Reducing Saturated Hydraulic Conductivity of Sandy Soils with Polyacrylamide

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Polyacrylamide (PAM) is being suggested as a new technology to reduce seepage losses in unlined canals. The goals of this research were to quantify the interactions of PAM and suspended sediment concentrations (SSCs) that reduced the saturated hydraulic conductivity ($K_{sat}$) of three sandy-textured soils to the greatest degree, and to better understand the mechanisms contributing to reductions in $K_{sat}$. Testing was conducted using a constant-head method in soil columns. Suspended sediment was continuously added to a constant-head water reservoir, into which PAM was added and mixed with an agitator. An unbalanced multifactorial design was used with soil type (fine [no. 70 mesh] sand, coarse [ASTM C33] sand, and loamy sand), PAM treatment level (0, 5.6, 11.2, 22.4, and 44.8 kg ha$^{-1}$), and SSC (0, 150, and 300 mg L$^{-1}$). Results showed that PAM treatment reduced $K_{sat}$ 40 to 98% in the sands but reductions were much less in the loamy sand (0–56%). Combining suspended sediment and PAM in a 0.005 mol L$^{-1}$ CaSO$_4$ test solution reduced $K_{sat}$ from 8 to 11 times more than adding PAM without suspended sediment. Mechanisms that reduced $K_{sat}$ included higher viscosity from dissolved PAM and the plugging of larger soil pores near the soil surface. The latter mechanism dominated when the PAM treatment exceeded 5.6 kg ha$^{-1}$ and when SSC was 150 mg L$^{-1}$ or higher. Significant $K_{sat}$ reductions were observed when tests were run on filter material (i.e., column experiments without soil), indicating that the creation of a thin soil seal, composed of PAM floculates, could partially explain the observed $K_{sat}$ reduction in soil.

Abbreviations: NTU, nephelometric turbidity units; PAM, polyacrylamide; SSC, suspended sediment concentration; USGS, United States Geological Survey; NRCS, Natural Resources Conservation Service.
in agricultural fields, scientists and water conservation managers in the late 1990s and early 2000s (e.g., Valliant, 1999; 2002) hypothesized that PAM might be a useful technology for reducing seepage in unlined water delivery canals. Recently, research findings have illustrated infiltration reduction through different experiment setups. Lentz (2003) conducted column experiments in which percolation volume was measured after treating the surface of dry soils of different textures with PAM (equivalent to 45 kg ha\(^{-1}\)). After saturating and ponding water, pulses of sediment were mixed into the water and percolation volumes were measured. The results showed higher reduction in infiltration rates for finer textured (silt loam) soils than the loamy sand soil. Ajwa and Trout (2006) also conducted column experiments with a sandy loam soil and varied electrical conductivity of the test solution, PAM type (dry and emulsified), PAM concentration, and application method (soil kept under water or allowed to dry). They found that higher PAM concentrations resulted in lower infiltration rates, and that solutions dominated by Na resulted in lower infiltration rates than solutions dominated by Ca (as gypsum). Lentz and Freeborn (2007) monitored seepage along a miniflume packed with silt loam soil, and used a randomized experimental design with PAM concentration, sediment type, and sediment concentration. The flume was constructed similarly to an irrigation furrow (i.e., a V-shaped channel was formed in the soil before initiating water flow). They found that seepage reduction was affected by several factors including particle size and concentration of suspended sediment and PAM concentration, although the interactions between experimental factors was shown to involve a number of mechanisms.

Seepage reduction from PAM treatment could be due to several processes, one of which is the increased viscosity of water. Numerous studies have suggested that increased viscosity from PAM addition explains the decrease in infiltration and conductivity in soil (i.e., Malik and Letey, 1992; Nadler et al., 1994; Letey, 1996; Ajwa and Trout, 2006). In the case of PAM use in irrigation furrows, the increase in infiltration due to the maintenance of pore structure is offset by the increased viscosity as the PAM concentration increases. In the case of PAM treatment in unlined canals, where “fresh” water from upstream of the treatment point can dilute treated water, the viscous effect is unclear, mostly because of lack of field data. Although the study of Lentz (2003) showed that PAM treatment can decrease infiltration rates and hydraulic conductivity without relying on the change in water viscosity to achieve the reduction, we suggest that viscous effects are likely to be low in full-scale field sites. In any case, in the column experiments used in this study, we considered viscous effects more thoroughly.

In summary, numerous previous studies have suggested that many factors may contribute to the decreased infiltration rates and hydraulic conductivities without a clear understanding of their interactions on the process. The main objectives in this study were to: (i) evaluate to what extent PAM affects the saturated hydraulic conductivity (\(K_{\text{sat}}\)) of three different sandy soil materials; and (ii) better understand the physical mechanisms that affect \(K_{\text{sat}}\) reduction. For the first goal, dosing experiments were performed to quantify the reduction of turbidity (through the creation of PAM flocculates). The results were then used to explain, in part, the \(K_{\text{sat}}\) reduction. For the second goal, three possible physical mechanisms that reduce seepage were considered, including: (i) PAM-treated water is more viscous than untreated water, thus reducing the infiltration rate; (ii) PAM–sediment flocculates physically plug large soil pores, especially in coarser grained sands; and (iii) PAM itself becomes a low-conductivity layer, similar to the thin-layer concept described by Lentz (2003).

### Materials and Methods

#### Experimental Materials

The specific PAM polymer used for the experiments is TACK Dry, distributed by Precision Polymer Corporation of Greeley, CO. It is an anionic, linear polymer with a molecular weight of approximately 18 Mg mol\(^{-1}\).

Recent studies (Wallace and Wallace, 1996; Lu et al., 2002; Deng et al., 2006) and preliminary test results showed that cations are needed in the test solution for the anionic PAM to flocculate sediment. Thus, we used a 0.005 mol L\(^{-1}\) CaSO\(_4\) test solution augmented with 0.3 g L\(^{-1}\) thymol as an antimicrobial agent (Klute and Dirksen, 1986, p. 692–693) for all experiments, providing Ca concentrations similar to those found in several canals in the Grand Junction area in Colorado (Susfalk, unpublished data, 2006).

Suspended sediment was used as an experimental variable to more closely replicate conditions in operational canals. To maintain consistency between experiments, kaolinitic material (type Huber 80, J.M. Huber Corp., Macon, GA) was used for all experiments where suspended sediment was needed. This material has a median particle diameter of 2.5 μm, a specific gravity of 2.60, and a surface area of 16 m\(^2\) g\(^{-1}\). This same material was also used in recent PAM experiments (Deng et al., 2006).

Three different soil materials were chosen to test PAM efficiency, including (i) an engineered washed silica (predominantly) fine-textured sand (obtained from a local home improvement store) used as a control (hereafter called no. 70 mesh sand), (ii) a natural coarse sand of mixed particle sizes that conforms to the ASTM (2007) C33 designation collected from Grand Junction, CO, and (iii) a loamy sand also collected from Grand Junction, CO. Particle size distributions are shown in Table 1. Material was prepared by air drying, sieving through a screen with 2-mm openings to remove larger stones and other material, homogenizing, and then storing in 20-L buckets for future use. Because the no. 70 mesh sand was already homogenized when purchased, no additional treatment was done. Particle size distributions of each material were determined using the laser light scattering technique (Digisizer, Micromeritics, Norcross, GA) at the Soil Characterization and Quaternary Pedology Laboratory at the Desert Research Institute in Reno, NV.

#### Flocculation Tests

The first set of experiments was done to examine optimum dosage rates of PAM given a range of SSCs. The PAM concentrations were varied from

<table>
<thead>
<tr>
<th>Material designation</th>
<th>&gt;1000 μm</th>
<th>500 μm</th>
<th>250 μm</th>
<th>125 μm</th>
<th>62.5 μm</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine (no. 70 mesh) sand</td>
<td>0.0</td>
<td>0.8</td>
<td>34.0</td>
<td>54.0</td>
<td>8.7</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Coarse (ASTM C33) sand</td>
<td>25.7</td>
<td>21.3</td>
<td>37.7</td>
<td>10.1</td>
<td>1.9</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>1.0</td>
<td>2.5</td>
<td>21.1</td>
<td>41.8</td>
<td>14.0</td>
<td>10.8</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Saturated Hydraulic Conductivity Testing

The second set of experiments was done to quantify the reduction in soil $K_{\text{sat}}$ given different combinations of soil texture, PAM concentration, and SSC. The experiments were conducted using a constant-head setup (Klute and Dirksen, 1986, p. 694–700). The factors for the soil column testing include material type (no. 70 mesh sand, C33 sand, and loamy sand), PAM treatment level\(^1\) (0, 5.6, 11.2, 22.4, 44.8 kg ha\(^{-1}\)), and suspended sediment concentration (0, 150, and 300 mg L\(^{-1}\)). Using the known dimensions of the water column to calculate a water volume, PAM treatment levels listed above were equivalent to PAM concentrations of 0, 4, 8, 16, and 32 mg L\(^{-1}\). The PAM treatment levels were chosen because they span up to the maximum treatment level recommended by the Colorado office of the NRCS (2005), the only agency known to have issued such guidance. All column tests were run in triplicate, yielding a total of 135 experiments.

Figure 1 shows the experimental apparatus. Soil and water columns (Soil Measurement Systems, Tucson, AZ) were made of non-reactive cast acrylic (6.35-cm i.d. by 15 cm long; volume, 475 cm\(^3\)). The outflow collector (3.18-cm i.d.) was equipped with a 7-kPa (1-psi) pressure transducer (Model PX26–001GV microswitch, Honeywell Sensing and Control, Golden Valley, MN) inserted through a stopper and contained in a 15-mL turbidity cell (Hach Chemical Co., Loveland, CO). The cell was shaken by hand to resuspend the floculates immediately before taking the initial reading with a turbidimeter (Model 2100P, Hach Chemical Co.). Turbidity measurements were taken every 30 s after the initial reading for the first 3 min, every 1 min up to 6 min, and then every 2 min until equilibrium was reached. For most tests, equilibrium was reached after approximately 20 min.

Filter Material Testing

The third set of experiments was done to examine the $K_{\text{sat}}$ of the PAM–floculate layer itself, allowing us to ascertain whether $K_{\text{sat}}$ reduction was due to pore plugging, which would not require a separate PAM layer, or whether the PAM floculate formed a thin layer with unique hydraulic properties. The filter material tests were performed using the same procedures as the soil column tests described above, except that the measurements were not taken in triplicate and that soil was replaced with Nitex Bolting Cloth (Wildco, Buffalo, NY), a woven nylon material with consistent aperture size of 20 μm.

To calculate the hydraulic gradient needed to estimate $K_{\text{sat}}$ for the test, an arbitrary thickness of 1 mm was assumed for the PAM and filter mesh together (similar to the hypothesis of Lenz [2003]). Also, because the $K_{\text{sat}}$ of the filter material is quite high, the hydraulic head level was reduced from 15 to 5 cm so that the constant-head apparatus could supply sufficient water to maintain constant water levels.

Measurement of Viscosity

Kinematic viscosity measurements were performed using a viscometer (Routine Type Viscometer for Transparent Liquids, Size 50, Cannon-Fenske, State College, PA). For these studies, a calibration curve was established that related kinematic viscosity to PAM concentration (mixed into deionized water) at a temperature of 25°C. The calibration curve included 10 PAM concentrations that ranged from 0.5, 1, 2, 4, 8, 16, and 32 mg L\(^{-1}\). Suspended sediment concentrations were varied from 0, 20, 60, 110, 203, and 368 mg L\(^{-1}\). When expressed in nephelometric turbidity units (NTU), as will be done henceforth for the flocculation tests, these sediment concentrations are equivalent to approximately 0, 25, 75, 160, 320, and 650 NTU, respectively, based on laboratory calibrations (linear regression model yielded $R^2 = 0.992$).

A flocculation apparatus (Model PB-700 Series, Phipps and Bird, Richmond, VA) was used to uniformly stir a prespecified mass of suspended sediment, taken from a 1000 mg L\(^{-1}\) stock solution, into a beaker containing the test solution described above. Varying amounts of PAM were then added while the apparatus stirred at 100 rpm for 5 min, allowing the PAM to hydrate in the presence of the sediment. The stirring was then slowed to 30 rpm for 15 min so that the PAM floculates could grow and settle.

Following the 20-min period, a depth-averaged sample was taken and contained in a 15-mL turbidity cell (Hach Chemical Co., Loveland, CO). The cell was shaken by hand to resuspend the floculates immediately before taking the initial reading with a turbidimeter (Model 2100P, Hach Chemical Co.). Turbidity measurements were taken every 30 s after the initial reading for the first 3 min, every 1 min up to 6 min, and then every 2 min until equilibrium was reached. For most tests, equilibrium was reached after approximately 20 min.

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\(^{1}\) PAM treatment level is expressed in units of kg ha\(^{-1}\) and is calculated as the quotient of the mass of PAM added to the canal, and the product of the wetted perimeter and a linear distance along the treated reach of the canal.
to 100 mg L$^{-1}$, and the results yielded a significantly linear relationship ($R^2 = 0.9886$; predictive error for PAM concentration = 3.67 mg L$^{-1}$).

At the conclusion of the flow-through column experiments, representative aliquots of test solution were taken from the water column and analyzed for viscosity. The PAM concentration was then estimated from the calibration curve. If the final aqueous PAM concentration was above the standard error established by the calibration curve, the $K_{sat}$ measurement was corrected by multiplying the $K_{sat}$ value by the ratio of viscosities of the test solution without PAM to the final solution sampled at the end of the experiment. This approach is equivalent to calculating the hydraulic conductivity with different values of viscosity:

$$K_{sat} = \frac{\kappa \rho g}{\eta}$$  \[1\]

where $\kappa$ is the intrinsic permeability [L$^2$], $\rho$ is the density of the fluid [M L$^{-3}$], $g$ is the gravity acceleration constant [L T$^{-2}$], and $\eta$ is the kinematic viscosity [L$^2$ T$^{-1}$].

**Statistical Analysis of Results**

Results of the soil column experiments were run through SAS (Version 9) software (SAS Institute, Cary, NC) using the general linear model (GLM) procedure and Duncan’s multiple range test. The test compared all pairs of means, including within and between treatments and used a Studentized range statistic to determine significance of differences (Montgomery, 2001).

**RESULTS AND DISCUSSION**

**Flocculation Tests**

Figures 2a to 2c show the turbidity reduction with time as PAM reacted with suspended sediment. In each case without PAM, only slight reductions were seen with time, indicating that the kaolinite remained suspended in solution. Even small amounts of PAM, as low as 0.5 mg L$^{-1}$, resulted in flocculation, regardless of the SSC. Results showed that even a low concentration of PAM effectively reacted with and flocculated the kaolinite. Polyacrylamide concentrations above 1.0 mg L$^{-1}$ resulted in slightly faster flocculation, but observed differences in flocculation rates tended to be obscured as the PAM concentration changed. Final turbidity values approached approximately 20 NTU for each experiment when PAM was added, regardless of the initial turbidity level or the PAM concentration. Although the original intent of these experiments was to quantify the reactivity of PAM and suspended sediment, readings for the turbidimeter required about 12 s to complete, and flocculates in the treated water fell too rapidly for the meter to record an accurate initial reading, affecting our ability to quantify the reactivity rates between PAM and the suspended sediment. Nonetheless, these qualitative observations show that flocculates can begin to form within a couple of minutes.

**Saturated Hydraulic Conductivity Testing**

Figures 3a to 3c show results from representative individual tests with the no. 70 mesh sand, C33 sand, and loamy
sand for a PAM treatment level of 44.8 kg ha\(^{-1}\) and SSC of 300 mg L\(^{-1}\). Figures 3a and 3b exhibit very similar characteristics (note the difference in the second y axis). In both cases, the outflow rate was high at the beginning of the experiment and then tapered off after approximately 5 min. When compared with linear outflow rates for untreated no. 70 mesh and C33 sands (data not shown), results on the treated columns indicate that the \(K_{sat}\) reduction with time was caused by the PAM treatment. The variability seen in the calculated value of \(K_{sat}\) (symbols in Fig. 3) was due to the timing of the individual drops of fluid when collected in the outflow collector. The cumulative flux (dashed line in Fig. 3) is smoother because it was processed with a five-point moving average. The cumulative flux became linear after approximately 60 min, as seen from Fig. 3a and 3b, indicating that the system had reached steady state. Figure 3c shows the nearly linear cumulative flux from the onset of the experiment, indicating that the system was close to steady state at the time PAM was applied and that the effect of PAM and the sediments was very small. Thus, \(K_{sat}\) changed very little in the loamy sand with time, even though a PAM treatment would be expected to affect the \(K_{sat}\) after only 5 min. Figures 3a and 3b also show that most of the \(K_{sat}\) reduction occurred within approximately the first 10 min of the test, indicating that the rapid reduction in \(K_{sat}\) could be explained by the rapid reduction in turbidity and creation of PAM flocculates (as shown in Fig. 2). But turbidity was reduced at a rate faster than \(K_{sat}\) reduction, which means that additional time was needed for the flocculates to sorb onto the soil surface, plug larger soil pores, and then reduce \(K_{sat}\), which we hypothesized is one of the physical mechanisms that explain \(K_{sat}\) reduction.

The means of the final \(K_{sat}\) values from triplicate experiments for each treatment combination were plotted in Fig. 4a to 4c as a function of PAM and SSC. Error bars are the range of data from the triplicate measurements, and letters above the bars represent statistical differences between treatments of PAM concentration for each SSC (note that the same letters above bars shown for conditions of “0 mg L\(^{-1}\) SSC” in Fig. 4a–4c). Results from the control (no PAM, SSC = 0) showed wide differences in \(K_{sat}\) among the three materials. The C33 sand had the highest \(K_{sat}\) and the loamy sand had the lowest \(K_{sat}\). Values did not change significantly for any soil when suspended sediment alone (i.e., no PAM) was added to the solution (open bars).

Adding PAM to the solution in increasing concentrations without suspended sediment, however, led to significant decreases \((P < 0.05)\) in \(K_{sat}\) for the no. 70 mesh and C33 sands for almost each step increase in PAM concentration (note letters above bars shown for conditions of “0 mg L\(^{-1}\) SSC” in Fig. 4a–4c). For the loamy sand, a significant \(K_{sat}\) reduction was recorded when the PAM treatment was 22.4 kg ha\(^{-1}\) or higher. The \(K_{sat}\) reductions when SSC = 0 were probably caused by a combination of increasing solution viscosity, which is described in more detail below, and the settling of partially hydrated PAM molecules. In the case of the no. 70 mesh and C33 sands (Fig. 4a and 4b), PAM that settled onto the soil would thus affect the \(K_{sat}\) of coarse-grained materials more than that of fine-grained materials because they would block the larger soil pores that contribute a large proportion of the flux. While partially hydrated PAM would also block pores in the loamy sand, its effect on \(K_{sat}\) was not as significant as in the no. 70 mesh and C33 sands because the soil pores of the loamy sand are smaller.

When sediment was not present (SSC = 0), the \(K_{sat}\) decrease was related to PAM treatment level using a second-order polynomial, with correlation coefficients \((R^2)\) for no. 70 mesh sand, C33 sand, and loamy sand of 0.9543, 0.9601, and 0.9875, respectively. Larger changes in \(K_{sat}\) were observed when PAM and suspended sediment were combined. For the PAM treatment of 5.6 kg ha\(^{-1}\) and SSC at 150 mg L\(^{-1}\), the \(K_{sat}\) decrease was 10 times greater than observed with PAM alone (from 726 to 73 cm d\(^{-1}\)). The \(K_{sat}\) decreased further (from 73 to 64 cm d\(^{-1}\)) when SSC was increased from 150 to 300 mg L\(^{-1}\).

For loamy sand (Fig. 4c), PAM treatment combined with SSC at 150 mg L\(^{-1}\) produced results similar to PAM alone; i.e., a significant difference from the control was observed only at the highest PAM treatment tested. When suspended sediment was present at 300 mg L\(^{-1}\), however, PAM treatments of 22.4 and 44.8 kg ha\(^{-1}\) resulted in statistically significant \(K_{sat}\).

![Fig. 4. Comparison of saturated hydraulic conductivity \((K_{sat})\) for treatments performed on (a) fine (no. 70 mesh) sand, (b) coarse (ASTM C33) sand, and (c) loamy sand. Note different scales on y axes.](Image 273x91 to 564x475)
reductions vs. the control. For all combinations of PAM and SSC, \( K_{sat} \) reductions were between 0 and 56%.

Using the PAM treatment levels and \( K_{sat} \) reductions, it is possible to calculate the efficiency of PAM treatment: we divided the reduction percentage by the PAM treatment level and plotted the results in Fig. 5. It is clear that PAM treatment efficiency decreased as PAM concentrations increased. For example, for the experiments using the no. 70 mesh sand (Fig. 5a), a test solution with PAM at 5.6 kg ha\(^{-1}\) and SSC at 300 mg L\(^{-1}\) caused a 94% reduction in \( K_{sat} \), equivalent to an efficiency of 16.9. When the PAM treatment level was increased to 44.8 kg ha\(^{-1}\) and combined with a SSC of 300 mg L\(^{-1}\), a 98% reduction in \( K_{sat} \) was observed, yielding a significantly \((P < 0.05)\) lower efficiency of 2.2 (i.e., more chemical treatment was needed without a consequent decrease in \( K_{sat} \)). For the C33 sand, the efficiency for the same treatment combinations were 18.9 and 2.2, respectively. Thus, although the PAM treatment of 44.8 kg ha\(^{-1}\) reduced \( K_{sat} \) to a greater extent than the PAM treatment of 5.6 kg ha\(^{-1}\), an eightfold increase in PAM mass was needed to reduce \( K_{sat} \) by the additional 4%. For the experiments using the loamy sand (Fig. 5c), PAM treatment was shown to be inefficient at all concentrations used when compared with the results for the no. 70 mesh sand and C33 sand. These results highlight the capability of PAM as a sealant for coarse sand, the relatively small amount of PAM needed to effectively reduce \( K_{sat} \) using the experimental conditions described here, and the need for suspended sediment to increase the efficiency of PAM.

Three-way interactions between soil, PAM treatment level, and SSC were quantified using ANOVA. The results showed that the interactions were significant \([F(16,110) = 3.964, P < 0.001]\). Of the three categories, SSC had a nonlinear effect on \( K_{sat} \) reduction; no significant reduction was observed when SSC was increased from 150 to 300 mg L\(^{-1}\). For categories of soil and PAM treatment, differences were significant as levels changed. The results showed that suspended sediment played an important role in reducing \( K_{sat} \), but that little additional benefit was realized when the concentration was increased above 150 mg L\(^{-1}\).

**Filter Material Testing**

The filter material tests showed clear \( K_{sat} \) reductions when PAM and suspended sediment were combined (Fig. 6). The filter material tests also verified that increasing PAM concentration without the presence of suspended sediment decreased \( K_{sat} \) linearly \((R^2 = 0.840)\), which is in contrast to the nonlinear relationship observed when the same treatment combinations were used with soil materials. Apparently, flow rates through the pores of the filter material were uniform because the pore size distribution was also uniform. So, when the PAM flocculates settled onto the filter paper, they occluded pores of the same diameter and flow capacity, leading to a linear reduction in flux. This phenomenon could be explained by the formation of a thin seal on top of the filter material. Thus, because the pore sizes are uniform on the filter paper, a percentage of pores blocked would lead to a similar percentage reduction in flux, as was seen in these experiments.

Filter \( K_{sat} \) for nonzero concentrations of PAM and suspended sediment tended to be lower than in the soil materials, indicating that PAM flocculates could be preferentially migrating into larger pores and nonuniformly covering the surface. In any case, the results of the filter material tests show trends similar to those for the sandy material: specifically, (i) sediment alone had little effect on decreasing \( K_{sat} \); (ii) increasing PAM concentration without suspended sediment decreased \( K_{sat} \) and (iii) the addition of suspended sediment increased the effectiveness of PAM to a much greater extent than using PAM without suspended sediment.

**Effect of Viscosity**

The calibration curve that relates kinematic viscosity to PAM concentration (corrected for a temperature of 25°C) showed good linearity \([\text{viscosity} = 0.019(\text{PAM concentration}) + 0.9628; R^2 = 0.9886]\), with a standard (predictive) error of PAM concentration of 3.67 mg L\(^{-1}\). The results showed...
that the viscosity of the test solution could increase almost threefold from the addition of PAM. Clearly this would lead to a significant \( K_{\text{sat}} \) reduction (Eq. [1]).

To quantify the extent to which \( K_{\text{sat}} \) reduction could be attributed to increased viscosity, a case is presented that shows the \( K_{\text{sat}} \) reductions measured as a function of PAM treatment level, and \( K_{\text{sat}} \) reductions predicted from the higher viscosity values measured for two time periods during the flow-through experiment. The first time period occurred before the experiment, when PAM was first mixed into water and allowed to hydrate but before flow through the soil material was started. For experimental conditions without suspended sediment, PAM flocculates were not expected to form, so loss of PAM through settlement likewise was not expected. Thus, in this case, the impact of PAM on solution viscosity was maximized. The second time period occurred at the end of the experiment, when a portion of the PAM mass had either dissolved or accumulated on the soil surface. To determine the concentration of PAM remaining in solution (and contributing to higher viscosity), aliquots of test solution from the water column above the soil (Fig. 1) were collected and analyzed for viscosity. Differences in viscosity were attributed to PAM loss from the solution.

At the start of each column experiment when PAM was hydrated and fully dispersed in the test solution, viscosity alone could account for a portion of the change in flux entering the soil column. For example, for the maximum PAM treatment level of 44.8 kg ha\(^{-1}\) in no. 70 mesh sand without suspended sediment, we observed an 80% reduction in \( K_{\text{sat}} \) (see Fig. 7 and 4), but \( \sim50\% \) of the \( K_{\text{sat}} \) reduction could be attributed only to the increased viscosity from the PAM (see trace labeled “Predicted \( K_{\text{sat}} \) from initial viscosity” in Fig. 7). At the end of the experiment, only 7% of the total reduction in \( K_{\text{sat}} \) could be attributed to increased viscosity of the test fluid (see trace labeled “Predicted \( K_{\text{sat}} \) from final viscosity”), even when PAM in this case had not reacted with suspended sediment or flocculated from the solution. This relatively low impact from solution viscosity would be further reduced in canal treatments, where upstream water in the canal would quickly dilute the PAM concentration and hence reduce the viscous effects.

The results indicate that viscous effects may not dominate the \( K_{\text{sat}} \) reduction, pointing to other physical effects, specifically that PAM either clogs large soil pores (called a “wash-in seal” by Lentz and Freeborn [2007]) or becomes a thin layer with distinct hydraulic properties. In any case, it is unlikely that the wash-in seal would extend more than a few centimeters into the soil because the PAM flocculate is typically retained close to the soil surface (Lu and Wu, 2003). These results differ from those described by Ajwa and Trout (2006), who found that viscous effects were a significant contributor to reduced \( K_{\text{sat}} \) but similar to their conclusions when they stated that viscous effects alone could not explain \( K_{\text{sat}} \) reduction. Finally, these results partially address our second objective and highlight the importance of suspended sediment in the sealing process as described in earlier results.

**CONCLUSIONS**

Increases in PAM concentration alone (i.e., without any suspended sediment) had the ability to decrease \( K_{\text{sat}} \) in all the soils tested. A portion of this reduction could be accounted for by viscous effects in the test solution, but these effects were found to be secondary to the PAM accumulation at the soil surface, which either clogged larger soil pores or otherwise formed a distinct layer separate from the soil. The results showed that PAM was less effective in treating loamy sand than the coarser grained materials tested, especially when using either the \( K_{\text{sat}} \) reduction or efficiency as gauges of success. For soils dominated by fine fractions, seepage rates already would be low and probably canals with this subsoil would not warrant PAM treatment in the first place. Therefore, PAM is better suited for...
coarse-grained canal sediments where water loss from seepage is a greater problem.

Information gained from these experiments can be useful for predicting the effectiveness of PAM treatment in unlined water delivery canals when field conditions (suspended sediment concentration, soil type, and PAM concentration) are known, and for developing the standards needed for PAM use as a canal sealant. As with many laboratory experiments, however, laboratory conditions do not fully simulate field conditions, especially those in full-scale canals. The experiments here were conducted in columns that limited water movement through the soil–water interface to only the vertical direction (even though a stirring mechanism was used to agitate the solution). In a field situation, lateral movement would inhibit the vertical settling of flocculates onto the canal bottom. Also, the viscosities of the test solution in our experiments were higher than should be expected in an operational canal where water without PAM is constantly being flushed through the system.

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