

Polyacrylamide Effects on Aggregate and Structure Stability of Soils with Different Clay Mineralogy

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Adding anionic polyacrylamide (PAM) to soils stabilizes existing aggregates and improves bonding between and aggregation of soil particles. However, the dependence of PAM efficacy as an aggregate stabilizing agent with soils having different clay mineralogy has not been studied. Sixteen soil samples (loam or clay) with predominantly smectitic, illitic, or kaolinitic clay mineralogy were studied. We measured aggregate sensitivity to slaking in soils that were untreated or treated with an anionic high-molecular-weight PAM using the high energy moisture characteristic (HEMC) method and deionized water. The index for aggregate susceptibility to slaking, termed stability ratio (SR), was obtained from quantifying differences in the water retention curves at a matric potential range of 0 to -5.0 J kg^{-1} for the treatments studied. For the untreated soils, the SR ranged widely from 0.24 to 0.80 and generally SR of kaolinitic > illitic > smectitic soils. The SR of PAM-treated aggregates exhibited a narrow range from 0.70 to 0.94. The efficiency of PAM in improving aggregate and structural stability relative to untreated soils ranged from 1.01 to 3.90 and the relative SR of kaolinitic < illitic < smectitic samples. These results suggest that the less stable the aggregates the greater the effectiveness of PAM in increasing aggregates stability (i.e., smectitic vs. kaolinitic samples). The effectiveness of PAM in improving structure and aggregate stability was directly related to clay activity and to soil conditions affecting PAM adsorption (e.g., electrolyte resources, pH, and exchangeable cations) to the soil particles and inversely to the inherent aggregate stability.

Abbreviations: EC, electrical conductivity; HEMC, high energy moisture characteristic; PAM, polyacrylamide; RSR, relative stability ratio; SR, stability ratio; VDP, volume of drainable pores; VDPR, volume of drainable ratio.

Aggregates may be subjected to stresses related to tillage, traffic, abrasion by wind and flowing water, and wetting and drying cycles. The ability of aggregates to resist stresses when wet (i.e., wet aggregate stability) was originally used to characterize soil erodibility (Yoder, 1936). However, wet aggregate stability is being increasingly used to evaluate cohesion of aggregates, and the dynamics and nature of the bonding between particles (Kay and Angers, 2000), all of which are major contributors to soil-structure stability.

The favorable effects of the environmentally friendly, non toxic, anionic PAM as a soil conditioner have recently been reviewed by Sojka et al. (2006). The positive effects of PAM are related, among others to (i) preserving or increasing soil aggregation and pore continuity (Ben-Hur and Keren, 1997; Green et al., 2004; Ajwa and Trout, 2006; Mamedov et al., 2007); (ii) increasing aggregate and structure stability of soils (Green et al., 2004; Mamedov et al., 2007) thus leading to stabilization of the soil surface against shear-inducing detachment (Lentz and Sojka, 1994), decreasing soil susceptibility to seal formation (Levy et al., 1992; Shainberg et al., 1990, 1992), runoff generation and soil erosion (Smith et al., 1990; Bjorneberg and Aase, 2000); (iii) increasing the size and thus decreasing settling time of particles suspended in runoff water (Lentz and Sojka, 1994); (iv) improving runoff water quality by reducing microorganisms, pesticides and nutrient loss (Lentz et al., 1998; Sojka and Entry,

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2000; Petersen et al., 2007). These potential benefits from using PAM are influenced by a complex set of relations among polymer properties (molecular weight, charge type, and density) and soil properties such as soil texture, organic matter content, composition and concentration of the soil solution, sediment properties, and soil clay mineralogy (e.g., Ben-Hur et al., 1992; Lu et al., 2002; Seybold, 1994; Letey, 1994; Levy and Agassi, 1995; Laird, 1997; Miller et al., 1998; Levy and Miller, 1999; Green et al., 2004; Mamedov et al., 2007, McLaughlin and Bartholomew, 2007).

Addition of PAM to soil affects soil dispersion and flocculation and assists in stabilization of existing aggregates and improved bonding between and aggregation of adjacent soil particles (Schamp et al., 1975; Ben-Hur and Keren, 1997). The stabilizing efficacy of PAM is largely determined by the adsorptive behavior of the polymer molecules onto soil particles (Nadler and Letey, 1989; Malik and Letey, 1991). Negatively charged PAM tends to be repelled from clay surfaces, and hence little adsorption occurs; for example, only 2 to 3 g of anionic PAM are adsorbed on 1 kg of Na-montmorillonite (Stutzmann and Siffert, 1977; Aly and Letey, 1988). Moreover, adsorption of PAM on soil was in the range of 1 mg polymer kg⁻¹ soil, being two to three orders of magnitude lower than those obtained for the same polymer on clay material (Malik and Letey, 1991). Adsorption of PAM may also depend on soil-clay mineralogy. For neutral and acidic conditions (pH ≤ 7) adsorption of anionic PAM by smectite, kaolinite, and illite was comparable; however, for pH > 7 PAM adsorption by clays was in the following decreasing order: illite > kaolinite > smectite (Deng et al., 2006). Ben-Hur et al. (1992) also observed a considerably greater adsorption of anionic PAM by illite (>200 times) than by montmorillonite under nonacidic conditions.

The impact of PAM on soil aggregate and structure stability has received some attention. Shainberg et al. (1992) noted, for three Israeli smectitic soils with low (~2) and high (>10) exchangeable Na percentage, that addition of PAM effectively stabilizes aggregates. Nadler et al. (1996) studied low rates of PAM application (25–75 mg polymer kg⁻¹ soil) on dry and wet aggregate stability of a smectitic semiarid sandy loam soil. Improvement in stability was noted for both dry and wet aggregates, and its magnitude depended on polymer charge density, soil moisture content, and type of exchangeable ion (e.g., Na vs. Ca). Mamedov et al. (2007), who studied the stability of PAM-treated 0.5- to 1- and 1- to 2-mm aggregates from four smectitic soils, concluded that to enhance aggregate stability it is enough to stabilize the exterior surfaces of the aggregates with PAM; PAM molecules that entered into the aggregates' pores did not appear to have any significant impact on aggregate or structure stability. Polyacrylamide also played a significant role in increasing the percentage of stable aggregates compared with untreated aggregates, in predominantly kaolinitic soils of varying texture (Miller et al., 1998) and aggregate size (Levy and Miller, 1999). Green et al. (2004) observed that PAM formulation with wide range of molecular weight (6 to 18 × 10⁶ Da) had comparable effects on enhancing the aggregate stability of soils with different textures and mineralogy. Conversely, in the case of controlling aggregate slaking, the effects of PAM were soil dependent; being more effective in reducing

aggregate slaking and erosion in an unstable smectitic silt loam soil than in a clay soil (Green et al., 2004).

Soil aggregate forming, macro- and micro aggregate stability, aggregate breakdown mechanism and chemical dispersion, depend not only on clay content, organic matter and/or sesquioxides, but also on clay mineralogy (Amezketta, 1999). However, the role of clay mineralogy in affecting aggregate or structure stability is difficult to assess because soils usually contain a mixture of clay minerals, so their behavior is modified by the association with other minerals. Under unstable conditions, such as high sodicity and/or low electrolyte concentrations, soils high in montmorillonite are unstable, whereas, soils with high contents of kaolinite and sesquioxides are relatively stable, and soils high in 2:1 clay minerals, but without or with low amounts of montmorillonite have an intermediate behavior (Emerson, 1964; McNeal et al., 1966; Le Bissonnais, 1996).

The dependence of PAM efficacy as a soil aggregate stabilizing agent on soil-clay mineralogy has received little attention. Moreover, as mentioned above, studies exploring the impact of clay mineralogy on the effects of PAM on aggregate stability yielded conflicting results. These inconsistencies in the results could be ascribed to variations in (i) the electrolyte concentration and composition of the soil solution, (ii) the content of some cementing agents such as CaCO₃, organic matter, and oxides, as well as type and history of cultivation among the samples compared (Lu et al., 2002; Ruiz-Vera and Wu, 2006; Norton et al., 2006).

Furthermore, there are numerous methods for determining aggregate stability, for example, wet sieving, the drop test technique, application of ultrasonic energy. Different processes dominate in the breakdown of the aggregates in the various stability tests (Loch, 1994). Thus, not surprising, it has been reported that use of different methods for determining aggregate stability have resulted in different rankings of the soils studied. Wet sieving is one of the most common methods, but results obtained by this method are difficult to reproduce and hence comparison of different sample populations entails a great amount of work if the differences obtained are to be significant (Amezketta et al., 1996; Le Bissonnais and Arrouays, 1997). Studying aggregate sensitivity to slaking with the high-energy-moisture-characteristic (HEMC) method could serve as a viable alternative. The HEMC has been found to be a sensitive and useful method of high reproducibility for determining aggregate and structure stability of arid and humid zone soils having a wide range of stability levels (Pierson and Mulla, 1989; Levy and Miller, 1997; Crescimano and Provenzano, 1999; Levy and Mamedov, 2002; Levy et al., 2003; Norton et al., 2006; Mamedov et al., 2007; De-Campos et al., 2009). The objective of this study was, therefore, to determine, by the HEMC technique, the impact of soil-clay mineralogy on the effectiveness of anionic PAM in enhancing aggregate and structure stability.

MATERIALS AND METHODS

Soils

Fifteen samples from the cultivated layer (0–250 mm), and one sub-soil sample (11 from the USA, 4 from Israel and 1 from Brazil) varying in their clay mineralogy and texture (loam and clay type soils by USDA

Table 1. Soil name, classification, dominant clay mineralogy and texture.

Soils	Location	Classification	Dominant clay minerals †	Texture‡	Resource
Fincastle	Indiana, USA	Aeric Epiaqualfs	S(3S), I(3), K(3), V(2)	Silt loam	Green et al., 2004
Nevatim	Israel	Calcic Haploxeralf	S(5), I(2–3), K(2), Q(1)	Loam	Mamedov et al., 2006
Fayette	Iowa, USA	Typic Hapludalfs	S(4), V(2), I(1), K(1),	Silty clay loam	Dontsova and Norton, 2002
Hafetz Haim	Israel	Chromic Haploxerert	S(5), I(3), K(2), Q(1)	Sandy clay	Mamedov et al., 2006
Yagur	Israel	Typic Haploxerert	S(5), I(3), K(2), Q(1)	Clay	Mamedov et al., 2006
Heiden	Texas, USA	Udic Haplusterts	S(5), K(1), Q(1), V(2)	Clay	Green et al., 2004
Eilon	Israel	Typic Haploxerert	S(5), I(3), K(2), Q(1)	Clay	Mamedov et al., 2006
Catlin	Illinois, USA	Oxyaquic Argiudolls	I(3), S(2), V(2), K(1),	Silt loam	Dontsova and Norton, 2002
Miami	Indiana, USA	Oxyaquic Hapludalfs	I(3), S(2), V(2), K(1)	Silt loam	Dontsova and Norton, 2002
Throckmorton	Indiana, USA	Mollic Oxyaquic Hapludalfs	I(3), S(2), V(2), K(1)	Silt loam	Norton et al., 2006
Blount	Ohio, USA	Aeric Epiaqualfs	I(3), K(1), HIV(2)	Loam	Dontsova and Norton, 2002
Hoytville	Ohio, USA	Mollic Epiaqualfs	I(3), S(1), Q(1)	Clay	Reichert et al., 2009
Cecil A	Georgia, USA	Typic Kanhapludults	K(5), Q(1), Ox(1), HIV(1)	Sandy loam	Green et al., 2004
Cecil B	Georgia, USA	Typic Kanhapludults	K(3), Q(1), Ox(1), HIV(1)	Clay	Reichert et al., 2009
Cecil Bt	Georgia, USA	Typic Kanhapludults	K(3), Q(1), Ox(1), HIV(1)	Clay	Reichert et al., 2009
Londrina	Parana, Brazil	Typic Eutrotrolox	K(3), Ox(2), HIV(1),	Clay	Reichert et al., 2009

† S, smectitic; I, illitic; K, kaolinitic; V, vermiculites; Q, Quartz; Ox, Fe and Al hydroxides; HIV, hydroxy-interlayered vermiculite.

‡ USDA classification.

§ 1 = 0–3; 2 = 3–10; 3 = 10–30; 5 = >50% of the total clay fraction.

classification) were used for this study. The soils' location, classification (based on the U.S. soil classification system of Soil Taxonomy), and mineralogy are given in Table 1. Selected physical and chemical properties of the soils, determined by standard analytical methods (Klute, 1986; Page et al., 1986), are presented in Table 2. Based on their dominant clay mineralogy the soils have been divided into the following three groups: smectitic (seven soils), illitic (five soils), and kaolinitic (four soils) (Tables 1 and 2).

Polymer

An anionic PAM of high-molecular-weight ($\sim 18 \times 10^6$ Da) and 30% hydrolysis with a trade name of Magnafloc 156 (Ciba Specialty Chemicals, Suffolk, VA, USA) was used. A polymer solution of 200 mg L⁻¹ was prepared with tap water (electrical conductivity [EC] of 0.9 dS m⁻¹, sodium adsorption ratio of 2 [mmol_c L⁻¹]^{0.5}, and pH of 6.7) under constant stirring

and slow addition of polymer granules over 4 h. Polymer solutions were prepared with tap water rather than deionized water to improve the dissolution of the polymer and minimize the impact of the dissolved polymer on the viscosity of the solution (Barvenik, 1994). We expected that use of the less viscous solution would reduce the undesired effect of solution viscosity on the degree of PAM penetration into intra-aggregate porosity.

Aggregates Preparation

The soil samples were air-dried, crushed, and sieved to 0.5- to 1-mm aggregates. To ensure that (i) aggregates will not slake during wetting with the polymer solution, and (ii) each individual aggregate will come in contact with the polymer solution, the following procedure was employed. Plastic boxes (15 × 15 cm) were filled with a very coarse sand to form a 5-mm thick layer that was then covered with a high

Table 2. Selected properties of the soils used.

Clay mineralogy or Soil groups	Soils	Soil texture			CEC†	Exchangeable cations				OM‡	CaCO ₃	pH§	EC§
		Sand	Silt	Clay		Ca	Mg	Na	K				
		—g kg ⁻¹ —				—cmol _c kg ⁻¹ —							
		—g kg ⁻¹ —				—cmol _c kg ⁻¹ —					—g kg ⁻¹ —		dS m ⁻¹
Smectitic	Fincastle	140	700	160	10.37	6.71	3.38	0.07	0.21	14.3	0.0	5.58	0.64
	Nevatim	413	362	225	17.68	13.43	3.04	0.37	0.84	12.2	182.4	7.82	1.80
	Fayette	57	652	291	16.50	9.90	6.10	0.20	0.30	14.0	0.0	5.70	1.50
	Hafetz Haim	465	154	381	34.76	24.78	7.49	0.57	1.92	11.0	96.2	7.46	2.60
	Yagur	145	342	513	57.43	43.45	10.48	0.94	2.56	17.6	202.0	7.61	0.81
	Heiden	125	306	569	69.26	64.24	4.16	0.16	0.70	36.5	45.0	7.62	1.34
	Eilon	137	213	650	64.90	46.23	15.32	0.73	2.62	18.2	46.0	7.33	0.91
Illitic	Catlin	234	585	181	19.90	17.40	2.20	0.22	0.08	39.0	0.0	7.10	0.60
	Miami	104	711	185	11.70	8.00	3.30	0.18	0.22	20.0	0.0	5.60	0.80
	Throckmorton	280	510	210	11.05	6.56	3.82	0.30	0.37	21.0	0.0	5.60	0.68
	Blount	306	440	254	16.00	12.80	2.90	0.21	0.09	24.0	0.0	6.00	1.70
	Hoytville	64	370	566	20.30	15.20	4.74	0.09	0.27	41.8	0.0	6.00	0.45
Kaolinitic	Cecil A	707	159	134	4.49	3.41	0.69	0.05	0.34	8.2	0.0	4.98	0.46
	Cecil B	420	174	406	2.80	1.50	0.88	0.07	0.35	3.5	0.0	5.80	0.33
	Cecil Bt	250	146	604	2.46	1.38	0.81	0.06	0.21	5.2	0.0	5.40	0.42
	Londrina	63	275	662	6.40	3.20	2.74	0.04	0.42	27.8	0.0	5.60	0.96

† CEC, cation-exchange capacity.

‡ OM, organic matter.

§ pH and EC (electrical conductivity) were determined in a saturated paste extracts.

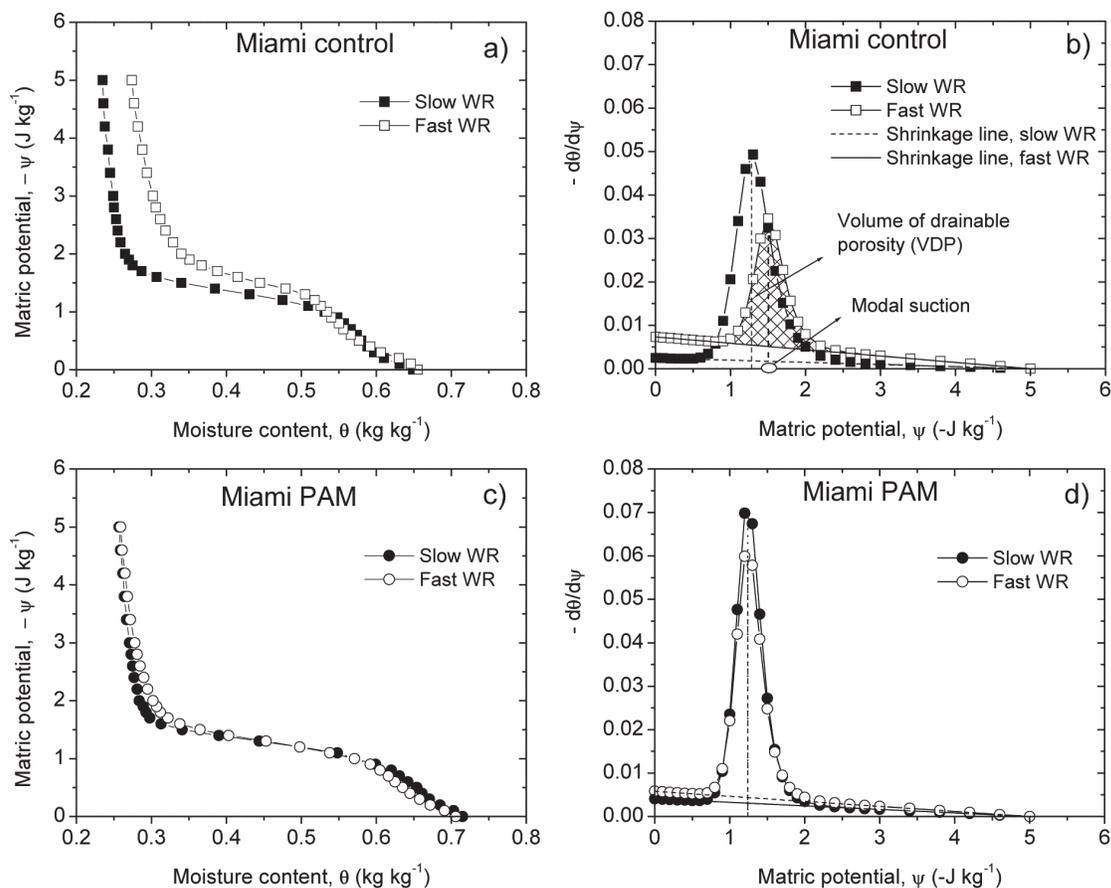


Fig. 1. (a) water retention, and (b) specific water capacity curves of the non-treated and polyacrylamide (PAM)-treated Miami (*Oxyaquic Hapludalfs*) silt loam aggregates subjected to fast and slow wetting. The dashed baseline in the specific water capacity curve represents soil shrinkage line.

porosity ($>60\text{-}\mu\text{m}$ pore size) filter paper allowing polymer molecules to diffuse to the aggregates (Mamedov et al., 2007). Aggregates from a given soil were gently spread on the filter paper to form a monolayer of aggregates. The aggregates were saturated from below with tap water or the 200 mg L^{-1} PAM solution during 1 h, at a rate of 4 mm h^{-1} using a peristaltic pump, and were then kept in their respective solution for 24 h to reach equilibrium. The boxes were covered with plastic lids to eliminate possible evaporation. Then the solutions from the boxes were drained and the aggregates were left to dry in an oven at 60°C for 24 h. The aggregates were sieved again ($0.5\text{--}1.0\text{ mm}$) after drying to eliminate broken ones. Finally, the polymer concentration in the solution before and after saturating the aggregates was determined. The analysis, using a total C analyzer, showed that polymer concentration decreased by $<3\%$, indicating no deficiency in polymer for adsorption by the aggregates.

Aggregate and Structure Stability Determination Theory

Aggregate and structure stability was characterized using a modified version of the HEMC method (Levy and Mamedov, 2002), which measures aggregate sensitivity to slaking. In this method, $0.5\text{--}1.0\text{-mm}$ aggregates are wetted either slowly or rapidly in a controlled manner, and then soil water retention curve at high energies (i.e., matric potential from 0 to -5.0 J kg^{-1} or from 0- to $50\text{-cm H}_2\text{O}$ tension) is performed. An index of aggregate stability is obtained by quantifying differences in soil water retention curves for fast and slow wetting (Fig. 1a, c). For a given wetting rate, a structural index is defined as the ratio of volume of drainable pores (VDP) to modal

suction (Collis-George and Figueroa, 1984). Modal suction corresponds to the matric potential ($\psi, \text{J kg}^{-1}$) at the peak of the specific water capacity curve ($d\theta/d\psi$), where θ is the water content (kg kg^{-1}) (Fig. 1b, d). The VDP is defined as the integral of the area under the specific water capacity curve and above its baseline (Fig. 1b, d) and thus is expressed in units of moisture content (kg kg^{-1}). The ratio of the structural index obtained from fast wetting to the structural index obtained from slow wetting is termed stability ratio (SR). In general, the SR is used to compare stability of aggregates on a relative scale of zero to one ($0 < \text{SR} < 1$). Unity SR indicates stable aggregates that resisted slaking by fast wetting. A value of zero SR indicates that fast wetting destroyed the aggregates to the extent that all pores that drain at the applied matric potential range no longer exist. However, use of other indices to describe the stability of aggregates, such as only the structural index for a given treatment (e.g., fast wetted soils), or the ratio of the structural index obtained from Treatment A to the structural index obtained from Treatment B (for instance control vs. PAM) at a similar wetting rate, when employing the HEMC method is also possible (Collis-George and Figueroa, 1984, Crescimano and Provenzano, 1999; Mamedov et al., 2007).

Procedure

Fifteen grams of the $0.5\text{--}1.0\text{-mm}$ depth of the oven-dried PAM-treated or untreated (control) aggregates were placed in a 60-mm i.d. funnel with a fritted disc to form a $\sim 5\text{-mm}$ thick bed. The fritted disc had a nominal maximum pore size of 20 to $40\text{ }\mu\text{m}$. The fritted disc was saturated before placing aggregates in the funnel. The funnel was connected from its bottom via tubing to a peristaltic pump, which was then

used to wet the aggregates in the funnel either at a fast (100 mm h⁻¹) or a slow (2 mm h⁻¹) rate. Wetting lasted until full saturation (the soil surface became shining) and thereafter a small positive difference of <0.5 mm between soil surface level in the funnel and water level in the pipette was maintained. Deionized water (EC ~ 0.004 dS m⁻¹) was used for wetting of the untreated and PAM treated aggregates in the funnel.

A water retention curve, at a matric potential range of 0 to -5.0 J kg⁻¹, was obtained using a hanging water column, whereby height of the meniscus in the pipette was decreased in increments of 0.1 to 0.2 J kg⁻¹ (i.e., 1.0–2.0 cm) thereby increasing the suction applied. The volume of water that drained from the aggregates at each matric potential was recorded after a 2-min equilibrium period and corresponding water content of the aggregates was calculated. Preliminary studies (Levy and Miller, 1997, Norton et al., 2006) showed that under our experimental conditions (0.5- to 1.0-mm macroaggregate size, and matric potential range at near saturation, e.g., from 0 to -5.0 J kg⁻¹), generally no additional change in volume of drainage is noted at equilibrium time >2 min. Each treatment was duplicated. The coefficient of variation between replicates of water content (θ , kg kg⁻¹) was <6%.

Data Analysis

To accurately calculate the VDP and modal suction, modeling of water retention curves was performed by precisely fitting ($R^2 = 0.96$ to 0.99 in all cases) the following seven-parameter modified van Genuchten model (Pierson and Mulla, 1989; Levy and Mamedov, 2002) to the measured data,

$$\theta = \theta_r + (\theta_s - \theta_r) \left[1 + (\alpha\psi)^n \right]^{1/(n-1)} + A\psi^2 + B\psi + C \quad [1]$$

where θ_s and θ_r are pseudo saturated and residual gravimetric water contents, respectively; α and n control location and steepness of the S-shape inflection of the water retention curve, respectively; and A, B, and C are the quadratic terms (Pierson and Mulla, 1989) to improve fitting of the model to the water retention curve. The specific water capacity curve ($d\theta/d\psi$), needed for obtaining the value of modal suction, was computed by differentiating Eq. [1] with respect to matric potential, and had the explicit form:

$$(d\theta/d\psi) = (\theta_s - \theta_r) \left[1 + (\alpha\psi)^n \right]^{1/(n-1)} (1/n-1)(\alpha\psi)^{n-1} / \left\{ \psi \left[1 + (\alpha\psi)^n \right] \right\}^{-1} + 2A\psi + B \quad [2]$$

The VDP was calculated by subtracting the terms for pore shrinkage ($2A\psi + B$) from Eq. [2], and analytically integrating the remainder of that equation.

Unlike the water retention curves for the untreated aggregates, generally the water retention curves of the slow- and fast-wetted PAM-treated aggregates were of similar shape and/or value for each clay mineralogy (Fig. 1 and 2), irrespective of soil texture. We, therefore, decided to deviate from the usual procedure used to determine the SR (e.g., Pierson and Mulla, 1989; Levy and Miller, 1997; Levy and Mamedov, 2002). Thus, the impact of PAM on soil aggregates and structure stability (relative to untreated aggregates) was also evaluated using a relative SR index (RSR), determined as the ratio of the SR of the PAM-treated aggregates to the SR of the untreated aggregates, that is, $RSR = SR(\text{PAM})/SR(\text{Control})$.

Statistical Analysis

The aggregate stability study tested three main treatments, clay mineralogy (three groups), soil texture (loam and clay), and PAM addition (untreated and PAM-treated). An unbalanced full factorial design was used for this study of 12 treatments (3 types of clay mineralogy \times 2 types of soil texture \times 2 treatments), each in two replicates. An ANOVA was conducted using the SAS Proc GLM procedure (SAS Institute, 1995) according to a completely randomized design to assess the effects of the treatments and or their interactions on structure and aggregate stability indices (Table 3). Although the treatments or their interactions had, generally, a significant effect ($P < 0.05$) on the various aggregate stability indices (Table 3), the interaction among the three main factors was not significant for most of the evaluated indices (e.g., moisture content, modal suction and VDP for fast wetting rate), probably because the investigated groups included soils that differed in some of their properties (e.g., CEC, pH, and EC), thus causing wide differences in soil pore-size distribution and aggregate stability following fast wetting. Hence, comparisons of the effects of the main factors and or their interaction, and also the contribution of soil properties to the studied indices have been evaluated by the following analyses (Fig. 3–7, Tables 3–6):

- (i) Between soil groups: SAS Proc GLM was used to analyze the effects of (a) clay mineralogy, soil texture, and their interaction on differences in moisture content at saturation ($\Delta\theta_s$) and RSR, and (b) clay mineralogy, PAM and their interaction on modal suction, VDP, and SR; a least squares means test with a Tukey adjustment ($P < 0.05$) was used to evaluate comparisons (Fig. 3a–7a, Table 3).
- (ii) Within soil groups: (a) a one-way ANOVA test was employed to compare the effects of each soil on the difference in moisture content at saturation ($\Delta\theta_s$) and RSR, and (b) a two-way ANOVA was applied to assess the effects of soil, PAM and their interaction on modal suction, VDP, and SR; separation of means was tested using Turkey HSD at $P < 0.05$ level (Fig. 3b–7b, Table 4).
- (iii) Between or within each clay mineralogy group: The soils studied varied with respect to clay content, CEC, exchangeable cations, content of carbonates and organic matter, and pH and EC of the soil solution. Since there were considerable differences in soils' properties, the Pearson pairwise correlation and the stepwise regression analysis ($P < 0.05$) were used to examine the influence of all soil properties, including clay mineralogy (CEC/clay content ratio; see discussion below) on the differences in soil structure and aggregate stability indices (e.g., VDP, modal suction, moisture content at saturation) between control and PAM-treated samples and also the RSR (Tables 2, 5, and 6).

Considering the importance of the charges on the clay surfaces in each soil, clay activity classes have been defined as the ratio of CEC to clay content (Tables 5 and 6), due to the fact that a small amount of smectitic material can greatly influence the overall charge of the soil due to its greater surface charge (Olson et al., 2000). The CEC/clay ratio is commonly used to assess in quantitative way soil clay mineralogy and to determine the classes of clay activity in Soil Taxonomy or Keys to Soil Taxonomy (Soil Survey Staff, 1998). Most of the soil properties correlated well with CEC/Clay content ratio and as well as with CEC in our study (Table 5). High activity clay minerals such as smectite and vermiculite usually have ratios > 0.7, low activity clays like kaolinite have ratios < 0.3, and clays of intermediate activity like illitic, mixed or chloritic

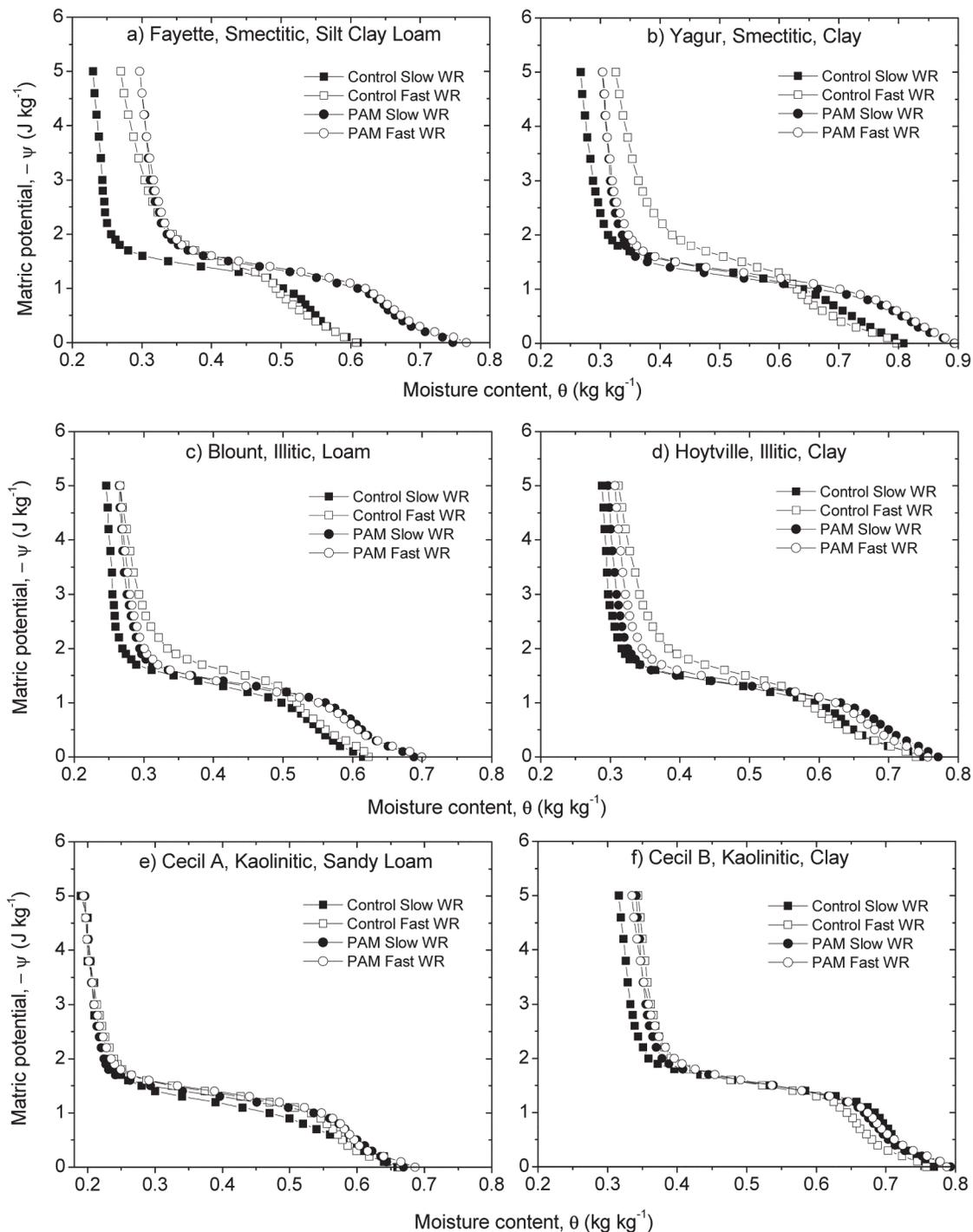


Fig. 2. Water retention curves (obtained by fast and slow wetting) of untreated control and polyacrylamide (PAM)-treated aggregates for soil samples varying in mineralogy and texture: (a and b) smectitic Fayette (Typic Hapludalfs) and Yagur (Typic Haploxerert) soils; (c and d) illitic Blount (Aeric Epiaqualfs) and Hoytville (Mollic Epiaqualfs) soils; and (e and f) kaolinitic Cecil A (Typic Kanhapludults) and Cecil B (Typic Kanhapludults) soils.

have ratios of 0.3 to 0.7 (Olson et al., 2000). Clay activity (CEC/clay) is indicative of the dominant clay type, and has been shown to be an important index in predicting moisture content at field capacity of soils with different mineralogy (Olson et al., 2000; Pachepsky and Rawls, 1999).

RESULTS AND DISCUSSION

Characteristics of the Water Retention Curves

The water retention curves for untreated and PAM-treated aggregates of six selected soils, representing one loam and one clay soil from each of the three clay mineralogy groups are pre-

sented in Fig. 2. As expected, clear differences were noted between the fast- and slow-wetting curves for the untreated control aggregates in each of the soils; the magnitude of this difference was related to soil clay mineralogy (Levy and Mamedov 2002; Norton et al., 2006). These differences between the fast- and slow-wetting curves were ascribed to aggregate slaking in the fast-wetting treatment that in itself was attributed to entrapped air, hydration of the exchangeable cations and clay surfaces of the soil particles, and differential swelling (Amezketta, 1999; Le Bissonnais, 1996; Norton et al., 2006). In each soil, the water retention curves of

Table 3. Significance of the effects of the treatments on the aggregate stability indices (between the groups).

Effect test	N par	DF	Aggregate stability indices for the two wetting rates ‡											
			θ_s , kg kg ⁻¹		Modal suction, m		VDP, kg kg ⁻¹		SI, m ⁻¹		VDPR	SR	$\Delta\theta_s$, kg kg ⁻¹	RSR
			fast	slow	fast	slow	fast	slow	fast	slow				
Clay Mineralogy (CM)	2	20 (10)	*	*	ns	ns	***	*	***	**	***	***	***	***
Texture	1	20 (10)	***	***	ns	ns	ns	***	ns	*	**	ns	ns	ns
CM x Texture	2	20 (10)	***	***	ns	***	***	***	***	***	**	ns	ns	ns
PAM	1	20	**	**	***	*	***	***	***	***	***	***	***	***
CM x PAM	2	20	*	*	**	ns	***	*	***	*	***	***	***	***
Texture x PAM	1	20	ns†	ns	ns	ns	**	*	**	*	ns	ns	ns	ns
CM x Texture x PAM	2	20	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† ns, nonsignificant at 0.05 level.

‡ θ_s , saturated moisture content; VDP, volume of drainable porosity; VDPR, volume of drainable pores ratio; SR, stability ratio; $\Delta\theta_s = \theta_s$ (PAM) - θ_s (untreated); RSR = SR (PAM)/SR (untreated).

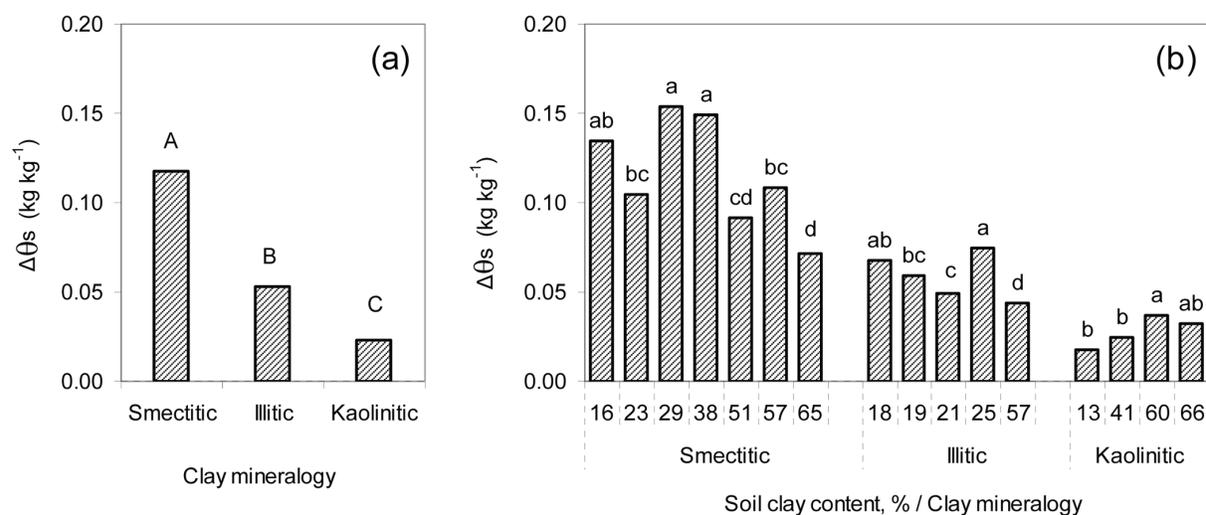


Fig. 3. Difference in moisture content at saturation between the PAM-treated and untreated fast wetted soil samples: (a) between soil groups (smectitic, $n = 7$, illitic, $n = 5$, and kaolinitic, $n = 4$), columns labeled with same capital letter are not significantly different at $P < 0.05$ level; (b) within each soil group, columns labeled with same lowercase letter are not significantly different at $P < 0.05$ level.

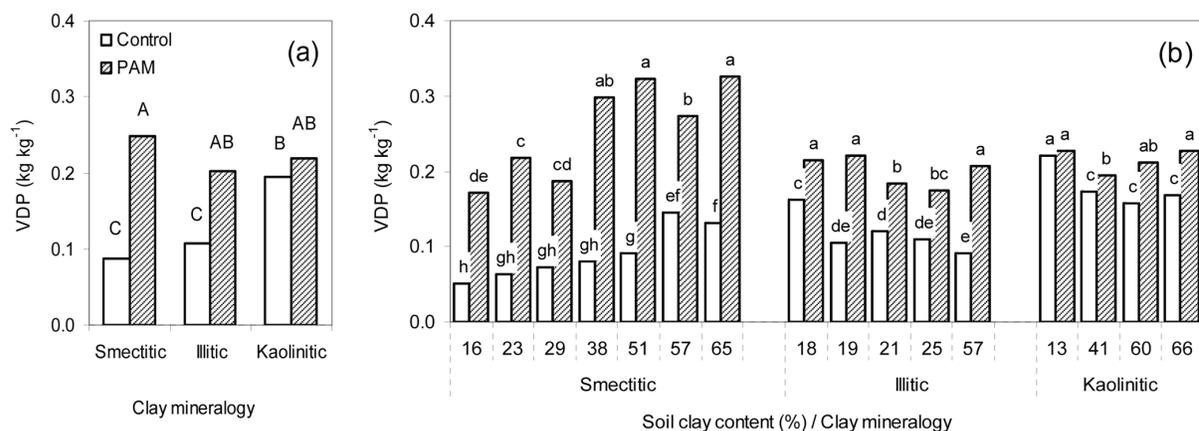


Fig. 4. Volume of drainable pores (VDP) as affected by clay mineralogy and polyacrylamide (PAM) addition for fast wetted soil samples: (a) between soil groups (smectitic, $n = 7$, illitic, $n = 5$, and kaolinitic, $n = 4$), columns labeled with same capital letter are not significantly different at $P < 0.05$ level; (b) within each soil group, columns labeled with same lowercase letter are not significantly different at $P < 0.05$ level.

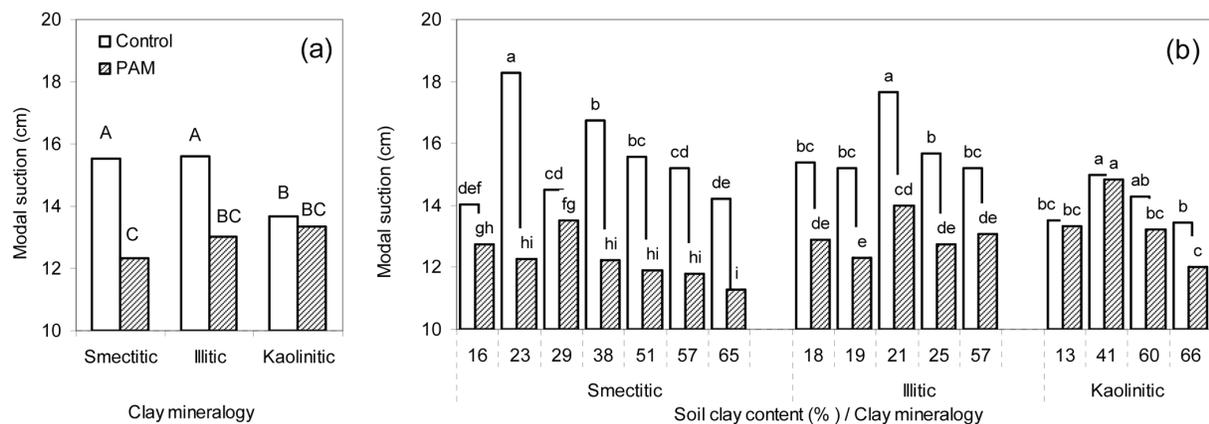


Fig. 5. Modal suction as affected by clay mineralogy and PAM addition for fast wetted soil samples: (a) between soil groups (smectitic, $n = 7$, illitic, $n = 5$, and kaolinitic, $n = 4$), columns labeled with same capital letter are not significantly different at $P < 0.05$ level; (b) within each soil group, columns labeled with same lowercase letter are not significantly different at $P < 0.05$ level.

the PAM-treated aggregates obtained under fast- and slow-wetting were, generally, of a similar shape. However, the curves for the PAM-treated aggregates were shifted to the right relative to the respective curves of the untreated aggregates (Fig. 2). This phenomenon indicates that treating the aggregates with PAM preserved large pores and inhibited formation of small pores during the wetting process. This is consistent with the expectation that PAM would stabilize the aggregates against the disintegrative forces induced by wetting. It was further noted that treating the aggregates with PAM had increased the moisture content at saturation relative to untreated aggregates subjected to both slow and fast wetting (Fig. 2). Both the ANOVA test between soils groups (Table 3, Fig. 3) and the stepwise analysis (Table 6) showed that the differences in moisture content at saturation ($\Delta\theta_s$) between the PAM-treated and the untreated fast-wetted aggregates depended mostly on soil clay mineralogy ($\sim 50\%$ of variation) along with other soil properties or prevailing conditions such as soil EC ($\sim 20\%$ of variation). The greatest $\Delta\theta_s$ values were noted for the smectitic soils ($0.072\text{--}0.15 \text{ kg kg}^{-1}$) and the lowest ($0.019\text{--}0.030 \text{ kg kg}^{-1}$) for the kaolinitic soils (Fig. 3). Assuming that treating the aggregates with PAM increases their stability at both rates of wetting, the above observation (i.e., increase in drainable pores and moisture content in PAM treated soils due to the re-

duced slaking), suggests that some aggregate slaking took place in the untreated aggregates even when slow wetting was employed (for instance due to the swelling), thus affecting the pore-size distribution and the moisture content at saturation.

In addition, following the observed differences in the water retention curves for fast wetting between the control and the PAM-treated samples the water retention curves may be divided into three subclasses of the very fine macropores diameter class ($75\text{--}1000 \mu\text{m}$, Soil Science Society of America, 1997) with matric potential range of (i) -0.3 to -1.2 J kg^{-1} (corresponding to $250\text{--}1000 \mu\text{m}$ coarse very fine macropores), (ii) -1.2 to -2.4 J kg^{-1} ($125\text{--}250\text{-}\mu\text{m}$ size medium very fine macropores), and (iii) -2.4 to -5.0 J kg^{-1} ($60\text{--}125\text{-}\mu\text{m}$ size fine very fine macropores) (Fig. 2). In the range of matric potential between 0 to -1.2 J kg^{-1} the PAM treated samples had greater moisture content levels than the control in all the soils; the differences in the moisture contents were in the following order of soil mineralogy: kaolinitic $<$ illitic $<$ smectitic (Fig. 2). However, for smaller macropore size classes, the effect of PAM on the water retention curves was limited. For the illitic soils (e.g., Blount loam and Hoytville clay) the PAM-treated aggregates either had lower moisture contents (-1.2 to -2.4 J kg^{-1} ; Fig. 2), or similar ones (-2.4 to -5.0 J kg^{-1}) to those of the untreated samples. In the

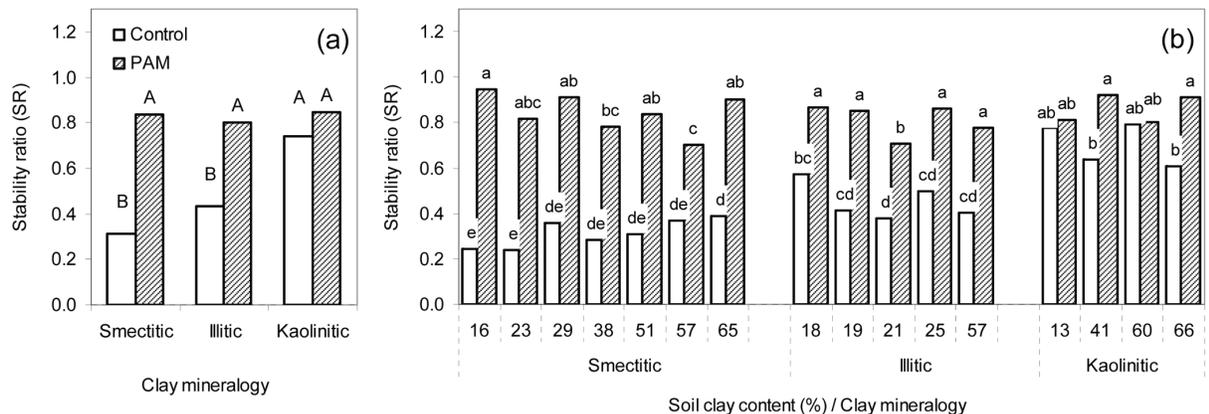


Fig. 6. Stability ratio (SR) of aggregates as affected by clay mineralogy and PAM addition: (a) between soil groups (smectitic, $n = 7$, illitic, $n = 5$, and kaolinitic, $n = 4$), columns labeled with same capital letter are not significantly different at $P < 0.05$ level; (b) within each soil group, columns labeled with same lowercase letter are not significantly different at $P < 0.05$ level.

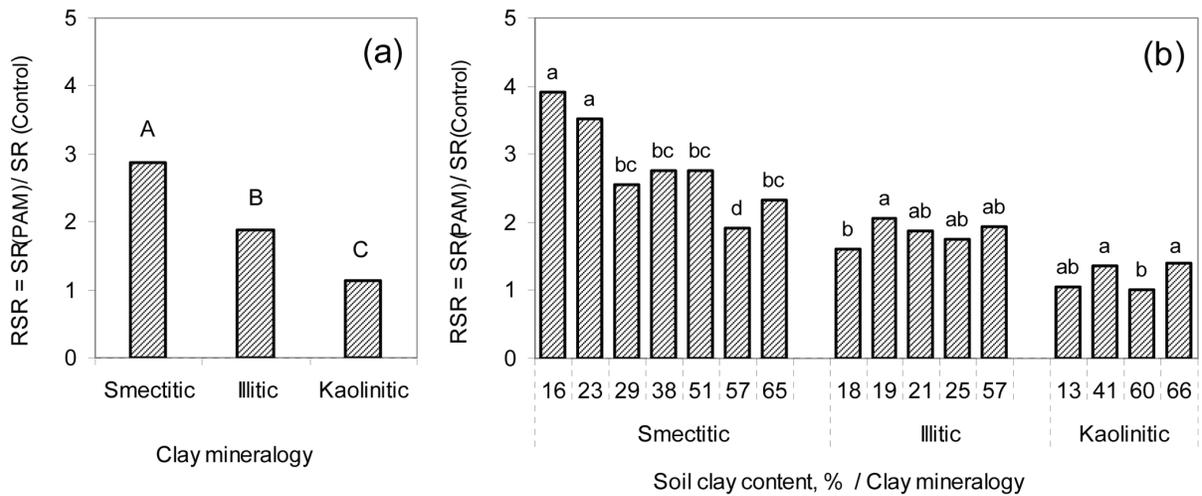


Fig. 7. Relative stability ratio (RSR = SR [PAM]/SR [Control]) for the different soils studied: (a) between soil groups (smectitic, $n = 7$, illitic, $n = 5$, and kaolinitic, $n = 4$), columns labeled with same capital letter are not significantly different at $P < 0.05$ level; (b) within each soil group, columns labeled with same lowercase letter are not significantly different at $P < 0.05$ level.

-1.2 to -2.4 and -2.4 to -5.0 J kg⁻¹ range of matric potential (corresponding to pore sizes of 125–250 and 60–125 μm, respectively), PAM-treated aggregates exhibited very close curves to those of the untreated aggregates for the kaolinitic soils. However, in the smectite-containing soils (i.e., smectitic and mixed-illitic soils) the PAM-treated aggregates maintained higher (Fayette and Miami loam) or lower (Yagur clay, and Nevatim loam, Hafetz Haim clay, Eilon clay- data not presented) moisture content levels than the untreated samples (Fig. 1a, d and 2a,b,c and d). This disagreement between the semiarid Yagur clay, and the humid Fayette loam was not fully understood. It could, however, be envisaged that this observation might depend on the amount of smectites in the soils' clay fraction, pH level (Tables 1, 2, 5, and 6, see further discussion below), and electrolyte re-

sources associated with PAM solution penetration depth and water release ability (Lu and Wu, 2003; Mamedov et al., 2007) in a given range of matric potential.

Effect of PAM on Stability Indices: Volume of Drainable Pores (VDP) and Modal Suction

The sensitivity of aggregates to slaking was used as the measure for their stability. Aggregate slaking by fast wetting, generally, results in the formation of a greater number of particles of smaller sizes than the original aggregates. This in turn, causes the interparticle pore-size distribution to shift toward a greater number of smaller pores and thus to a decrease in the VDP and a higher value for the modal suction.

Table 4. Significance of the effects of the treatments on the aggregate stability indices (within each group).

Group	Source	df	$\Delta\theta_s$ kg kg ⁻¹	RSR	Source	df	Modal suction m	VDP kg kg ⁻¹	SR
Smectitic	Soil	6	***	***	Soil	6	***	***	***
	Error	7			PAM	1	***	***	***
	Total	13			Soil × PAM	6	***	***	***
					Model	13	***	***	***
					Error	14			
					Total	27			
Illitic	Soil	4	***	**	Soil	4	***	***	***
	Error	5			PAM	1	***	***	***
	Total	9			Soil × PAM	4	*	***	*
					Model	9	***	***	***
					Error	10			
					Total	19			
Kaolinitic	Soil	3	**	***	Soil	3	***	***	ns
	Error	4			PAM	1	**	***	**
	Total	7			Soil × PAM	3	*	***	*
					Model	7	***	***	*
					Error	8			
					Total	15			

Table 6. Stepwise regression analysis of the effect of soil properties on the difference in soil aggregate stability indices, between the untreated and PAM-treated samples, and on relative stability ratio. The (-) sign indicates a negative linear relationship between the stability indices and soil property.

Indices†	Parameters	P > F	R ^{2‡}
$\Delta\theta_s = \theta_s \text{ (PAM)} - \theta_s \text{ (untreated)}$,	CEC/Clay	0.001	0.450
	EC	0.001	0.626
	Silt	0.007	0.713
	OM (-)	0.030	0.760
	Sand (-)	0.032	0.800
	Na + K (-)	0.219	0.812
$\Delta\text{VDP} = \text{VDP(PAM)} - \text{VDP(untreated)}$	CEC/Clay	0.001	0.296
	CaCO ₃	0.003	0.563
	EC	0.025	0.638
	Sand (-)	0.030	0.697
	OM	0.243	0.712
$\Delta(\text{Modal Suction}) = \text{Modal Suction (PAM)} - \text{Modal Suction (untreated)}$	CEC/Clay (-)	0.001	0.595
	Na + K	0.001	0.762
	EC	0.039	0.798
	Sand (-)	0.044	0.821
	CaCO ₃	0.109	0.838
RSR = SR (PAM)/SR (untreated)	CEC/Clay	0.001	0.300
	Ca+Mg	0.016	0.429
	Clay	0.017	0.536
	OM (-)	0.061	0.593
	Sand (-)	0.116	0.631

† θ_s , moisture content at saturation; VDP, volume of drainable porosity; MS, modal suction; RSR, relative stability ratio; SR, -stability ratio.

‡ R^2 , coefficient of regression.

Clay mineralogy and other soil properties had a substantial impact on the stability indices of the aggregates (Tables 3–6). The VDP for the fast-wetted soil samples ranged from 0.05 to 0.22 kg kg⁻¹ for the untreated samples and 0.17 to 0.33 kg kg⁻¹ for PAM-treated soils (Fig. 4). A wide variation has also been

noted for the modal suction values (Fig. 5) in both treatments (from 13.5 to 18.3 cm, and from 4.8 to 11.3 cm for the untreated and PAM-treated samples, respectively).

For 14 of the 16 soils, treating the aggregates with PAM under fast wetting increased VDP and decreased modal suction levels compared with the untreated aggregates (Fig. 4 and 5). In the predominantly smectitic and illitic soils, the VDP values of the fast-wetted PAM-treated samples were 2 to 3 times greater than those of the untreated samples, while for the kaolinitic soils, PAM increased the VDP by <1.3 times that of the untreated samples (Fig. 4). Likewise, the effects of PAM on decreasing the modal suction (i.e., increasing the size of the most frequent pore) relative to its values in the untreated samples, were most prominent in the smectitic and illitic soils (up to 6.0 and 4.0 cm, respectively), and much less so (up to 1.4 cm) for the kaolinitic soils (Fig. 5). The effects of the PAM on the VDP and the modal suction seem to depend largely on clay mineralogy (e.g., CEC/clay ratio from 30 to 60% of variation) and to a lesser extent on soil EC, texture, and exchangeable cations (Tables 3–6; Fig. 4 and 5). Similar to their effect on $\Delta\theta_s$, the electrolyte resources of soils (EC and CaCO₃) played an important role (up to 35% of variation) in determining the impact of PAM on the VDP and modal suction relative to that of the untreated samples (Table 6).

The effects of soil texture on VDP and modal suction were variable. The VDP values for the control and PAM-treated aggregates tended to increase with the increase in soil clay content in the smectitic soils; for the other soil types no consistent trend was observed (Fig. 4). The modal suction values appeared to be unrelated to clay content in any of the soil types studied (Fig. 5, Tables 3 and 6). Similar observations, with respect to VDP, for a number of soils varying in their mineralogy and texture have been reported by Norton et al. (2006).

Table 5. Pearson pair-wise correlation coefficients for properties of the soils used in the stepwise regression analysis. Units of the respective properties are as in Table 2.

Variable	CEC/Clay	Sand	Silt	Clay	CEC	Ca	Mg	Na	K	OM	CaCO ₃	pH	EC
CEC/Clay	1												
Sand	-0.18	1											
Silt	0.19	-0.48**	1										
Clay	-0.03	-0.43**	-0.55**	1									
CEC	0.84***	-0.29(0.1) †	-0.18	0.47**	1								
Ca	0.83***	-0.27	-0.18	0.46**	0.99***	1							
Mg	0.65***	-0.33*	-0.08	0.41*	0.79***	0.68***	1						
Na	0.69***	-0.05	-0.15	0.21	0.70***	0.60***	0.84***	1					
K	0.61***	-0.02	-0.38*	0.43*	0.77***	0.67***	0.88***	0.93***	1				
OM	0.24	-0.52**	0.31(0.08)	0.19	0.28(0.12)	0.32*	0.07	-0.08	-0.15	1			
CaCO ₃	0.58***	0.12	-0.22	0.12	0.51**	0.48**	0.44*	0.76***	0.69***	-0.16	1		
pH	0.74***	-0.04	-0.13	0.26(0.15)	0.73***	0.72***	0.54**	0.69***	0.65***	0.26(0.16)	0.74***	1	
EC	0.53**	0.15	-0.03	-0.11	0.33*	0.32*	0.27(0.14)	0.36*	0.31*	-0.08	0.44*	0.51*	1

*Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 level.

† Significant at 0.05–0.15 probability level.

Stability Ratio

The SR values for the control samples varied over a wide range from 0.24 to 0.80 (Fig. 6), and with respect to clay group, followed the order: kaolinitic > illitic > smectitic. This ranking of the soils with respect to aggregate and structure stability according to clay mineralogy type was in agreement with previous studies. Predominantly smectitic soils are known to have an unstable structure, soils with high contents of kaolinite are considered to be relatively stable, and soils high in 2:1 clay minerals, but without or with low amounts of smectite have an intermediate degree of stability (Emerson, 1964; McNeal et al., 1966; Le Bissonnais, 1996).

In the PAM-treated aggregates the SR data exhibited a narrow range from 0.70 to 0.94 irrespective of soil mineralogy groups or texture. However, the efficacy of PAM in improving aggregate and structure stability, expressed as a RSR, increased from 1.01 to 3.90, where RSR of kaolinitic < illitic < smectitic soils (Fig. 7). The RSR was mostly related to clay mineralogy (Fig. 7) and to CEC/clay ratio (~ 30% of variation) and to a lesser extent to the divalent exchangeable cations together with clay content (~ 25% of variation). This trend was similar to that noted for the impact of PAM on the moisture content at saturation (Table 6, Fig. 3), and indicated that PAM's ability to stabilize soil aggregates is inversely linked to the stability of the untreated aggregates; that is, the less stable the aggregates the greater the effectiveness of PAM in enhancing their stability.

Unlike for clay mineralogy, our results indicate that soil texture did not play a dominant role in determining the SR and thus aggregate stability for both untreated and PAM-treated aggregates (Table 3, Fig. 6). It is postulated that the commonly observed increase in aggregate stability with the increase in clay content (e.g., Kemper and Koch, 1966; Goldberg et al., 1988; Levy and Mamedov, 2002) did not emerge in our study possibly because the effects of clay content were masked by the effects of other stabilizing and cementing agents present in the soils studied such as organic matter, CaCO₃, and iron oxides (Amezqueta, 1999, Norton et al., 2006).

The high effectiveness of PAM in improving aggregate stability (Fig. 6 and 7) in the smectitic soils (SR = 0.38–0.57; RSR = 1.91–3.90) can be explained by the following. The predominantly smectitic soils from semiarid zone had, in general, an optimal level of pH (7.3–7.6) for anionic PAM adsorption to the soil particles (Theng, 1982; Lu et al., 2002). In addition, the high CEC of these soils (and clay activity), mostly occupied by divalent Ca and Mg cations (>90% of the CEC), together with the presence of CaCO₃ (Tables 2 and 6) can provide ample electrolytes and divalent cations that enhance the cation bridging process that is important in PAM adsorption to the negative surface of the clays in these soils (Laird, 1997). Consequently, such optimal conditions for PAM adsorption coupled with the observed low aggregate stability in the smectitic soils (Fig. 6) enhanced the ability of PAM to stabilize existing aggregates and improve bonding between, and aggregation of adjacent soil particles in this group of soils. Moreover, in the two smectitic soils with the lower pH (Fincastle

and Fayette) and no source of electrolytes (e.g., CaCO₃), but with relatively high EC, high CEC, and divalent exchangeable cations (Ca+Mg > 97% of CEC), and thus clay activity (Tables 2 and 6), the efficacy of PAM in increasing the VDP and/or decreasing the modal suction was relatively small; however the SR or RSR of these soils was still high (Fig. 6 and 7).

The kaolinitic soils emerged, as expected, as the soils with the most stable aggregates (Fig. 6). The stability of aggregates (SR = 0.61–0.78) in these soils is often associated with the presence of Fe and/or Al-oxides (McNeal and Coleman, 1966; El-Swaify and Emerson, 1975; El-Swaify, 1976; Goldberg et al., 1990). It was, however, expected that the samples having kaolinitic mineralogy with possibly small amount of smectites will have somewhat less stable aggregates than the non-contaminated kaolinitic soils, because addition of small amounts of montmorillonite to predominantly kaolinitic soils promotes the dispersion of the soil clays (Frenkel et al., 1978; Stern et al., 1991). Apparently, in our aggregate stability test the role of clay dispersion in determining aggregate sensitivity to slaking was minor, probably due to the effect of Fe and Al oxides on microaggregation through limiting clay dispersion and swelling (El-Swaify and Emerson, 1975; Amezqueta, 1999).

Addition of PAM to the kaolinitic soils had only a small beneficial effect (Fig. 7) on aggregate stability (RSR = 1.04–1.40). These soils are non-calcareous with low EC of the soil solution and, therefore, had no source of readily dissolving salts that could support the presence of divalent cations in the soil solution for the enhancement of PAM adsorption (Lu et al., 2002). It is postulated that the combined effects of initially stable aggregates together with unfavorable conditions for PAM adsorption (low or very low CEC, pH and clay surface charge) were responsible for the limited success of PAM in improving the aggregate stability in these soils (Tables 2 and 6).

The illitic soils occupied an intermediate position between the smectitic and the kaolinitic soils with respect to aggregate stability (SR = 0.38–0.57) (Fig. 6). Illite is a clay most sensitive to dispersion (El-Swaify, 1976; Shainberg and Letey, 1984). This is due to the smaller edge-to-face attraction forces in comparison to the other clays, because of the irregular and terraced surfaces of the illite particles. The greater stability of the aggregates from the illitic soils compared with those from the smectitic soils could be ascribed to the greater organic matter content (20–42 kg kg⁻¹), and lower pH values (5.6–6.0, acidic) in the former type soils (Table 2).

Addition of PAM increased the aggregate stability (RSR = 1.52–2.05) in the illitic soils, but to a lesser extent than that observed in the smectitic soils (Fig. 6 and 7). Under acidic conditions, similar to those of our illitic soils (Table 2, Fig. 6), adsorption of anionic PAM by smectite, kaolinite, and illite is similar (Deng et al., 2006). Furthermore, the predominantly illitic soils were non-calcareous, with low EC of the soil solution (Table 2), and hence, similar to the kaolinitic soils, they lacked readily dissolved minerals that could immediately provide divalent cations to the soil solution that could boost PAM adsorption to the soil. Generally, the effects of PAM on the modal suction, VDP, SR, and/or the RSR of the illitic Miami soil with the substantial de-

gree of smectite contamination and lower organic matter content seemed to be relatively greater than its effects on these determinants for the Catlin, Hoytville, or Blount illitic soils; the Catlin soil contains a higher organic matter content (39.0 g kg⁻¹), and the other two soils are less contaminated with smectite (Table 1, Fig. 4–7) compared with the Miami soil. Consequently, it is suggested that PAM was less effective in improving aggregate stability in the illitic soils compared with the smectitic soils because of the lower CEC and clay activity, and absence of readily dissolving minerals, and thus lesser adsorption of the PAM to the soil particles (Tables 2 and 6). Yet, when compared with the kaolinitic soils, it seems that the greater beneficial effect of PAM on aggregate stability in the illitic soils arises from the weaker structure of aggregates in the latter soils compared with the former, and possibly also to the greater impact of PAM on the flocculation of illite compared with kaolinite (McLaughlin and Bartholomew, 2007; Bhardwaj et al., 2009).

SUMMARY AND CONCLUSIONS

We studied the efficiency of an anionic high molecular weight PAM as a stabilizing agent on 16 soil samples varying in clay mineralogy and texture. Aggregate and structure stability was estimated from the sensitivity of aggregates to slaking. For the non-treated aggregates from the 16 soils tested, aggregate, and structure stability decreased in the order of kaolinitic > illitic > smectitic soils. Addition of PAM increased the moisture content (up to 0.15 kg kg⁻¹) of the aggregates at saturation, increased the VDP and decreased the modal suction, all leading to an increase in the stability of the aggregates compared with the untreated ones. The effectiveness of PAM in improving aggregate stability in these soils followed in the order of kaolinitic < illitic < smectitic soils. Unlike clay mineralogy, soil texture (clay content) did not affect the ability of PAM to stabilize aggregates, particularly in the illitic and the kaolinitic soils. The efficacy of PAM in improving aggregate stability was therefore proposed to be (i) inversely related to the inherent stability of the aggregates, and (ii) directly linked to soil conditions affecting PAM adsorption to the soil; the latter could also be associated with the type of the dominant clay mineral (clay activity) in the soil. Optimal pH levels and presence of readily dissolving minerals that provide a source of divalent cations to the soil solution (e.g., smectitic soils) may enhance PAM adsorption to soil particles and thus its ability to increase aggregate stability.

Anionic high-molecular weight PAM is an environmentally safe soil amendment, commonly used for improving soil-structure stability, reducing erosion and preventing sediment and other pollutants from entering runoff water. Our results suggest, however, that soil clay mineralogy (e.g., predominantly, mixed) and/or clay activity which is readily available from soil survey data (e.g., USDA-NRCS) should be considered before the use of PAM to obtain maximal effectiveness from its use in arid and humid regions. Future experiments on the effects of wetting-drying cycles, PAM concentration and electrolyte composition

(Ca, Mg, K, or Na) on soil aggregates and structural stability will contribute to better utilization of PAM under field conditions.

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