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AGGREGATE STABILITY AND WATER RETENTION NEAR SATURATION CHARACTERISTICS AS AFFECTED BY SOIL TEXTURE, AGGREGATE SIZE AND POLYACRYLAMIDE APPLICATION

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ABSTRACT

Understanding the effects of soil intrinsic properties and extrinsic conditions on aggregate stability is essential for the development of effective soil and water conservation practices. Our objective was to evaluate the combined role of soil texture, aggregate size and application of a stabilizing agent on aggregate and structure stability indices (composite structure index [SI], the α and *n* parameters of the VG model and the S-index) by employing the high energy (0–5·0 J kg^{-1}) moisture characteristic (HEMC) method. We used aggregates of three sizes (0·25–0·5, 0·5–1·0 and 1·0–2·0 mm) from four semi-arid soils treated with polyacrylamide (PAM). An increase in SI was associated with the increase in clay content, aggregate size and PAM application. The value of α increased with the increase in aggregate size and with PAM application but was not affected by soil texture. For each aggregate size, a unique exponential type relationship existed between SI and α. The value of *n* and the S-index tended, generally, to decrease with the increase in PAM application; however, an increase in aggregate size had an inconsistent effect on these two indices. The relationship between SI and *n* or the S-index could not be generalized. Our results suggest that (i) the effects of PAM on aggregate stability are not trivial, and its application as a soil conservation tool should consider field soil condition, and (ii) α, *n* and S-index cannot replace the SI as a solid measure for aggregate stability and soil structure firmness when assessing soil conservation practices. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil conservation; stable aggregates; pore size distribution; soil structure; retention curve

INTRODUCTION

Problems associated with soil and water conservation in cultivated and irrigated lands, e.g. enhanced spatio-temporal variation of agricultural fields; intensified soil degradation; increased runoff generation, sediment and pollutant transport under irregular rain with high intensity, are all expected to become more severe with climate change (e.g. Mohawesh *et al.,* 2015; Rodrigo Comino *et al.,* 2015; Prosdocimi *et al.,* 2016). These aforementioned problems are expected to severely harm crop growth and the production of food and fiber resources (Anaya-Romero *et al.,* 2015; Ochoa *et al.,* 2016). Thus, there is a growing need for implementing soil and water conservation technologies to protect soil and water quality in order to mitigate and adapt to climate change. As a key element of soil health, soil aggregate stability studies serve as primary indicators of recovery or degradation of soils and are important for evaluating the effects of land use and land management and the impacts of applied soil erosion control strategies (Cerda, 2000; Mamedov and Levy, 2013).

Use of soil amendments such as a non-toxic anionic polyacrylamide (PAM) has been shown to be beneficial for soil and water conservation and water quality (e.g. reviews by Sojka *et al*., 2006; Levy & Warrington, 2015 and cited references). However, the potential benefits from using PAM might be inconsistent because PAM effectiveness is influenced by a complex set of relations among polymer properties (concentration, molecular weight, charge type and density) (Green *et al*., 2004; McLaughlin & Bartholomew, 2007), its mode of application (e.g. dry, wet, emulsion) (Mamedov *et al*., 2009; Shainberg *et al*., 2011; Liu *et al*., 2014) and soil properties such as clay mineralogy, texture, organic matter content, composition and concentration of the soil solution and associated soil microbiological activity, (e.g. Miller *et al*., 1998; Levy & Miller, 1999; Busscher *et al*., 2007; Mamedov *et al*., 2010; Wu *et al*., 2010; Dou *et al*., 2012).

Miller *et al*. (1998) investigated aggregate (6·3–9·5 mm) stability in three kaolinitic soils amended with an anionic PAM with high molecular weight and concluded that (i) under 20 mm of high kinetic energy rain, PAM addition significantly increased the percentage of stable aggregates, and (ii) PAM was more effective at stabilizing aggregates from light to medium textured soils than those from a clayey soil. These results suggest that PAM efficacy was greatly affected by soil texture. Levy & Miller (1999) observed that stabilization efficacy of the high molecular weight PAM in predominantly kaolinitic sandy loam and sandy clay soils (0·5–1·0 to 6·0–9·5 mm aggregates) depended, in addition to soil texture, also on aggregate size,

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with this phenomenon being more pronounced in the sandy loam. It was concluded that aggregate stability was higher for PAM-treated aggregates compared with untreated aggregates and increased with increase in aggregate size, as a result of penetration of PAM molecules into the aggregates and its adsorption on internal surfaces (Levy & Miller, 1999).

A few recent studies highlighted the importance of clay mineralogy in determining the efficacy of an anionic high molecular weight PAM as a stabilizing agent. Mamedov *et al*. (2010) observed that (i) PAM efficacy in improving aggregate and structural stability followed in the order of kaolinitic < illitic < smectitic soils, and (ii) addition of PAM had only a limited effect on kaolinitic soils, but increased the structure stability and moisture content near saturation (up to 0·15 kg kg^{-1}) and thus total porosity for the smectitic soil samples mostly with low clay content (Mamedov *et al*., 2010). Green *et al*. (2004) who studied stability of aggregates (<2·0 mm) from three soils differing in texture and mineralogy (a smectitic clay, a kaolinitic sandy loam and a mixed mineralogy silt loam), treated with anionic PAM of different molecular formulation (e.g. 6–18 Mg mol^{-1} molecular weight and 20–40% charge densities) concluded that PAM was more effective in enhancing the stability of dry aggregates compared with its effects on controlling the slaking of fast wetted aggregates. McLaughlin & Bartholomew (2007), who examined the effects of PAM concentration, molecular weight (14–28 Mg mol^{-1}) and charge density (from neutral to 50% anionic molar charge) on the flocculation of suspensions from 13 subsoils (ranging from sand to clay) sampled from the US Coastal Plain, noted that increase in smectite and vermiculite content (>20%) in these subsoils reduced the effectiveness of anionic PAM as a flocculent. It was further noted that differences in the reduction in water turbidity between control and PAM-treated samples were highly correlated with soil texture, mineralogy, and extractable Fe reductions, with most of the differences in flocculation occurring in subsoils with >20% smectite or vermiculite (McLaughlin & Bartholomew, 2007).

Melo *et al*. (2014) studied the contribution of different rates of PAM (0–100 mg kg^{-1}) on aggregates' mean weight diameter and geometric mean diameter and structural quality of cohesive and non-cohesive soils from five to six horizons of two Brazilian soils. The authors stressed that, although PAM contribution was soil dependent, PAM was effective in stabilizing aggregates in the two larger-size classes (0·25–2·0, >2·0 mm) in both soils (Melo *et al*., 2014). Caesar-Tonthat *et al*. (2008) who studied addition of three PAM rates to three aggregate sizes (0·25–0·5, 0·5–1·0 and 1·0–2·0 mm) of a Norfolk loamy sand soil reported that adding PAM (120 mg kg^{-1}), with and or without wheat residue, to aggregates (0·5–1·0 and 1·0–2·0 mm) favored the growth and survival of specific fungi and bacterial species functioning as soil aggregators *in vitro*, and consequently considerably enhanced aggregation, pore continuity and soil physical condition (Busscher *et al*., 2007; Caesar-Tonthat *et al*., 2008).

Many different aggregate stability and structure firmness tests (e.g. wet sieving, drop test technique, application of ultrasonic energy, etc.), employing diverse primary breakdown mechanisms have been used for establishing an index of soil structure stability. The aggregate breakdown mechanisms and the size distribution of the disrupted products depend on the type of energy involved in aggregate disruption, but could also be affected by the initial size of studied aggregates (Le Bissonnais, 1996; Amezketa, 1999; Pulido Moncada *et al*., 2015). Aggregate size distribution, which is affected by soil properties and management, and climatic conditions, is closely related to soil pore size distribution. The latter can be derived from the water retention characteristics and is considered as a basic index for soil physical quality (Dexter & Czyz, 2007; Saha & Kukal, 2015.). Changes in the water retention characteristics curve (e.g. the location of the inflection point and the steepness of its slope) are commonly quantified by the van Genuchten model parameters (van Genuchten, 1980; Guber *et al*., 2003; Dexter, 2004a; Porebska *et al*., 2006; Lipiec *et al*., 2007; Mamedov & Levy, 2013). Furthermore, Dexter (2004a) proposed the use of the angular coefficient of the water retention curve at the inflection point, termed S-index, as a proxy for soil physical quality because it is indicative of the extent to which the soil porosity is concentrated into a narrow range of pore sizes. In many soils, S-index values >0·035 were found to be indicative of soils with good physical conditions (Dexter, 2004a,2004b,2004c; Tormena *et al*., 2008; Calonego & Rosolem, 2011), although Andrade & Stone (2009) proposed the threshold of S-index = 0·045 to be appropriate to separate soils with good structural conditions from degraded soils. It was, therefore, deemed suitable to use, in the current study, the high energy moisture characteristic (HEMC) method, in which water retention curves at near saturation, characterized by a modified version of the van Genuchten model (Pierson & Mulla, 1989; Levy & Mamedov, 2002; Mamedov & Levy, 2013), are employed for evaluating soil aggregate stability.

We hypothesized that, among others (e.g. clay mineralogy), the efficacy of PAM as a soil conservation measure for improving aggregate and structure stability depends on both soil texture and aggregate size. Thus, the prime objective of the study was to evaluate the role of soil texture (intrinsic property), and aggregate size, and application of a stabilizing agent (extrinsic conditions) on aggregate stability. A secondary objective was to test the suitability of the α and/or *n* parameters of the aforementioned modified van Genuchten model and the S-index (Dexter 2004a) to serve as indices for aggregate stability and thus in turn as indices for assessing soil conservation practices efficacy.

MATERIALS AND METHODS

Soils

Four smectitic, calcareous soils representing the main arable soils in Israel, were chosen for this study. The soils were a loam (Calcic Haploxeralf) from the northern Negev, a sandy clay (Chromic Haploxerert) from Hafetz Haim in the Pleshet Plains, and two clays (Chromic Haploxerert) from Yagur in the Zevulun Valley (Clay Y) and Eilon in the Western Galilee (Clay E). Samples from the cultivated layer (0–250 mm) of

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each soil type were brought to the laboratory. Selected physical and chemical properties of the soils, determined by standard analytical methods (Klute, 1986; Page *et al*., 1986), are presented in Table I.

Polymer

An anionic PAM of high-molecular-weight (~18×10^6 Da) and 30% hydrolysis with a trade name of Magnafloc 156 (Ciba Specialty Chemicals, Suffolk, VA, USA) was used. A polymer solution of 100 mg L^{-1} was prepared with tap water (electrical conductivity [EC] of 0.5 dS m^{-1}, sodium adsorption ratio of 2.0 [$mmol_c$ L^{-1}]$^{0.5}$, and pH of 6·5) 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 a less viscous solution would reduce the undesired effect of solution viscosity on the degree of PAM penetration into intra-aggregate porosity.

Preparation of Aggregates

The soil samples were air-dried, gently crushed and sieved to 0·25 to 0·5; 0·5 to 1·0; 1·0 to 2·0 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 (30 × 60 cm) were filled with a very coarse sand to form a 5-mm thick layer that was then covered with a high porosity (>60-μm pore size) filter paper allowing polymer molecules to diffuse to the aggregates (Mamedov *et al*., 2010). 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 100 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. Thereafter, the solutions from the boxes were drained and the aggregates were placed in an oven to dry at 60 °C for 24 h. The aggregates were sieved again after drying to eliminate broken aggregates outside of the described size range. 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%, indicting no deficiency in polymer for adsorption by the aggregates.

Aggregate Stability Determination

Stability of aggregates in the size range of 0·25–0·5, 0·5–1·0 and 1·0–2·0 mm was studied using a modified version of the HEMC method (Levy & Mamedov, 2002). Briefly, 15 g of aggregates from a given size range was placed in a 60-mm I.D. funnel with a fritted disc to form a bed ~5·0 mm thick with a bulk density of ~1·05 g cm^{-3}. The fritted disk had a nominal maximum pore size of 20 to 40 μm. Saturation of the fritted disc was ensured prior to placing aggregates in the funnel. The aggregates were wetted from the bottom in a controlled manner with a peristaltic pump at a fast rate (100 mm h^{-1}). Wetting lasted until full saturation (the soil surface became shiny); thereafter, a small positive difference of <0·5 mm between the 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.

After completion of the wetting, a soil water retention curve at high energies of matric potential from 0 to −5·0 J kg^{-1} (0 to −50 cm H_2O), corresponding to drainable pores of 50 to 2000 μm, using small steps of 0·1–0·2 J kg^{-1} (1·0–2·0 cm), was performed (Figure 1a). 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 & Mamedov, 2002) showed that under our experimental conditions (0·25- to 2·0-mm macro aggregate 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%.

Aggregate stability was then inferred from differences among the water retention curves (i.e. differences in pore size distribution) of the treatments tested by characterizing the retention curves with a modified version (Pierson & Mulla, 1989) of the van Genuchten model (van Genuchten, 1980). This analysis yields the following indices: (i) α (cm^{-1}), and *n* (dimensionless) that represent the location of the inflection point and the steepness of the S-shaped water retention curve (Figure 1a); (ii) the volume of drainable pores (VDP, g g^{-1}), defined as the integral of the area under the specific water capacity curve ($d\theta/d\psi$) and above its

Table I. Selected properties of the four soils studied: sand, silt and clay contents, cation exchange capacity (CEC), exchangeable sodium percentage (ESP), $CaCO_3$ content and organic matter (OM) content

Soil site type		Particle-size distribution			CEC	ESP	$CaCO_3$	OM
		Sand	Silt	Clay				
		g kg^{-1}			$cmol_c$ kg^{-1}		g kg^{-1}	g kg^{-1}
Loam	Nevatim	413	362	225	17·7	2·10	182·4	12·2
Sandy clay	Hafetz Haim	465	154	381	34·8	1·63	96·2	11·0
Clay-Y	Yagur	145	342	513	57·4	1·64	202·0	17·6
Clay-E	Eilon	137	213	650	64·9	1·12	4·6	18·2

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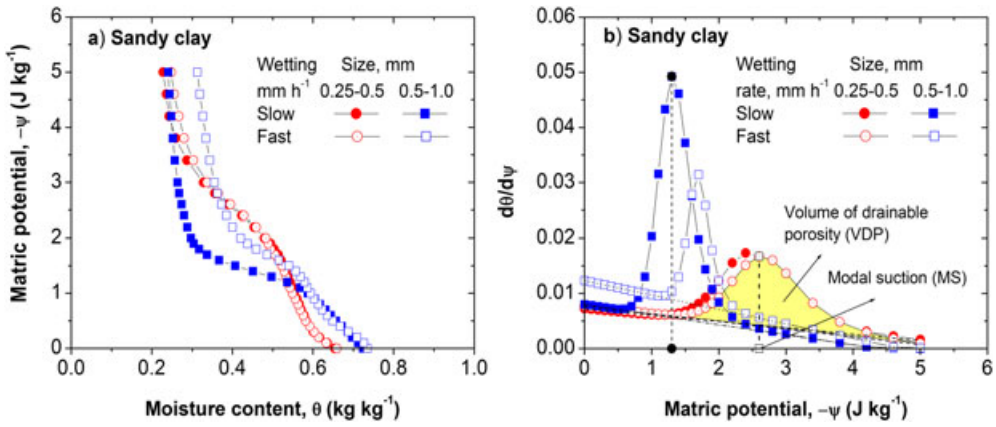

Figure 1. Water retention (a) and specific water capacity (b) curves of the sandy clay (Chromic Haploxerert) soil aggregates (0·25–0·50 mm and 0·5–1·0 mm) subjected to fast and slow wetting. The dashed baseline in the specific water capacity curve represents soil shrinkage line. [Colour figure can be viewed at wileyonlinelibrary.com]

baseline (Figure 1b); and (iii) the modal suction (MS, cm), which is the matric potential at the peak of the specific water capacity curve (Figure 1b) and corresponds to the most frequent pore size; the higher the value of the MS, the smaller the size of the most frequent pore. A composite index termed "structural index" (SI, cm^{-1}), which is defined as the ratio of the VDP to the MS (SI = VDP/MS), is then used to characterize the stability of the aggregates. Use of additional indices to describe the stability of aggregates, such as the ratio of the SI obtained from Treatment A to the SI obtained from Treatment B (for instance control vs. PAM) at a similar wetting rate, when employing the HEMC method is also possible (Mamedov & Levy, 2013; Hosseini *et al*., 2015).

In addition, because, as was mentioned above, the water retention curves in the range of full saturation to wilting point, and the water retention curve used in the HEMC method have a similar shape, we also calculated the S-index proposed by Dexter (2004a):

$$S = -n \cdot (\theta s - \theta r) \cdot [(2n-1)/(n-1)]^{((1/n).-2)} \quad (1)$$

where S = angular coefficient of the water retention curve at the inflection point [S-index]; θ_r = soil gravimetric moisture at the matric potential of 50 cm H_2O (g g^{-1}); θ_s = saturated soil gravimetric moisture (g g^{-1}); n = coefficient of the water retention curve obtained from the modified version (Pierson & Mulla, 1989; Mamedov & Levy, 2013) of the van Genuchten model.

Statistical Analysis

The aggregate stability study tested three main treatments: soil type (represented by clay content), PAM addition (untreated and PAM-treated) and aggregate size (Table II). A balanced full factorial design was used for this study containing 24 treatments (4 soil clay contents × 2 PAM treatments × 3 aggregate size), each in two replicates. An ANOVA test 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 (i) water retention curve parameters (α, n and S-index), and (ii) aggregate stability index (SI). Treatment mean comparisons were made by employing the Tukey–Kramer HSD test (SAS Institute, 1995) using a significance level of 0·05. In the case of the relative SR index (RSR = SI [PAM]/SI [Soil] determined for the same aggregate size), because a ratio is considered, standard deviation of the ratios was used rather than the Tukey test, as no normal distribution of these variables could be assumed.

Table II. Significance levels for treatment (soil texture, polyacrylamide [PAM], and aggregate size [AS, 0·25 to 0.5 mm, 0·5 to 1·0 mm and 1·0 to 2·0 mm]) effects on the stability indices (SI, structural index; RSR, relative stability ratio; α and n, model parameters which represent the location of the inflection point and the steepness of the water retention curve respectively, and S-index angular coefficient of the water retention curve at the inflection point). NS, not significant; * Significant at the 0·05 level; ** Significant at the 0·01 level; *** Significant at the 0·001 level

Source	df	α	n	SI	S-index	RSR
Soil	3	***	NS	***	***	*
PAM	1	***	***	***	***	***
Soil × PAM	3	*	NS	***	NS	***
Aggregate size (AS)	2	***	***	***	***	
Soil × AS	6	***	***	***	***	
PAM × AS	2	***	***	***	***	
Soil × PAM × AS	6	***	***	**	***	

RESULTS AND DISCUSSION

Characteristics of the Water Retention Curves

The water retention curves for untreated and PAM-treated aggregates of three sizes for the four soils are presented in Figure 2. Clear differences were noted, especially with respect to the location of the inflection point (α) and the steepness (n) of the curves, between the water retention curves of the small aggregates (0·25–0·5 mm) and those of the other

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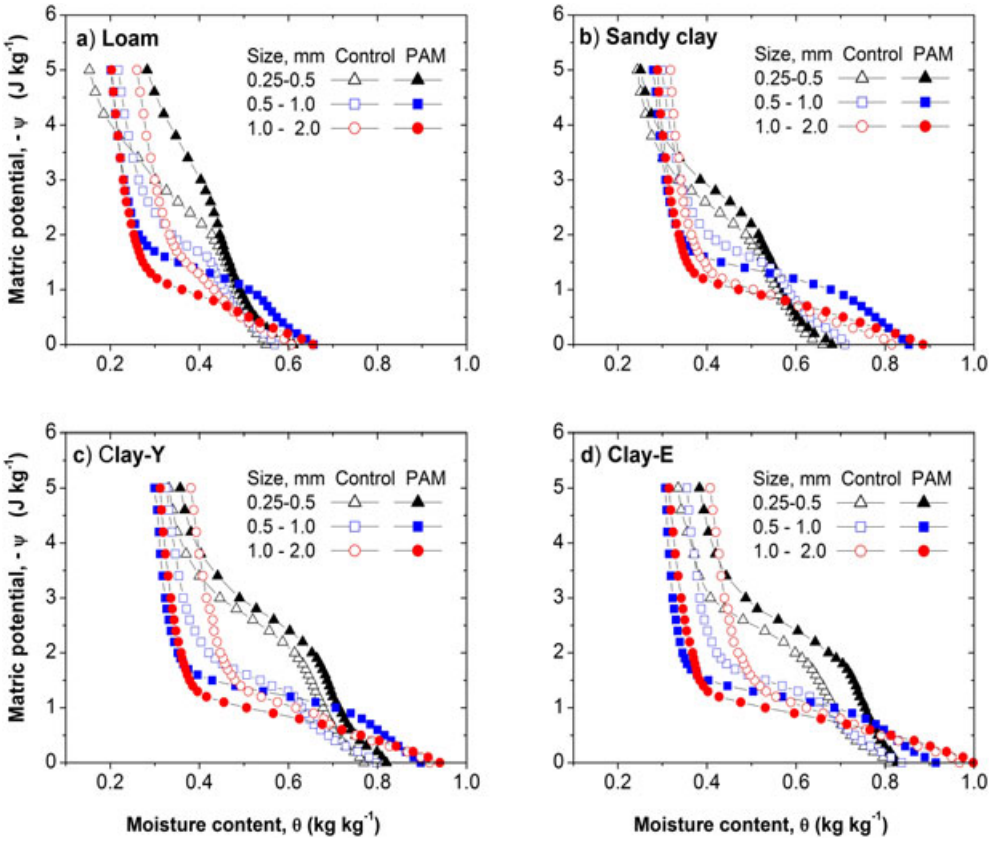

Figure 2. Water retention curves of untreated (control) and polyacrylamide treated (PAM) aggregates from a) loam (Calcic Haploxeralf), b) sandy clay (Chromic Haploxerert), c) clay-Y (Chromic Haploxerert) and d) clay-E (Chromic Haploxerert) soils as affected by aggregate size. [Colour figure can be viewed at wileyonlinelibrary.com]

two larger-size groups. Some considerable differences in the curves were also noted between untreated and PAM-treated aggregates in each soil (Figure 2). The observed differences among the treatments were ascribed to the impact of the treatments on the sensitivity of the aggregates to slaking, that in itself is associated with entrapped air, hydration of the exchangeable cations and clay surfaces of the soil particles, and differential swelling (Amezketa, 1999; Mamedov & Levy, 2013).

The aforementioned effects of the aggregate size on the retention curves were also notable in each soil in conjunction with the PAM-treated aggregates, where for the larger aggregates (0·5–1·0 and 1·0–2·0 mm) the curves were located close to each other and separated from that of the PAM-treated small aggregates (0·25–0·5 mm) (Figure 2). Moreover, the water retention curves for the PAM-treated larger aggregates were mostly located on the left side (e.g. at $\psi < -1{\cdot}2\,\mathrm{J\,kg^{-1}}$) of the untreated aggregates, whereas for the small aggregates (0·25–0·50 mm) the opposite was observed (Figure 2).

Effect of Aggregate Size and PAM Application on the Structure Stability Indices

Results of a multifactor ANOVA (SAS Institute, 1995) (Table II) showed that the effects of the three main factors (soil type, aggregate size and PAM application), as well as their interactions on (i) the aggregate-structure index (SI), (ii) PAM application on the RSR, and (iii) the model parameters (α, n and S-index), were significant (with exception of Soil and Soil × PAM treatments for *n* and S-index). The results of the statistical analyses (Table II) suggest that, similar to the aforementioned qualitative analysis of the water retention curves, the impact of PAM on soil physical properties is intricate and depends on both intrinsic (clay content) and extrinsic (aggregate size) soil properties.

The effects of the treatments on soil SI were complex, i.e. the SI increased with the increase in soil clay content and PAM application; yet the effects of aggregate size on the SI values were PAM dependent (Figure 3, Table III). In the case of the PAM-treated aggregates the SI increased with the increase in aggregate size. However, for the untreated aggregates, mostly similar SI values were noted in the two groups of the smaller-size aggregates which were also significantly lower than the SI values noted in the largest-size aggregates (Figure 3, Table III).

A direct evaluation of the impact of the PAM treatment, as obtained from the RSR parameter, indicated that the effects of PAM on aggregate stability were aggregate size dependent (Figure 4). In the smallest size group (0·25–0·5 mm) PAM did not improve aggregate stability beyond that of the untreated aggregates. In the 0·5–1·0 mm aggregates PAM had the largest effect on aggregate stability; moreover, a trend was noted whereby the effect of PAM was inversely related to soil clay content. In the largest aggregate size

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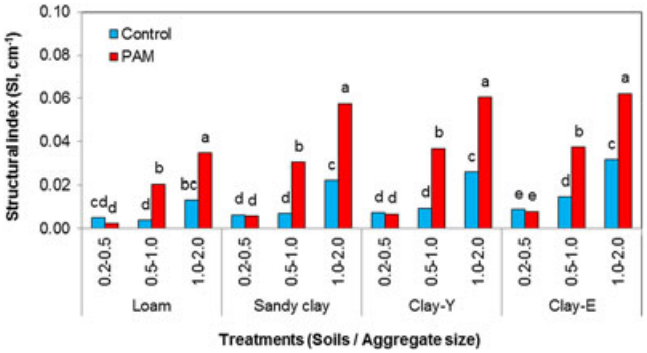

Figure 3. Structural index (SI) as affected by treatments (soil, aggregate size, PAM treatments). For each soil, columns labeled with same letter are not significantly different at $P < 0{\cdot}05$ level. [Colour figure can be viewed at wileyonlinelibrary.com]

(1·0–2·0 mm), PAM improved aggregate stability relative to the untreated aggregates, but its effects were independent of soil texture (Figure 4). It had been proposed in former studies that the pores in large aggregates are big enough to enable some of the PAM molecules to penetrate into the aggregate and to adsorb on internal surfaces (Levy & Miller, 1999; Mamedov *et al*., 2007; Ashgari *et al*., 2009; Melo *et al*., 2014), and thus to enhance aggregate resistance against slaking during wetting. This mechanism could explain the observed beneficial effect of PAM in our 0·5–1·0 mm aggregate size. The lesser effectiveness of PAM in stabilizing the aggregates in the largest size ones (1·0–2·0 mm), compared with the mid-size group (0·5–1·0 mm), could be explained by the fact that the inherent stability of the untreated aggregates in the 1·0–2·0 mm group was already fairly high (Figure 3), thereby limiting the ability of PAM to further stabilize the aggregates (Figure 4). Conversely, in small aggregates the pores are probably too small to enable PAM molecules to fully penetrate into the aggregates (Levy & Miller, 1999); thus, PAM efficacy in stabilizing the small aggregates had probably been limited. The latter explains the observed lack of efficacy of PAM in improving the resistance to slaking of our smallest aggregate size group (0·25–0·50 mm), which was, generally, in agreement with other studies (Busscher *et al*., 2007; Caesar-Tonthat *et al*., 2008; Melo *et al*., 2014).

Effects of Aggregate Size and PAM Application on the Model Parameters

The contribution of agricultural management and treatments on soil water retention could also be quantitatively characterized by the α and *n* parameters from the modified van Genuchten model and by the S-index (Dexter, 2004a), because changes in α, *n* and the S-index are considered to be closely related to pore size distribution and therefore to aggregate and particle size distribution (e.g. Guber *et al*., 2003; Dexter, 2004a,2004b,2004c; Porebska *et al*., 2006; Lipiec *et al*., 2007). In the case of smectitic soils, model parameters α and *n* were also noted to depend on aggregate size along with soil texture (Mamedov & Levy, 2013). These authors also proposed that under conditions of near saturation (ψ between 0 and $-5{\cdot}0\,J\,kg^{-1}$), the α and *n* parameters can also be used to characterize the contribution of both large aggregate size

Table III. Linear regression between soil structure indices (SI, α, n and S-index) and soil clay content (SI, soil structural index; α and *n* model parameters which represent the location of the inflection point and the steepness of the S-shaped water retention curve, respectively; S-index, angular coefficient of the water retention curve at the inflection point)

Parameters	Treatments	Aggregate size, mm	Equation	R^2 ($P < 0{\cdot}05$)
SI, cm^{-1}	Control	0·25–0·5	y = 0·00009x + 0·003	0·99
		0·5–1·0	y = 0·0002x + 0·002	0·96
		1·0–2·0	y = 0·0004x + 0·004	0·98
	PAM	0·25–0·5	y = 0·0001x − 0·00001	0·93
		0·5–1·0	y = 0·0004x + 0·013	0·89
		1·0–2·0	y = 0·0006x + 0·026	0·77
α, cm^{-1}	Control	0·25–0·5	y = 0·0002x + 0·029	0·81
		0·5–1·0	y = 0·0004x + 0·044	0·99
		1·0–2·0	y = 0·0002x + 0·096	0·23
	PAM	0·25–0·5	y = 0·0003x + 0·019	0·91
		0·5–1·0	y = 0·0002x + 0·072	0·99
		1·0–2·0	y = 0·0001x + 0·120	0·26
n	Control	0·25–0·5	y = 0·1546x + 2·239	0·92
		0·5–1·0	y = −0·1433x + 19·768	0·97
		1·0–2·0	y = 0·0266x + 4·191	0·53
	PAM	0·25–0·5	y = 0·0203x + 7·585	0·51
		0·5–1·0	y = −0·003x + 7·446	0·45
		1·0–2·0	y = 0·0187x + 4·317	0·61
S-index	Control	0·25–0·5	y = 0·018x + 0·064	0·93
		0·5–1·0	y = 0·0087x + 0·376	0·75
		1·0–2·0	y = −0·0052x + 1·433	0·44
	PAM	0·25–0·5	y = 0·0052x + 0·649	0·63
		0·5–1·0	y = 0·008x + 0·155	0·86
		1·0–2·0	y = 0·0086x + 0·216	0·98

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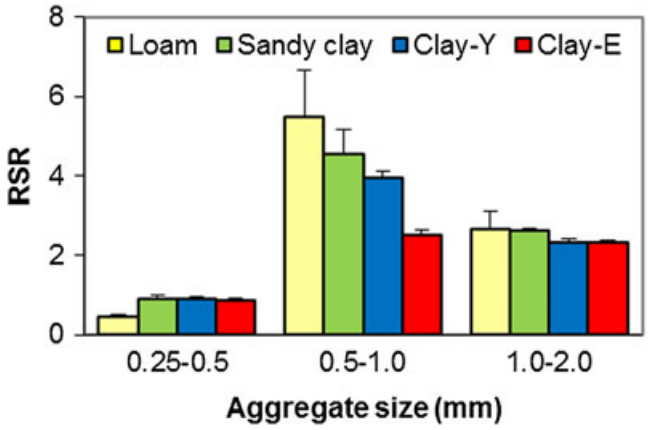

Figure 4. Relative stability ratio (RSR= SI[PAM]/SI[Soil]) as affected by treatments. The error bar represents one standard deviation. [Colour figure can be viewed at wileyonlinelibrary.com]

(>0·25–0·5 mm, $\psi \sim 0$ to $-1{\cdot}2\,J\,kg^{-1}$) and small (<0·25–0·5 mm, $\psi \sim -1{\cdot}2$ to $-5{\cdot}0\,J\,kg^{-1}$) aggregates/particles, respectively, to soil structure condition.

For each soil, α increased significantly with (i) the increase in aggregate size and (ii) PAM application for the 0·5–1·0 and 1·0–2·0 mm aggregates. In the small-sized (0·25–0·5 mm) aggregates, addition of PAM had no significant effect on α. Furthermore, for all aggregate sizes and irrespective of PAM addition, α was not affected by soil clay content (Figure 5, Table III). Bearing in mind that 1/α (~MS) represents the most frequent pore size (the smaller the value of 1/α or the larger the value of α, the larger the size of the most frequent pore), then an increase in α implies an increase in the size of the most frequent pore. Larger pores are associated with larger aggregates (Hamamoto *et al.*, 2011; Mamedov & Levy, 2013). Hence, the observed trends in the increase in α following the increase in the size of the aggregates or addition of PAM, implies an increase in the stability of the aggregates and their resistance to slaking by wetting. The above analysis might suggest that α could serve as a good proxy for evaluating changes in aggregate stability following changes in soil extrinsic conditions such as changes in size of aggregates (e.g. following different tillage practices) and/or application of soil amendments (e.g. PAM) (Porebska *et al.*, 2006; Lipiec *et al.*, 2007; Mamedov *et al.*, 2010). Under our experimental conditions, α was affected by aggregate size, but not by soil texture, while aggregate stability in our study (expressed by the SI index) as well as stability indices in former studies (e.g. Kemper & Koch, 1966) were strongly associated with soil texture (Table III). Attempts to associate the SI with α indicated that a strong ($R^2 > 0.83$) exponential type relation existed between the two parameters (Figure 6). The fact that the relations between the SI and α were unique for every aggregate size may suggest that soil texture plays a secondary role to aggregate size in determining soil structure stability in untreated and PAM-treated aggregates.

Unlike α, the effects of the treatments on the parameter *n* were inconsistent (Figure 7, Table III). In the loam, sandy clay and clay-Y soils (22, 38 and 51% clay, respectively), *n* values for the 0·5–1·0 mm aggregates were the highest, with values for the untreated aggregates being significantly higher than those for the PAM-treated aggregates (Figure 7). The *n* values for the 1.0–2.0 mm aggregates were similar to or lower than those for the 0.25–0.5 mm aggregates; PAM had no effect on

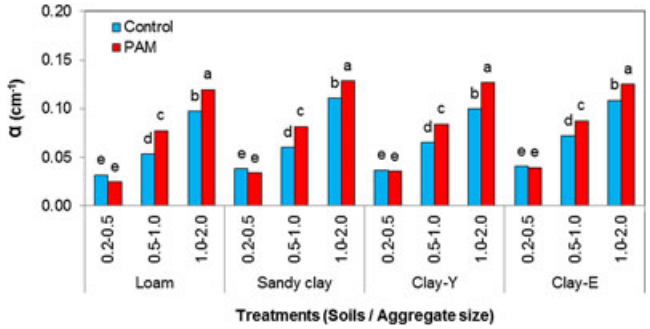

Figure 5. Model parameter α as affected by treatments (soil, aggregate size, PAM treatments). For each soil, columns labeled with same letter are not significantly different at $P < 0{\cdot}05$ level. [Colour figure can be viewed at wileyonlinelibrary.com]

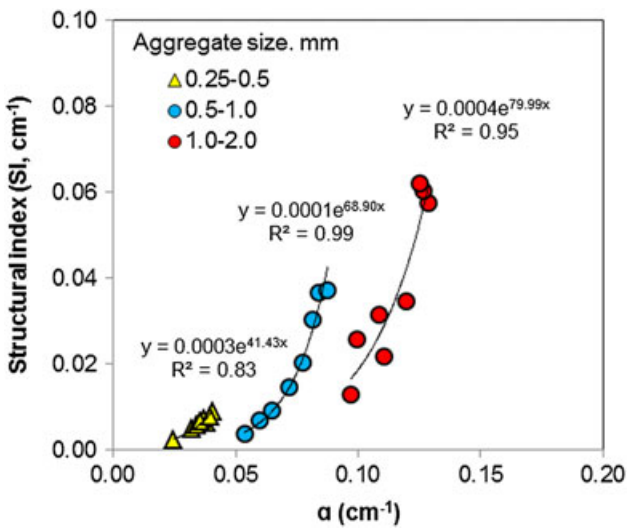

Figure 6. Structural index (SI) as a function of α, the location of the inflection point of the S-shaped water retention curve. [Colour figure can be viewed at wileyonlinelibrary.com]

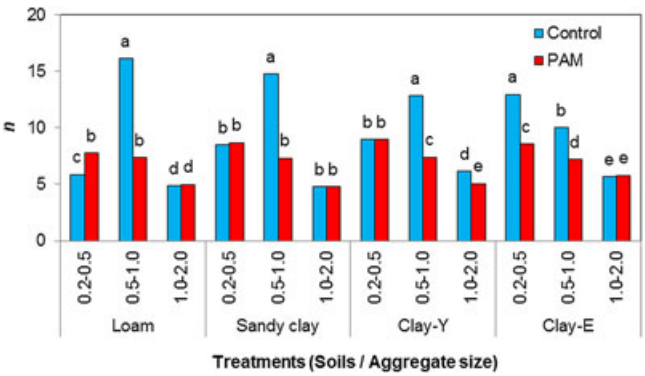

Figure 7. Model parameter *n* as affected by treatments (soil, aggregate size, PAM treatments). For each soil, columns labeled with same letter are not significantly different at $P < 0{\cdot}05$ level. [Colour figure can be viewed at wileyonlinelibrary.com]

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the n values in these two aggregate sizes. Conversely, in the soil with 65% clay, n decreased with the increase in aggregate size, with PAM addition leading to lower n values compared with the untreated aggregates only in the two smaller aggregate sizes (Figure 7). The parameter n represents the steepness of the water retention curve which is related to the spread of the pore-size distribution in the tested sample (Mamedov and Levy, 2013). There was a strong relationship ($R^2 > 0{\cdot}9$) between parameter n and clay content for the untreated small (0·25–0·5 mm, positive) and medium size aggregates (0·5–1·0 mm, negative), whereas for large and PAM-treated aggregates this relationship was significantly weaker ($R^2 < 0{\cdot}6$; Table III). Our results suggest, therefore, that n cannot serve as a direct indicator for changes in aggregate stability following changes in the conditions prevailing in the soil.

The relationship between SI and n could not be generalized as it was strongly aggregate size dependent (Figure 8). For the small (0·25–0·5 mm) and the large (1·0–2·0 mm) aggregates no relations between SI and n were identified. In the case of the small aggregates, the SI was hardly affected by changes in n, while for the large aggregates a big increase in SI was noted over a small change in n (Figure 8). Only for the intermediate size aggregates (0·5–1·0 mm), the SI decreased linearly ($R^2 = 0{\cdot}81$) with the increase in n (Figure 8).

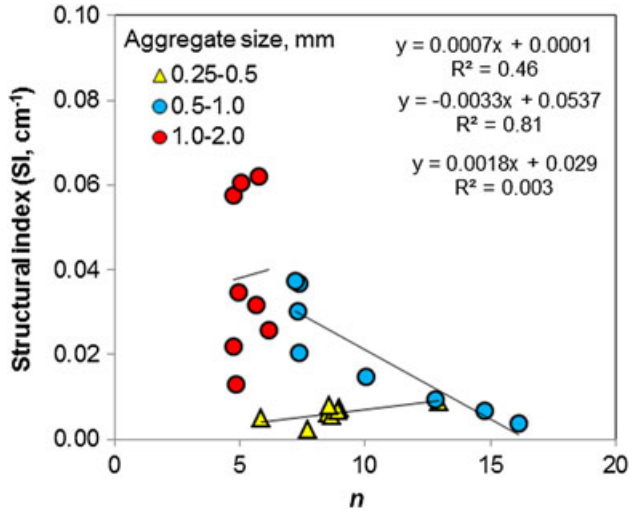

Figure 8. Structural index (SI) as a function of n, the steepness of the S-shaped water retention curve. [Colour figure can be viewed at wileyonlinelibrary.com]

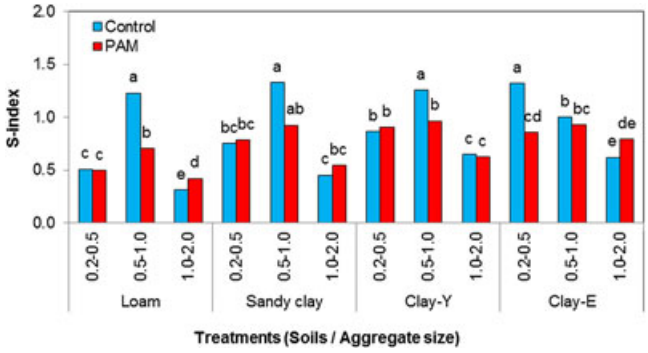

Figure 9. S-index as affected by treatments (soil, aggregate size, PAM treatments). Within each soil texture the column labeled with same letter is not significantly different at $P < 0{\cdot}05$ level. [Colour figure can be viewed at wileyonlinelibrary.com]

The effects of the treatments on the S-index values are presented in Figure 9. In the loam, sandy clay and clay-Y soils (22, 38 and 51% clay, respectively), the S-index values for the 0·5–1·0 mm aggregates were the highest, with values for the untreated aggregates being significantly higher than those for the PAM-treated aggregates (Figure 9). In the other two aggregate sizes a trend was noted whereby the S-index values for the PAM-treated aggregates were similar to, or higher, than those for the untreated aggregates. In the Clay-E (65% clay) the S-index decreased significantly with the increase in aggregate size for the untreated aggregates. For the PAM treated aggregates in this soil, the S-index values were comparable for the different aggregate size classes (Figure 9); consequently, the S-index for the PAM-treated 1·0–2·0 mm aggregates was higher than that in the untreated ones.

Similar to the case with the parameter n, the relationship between SI and the S-index could not be generalized as it was strongly aggregate size dependent (Figure 10). For the small (0·25–0·5 mm) and the large (1·0–2·0 mm) aggregates a positive linear relation between SI and the S-index was identified. Conversely, for the intermediate size aggregates (0·5–1·0 mm), the SI decreased linearly with the increase in the S-index (Figure 10). Some resemblance in the SI versus S-index and SI versus the n relationships could be noted, especially for the small- and mid-size aggregates (Figures 8 and 10). This resemblance may arise from the linear association between the S-index values and the n values (S-index = 0·096n [$R^2 = 0{\cdot}75$]), which could be expected from Equation 1.

It should be pointed out that the S-index values in our study were very high (>0.4), being almost one order of magnitude higher than those reported in the literature for soils having good physical (0.035–0.059) condition (Dexter, 2004b). Similarly, our n values that were in the range of 5–16 (Figures 7 and 10) are substantially higher than n

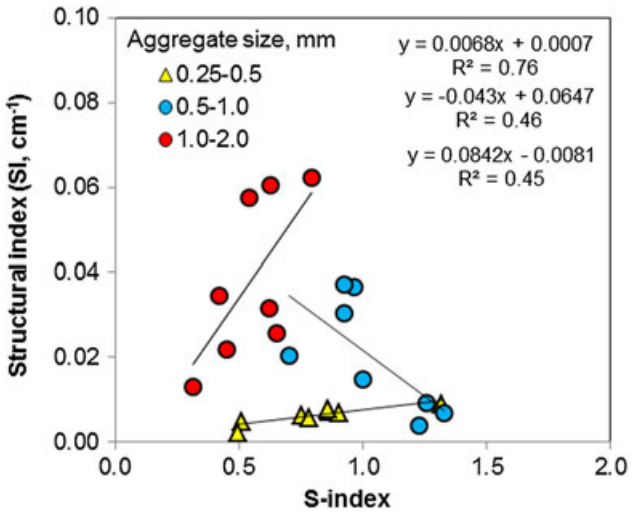

Figure 10. Structural index (SI) as a function of S-index, the slope of the water retention curve in its inflection point. [Colour figure can be viewed at wileyonlinelibrary.com]

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values reported by Dexter (2004a) for 12 FAO/USDA soil texture classes (n in the range of 1 to 1.6), or n values reported by Calonego & Rosolem (2011) for tropical soils from Brazil (n in the range of 1 to 6). It is postulated that our uncharacteristically high S-index and n values stem from the fact that we studied water retention curves at near saturation, which affects water emptying of meso- and macropores only (50–70 and >70-μm pores, respectively). When developed, the S-index was intended to reflect changes in microstructural porosity (Dexter, 2004a). Our results suggest, therefore, that the S-index seems to be an incompatible index for assessing changes in meso- and macroporosity and subsequently for evaluating aggregate and structure stability as determined by the HEMC method.

CONCLUSIONS

Both intrinsic soil properties (soil texture) and extrinsic conditions (aggregate size and addition of PAM) were found to have significant effects on aggregate stability. However, PAM cannot be considered as a universal stabilizing agent in cultivated fields and thus as a general tool for soil and water conservation management practice. PAM application should, therefore, be decided upon based on soil type and conditions prevailing in the field.

The composite index used for characterizing aggregate stability (SI) and thus reflecting on soil structure firmness, can be directly associated with the size of the most frequent pore (expressed by α) of the soil system studied. However, the relationship between SI and α was not unique, but depended on the conditions prevailing in the soil (e.g. aggregate size in our study). Moreover, the contribution of the steepness of the retention curve (expressed by n) or the angular coefficient of the water retention curve at the inflection point (i.e. S-index) to aggregate stability was found to be indirect and/or partially obscured by additional factors. It is, therefore, finally concluded that the parameters used for the fitting of the commonly used van Genuchten model to the water retention curve at low matric potential cannot replace the composite SI, as an index for aggregate stability, and thus in turn as an index for assessing soil conservation practices efficacy.

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