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Pore size distribution and hydro-physical properties of cohesive horizons treated with anionic polymer

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Long molecular chain of polymers with active groups, combined with its complexity and flexibility to different environmental conditions provides an interaction of these groups with the mineral soil clays, thereby qualifying the polymers as soil flocculants effective. This study is aimed at evaluating the pore size distribution and hydro-physical properties of soils with cohesive horizons of the coastal plains of Pernambuco State, Brazil, with the application of anionic polyacrylamide (PAM). Thus, three horizons, one cohesive (Bt1) and two non cohesive (E and Bw/Bt) Ultisol were evaluated and, to compare the cohesive horizons, a BA horizon of Oxisol was selected. PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control = 0 mg kg^{-1}) were applied in undeformed samples by capillary. Pore volume was evaluated by diameter (macro, meso and micropores), total porosity, saturated hydraulic conductivity (Ksat), soil penetration resistance (PR) and soil-water characteristic retention curve. Polymer solutions reduced Ksat, macroporosity and total porosity of cohesive horizons (micropores dominated). More concentrated solutions increased PR of the Bt1 horizon. The excess negative charges in the system are the main factor for the negative effects of PAM on clay horizons. We hope that less electronegative PAMs may improve the hydro-physical characteristics of cohesive horizons.

Key words: Polyacrylamide, coastal tablelands, soil penetration resistance, negative charges, water retention, macroporosity.

INTRODUCTION

The low physical quality of soils located in the Coastal Tablelands ecosystem in Brazil is due to subsurface cohesive horizons (Correa et al., 2008). Despite the limited agricultural potential of these soils, this region is among the best agricultural regions in the rankings of agricultural production in Brazil (Souza et al., 2006; Gomes et al., 2012). There are several ecosystems and various functions for which soil can be used, but there is no specific methodology to characterize the soil quality by a universal set of indicators (Bouma, 2002). Thus, soil
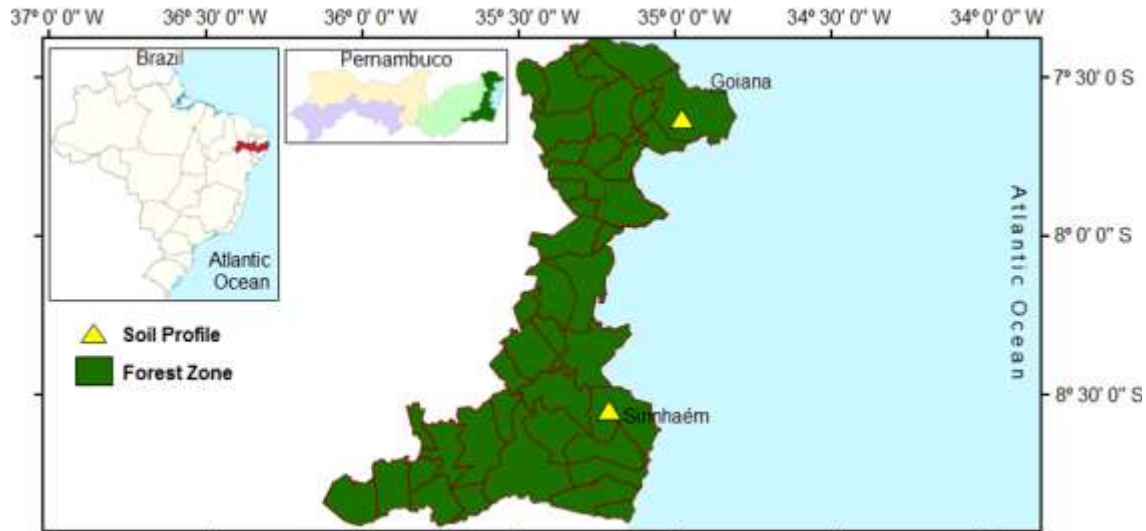
Figure 1. Location of soil profiles in the Forest Zone in Pernambuco State.

quality indicators can be selected according to the function of interest (Nortcliff, 2002). In recent decades, research has been conducted in order to establish quantitative parameter diagnostics of cohesion in soils, which broadens the discussion and provides their identification in agro-ecosystems (Silva et al., 2006; Silva et al., 2007). Thus, these parameters can act properly as change monitoring tools on the soil's physical quality at cohesive horizons under different management.

Studies involving water-soluble polymers used as chemical soil conditioners are concentrated on structural stability parameters and discussions about infiltration rates and sediment transport (Mamedov et al., 2009, 2010; Liu et al., 2009; Melo et al., 2014). Therefore, the absence of studies about soil structure is evident, with a focus on soil matrix qualitative arrangement and resulting pore space. Polyacrylamide (PAM) is one of the most important commercial polymers and has been widely used as a soil conditioner. PAM is made industrially with different molecular characteristics in terms of ionic type, molecular weight and charge density, reflecting its behavior in the solid-solution interface (Lentz and Sojka, 2009; Sepaskhah and Shahabizad, 2010). This study is aimed at evaluating the qualitative pore distribution and hydro-physical properties of cohesive and non-cohesive horizons of two soil profiles of Coastal Plains of Pernambuco State, Brazil, treated with polyacrylamide.

MATERIALS AND METHODS

Location and climatic characteristics of the study areas

Two soil profiles located at different regions in Pernambuco State, Brazil (Figure 1) were studied in 2012: (i) Goiana City, at the Experimental Station of Itapirema of the Agricultural Research Institute of Pernambuco - IPA (7° 37' 30'' S, 34° 57' 30'' W), with climate classified as Ams', according to Köppen, average annual rainfall 2,003 mm, vegetation predominantly sub-perennial rainforest; (ii) Sirinhaém City, (8° 36' 47'' S, 35° 19' 36'' W), with climate As' (Köppen) where the average annual rainfall is 1,310 mm and vegetation predominantly sub-perennial rainforest.

Characterization and classification of soil profiles and selection of horizons

Soil profiles were classified as Ultisol (Goiana) and Oxisol (Sirinhaém) according to the Soil Taxonomy. Physical and chemical characterizations of the horizons are given in Table 1 and 2, respectively. The horizons for study were selected based on detailed morphological characteristics in the diagnosis of the cohesive character. Three horizons were selected in the Ultisol, horizon Bt1 (cohesive), and two non-cohesives (E and Bw/Bt horizons). From the Oxisol profile chosen for comparative cohesive character purposes under different pedogenetic conditions, the most characteristic cohesive horizon (BA) was selected, based on morphological characteristics. Disturbed samples were collected from the horizons for physical and chemical characterization.

Chemical conditioner and sampling

The performance of the anionic polymer based on synthetic polyacrylamide (Polyacrylamide SuperflocA-130) at soil pore size distribution by diameter class and hydro-physical properties were evaluated in cohesive and non-cohesive soils. This polymer has a molecular weight of 15.0 Mg mol^{-1} and charge density (hydrolysis) of 35%.

Undisturbed soil samples were collected in the field in block form (0.5 × 0.4 × 0.3 m), according to average thickness of horizons, and first wrapped in plastic film, then in bubble wrap, packed in styrofoam boxes to preserve their structure, and transported to Soil Physics Laboratory at Federal Rural University of Pernambuco (UFRPE). These blocks were placed in plastic trays and wrapped in a protective layer of gypsum of about 50.0 mm thickness, aiming at maintaining the block structure, which could be damaged by the pressure of collection when inserting the stainless steel cores (total volume $\cong$ 100 cm^3). After that, the blocks were moistened with

Table 1. Physical properties of the evaluated soil horizons.

Horizon	Particle Size Analysis[1]						Silt/Clay Ratio	DI[3]	FI[4]	Pd[5]	Bd[6]
	Total Sand	Coarse Sand	Fine Sand	Silt	Clay	WDC[2]					
	g kg^{-1}									― kg dm^{-3} ―	
Ultisol											
E	855.11	720.0	135.11	18.62	126.27	101.02	0.15	0.80	0.20	2.60	1.70
Bt1	648.41	438.85	209.56	14.01	337.58	155.81	0.04	0.46	0.54	2.63	1.67
Bw/Bt	591.06	413.17	177.89	29.88	379.06	0.00	0.08	0.00	1.00	2.56	1.22
Oxisol											
BA	369.43	284.82	84.62	63.00	567.57	0.00	0.11	0.00	1.00	2.72	1.33

[1]Method of hydrometer reading with clay fraction after 24 h of settling (Almeida, 2008); [2]Water dispersible clay; [3]Dispersion Index = 1 - FI; [4]Flocculation Index = [(clay - water dispersed clay)/clay]; [5]Particle density: volumetric method pycnometry (Flint and Flint, 2002); [6]Bulk density: core method (Grossman and Reinsch, 2002).

Table 2. Chemical properties of the evaluated soil horizons.

Horizon	pH (H$_2$O)[1]	Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB[2]	CEC$_{ef}$[3]	CEC$_{pot}$[4]	BS[5]	m[6]	ESP[7]	P
						mmol$_c$ kg[-1]					――― % ―――			mg kg^{-1}
Ultisol														
E	4.9	0.0	0.1	10.6	0.3	2.8	12.5	11.1	13.9	23.6	47.1	20.2	0.0	5.1
Bt1	4.9	0.1	0.1	11.3	0.7	3.1	14.5	12.3	15.5	26.8	46.0	20.3	0.6	3.1
Bw/Bt	5.0	0.1	0.0	6.3	0.5	3.5	17.0	6.9	10.4	23.9	29.0	33.5	0.4	9.0
Oxisol														
BA	4.8	0.2	0.0	5.9	0.8	1.6	18.5	6.9	11.3	25.4	27.4	38.2	0.8	6.3

[1]pH in Water (1:2.5 soil to water ratio); [2]Sum of bases; [3]Effective cation exchange capacity; [4]Potential cation exchange capacity; [5]Bases saturation; [6]Aluminum saturation; [7]Exchangeable sodium percentage = (Na$^+$/CEC$_{pot}$) 100

distilled water by capillarity action to collect a soil core sample. Obtaining soil core samples were performed using a kind of sampler that inserts the core into the block continuously by the device hydraulics without impact. Thus, cores were inserted into soil blocks to obtain soil samples with the minimum possible disturbance.

Treatments and application

Soil samples were treated with PAM aqueous solutions at three concentrations: 12.5; 50.0 and 100.0 mg kg^{-1}, and distilled water was used as a control treatment without PAM (0 mg kg^{-1}). The soil core samples were placed on plastic trays lined with foam (of thickness 20 mm) that was soaked with PAM aqueous solutions and distilled water as a control, to be taken up slowly by capillary action until saturation without change continuity of pores. After that, the core soil samples were removed from the trays and left to stand for 72 h: enough time to reach chemical equilibrium between the PAM solutions and soil matrix based on chemical kinetics of PAM adsorption (Deng et al., 2006; Melo et al., 2014). The experimental design was randomized blocks with four replications, so 16 soil core samples for each horizon were collected, totaling 64.

Hydro-physical parameters

After standing time, the saturated hydraulic conductivity was given by the constant head permeameter method (Booltink and Bouma, 2002) and calculated according to the Darcy equation (Equation 1):

$$K_{sat} = \frac{Ve \times L}{A \times t \times (h+L)} \tag{1}$$

Where: K_{sat} is hydraulic conductivity of the saturated soil (cm h^{-1}); Ve is effluent collected volume (cm^3); L is length of soil sample = 5 cm; A is cross-sectional area of the soil column = 5 cm^2; t is time (h); and h is hydraulic head = 1.7 cm. The total porosity of the horizons was quantified by the soil moisture saturation method; the water volume is equivalent to pore volume and is calculated as follows:

$$P = \frac{V_{pores}}{V_t} \tag{2}$$

Where: P is total porosity, m^3 m^{-3}; V_{pores} is pores volume in m^3, obtained from difference between saturated soil mass and dry soil mass at 105°C, transforming water mass to volume (assuming water density =1,000 kg m^{-3}); V_t is total volume, assumed to be equal to core volume (10^{-4} m^3). The pore size distribution by diameter class was performed using sand table. Macroporosity was determined at the sand table by 1 kPa of soil suction and calculated as follows:

$$Macroporosity = \frac{V_{macropores}}{V_t} \tag{3}$$

Where: Macroporosity, m^{3}m^{-3}; $V_{macropores}$ is macropores volume,

Table 3. Hydraulic conductivity mean and standard deviation in saturated soil (Ksat) of horizons E, Bt1 and Bw/Bt (Ultisol) and BA (Oxisol) with the application of PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control = 0 mg kg^{-1}).

Horizon	Aqueous Solution (mg kg^{-1})			
	0	12.5	50.0	100.0
	Ksat (cm h^{-1})			
Ultisol				
E	38.72 ± 11.47	43.99 ± 27.75	71.44 ± 40.52	44.63 ± 32.35
CV[1]	29.62	63.08	56.72	72.48
Bt1 (cohesive)	1.46 ± 0.98	0.51 ± 0.44	0.56 ± 0.20	0.62 ±0.20
CV[1]	67.28	87.19	36.29	40.65
Bw/Bt	7.35 ± 5.81	4.62 ± 4.77	21.38 ± 31.61	5.69 ± 4.59
CV[1]	79.01	103.15	147.82	80.75
Oxisol				
BA (cohesive)	1.99 ±0.39	1.39 ± 0.88	1.08 ±0.53	1.46 ± 0.23
CV[1]	19.69	63.41	49.61	15.63

[1]Coefficient of variation (%).

obtained by water volume taken off the soil sample after reaching equilibrium at 1 kPa, m^3; V$_t$ is total volume, assumed to be equal to core volume (10^{-4} m^3). From the data of the total porosity, the ratio macroporosity/total porosity (Macro/P) was calculated, as initially proposed by Taylor and Aschcroft (1972). Mesoporosity was determined at 6 kPa in the sand table, and calculated as follows:

$$\text{Mesoporosity} = \frac{V_{mesopores}}{V_t} \qquad (4)$$

Where: Mesoporosity, m^{3}m^{-3}; V$_{mesopores}$ is mesopores volume, obtained by water volume taken off soil sample after reaching equilibrium at 1 and 6kPa, m^3; V$_t$ is total volume, assumed to be equal to the core volume (10^{-4} m^3). Microporosity (m^3 m^{-3}) was quantified as total porosity minus macro and mesoporosity, according to Equation (5):

$$\text{Microporosity} = P - (\text{Macroporosity} + \text{Mesoporosity}) \qquad (5)$$

The soil water retention curve (SWRC) was done in undisturbed samples at sand table (Romano et al., 2002) in the low-tension range (0 to 10 kPa), and the pressure plate extractor (Dane and Hopmans, 2002) was used to higher tensions (10 to 1500 kPa). At SWRC the measured matric potential (Ψ) was converted to soil water content (θ) according to van Genuchten (1980), using the RetC software of Soil Salinity Laboratory (van Genuchten et al., 1991). Thus, we obtain the empirical parameters of fitting using Equation (6):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha\Psi)^n]^m} \qquad (6)$$

Where, θ is soil water content, cm^3 cm^{-3}; θ$_r$ is soil residual water content, corresponding to permanent wilting point, cm^3 cm^{-3}; θ$_s$ is soil saturated water content, cm^3 cm^{-3}; Ψ is soil water potential (cwc); α is a scale parameter inversely proportional to mean pore diameter, cm^{-1}; n and m are shape parameters of soil water retention curve, m = 1 − 1/n, 0 < m <1, according to van Genuchten (1980). Root penetration resistance (PR) was quantified in the soil core samples containing moisture equilibrated at 10 kPa, determined by an electronic penetrometer bench with a needle to simulate root penetration in the soil. The penetrometer operated at 1 cm min^{-1} speed and the cone base was 4mm thick. The data acquisition system was connected to the penetrometer, and PR was expressed in MPa.

Statistical analysis

The results were analyzed using descriptive statistics and subjected to analysis of variance (ANOVA), and the means compared by the Scott-Knott test (p <0.05) using the statistical program SAEG (2009).

RESULTS AND DISCUSSION

Among the soils treated with PAM aqueous solutions, only the Bw/Bt horizon at Ultisol showed no consistent behavior of hydro-physical properties. This horizon is intermediate between Bw and Bt horizons (Melo et al., 2014); thus it has materials of both horizons, which can explain such behavior.

In other horizons, PAM aqueous solutions provided changes in Ksat values influenced by both soil texture and solution viscosity. Ksat value increased in the E horizon, which is typically sandy soil, and in cohesive soils from horizons Bt1 and BA, both clay soils, there was reduction in permeability with application of PAM (Table 3).

The viscosity has a greater influence in soils where macropores are predominant, as evidenced by the reduction of Ksat in half on E horizon, when 100 mg kg^{-1} was used compared to 50 mg kg^{-1}. A similar trend was found by Ajwa and Trout (2006), who obtained a reduction of Ksat in coarse soil when increasing the polymer concentration. According to them, the negative effects of PAM solution viscosity in infiltration rates are less harmful compared to hydraulic conductivity, due to

Table 4. Macro, meso and micropores volume at E, Bt1 and Bw/Bt (Ultisol) and BA (Oxisol) Horizons with PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control = 0 mg kg^{-1}).

Soil	Horizon	Aqueous Solution (mg kg^{-1})			
		0	12.5	50.0	100.0
Macropores (cm^3)					
	E	3.55 ± 0.35	4.44 ± 0.58	4.27 ± 0.67	4.78 ± 0.64
	CV[1]	11.79	7.34	26.03	11.10
Ultisol	Bt1(cohesive)	6.45 ± 1.68	3.62 ± 0.58	3.27 ± 0.23	3.61 ± 0.68
	CV[1]	25.89	16.60	7.21	19.14
	Bw/Bt	5.18 ± 1.08	4.11 ± 0.65	5.43 ± 1.98	4.82 ± 1.29
	CV[1]	20.85	15.77	36.23	26.64
Oxisol	BA(cohesive)	5.53 ± 0.68	3.56 ± 0.26	3.56 ± 0.92	3.69 ± 0.43
	CV[1]	11.79	7.34	26.03	11.10
Mesopores(cm^3)					
	E	17.39 ± 1.66	17.40 ± 1.79	18.32 ± 2.46	17.85 ± 1.38
	CV[1]	16.46	9.24	14.80	11.14
Ultisol	Bt1(cohesive)	4.88 ± 0.32	4.12 ± 0.70	3.50 ± 0.32	3.51 ± 0.59
	CV[1]	6.73	16.41	8.55	17.28
	Bw/Bt	8.17 ± 1.75	7.29 ± 2.92	7.55 ± 2.91	7.90 ± 2.61
	CV[1]	21,61	39,56	35,56	32.47
Oxisol	BA(cohesive)	7.66 ± 1.25	8.25 ± 0.75	8.19 ± 1.16	6.66 ± 0.69
	CV[1]	16.46	9.24	14.80	11.14
Micropores(cm^3)					
	E	13.55 ± 1.26	13.41 ± 1.58	13.99 ± 1.74	12.94 ± 0.87
	CV[1]	1.32	1.56	1.39	2.54
Ultisol	Bt1(cohesive)	23.21 ± 2.48	22.58 ± 0.56	22.28 ± 0.31	22.14 ± 0.45
	CV[1]	10.49	2.69	1.46	2.48
	Bw/Bt	30.42 ± 0.19	29.63 ± 0.90	28.43 ± 2.47	29.09 ± 0.96
	CV[1]	0.72	3.40	8.61	2.63
Oxisol	BA(cohesive)	34.23 ± 0.69	34.74 ± 0.87	34.79 ± 0.71	34.77 ± 1.15
	CV[1]	1.32	1.56	1.39	2.54

[1]Coefficient of variation (%)

complex relationship between conductivity, water content and soil matric potential. These findings also explain the results of Trout et al. (1995), where an increase of infiltration rates was observed with PAM application in soils of fine texture.

Soil permeability is measured by Ksat, and as a soil intrinsic property, represents water seepage through pore spaces. According to Sojka et al. (1998), the PAM effect on the soil permeability depends on several soil properties, mainly texture; if any sediment is entrained in the flow, on furrow irrigation, it is readily flocculated in the presence of PAM. As a result, infiltration rate is increased, mainly on finer textured soils. Dexter and Richard (2009) point out that more macropores do not necessarily imply increasing of soil permeability, since it must be connected. According to a qualitative study of pore space in each horizon, there was a predominance of micropores with decreasing sequence in terms of volume:

micropores<mesopores<macropores, except for the E horizon, where mesopores are predominant (Table 4).

PAM effects on macropore volume were consistent with Ksat values. Once again, soil texture was the predominant factor, that is, there was an increase in the macroporosity of the E horizon and reduction in cohesive horizons Bt1 and BA (Figure 2a) compared to the control (p <0.05). For both of them, there were no differences between polymer solutions. We believe that soil texture can influence PAM effects in macroporosity from a physical-chemical point of view. Cohesive horizons are clay and have greater electronegativity that can be increased by polymer solutions, since this kind of PAM has 35% of carboxylic groups, thus, increasing negative charge density in soil dispersion. As a result, macroporosity is reduced. In this context, Green et al. (2004) highlighted the repulsion arising from the interaction between PAM charge density and high-activity
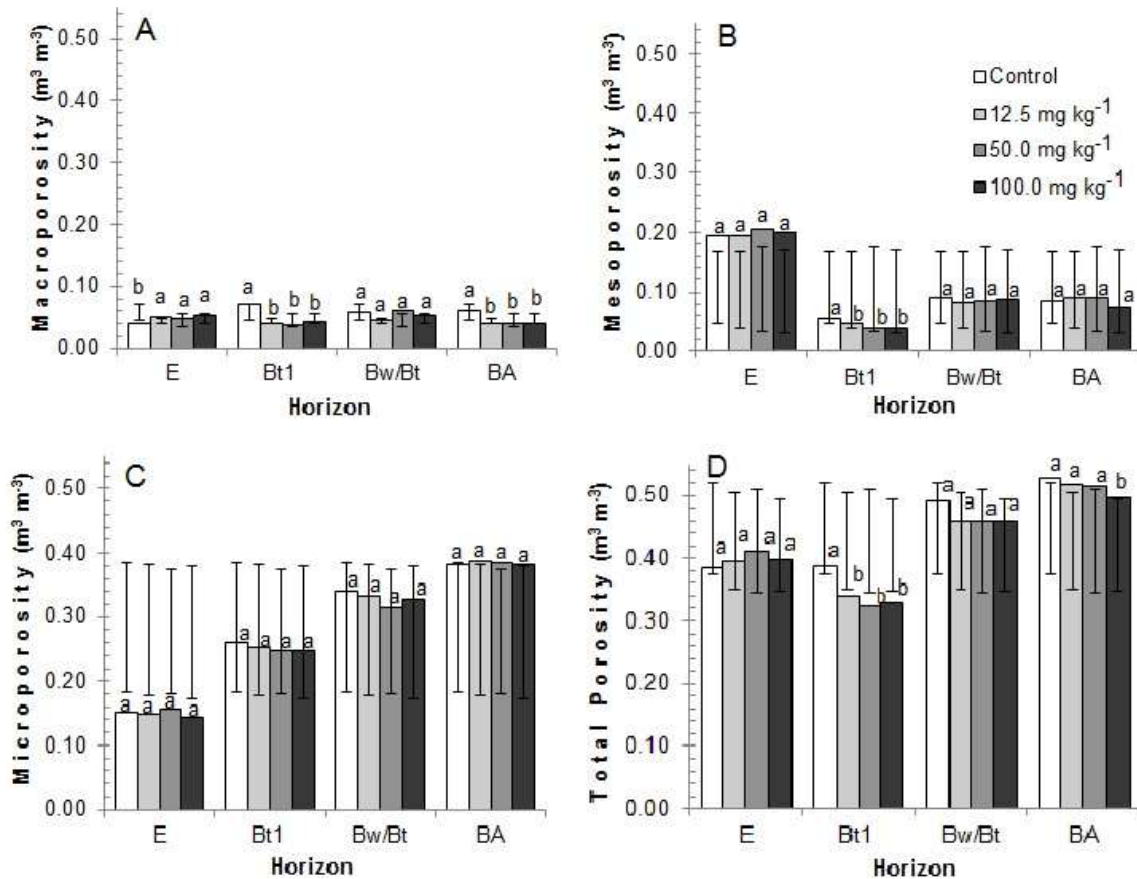
Figure 2. Macro, meso, microporosity and total porosity of E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) horizons with PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control=0 mg kg^{-1}). Means followed by the same letter with the same horizon = no significant difference using the Scott-Knott test (p <0.05).

clays.

PAM solutions reduced the mesopores volume and consequently the mesoporosity of the Bt1 horizon (Table 4 and Figure 2b). On the other hand, there were no differences between treatments for microporosity (p <0.05) (Figure 2c). Then, changes caused by PAM in the total porosity (P) at horizons were controlled mainly by macroporosity, with its reduction at cohesive horizons Bt1 and BA (Figure 2d). The most concentrated solution (100 mg kg^{-1}) provided the lowest values of total porosity at the BA horizon (p <0.05). Lima et al. (2005) found total porosity at the cohesive horizon of Greying Ultisol as 0.34 m^3 m^{-3}, which was significantly lower than for non-cohesive horizons. This reduction occurred also for volume of macro and mesopores, with a predominance of micropores, similar to the Bt horizon here. The cohesive horizon BA presented the highest total porosity (Figure 2d) due to the higher micropores volume (Table 4 and Figure 2c). However, total porosity decreased at 100.0 mg kg^{-1} PAM rate, due to the polymer effect on reduction of macroporosity (Figure 2a), since for mesoporosity and microporosity no significant differences were observed (Figures 2b and 2c, respectively). Corrêa et al. (2008)

studied soils from three toposequences of Coastal Tablelands in Bahia and Espírito Santo (both states of Brazil) and found total porosity values for cohesive horizon (Bt1) ranging from 0.37 m^{3}m^{-3} (Red Argisol - Ultisol) to 0.21 m^{3}m^{-3} (Yellow Argisol - Ultisol). These values are lower than the cohesive soil of Coastal Tablelands of Pernambuco investigated here, which range from about 0.39 m^{3}m^{-3} (Bt1) to 0.53 m^{3}m^{-3} (BA) (Figure 2d). PAM aqueous solutions increased the PR values of Bt1 horizon (Table 5) similar to the study of Busscher et al. (2007), who used PAM doses of 30 and 120 mg kg^{-1} in Acrisol. Strengthening the soil while increasing the volume would be consistent with the fact that PAM can improve aggregation, causing compact aggregates with larger inter-aggregate spaces; though this result could be unique to this study or condition.

The application form of PAM on soil may have affected our results of PR. Busscher et al. (2009) studied PR in two soils of US Coastal Tablelands, under field conditions, with different PAM concentrations, application forms and physical states (solution or granular), and concluded that treatments with the granular PAM had lower PR than those with the liquid PAM, probably a

Table 5. Soil penetration resistance of root system (PR) with soil moisture at 10 kPa in E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) horizons PAM aqueous solutions (12.5; 50.0 and 100.0 mg kg^{-1}) and distilled water (control=0 mg kg^{-1}).

Horizon	Aqueous Solutions (mg kg^{-1})			
	0	12.5	50.0	100.0
PR (MPa)				
Ultisol				
E	0.60[a]	0.86[a]	0.60[a]	0.91[a]
CV[1]	23.62	27.04	30.62	45.24
Bt1 (cohesive)	1.20[c]	2.52[b]	3.46[a]	3.16[a]
CV[1]	37.24	16.19	13.71	15.41
Bw/Bt	0.32[a]	5.34[a]	5.76[a]	4.82[a]
CV[1]	105.11	99.36	87.40	66.47
Oxisol				
BA (cohesive)	1.26[a]	5.50[a]	2.30[a]	2.15[a]
CV[1]	26.98	121.30	16.17	12.84

[1]Coefficient of variation (%); Means followed by the same letter with the same row = no significant difference using the Scott-Knott ($p < 0.05$).

result of being able to add higher amounts of PAM per ha in dry granular form. Thus, PAM can reduce penetration resistance by increasing soil aggregation, which disrupts the massive structure that constitutes the hard layer. Santana et al. (2006) defined a PR value of 2.0 MPa to characterize soils as cohesive, and highlighted how it is important to know the critical humidity below which cohesion manifests. Here, PR was determined on the samples under low matric potential (10 kPa), that is, moisture equivalent as a measure of the field capacity. Even so, we observed values above the critical value.

Macropores may be regarded as inter-aggregate pores (Othmer et al., 1991) and, therefore, as the PAM decreased macroporosity, this reduction was due to the reduction between the spaces of the aggregates, increasing soil aggregation, reflected by the PR increase in Bt1 compared to the control (Table 5). The PAM effect on macroporosity was evaluated also by Macro/P, which according to Taylor and Ashcroft (1972) must be 0.33 (dimensionless), considered an ideal value for crop development. In this study, two classifications of macropores size diameter ($\varnothing$) were used to evaluate PAM influence on Macro/P ratio: (i) macropores with $\varnothing >$ 300µm and (ii) macropores with $\varnothing >$ 50µm. Both macropores size classifications resulted in a Macro/P ratio below 0.33 for cohesive soils, with the exception of the E horizon (Figure 3). In fact, the E horizon that has a sandy texture, basically has macropores, and when these were classified as pores with $\varnothing >$ 300 µm, the ratio values Macro/P were lower than 0.2 for all horizons, regardless of treatment (Figure 3b). However, when the macropores were ranked with $\varnothing >$ 50 µm, the ratio values Macro/P to E horizon were greater than 0.33 (Figure 3a). For other horizons, microporosity (Figure 2c) and

macroporosity values (Figure 2a) explain the low values of the ratio Macro/P (Figure 3).

In cohesive horizons (Bt1 and BA), PAM application reduced the ratio Macro/P compared to the control (Figure 3), mainly for Bt1, where macro and mesoporosity were reduced (Figures 2a and 2b) due to the mechanism of action of PAM solutions reducing first the larger pores (inter-aggregates), as discussed in Akelah (2013). These results indicate that this kind of classification for macropores size of these soils could be re-evaluated using other criteria that can diagnose the resilience of them under treatment with chemical conditioners. Thus, we suggest that macropores could be better classified as pores of $\varnothing >$ 50µm. The macro/P relationship and pore size distribution of soil under treatment of chemical conditioners led to water movement in soil pores and consequently, water availability and retention in these pores. Soil size pore distribution influences the physical-hydraulic behavior. In this regard, soil water retention curves (SWRC) illustrate the soils' behavior under treatments (Figure 4).

Except for the Bw/Bt horizon, which showed a typical behavior in response to the action of PAM solutions (Figure 4c), the other horizons showed increased humidity from the field capacity (θ_{CC}, when $\Psi \cong 10$ kPa $\cong$ 2.0 log cwc), for the concentration of 50.0 mg kg^{-1} compared to other treatments (Figure 4, red arrows). These results show that the action of PAM reduced the cohesion of these soils, mainly for the Bt1 and BA horizons in the drier range of SWRC, when cohesive soils become harder as the humidity decreased gradually, preventing the penetration of roots (Aly and Letey, 1989). In general, it is observed that soil water retention capacity was improved for the E horizon when PAM solutions
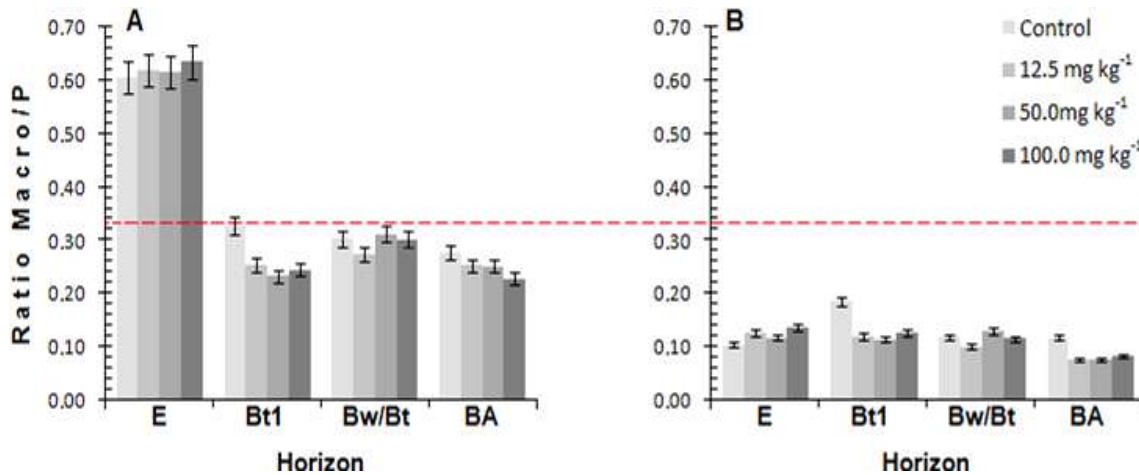
Figure 3. Macroporosity: total porosity (Macro/P) ratio at E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) horizons with PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control=0 mg kg^{-1}). Dashed line is dimensionless value of 0.33 as a reference: (A) macroporosity assumed macropores $\varnothing$ > 50 µm; (B) macroporosity assumed macropores $\varnothing$ > 300 µm.
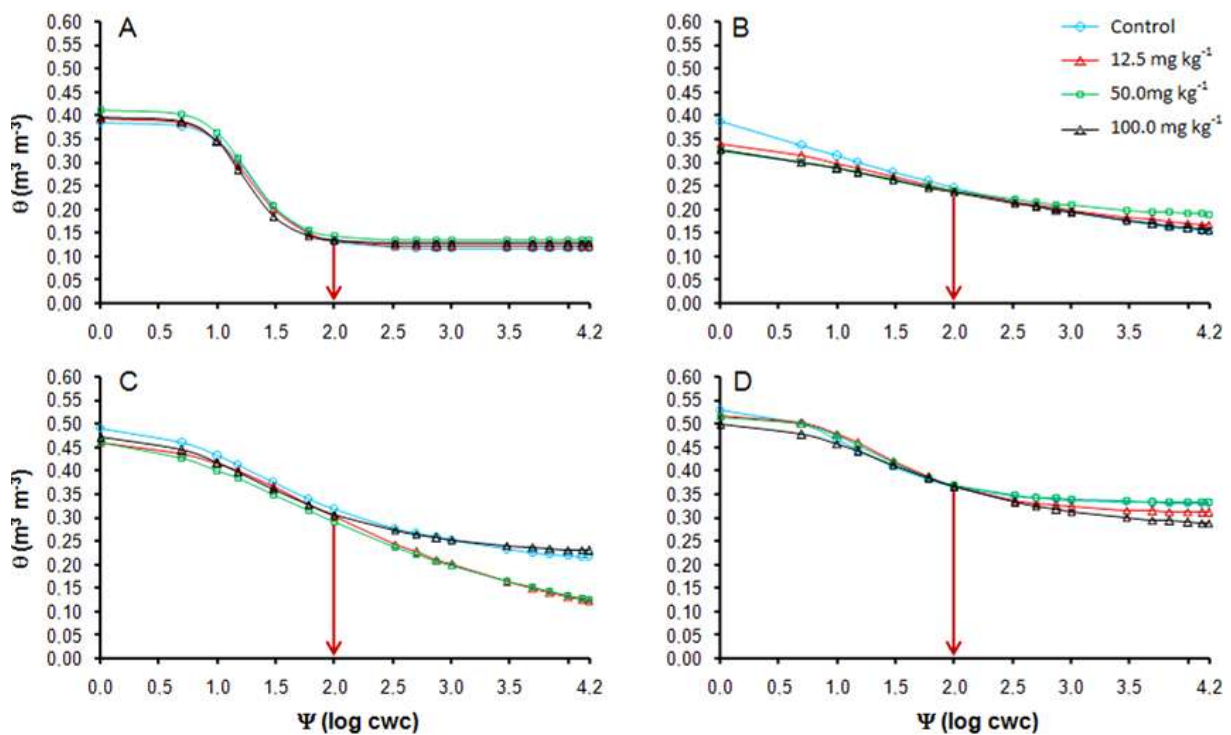

Figure 4. Soil water retention curve of E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) horizons with PAM aqueous solutions (12.5, 50.0 and 100.0 mg kg^{-1}) and distilled water (control = 0 mg kg^{-1}): (A) E Horizon; (B) Bt1 Horizon; (C) Bw/Bt Horizon; (D) BA Horizon, fitted according to the van Genuchten model by RetC software of Soil Salinity Laboratory (van Genuchten et al., 1991).

were applied, especially 50.0 mg kg^{-1}. Adding the amount of PAM in the sandy horizon (E) reduced the largest pores in the soils, and the pressure required for water expulsion is increased, as observed by Abedi-Koupai et al. (2008), when evaluated use of hydrogels, increasing the time that water will be available to plants. This result is very important, because this horizon is typically sandy with many macropores and loses water through seepage;

as a result, there is low water retention capacity (Figure 4a).

Abedi-Koupai et al. (2008) explain that volumetric water content increased due to the presence of a functional group (amide) on the chemical structures of PAM form hydrogen bonding with water. As a result, most of the water stored in the polymers is available to plants at relatively low tensions (Akelah, 2013). Regarding the effect of PAM at soil water retention capacity and water availability in cohesive horizons, SWRC of BA horizon (Figure 4d) compared to the Bt1 horizon (Figure 4b), is typical for soils with pore size distribution more assorted. Thus, we observed that the behavior of the BA curve (more winding) reflects higher values of meso and microporosity (Figures 2b and c), generally classified in structural pores (larger), and textural (smaller), as observed by Dexter and Richard (2009). On the other hand, the Bt1 curve (more horizontal), lower pitch is explained by higher values of microporosity (Figure 2c).These results are an indicator that cohesive horizon BA (Oxisol) has better structural conditions that favor soil physical-water properties.

Mamedov et al. (2009, 2010) also observed considerable effects on the shape of the SWRC for clay soils treated with PAM, which increased the water content, especially in the drier range of the curve. These authors explained that there was a possible effect of PAM in the hydration of aggregates, which increased their stability when wet (no slaking), reflecting the best hydro-physical conditions when the soil is dry.

Similarly, for cohesive horizons (Bt1 and BA), the effect of the application of PAM (50 mg kg^{-1}) can be observed at higher tensions ($\geq$ 2.0 log cwc) than field capacity (Figure 4; after tensions indicated by red arrows).There is an increase in soil water storage when PAM was applied at 50 mg kg^{-1}, which indicates that this polymer can prevent or reduce water loss by seepage, as also verified by Lentz and Kincaid (2008).

Conclusion

1. The PAM aqueous solution effect on Ksat of cohesive and non-cohesive soils depends both on soil texture and solution viscosity.
2. Except for the E horizon, micropores volume was prevalent, followed by mesopores and macropores.
3. Macroporosity on cohesive horizons was reduced by PAM solutions, which contributed to decreasing: Ksat, total porosity and Macro/P ratio, unlike for non-cohesive soils.
4. PAM solutions of 50 and 100 mg kg^{-1} increased PR on the Bt1 cohesive horizon of Ultisol, distinct from other horizons.
5. The PAM solution effect on macroporosity redistribution of soil was more evident when the macropores were classified from $\varnothing$ > 50 μm.
6. PAM solutions with 50 and 100 mg kg^{-1} provided a

better distribution of pore sizes in cohesive soils, resulting in higher water retention in the high-tensions range of the SWRC.

Conflicts of Interests

The authors have not declared any conflicts of interest.

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