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Transport of dissolved polyacrylamide through a clay loam soil

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ABSTRACT

Polyacrylamide (PAM) is becoming a widely used soil conditioning and erosion control agent, and a better understanding of its transport is required to improve its use. In this study vertical PAM transport through a clay loam soil was investigated using thin soil columns (7.62-cm diameter × 2-cm thick) under saturated condition. The columns received a water-soluble, anionic PAM solution (16 Mg mol^{-1} with 50 mol% charge density) under pulse and step (continuous) inputs using a constant-head method. The pulse input was 500 mg L^{-1} PAM solution applied for 0.6 pore volume (*PV*), after which the input was switched to deionized (DI) water for 25 *PVs*. The step input was 25 mg L^{-1} PAM solution applied continuously for 129 *PVs*. Saturated hydraulic conductivity (K_{sat}) was measured prior to PAM application and was monitored during PAM and DI water leaching. Leachate samples were collected frequently with time from each column and analyzed for the dissolved PAM concentration. The PAM applications reduced K_{sat} to 1% of the initial K_{sat} (4 cm h^{-1}) under the pulse input and to 0.3% of the initial K_{sat} under the step input. Transport of PAM was best-fitted with a two-region (dual-porosity) model. The fitted retardation factor (R) was more than two-fold greater for the step input ($R = 2695$) than for the pulse input ($R = 1242$). The results from transport modeling and pore size distribution analysis suggested that viscous PAM solution contributes to a mechanical entrapment of the PAM molecules, clogging most water-conducting pores smaller than 225–274 μm in diameter. Under saturated condition, either the pulse or step input of dissolved PAM could reduce seepage with limited mobility in the soil profile.

1. Introduction

Polyacrylamide (PAM) is a high molecular weight polymer that is widely used for industrial applications. Its largest uses are in well-drilling and wastewater treatment as a flocculant, and in paper and pulp production as an adhesion and flooding agent (Seybold, 1994; Abidin et al., 2012). In agriculture, PAM has been used as a soil conditioner for stabilizing soil aggregate structure in irrigation furrows (Letey, 1996; Sojka et al., 2007). Polyacrylamide has also been used for erosion and turbidity control at construction sites (Hayes et al., 2005; Orts et al., 2007; McLaughlin et al., 2009; Kang et al., 2013a).

Various methods of PAM application to soil have been tested to examine impacts on seal formation, infiltration, runoff, and erosion. In the case of surface or overhead irrigation, dissolved PAM injected into the main irrigation pipe has proven to be effective in minimizing irrigation-induced runoff and enhancing infiltration when applied in low concentration (<10 mg L^{-1}) (Sojka et al., 2007). Once the PAM molecules are in contact with soil, the cohesive properties of PAM bind soil particles and peds together, keeping open the larger soil pores through which water preferentially flows. For its application to construction sites, PAM is typically applied after dissolving PAM granules in a hydroseeder tank at relatively high concentrations of 500 to 1000 mg L^{-1} for application rates of 20 to 80 kg ha^{-1}. Dry PAM granules are also applied directly with some success in turbidity reduction, but dissolved PAM is considered to be more reliable because of better distribution and soil contact (Babcock and McLaughlin, 2013; Kang et al., 2014).

Polyacrylamide application can either increase or decrease infiltration rate and hydraulic conductivity, depending on the type and concentration of the applied PAM, soil properties, and application protocol. Infiltration of dissolved PAM on dry loamy sand or pre-saturated sand columns has been found to decrease with increasing PAM concentration (Malik and Letey, 1992; Falatah et al., 1999). Lentz et al. (2000) demonstrated that infiltration reductions were profound with increasing charge density of the PAM material, which they attributed to increased viscosity of the applied PAM solution. In general, increasing polymer molecular weight increases the physical volume of the solvated polymer molecule, which in turn increases solution viscosity (Kulicke et al., 1982). Increasing charge density also results in larger electrical repulsive forces within the polymer molecules, expanding their solvated size and increasing the viscosity of polymer solution (Knudson et al., 1992). When concentrated PAM (>125 mg L^{-1}) was applied as a pulse, or step input was applied at a lower concentration (5–20 mg L^{-1}), infiltration was found to decrease (Lentz, 2003; Ajwa and Trout, 2006). Whereas,

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when the soils were pretreated with PAM solutions and allowed to dry before water irrigation, there was no such reduction in infiltration and hydraulic conductivity in medium- to fine-textured soils (Ajwa and Trout, 2006; Shainberg et al., 2011).

Previous studies suggested that increased infiltration rates were only found with single PAM applications at low rates (<20 kg ha^{-1}) and diluted concentrations (<20 mg L^{-1}) in soils with high clay or silt contents (Lentz, 2003; Ajwa and Trout, 2006; Sojka et al., 2007). Under these conditions, PAM may maintain higher infiltration rates primarily by preventing the breakdown of soil aggregates, reducing dispersion of dislodged soil particles, and limiting formation of infiltration-inhibiting surface seals. The effects of PAM on infiltration may be a balance between prevention of surface sealing and apparent viscosity increases in soil pores (Sojka et al., 2007; Young et al., 2009). If there is a lack of aggregation (e.g., sandy soil), PAM's tendency to increase viscosity of the infiltrating water becomes the dominant phenomenon due to the limited influence of soil structure on the sealing. A column study by Ajwa and Trout (2006) demonstrated that the fluid properties of PAM solutions increased resistance of flow rather than preserving aggregate structure, which reduced infiltration in sandy loam soils. Recent PAM usage to reduce seepage in unlined canals provides examples of different applications of the PAM's hygroscopic properties (Valliant, 2000; Lentz and Kincaid, 2008; Story et al., 2012).

Polyacrylamide penetrates only a few millimeters below the soil surface in applied areas due to its strong affinity for adsorption on soil materials. Lu and Wu (2003) investigated vertical PAM distribution in laboratory columns (60-cm depth, dry soil) following a single application of dissolved PAM (8-cm application) either by ponded or drip irrigation. They found that longer soil-solution contact time and lower initial soil water content caused the high PAM retention (16 to 66% of the total amount applied) in the top few centimeters of the soil. More PAM was retained on the surface soil under ponded application and PAM penetrated deeper under drip application. They suggested that ponded application (e.g., furrow and flood irrigation) is preferred if the PAM application is aimed to mainly stabilize the surface soil.

Although previous studies investigated the strong retention of PAM and its impact on water flow in soils, there is limited information combining these two aspects into PAM transport modeling. The objectives of this study were 1) to determine the extent to which PAM affects the saturated hydraulic conductivity (K_{sat}) of a clay loam soil with different application modes (e.g., pulse vs. step), and 2) to relate the changes in K_{sat} to the PAM transport in the soil using thin (2 cm) soil columns. The results were used to explain the PAM retention and changes in soil pore space with the differing PAM application modes.

2. Materials and methods

A fill soil material collected from a local construction site in the Piedmont region of North Carolina, USA, was used for the experiments. The soil had a clay loam texture with a pH$_{H_2O}$ of 5.3 (Table 1). The soil was air-dried, passed through a 2-mm sieve, and mixed thoroughly before use. Kaolinite has been found to be the dominant clay mineral (>60%) in the fill soils of the Piedmont region, with mica and vermiculite also present (McLaughlin and Bartholomew, 2007). A total of 10 soil columns (7.62-cm diameter metal cylinders) were packed to a depth of 2 cm (thickness of the soil in the 7.62-cm long columns) with 121 g of the soil at a bulk density (ρ_b) of 1.3 g cm^{-3}. To prevent soil loss, the bottom of each cylinder was covered with cheese cloth.

Table 1
Selected soil properties of Piedmont clay loam for the column study.

pH[a]	Sand[b]	Silt[b]	Clay[b]	OM[c]	EC[d]
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	µS/cm
5.3	412	219	369	9.5	11.6

[a] pH by glass electrode (ExStik EC500, Extech Instr. Corp., Nashua, NH) at 1:1 soil-to-solution ratio in deionized water.
[b] Particle size analysis by hydrometer method (Gee and Bauder, 1986).
[c] Organic matter (OM) by loss-on-ignition.
[d] Electrical conductivity (EC) by an EC Tester (ECTestr, Oaklon Instr., Vernon Hills, IL) at 1:20 soil-to-solution ratio in deionized water.

2.1. Saturated hydraulic conductivity

To prevent air entrapment, the columns were saturated from the bottom with deionized (DI) water and kept saturated overnight. Following saturation, the columns were placed inside a flat bottom funnel for drainage on a wooden rack. To determine K_{sat}, the columns were leached from the top with DI water under a constant head (Klute, 1965), and the leachate was collected in a fraction collector (Fig. 1). After the water ponding level was stabilized (≈9 cm), the leachate was collected on a regular basis until the flow reached steady-state. The K_{sat} (L T^{-1}) was then determined by measuring the volume of leachate outflow (Q, L^3) that passed through the soil column during a known time interval, t (T), using Darcy's law:

$$K_{sat} = (Q/At)\,(L/\Delta H) \qquad (1)$$

where A is the cross-sectional area (45.6 cm^2), L is the length of the column (2 cm), and ΔH is the head difference across the flow path (11 cm). The average reading in five trials was used to calculate an initial K_{sat} value prior to PAM addition at $t = 0$. The K_{sat} measurements continued during the PAM displacement tests.

2.2. PAM displacement

The PAM used for this study was a high molecular weight (16 Mg mol^{-1}), water-soluble anionic polymer with 50 mol% of charge density (Superfloc A150, Kemira Chemicals Inc., Atlanta, GA). In a previous study, A150 PAM flocculated the study soil well and had high analytical sensitivity in measuring dissolved PAM concentration turbidimetrically (Kang et al., 2013b). Stock solution of the PAM (500 mg L^{-1}) was made in DI water and stirred for at least 24 h at room temperature.

We selected two columns that had the most similar K_{sat} at $t = 0$ for the PAM displacement tests. Two different PAM application modes were

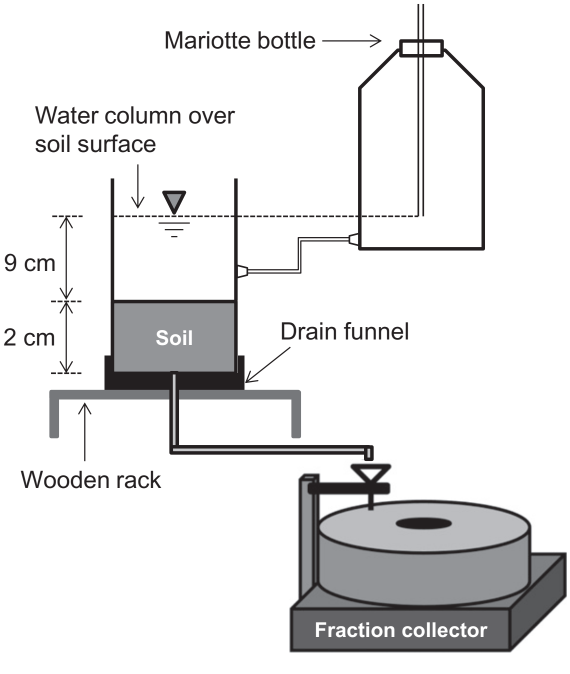

Fig. 1. Schematic diagram of column experiment. The drawing is not to scale.