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STRUCTURAL QUALITY OF POLYACRYLAMIDE-TREATED COHESIVE SOILS IN THE COASTAL TABLELANDS OF PERNAMBUCO[1]

Diego Vandeval Maranhão de Melo[2], Brivaldo Gomes de Almeida[3], Edivan Rodrigues de Souza[3], Laércio Santos Silva[4] & Paulo Klinger Tito Jacomine[5]

SUMMARY

Water-soluble polymers are characterized as effective flocculating agents due to their molecular features. Their application to soils with horizons with structural problems, e.g, a cohesive character, contributes to improvements in the physical quality and thus to the agricultural suitability of such soils. The purpose of this study was to evaluate the structural quality of soils with cohesive horizons of coastal tablelands in the State of Pernambuco treated with polyacrylamide (PAM) as chemical soil conditioner. To this end, three horizons (one cohesive and two non-cohesive) of a Yellow Argisol (Ultisol) were evaluated and to compare cohesive horizons, the horizon of a Yellow Latosol (Oxisol) was selected. The treatments consisted of aqueous PAM solutions (12.5; 50.0; 100.0 mg kg^{-1}) and distilled water (control). The structural aspects of the horizons were evaluated by the stability (soil mass retained in five diameter classes), aggregate distribution per size class (mean weight diameter- MWD, geometric mean diameter - GMD) and the magnitude of the changes introduced by PAM by measuring the sensitivity index (Si). Aqueous PAM solutions increased aggregate stability in the largest evaluated diameter class of the cohesive and non-cohesive horizons, resulting in higher MWD and GMD, with highest efficiency of the 100 mg kg^{-1} solution. The cohesive horizon Bt1 in the Ultisol was most sensitive to the action of PAM, where highest Si values were found, but the structural quality of the BA horizon of the Oxisol was better in terms of stability and aggregate size distribution.

Index terms: anionic polymer, coagulation/flocculation, aggregate stability.

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RESUMO: *QUALIDADE ESTRUTURAL DE SOLOS COESOS DOS TABULEIROS COSTEIROS DE PERNAMBUCO TRATADOS COM POLIACRILAMIDA*

Polímeros solúveis em água caracterizam-se como eficientes agentes floculantes relacionados aos seus aspectos moleculares, cuja aplicação em solos com horizontes que apresentam problemas estruturais, como acontece com o caráter coeso, favorece a melhoria da qualidade física e, assim, amplia a aptidão agrícola desses solos. Esta pesquisa teve como objetivo avaliar a qualidade estrutural de solos com horizontes coesos dos Tabuleiros Costeiros de Pernambuco com a aplicação de Poliacrilamida (PAM) como condicionador químico. Para isso, foram avaliados três horizontes (um coeso e dois não coesos) de um Argissolo Amarelo e, para fins comparativos de horizontes coesos, foi selecionado o horizonte de um Latossolo Amarelo. Como tratamentos, foram aplicadas soluções aquosas de PAM (12,5; 50,0; e 100,0 mg kg^{-1}) e água destilada (controle). Os aspectos estruturais dos horizontes foram avaliados pela estabilidade (massa de solo retida em cinco classes de diâmetro), distribuição de agregados por classe de tamanho (diâmetro médio ponderado - DMP, diâmetro médio geométrico - DMG) e magnitude das alterações promovidas pela PAM, medindo o índice de sensibilidade (Is). As soluções aquosas de PAM aumentaram a estabilidade de agregados na maior classe de diâmetro avaliada dos horizontes coesos e não coesos, repercutindo em maiores valores de DMP e DMG, com a solução de 100 mg kg^{-1} mais eficiente. O horizonte coeso Bt1, do Argissolo, evidenciou-se mais sensível à ação da PAM, onde foram encontrados maiores valores do Is; porém, o horizonte BA, do Latossolo, apresentou melhor qualidade estrutural inferida pela estabilidade e distribuição de tamanho de agregados.

Termos de indexação: polímero aniônico, coagulação/floculação, estabilidade de agregados.

INTRODUCTION

The agroecosystem of coastal tablelands in Brazil has been discussed in studies on the soil quality in these areas (Barreto et al., 2012; Gomes et al., 2012). These tableland regions are socially relevant due to the great importance for the national livestock and agriculture sector, mainly for citrus and sugar cane production and extensive and semi-extensive livestock (Cintra et al., 2004; Souza et al., 2006; Silva et al., 2007).

The low agricultural potential of the soils of the coastal tablelands region of Pernambuco is related to the presence of cohesive layers (Giarola & Silva, 2002; Lima et al., 2005), which have crop-growth-limiting physical and hydro-physical properties (Araújo Filho et al., 2001; Giarola et al., 2003; Santana et al., 2006; Corrêa et al., 2008).

In Brazil, studies on the improvement of the physical quality of soils with cohesive horizons restrictedly address mechanical soil tillage practices, and few studies focus on the application of chemical flocculating agents (Almeida, 2008), investigating mostly hydro-absorbent polymers (Azevedo et al., 2002; Oliveira et al., 2004). However, the use of water-soluble synthetic polymers such as polyacrylamide (PAM) can reduce the cohesive strength of such soils when dry (Aly & Letey, 1989), even at an international level.

The positive effects of PAM on soil preservation are related to increased aggregation of soil particles and pore continuity (Green et al., 2004; Caesar-Ton That et al., 2008), stabilization of the surface structure (Dou et al., 2012), increased water infiltration rates, and reduced surface sealing (Sepaskhah & Shahabizad, 2010) and resistance to root penetration (Busscher et al., 2009).

The adsorption of PAM to the soil particles is defined by the characteristics of both groups; those related to soil texture, clay type, organic matter content and type of ions present in the solution are the most dominant, whereas molecular weight and load type and density are the main properties of PAM involved in the process, defining its remediation potential (Seybold, 1994; Deng et al., 2006).

Thus, this study tested the effects of aqueous polyacrylamide solutions at different concentrations (0, 12.5, 50.0, 100.0 mg kg^{-1}) on the structural quality of cohesive and non-cohesive horizons in two soil profiles (Yellow Argisol - Ultisol and Yellow Latosol - Oxisol) in a sugarcane-producing region in the Coastal Tablelands of Pernambuco, evaluated by the aggregate stability and aggregate distribution indices per diameter class (MWD, GMD, Si).

MATERIAL AND METHODS

Location and climatic characteristics of the study areas

The study was conducted at two locations in the State of Pernambuco : in Goiânia, at the Experimental Station of Itapirema of the Agricultural Research Institute of Pernambuco - IPA (07° 37' 30" S, 34° 57' 30" W), the climate classified as Ams', according to Köppen, average annual rainfall 2,003 mm, vegetation predominantly sub-perennial rainforest, and Serinhaém, (08º 36' 47" S, 35º 19' 36" W), with climate As' (Köppen). In this region, the average annual rainfall is 1,310 mm and vegetation predominantly sub-perennial rainforest.

Characterization and classification of study horizons and selection of profiles

In Goiânia, the selected profile was classified as Argissolo Amarelo distrocoeso latossólico (Yellow Argisol - Ultisol), and in Serinhaém, as Latossolo Amarelo distrocoeso típico (Yellow Latosol - Oxisol). Both soil profiles were classified according to the Brazilian System of Soil Classification - SiBCS (Embrapa, 2006).

The horizons for the study were selected based on detailed morphological characteristics in the diagnosis of the cohesive character. Three horizons were selected in the Yellow Argisol (Ultisol), horizon Bt1 (cohesive), and two non-cohesive layers (E and Bw/Bt) serving as reference between cohesive and non-cohesive horizons. From the Yellow Latosol (Oxisol) profile, chosen for comparative purposes of the cohesive character under different pedogenetic conditions, the most characteristic cohesive horizon (horizon BA) was selected, based on morphological characteristics. Disturbed samples were collected from the horizons for physical (Table 1) and chemical characterization (Table 2) of the profiles.

The horizons were selected and sampled in March 2012, and the laboratory tests carried out between April and July of that year.

Chemical conditioner, sampling and evaluated properties

The performance of a high molecular-weight anionic polymer was evaluated, based on synthetic polyacrylamide (PAM), i.e., polyacrylamide Superfloc A-130, with a molecular weight of 15.0 Mg mol^{-1} and charge density (hydrolysis) of 35 %, respectively.

Aqueous solutions with PAM were applied to the aggregates at three concentrations: 12.5; 50.0 and 100.0 mg kg^{-1}, aside from a control treatment consisting of distilled water.

Undisturbed soil samples were collected in the field in block form (50 × 40 × 30 cm), and first wrapped in plastic film, then in bubble wrap and packed in styrofoam boxes to preserve their structure. Three representative blocks per horizon were collected. In the soil physics laboratory of the Universidade Federal Rural de Pernambuco - UFRPE, the blocks were placed on plastic trays lined with foam (thickness @ 20 mm) and moistened with distilled water. When the consistency became friable, the blocks were fractionated in two sieves and separated by hand in aggregates with an average diameter of 5.91 mm (by passing through a 7.1 mm sieve and retained on a 4.71 mm sieve). The aggregates were air-dried and subjected to treatments with aqueous PAM solutions (12.5, 50.0, 100.0 mg kg^{-1}) as follows: the material was distributed on trays lined with foam (thickness @ 20 mm), which was soaked with aqueous PAM solutions (12.5, 50.0, 100.0 mg kg^{-1}) and distilled water (control), to be taken up slowly by the aggregates, by capillary action during 72 h.

Table 1. Physical properties of the evaluated soil profiles

Horizon	Total sand	Coarse sand	Fine sand	Silt	Clay(2)	WDC(3)	Silt/Clay	DI(4)	FI(5)	Dp(6)	Bd(7)
	g kg^{-1}									kg dm^{-3}	
				Argissolo Amarelo distrocoeso latossólico (Ultisol)							
A	912.07	713.39	198.68	12.39	75.54	25.18	0.16	0.33	0.67	2.56	-
EA	876.88	622.12	254.76	21.22	101.90	50.95	0.21	0.50	0.50	2.61	1.52
E(1)	855.11	720.0	135.11	18.62	126.27	101.02	0.15	0.80	0.20	2.60	---
Bt1(1)	648.41	438.85	209.56	14.01	337.58	155.81	0.04	0.46	0.54	2.63	1.67
Bt2	648.91	474.12	174.79	10.94	340.15	0.00	0.03	0.00	1.00	2.60	-
Bt3	632.01	480.33	151.68	3.12	364.87	0.00	0.01	0.00	1.00	2.61	-
Bw/Bt(1)	591.06	413.17	177.89	29.88	379.06	0.00	0.08	0.00	1.00	2.56	1.22
				Latossolo Amarelo distrocoeso típico (Oxisol)							
A	393.72	300.73	92.99	62.32	543.96	388.54	0.11	0.71	0.29	2.63	-
AB	327.03	250.13	76.90	25.65	647.32	0.00	0.04	0.00	1.00	2.67	-
BA(1)	369.43	284.82	84.62	63.00	567.57	0.00	0.11	0.00	1.00	2.72	1.33
Bw1	350.35	268.22	82.13	51.87	597.78	0.00	0.09	0.00	1.00	2.65	-
Bw2	341.70	265.13	76.57	37.50	620.80	25.87	0.06	0.04	0.96	2.70	-
Bw3	259.43	184.53	74.90	14.88	725.69	0.00	0.02	0.00	1.00	2.74	-

(1) Horizons selected for the study; (2) Method of hydrometer reading with clay fraction after 24 h of settling (Almeida, 2008); (3) Water dispersible clay; (4) DI (dispersion index) = 1 - FI; (5) FI (flocculation index) = [(clay - water-dispersible clay)/clay]; (6) Pd (particle density): volumetric flask method (Embrapa, 1997); (7) BD (bulk density): volumetric ring method.

Table 2. Chemical properties of the evaluated soil profiles

Horizon	pH(H_2O)[2]	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	CEC_{ef}[3]	CEC_{pot}[4]	V	m	ESP[5]	P
		$mmol_c$ kg^{-1}									%			mg kg^{-1}
							Argissolo Amarelo distrocoeso latossólico (Ultisol)							
A	4.8	0.1	0.4	31.9	1.8	2.1	14.5	34.3	36.5	48.8	70.3	5.9	0.3	18.3
EA	4.7	0.0	0.2	10.7	1.1	3.8	13.5	12.0	15.9	25.5	47.2	24.0	0.0	5.4
E[1]	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[1]	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
Bt2	4.8	0.1	0.1	8.7	0.3	5.0	15.0	9.2	14.2	24.2	38.2	34.9	0.4	4.7
Bt3	5.1	0.1	0.3	8.7	0.6	5.3	14.5	9.9	15.2	24.4	40.6	34.9	0.7	5.2
Bw/Bt[1]	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
							Latossolo Amarelo distrocoeso típico (Oxisol)							
A	4.6	1.0	1.1	6.1	2.9	14.5	34.0	11.2	25.7	45.2	24.8	56.3	2.3	13.1
AB	4.8	0.4	0.2	5.8	1.7	7.6	22.5	8.3	16.0	30.8	27.0	47.9	1.4	6.4
BA[1]	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
Bt1	5.0	0.0	0.0	5.8	1.3	4.3	16.5	7.2	8.9	23.7	30.5	18.7	0.2	6.5
Bt2	4.8	0.0	0.0	5.4	0.8	1.0	16.0	6.2	7.2	22.2	28.0	13.8	0.0	8.0
Bt3	4.9	0.0	0.1	5.4	0.5	2.8	18.2	6.2	9.0	24.4	25.4	25.4	31.3	6.1

(1) Horizons selected for the study; (2) Air-dried fine earth suspension: solution at a 1:2.5 ratio (V:V); (3) Effective cation exchange capacity; (4) Potential cation exchange capacity; (5) Exchangeable sodium percentage = $Na^+/CEC_{pot}*100$

This settling time was considered sufficient for the effect of the treatments and possible changes introduced by PAM, since the equilibrium between the soil matrix and polymer solutions is established in this period, as reported in the literature (Nadler et al., 1992; Bajpai & Bajpai, 1995; Chan & Sivapragasam, 1996; Deng et al., 2006).

When the equilibrium between the treatments and aggregates was reached, these were air-dried, separated by wet sieving, based on the procedures suggested by Yoder (1936), according to Nimmo & Perkins (2002), with a few modifications described below.

The aggregates were initially slowly moistened with distilled water by capillarity for 15 min, to eliminate the air trapped within the aggregates, avoiding a sharp increase in the internal pressure during wet sieving, which could cause aggregate breakdown. The sieving system used in this test consisted of three cylinders with a series of five connected sieves, with different mesh sizes (2.00, 1.00, 0.50, 0.25, and 0.125 mm). The aggregates were immersed in water and a piston was moved vertically (amplitude 5 cm), to raise and lower the entire assembly. The stirring time (oscillation) was 10 min. The initial weight of the sieved aggregates (diameter 7.1-4.71 mm) was 25 g, with three replications.

The aggregate distribution per diameter class was expressed by the mean weight diameter (MWD) (Equation 1) and the geometric mean diameter (GMD) (Equation 2), both as indicated by Nimmo & Perkins (2002)

$$MWD = \sum_{i=1}^{n} (Xi \cdot Wi) \quad (1)$$

where *Xi*: mean diameter class (mm); *Wi*, proportion of each class in relation to the total.

$$GMD = EXP \frac{\sum_{i=l}^{n} n.\log xi}{\sum_{i-l}^{n} wi} \quad (2)$$

where n represents the stable aggregates in each class (%).

In the analytical procedure, the sample fraction with a diameter of over 2.0 mm (gravel) was considered inert and removed, for not being directly involved in the aggregation process.

To measure the influence of the aqueous PAM solutions on MWD and GMD in the horizons of the study compared to the control treatment, a sensitivity index (Si) was used, as suggested by Bolinder et al. (1999) (Equation 3). This index is based on the principle of relative comparison between treatments and allows a comparison of the responses between horizons in terms of PAM action.

$$Si = \frac{As}{Ac} \quad (3)$$

where As is the MWD or GMD value of each horizon exposed to each aqueous PAM solution, and Ac is the GMD or MWD value of each horizon in the control treatment.

The sensitivity index (Si) evaluates whether the GMD or MWD values of soil treated with PAM were different from those in the control treatment, where: Si = 1, the treatments do not differ from each other; Si >1, increase in aggregation; and Si <1, reduction in aggregation.

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

Aggregate stability

The distribution of aggregate diameter classes after wet sieving (Table 3) showed that the application of aqueous PAM solutions significantly increased the stability in water of aggregates from the cohesive horizons of the two profiles, maintaining them in the largest diameter class (4.71-2.00 mm).

The highest values (%) for the largest diameter class (4.71-2.0 mm) were obtained at a PAM rate of 100.0 mg kg^{-1}, i.e., 80.87, 44.83, 94.35 and 89.14 % for the horizons E, Bt1 (cohesive), Bw/Bt and BA (cohesive), respectively, but not significant ($p<0.05$) for the horizons E and Bw/Bt (non-cohesive). These results represent an increase in stability over the control treatment, with approximately 60, 569, 2, and 48 % for the same horizon sequence in the same diameter class. This response of the Bt1 horizon (cohesive horizon of the Yellow Argisol), with an increase of over 500 % in aggregate stability (4.71-2.0 mm), shows that the aggregate structure of this horizon was the most sensitive to the action of PAM.

The increased aggregate stability (Table 3) with the application of polymer solutions can be explained by the chemical-physical interactions between the molecules of the hydrophilic polymer and the constituents of the aggregate particles by means of ionic bonds, hydrogen bonds, and Van der Waals forces, which vary according to the aggregate properties as well as the dynamics of the polymer solution (Liu et al., 2009). Thus, macromolecules involving the aggregate surface form a viscous and

Table 3. Distribution of diameter classes of water-stable aggregates of the horizons E, Bt1, Bw/Bt (Ultisol), and BA (Oxisol) with the application of aqueous solutions of PAM (12.5, 50.0 and 100.0 mg kg^{-1}) and control (distilled H_2O)

Horizon	Diameter class	Treatment (mg kg^{-1})				CV
		Control	12.5	50.0	100.0	
	mm	%				
		Argissolo Amarelo distrocoeso latossólico (Ultisol)				
E	4.71-2.00	50.68 A	64.27 A	61.53 A	80.87 A	16.88
	2.00-1.00	4.34 A	6.11 A	6.27 A	3.50 A	36.88
	1.00-0.50	11.46 A	8.82 A	10.52 A	5.03 A	31.07
	0.50-0.25	17.72 A	12.23 A	12.23 A	6.16 A	33.31
	0.25-0.125	11.14 A	6.28 A	6.81 A	3.22 A	34.98
Bt1 (cohesive)	4.71-2.00	6.70 B	17.65 B	37.72 A	44.83 A	28.87
	2.00-1.00	9.03 B	14.08 A	15.70 A	16.47 A	18.69
	1.00-0.50	26.19 A	28.60 A	21.11 B	18.47 B	10.33
	0.50-0.25	35.74 A	25.40 B	16.24 C	13.07 C	10.15
	0.25-0.125	15.76 A	9.70 B	6.59 B	4.79 C	18.60
Bw/Bt	4.71-2.00	92.85 A	93.51 A	92.85 A	94.35 A	1.58
	2.00-1.00	2.03 A	1.87 A	1.71 A	2.02 A	26.01
	1.00-0.50	1.84 A	1.79 A	1.64 A	1.62 A	29.45
	0.50-0.25	1.60 A	1.60 A	1.33 A	1.18 A	22.56
	0.25-0.125	0.93 A	0.87 A	0.82 A	0.62 A	24.66
		Latossolo Amarelo distrocoeso típico (Oxisol)				
BA (cohesive)	4.71-2.00	60.31 B	71.43 B	68.57 B	89.14 A	7.71
	2.00-1.00	18.11 A	13.92 A	15.93 A	5.29 B	18.46
	1.00-0.50	12.74 A	9.00 A	9.42 A	3.35 B	23.34
	0.50-0.25	5.92 A	3.83 A	4.25 A	1.50 B	25.36
	0.25-0.125	2.02 A	1.31 A	1.18 A	0.56 A	23.89

Means followed by the same letter in the row do not differ by the Scott-Knott test ($p<0.05$).

elastic membrane that ensures the stability of the structure. However, according to these authors, the stabilization efficiency depends directly on the capacity of the polymer coating which is attributed mainly to the molecular weight. Molecules with low molecular weight polymers are not able to cover the aggregate surface completely but can coat only the secondary aggregates. On the other hand, high molecular weight polymers such as PAM used in this study quickly cover the aggregate surface, thus limiting water entry, reducing or eliminating a breakdown of the aggregate. This seems to be the mechanism of action that occurred when polyacrylamide (15.0 Mg mol^{-1}) was applied to the soils of this study.

The presence of hydrophilic groups along the PAM macromolecule as of COOH, $CONH_2$ and NH_2 favor connections with cations (cation bridges) as well as hydrogen bonds with the aggregate, characterizing the nature of the polymer - soil interaction (Laird et al., 1997; Liu et al., 2009).

Aggregate size distribution

The PAM solutions promoted structural stability in the largest diameter class, with significant effects on the MWD aggregates of cohesive and non-cohesive layers. In general, an increased PAM concentration promoted the stabilization of larger aggregates, as evidenced by higher MWD values that differed from the control treatment ($p<0.05$), except for the horizons E and Bw/Bt of the Argisol, where no significant differences were observed (Table 4).

The physical (Table 1) and morphological characteristics of these horizons explain the lack of response to PAM applications. In fact, the structure of horizon E, which is sandy, friable and very poor in fine fractions, impairs the development of aggregates. On the other hand, Bw/Bt is an intermediate horizon with mostly Bw characteristics, which occupies a larger volume, is mixed with parts of Bt (Santos et al., 2013), has a high flocculation rate (1.00) with the development of microaggregates with high aggregate stability (MWD >3mm). Thus, due to the absence of aggregation in E and the presence of already stable aggregates in Bw/Bt, the MWD of the aggregates in these PAM-treated horizons did not differ from their respective controls (Table 4).

For BA and Bt1 (cohesive) horizons, the most concentrated solution (100 mg kg^{-1}) induced higher MWD (means of 1.95 and 3.10 mm, respectively). This greater stability of cohesive aggregates promoted by higher PAM concentrations prevented aggregate breakdown by the adsorption of the polymer macromolecules, forming a viscous and elastic membrane (Liu et al., 2009). This induced further flocculation by reducing the hydration and dispersion of cohesive soils, a dominant mechanism, leading to the total collapse of these soils (Mullins et al., 1990; Chan, 1995; Mullins, 2000).

Le Bissonnais (1996) established five aggregate stability classes, based on MWD values: very stable for MWD >2.0 mm; stable for MWD of 2.0 to 1.3 mm; average MWD of 1.3 to 0.8 mm; unstable for MWD of 0.8 to 0.4 mm, and very unstable for MWD <0.4 mm.

According to this classification, the PAM application stabilized the aggregates: Bt1 became stable and the other horizons very stable, including horizon E, in spite of being sandy. The apparent contradiction in the higher MWD values of E (2.83 mm) than Bt1 (1.95 mm) can be explained by the clay fraction content and pore sizes. In this regard, Levy & Miller (1999) related the adsorption dynamics of anionic PAM to the stability of aggregates with different sizes and found that aggregates with highest clay content (as in Bt1 in this study) resulted in lower PAM adsorption and hence lower MWD. The authors also stated that the difficulty of penetration of the polymer into the aggregates, due to the smaller intra-aggregate pore size, was responsible for the lower MWD values than in aggregates with coarser texture. This can explain the higher MWD values in the E (sandy) than the Bt1 (clay) horizon. However, the same is not true for the very stable aggregates (3.16 mm) of the BA horizon, due to their greater stability.

The mean GMD of the aggregates of the studied horizons was highest in the PAM treatments, with significant effect compared to the control ($p<0.05$), except for the horizons E and Bw/Bt, where no significant differences were observed (Table 4).

Table 4. Mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates of the horizons E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) with the application of aqueous polyacrylamide solutions of (12.5, 50.0 and 100.0 mg kg^{-1}) and a control treatment (distilled H_2O)

Horizon	Treatment (mg kg^{-1})				
	Control	12.5	50.0	100.0	CV
			MWD		
	mm				%
Argissolo Amarelo distrocoeso latossólico (Ultisol)					
E	1.94 A	2.37 A	2.30 A	2.83 A	12.86
Bt1 (cohesive)	0.73 C	1.14 B	1.73 A	1.95 A	14.67
Bw/Bt	3.16 A	3.18 A	3.16 A	3.21 A	1.20
Latossolo Amarelo distrocoeso típico (Oxisol)					
BA (cohesive)	2.41 B	2.69 B	2.62 B	3.10 A	4.89
			GMD		
Argissolo Amarelo distrocoeso latossólico (Ultisol)					
E	1.15 A	1.69 A	1.60 A	2.31 A	21.36
Bt1 (cohesive)	0.49 B	0.73 B	1.17 A	1.36 A	18.22
Bw/Bt	2.94 A	2.99 A	2.90 A	3.06 A	2.60
Latossolo Amarelo distrocoeso típico (Oxisol)					
BA (cohesive)	1.94 B	2.28 B	2.21 B	2.89 A	6.82

Means followed by the same letter in the row do not differ by the Scott-Knott test ($p<0.05$).

In general, the aggregates treated with PAM solution of 100.0 mg kg^{-1} had higher GMD (2.31, 1.36, 3.06 and 2.89 mm in the horizons E, Bt1, Bw/Bt and BA) than when treated with the other PAM solutions, with a significant difference only in the BA horizon. For the cohesive horizon Bt1 (cohesive), solutions of 50.0 and 100.0 mg kg^{-1} differed statistically ($p<0.05$).

The structural quality expressed by the MWD and GMD (Table 4) is an important indicator of soil quality. Higher values of these variables indicate better physical conditions for crop development due to the better spatial pore distribution (structural and textural porosity), reducing the penetration resistance to the root system, better moisture retention, reduced surface runoff, and good aeration. Furthermore, it is positively related with organic carbon, macroporosity, flocculation degree, clay dispersible in water, and microporosity (Silva et al., 2006). Thus, the preservation of a high stability of large-diameter aggregates is crucial for the maintenance of soil productivity (An et al., 2010).

Busscher et al. (2007), reported higher aggregation with increasing PAM concentrations by the application of anionic PAM (12 Mg mol^{-1} and 35 % charge density) to a cemented sandy loam soil, at rates of 30 and 120 mg kg^{-1}. On the other hand, Green et al. (2000) found that the molecular weight of anionic PAM was effective for the stabilization of coarse-texture soils, unlike when applied to soil with a fine texture.

The behavior of the sensitivity index for GMD and MWD of the horizons was similar, inferred from the values above 1, indicating that the results of all treatments were better than of the control (distilled water); the solution with highest concentration induced the greatest changes (Figure 1).

The Si calculated from the MWD indicated the cohesive horizon Bt1 of the Ultisol as the most sensitive to changes promoted by PAM (Si of 1.56, 2.40, and 2.67 in the PAM treatments of 12 5, 50.0 and 100.0 mg kg^{-1} respectively). In fact, the aggregates of Bt1 without PAM application (control), with low MWD (0.73 mm), were classified as unstable (Le Bissonnais, 1996), but became stable (1.95 mm) by PAM adsorption, as shown by the increase in Is.

For Si_{MWD} as well as Si_{GMD}, the highest dose (100.0 mg kg^{-1}) was the most effective; the most pronounced response was observed in horizon Bt1, indicating that the aggregation promoted by PAM adsorption was high enough to overcome the aggregate breakdown caused by wet sieving, reducing the susceptibility to water action. On the other hand, Si_{MWD} and Si_{GMD} were lower for the aggregates of horizon Bw/Bt (Figure 1).

With regard to the aggregates of cohesive layers, the results of Si for the MWD (Figure 1) showed that PAM is effective in structural stabilization and consequently in improving the soil physical quality. The weaker effect of the treatments on the cohesive BA horizon of the Oxisol compared to the control can be attributed to the natural structural condition (weak, very small and small aggregates; subangular and angular blocks; friable with firm parts), along with the physical properties of the soil (Table 1) and higher levels of exchangeable Al^{3+} (Table 2), which contributed to the low Si (1.28), even at the highest PAM concentration. The Si was highest for aggregates of Bt1, explaining the greater increase in aggregation. This proves that the aggregate stability of cohesive layers is different, and that the Oxisol (BA) was less prone to increases in MWD by PAM applications than the Ultisol (Bt1).

The higher soil mass portion contained in the largest evaluated diameter as well as the higher MWD with GMD values in the PAM treatments indicated that the polymer solutions were preferentially adsorbed to the external aggregate surface and were most effective with the most concentrated solution. Levy & Miller (1999) attributed the occurrence of adsorption to the internal or external surface to the size of aggregates and pores. Small pores would hinder

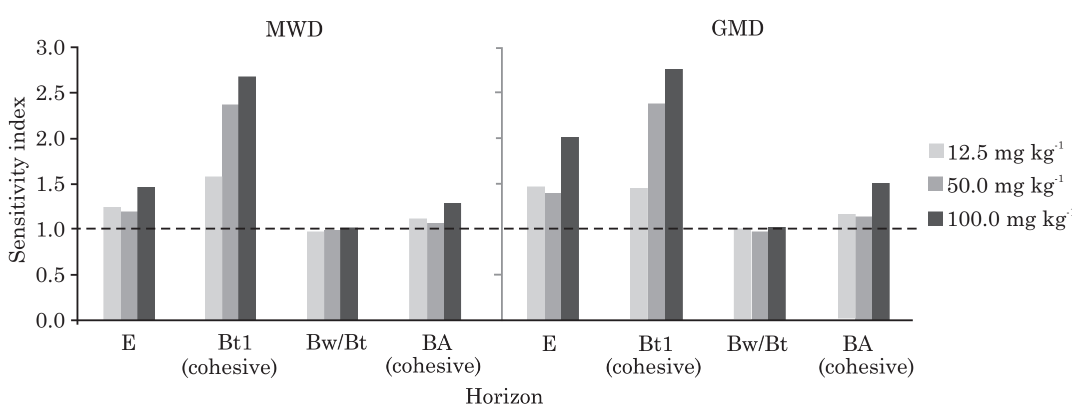

Figure 1. Sensitivity index for mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates of the horizons E, Bt1, Bw/Bt (Ultisol) and BA (Oxisol) with the application of aqueous solutions of PAM (12.5; 50.0 and 100.0 mg kg^{-1}).

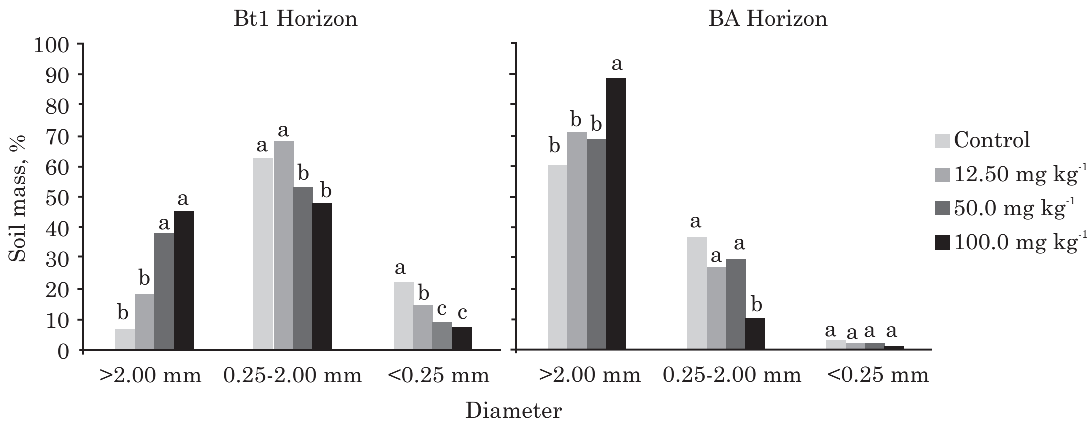

Figure 2. Water-stable aggregates (soil mass in %) of the cohesive horizons Bt1 (Ultisol) and BA (Oxisol) in three diameter ranges (>2.00, 0.25-2.00, <0.25 mm) resulting from the application of aqueous PAM solutions (12.5; 50.0 and 100.0 mg kg^{-1}) and a control treatment (distilled H_2O). Means followed by the same letter in the column do not differ by the Scott-Knott test (p <0.05).

the penetration of PAM into aggregates, while those with larger pores would not restrict the entry, i.e., the texture is influential. Other studies also confirmed the external action of PAM on the aggregates (Malik & Letey, 1991; Miller et al., 1998; Mamedov et al., 2007).

Figure 2 shows a comparative study of the structural stability of cohesive layers treated with PAM solutions, based on the reduction of diameter classes and increase in intraclass intervals. The PAM solutions improved the stabilization of macroaggregates (>0.25 mm) and the structural quality by increasing the percentage of soil mass in this larger diameter class (>2.0 mm) in both horizons.

The 100 mg kg^{-1} treatment induced the highest values of stable aggregates (soil mass) (BA - 89.14 % and Bt1 - 44.83 %), differing significantly from the other treatments ($p<0.05$). The Bt1 horizon had the highest concentration of soil mass in the intermediate diameter class (2.00-0.25 mm), differing from BA, in which in the larger class (>2.00 mm) predominated, indicating the occurrence of distinct structural conditions, despite the cohesive character of both.

Under natural conditions (no PAM application), approximately 63.0 % of the soil mass of the Bt1 horizon was grouped in the intermediate diameter class, i.e., far superior to the material in the same class in the BA horizon (≅ 37 %). This is related to the specific pedogenetic characteristics of each horizon and is reflected in several physical-hydric parameters.

In the studied non-cohesive layers, the heterogeneity of Bw/Bt with spatially variable consistency (intermediate horizon) did not allow a direct evaluation of the PAM effects, due to the high variability of results in all parameters evaluated, in addition to Is values very close to 1.0.

CONCLUSIONS

1. Aqueous polyacrylamide (PAM) solutions promoted the structural stabilization of cohesive and non-cohesive horizons, increasing macroaggregation (>0.250 mm).

2. There was an increase in MWD and GMD of the cohesive and non-cohesive horizons treated with PAM solutions.

3. The solution of 100 mg kg^{-1} was most efficient in the structural stabilization of the horizons.

4. The structural aspects evidenced by the sensitivity index in the cohesive horizon Bt1 of the Argisol (Ultisol) were most sensitive to the action of PAM;

5. The structural quality of the cohesive horizons was best in the BA of the Latosol (Oxisol).

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