POLYMER CHARGE AND MOLECULAR WEIGHT EFFECTS ON TREATED IRRIGATION FURROW PROCESSES

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ABSTRACT

Application of 5-10 mg L^{-1} water soluble anionic polyacrylamide (PAM) to furrow irrigation water during flow advance substantially reduces sediment loss and increases net infiltration. We hypothesized that PAM_s solvated molecular conformation influences its irrigation-management efficacy. The study was conducted in Kimberly, Idaho, on Portneuf silt loam (Durinodic Xeric Haplocalcids); under furrow-irrigated beans (Phaseolus vulgaris) at a 1.5% slope. Polyacrylamides with contrasting molecular weight (anionic: 4-7, 12-15 and 14-17 MDa, i.e. Mg mol^{-1}), charge type (neutral, anionic, cationic), and charge density (8, 19, 35 mol %) were tested in two studies. Inflow rate was 23 L min^{-1} during furrow advance, and 15 L min^{-1} for the remaining set. Anionic and neutral PAMs were twice as effective as cationic PAMs for controlling sediment loss in *new* furrows. The order of effectiveness for overall soil-loss control was: anionic > neutral > cationic PAM, and efficacy increased with increasing charge density and/or molecular weight. Net furrow infiltration increased by 14 to 19% when PAM treatment molecular weight was reduced from 17 to 4 MDa. General trends suggested that medium and high charge density anionic and neutral PAM produced the greatest increase in infiltration compared with controls. Compared with untreated furrows, neutral PAM gave the greatest season-long net infiltration gains (5%); while charged PAMs tended to increase net infiltration early in the season on *new* furrows but decreased infiltration on *repeat*-irrigated furrows later in the season.

Key Words: Polymer charge, Molecular weight effect, Soil loss control, Charge Density, Infiltration capacity

1 INTRODUCTION

Furrow irrigation supplies water to the head of individually formed soil channels at a rate that matches or exceeds furrow infiltration capacity, so that water advances down slope through the field to the furrow outflow. Increasing inflow rate increases stream depth, wetted perimeter, velocity, and furrow-stream advance rate. This increases infiltration and improves irrigation application uniformity. However, boosting inflows also increases the stream_s hydraulic shear and soil detachment rate, and sediment concentration, transport, and field losses. Higher stream sediment concentrations are associated with reduced infiltration (Trout et al., 1995), which counters the infiltration benefits produced by the initial inflow adjustment. Hence, furrow irrigation uniformity, efficiency and runoff water quality can be improved by increasing initial furrow stream flow only if simultaneously reducing or eliminating erosion.

Water soluble anionic polyacrylamide (PAM) polymer with 18% charge density and molecular weight of 12-15 MDa (MDa = 10^6 Dalton = Mg mol^{-1}) has been shown to greatly reduce erosion and sediment losses and effectively increase infiltration in furrow irrigated soils (Lentz et al., 1992, 1998; Sojka et al., 1998b). A study encompassing different soils and locations in southern Idaho showed that application of 10 mg L^{-1} PAM during furrow advance (as water first wets the furrow) reduced total sediment loss from treated furrows by 94% and increased net infiltration 15% (Lentz and Sojka, 1994). PAM (150 mg L^{-1}) increased initial furrow infiltration rates in a clayey soil by 30 to 57% when added to furrow irrigation inflows (Mitchell, 1986).

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Note: The manucript of this paper was received in March 1999, Discussion open until March 2001

dilute PAM-treated irrigation water stabilizes soil aggregates (Terry and Nelson, 1986; Sojka et al., 1998b), flocculates suspended sediment (Aly and Letey, 1988), increases soil wettability (Janczuk et al., 1991), and produces greater soil hydraulic conductivities (El-Morsy et al., 1991; Sojka et al., 1998a), compared with untreated water. Dissolved PAM binds to soil particles in a thin layer at the soil aggregate surface during water imbibition and increases the soil_s saturated cohesive strength. For highly erosive soils like Portneuf, the increased stability imparted by the polymer is especially critical during furrow stream advance, when irrigation water inundates and rapidly wets the initially dry furrow soil (3% g/g water content). Kemper et al. (1985) showed that under rapid wetting, water stable aggregate fraction of dry 2 mm Portneuf aggregates was 0.21, less than half that measured under slow wetting conditions. At higher antecedent soil water contents (10% g/g), wet aggregate stability under rapid wetting was three times higher than that for dry soil. PAM also influences furrow erosion processes by flocculating detached sediment suspended in the streamflow. The soil floccules rapidly settle out of the flow.

PAM's soil aggregate stabilizing and anti-dispersion properties likely influence furrow infiltration via effects on surface-seal formation (Lentz, 1995). Sediments suspended in the stream clog soil pores at the furrow surface as water infiltrates (Shainberg and Singer, 1985). In untreated furrows, this process forms a thin depositional layer, or seal, having conductivity values that are a fraction of that for the underlying soils, e.g. 0.1 to 8% of the underlying soil for Portneuf silt loam (Segeren and Trout, 1991). In PAM-treated furrows, dispersed sediments flocculate and form large aggregates. These settle and form a depositional seal that is more porous than that of untreated furrows. For Portneuf silt loam, Sojka et al. (1998a) concluded that consolidated depositional seals of PAM furrows contained greater numbers of soil pores in both 0.30 to 0.75 mm and <30mm size ranges, compared with untreated furrows. This resulted in greater unsaturated and saturated infiltration rates for PAM-treated furrows.

PAM's differ with respect to molecular weight, charge type, and charge density (mole percent of charged comonomer). These characteristics determine the size and conformation (shape) of the molecules in solution and manner of interaction with soil particles. Increasing polymer molecular weight increases the physical volume of the solvated molecule, which increases solution viscosity (Kulicke et al., 1982) and decreases its adsorption on soil particles (Lakatos et al., 1981). Polymer flocculation activity often increases with increasing molecular weight (Herrington et al., 1993), however, the polymer molecular weight at which maximum flocculation occurs may differ depending on the polymer and adsorbent (LaMer and Healy, 1963).

PAM charge type (cationic, anionic, neutral) affects solvated molecular conformation and solution viscosity, sorbed conformation, and influences soil stabilization under rainfall. Charged polymers have a greater solvated volume than nonionic forms owing to the presence of repulsive electrostatic charges (Knudson et al., 1992). Consequently, the nonionic polymers have a notably lower effective viscosity (Letey, 1996), and when surface applied, may penetrate more deeply into soils than larger-volume charged types. Accordingly, dissolved charged polymer molecules tend to contract as solution salt concentration increases, while neutral PAM_s are unaffected (Tam and Tiu, 1993). Cationic PAMs adopt a flat configuration on the predominantly negatively-charged soil particles. Adsorbed anionic PAMs are less tightly bonded to the soil surface. Their unattached polymer loops project into the solvent (Lyklema and Fleer, 1987) and better promote bridging interactions between soil particles (Gregory, 1989). Nadler et al. (1996) showed that, compared with untreated soils, anionic PAM (21% charge) increased wet aggregate stability and saturated conductivity of Na-saturated soils more than nonionic PAM.

Increasing charge density intensifies electrical repulsive forces within polymer molecules and expands their solvated size (Knudson et al., 1992). This may increase viscosity of polymer solutions and decrease polymer adsorption on soil particles (Lakatos et al., 1981).

Some polymers may have certain advantages over others, with regard to their manufacture, cost, or environmental impact. Industry and researchers seeking to develop new erosion inhibiting polymers for irrigated soils need to know how conformational polymer factors influence furrow erosion processes.

We found no furrow irrigation field studies that had compared the efficacy of different PAM formulations with regard to these considerations. The objective was to test the hypothesis that polymer charge type and density, and molecular weight characteristics affect PAM's ability to reduce furrow sediment-loss and maintain infiltration during furrow irrigation of a highly erodible silt loam soil.

2 METHODS AND MATERIALS

We conducted two experiments, a molecular-weight study examined molecular-size influences, and a PAM-type study tested PAM charge type and density effects on furrow irrigation processes. The field plot was a 0.6 ha field located near Kimberly, Idaho; the soil was Portneuf silt loam (coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcids); and slope was 1.5%. Portneuf contains 675 g kg^{-1} silt and 190 g kg^{-1} clay, includes 10 to 17 g kg^{-1} organic matter, has a cation exchange capacity of 18 to 20 c mol_c kg^{-1}, an electrical conductivity of 0.6 dS m^{-1}, and pH of 7.8 to 8.2.

All furrow irrigation treatments used Snake River water; with an average electrical conductivity of 0.5 dS m^{-1}, and SAR of 0.6. Only trafficked furrows were irrigated and monitored to avoid large infiltration variability introduced by the inclusion of both wheel-tracked and nonwheel-tracked furrows. Irrigation water was applied to every other furrow from individually regulated valves on gated pipe. Furrows were 175 m long. Irrigations were 12 h in duration. Inflow rate was 23 L min^{-1} during the initial advance of water (typically about 1 hr) and 15 L min^{-1} for the remainder of the irrigation.

Irrigations were numbered in the order applied. Each successive irrigation on a newly formed furrow produced a physical consolidation and settling of the soils exposed to stream flow. Therefore, we also characterized an irrigation according the sequence it was applied after a furrow-shaping tillage operation. For example, a C1 irrigation was one applied to newly-formed furrows containing loose unconsolidated soils and aggregates; C2 was the 2nd irrigation applied to the furrow after formation; C3 was the 3rd irrigation, etc. We will refer to C1 irrigations as those occurring on *new* or freshly-shaped furrows, and C2 through C7 irrigations as those applied to *repeat*-irrigated furrows. Water in *repeat*-irrigated furrows encounters soils that have already been consolidated by one or more previous irrigations. In the PAM-type study, the residual effect of PAM was tested by applying PAM in a treated C1 irrigation but not in the C2 (untreated).

Details of the irrigation inflow and runoff monitoring procedure were described by (Lentz et al., 1992). The sediment content in 1-L runoff samples was measured using the Imhoff cone technique (Sojka et al., 1994). Infiltration rates were calculated as described in Lentz and Sojka (1994). Cumulative sediment loss and infiltration were computed from field data with WASHOUT, an analytical computer program (Lentz and Sojka, 1995). Each study employed a randomized block design with three replications. The PAM formulations used here were manufactured by CYTEC Industries (Wayne, NJ)[3]. All but the low and high molecular weight formulations were off-the-shelf products.

Molecular-Weight Experiment. This experiment included four treatments , a control and three moderately anionic (18 mol %) polyacrylamide treatments with varying molecular weights: Low MW = 4-7 MDa; Med MW = 12-15 MDa, and High MW = 14-17 MDa. The Med MW PAM was identical to that used by Lentz and Sojka (1994). PAM was applied in all five irrigations in 1995 (Table 1). Polyacrylamide was applied in irrigation water at 10 mg L^{-1} during the full furrow advance phase only (**$I_{10, full}$**). The total PAM application was about 1.1 kg ha^{-1} per irrigation. Plot preparation included fall disking the previous bean crop and spring seedbed prep with moldboard plow and roller-harrow. Beans (Phaseolus vulgaris) were planted on 0.56 m rows. Treatment means were evaluated with Duncan_s multiple comparison procedure ($P < 0.05$). We also measured infiltration characteristics of

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semi-consolidated depositional seals (in furrows)12 hr after irrigation ceased. Steady-state infiltration rates at lower mid-furrow positions were measured under soil water tensions of 40 and 100 mm (Sojka, et al., 1999). Each irrigation treatment value was the mean of six measurements. Treatment differences were tested across the five irrigations using Duncan_s multiple comparison procedure ($P < 0.05$).

Table 1 Irrigation and furrow characteristics for molecular-weight study. Hydraulic values are overall means.

Irrigation Number	Date (1995)	Sequence After Cultivation*	Total Inflow (mm)	Advance Time (min)	Net Infiltration (mm)
1	June 28	C1	57	32	25
2	July 12	C1	54	44	31
3	July 19	C1	74	70	43
4	July 26	C2	62	51	34
5	August 2	C3	62	65	35

* Furrows were formed on June 14, and cultivated and reformed on July 10. Alternate, new furrows irrigated on June 19. Repeat furrows were undisturbed since the last irrigation.

PAM-Type Experiment. Seven PAM treatments of different charge type and density (Table 2), and an untreated control were tested. The A18 PAM was identical to that used by Lentz and Sojka (1996a), Superfloc A836, the moderately anionic PAM commonly used as a furrow irrigation erosion deterrent. PAM molecular weights were either 6 MDa or 15 MDa. These molecular-weight differences appear to have had little confounding impacts on PAM-type outcomes, considering results from the molecular-weight study. The sediment-loss vs. molecular-weight relationship was described for new furrows using regression analysis, where the control treatment was equated to that of an extremely low molecular weight PAM.

Table 2 Treatment and product codes, and properties of polyacrylamides employed in the PAM-type experiment.

Treatment Code	SUPERFLOC Designation	Charge Type	Charge Density (mole %)	Molecular Weight (MDa *)
Neutral	905N	Neutral	0	15
A7	837A	Anionic	7	15
A18	836a	Anionic	18	15
A35	835A	Anionic	35	15
C10	492C	Cationic	10	6
C20	494C	Cationic	20	6
C30	496C	Cationic	35	6

* MDa = 10^6 g mol^{-1}

PAM was added into irrigation water at 10 mg L^{-1} during the initial 0.5 hr of each irrigation, which coincided with the first half of the advance phase. Then two additional 0.63 L applications of stock solution were applied over a 10 min period (~5 mg L^{-1} in furrow water) at 4 and 8 hrs into the irrigation (**$IE_{10, half}$**). The application period used was not optimal for erosion control. It was expected that the reduced application rate would emphasize potential differences in polymer performance and it also simplified irrigation logistics. In the 7th irrigation, on repeat irrigated furrows, PAM was applied during the entire advance, with no episodic additions, ie. an **$I_{10, full}$** treatment. PAM treatment concentrations were achieved by metering an appropriate quantity of 1200 mg L^{-1}, stock solution into irrigation water at each furrow head. The total PAM application was 0.26 kg ha^{-1} per irrigation.

The study was conducted in 1992 on a conventionally prepared and planted field of silage corn (Zea mays L.). Corn was planted on 76 cm rows. All seven irrigations were monitored (Table 3). During the season, irrigations were made on *new* and *repeat*-irrigated furrows. Irrigations 2 and 4 (C2 type) were not treated in order to observe potential residual impacts of the previous PAM application. The canal district added a moss herbicide (Acrolein) to irrigation water during much of the third irrigation. Data from this irrigation and the following untreated irrigation (#3, 4) were excluded from the analysis because the furrow stream acrolein concentration may have been high enough to differentially degrade injected PAMs (Castor et al., 1981). The Duncan and Waller multiple comparison procedures examined mean separations ($P < 0.05$) for treatments in each irrigation category. Sediment-loss and advance-time data were log-transformed to stabilize sample variance for charge-type comparisons. Standardized relative sediment loss and relative net infiltration values were computed for each treated irrigation type by subtracting the average charge-density value (for all anionic or cationic treatments) from the treatment mean. The three treated irrigation types were *new* **$IE_{10, half}$**, irrigation #1; *repeat* **$IE_{10, half}$**, #5 & 6; *and repeat* **$I_{10, full}$**, #7. Sediment losses and infiltration values were computed based on an alternate-furrow irrigation scheme (1.52 m between watered furrows). These values are half those given in a preliminary report (Lentz and Sojka, 1996b), where calculations were based on individual 0.76 m furrows.

Table 3 Irrigation, furrow, and PAM application parameters for the PAM-Type study.

Irrigation Number	Month/day (1992)	Sequence After Cultivation[1]	PAM Application Rate[2] (conc., initial and supplemental)
1	6/4	C1	10 mg L^{-1}, 30 min. initial + interm.
2	6/18	C2	0
3*	7/15	C1	10 mg L^{-1}, 30 min. initial + interm.*
4	7/29	C2	0
5	8/12	C3	10 mg L^{-1}, 30 min. initial + interm.
6	8/19	C4	10 mg L^{-1}, 30 min. initial + interm.
7	8/26	C5	10 mg L^{-1}, full advance

Note: 1. Furrows were formed on June 1, and cultivated and reformed on July 10. Repeat furrows were undisturbed since the last irrigation.

2. Initial application began when flow commenced. Supplemental, intermittent applications (5 g m^{-3} PAM for 10 min) were made at 4 and 8 hrs. into irrigation.

* Acrolein (moss herbicide) present in irrigation water.

3 RESULTS AND DISCUSSION

3.1 Molecular-Weight Experiment.

Molecular Weight Effects. All PAM molecular-weight formulations reduced runoff sediment concentration and sediment loss for treated, *new* furrows. The Med MW (Superfloc 836a) and High MW PAM reduced sediment losses and concentrations by about 87% relative to control furrows (Table 4).

Reductions produced by Low MW PAM were 61 to 67%, significantly less than that for higher MW PAMs. Sediment losses from *new* furrows were exponentially ($P < 0.001$, $R^2 = 0.78$) related to the molecular weight of PAM applied. These data indicate that only a slight increase in erosion control efficiency was obtained by increasing the molecular weight of a PAM treatment above about 12 MDa. PAM treatments also dramatically reduced sediment-losses and sediment-concentrations for *repeat*-irrigated furrows relative to controls (Table 5). In this regard, PAM applied in *repeat* irrigations was about nine percent more effective than for *new*. But for *repeat* irrigations, PAM MW treatments did not differ from each other with respect to sediment parameters. Erosion control for *new* furrows was less than typical for these soils, possibly because PAM was applied to soils with relatively high soil water contents. Under such circumstances, infiltration, and hence PAM delivery and the strength of the resulting PAM-reinforced soil layer, may have been less than optimal. The severity of erosion in *repeat* furrows was less than for *new*, due to soil consolidation caused by the previous irrigation. These factors may have contributed to PAM_s greater efficacy in *repeat* furrows.

Average net infiltration values for PAM treatments trended higher than those of controls for *new* ($P = 0.06$) and for *repeat* ($P = 0.13$) furrows; and the Low MW PAM produced significantly greater net infiltration than controls (Tables 4 & 5). Net infiltration for the Low MW treatment exceeded that of the High MW for *repeat* irrigations, and trends for both *new* and *repeat* irrigations indicate an increase in net infiltration with decreasing PAM molecular weight. Interestingly, the furrow advance period for the *new*-furrow Low- and Med-MW treatments were significantly shorter than that of the High MW (Table 4), and a similar trend was observed for *repeat*-irrigated furrows (Table 5). Therefore, although infiltration rates during the advance phase were greatest for High-MW furrows, by irrigation end, it was the Low-MW treatment that had produced the greatest net infiltration (see discussion below).

Table 4 Sediment loss, net infiltration, and runoff sediment concentration for anionic molecular weight treatments on irrigated *new* furrows (irrigations 1,2,3 as described in Table 1).

	Control	Low MW 4-7 Mda**	Med MW 12-15 MDa	High MW 14-17 MDa
Sediment loss (Mg/ha)	2.31_c*	0.75_b	0.33_a	0.39_{ab}
Sediment Conc. (g L^{-1})	7.3_c	2.8_b	1.1_a	1.1_a
Net Infiltration (mm)	29_a	34_b	31_{ab}	30_a
Furrow Advance (min)	39_a	48_a	47_a	54_b

Note: * Similar letters across rows indicate nonsignificant differences (P < 0.05).
** MW = polymer molecular weight, MDa = 10^6 g mol^{-1}

Table 5 Sediment loss, net infiltration, and runoff sediment concentration for anionic molecular weight treatments on *repeat* irrigated furrows (irrigations 4,5 as described in Table 1).

	Control	Low MW 4-7 Mda**	Med MW 12-17 MDa	High MW 14-17 MDa
Sediment loss (Mg/ha)	1.32_b *	0.26_a	0.10_a	0.11_a
Sediment Conc. (g L^{-1})	4.2_b	1.0_a	0.35_a	0.34_a
Net Infiltration (mm)	32_a	38_b	33_{ab}	32_a
Furrow Advance (min)	47_a	61_{ab}	60_{ab}	65_b

Note: * Within a given row, means followed by similar letters are not different (P < 0.05).
** MW = polymer molecular weight, MDa = 10^6 g mol^{-1}

Unsaturated infiltration rates through semi-consolidated furrow depositional seals differed among control and PAM MW treatments (Fig. 1). Rates tended to increase with polymer molecular weight, although Med-MW and High-MW rates were not significantly different. Infiltration rates of Med-MW and High-MW treated furrows were about double those of controls at 40 mm water tension, and 1.4x greater than controls at 100 mm water tension (Fig. 1). Control and Low-MW treatment rates did not differ significantly. Compared to control and Low-MW treatments, the Med-MW and High-MW PAM seals contained greater numbers of flow-conducting pores with equivalent mean spherical diameters of <0.30 mm (P=0.0004) and 0.3-0.75 mm (P=0.0001). Note that furrow net infiltration data did not correspond well with unsaturated seal infiltration observations; e.g. net infiltration for Low-MW furrows exceeded control and High-MW values, yet unsaturated seal infiltration for Low-MW furrows was equal to control values and less than that of High MW. This suggests that PAM impacts on furrow soils were temporal and dynamic (see discussion below).

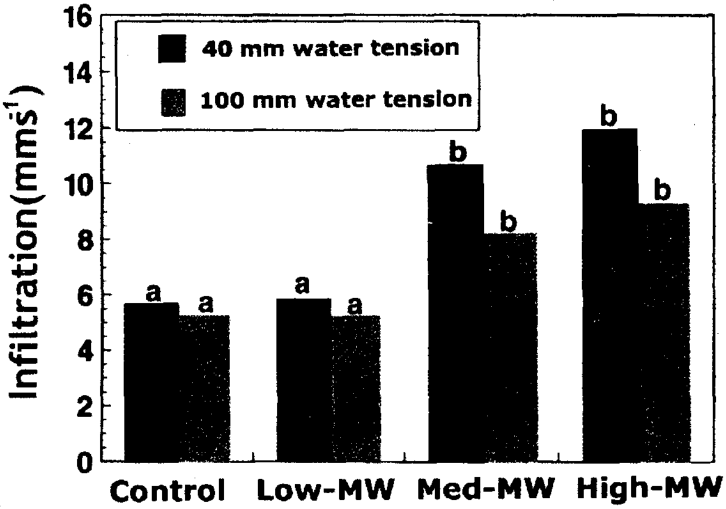

Fig. 1 Polyacrylamide molecular weight effects on water infiltration through semi-consolidated furrow depositional seals at water tensions of 40 and 100 mm

PAM MW and Soil Interactions. Two important PAM-soil interactions appear to occur in these furrows. One exerts a dominant influence on erosion processes, and the other has a more pronounced impact on furrow infiltration. The two mechanisms respond differently to changes in PAM molecular weight and solvated volume.

PAM MW-effects on furrow infiltration may be a viscosity-induced phenomenon. Less viscous low MW PAM solutions may better penetrate and treat the furrow soil, better preserve soil pore structure, and produce a stronger soil interface, compared with that of more viscous, higher-MW PAMs. But this explanation also implies that the best soil-loss control and highest initial infiltration rates would result from the use of Low MW, which was not the case. An alternative explanation focuses on the polymer effect on depositional-seal development and permeability.

We hypothesize that MW affects infiltration via its influence on the size, compactness, and strength of flocs or aggregates formed in the furrow stream. Herrington et al. (1993) reported that kaolinite flocs produced with PAM became more dense and compact as PAM MW increased. Larger, less dense flocs produced in the Low MW system would form a more porous depositional layer and be more easily transported downstream than those of higher-MW treatments. In contrast, the higher-MW PAMs produced smaller, denser aggregates that resisted transport, and formed a tighter depositional seal, with smaller pores and lower permeability than that of Low MW PAM treatments. Given that depositional seal formation occurs after the advance phase, this hypothesis explains why the infiltration rate for High

MW PAM exceeded that of the Low MW early in the irrigation, and why this infiltration-treatment relationship was reversed in the post-advance phase. Compared to furrow depositional seals formed from tighter and denser aggregates, seals composed of less dense flocs may have a greater tendency to collapse during post-irrigation dewatering and consolidation. This could account for low unsaturated infiltration-rate values we observed for semi-consolidated seals of both control and Low-MW furrows.

The Low MW PAM had a greater impact on soil erosion processes than our soil-loss data show. The Low MW PAM treatment simultaneously increased furrow infiltration. This reduced runoff and sediment transport capacity of the furrow-stream. Thus, while sediment concentration in runoff from Low MW furrows was 1.7x that in Med and High MW furrows, total sediment loss of the Low MW was only 1.3x greater than the others.

3.2 PAM Type Experiment

The PAM treatment used in the majority of this experiment_s irrigations ($\mathbf{IE_{10,\ half}}$) was only moderately effective for controlling sediment loss in *new* furrows, and compared with controls, did not significantly reduce sediment losses in any of the *repeat* irrigations (Table 6). Clearly PAM_s maximum erosion-control benefit cannot be realized unless the entire furrow advance and wetted furrow soils are treated. When the full-advance $\mathbf{I_{10,\ full}}$ treatment was applied in the 7th *repeat* irrigation, the anionic PAM_s performance improved notably.

Table 6 PAM charge-type effects on sediment loss (Mg/ha) for each irrigation category (excludes irrigations 4 and 6; see Table 2).

Irr. No.	Application	Sequence After Cultivation	Control	Anionic	Neutral	Cationic
1	$IE_{10,\ half}$	C1	0.98_c*	0.35_a	0.34_a	0.66_b
2	Untreated	C2	0.70_{ab}	0.50_a	0.53_{ab}	0.90_b
5,6	$IE_{10,\ half}$	C3,C4	0.17_a	0.21_{ab}	0.22_{ab}	0.31_c
7	$I_{10,\ full}$	C5	0.25_b	0.12_a	0.23_b	0.36_b

Note: * Within a given row, means followed by similar letters are not different ($P < 0.05$).

Influence of Charge Type. Polymer charge type significantly influenced sediment losses for all irrigation categories, *new*, *untreated-repeat*, and *treated-repeat* furrows (Table 6). Compared with controls, neutral or anionic PAMs were about twice as effective as cationic forms for reducing sediment loss on *new* furrows. Neutral and anionic PAMs also outperformed the cationics on *repeat* furrows. While cationic PAMs reduced sediment loss relative to controls for *new* furrows, they increased (Irr. #5 & 6) or tended to increase sediment loss (Irr. #7) relative to controls for *repeat* furrows (Table 6). This sediment-loss increase resulted from heightened erosion, which increased sediment concentration (Table 7) in cationic PAM-treated furrows, relative to controls. The data also suggest that cationic-PAM_s influence on infiltration and runoff processes also differed between *new* and *repeat* irrigations. Cationic-PAM increased infiltration, i.e. produced a negative infiltration reduction, in 7 out of 9 *new* furrows (data for individual furrow not shown), but decreased infiltration in each *repeat-treated* irrigation, when compared with controls (Table 8). An increase in furrow infiltration results in a proportionate decrease in runoff.

Cationic PAMs were unable to stabilize furrows after the initial cationic-PAM irrigation had treated and consolidated the loose, well-developed soil structure initially present in the *new* furrows. We hypothesize that the cationic polymer initially neutralized surface charge associated with furrow soil colloids, inducing flocculation and strengthening aggregates. But continued treatment in subsequent irrigations caused the soil to adsorb excess polymer and to develop repulsive positive charges that destabilized aggregates and increased dispersion (Herrington et al., 1993). Thus in later irrigations, cationic-PAM produced greater furrow-stream sediment concentrations than the controls, which led to a relative decrease in net infiltration (Trout et al., 1995).

Table 7 PAM charge-type effects on sediment concentration (g L^{-1}) and reductions relative to the control for each irrigation category (excludes irrigations 4 and 6; see Table 2)

Irr. No.	Application	Sequence After Cultivation	Control Conc.	Anionic Conc.	Anionic (Reduction)	Neutral Conc.	Neutral (Reduction)	Cationic Conc.	Cationic (Reduction)
1	IE_{10}, half	C1	4.6_b*	1.9_a	(2.7)	1.6_a	(3.0)	3.1_{ab}	(1.2)
2	Untreated	C2	2.8_{ab}	2.2_a	(0.6)	2.8_{ab}	(0)	3.7_b	(-0.9)
5,6	IE_{10}, half	C3,C4	1.3_a	1.6_a	(-0.3)	1.7_{ab}	(-0.4)	2.1_b	(-0.8)
7	I_{10}, full	C5	1.8_b	0.8_a	(1.0)	1.87_b	(-0.07)	2.3_b	(-0.5)
Mean reduction for repeat irrigations only					(0.4_b)		(-0.2_{ab})		(-0.7_a)

Note: * Within a given row, means followed by similar letters are not different (P < 0.05).

Table 8 PAM charge-type effects on net Infiltration (mm) and reductions relative to the control for each irrigation category (excludes irrigations 4 and 6; see Table 2).

Irr. No.	Application	Sequence After Cultivation	Control Infilt.	Anionic Infilt.	Anionic (Reduction)	Neutral Infilt.	Neutral (Reduction)	Cationic Infilt.	Cationic (Reduction)
1	IE_{10}, half	C1	20.5_a*	22.4_a	(-1.9)	21.4_a	(-0.9)	21.2_a	(-0.7)
2	Untreated	C2	17.9_a	19.1_a	(-1.2)	20.8_a	(-2.7)	18.9_a	(-1.0)
5,6	IE_{10}, half	C3,C4	30.6_a	29.5_a	(1.1)	29.7_a	(0.9)	28.5_a	(2.1)
7	I_{10}, full	C5	28.7_a	27.3_a	(1.4)	29.7_a	(-1.0)	27.3_a	(1.4)
Mean reduction for repeat irrigations only					(0.4_a)		(-0.8_a)		(0.8_a)

Note: * Within a given row, means followed by similar letters are not different (P < 0.05).

The inferior performance of cationic PAMs relative to anionic forms may have resulted, in part, from their lower molecular weights. Results from the MW study suggest, however, that reducing the molecular weight from 12-15 MDa (Med MW) to 4-7 MDa (Low MW) would only moderately reduce PAM_s soil-protective effects, and not cause a reversal in the PAM_s mode of action. Thus, results suggest that anionic and neutral PAMs are inherently more effective for furrow irrigation management than cationic forms. Compared with the loose-tail and uncoiled configuration of adsorbed anionic and neutral PAMs, the flat configuration assumed by adsorbed cationic PAMs may limit the number and extent of initiated interparticle linkages, The number and physical extension of these interparticle linkages form the basis for PAM_s soil-strengthening and flocculating capabilities.

Overall, PAM charge types tended to increase net infiltration for *new-treated* furrows when compared with controls ($P = 0.09$, Table 8, reductions). In *repeat* irrigations, this trend was reversed for anionic and cationic PAMs, which tended to decrease net infiltration relative to controls (Table 8). The fact that little or no furrow bottom broadening was observed in PAM and control furrows, suggests that the dissimilar *repeat*-irrigation effects of charged vs neutral PAMs on infiltration resulted from differences in the nature of their polymer-soil interactions, rather than a differential alteration of furrow wetted perimeters (Sojka et al., 1998b). Anionic PAMs are especially favored for treatment of irrigation water because of their superior erosion inhibiting capabilities, but also because they are more environmentally benign than neutral or cationic PAMs (Barvenik, 1994).

Charge Density Relative sediment losses for anionic-PAM treatments in all *treated* irrigations (excluding #4) decreased curvilinearly with polymer charge density, $P < 0.01$, $R^2 = 0.65$ (Fig 2). A similar, though less well defined linear relationship ($P = 0.07$) was found for cationic forms. Thus, sediment loss in PAM *treated* furrows decreased with increasing polymer charge density. Charge density effects on runoff sediment concentration were generally similar to that of sediment losses (Tables 9, 10).

Table 9 PAM charge-density effects on furrow sediment loss (Mg ha^{-1}) for each irrigation category (excludes irrigations 4 and 6).

Irr. No.	Application *	Sequence After Cultivation	Control	A35-7	A18-6	A7-5	Neutral-4	C10-3	C20-2	C30-1
1	$IE_{10, half}$	C1	0.98_c **	0.29_a	0.40_a	$0..37_a$	0.34_a	0.86_{bc}	0.53_{ab}	0.60_{abc}
2	Untreated	C2	0.70_{ab}	0.57_{ab}	0.41_a	0.51_{ab}	0.53_{ab}	0.91_{bc}	1.2_c	0.57_{ab}
5,6	$IE_{10, half}$	C3,C4	0.17_a	0.18_a	0.20_{ab}	0.27_{ab}	0.22_{ab}	0.31_{ab}	0.33_b	0.26_{ab}
7	$I_{10, full}$	C5	0.25_{ab}	0.06_a	0.07_a	0.24_{ab}	0.23_{ab}	0.38_b	0.41_b	0.28_b

Note: * $IE_{10, half}$ = 10 ppm PAM applied for first half furrow advance + 2-ten min applications (~5 mg L^{-1} in furrow water) at 4 and 8 hrs into the irrigation; $I_{10, full}$ = 10 ppm PAM applied for full furrow advance

** Similar letters across rows indicate nonsignificant differences (P < 0.05).

Table 10 PAM charge-density effects on mean runoff sediment concentration (g L^{-1}) for each irrigation category (excludes irrigations 4 and 6).

Irr. No.	Application *	Sequence After Cultivation	Control	A35-7	A18-6	A7-5	Neutral-4	C10-3	C20-2	C30-1
1	$IE_{10, half}$	C1	4.6_b **	2.1_a	1.9_a	1.9_a	1.6_a	3.8_{ab}	2.4_{ab}	3.1_{ab}
2	Untreated	C2	2.8_{ab}	2.6_{ab}	1.8_a	2.1_{ab}	2.8_{ab}	3.5_b	5.1_c	2.6_{ab}
5,6	$IE_{10, half}$	C3,C4	1.4_a	1.3_a	1.6_{ab}	1.7_{ab}	1.7_{ab}	2.3_b	2.1_b	2.1_b
7	$I_{10, full}$	C5	1.8_{cd}	0.4_a	0.5_{ab}	1.3_{bc}	1.8_{cd}	2.5_d	2.4_d	1.9_{cd}

Note: * $IE_{10, half}$ = 10 ppm PAM applied for first half furrow advance + 2-ten min applications (~5 mg L^{-1} in furrow water) at 4 and 8 hrs into the irrigation; $I_{10, full}$ = 10 ppm PAM applied for full furrow advance

** Similar letters across rows indicate nonsignificant differences (P < 0.05).

Net infiltration trends for *new* furrows (Irr. #1) suggest that net infiltration increased with increasing polymer charge density, however, no statistically significant differences among treatments were indicated (Table 11). Net infiltration responded differently for *repeat*-irrigated furrows. In this case, relative net infiltration and charge density were related via second-order quadratic functions (Fig 3). Figures 3a and 3b indicate that when comparing charge-density treatments of a given charge type for *repeat*-irrigated furrows, the moderately-charged PAMs produced the greatest net infiltration among anionic treatments ($P = 0.03$), but produced the lowest net infiltration among cationic treatments ($P < 0.01$). These

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resulting floc size/density; and hence the nature of these relationships may differ among soils, depending on soil mineralogy, pH, CEC, and other factors.

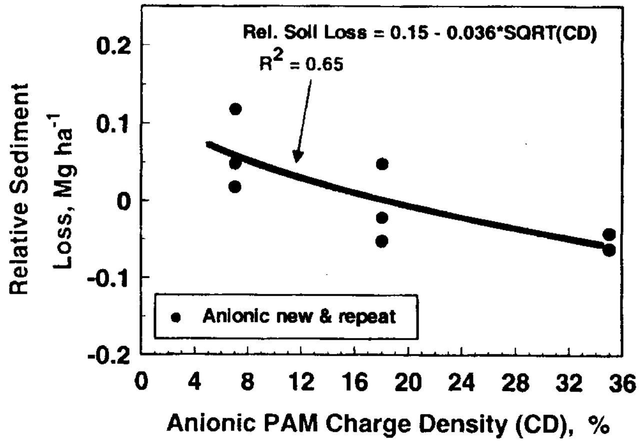

Fig. 2 Relative sediment losses for Anionic PAM-treateed irrigations (#1, 5&6, 7) as a function of applied polymer charge density. (Rel. Sediment loss=anionic treatment mean minus average sediment loss of all anionic treatments)

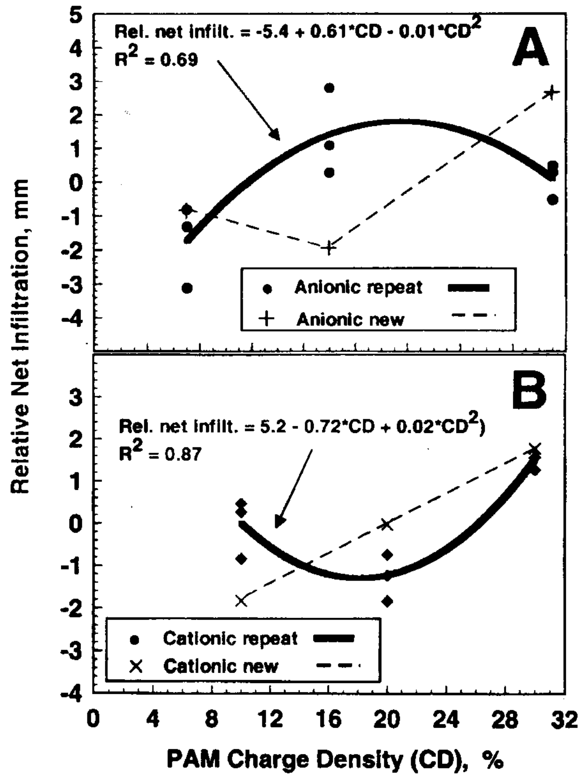

Fig. 3 Relative net infiltration for anionic (A) and cationic (B) treatments on new and repeat-irrigated furrows as a function of applied polymer charge density. (Rel. Net infilt.=anionic [cationic] treatment mean minus mean net infiltration from all anionic [cationic] treatments)

Table 11 PAM charge-density effects on net infiltration (mm) for each irrigation category (excludes irrigations 4 and 6).

Irr. No.	Application *	Sequence After Cultivation	Control	A35-7	A18-6	A7-5	Neutral-4	C10-3	C20-2	C30-1
1	$IE_{10, half}$	C1	20.5_{ab}**	25.1_{ab}	20.5_{ab}	21.6_{ab}	21.4_{ab}	19.4_{a}	21.2_{ab}	23_{ab}
2	Untreated	C2	17.9_{a}	19.6_{a}	19.4_{a}	18.3_{a}	20.8_{a}	18.1_{a}	18.2_{a}	20.2_{a}
5,6	$IE_{10, half}$	C3,C4	30.6_{a}	29_{a}	30.6_{a}	28.2_{a}	29.7_{a}	29_{a}	27.3_{a}	30.1_{a}
7	$I_{10, full}$	C5	28.7_{ab}	27.6_{ab}	30.1_{b}	24.2_{a}	29.7_{b}	27.6_{ab}	25.5_{ab}	28.9_{ab}

Note: * $IE_{10, half}$ = 10 ppm PAM applied for first half furrow advance + 2-ten min applications (~5 mg L^{-1} in furrow water) at 4 and 8 hrs into the irrigation; $I_{10, full}$ = 10 ppm PAM applied for full furrow advance

** Similar letters across rows indicate nonsignificant differences ($P < 0.05$).

The different charge-density relationships observed for sediment loss and net infiltration further supports the concept that PAM influences furrow processes via at least two different mechanisms. One mechanism primarily influences soil-loss, and the other dominantly affects infiltration. Our results indicate that these mechanisms are sensitive to PAM MW and charge characteristics, and therefore, to size and density of the dissolved PAM molecule, and/or to a correlated property such as adsorption.

4 CONCLUSIONS

This investigation demonstrated that PAM molecular weight (4 to 17 MDa), charge type (anionic, neutral, cationic), and charge density (7 to 35 mol %), all affect the capacity of PAM to mitigate furrow-irrigation erosion and infiltration on Portneuf soils. However, these parameters influenced furrow erosion processes somewhat differently than they affected infiltration, and their effects varied depending on the type of irrigations treated.

The order of effectiveness for overall soil-loss control in *new* and *repeat* furrows was: **anionic > neutral > cationic PAM**, and for a given charge type, efficacy increased with increasing size of the dissolved PAM molecule, ie. increasing charge density and/or molecular weight. Net infiltration increased with decreasing polymer molecular weight, when compared with controls. The effect of PAM charge-type on net infiltration increase was not conclusive, but overall trends suggested that medium and high charge anionic and neutral PAMs produced the greatest net infiltration gains, while low and medium charge cationic PAMs produced the least. Neutral PAM produced more consistent net infiltration gains throughout the irrigation season.

Anionic and cationic PAMs tended to increase net infiltration (relative to controls) on *new* furrows but had the reverse effect on *repeat*-irrigated furrows.

PAM treatment impacted both furrow infiltration and runoff sediment concentration, and these in turn determined the magnitude of furrow sediment losses. However, the influence of PAM molecular characteristics on these factors was not always complementary with respect to sediment loss. For example, when polymer molecular weight was reduced, it decreased aggregate stability and increased runoff sediment concentrations relative to the higher molecular weight polymer treatment. Yet this impact on sediment loss was mitigated by a simultaneous increase in infiltration and reduction in runoff.

Results imply that at least two types of PAM-soil interactions are involved, each having a primary impact on either erosion or infiltration processes. It is likely that these interactions determine the character of PAM_s soil flocculation and aggregate stabilization activity in furrow-irrigated Portneuf soils. We hypothesize that PAM effects on furrow infiltration result mainly from its effects on the dynamic character and physical structure of the depositional seal. More study is needed to identify and understand the nature of these PAM-soil interactions. This knowledge will help scientists and industry irrigated agriculture scenarios.

ACKNOWLEDGMENTS

This work was supported in part by the Cooperative Research and Development Agreement with CYTEC Industries under contract 58-3K95-4-216. We thank Jim Foerster and Ron Peckenpaugh for their technical support, and Emily Aston, Michelle Garrison, Alan Heck, Paul Miller, and Elizabeth Whitchurch for their able lab and field assistance.

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