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Depositional seals in polyacrylamide-amended soils of varying clay mineralogy and texture

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Abstract

Purpose Depositional seals, formed when turbid waters infiltrate into soils, lead to a reduction in soil hydraulic conductivity (HC) and enhance runoff and soil erosion. Since clay size particles constitute a dominant proportion of depositional seals, soil texture and clay mineralogy play a significant role in determining the seal's hydraulic characteristics. Presence of high molecular weight anionic polyacrylamide (PAM) in suspension flocculates fine sediments, and therefore, its application to the soil surface may modify the characteristics of the depositional seal. The impact of PAM on the latter is expected to be influenced by soil properties. The aim of this study was to elucidate the effects of PAM application on clay flocculation and the HC of depositional seals formed in four soils varying in texture (ranging from loamy sand to clay loam), and diverse proportions of clay mineral constituents (kaolinite, smectite, and vermiculite).

Materials and methods Soils from four physiographic regions of North Carolina, with different textures and clay mineral compositions, were used in the study. Clay size particles were extracted from each soil using common procedures and used for preparing 5 $\mathrm{g L^{-1}}$ clay suspension. The effects of adding an anionic high molecular weight (12×10^6 Da) PAM in various concentrations (0–10 mg $\mathrm{L^{-1}}$) to 5 $\mathrm{g L^{-1}}$ clay suspensions on sediment flocculation were studied with a nephelometer probe. The HC of depositional seals was studied by leaching soil columns with either deionized water (DW) or 5 $\mathrm{g L^{-1}}$ clay suspensions in the presence or absence of PAM at the soil surface. PAM was applied either as dry granules to the soil surface (at a rate equivalent to 20 kg $\mathrm{ha^{-1}}$) or by filling the overhead volume in the columns with a 0.5 mg $\mathrm{L^{-1}}$ PAM solution.

Results and discussion Even at a PAM concentration of 0.5 $\mathrm{g L^{-1}}$, there was an increase of >50% in clay flocculation. Leaching the columns with DW in the presence of PAM caused a significant reduction in the HC. Conversely, during leaching with clay suspensions, addition of PAM in solution resulted in HC values (both initial and at apparent steady state) that were generally higher than those obtained in the absence of PAM. The impact of adding dry PAM varied with soil type. It had a negative impact on the HC of the depositional seals in the loamy sand and had no effect in the sandy loams; it did increase the HC of the seal in the clay loam from 3.6 mm $\mathrm{h^{-1}}$ in absence of PAM to 9.9 mm $\mathrm{h^{-1}}$ with PAM application.

Conclusions The HC of the depositional seals studied depended on the combined effects of soil texture and clay mineral constituents. The effects of PAM on the HC of depositional seals depended on soil texture and on the mode of PAM application. Our results suggest that, in fine-textured soils, PAM is effective in improving the HC of depositional seals because it leads to the flocculation of the suspended material and thus to the formation of a less dense

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and more permeable seal on the soil surface. In coarse-textured soils, the lack of success of PAM in improving the permeability of depositional seals may stem from either the formation of a PAM layer at the soil surface with a distinct lower HC than that of the bulk soil and the depositional seal, or due to accumulation of the flocculated material in the pores at the upper few millimeters of the soil, thus forming a layer with a permeability even lower than that of the depositional seal itself.

Keywords Anionic PAM · Clay mineral · Depositional seals · Flocculation · Kaolinite · Runoff · Smectite · Suspended sediment · Turbidity · Vermiculite

1 Introduction

Seal formation at the soil surface is a common phenomenon in many cultivated and disturbed soils worldwide. Sealed surfaces have prominent effects on numerous soil phenomena; e.g., when wet they decrease infiltration and increase runoff and erosion, and when dry they could slow soil–atmosphere gas exchange and interfere with seedling emergence.

Surface seals are commonly classified according to the mode by which they are formed. There are *structural* seals that are formed by the impact energy of water drops whether from rain (Duley 1939; McIntyre 1958) or from overhead sprinkler irrigation (Aarstad and Miller 1973), and there are *depositional* seals that are formed as a result of the detachment of fine soil particles by the shear force exerted on them by overland flow. The detached particles are transported by the runoff water and finally deposited in a size-sorted manner (West et al. 1992) at various distances from their original location (Chen et al. 1980; Arshad and Mermut 1988), as often occurs in furrow/basin irrigation (Kemper et al. 1985). These seals tend, however, to be spatially patchy (Bresson and Moran 1995). While structural seals have been studied extensively over the years (Hillel 1980; Shainberg and Letey 1984), depositional seals have been the subject of interest only recently.

Depositional seals are characterized by high bulk density and low porosity, and thus impede infiltration of water through them. The density and micromorphology of depositional seals depend strongly on the electrolyte concentration of the soil solution (Bresson and Boiffin 1990; West et al. 1992; Southard et al. 1988). Depositional seals have many times lower hydraulic conductivity (HC) than structural seals (Fox et al. 1998). Seals formed from soil material suspended in deionized water (DW) have a higher bulk density and oriented birefringent layers of clay (Southard et al. 1988; Bresson and Boiffin 1990; Fox et al. 1998). Conversely, when the soil material is suspended in solutions containing some electrolytes, less dense and more porous seals with no birefringent clay layers within and below the seal are evident (Southard et al. 1988). The electrolyte concentration of suspensions has a large influence on the morphology of the seals by controlling the degree of dispersion of soil particles and the stability of the suspension. The HC of a depositional seal depends on whether or not the clay in the suspended solution is in a flocculated state (Shainberg and Singer 1985). When the electrolyte concentration of suspensions exceeds the flocculation value of the suspended clay, the seal formed consists of flocculated particles deposited randomly in an open structure resulting in high permeability. Depositional seals made of flocculated particles have much higher permeability than those made of dispersed clay and silt particles because the flocculated particles are deposited randomly in an open structure whereas the dispersed clay particles are deposited in a dense structure oriented parallel to the soil surface (Shainberg and Singer 1985).

In soil, the plate-shaped clay particles are assembled into parallel or near parallel alignment to form clay domains (Quirk 1994; Quirk and Murray 1991). Studies have indicated that 2:1 clays are more dispersive than 1:1 clays (Arora and Coleman 1979; Chorom and Rengasamy 1995). The type of exchangeable cations also has an impact on the dispersion and arrangement of clay particles. In pure calcium systems, there is a near parallel arrangement of particles and strong overlap, while in sodium systems, swelling increases with a decrease in electrolyte concentration and particles ultimately disperse into separate entities (Rengasamy and Sumner 1997).

Studies under both controlled conditions and in the field have revealed the beneficial effects of polyacrylamide (PAM) in controlling soil erosion and turbidity reduction in the runoff water (Bhardwaj and McLaughlin 2008; Bhardwaj et al. 2008). The efficacy of PAM in enhancing clay flocculation depends on the type of the saturating cation (Ca>Na), clay mineralogy (kaolinite>illite>quartz), and treatment (acid>salt>water>base) (Laird 1997). Presence of PAM in the irrigation water flocculates the suspended clay and silt particles that enter the water and causes them to settle at the bottom of the furrow (Sojka and Lentz 1997; Sojka et al. 2007). Addition of PAM to the irrigation water also reduced losses of phosphorus, nitrate, and total sediments in furrow irrigation (Lentz and Sojka 1994). Most of further studies have indicated an influence of soil texture on effectiveness of PAM (Green et al. 2000; Ajwa and Trout 2006).

More recently, it has been noted that reductions in the turbidity of soil suspensions in the presence of PAM are highly correlated with soil texture, mineralogy, and exchangeable cations (McLaughlin and Bartholomew 2007). The use of PAM for mitigation of depositional seals of pure homoionic clay systems leads to significant interactions between clay mineralogy and the saturation cations with respect to their effect on the flocculation of the clay suspensions (Bhardwaj et al. 2009). The resulting depositional seals have lower hydraulic resistance and higher permeability in the presence of PAM. PAM not only enhances clay flocculation but also affects the densities of the flocs which vary with the type of clay minerals. However, these findings have not been validated for soil systems where mixed mineralogy exists, and where, for instance, the presence of small amounts of montmorillonite in palygorskite (Neaman and Singer 2000) or kaolinite (Keren 1989, 1991) can significantly alter the rheological behavior of the system. Thus, the present study was undertaken to determine the effectiveness of PAM in ameliorating the adverse impact of depositional seals consisting of mixed clay mineralogy on the permeability of soils. We hypothesize that, similar to its impact on pure clay systems, PAM can be used effectively to change the hydraulic characteristics of depositional seals by enhancing flocculation of the suspended soil sediments.

2 Materials and methods

2.1 Soils

Four soils from different physiographic regions of North Carolina (Tidewater region, Coastal Plains, Piedmont region, and Blue Ridge Mountain region), USA, and differing in texture and clay mineralogy, were investigated in this study. The coastal plain soils had higher smectite and lower Fe and Al oxides compared to the Piedmont and Mountain physiographic regions (Coleman et al. 1949). Selected chemical and physical characteristics of the soils along with their clay mineral composition are presented in Table 1 and Table 2, respectively.

Clay mineralogy (<2 µm) was determined by X-ray diffraction analysis (Whittig and Allardice 1986). X-ray diffraction patterns were interpreted by integrating the area under the curve for each clay mineral (smectite, vermiculite, mica, and kaolinite) in the Mg-glycerol-saturated samples. The area of each clay mineral was divided by the total area of all clay minerals to give the percent of each clay mineral present in the soil.

Soil particle size distribution was determined by the hydrometer method (Gee and Bauder 1986) after addition of H_2O_2 for removal of organic matter (Day et al. 1965). Soil electrical conductivity (EC) and pH were determined in a 1:1 soil to water extract (Thomas 1996). Organic carbon was determined by combustion using a CHN elemental analyzer (Model 2400 series II, PerkinElmer Corp., Norwalk, CT, USA). Exchangeable cations (Ca, Mg, and Na) were extracted by Mehlich-3 procedure (Mehlich 1984) and measured using an inductively coupled plasma (ICP) emission spectrometer.

Extractable Fe was determined by ammonium oxalate (for amorphous and organically bound Fe) and citrate–bicarbonate–dithionite (CBD; for all forms of Fe oxide—crystalline and non-crystalline) extraction and determination by ICP emission spectrometry (Jackson et al. 1986; Phillips and Lovley 1987).

2.2 Suspension preparation

Suspensions with a concentration of 5 gL^{-1} clay were prepared as follows. For each soil, based on its texture, samples were weighed to contain 5 g of clay in the sample and suspensions were made with DW. The suspensions were mixed for 12 h with a magnetic stirrer and then passed through a 53-µm sieve to remove the sand and coarser fragments. Repeated washing of soil through the sieve was done with increments of water to make sure that no clay and silt particles were left on the sieve. In addition to confirm that no aggregated silt and clay size material was left on the sieve, the sand fraction remaining on the sieve was washed into a beaker and dispersed with Na–hexametaphosphate. This procedure for suspension preparation was chosen because in the field the turbid irrigation water responsible for depositional seal formation is likely to contain mainly clay and silt particles.

Finally, as a confirmatory test, subsamples from the suspensions were subjected to chemical and ultrasonic dispersion and centrifuged to separate the clay fraction from the silt fraction. The suspension subsamples were treated with 0.001 mol L^{-1} Na_2CO_3 (pH 10) solutions and sonicated to mix the sediments. The suspension subsamples were then transferred to centrifuge bottles. Based on the equation for Stoke's law adapted for centrifugation as given by Dixon and White (1999, p. 35), samples were centrifuged for 3 min and 55 s at 750 rpm using GSA fixed angle rotor. The supernatant solution containing the clay fraction was decanted. Again, Na_2CO_3 solution was added to the silt in the tube, dispersed, centrifuged and decanted, and repeated until clear supernatant solution started appearing after centrifugation. Clay content in the separated (decanted) solution was then determined by mass balance to confirm that each suspension contained 5 gL^{-1} of clay.

2.3 Flocculation analysis

A stock solution of 1,000 mg L^{-1} of a negatively charged PAM (A110, Cytec Inc., West Patterson, NJ, USA) of high molecular weight (12×10^6Da) and 15% hydrolysis was prepared by adding PAM granules slowly to magnetically stirred DW and mixed for at least 24 h at room temperature.

Table 1 Soil textural parameters and selected chemical properties of Tide Water loamy sand (TWls), Coastal sandy loam (Csl), Piedmont sandy loam (Psl), and Mountain clay loam (Mcl) soils

Property	Soil			
	TWls	Csl	Psl	Mcl
Textural class	Loamy sand	Sandy loam	Sandy loam	Clay loam
Sand (g kg^{-1})	800	720	540	375
Silt (g kg^{-1})	100	178	352	305
Clay (g kg^{-1})	100	102	108	320
Silt/clay	1.0	1.7	3.2	0.9
pH (1:1, H_2O)	4.7	4.8	5.8	5.0
SAR	0.5	1.6	0.3	0.8
OC (g kg^{-1})	2.0	3.3	0.9	1.6
CBD Fe	6.9	16.4	88.3	761.2
Oxalate Fe	6.9	2.6	4.3	13.9
Ca^{2+} (cmol$_c$ kg^{-1})	0.2	0.5	4.1	0.1
Mg^{2+} (cmol$_c$ kg^{-1})	0.1	0.3	1.3	0.1
SAR	0.7	0.3	1.6	0.8

SAR sodium adsorption ratio, *OC* organic carbon, *CBD Fe* citrate–bicarbonate–dithionite-extractable iron, *Oxalate Fe* ammonium oxalate extracted iron, *SAR* sodium adsorption ratio

PAM solutions were added by pipette to 200-mL portions of the soil suspensions that were placed in 330-mL Nalgene containers (i.d.=63.75 mm and depth=104.95 mm) for final PAM concentrations of 0, 0.01, 0.1, 0.5, 2.5, 5, and 10 mg L^{-1}; the suspensions were then hand shaken for 10 s. Thereafter, a nephelometer (Analite 152, McVan Instruments, Mulgrave, Australia) probe was inserted into the suspensions to a depth of 25 mm and turbidity (nephelometric turbidity units) was recorded after 0.5, 1, 5, 10, and 20 min. Relative flocculation index (FI) was calculated from the turbidity data using,

$$\mathrm{FI} = (T_\mathrm{i}/T_\mathrm{o})*100 \qquad (1)$$

where T_i is the turbidity with PAM and T_o is the turbidity reading without PAM, but otherwise under the same conditions.

2.4 Hydraulic conductivity studies

Two sets of HC experiments were conducted: (1) soil without a depositional seal—in these experiments, the HC of soil columns leached with DW was measured; and (ii) soil with a depositional seal—in these experiments, the HC of soil columns leached with soil suspensions was measured. Each soil type that was packed in the columns was leached with a suspension made up from the same soil, as described in Section 2.2.

2.4.1 HC determination

The HC determination was carried out using Plexiglas columns (i.d.=50 mm and height=150 mm). Each column was packed with 120 g of air-dried soil (aggregates <2 mm) to a bulk density (BD) of 1.25 Mg m^{-3} on top of a 2-cm layer of acid-washed coarse quartz sand. The height of the soil layer in the columns was 50 mm. The different soils were packed to the same BD so as to keep the total pore space in the packed soil constant. The use of a unique total porosity in all the soils ensured that the HC was controlled by the clay mineralogical composition of the suspensions rather than the porosity of the base soils.

Each soil column was then wetted from below to saturation with DW at a rate of 35 mm h^{-1}, using a peristaltic pump. Following saturation, flow direction was reversed and the column was then leached from the top with DW or a soil suspension using a constant hydraulic

Table 2 Clay mineralogy for the Tide Water loamy sand (TWls), Coastal sandy loam (Csl), Piedmont sandy loam (Psl), and Mountain clay loam (Mcl) soils

Soil	Smectite		Vermiculite		Mica		Kaolinite	
	(%)							
	(<1μm)	(1–2μm)	(<1μm)	(1–2μm)	(<1μm)	(1–2μm)	(<1μm)	(1–2μm)
TWls	25	5	25	20	–	15	50	60
Csl	0	0	42	59	7	4	52	37
Psl	0	1	19	49	0	0	81	50
Mcl	0	0	9	2	1	2	90	96

head of 0.3 m (Fig. 1). When soil suspensions were used, the suspensions in the Marriott bottles were constantly stirred with a magnetic stirrer to prevent settling and ensure uniform distribution of the suspended material in the suspensions. Under most conditions where depositional seals are formed, a hydraulic head of >0.1 m is very common during long rainfall spells (ranging from >0.1 m under row crops conditions and agricultural landscapes with depressions to >0.3 m in sedimentation basins in suburban landscapes). A hydraulic head of 0.3 m was chosen to simulate and understand processes applicable to all these conditions.

The leaching medium was allowed to percolate through the soil column until steady state was achieved with respect to the EC and pH of the leachate, and its flow rate. The arrangement of the soil column in the experimental setup was such that the surface of soil in the columns was always below the outlet for the water (see Fig. 1). Such an arrangement assured saturated conditions in the soil packed in the column, thus eliminating the risk of development of unsaturated conditions below the depositional seals in any condition. The leachate from the outlet was continuously collected in tubes, using a fraction collector. The leachate volume, EC, and pH were determined in each tube.

2.4.2 *Polyacrylamide treatments*

Experiments with both leaching solutions (i.e., DW and soil suspension) were carried out with and without PAM addition. PAM was applied in two forms: (1) dry granules (4.4 mg) were spread on the surface of the soil in the columns to obtain an equivalent rate of 20 kg ha^{-1} prior to leaching the column with DW or with the suspensions, and (2) PAM solution (10 mg L^{-1}) was pipetted to the overhead volume above soil surface (108 cm^3) to obtain a PAM concentration in the overhead solution equal to 0.5 mg L^{-1}. Thus, a total amount of 0.054 mg PAM was added to the column prior to leaching the column with DW or with the suspensions.

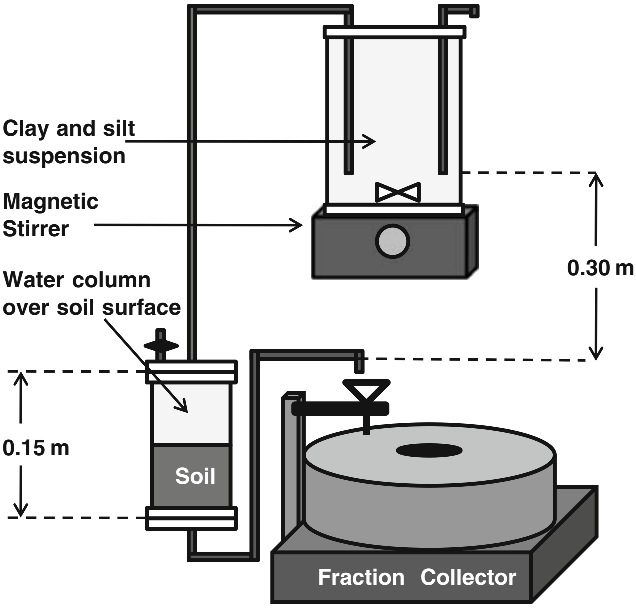

Fig. 1 Schematic diagram of the experimental setup of the hydraulic conductivity measurements

2.4.3 *HC calculation*

The HC was determined using Darcy's law:

$$K_s = -q/[(\Delta H/L)] \tag{2}$$

where K_s [LT^{-1}] is saturated hydraulic conductivity, q [LT^{-1}] is the flux through the column, ΔH [L] is the difference in hydraulic head across the core, and L [L] is column length.

Two parameters were used to a quantitative evaluation of the effects of leaching with DW and clay suspensions on the HC of the soils: initial hydraulic conductivity, HCi (i.e., the HC measured at the beginning of the leaching from the top, ~0.5 pore volume), and apparent steady-state hydraulic conductivity, HCss (i.e., the HC that was approaching asymptotically steady-state value).

When the soil was leached with a clay suspension, a depositional seal was formed at the surface of the base soil due to blocking of surface pores by the suspended clay particles. Thus, a two-layered system was obtained, with the permeability of the upper layer (i.e., depositional seal) being expected to be lower than that of the lower layer (i.e., the base soil). Calculation of the HC of the depositional seal is not possible as its thickness cannot be accurately determined. We have opted, in addition to the calculation of the HCi and HCss, to also use the hydraulic resistance (HR) of the depositional seal when HCss was obtained as an indicator of the hydraulic properties of this seal (Freebairn et al. 1991; Fox et al. 1998). We have calculated the HR using the equation (Lado et al. 2007; Bhardwaj et al. 2009):

$$\mathrm{HR} = \Delta H/q - L/K_s \tag{3}$$

where K_s is the HCss under leaching with DW and q is the measured flux at the apparent steady state when leaching with the suspension. For a detailed explanation regarding the HR of depositional seals, the readers are referred to Lado et al. (2007).

2.5 Statistical analysis

Each of the experiments and treatments was conducted in three replicates and the data were subjected to analysis of variance as a complete randomized design. Separation of means was obtained by Tukey's Honestly Significant Difference Test (SAS v. 9.1, 2004). All tests were performed at the 0.05 significance level.

3 Results and discussion

The soils used in the current study varied in texture from loamy sand to clay loam (see Table 1). The soils were predominantly kaolinitic but contained also significant amounts of expanding clay minerals (vermiculite and smectite) and some proportion of mica (see Table 2).

3.1 Flocculation

In general, the effects of PAM in promoting flocculation of the suspended clay material increased with the increase in PAM concentration for all the soils studied (Fig. 2). Moreover, already a concentration of 0.5 mg L^{-1} PAM resulted in FI values of <50%. Bhardwaj et al. (2009) noted for similar PAM concentrations (≤2.5 mg L^{-1}) that PAM was extremely effective in flocculating specimen clays. Apparently, albeit the difference in flocculation values between specimen clays and soil clays (e.g., Frenkel et al. 1992), our results indicate that these similar low concentrations of PAM are effective also in flocculating soil clays. The high efficacy of PAM in flocculating our soil clays could be ascribed to the acidic nature of our soils (see Table 1) which has been known to promote the flocculation capabilities of the anionic PAM (Laird 1997; Deng et al. 2006). The observed effectiveness of PAM in flocculating the soil clays is part of the basis of our hypothesis. It is expected, based on the findings of Shainberg and Singer (1985), that depositional seals formed by suspensions containing flocculated material (following the presence of PAM) will have greater permeability than seals formed by suspensions containing non-flocculated (dispersed) material.

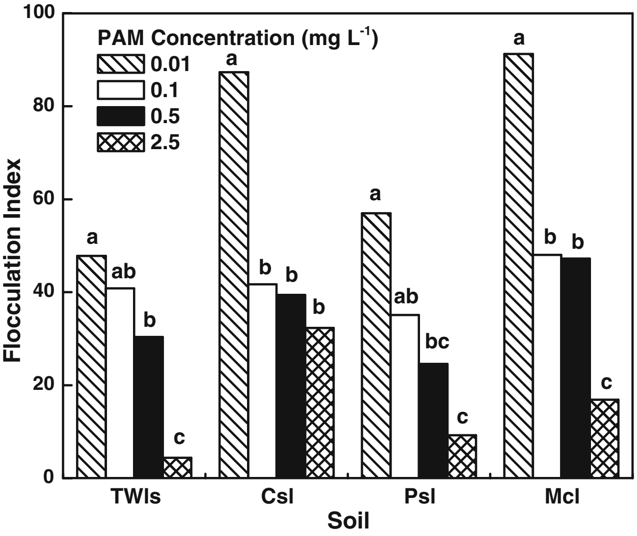

Fig. 2 Flocculation index (FI) of different soil suspensions (for 10 min duration) at different concentrations of polyacrylamide (PAM). For a given soil type, histograms followed by the same *letter* do not differ significantly at *P*>0.005. *TWls* Tide Water loamy sand, *Csl* Coastal sandy loam, *Psl* Piedmont sandy loam, *Mcl* Mountain clay loam

3.2 Hydraulic conductivity

3.2.1 Leaching with deionized water

Leaching the soils with the DW resulted in a decrease in the HC (Figs. 3, 4, 5, and 6) which was ascribed mainly to in situ clay swelling. No suspended clay was noted in the leachate from any of the columns, thus there was no direct evidence of clay dispersion. However, dispersion and short distance migration of clay to "bottle necks" where it could settle out of the solution and clog soil pores could have also contributed towards the observed reduction in the HC (Frenkel and Rhoades 1978; Pupisky and Shainberg 1979).

The HCi and HCss for the soils were in the order: Tide Water loamy sand (TWls)>Coastal loamy sand (Csl)> Mountain clay loam (Mcl)>Piedmont loamy sand (Psl) (Table 3). The soils from the coastal region (TWls and Csl), as anticipated, had comparatively high HCi and HCss values because of their high sand content. The other two soils (Mcl and Psl) had higher clay and silt contents (see Table 1) that led to the lower HC. Although Mcl had significantly higher clay content than Psl, with silt content being almost the same for both soils, Mcl had about four times higher HCi and HCss than Psl. This observation suggested that, in addition to soil texture, the type of clay minerals in the soil might also be playing a role in controlling the HC. Both soils contain high amounts of kaolinite but Pcl contains also significant amounts of vermiculite (19% and 49% for <1 μm and 1–2 μm fractions, respectively) compared to the negligible amounts found in Mcl (see Table 2). This difference in the amount of vermiculite, which is an expanding clay (though less than smectite), could explain the differences in HC between the Psl and Mcl soils.

In the Csl and Mcl soils addition of PAM (in both forms of application) caused the HC to decrease to a significantly lower level compared with that obtained when leaching with DW only (see Table 3, Figs. 4 and 6). In the TWls and Psl, the addition of a solution with dissolved PAM resulted in HC values (HCi and HCss) comparable to those obtained when leaching with DW (see Table 3, Figs. 3 and 5). Conversely, when PAM was added as dry granules, the HC in the TWls was significantly lower than that obtained when only DW was used (see Table 3, Fig. 3) while in the Psl a trend opposite to that observed in the TWls was noted,

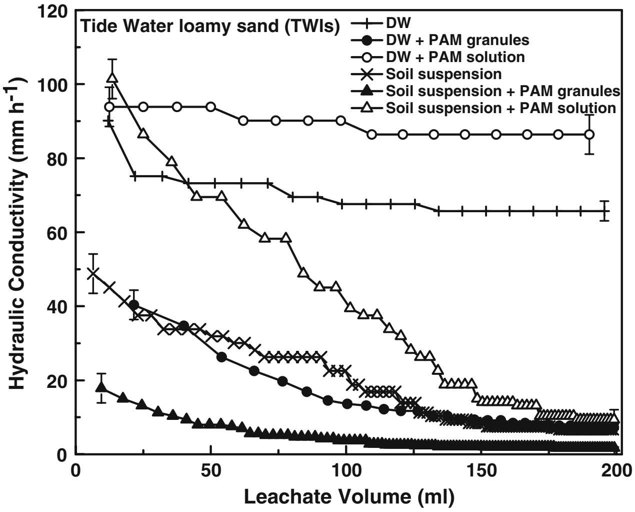

Fig. 3 The hydraulic conductivity (K_s) of the Tide Water loamy sand (*TWls*) soil with and without depositional seals, and the effect of polyacrylamide (*PAM*) formulations. *Bars* on the K_s curves indicate ±1 SD

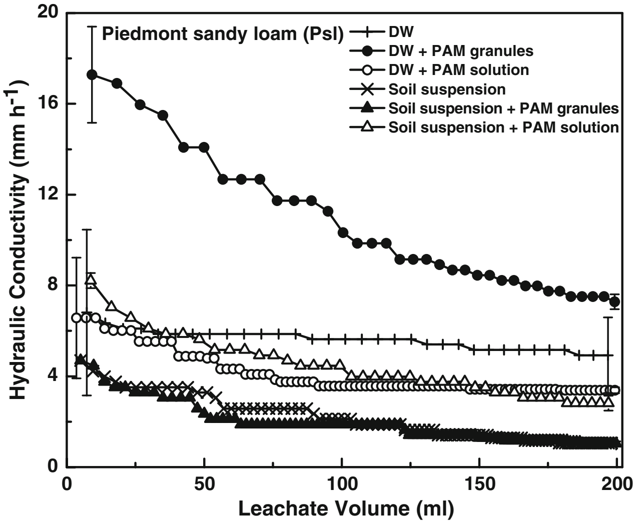

Fig. 5 The hydraulic conductivity (K_s) of the Piedmont sandy loam soil (*Psl*) soil with and without depositional seals, and the effect of polyacrylamide (*PAM*) formulations. *Bars* on the K_s curves indicate ±1 SD

namely dry PAM had a favorable impact on the HCi (see Table 3, Fig. 5). The adverse effects of PAM on the HC in the Csl and Mcl were in agreement with previously published studies (e.g., Malik and Letey 1992; Lentz and Bjorneberg 2003; Ajwa and Trout 2006; Young et al. 2009). The decrease in the HC in the presence of PAM was ascribed to the increase in the viscosity of the leaching solution and to the possible formation of a thin polymer layer at the soil surface having distinct hydraulic properties that differ from those of the bulk soil (Young et al. 2009). In the case of the TWls, it is suggested that the very low concentration of the PAM solution used (0.5 mg L^{-1}), combined with the coarse texture of the soil and the stabilizing effect of PAM on soil aggregates (e.g., Mamedov et al. 2006), led to similar HC levels in this treatment and the DW only one. The favorable effect of dry PAM on the HCi of the Psl is not fully understood and needs further studying.

3.2.2 Leaching with soil suspensions

When the soil columns were leached with soil suspensions, a considerable decrease in the HC of all the soils was

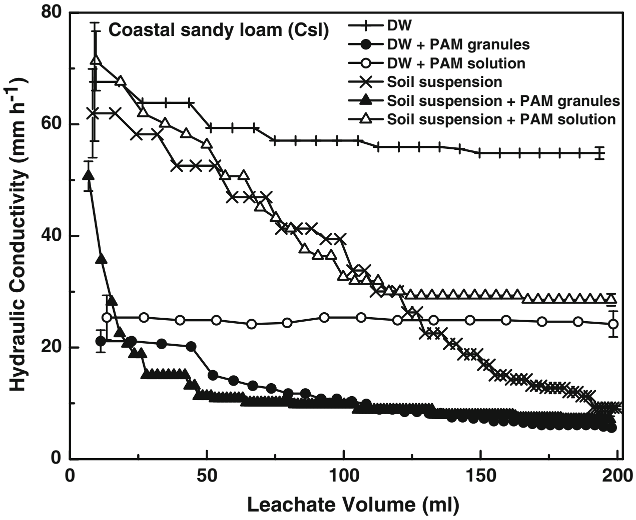

Fig. 4 The hydraulic conductivity (K_s) of the Coastal sandy loam (*Csl*) soil with and without depositional seals, and the effect of polyacrylamide (*PAM*) formulations. *Bars* on the K_s curves indicate ±1 SD

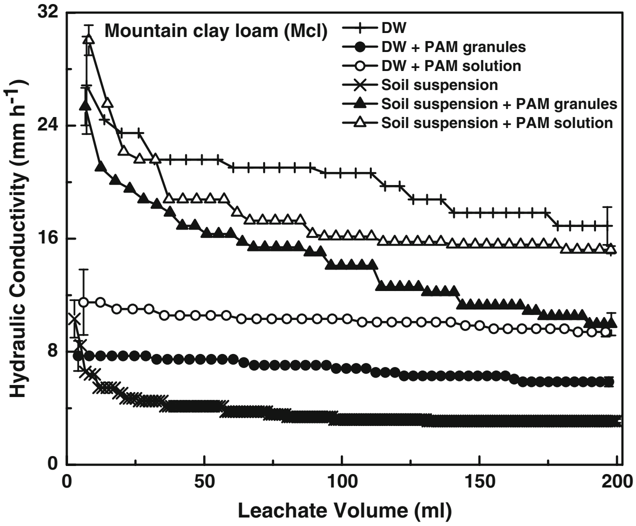

Fig. 6 The hydraulic conductivity (K_s) of the Mountain clay loam (*Mcl*) with and without depositional seals, and the effect of polyacrylamide (*PAM*) formulations. *Bars* on the K_s curves indicate ±1 SD

Table 3 Initial hydraulic conductivity (HCi), apparent steady-state hydraulic conductivity (HCss), and hydraulic resistance at HCss (HR) for the different soil types and treatments

Hydraulic conductivity (mm h^{-1})	Soil type[a]			
	TWls	Csl	Psl	Mcl
	No seal[b]			
HCi	90.1 a[d]	67.6 ab	6.8 bc	26.8 a
HCss	65.7 bc	46.2 c	4.7 bc	15.6 b
	With seal[c]			
HCi	48.8 cd	62.0 abc	4.7 bc	10.3 bcd
HCss	8.4 f	9.2 def	1.6 c	3.6 e
HR	4.5 B	3.7 A	17.3 A	11.1 A
	No seal+dry PAM (20 kg ha^{-1})			
HCi	40.4 d	21.1 de	17.3 a	7.7 de
HCss	4.0 fg	2.3 f	5.9 bc	5.9 de
	With seal+dry PAM (20 kg ha^{-1})			
HCi	17.8 e	50.7 bc	4.7 bc	25.3 a
HCss	2.3 g	7.1 ef	1.9 c	9.9 bcd
HR	18.4 A	5.1 A	13.7 A	1.5 B
	No seal+PAM in solution (0.5 mg L^{-1})			
HCi	93.9 a	25.3 d	6.6 bc	11.5 bcd
HCss	83.1 ab	19.2 def	3.4 bc	9.2 cde
	With seal+PAM in solution (0.5 mg L^{-1})			
HCi	101.4 a	71.3 a	8.2 b	30.0 a
HCss	14.1 ef	25.5 d	2.6 bc	13.7 bc
HR	2.3 B	0.8 B	7.6 B	0.4 B

[a] *TWls* Tide Water loamy sand, *Csl* Coastal sandy loam, *Psl* Piedmont sandy loam, *Mcl* Mountain clay loam

[b] Soil leached with DW with no development of depositional seal at the surface

[c] Soil with depositional seal developed by leaching with soil suspension

[d] For a given soil type, numbers followed by the same lowercase letters do not differ significantly at $P>0.005$; numbers followed by the same uppercase letters do not differ significantly at $P>0.005$

observed (see Table 3, Figs. 3, 4, 5, and 6) which was ascribed to the development of a depositional seal on the soil surface. The same hydraulic head was used for all the leaching experiments, and the amount of suspended material that was added to each soil was identical for any given cumulative suspension addition; therefore, the differences in the HC among the soil columns could only be due to variations in the hydraulic properties of the depositional seals that had developed. Concerning the coarse-textured soils (TWls and Csl), both soils had a high sand content and equivalent clay contents, but the Csl soil had higher silt content and therefore it was expected that its HC would be more severely affected than that of the TWls. The results, however, showed that in the TWls there was an immediate reduction in the HC when leaching with the suspension started, a nearly 50% reduction in the HCi compared to leaching with DW (see Table 3, Fig. 3); conversely, in the Csl, the HCi decreased only by ~10% compared to the HCi when DW was used (see Table 3). In both soils, the HC continued to decrease gradually as the deposition of fine particles progressed and it reached a HCss that was ~15% of the HCi for each soil (see Table 3). It is suggested, therefore, that the dissimilarity in clay mineralogy between the two soils could explain the difference in the changes in their HCs. The two soils contained significant amounts of kaolinite and vermiculite; however, the TWls contained also smectite. Smectitic clays have been found in earlier studies to form depositional seals of very low HC (Bhardwaj et al. 2009). It seems that the presence of smectite in the suspension of the TWls but not in that of the Csl led to the development of a seal with lower HCi and HCss in the former soil compared to that in Csl.

In the other two soils, following the leaching with the soil suspensions the HCi and HCss in the finer-textured Mcl were substantially higher than their respective values in the Psl (see Table 3). However, leaching with the suspension caused only a mild reduction in the HCi of the Psl to ~70% of its value when DW was used, while in the Mcl the HCi dropped to <40% of the HCi obtained when DW was used (see Table 3, Figs. 5 and 6). The greater reduction in the HC of the Mcl following seal development compared with that in the Psl could be ascribed to its higher clay content (see Table 1) which imparts on the soil a large portion of fine pores that are more susceptible to blocking by the dispersed clay particles present in the suspension used for leaching the soil. The clay in the suspensions penetrates the soil surface to some extent before sealing the pores and thus with the reduction in the HC starts depositing on the surface. The process of sealing in the soil with the higher clay content, compared to those with the lower clay content, was quicker and of greater magnitude (see Table 3, Figs. 3, 4, 5, and 6) because of the presence of micropores in the former soil that can easily be blocked by the suspended particles during the leaching process.

Addition of PAM as well as the form in which it was added had an impact on the HC of the soils studied. Polyacrylamide introduced in solution resulted in a trend where by the HC values in all four soils were similar or significantly higher compared to the HC of the untreated seals (see Table 3, Figs. 3, 4, 5, and 6). In the case of HCi, addition of PAM to the leaching suspension resulted in values that were similar to those obtained for leaching the soil with deionized water (see Table 3). The HCss for seals formed with solution PAM were higher than those with seal development without PAM but lower than the HCss of the soils leached with deionized water alone (see Table 3). Moreover, in three of the soils the HR was significantly lower in the PAM treatment than in the untreated seals (see Table 3), providing an additional indication that the permeability of the depositional seals formed in the PAM treatment were higher than that in the untreated seals. It is postulated that the presence of PAM in the suspension leads to the flocculation of suspended particles (see Fig. 2) and hence to the formation of a depositional seal comprising of coarser particles and of a higher permeability.

The response of the soils to addition of dry granules of PAM differed (see Table 3). In the TWls, a significant decrease in both the HCi and HCss and a significant increase in the HR of the soil compared to their respective values for the depositional seal without addition of PAM were observed (see Table 3, Fig. 3), indicating that the presence of PAM had an adverse effect on the permeability of the depositional seal compared to a non-treated seal. In the Csl and the Psl, addition of PAM had no significant effect on the HCi, HCss, and HR values (see Table 3, Figs. 4 and 5). However, albeit the similar HCss for the PAM and no PAM treatment in the Csl, the HCi in this soil dropped exponentially within one pore volume of leaching to its HCss in the case of the PAM treatment (see Fig. 4); this phenomenon was not noted in the Psl (see Fig. 5). Furthermore, as previously noted, the presence of smectite in the suspension of the TWls but not in that of the Csl and Psl led to the development of a seal with lower HCi and HCss in the former soil compared to that of the other two, which could explain, at least in part, the inability of PAM addition to improve the HC of the depositional seal in the case of the TWls.

Contrary to the other soils, in the Mcl addition of PAM significantly increased the HCi and HCss and decreased the HR (see Table 3, Fig. 6). These results suggest that the texture of the soil plays an important role in determining the impact of PAM on the HC of the depositional soil; the coarser the soil, the greater the adverse effect of PAM on the HC. This observation is in agreement with the findings of Young et al. (2009) who reported that adverse effects of PAM on the HC of depositional seals decreased in the following order: coarse sand>fine sand>loamy sand.

In both methods of PAM application, the HCss was always substantially lower than the corresponding HCi (see Table 3). Our system had a limited source of PAM and a continuous source of sediments. It is postulated that the initial improvement in the HC of the PAM treated depositional seals in comparison to the HC of the non-treated seals was gradually masked by the deposition of more sediments with the continued leaching of the soil. Considering the impact of PAM on soil HC in the absence of depositional seal and its effect on the permeability of depositional seal it is suggested that addition of PAM to the soil surface could have two opposing effects on soil permeability in the presence of depositional seals: (1) reducing the HC due to viscosity-induced resistance to flow or the formation of a layer at the soil surface with a distinct lower HC than that of the bulk soil (Young et al. 2009) and (2) flocculating the suspended particles in the leaching suspension and thus leading to the formation of a depositional seal of a greater permeability.

Based on our results and those of Young et al. (2009), it seems that the second mechanism is more effective in the case where the seal is formed over a finer-textured material (clay loam and soils of similar texture). In coarse-textured materials (sand and sandy soils) where PAM addition was ineffective in controlling the permeability of the depositional seals, it is possible that the first mechanism was more effective than the second one in controlling the permeability of depositional seals formed in the presence of PAM. However, in coarse material, due to the presence of relatively large pores at the soil surface, there is greater possibility of blockage of such pores by the suspended particles (whether flocculated by PAM or not). It may lead to a layer of lower permeability than the depositional seal itself.

4 Conclusions and recommendations

Soil texture and clay mineralogical composition were found to have combined effects on the hydraulic characteristics of depositional seals made from clays extracted from the respective soils. In contrast, the effects of PAM on the permeability of the depositional seals were largely controlled by the texture of the base soil and on the mode of PAM application. Presence of PAM enhanced the flocculation of clays extracted from soils. In the fine-textured Mcl soil, addition of PAM, irrespective of its mode of application, led to increased HC (and lower HR) in treated seals compared to the untreated sealed soil. In the sandy loams (Csl and Psl), addition of PAM (in both granular and solution form of application) had no significant effect on the HC of the sealed soils compared to the untreated sealed soil. However, the HR of the seals with PAM in solution treatment in these two soils was significantly lower compared to that of the control, indicating that slow dissolution of PAM in the sediment-laden water can be a constraint to its effectiveness in medium-textured soils. The dry granular form of PAM application may not be effective in changing the hydraulic characteristics of depositional seals in these soils. In the loamy sand (TWls), the mode of PAM application dictated whether addition of PAM is beneficial or harmful to the HC of depositional seals. Compared to the HC of an untreated seal, PAM in the form of dry granules had an adverse effect on the HC while addition of dissolved PAM had a positive impact on the HC.

Our results suggest that, in fine-textured soils, PAM is effective in increasing the HC of depositional seals because it leads to the flocculation of the suspended material and thus to the formation of a less dense seal on the soil surface with a greater permeability. In coarse-textured soils, PAM may either be not effective or even decrease the HC of soils covered with depositional seal. In coarse-textured soils, the lack of success of PAM in increasing the permeability of depositional seals may stem from either the formation of a PAM layer at the soil surface with a distinct lower HC than that of the bulk soil and the depositional seal, or the formation of a layer at the upper few millimeters of the soil of lower permeability (due to pore blockage by suspended material) than the depositional seal itself. Further studies are needed to elucidate this effect.

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