mean |
	/cm hour^{-1}			
Bejucal	1.2	4.5	1.6	2.4
Non-Pareil	21.2	50.7	367	146
Piarco	4.1	6.3	7.1	5.8
Ca^{2+} Mean	8.8	20.5	125	
	Soil	Ca^{2+}	Soil × Ca^{2+}	
LSD	4.0	4.0	7.0	

with clay that is almost entirely kaolinitic with negligible smectites and vermiculites, as in the case of Non-Pareil, K_s will be several times larger. The cementing effect of the clay coupled with the largely kaolinitic mineralogy confers great pore stability, to the extent that the pores were not disrupted during wetting.

Saturated hydraulic conductivity increased with addition of Ca^{2+} in Non-Pareil and Piarco soils (Table 5). Non-Pareil soil at the maximum level of Ca^{2+} application gave the greatest K_s (367 cm hour^{-1}), whereas Bejucal with no Ca^{2+} added gave the least (1.2 cm hour^{-1}). The ability of Ca^{2+} to inhibit dispersion and disruption of aggregates by replacing Na^{2+} and Mg^{2+} in clay and aggregates is most likely to be responsible for the observed response. Yilmaz *et al.* (2005) reported a significant positive relationship between K_s with increasing Ca^{2+}. Clay particles often flocculate in the presence of polyvalent cations. Hence, the addition of Ca^{2+} encouraged flocculation, enhancing pore stability during wetting and increasing K_s. The phenomenon was masked in Bejucal as the increase due to Ca^{2+} was delayed, and dispersion occurred as described for aggregate stability.

Positive effects of organic matter on the K_s of Non-Pareil and Piarco soils (Table 6) can be explained from the reduction of disruptive forces such as increase pressure and differential swelling during wetting. The effect was exaggerated at 12% organic matter. The data confirmed that the structural stability of coarse textured soils is more sensitive to changes in organic matter than that of fine-textured soils (Kay & Angers, 1999; Ekwue *et al.*, 1993). Additions of organic matter to soils with appreciable clay seemed significantly to reduce K_s in the short term. On further investigation of the interaction among soil, Ca^{2+} and organic matter, increasing Ca^{2+} concentration to 0.05 M for 4% organic matter resulted in significantly smaller values of K_s for the Non-Pareil soil (Table 7). This indicates that for this soil, optimum levels of aggregating and stability factors were not attained and hence some dispersion occurred. However, for Bejucal organic matter contributed to the sealing of pores, which was further augmented by the influence of increased Ca^{2+}. Freshly added organic matter requires time to decompose and release compounds that assist in aggregate stabilization. Our study was not long enough to observe such developments.

Conclusion

We found that the positive effects of clay on aggregation depend largely on clay mineralogy, particularly at large clay contents. While the aggregate stability and K_s of soils dominated by non-expanding, crystalline clays, such as kaolinite, increase with increase in clay content, the other clay minerals promote increases in disruptive agents and reduce aggregate stability and K_s. Calcium in addition with organic matter improved aggregation and increased K_s in the Non-Pareil and Piarco soils, dominated by kaolinite, but aggravated disaggregation in Bejucal. This implies that while treating a clayey-kaolinitic soil and a sandy-kaolinitic soil with Ca^{2+} and organic matter will improve aggregation and increase K_s within a short time, caution is needed in bringing a clayey-smectitic soil recently treated with Ca^{2+} and organic matter under cultivation. Allow adequate time for aggregate improvement through Ca^{2+} bridging.

Table 6 Saturated hydraulic conductivity for three soils treated at three levels of organic matter (OM)

| Soil type | Organic matter/% | | |
| | 0 | 4 | 12 |
	/cm hour^{-1}		
Bejucal	2.8	0.8	3.6
Non-Pareil	55.6	44.1	340
Piarco	4.3	5.8	7.4
OM Mean	20.3	16.9	116
	OM	Soil × OM	
LSD	4.0	7.0	

Table 7 Saturated hydraulic conductivity for three soils treated at three levels of organic matter and three of Ca^{2+}

| Soil type | Organic matter/% | Ca^{2+} concentration/M | | |
| | | 0 | 0.05 | 1 |
		/cm hour^{-1}		
Bejucal	0	2.0	3.6	2.7
	4	0.5	0.8	1.2
	12	0.9	9.1	0.9
Non-Pareil	0	11.7	57.1	98.0
	4	9.3	13.5	109
	12	42.5	81.4	895
Piarco	0	7.6	2.7	2.5
	4	2.8	8.7	6.0
	12	2.0	7.5	12.8
LSD	12.1			

The effect of organic matter is more pronounced in the stability of soils containing little clay. Increases in slaking and dispersion at medium and large clay content upon short-term incorporation of organic matter indicates that organic matter does not contribute much to the stability of soils rich in clay, dominated by expanding minerals.

Acknowledgements

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