

Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam



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ABSTRACT

Researchers seek a more renewable and natural alternative for water soluble anionic polyacrylamide (PAM), a highly-effective, petroleum-derived polymer used in agriculture to control erosion and reduce water seepage from unlined irrigation structures. This study evaluated four anionic polymers including low- (0.5 Mg mol^{-1}) or high molecular-weight (MW) ($10\text{--}20 \text{ Mg mol}^{-1}$), bacteria-produced polysaccharides (biopolymers) and low- (0.2 Mg mol^{-1}) or high-MW ($12\text{--}15 \text{ Mg mol}^{-1}$) PAMs. We evaluated their influence on (1) the rate and efficacy of colloid flocculation in 1- and 10-mg L^{-1} , high-MW, PAM or biopolymer solutions; (2) percent water stable aggregates in silt loam soil treated with water or 1000-mg L^{-1} solutions of the four polymers; and (3) effective saturated hydraulic conductivity (seepage loss) when water or 500-mg L^{-1} , high-MW biopolymer or PAM solutions were applied to silt loam. The biopolymer most effectively flocculated the colloids at a concentration of 1 mg L^{-1} , but was still 30% less effective than PAM at 1 mg L^{-1} and 50% less effective than PAM at 10 mg L^{-1} . Overall, both polymer types increased the percent of stable soil aggregates in the silt loam, 1-to-2-mm-diam. size fraction, though PAM produced 1.35-times more stable aggregates than the biopolymer, 88.7% vs. 65.5%. These results suggested that the biopolymer's bulkier molecular conformation limited the extension and flexibility of the molecule in solution, compared to PAM. After 140 h, the biopolymer reduced seepage loss rates by 21%, while PAM increased loss rates 1.6-fold, compared to controls. These data suggest that the biopolymer would be less effective than PAM for reducing water erosion owing to its lesser flocculation and aggregate-stabilizing potential. However, the biopolymer could be a more desirable alternative to PAM for controlling seepage from unlined irrigation canals and reservoirs; it (i) can be used effectively at lower concentrations, (ii) is considered more environmentally friendly, and (iii) is produced from a renewable resource.

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1. Introduction

Water soluble polymers are employed in agriculture to control furrow-irrigation and sprinkler induced erosion, inhibit soil seal formation and manage water infiltration, and reduce sediment, nutrient, and pesticide losses in runoff (Sojka et al., 2007). Polymer treatments can either increase or decrease infiltration into soils depending on the type and concentration of polymer applied, soil type, and application method (Lentz, 2008). Hence they can also be used to reduce water seepage from unlined irrigation ponds and conveyance channels (Lentz and Kincaid, 2008; Story et al., 2009). Their potential for use in rainfed agriculture soils, construction sites, and post-fire forested landscapes is being recognized now as well (Lee et al., 2010; Flanagan et al., 2002; Hayes et al., 2005; Davidson et al., 2009).

Water soluble anionic polyacrylamide (PAM), a linear polymer synthesized from the petrochemical propylene is commonly used for these agricultural purposes. Though PAM has been shown to be highly effective and relatively inexpensive, its manufacture currently utilizes a

non-renewable carbon source that ultimately contributes to increased atmospheric carbon loads (Orts et al., 2000; Sojka et al., 2007). Researchers seek a natural alternative to PAM that is equally effective, but derived from renewable biomass carbon sources and more biodegradable (Susfalk, 2008; Orts et al., 2000; Rehm, 2010). Further concerns arise when PAM is used in irrigation canals, because it contains a minute quantity of acrylamide monomer. Acrylamide is a suspected carcinogen, although no direct effect of acrylamide on human carcinogenicity has been documented (Friedman, 2003; Labahn et al., 2010).

A potential alternative to PAM may be found among the polysaccharide class of long-chain polymers. These can be derived from plant materials directly (e.g., guar gum) or via bacterial production using various biomass carbon sources (bacterial biopolymer). Research on polysaccharides has shown that some biopolymers interact with soil in much the same way as PAM. Cationic guar with a molecular weight (MW) of 0.2 to 2 Mg mol^{-1} increased infiltration, hydraulic conductivity, and resistance to erosion of a treated soil (Ben-Hur and Lety, 1989; El-Morsy et al., 1991; Agassi and Ben-Hur, 1992). Researchers have known for many years that bacterial polysaccharides promote soil aggregation (Rennie et al., 1954; Acton et al., 1963) and can flocculate suspensions of bacteria and inorganic colloids (Busch and Stumm, 1968). Both

Abbreviations: MW, molecular weight; PAM, polyacrylamide
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neutral (e. g., dextran) and anionic (e.g., polygalacturonic acid) polysaccharides were found to flocculate clay suspensions, with flocc efficacy increasing with polysaccharide molecular weight (Fuller et al., 1995; Tarchitzky and Chen, 2002). Orts et al. (2000) evaluated starch and cellulose xanthates and chitosan polysaccharides for use in reducing furrow-irrigation induced erosion, reporting that neither worked as well as PAM when applied at the standard 10 mg L⁻¹ concentration.

We conducted a laboratory evaluation of biopolymer and PAM in order to better understand how biopolymer interacts with soil, and to assess its potential for use in agricultural applications. The objective was to compare the two polymer's capacity to flocculate soil colloids, stabilize soil aggregates, and alter the effective hydraulic conductivity of water through a soil column.

2. Materials and methods

2.1. Soils, polymers, and experimental design

The soil used in aggregate stability and effective hydraulic conductivity assessments was collected from 0-to-15-cm depths of a Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) located 1.7 km southwest of Kimberly, ID (42E 31' N, 114E 22' W, elevation of 1190 m). The soil contains on average 100 g kg⁻¹ clay, 650 g kg⁻¹ silt, 250 g kg⁻¹ sand, 10 g kg⁻¹ organic matter, and 50 g kg⁻¹ calcium carbonate equivalent. The soil has a saturated-paste-extract electrical conductivity (EC) of 0.07 S m⁻¹, exchangeable sodium percentage of 1.5, and pH of 7.7 (H₂O saturated paste).

Characteristics of polymer treatments employed in the study's experiments are given in Table 1. Two formulations of PAM were employed: a medium molecular-weight (MW), liquid product (Aerotill) obtained from Kemira Water Solutions (1937 West Main Street, Stamford, CT¹); and a very-high MW, granular product obtained from SNF (1 Chemical Plant Road, Riceboro, GA). For simplicity the two will be identified as the low-MW and high-MW PAMs, respectively. Both forms were acrylate-acrylamide copolymers with a chain-like molecular structure and lacked side branching (Barvenik, 1994). The liquid was 17% active ingredient (a.i.) while the granular was 90% a.i., with the remainder water. The high-MW PAM is typically used for agricultural applications, the low-MW product was included because it is sometimes more effective as a soil stabilizing agent (Shaviv et al., 1987).

Medium- and very high-MW versions of a linear, biopolymer (Table 1) were obtained from NanoQuantics (5934 Windswept Blvd., Wise, VA), and were characterized as follows (personal communication, Tim Hopkins, 2011). Both products were derived from an identical bacterial polymer synthesis. Each was obtained as an aqueous solution, the medium-MW product contained 2.5% a.i. and the very high-MW, 0.1% a.i. The biopolymer's molecular structure differed from that of PAM in that the linear backbone of the polymer included short side branches that made up 30 to 40% of the total polymer mass. Like PAM, the biopolymer's negative charge is derived from carboxyl functional groups, although for the biopolymer, most charges are located on the side branches. Again, for simplicity, the two will be identified as the low-MW and high-MW biopolymers.

The study consisted of three experiments. A flocculation efficacy experiment employed a completely randomized design, while the aggregate stability and hydraulic conductivity experiments used a randomized complete block design. Treatments and number of replicates varied depending on the experiment. Polymer solutions employed in the various treatments were prepared using reverse-osmosis (RO) water.

Table 1

Characteristics of anionic biopolymer and polyacrylamide copolymer (PAM) treatment solutions used in flocculation, aggregate stability and effective hydraulic conductivity experiments.

ID	Polymer type	Product	Charge density %	Molecular weight Mg mol ⁻¹	Concentration mg L ⁻¹
<i>Flocculation experiment</i>					
BP-0.5	Biopolymer	SSX-10	30	10–20	0.5
BP-1	Biopolymer	SSX-10	30	10–20	1.0
BP-10	Biopolymer	SSX-10	30	10–20	10.0
BP-50	Biopolymer	SSX-10	30	10–20	50.0
BP-100	Biopolymer	SSX-10	30	10–20	100.0
PAM-1	PAM	AN-923-PWG	20	12–15	1.0
PAM-10	PAM	AN-923-PWG	20	12–15	10.0
<i>Aggregate stability experiment</i>					
Control	–	RO H ₂ O ^a	–	–	0
BP-L	Biopolymer	SS2500	30	0.5	1000
BP-H	Biopolymer	SSX-10	30	10–20	1000
PAM-L	PAM	Aerotill	70	0.2	1000
PAM-H	PAM	AN-923-PWG	20	12–15	1000
<i>Effective hydraulic conductivity experiment</i>					
Control	–	RO H ₂ O ^a	–	–	0
BP-500	Biopolymer	SSX-10	30	10–20	500
PAM-500	PAM	AN-923-PWG	20	12–15	500

^a RO H₂O = reverse osmosis water; electrical conductivity = 0.0005 S m⁻¹.

2.2. Flocculation

Seven high-MW polymer treatments with three replicates were included in the experiment: two PAM concentrations (1 and 10 mg L⁻¹); and five biopolymer concentrations (0.5, 1, 10, 50, and 100 mg L⁻¹). These are identified as PAM-1, PAM-10, BP-0.5, BP-1, BP-10, BP-50, and BP-100 (Table 1). We utilized an instrumented flocculation test adapted from Lentz et al. (1996), which employed (1) a Scientific Industries Model G-560 (Bohemia, NY) vortex mixer; (2) Milton Roy Spectronic 21 Spectrophotometer (Rochester, NY) using a 10-mm-pathlength and 7-mL test-tube cuvettes; and (3) a clay substrate (Fertogel), a ground attapulgite mineral product with a particle size distribution dominated (>92% on mass basis) by <75 mm diam. particles, obtained from Zemex Industrial Minerals, Inc. (1040 Crown Pointe Parkway, Atlanta, GA).

In the first step of the procedure, 0.05 g (dry wt.) of Fertogel substrate was weighed (± 0.001 g) into a test tube cuvette. A 5-mL volume of polymer solution was then pipetted into the Fertogel-loaded cuvette and the mixture was immediately vortex mixed at maximum speed, i.e. 3000 rpm, for 120 s. When agitation was complete, the cuvette was promptly placed (within 4 s) into the spectrophotometer, covered, and sample transmittance (560 nm) measured every second during the next 5 min. The procedure documented the change in the suspension's clarity with time, which was interpreted as indicator of the treatment's flocculation efficacy.

2.3. Aggregate stability

This experiment determined the effect of polymer-type and MW effects on the percent water stable soil aggregates in the 1 to 2 mm size fraction of air-dry the Portneuf silt loam. Five soil aggregate treatments with four replicates were included in the experiment, one RO-water treatment and four 1000 mg L⁻¹ polymer treatments. The polymer treatments were the low-MW biopolymer (identified as BP-L, Table 1); high-MW biopolymer (BP-H); low-MW PAM (PAM-L); and high-MW PAM (PAM-H).

Aggregates 1 to 2 mm in size were sieved from the air-dried soil sample. A 4-g sample of aggregates was wetted with a 2-mL volume of the treatment solution (equating to 0.5 g polymer kg⁻¹ soil, assuming complete adsorption to the soil). Solutions were applied slowly at the outset, to prevent aggregate breakdown. A few drops of solution were

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applied to the paper holding the aggregates so that initial moistening was via capillary transfer. Treated aggregates were allowed to air dry at room temperature for 24 to 48 h. The percent stable aggregates in treated samples was determined using wet sieving (Method 2.6.2.1.d; Nimmo and Perkins, 2002). However, the aggregate sample pre-wetting step was eliminated to evaluate soil stability under rapid wetting, a characteristic of surface irrigation events. After wet sieving, the percent stable soil aggregates in the 1 to 2 mm size fraction were calculated as 100 times the mass ratio of stable soil divided by total soil. Aggregates 1 to 2 mm in size were sieved from the air-dried soil sample. A 4-g sample of aggregates was wetted with a 2-mL volume of the treatment solution (equating to 0.5 g polymer kg⁻¹ soil, assuming complete adsorption to the soil). Solutions were applied slowly at the outset, to prevent aggregate breakdown. A few drops of solution were applied to the paper holding the aggregates so that initial moistening was via capillary transfer. Treated aggregates were allowed to air dry at room temperature for 24 to 48 h. The percent stable aggregates in treated samples were determined using wet sieving (Method 2.6.2.1.d; Nimmo and Perkins, 2002). However, the aggregate sample pre-wetting step was eliminated to evaluate soil stability under rapid wetting, a characteristic of surface irrigation events. After wet sieving, the percent stable soil aggregates in the 1 to 2 mm size fraction were calculated as 100 times the mass ratio of stable soil divided by total soil.

2.4. Effective hydraulic conductivity

The experiment included three treatments (Table 1), a control, a 20 mL application of RO water, and two 500 mg L⁻¹ high-MW polymer treatments, either a 20 mL biopolymer solution (BP-500), or a 20 mL PAM solution (PAM-500). Previous research indicated that this polymer concentration effectively altered seepage through soil columns (Unpublished data, 2001; Lentz, 2003). Each treatment included five replicates.

The experimental procedure used was designed to evaluate the polymers' capacity to inhibit infiltration and reduce seepage loss in irrigation ponds and canals under a specifically defined field application scenario that included three phases: (1) The amendment solution is applied to dry soil lining the pond or canal and allowed to dry. (2) Untreated irrigation water floods the pond or canal in a turbulent flow containing a heavy sediment load. (3) After the water fills the structure, the subsequent irrigation flows are less turbulent and contain substantially less sediment. Because the procedure approximated this field approach, the measured value was termed the effective hydraulic conductivity.

Column Preparation: Portneuf silt loam soil was air dried, sieved through a 2-mm screen (#10), and a 100-g portion placed into a 40-mm I.D. by a 133-mm-long PVC cylinder fitted with a nylon fabric base. Soils were packed to an average air-dry bulk density of 1.18 g cm⁻³. The soil columns were incrementally saturated from below over a 6- to 12-h period with de-aerated, simulated irrigation water. The simulated irrigation water had an electrical conductivity of 0.04 S m⁻¹ and sodium adsorption ratio of 1.3 [mmol_c L⁻¹]^{0.5}, and was prepared by diluting well water 1:1 with RO water.

Phase 1: To simulate dry soil conditions at the time of polymer application, the saturated soil in each column was covered with 25 g of air dried, 1 to 5-mm-diam. Portneuf soil aggregates, which were immediately treated with either control, BP-500, or PAM-500 solutions. The soil columns were allowed to air dry at 21 °C for 36 to 48 h. To reduce variability caused by entrapped air, the soil was saturated as done previously. We then placed the columns on a constant-head apparatus like that used for measuring hydraulic conductivity at saturation (Klute and Dirksen, 1986). A constant 3.5-cm head of de-aerated, simulated irrigation water was applied to each column.

Phase 2: Five minutes after the flow to soil columns was started and every h thereafter for 6 h, 1.25 mL of a soil–water slurry (500 g Portneuf soil L⁻¹ water) was stirred vigorously into the ponded water producing a resulting concentration of 29 g sediment L⁻¹. The soil surface itself was not directly disturbed during the 3-second stirring. The sediment

was allowed to settle between column applications. Seepage draining from each column was measured over 60 min intervals for 6 consecutive hours in day one.

Phase 3: No sediment was introduced to ponded column water for remainder of the experiment (days 2 through 6). Seepage draining from each column was measured twice a day for days 2–4, and once a day for days 5 and 6, giving a total measurement period of 140 h. This seepage was assumed equal to infiltration and reported as mm of water infiltrated per hour.

The effective saturated conductivity (K_s , mm h⁻¹) of soils was calculated as:

$$K_s = 10LV \cdot [At(H_2 - H_1)]^{-1} \quad (1)$$

where L is the soil column length (cm); V is the water volume (cm³) collected through the cross-sectional area A (cm²) during time t (h); and $(H_2 - H_1)$ is the difference in the hydraulic head between the upper and lower core boundary (cm), equal to the depth of water ponded on the soil. The constant 10 in Eq. (1) is a unit conversion factor. At the end of the 140-h period, the distance from column top to the soil surface was measured by inserting a ruled hollow rod into the ponded water and placing its 1.5-cm-diam. flat foot upon the soil. This measurement was used to calculate the length, and ultimately, the bulk density of the soil column.

2.5. Statistical analysis

We examined the transmittance responses for flocculation suspensions at the first second after mixing and at 10-s intervals thereafter. A separate analysis of variance (ANOVA) was conducted for each time using PROC Mixed (SAS Institute Inc., 2009). The statistical model included treatment as the fixed effect and no random effect (completely randomized design). Pairwise comparisons of treatment means were performed using the Tukey option (SAS Institute Inc., 2009). An ANOVA was employed to analyze percent stable-aggregate responses using SAS PROC Mixed. The statistical model included treatment as the fixed effect and block as the random effect, and included the orthogonal class comparisons (water vs. polymer; PAM vs. biopolymer; low molecular-weight polymer vs. high; and the polymer-type × molecular-weight interaction). The effective hydraulic conductivity at each measurement time, cumulative outflow, and ending bulk density were analyzed separately with ANOVA, using the same approach employed for the stable-aggregate analysis. However, in this case, pairwise comparisons of treatment means were performed using the Tukey option. All analyses were conducted using a $P = 0.05$ significance level.

3. Results and discussion

3.1. Flocculation efficacy

The flocculation curves presented in Fig. 1 show similar transmittance values at 1 s ($P = 0.21$), increasingly dissimilar values at 10 s and 20 s ($P < 0.02$), then strongly divergent values for the remainder of the period ($P < 0.001$). The biopolymer flocculated the clay best at an application concentration of 1 mg L⁻¹ (BP-1), with lesser and greater biopolymer concentrations generating less flocculation (Fig. 1). The occurrence of an optimum flocculation polymer concentration (dose) is common due to steric stabilization, where excess polymer binds to individual colloids and prevents close interaction between the particles (Caskey and Primus, 1986; Gregory and Barany, 2011). At optimum concentration, the biopolymer settling curve BP-1 shows that flocculation was delayed several minutes before settling began in earnest. After 5 min, the maximum transmittance attained by BP-1 was 30% less than PAM-1 and 50% less than PAM-10. Late in the test, the rate of settling for BP-1 was greater than for PAM curves, presumably because clay was still settling out in BP-1, whereas most clay had already settled

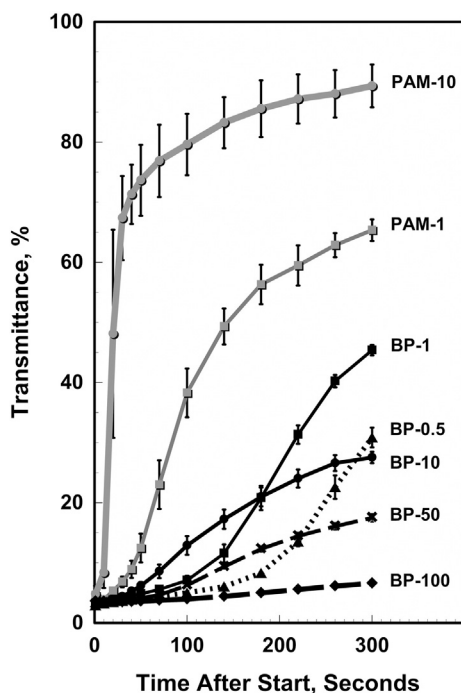


Fig. 1. Change in light transmittance through a clay suspension with time after mixing with 1 or 10 mg L⁻¹, high-molecular-weight PAM solutions (PAM-1, PAM-10) and 0.5, 1, 10, 50, or 100 mg L⁻¹ high-molecular-weight biopolymer solutions (BP-0.5, BP-1, BP-10, BP-50, BP-100). Each leg of the error bars represents one standard error ($n = 3$).

out in the PAM treatments. These results suggest that biopolymer flocules were smaller than those produced by PAM.

The steep rise in transmittance in the PAM-treated suspension relative to that of biopolymer-treatments (Fig. 1) indicated that PAM more rapidly initiated flocculation and formed larger flocs, which settled more quickly than those formed by the biopolymer (Gregory and Barany, 2011). Polymer-generated flocules are stronger than those produced by other means of particle agglomeration because they are formed from the bridging of particles together by polymer chains, and because bridging polymers are flexible and stretchable (Gregory and Barany, 2011). Polymers that exhibit the greatest chain extension in solution give faster flocculation settling rates (Caskey and Primus, 1986; Hocking et al., 1999). This suggests that the biopolymer produced smaller flocules than PAM because (i) the extension of the dissolved biopolymer was less great, which reduced its capacity to bridge soil particles, and/or (ii) the biopolymer produced flocs were more unstable because the biopolymer chains were less flexible. During the experiment, we noted that the viscosity of the PAM-1 solution was more viscous than that of BP-1, which lends support to the argument that PAM molecules exhibited greater extension in solution than the biopolymer molecules. Many polysaccharides adopt a single helix or double helix conformation in solution, which makes them less flexible than the linear, single-chain, PAM (Holzwarth and Prestridge, 1977; Labille et al., 2004). He and Horikawa (1996) attributed biopolymer-induced dispersion at very dilute concentrations, not observed for PAM polymer, to the reduced flexibility of the polysaccharide. When the biopolymer concentration declined below 1 mg L⁻¹ (BP-0.5) in the current study, we observed a similar dispersed condition that inhibited flocculation (Fig. 1, BP-0.5).

3.2. Aggregate stability

All orthogonal contrasts were highly significant, indicating that each factor, including the polymer-type \times MW interaction influenced the percent water stable soil aggregates in the Portneuf, 1-to-2-mm size fraction under rapid wetting (Table 2). Overall, polymer treatments

increased percent water stable soil aggregates 1.7-fold over the water-only treatment (77.1% vs. 44.8%). Of the two polymer types, PAM produced an average 1.35-fold more stable aggregates than the biopolymer, 88.7% vs. 65.5%. And, of the two polymer MW classes, the high-MW polymers produced 1.5-fold more stable aggregates than the low-MW polymers, 92.6% vs. 61.7%. These results are consistent with research showing that aggregate stability of polymer-treated silt loam increases with molecular weight (Levy and Agassi, 1995; Green et al., 2000). Similarly, Awad et al. (2013) reported that PAM and biopolymers both increased 1-2-mm aggregate size fraction in sandy and sandy loam soils.

Furthermore, the significant interaction between polymer type and MW indicated that the stabilizing efficacy of the biopolymer was more sensitive to changing MW than for PAM (Fig. 2). A \sim 30-fold increase in biopolymer MW produced a 1.9-fold increase in stable aggregates, while a \sim 70-fold increase in PAM MW increased aggregate stability only 1.3-fold. It is possible that the MW of the 0.5-Mg mol⁻¹ biopolymer (BP-L) was less than the critical value needed to increase aggregate stability in these soils, such that the stability of the low-MW biopolymer-treated soils was no better than that of the control (Fig. 2). This is consistent with a model describing the biopolymer as a more rigid chain than PAM (Holzwarth and Prestridge, 1977; Labille et al., 2004), with less flexibility and ability to conform to irregular soil surfaces as chain length decreased. An alternative explanation is that the treatment biopolymer concentration was below the critical value needed for BP-L to stabilize soil aggregates. However, the 0.5 g polymer kg⁻¹ soil treatment rate used here represents a relatively substantial dose, suggesting that a further benefit from increasing the polymer concentration might be unlikely.

The PAM polymer provided a more effective stabilizing treatment for the Portneuf silt loam soil, which contains relatively little clay (100 g/kg). This would be expected if the length of PAM was greater than that of the biopolymer. If this implication is correct, then PAM and the biopolymer may prove to be equally effective treatments for soils with higher clay content, since low MW polymers demonstrate a greater stabilizing-efficacy in high-clay, than in low-clay, soils (Levy and Agassi, 1995; Green et al., 2000).

In the current study, the MW and charge density for the low-MW PAM and biopolymers, in particular, were slightly different. The effect of the small MW difference (0.2 vs. 0.5 Mg mol⁻¹) on results was considered negligible because its effect on soil stability was small relative

Table 2

The influence of water, polymer type, polymer molecular weight (MW), and polymer type \times MW interaction on the percent of water stable soil aggregates in the Portneuf silt loam 1-to-2-mm size fraction. Table includes *P*-values from an analysis of variance for factor effects and class comparison means.

Source of variation	<i>P</i> -value
Polymer ^b	a
Polymer type	a
Molecular weight	a
Polymer type \times MW	a
Class comparisons	
Water vs.	Percent Stable Aggregates (%)
Polymer	44.8 b ^c
Polymer	77.1 a
PAM vs.	88.7 a
Biopolymer	65.5 b
Low MW polymer vs.	61.7 b
High MW polymer	92.6 a

^a Significant at the 0.001 probability level.

^b Polymer = all PAM and biopolymer treatments; PAM = PAM-L + PAM-H; Biopolymer = BP-L + BP-H; Low MW = PAM-L + BP-L; High MW = PAM-H + BP-H (treatment names defined in Table 1).

^c For each class comparison, means followed by the same letter are not significantly different ($P < 0.001$).

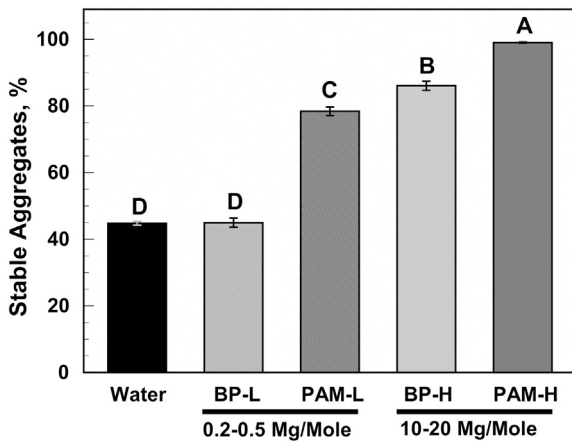


Fig. 2. The influence of polymer type and molecular-weight on percent of water stable soil aggregates in the Portneuf 1-to-2-mm size fraction after treatment with water only, or 1000 mg L⁻¹ solutions of low and high molecular-weight biopolymer (BP-L, BP-H) and water-soluble polyacrylamide (PAM-L, PAM-H). Each leg of the error bars represents one standard error (n = 4).

to that between the low and high MW polymer classes (Levy and Agassi, 1995; Lentz et al., 2000). Likewise, the charge density difference (30 vs. 70%) likely had minor influence on results because the relative effect of polymer charge density on soil stability declines as charge density increases beyond about 25% (Lentz et al., 2000).

3.3. Effective hydraulic conductivity

The hydraulic conductivity or seepage rate from the PAM-treated soil initially trended lower than that of the control and biopolymer-amended soil (Table 3). However, this pattern was reversed after 30 h (Fig. 3). During the remainder of the period, PAM increased seepage by 1.3 to 2.1 times over that of the control, while the biopolymer reduced seepage by 15 to 40% relative to the control (Fig. 3). This outcome was also reflected in the 16-h and 140-h seepage rates and total cumulative seepage shown in Table 3. Thus the biopolymer was more effective than PAM for reducing seepage losses. The PAM's influence on seepage loss is strongly a function of concentration. When a 1000-mg L⁻¹ PAM solution was applied using a similar PAM and method employed here, the polymer reduced seepage loss rather than increasing it (Lentz, 2003; Lentz and Kincaid, 2008).

Note that PAM also slightly but significantly reduced the bulk density of the soil column measured at the end of the monitoring period (Table 3). This was not attributed to the difference in settled depth of added sediment because the same amount of sediment was added to each column, and it was unlikely that the measurement approach used could have distinguished differences in thicknesses of soft flocculated layers. Apparently the PAM caused greater swelling in this silt loam soil than did the either the control or biopolymer treatments. Similar PAM effects on bulk density were observed in a prior study

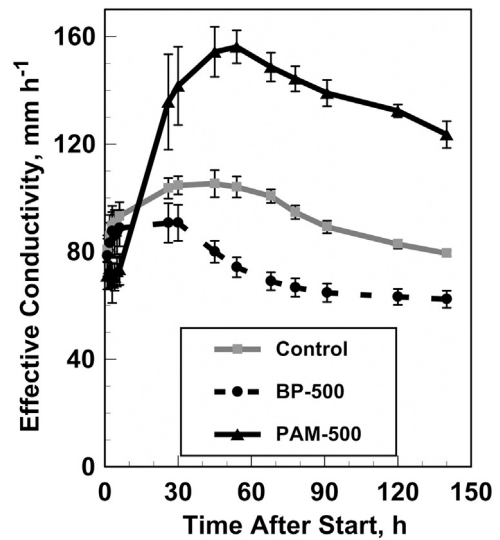


Fig. 3. Effective hydraulic conductivity of Portneuf silt loam soil columns as a function of time after treatment with water only, or 500 mg L⁻¹ solutions of high molecular-weight biopolymer (BP-500), or water-soluble polyacrylamide (PAM-500). Each leg of the error bars represents one standard error (n = 5).

under identical treatment conditions (Unpublished data, 2001). These results were antithetical to other reports, which state that PAM does not promote clay swelling by intercalating between clay layers (Theng, 1970; Stutzmann and Siffert, 1977) and that, when PAM complexes with clay in water, PAM acts to reduce clay swelling during a subsequent wetting (Emerson, 1963).

Treatment seepage-loss results (Table 3) can be attributed to four main factors: First, the more viscous PAM solution initially present in soil pores decreased conductivity more than the less viscous biopolymer solution. Second, both PAM and the biopolymer improved soil aggregate stability of the surface soil and prevented the breakdown of aggregates into smaller particles that clog soil pores. Third, when sediment was stirred into the ponded water, PAM more effectively flocculated the suspended particles than the biopolymer. The biopolymer flocculated colloids at some concentrations tested, while at other concentrations it dispersed and partially stabilized the colloid suspensions (Fig. 1). Thus the biopolymer supported the development of a less conductive surface seal than PAM. Fourth, increased conductivity of soils appears to be related to the polymer's influence on soil swelling and attendant decrease in soil bulk density. Polyacrylamide-induced swelling may have disrupted the surface seal that formed in the initial 6 h of flooding. Likewise, by stabilizing the surface soil and preventing swelling, the biopolymer eliminated swelling forces perpendicular to the surface and prevented seal disruption. This would help maintain lower infiltration and decrease seepage losses relative to the PAM treatment. However, previous experiments have shown that PAM-induced soil swelling was associated with increased conductivity, even when inflowing

Table 3

Effective hydraulic conductivity (seepage rate) at 16 and 140 h after treatment, and total cumulative seepage and soil bulk density at 140 h after starting the conductivity test. Standard error of mean is shown in parentheses.

Treatment	Effective hydraulic conductivity (seepage rate)		Total cumulative seepage at 140 h	Bulk density @ 140 h
	16 h	140 h		
	mm h ⁻¹			
Control	88.4 (4.5) a ^a	79.4 (1.0) b	6.40 (0.25) a	1.16 (0.004) a
Biopolymer (BP-500)	85.1 (8.0) a	62.3 (3.2) c	5.23 (0.23) b	1.15 (0.006) ab
PAM (PAM-500)	71.6 (5.4) a	123.5 (5.0) a	8.52 (0.19) c	1.13 (0.011) b

^a For a given response variable, means in the same column followed by the same letter are not significantly different (P < 0.05).

sediment and seal formation were prevented (Unpublished data, 2001). This suggests that PAM-induced swelling and decrease in surface soil's bulk density resulted in increased soil porosity and conductivity. However, this occurrence contradicts the commonly held concept that water-induced soil swelling results in smaller pores and less total porosity.

4. Conclusions

This study compared two types of water soluble, high-molecular-weight, anionic polymers, a bacteria-produced polysaccharide biopolymer and a petroleum-derived PAM polymer. The polymers' effects on soil flocculation, aggregate stability, and water conductivity in a soil column were determined to assess the polymers' potential for addressing erosion and water-seepage problems in agriculture. In spite of their similar MW and charge density characteristics, the performance of the two polymers differed. The biopolymer proved to be a less effective flocculating and soil stabilizing agent than PAM. This suggested that the polysaccharide's bulkier molecular conformation limited the extension and flexibility of the molecule in solution, compared to PAM. Since flocculation and aggregate stabilizing capabilities play key roles in preventing soil erosion in irrigation furrows, these results suggest that the biopolymer efficacy for reducing water erosion would be less than that of the PAM. If the biopolymer's limited molecular extension relative to PAM is responsible for its lesser efficacy, then the biopolymer's effectiveness should improve if tested with soils having greater clay contents, due to an increase in potential clay-polymer binding sites (Levy and Agassi, 1995; Green et al., 2000). On the other hand, the polysaccharide biopolymer demonstrated a greater propensity to manage seepage loss and decrease infiltration when tested in a scenario that simulated soil conditions during the initial spring flooding of unlined irrigation canals. The biopolymer may provide a more desirable alternative to PAM for seepage control in unlined irrigation canals and reservoirs because it can be used effectively at lower concentrations, is viewed as more environmentally neutral, and is produced from a renewable resource.

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