Soil texture, mineralogy, and organic matter effects on structural stability and soil loss of selected Trinidad soils after rainfall

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Clay and organic matter both have cementing and binding abilities that play crucial roles in the formation and stability of soil aggregates. The interactions of clay and organic matter on the extent of differential swelling and the volume of entrapped air in soil aggregates during fast wetting both in the presence and in the absence of rainfall were investigated. The influence of clay mineralogy was also examined. The parameters assessed in the study were water-stable aggregates (WSA), final infiltration rate (FIR), runoff (Q), and soil loss (E). Samples from the surface (0-10 cm) of six agricultural soils in Trinidad with three levels of clay (low, <20%; medium, 20-45%; and high, >45%) and two of organic matter (low, 53% and high, >3%) were used. Generally, aggregate stability and infiltration rate increased while seal formation, runoff, and soil loss decreased with increasing clay content. The high clay, high organic matter sample dominated by high activity clay yielded the highest WSA (68.8%) and the smallest E (0.99 kg m^{-2}), whilst the low clay, low organic matter sample dominated by low activity clay minerals had the lowest WSA value (5.3%). The high cation exchange capacity (20.2 cmol kg^{-1}) of Oropuna, a high clay, low organic matter content soil, classified as kaolinitic, indicates the presence of appreciable quantities of smectites. Therefore, the significantly lower WSA (56.5%) and FIR (3.2 mm h^{-1}) and higher Q (100.6 mm) and E (5.59 kg m^{-2}) of Oropuna over Montserrat (WSA = 61.5%; FIR = 109.9 mm h^{-1}; Q = 6.3 mm; and E = 3.06 kg m^{-2}) and Godineau (WSA = 68.8%; FIR = 60.7 mm h^{-1}; Q = 41.3 mm; and E = 0.99 kg m^{-2}) medium and high clay smectitic soils high in organic matter demonstrates the importance of organic matter in alleviating clay dispersion and slaking in soils predominated by high activity expanding clays. The results also demonstrate that there is a threshold clay content above which the support of organic matter is required to weaken disruptive forces and below which organic matter and slow wetting are not effective in diminishing disruptive forces.

Keywords: Aggregate stability; Aggregate slaking; Seal formation; Fast wetting; Low and high activity clay; Clay content; Organic matter content; Simulated rainfall

High aggregate stability is crucial for the maintenance of adequate pore space for infiltration and desirable soil hydraulic properties. Aggregate stability expresses the soil's resistance to the destructive actions of wetting, raindrop impact, and other soil disturbances. Hence, the extent to which soil aggregates succumb to disruption will depend on the strength of cohesive forces holding the structural units together (Mbagwu and Bazzoffi, 1998) and the magnitude of disruptive forces in operation (Rengasamy and Sumner, 1998). Normally, when disruptive forces overcome cohesive ones, aggregates break down, hydraulic conductivity and infiltration rate decrease, runoff increases, and the likelihood of soil degradation through erosion becomes imminent (Spacini et al., 2004). Knowledge of binding factors which confer cohesive strength to the

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soil aggregates to maintain structural integrity under continuous wetting and raindrop impact, is therefore important, particularly in the high rainfall of the humid tropics.

The main processes by which soil aggregates are disrupted upon rainfall are slaking, which is the disruption of aggregates due to the forces exerted by compressed air entrapped during re-wetting; differential swelling of clays; mechanical dispersion due to the kinetic energy of raindrops; and physico—chemical dispersion (Le Bissonnais, 1996). Rapid soil wetting and raindrop impact have been identified as the most important disruptive mechanisms (Geeves, 1997) that modify the number, shape, continuity, and size distribution of pores as well as the strength and stability of the soil (Lado et al., 2004). Geeves (1997) reported that fast wetting was the dominant agent causing aggregate breakdown when the soil was initially dry, whilst raindrop kinetic energy dominates on slow pre-wetting of aggregates. Exchangeable sodium percentage (ESP) is important in the physico—chemical dispersion of soil aggregates. Sodium on the exchange complex may negatively affect soil structure and aggregate stability (Abu-Sharar et al., 1987). Clay swelling and (or) dispersion and slaking of unstable aggregates increase at increasing ESP (Crescimanno et al., 1995).

In the Caribbean region, the agents of aggregate breakdown are very active. The rainfall of the region is high, ranging from 1270 mm to as high as 7600 mm yr^{-1}, and the rainfall intensities usually exceed 127 mm h^{-1} (Gumbs, 1982). Under these conditions, the susceptibility of soils to structural breakdown with attendant runoff generation and soil loss is increased. Also, the preponderance of soils of medium to heavy textures with low organic matter (OM) and low free iron oxides in the region, the ills of surface structural instability are accentuated (Ahmad and Roblin, 1971). The susceptibility of River Estate Series in Trinidad to crusting was a result of weak structure associated with very low OM (<1.5%), low free iron oxide contents, and micaceous nature of the soil minerals (Ahmad and Roblin, 1971). In the Caribbean region, therefore, the major challenge is to achieve an open aggregated structure to ensure adequate water movement and infiltration and sustaining it under continued wetting and raindrop impact.

Clay acts as a cementing material which holds particles together and thus protects aggregates against disruptive forces (Lado et al., 2004). Therefore, increasing the content of cementing materials results in increasing aggregate stability (Boix-Fayos et al., 2001). Alternatively, under fast wetting, an increase in clay content could also increase the extent of differential swelling and the volume of entrapped air (Zaher et al., 2005) which, in turn, increases aggregate slaking (Lado et al., 2004). In addition to clay content, clay mineralogy has a substantial effect on aggregate stability and dispersion. Smectites more readily form aggregates but can show extensive intra-crystalline swelling and dispersion on contact with water. The great swelling and shrinkage which may occur in smectitic clays on wetting and drying can render the aggregates less stable than those formed from kaolinite (Singer, 1994; Igwe et al., 1999). Wuddivira and Camps-Roach (unpubl.) showed the higher stability observed in kaolinitic dominated clays when compared to the smectitic dominated swellable clays in Trinidad.

Soil OM binds primary particles in the aggregate physically and chemically, and this in turn, increases the stability of the aggregates and limits their breakdown during wetting (Sullivan, 1990). Organic matter acts by (i) increasing aggregate cohesion resulting from adsorption of organic materials onto colloidal surfaces, (ii) decreasing the wettability of individual aggregates, and (iii) the occlusion of individual aggregate pores sensitive to slaking (Sullivan, 1990; Chenu et al., 2000; Zaher et al., 2005).

Most studies so far have focussed on the separate individual effects of OM or clay content on aggregate stability, with minimum research into the interactive effects of these parameters. Strong links have been established between aggregate stability and clay and OM (Levy and Mamedov, 2002). Nonetheless, the variations in reported relations between aggregate stability and clay or OM content suggest that aggregate stability cannot be inferred solely from clay or OM content. This study investigates the interactive effects of clay, OM contents, and clay mineralogy on soil aggregate stability, infiltration, runoff, seal formation, and soil loss.

Materials and Methods

Soils

Soil samples were taken from the top 0-10 cm of six agricultural soil series in Trinidad. Selection of soils was based on inherent clay and OM contents, since the other key factors affecting aggregation such as ESP and sesquioxides are generally low in Trinidad soils (Wuddivira and Camps-Roach, unpubl.). Trinidad is characterized by a humid tropical climate, with average annual rainfall that decreases from 3000 mm in the north to 1250 mm in the south. The wet season is from May to December which is often interrupted by a short dry spell, referred to as the *Petite Careme* (Gumbs, 1982). Soil classification, texture, and selected soil properties are presented in Table 1. All soil properties were determined by standard analytical methods described in Klute (1986) and Page et al. (1986).

Aggregate stability

The aggregate stability of the 1-2 mm size fraction of the samples was determined by wet sieving (Nimmo and Perkins, 2002). A single sieve apparatus with a stroke of 1.3 cm and a frequency of 34 cycles min^{-1} and two pre-wetting treatments were used: Prior to wet sieving in deionized water through a 0.25-mm sieve opening, 4-g triplicate samples of the 1-2 mm air-dried aggregates were either abruptly immersed in deionized water and allowed to stand for 10 min (fast wetting), or wetted slowly under tension by placing the sample on a filter paper in a tension table to saturate under 10 cm of water tension (slow wetting). Thereafter, the sieving commenced and continued for 15 min. The materials that passed through the sieve (unstable aggregates) were oven-dried at 105°C for 48 h. 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).

$$WSAf = [Ms/(Ms + Mu)] \times 100 \quad [1]$$

$$WSAs = [Ms/(Ms + Mu)] \times 100 \quad [2]$$

where, WSAf and WSAs are water-stable aggregates under fast wetting and slow wetting, respectively, Ms is mass of stable aggregates, and Mu is mass of unstable aggregates.

Infiltration and runoff studies

A continuous spray full jet nozzle (12.7 mm in diameter) attached to a Guelph Rainfall Simulator II (Tossell et al., 1990) was used to simulate rainfall of 120 mm h^{-1} intensity, which is common in Trinidad (Gumbs, 1982). Triplicate samples of air-dried

Table 1 Physical and chemical properties of the six soils used in the study

Soil properties	River Estate[1] (Fluventic Eutropepts)	Cleaver[2] (Orthoxic Tropudults)	St Augustine[3] (Orthoxic Tropudults)	Montserrat[4] (Typic Tropudolls)	Oropuna[5] (Aeric Tropaquepts)	Godineau[6] (Tropic Fluvaquents)
Clay (%)	19.4	17.5	35.3	43.3	63.3	67.3
Silt (%)	10.7	8.7	15.4	11.4	7.4	11.4
Sand (%)	69.9	73.8	49.3	45.3	29.3	21.3
Texture	Sandy loam	Sandy loam	Sandy clay loam	Sandy-clay	Clay	Clay
Organic matter (%)	2.3	3.7	1.4	3.9	1.8	6.9
Dry bulk density (Mg m^{-3})	1.4	1.5	1.5	1.0	1.4	0.8
CEC[7] (cmol kg^{-1})	4.2	7.7	10.5	27.1	20.2	33.4
ESP[8] (%)	4.5	7.6	0.7	0.8	0.5	1.1
pH in H_2O	4.3	6.4	6.4	5.9	4.7	3.4

[1]Low clay (<20%), Low organic matter (≤3%); [2]Low clay (<20%), High organic matter (>3%); [3]Medium clay (20–45%), Low organic matter (≤3%); [4]Medium clay (20–45%), High organic matter (>3%); [5]High clay (>45%), Low organic matter (≤3%); [6]High clay (>45%), High organic matter (>3%); [7]CEC, Cation exchange capacity; [8]ESP, Exchangeable sodium percentage

aggregates <5 mm in size were packed in columns 7.3 cm in diameter and 5 cm high and placed in the rainfall simulator at a slope of 9%. During each simulated rainstorm, water infiltrating through the soil was collected in measuring cylinders and the volumes were recorded at 5-min intervals for 60 min. Runoff (Q) was calculated as:

$$Q = S - Ic + H \quad [3]$$

where,

Q is total runoff in 60 min (mm), S is total depth of water supplied during 60 min simulated rainfall, Ic is cumulative infiltration (mm), and H is depth of water held by soil after 60 min of rainfall (mm). The soil loss (E) by splash and runoff over the period of 60 min was assessed by taking the dry weight of soil thrown out of the columns during rainfall, which is the difference in weight between the soil before and after the application of rain.

Statistical analysis

Three replicates of the studied parameters were run in a completely randomized design. Analysis of variance (ANOVA) was used to compare means. To study interactions for treatment effects on studied parameters, three levels of clay (low, <20%; medium, 20-45%; and high, >45%), and two of OM (low, <3.0% and high, >3.0%) were used in a 3 x 2 factorial combination. Soils with <3% organic matter are normally unstable (Guerra, 1994). Where significant interactions were observed, Tukey's Honestly Significant Difference at a single confidence limit was used to discriminate among the treatment means (Steel and Torrie, 1981). Also, regression analyses were performed in order to obtain relationships between dependent and independent variables and to extract best predictors for response variables.

Results and Discussion

Aggregate stability

The F values from ANOVA showed that the effects of clay and OM as well as their interaction on aggregate stability indices of WSAf and WSAs were significant ($P < 0.001$) (Table 2). The differences between the

Table 2 *F* Values of the analysis of variance (ANOVA) of the effects of clay and organic matter on stability indices and hydraulic properties

		Measured parameters				
Source of variation	df	WSAf	WSAs	Final infiltration rate	Runoff	Soil loss
Clay	2	5926.9[1]	440.8	791.9	257.0	13.4
OM[2]	1	2186.4	86.1	2164.8	713.4	6464.7
Clay × OM	2	82.8	40.4	411.2	121.1	13494.50

WSAf, Water stable aggregates (fast pre-wet); WSAs, Water stable aggregates (slow pre-wet); [1]*F* Values were significant for all parameters at $P \leq 0.001$; [2]OM, Organic matter

Table 3 Aggregate stability indices, final infiltration rate (FIR), runoff (Q), and soil loss (E) for the six soils

	Measured properties					
Soil sample	WSAf[1]	WSAs	ΔWSA	FIR	Q	E
	%	%		(mm h^{-1})	(mm)	(kg m^{-2})
River Estate	5.3	18.9	13.6	5.7	95.0	2.55
Cleaver	28.6	56.4	27.8	16.3	86.3	4.08
St Augustine	46.1	88.3	42.2	20.8	77.3	3.71
Montserrat	61.5	94.1	32.6	109.9	6.3	3.06
Oropuna	56.5	89.6	33.1	3.2	100.6	5.59
Godineau	68.8	93.8	25.0	60.7	41.3	0.99

[1]WSAf, Water stable aggregates (fast pre-wet); WSAs, Water stable aggregates (slow pre-wet)

soils with respect to the measured stability index of WSAf were significant (Table 3). This implies that the intrinsic soil properties of texture and OM content are important in the stability of these soils under fast wetting.

Aggregate stability results are presented in Table 3. In both low and high OM soils, aggregate stability increased with increasing clay content. The lowest WSAf value was obtained in samples belonging to the low clay category, followed by the medium clay category, and the highest value occurred in the high clay category (Table 3). The foregoing indicates the positive effects of clay in building aggregates and increasing the resistance of the soils to breakdown and slaking by water during fast wetting. Amongst the low clay content soils, WSAf was significantly higher in Cleaver, a low activity clay dominated soil high in OM content (3.7%) than River Estate, another low activity clay dominated soil low in OM content (2.3%; Figure 1 a). The clay mineralogy was important in determining the stability of aggregates in the medium to high clay soils to fast wetting. The stabilities of the medium clay soil (Montserrat) and the high clay soil (Godineau) which are both dominated by high activity clay minerals were not significantly different. However, they were both significantly higher than the medium (St Augustine) and high (Oropuna) clay content soils low in OM dominated by low activity clay (Figure I a). An earlier study conducted by Wuddivira and Camps-Roach (unpubl.) on some Trinidad soils varying in clay mineralogy and low in OM, revealed that kaolinitic soils were more stable than smectitic swellable clays. In this study, however, soils dominated by swelling clays and high in OM were more stable than soils dominated by kaolinitic clays low in OM. This implies that high OM content in swelling clay soils can lead to great structural integrity under fast wetting.

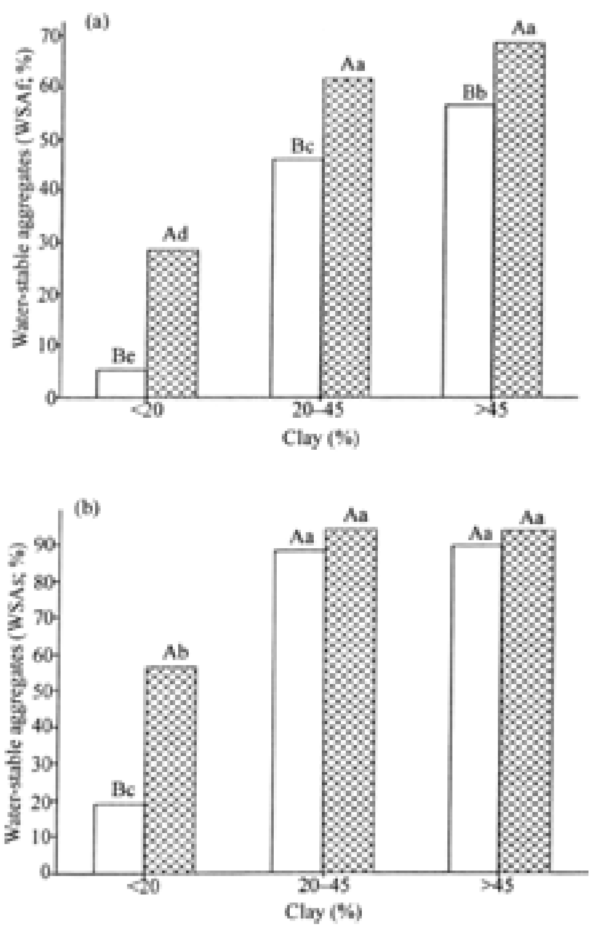

Figure 1 The effects of the interaction between clay and organic matter contents on (a) Water-stable aggregates, WSAf (fast pre-wet) and (b) Water-stable aggregates, WSAs (slow pre-wet). Values followed by dissimilar lower case letters within measured property and upper case letters within each clay level are significantly different at $P \leq 0.05$ □, Low organic matter level (≤3%), ▦; High organic matter (>3%)

Montserrat, a medium clay, high OM soil had statistically significant higher WSAf over Oropuna, a high clay, low OM soil (Figure I a). This is an indication that clay content increases stability under fast wetting to a certain level above which it needs the support of OM to withstand the disruptive effects of fast wetting. Increase in OM content will improve cohesion and lower the wettability of aggregates and increase their resistance to slaking stresses (Chenu et al., 2000; Zaher et al., 2005). The statistical similarity of the WSAf of Godineau to that of Montserrat supports this fact and indicates that medium clay soils that are usually considered unstable can achieve comparable structural integrity to high clay, high OM soils if their OM content is high. From a practical standpoint, under the aggressive climatic conditions of the humid tropics, it is important to increase and maintain a high level of OM in medium clay soils and soils dominated by high activity clays that are often prone to disaggregation by fast wetting. This will increase the amount of air encapsulation within soil aggregates during fast wetting sufficiently to prevent slaking (Sullivan, 1990).

For each clay level, the aggregate stability by fast wetting of the high OM soils was significantly higher than that of the low OM soils (Figure la). Organic matter in the high OM soils encourages aggregation by increasing inter-particle cohesion within the aggregate. In the low OM soils, however, disaggregation stresses were strengthened resulting in extensive aggregate breakdown. The importance of clay in the stability of these soils is also shown by its significant relationship [Coefficient of Determination (R^2) = 0.63] with WSAf. Unlike the clay content, however, the regression of WSAf and OM content was low (R^2 = 0.13). This was because Cleaver, a low activity, low clay soil with high OM, had significantly lower WSAf value than the low activity clay samples with medium (St Augustine) and high (Oropuna) clay contents and low in OM. This may suggest that there is a threshold clay content below which OM is not effective in providing the cohesive force necessary to protect the soil aggregates against disruptive forces during the wetting process. The level of combination of clay and OM in a soil sample is therefore very important and cannot be dismissed even at high clay level.

Cation exchange capacity (CEC) positively correlated with WSAf (r = 0.84). The CEC was more closely related to aggregate stability than clay content. This supports the importance of the interaction between clay mineralogy and OM in the stability of these soils. The high activity clay soils with the largest values of CEC and OM (Table 1) (Montserrat and Godineau) had the largest WSAf (Table 3). Exchangeable sodium percentage negatively correlated with WSAf (r = —0.69), indicating that dispersibility of the studied samples increased with increase in this variable. The significantly negative correlation between WSAf and ESP was in spite of the generally low values of ESP in the soils (Table 1) and it shows that dispersion could occur in the soils even at low ESP values.

Slow pre-wetting significantly improved aggregate stability when compared with fast wetting. This is presumably due to the weakening of intra-aggregate pressure build-up, and thus, slaking by the gradual expulsion of air when aggregates were slowly wetted under tension. The soils at the medium clay level showed much greater improvement in stability as a result of slow wetting as shown by the AWSA, which is the difference between WSAs and WSAf (Table 3). Cleaver, a high OM low clay soil, had significantly higher WSAs than River Estate. Ahmad and Roblin (1971) linked the instability and high crustability of River Estate Loam to the micaceous nature of its minerals and low OM content. Both the stabilities of Cleaver and River Estate though significantly improved by slow wetting when compared to fast wetting, remained in the high instability class (Mbagwu, 1986). Though the medium to high clay soils had significantly higher WSAs over their low clay counterparts, there was, however, no statistical significance in the WSAs of medium and high clay soils irrespective of OM, clay mineralogy, and content (Figure 1 b). This shows that once the clay content is at the medium level, there is the tendency to achieve high structural integrity under slow wetting that could make the effects of clay content, mineralogy, and OM negligible. Therefore, slow wetting before application of water at faster rates will ensure sustainable structural integrity and productivity of medium to high clay soils by improving aeration and infiltration and reducing the rate of seal formation and subsequent runoff and erosion under intenserainfall. The aggregates in low clay soils, however, even at high OM level, will quickly form seals and generate high volumes of runoff under the devastating action of raindrop impact and intense rainfall.

This demonstrates that there is a threshold clay content below which slow wetting is not effective in improving structural stability sufficiently to alleviate the devastating action of intense rainfall. The stronger linear relationship of WSAs with ESP (r = —0.78) than WSAf with ESP (r = —0.69), however, suggests that at high sodicity levels, slow wetting may not be effective in reducing clay dispersion and slaking. This corroborates the findings of Levy et al. (2003, 2005) that soils at different sodicity levels exhibited low structural stability even at slow wetting. Therefore, agricultural practices that result in the build-up of sodicity must be avoided for sustainable productivity of these soils. Stepwise multiple linear regression analysis, including all independent variables to extract the most important predictors, revealed that clay and OM and the dispersing property of ESP are the most important predictors, accounting for 82% of the variability in WSAf (Table 4). Conversely, the dispersing property of ESP was the only and most important predictor accounting for 62% of variability in WSAs (Table 4).

Infiltration rate, seal formation, runoff, and soil loss

Results of surface hydraulic properties and soil loss are presented in Table 3. Aggregate stability under rainfall followed a slightly different trend to stability under fast wetting in the absence of rainfall. This is likely due to the disruptive effects of raindrop impact and fast wetting in operation under rainfall, as opposed to only fast wetting in the absence of rainfall. The multifactor analysis revealed that the main effects of clay and OM and their interaction were significant on FIR, Q, and E (Table 2).

Table 4 Step-wise multiple regression equations in the form of $Y = a + bx_1 + cx_2 + dx_3$ and Coefficient of Multiple Determination (R^2) relating measured processes (Y) and different soil properties (X)

Response parameter (Y)	Predictors	Regression equations a	b	c	d	R^2	Significance
WSAf [1]	Clay (x_1)	16.00	0.78			0.63	***
	Clay (x_1) and ESP (x_2)	29.40	0.57	−3.16		0.71	***
	Clay (x_1), ESP (x_2), and OM (x_3)	27.00	0.37	−4.86	4.86	0.82	***
WSAs	ESP (x_2)	94.10	− 8.23			0.62	***
FIR	OM (x_3)	−24.20	18.70			0.60	***
	OM (x_3) and ESP (x_2)	−19.50	20.20	−5.25		0.69	***
	OM (x_3), ESP (x_2), and Clay (x_1)	4.30	23.50	− 9.10	− 0.66	0.76	***
Q	OM (x_3)	121.00	−16.80			0.59	***
	OM (x_3) and ESP (x_2)	116.00	−18.20	5.07		0.70	***
	OM (x_3), ESP (x_2), and Clay (x_1)	91.30	−21.70	9.12	0.69	0.79	***
E	OM (x_3)	5.37	−0.64			0.37	*

*, ***, Significant at $P < 0.05$ and $P \leq 0.001$, respectively; WSAf, Water stable aggregates (fast pre-wet); WSAs, Water stable aggregates (slow pre-wet); FIR, Final infiltration rate; Q, Total runoff; E, Soil loss; ESP, Exchangeable sodium percentage; OM, Organic matter

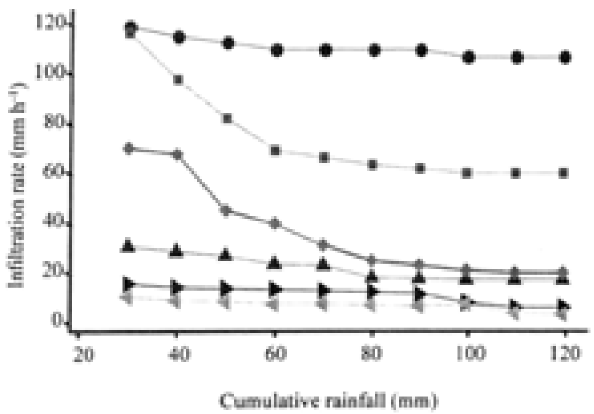

Figure 2 Infiltation rate as a function of cumulative rainfall for low, medium, and high clay soils at low and high organic matter (OM) levels. Clay: OM levels: ◆, Medium–high; ■, High–high; ✚, Medium–low; ▲, Low–high; ►, Low–low; and ◄, High–low

In all soils, infiltration rate decreased with increase in cumulative rainfall until the attainment of a FIR (Figure 2). This decrease in infiltration rate with increase cumulative rainfall (Figure 2) is an indication of increasing soil structural degradation caused by slaking due to fast wetting and the destructive impact of raindrops on soil aggregates. The destruction led to aggregate breakdown and generation of finer particles that became substrate for seal formation. Once a seal was formed at the soil surface, the hydraulic conductivity of the soil layer was decreased, leading to low in filtration and high runoff. The faster a seal was formed, the lower the cumulative amount of water infiltrated until the attainment of FIR.

The rate of seal formation was fastest and of the same statistical magnitude in Oropuna when compared to River Estate (Figure 3a). Oropuna is high clay kaolinitic low OM soil, while River Estate is low clay micaceous soil (Smith, 1983) low in OM content. The high susceptibility of Oropuna to seal formation compared to the smectite dominated Montserrat and Godineau, disagrees with earlier studies that high structural stability and thinner crust occur on soils rich in kaolinite than those rich in smectites (Reichert and Norton, 1994; Singer, 1994; Wakindiki and Ben-Hur, 2002). However, the high CEC of Oropuna (20.2 cmol kg^{-1}) which would have been contributed basically by clay mineralogy since the OM content of this soil is low (Igwe et al., 1999), indicates the presence of appreciable amounts of smectites. Igwe et al. (1999) pointed out that those soils containing small amounts of these expanding minerals show weak structural stability. The high dispersibility of River Estate, however, agrees with previous reports that the dispersibility of illitic soils may sometimes exceed that of smectitic soils (Singer, 1994). Therefore, the high structural stability and slowest rate of seal formation in Montserrat and Godineau soils dominated by expanding smectitic clays must have been a consequence of decreased wettability and the stabilizing effect of high OM conferred to these soils.

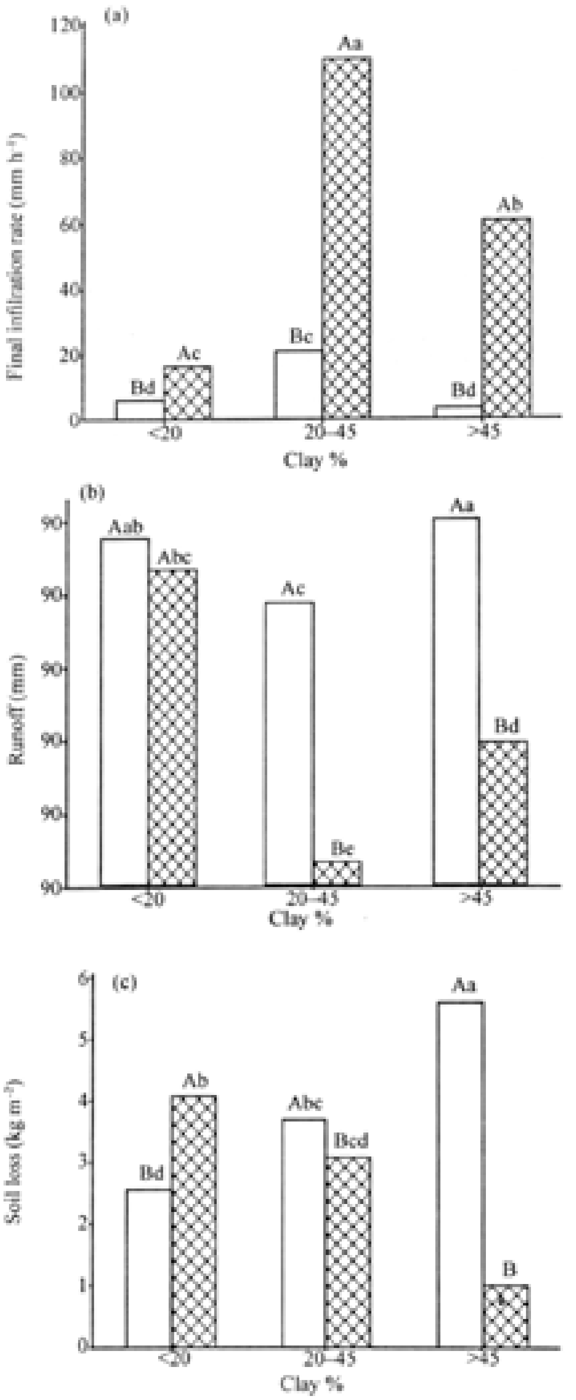

Figure 3 (a) Final infiltration rate, FIR, (b) total runoff, Q, and (c) soil loss, E, as functions of the effects of the interaction between clay and organic matter contents. Values followed by dissimilar lower case letters within letters within measured property and upper case letters within each clay level are significantly different at $P \leq 0.05$ level. □, Low organic matter level (≤3%); ▩, High organic matter level (>3%)

It can be concluded that for smectite-rich soils that are known to be unstable, maintenance of high OM is necessary to reduce wettability and subsequent incipient failure of aggregates due to swelling during fast wetting. The higher F value of the main effect of OM on FIR over clay supports this fact since these soils had larger FIR (Table 2). The highest runoff and soil loss were obtained in Oropuna (Table 3) indicating the weak stability of the soil under raindrop impact and wetting. Whilst the runoff of River Estate was on par with Oropuna (Figure 3b), its E was significantly lower ($P < 0.01$) than all other soils except for Montserrat and Godineau (Figure 3c). This would indicate that the seal formed on River Estate was strong enough to resist ease of removal of particles and aggregates from its surface by the detachable force of raindrops and runoff water. On the other soils, however, the slower rate of seal formation allowed the easier movement and subsequent loss of soil particles and aggregates by splash and in runoff. The apparent large-sized aggregates at the surface of Godineau at the end of 60 min of simulated rain, despite the lack of seal formation, appeared to be responsible for the low E.

Lado et al. (2004) reported a linear increase in aggregate slaking by fast wetting with an increase in clay content, and showed that with increase in clay content, there is an increase in the slaking mechanisms (e.g., differential swelling and explosion of entrapped air) that compensate for the increase in aggregate stability. In this study, however, the ability of OM to reduce pressure build-up by reducing the rate of water entry into individual aggregates suppressed slaking mechanisms during fast wetting. Thus, high stability and high infiltration rate are sustained when increase in clay is accompanied by increase in OM.

Soil OM showed a strong positive correlation ($r = 0.80$) with surface hydraulic characteristics of FIR and a strong negative correlation ($r = —0.80$) with Q. Organic matter accounted for up 60% of the variability in these processes. Stepwise multiple linear regression analysis, including all independent variables to extract the most important predictors, reveals that OM, ESP, and clay are the most important predictors accounting for 76 and 79% of the variability in FIR and Q, respectively (Table 4). This suggests that OM, sodicity, and clay are very important in the stability, seal formation, and runoff generation of these soils under intense rainfall. Since the aggregates experienced fast wetting during simulated rainfall, WSAf was the only stability index that significantly correlated ($r = 0.50$) with the surface hydraulic characteristics. However, the magnitude of correlation was smaller than expected. This could be as a result of fast wetting being the only operating disaggregation mechanism in the absence of rainfall, while both fast wetting and raindrop kinetic energy impact were operational under simulated rainfall.

Conclusion

Clay and OM contents both increase aggregate stability under fast wetting, but the effect of clay content decreases at higher clay contents, while the effect of OM increases at higher OM contents. Moreover, clay mineralogy has a significant influence on aggregate stability such that higher activity clays are generally less stable than low activity clays. However, increasing the OM content of high activity clays can improve aggregate stability to a level, comparable to that of low activity clays with high OM contents.

There is a clay content threshold necessary for soils to achieve a high aggregate stability. Below this threshold, high levels of OM are not effective in providing the cohesive force necessary to protect soil aggregates against disruptive forces during the wetting process. Above this threshold, clay mineralogy and OM contents have negligible impact on further increasing aggregate stability. Additionally, above this threshold, increases in clay content and OM suppressed aggregate slaking, soil loss, and seal formation thereby facilitating increased infiltration rates under intense rainfall.

The practical implication of this study is that to avoid significant slaking, dispersion, aggregate breakdown, and soil loss in high clay soils and (or) soils dominated with high activity clays exposed to intense rainfall, the soil OM content must be maintained at high levels.

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