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Inhibiting Water Infiltration into Soils with Cross-linked Polyacrylamide: Seepage Reduction for Irrigated Agriculture

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High water infiltration rates in unlined canals, reservoirs, and the inflow end of furrows relative to outflow ends result in excessive seepage losses and reduced furrow irrigation application uniformity. This study evaluated the use of cross-linked, anionic, polyacrylamide hydrogel (XPAM), a water-absorbing, swellable polymer solid, for reducing infiltration and seepage losses though soil. Experiments 1 and 2 measured the influence of soil treatments on seepage rate in soil columns under constant-head conditions: Exp. 1 treated five soils with 0, 2.5, 5, and 10 g kg^{-1} XPAM; Exp. 2 applied combined XPAM (0–5 g kg^{-1}) and NaCl (0–5.1 g kg^{-1}) treatments to a silt loam soil, and separately tested the effect of XPAM granule size and treated soil layer thickness on seepage rate. In Exp. 3, a miniflume was used to determine how a 5-mm-thick, XPAM-treated (0–5 g kg^{-1}) soil layer at the inflow end of the "minifurrow" influenced water distribution. The 21-h seepage rates of all soils except the loamy sand decreased curvilinearly with increasing XPAM rate, with maximum reductions of 87 to 94% for 5 and 10 g kg^{-1} XPAM rates, relative to controls. The <300-μm-diam. XPAM granules were significantly more effective than the coarser grained XPAM for reducing seepage, and reducing the thickness of the treated soil layer from 71 to 24 mm had no significant effect on the seepage reduction obtained with XPAM. The 5 g kg^{-1} XPAM treatment applied to inflow-end miniflume soils significantly decreased the "furrow-stream" advance period and reversed the infiltration patterns observed in miniflumes, relative to controls. These XPAM treatments could potentially be used to increase the uniformity of furrow water applications and reduce seepage from unlined irrigation ponds and canals.

Abbreviations: EC, electrical conductivity; ESP, exchangeable sodium percentage; SAR, sodium adsorption ratio; WSPAM, water-soluble, anionic polyacrylamide copolymer; XPAM, cross-linked, anionic polyacrylamide hydrogel.

Seventeen percent of the water diverted for irrigation in the USA, 89.3 Mm^3 d^{-1}, is lost due to uncontrolled seepage of the water from soil-lined distribution channels (USGS, 1990). Increasingly, water managers seek economical methods that will allow them to conserve and return these lost waters to the farmer's fields and drought-hindered crops for which they were intended. Two specific means of doing this are to: (i) reduce seepage losses from soil-lined distribution channels; and (ii) increase surface irrigation application uniformity. Furrow irrigation produces a less uniform water application across the field than level basin or sprinkler irrigation because infiltration opportunity time is greater at the inflow end of furrows relative to the outflow end. This leads to excessive water application to the inflow-end soils, which increases leaching losses of water, nutrients, and agrochemicals there.

Seepage from irrigation channels can be nearly eliminated by lining them with concrete or membranes of rubber or plastic, but these methods are costly and are ineffective in irrigation furrows, where the objective is to reduce, not eliminate, water infiltration into inflow-end soils. The addition of silt or clay to irrigation flows can inhibit infiltration in canals but has not met with consistent success (Withers and Vipond, 1980). Field demonstrations have suggested that intermittent applications of water-soluble, anionic polyacrylamide copolymer (WSPAM) to canal flows (J. Valliant, personal communication, 1998) or to canal soils (D. Crabtree, personal communication, 2000) can reduce seepage loss. Lentz (2003) evaluated WSPAM and surfactant applications for seepage reduction in soil columns and miniflumes. The WSPAM applied to soil surfaces at concentrations of 10 to 500 mg L^{-1} before ponding failed to reduce water infiltration into undisturbed silt loam soil cores, but in packed soil columns, 250 and 500 mg L^{-1} WSPAM treatments reduced the seepage rate by half relative to controls. A 1000 mg L^{-1} treatment reduced seepage rate by 0 to >99% in packed soil columns, varying as a function of soil texture and Na content (Lentz, 2003). When applied to inflow-end "furrow" soils in a miniflume, immediately before irrigation, a >125 mg L^{-1} WSPAM treatment improved furrow water application uniformity (Lentz, 2003).

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Soil conditioners added to soils to increase plant-available water capacity were also found to alter water infiltration (Miller, 1979; Parichehr and Nofziger, 1981). Soil seepage rate and penetrability decreased, and swelling increased, with increasing additions (0–16 g kg^{-1} of an organic supergel to sandy soils (Mustafa et al., 1988; Al-Darby, 1996), although decreasing the salinity of the applied irrigation water lessened the impacts (Mustafa et al., 1989). The organic supergel is composed of water and humic acid, humate, and polysaccharide polymers and its composition differs from that of cross-linked polyacrylamide hydrogels (XPAM), which are similarly used soil amendments (Johnson and Veltkamp, 1985). Salem et al. (1991) reported that XPAM absorbed 80 to 300 L water kg^{-1} polymer and water absorption increased with increasing water sodium adsorption ratio (SAR) and decreased with increasing total soluble salts. The absorption reductions caused by increasing total soluble salts varied depending on dissolved salt species, $MgSO_4 > CaCl_2 >> NaCl$ (Hussain et al., 1992). Little research has examined the infiltration-inhibiting properties of XPAM.

The objectives of this study were to: (i) determine the effect of XPAM application rate and soil type on the seepage rate through soil columns; (ii) examine the effect of NaCl concentration in the soil, XPAM granule size, or thickness of the treated soil on seepage rates in silt loam soils; and (iii) evaluate XPAM's potential for improving irrigation application uniformity in a miniflume for a silt loam soil.

MATERIALS AND METHODS

The first two objectives were evaluated using soil column experiments designed to evaluate treatments under conditions expected during application to irrigation ponds or canals.

Soils and Polymers

The effect of XPAM application rate on infiltration and seepage in soil columns was evaluated using several soil types including: Portneuf silt loam, which is similar to many of the irrigated soils in the Pacific Northwest USA (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids, collected at Kimberly, ID); Killpack Variant silt loam (fine-silty, mixed, calcareous, mesic Typic Torriorthents, Montrose County, CO); Darkbull loam (loamy-skeletal, mixed, superactive, mesic Sodic Xeric Haplocalcids, Cassia County, ID); Taunton loamy sand (coarse-loamy, mixed, superactive, mesic Xeric Haplodurids, Gooding County, ID); and Roza clay loam (fine, smectitic, mesic Xerertic Haplocambids, Twin Falls County, ID). Calcium is the dominant soluble cation in the soils, except for Killpack Variant silt loam and Darkbull loam, for which Na is the dominant soluble cation. Soil characteristics are described in Table 1. Portneuf silt loam no. 1 was used in Exp. 1 and Portneuf silt loam no. 2 in Exp. 2.

The XPAM treatments used two commonly available anionic cross-linked K-acrylate–polyacrylamide copolymers (Stockosorb Agro-F and Agro-S, Stockhausen Inc., Greensboro, NC). The products differed only with respect to the granule size. The talc-sized Stockosorb Agro-F granules (< 300 μm diam.) were used exclusively, except for one experiment that compared the efficacy of Agro-F with that of the coarser Agro-S granules (200 to 800 μm).

The XPAM was manufactured by cross-linking linear polyacrylamide copolymer molecules having an anionic charge density of 27 to 35% and molecular weight of 12 to 15 Mg mol^{-1}. The resulting cross-linked XPAM products had a cross-link density of 0.5 to 1%, a charge density of 27 to 35%, and contained 90 to 95% active ingredient and 5 to 10% water. The XPAM was dried in an oven at 100°C to remove the water before weighing and adding to the soil.

A WSPAM commonly used to control irrigation-induced erosion was used in a miniflume treatment. It was an anionic polyacrylamide copolymer with 20% charge density and 12 to 15 Mg mol^{-1} molecular weight (AN-923-PWG, Chemtall Inc., Riceboro, GA).

Experiment 1: Evaluating XPAM Application Rate and Soil Type Effects

Treatment effects on the water seepage rate were evaluated using soil columns and a constant-head apparatus like that used for measuring hydraulic conductivity (Klute and Dirksen, 1986, p. 695, Fig. 28–5). A flow of simulated irrigation water at a constant head was applied to the soil columns for 21 h. Because the laboratory tap water's electrolyte concentration was twice that of local irrigation water, we prepared simulated irrigation water by diluting tap water 1:1 with reverse osmosis water. The simulated irrigation water had an electrical conductivity (EC) of 0.04 S m^{-1} and SAR of 1.3.

Table 1. Selected characteristics of soils evaluated in the study.

Soil	Texture	Sand†	Silt†	Clay†	pH‡	EC‡	OC§	$CaCO_3$¶	Soluble cations# Na^+	Mg^{2+}	K^+	Ca^{2+}	CEC††	SAR‡‡	ESP§§
		g kg^{-1}				S m^{-1}	g kg^{-1}		mmol$_c$ L^{-1}				cmol$_c$ kg^{-1}		%
Portneuf no. 1	silt loam	240	560	200	7.0	0.4	8.8	130	3.6	14.7	1.3	20.1	23.9	0.9	2
Portneuf no. 2	silt loam	200	570	230	7.3	0.2	8.5	101	1.6	5.4	0.9	12.0	24.5	0.5	2
Killpack Variant	silt loam	150	730	120	7.8	1.08	4.2	127	78.3	4.9	0.6	23.5	15.0	20.8	72
Darkbull	loam	520	360	120	8.7	1.21	6.4	83	112	4.0	13.5	0.6	14.4	73.3	20
Taunton	loamy sand	880	50	70	8.0	0.4	1.3	18	14.7	8	2.3	15.1	5.5	4.3	< 0.1
Roza	clay loam	295	370	335	6.4	0.05	8.3	29	0.8	1	0.7	1.9	15.3	0.5	0.7

† Particle size analysis by the hydrometer method following removal of organic matter.

‡ Determined on saturated extract.

§ Organic carbon determined using dry combustion after pretreatment to remove inorganic carbon (Shimadzu Total Carbon Analyzer).

¶ Cacium carbonate equivalent (gravimetric method).

Analyzed saturated soil extract using an atomic adsorption spectrophotometer.

†† Cation exchange capacity (NH_4^+).

‡‡ Sodium adsorption ratio.

§§ Exchangeable sodium percentage.

We sieved air-dried soils through a 2-mm screen (no. 10) and mixed 100 g of each soil with <300-μm XPAM (Agro-F) at concentrations of 0, 2.5, 5.0, and 10 g kg^{-1}. A stepwise mixing procedure dispersed the XPAM into progressively larger fractions of the 100-g soil portion, ensuring uniform polymer distribution. We placed the soil–XPAM mixtures into 40-mm i.d. by 131-mm-long polyvinyl chloride (PVC) cylinders. Soils were packed by striking the cylinder base firmly against a solid countertop 10 times. Resulting soil bulk densities were 1.17 Mg m^{-3} for Portneuf silt loam no. 1 used in Exp. 1, 1.12 Mg m^{-3} for Portneuf silt loam no. 2 (Exp. 2), 1.29 Mg m^{-3} for Roza clay loam, 1.47 Mg m^{-3} for Darkbull loam, 1.50 Mg m^{-3} for Killpack Variant silt loam, and 1.55 Mg m^{-3} for Taunton loamy sand. (Addition of XPAM and NaCl treatments in Exp. 2 increased bulk density by <0.02 Mg m^{-3}.) Soil columns were saturated from below with simulated irrigation water during a 12- to 24-h period before testing. The PVC columns and soil were placed in a bucket containing 1- to 2-cm-deep irrigation water and the water level in the bucket was increased at 2- to 6-h intervals until it matched the soil surface elevation. At this point, soil columns were left in the water for 8 to 12 h. Saturation was considered complete when free water appeared on the soil surface. The soils treated with 10 g kg^{-1} XPAM typically required a longer period to saturate—48 h.

The experimental protocol simulated treatment application to irrigation ponds and canals. In this scenario, amendments would be applied to the soil lining an empty pond or canal a day or two before filling in the spring. The first irrigation water flows to occupy the structures typically contain high sediment loads. In the laboratory, six saturated soil columns in PVC cylinders were transferred to the constant-head apparatus and irrigation water was supplied to the soil surface through siphons from a constant-head reservoir. We then measured the length of the soil column and depth of ponded water above the soil in each of the PVC cylinders. The water level over the soil in each column was maintained at a constant elevation for the entire 21-h monitoring period. The depth of the ponded water above the soil was 2 to 4 cm, depending on the soil type and its treatment, which influenced the bulk density of the saturated soils.

We prepared a soil–water slurry of 500 g soil L^{-1} water from each soil being evaluated. A 1.25-mL aliquot of the corresponding slurry was added to the ponded irrigation water immediately after water was applied to each soil column, and the ponded water was stirred vigorously for 3 s with a metal spatula to suspend soil fines and provide initial turbulence. A series of seven hour-long percolation volume measurements was initiated 20 to 30 min after starting the flow. At the start of the first six hourly measurements, a 0.25-mL aliquot of the soil slurry was added to the ponded water with stirring. Another1-h measurement was made at 21 h after the flow was started. Soil column length and ponded water depth were monitored in cylinders each time percolation volumes were determined.

The combined effects of settling sediment and soil treatments probably produced the greatest conductivity reductions near the soil surface, and, since water was allowed to drip freely from the column base, some drainage from the lower soil column may have occurred. Thus the seepage measurements determined here should not be confused with saturated hydraulic conductivity values. Soil swelling varied between treatments, which led to differences in wetted soil column length and ponded water depth between soil column treatments. Hence treatments were most accurately compared using a normalized seepage rate value, i.e., by multiplying the seepage rate by the total soil column length and dividing the product by the depth of ponded water. This normalized value, henceforth referred to as the seepage rate (S, mm h^{-1}) was calculated for treated soils at each measurement time using

$$S = 10LV\left[At\left(H_2 - H_1\right)\right]^{-1} \quad [1]$$

where L is the soil column length (cm) at the time of flow measurement; V is the water volume (mL) collected through the cross-sectional area A (cm^2) during time t (h); and ($H_2 - H_1$) is the depth of water (cm) ponded on the soil during the time of flow measurement.

After completion of the seepage test, ponded water was removed from the soil surface. The soil was ejected from the cylinder into a tared evaporation dish, weighed before and after drying at100°C, and final soil pore volume calculated. The seepage rate reduction for a given soil was computed by subtracting the seepage rate of the treated soil from that of its untreated counterpart, and dividing this quantity by the seepage rate of the untreated soil. The swelling index was calculated as a ratio of the soil column length, measured after soil saturation but before seepage testing, divided by the mean soil column length of the 0 g kg^{-1} XPAM treatment for the corresponding soil. Cumulative drainage volumes through the first 7 h and for the 21st h were measured. The cumulative drainage volume through the 21st h was computed by summing volumes from the 1st through the 7th h, the 21st h, and the intervening period. The last quantity was calculated as the product of the drainage rate (mean from the 7-h and 21-h measurements) and the intervening time.

Experiment 2: Influence of Sodium Chloride, XPAM Granule Size, and Treated Soil Depth

Three subexperiments within Exp. 2 used the soil column procedure described above to evaluate the effect of several factors on XPAM's soil water-seepage impacts. Each trial used Portneuf silt loam no. 2 soil. The effective seepage value observed at 21 h and the swelling index were included as response variables.

Experiment 2a examined two main effects, the XPAM rate and NaCl amendment rate, on the seepage rate and swelling index of the treated soil. The experimental design included three levels of XPAM—0, 2.5, and 5 g kg^{-1}—and three levels of NaCl—0, 1.7, and 5.1 g kg^{-1}—for a total of nine treatments. The NaCl was added to the soil as granules similar in size to that of the XPAM. A swelling index was computed as the soil column length divided by the mean soil column length of the 0 XPAM, 0 NaCl control treatment. The addition of NaCl appeared to slow the rate of soil swelling (see below), hence the soil swelling index was calculated from soil column lengths measured at the end of the seepage test, 21 h, rather that at the beginning, as for Exp. 1.

Experiment 2b compared the effect of XPAM granule size on the seepage rate of treated soil columns. The four treatments included two levels of XPAM rate—2.5 and 5 g kg^{-1}—with XPAM provided either as <300-μm- diameter granules or as 200- to 800-μm-diameter granules. All soil treatments included a 5.1 g kg^{-1} NaCl soil amendment.

Experiment 2c evaluated the influence of the thickness of the treated soil layer on the seepage rate. In this case, three treatments applied amendments to the upper 33, 66, or 100% of the dry soil column, corresponding to treated soil layer thicknesses of 24, 48, and 71 mm. The treated portion of the soil was amended with 5 g kg^{-1} XPAM and 5.1 g kg^{-1} NaCl.

Experiment 3: Application Uniformity in Miniflumes

Miniflumes simulated furrow irrigation processes that occurred in the field, but at a scale that permitted laboratory testing. In this experiment, a thin layer of soil just below "furrow" depth at the inflow end of the miniflume was amended with XPAM. The miniflume design allowed evaluation of treatment effects on runoff and infiltration along different quarter-sections of the minifurrow during irrigation.

We constructed the 1000-mm-long, 85-mm-wide, and 150-mm-deep miniflumes from 6-mm-thick Plexiglas (Lentz, 2003). Three 30-mm-tall dividers projecting up from the base partitioned the box into four compartments, each with a drain on the downslope end. A 55-mm layer of sand was lightly packed into the box (bulk density of 1.5 Mg m^{-3}), followed by 75 mm of Portneuf soil (bulk density of 1.22 Mg m^{-3}). A wood block was used with light hand pressure to smooth and press two lifts of soil into place. This simulated field soil that had been disturbed through tillage. A 5-mm layer of unpacked, XPAM-treated Portneuf soil was placed over the soil in the upper half (inflow end) of the miniflume. A similar thickness of untreated soil was placed at the outflow end. Finally, a 10-mm layer of unpacked, untreated soil was placed over the soil in the entire miniflume. A 10-mm-deep, v-shaped "furrow" was formed in the soil along the length of the miniflume by pulling a v-shaped form across the soil surface. The slope was 7%. While this slope is not typical of furrow slopes in many irrigated areas, the average flow shear produced by the miniflume "furrow stream" matched that of field-scale furrows (Lentz, 2003). Flume inflow rate was 80 mL min^{-1}. Drainage volumes from the four furrow quarter-sections and surface runoff were monitored for 6 or 7 h. Drainage and runoff rates and cumulative amounts were determined every 0.5 h for 2 or more hours after runoff or drainage began, and hourly thereafter. Measured parameters included the drainage rates for inflow and outflow half-sections of the miniflume at 20 and 365 min, and the corresponding 365-min cumulative drainage values. In addition, irrigation uniformity along the miniflume was evaluated by examining the spreading ratio, calculated by dividing the inflow-half drainage value by that of the outflow half.

The experiment included three treatments: (i) control—no XPAM or WSPAM; (ii) 2.5 g kg^{-1} XPAM amended subfurrow soil layer; and (iii) 5 g kg^{-1} XPAM amended subfurrow soil layer, coupled with a 10 mg L^{-1} WSPAM irrigation water treatment applied during the advance phase only.

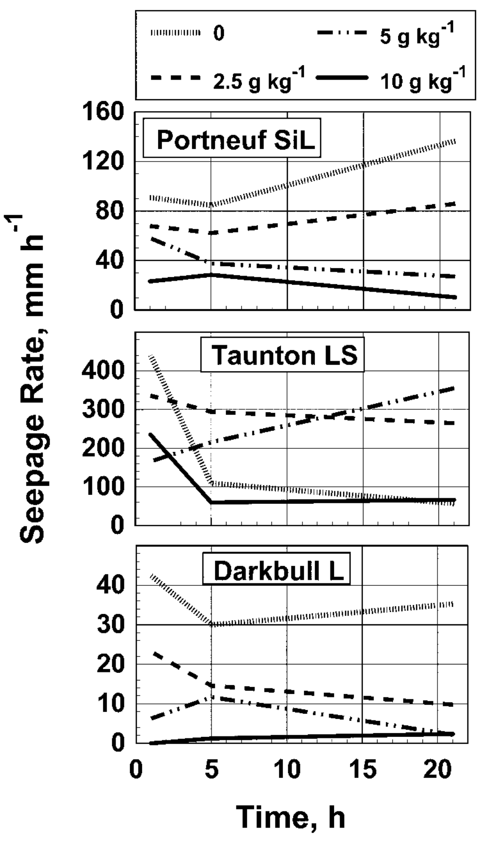

Fig. 1. Seepage rate for 1, 5, and 21 h of Portneuf silt loam sample no. 1, Taunton loamy sand, and Darkbull loam soils treated with XPAM at three rates (means of three replicates). The seepage rate vs. time results for Killpack Variant silt loam and Roza clay loam soils (not shown) were similar to that of the Darkbull loam.

Statistical Analysis

Experiment 1: Application Rate and Soil Type Effects

The completely randomized design included two main factors, soil (five types) and XPAM (four rates), with three replicates. An ANOVA on these parameters was conducted and confidence intervals on soil × XPAM treatment means constructed using the PROC GLM procedure (SAS Institute, 1999) at a $P = 0.05$ significance level. Stepwise multiple regression analyses using the PROC REG procedure (SAS Institute, 1999) described the relationships between seepage rate, seepage-rate reduction, soil column length, or swelling index values and soil characteristic predictors of sand, silt, and clay content, EC, $CaCO_3$ equivalent, organic C, exchangeable sodium percentage (ESP), SAR, XPAM, and XPAM × XPAM. When fitting seepage-rate data, the soil swelling index was also included as a predictor. Pearson's correlations, which measure the strength of the linear relationship between these variables, were constructed using the SAS PROC CORR procedure (SAS Institute, 1999). Before the ANOVA, regression, and correlation analysis, seepage rate and seepage-rate reduction values were transformed using the square root function to stabilize variances (to ensure that the residuals from the model had constant variance) and improve normality (Snedecor and Cochran, 1980). Means were back-transformed to the original units for reporting in Fig. 1, 2, 3, and 4.

Experiment 2: Sodium Chloride, Granule Size, and Treated Depth Effects

All subexperiments—2a, 2b, and 2c—used completely randomized designs with one or two main factors and three replications. An ANOVA was conducted and confidence intervals on treatment means constructed using the SAS PROC GLM procedure (SAS Institute, 1999) at the $P = 0.05$ significance level.

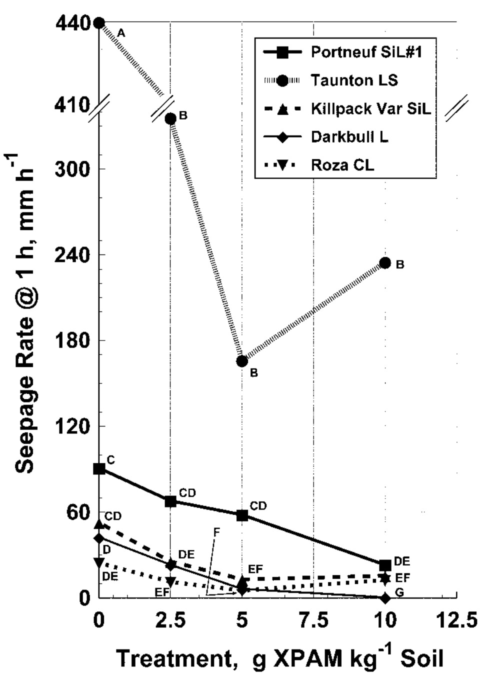

Fig. 2. Seepage rate of XPAM-treated soils in soil columns measured 1 h after water flow was initiated. Symbols followed by the same letters indicate no significant difference between soil and XPAM treatments, determined from confidence limits constructed on treatment means ($P = 0.05$).

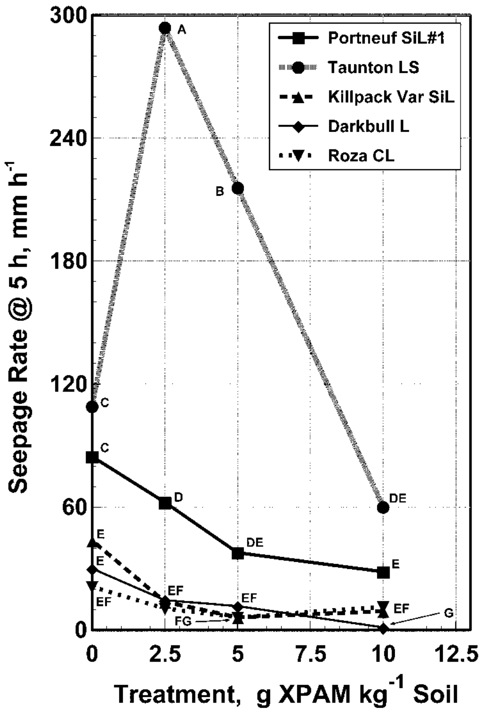

Fig. 3. Seepage rate of XPAM-treated soils in soil columns measured 5 h after water flow was initiated. Symbols followed by the same letters indicate no significant difference between soil and XPAM treatments, determined from confidence limits constructed on treatment means ($P \leq 0.05$).

Experiment 2a: Seepage-rate values for NaCl–XPAM treatments were transformed using the logarithmic function before analysis to stabilize variances and improve normality (Snedecor and Cochran, 1980).

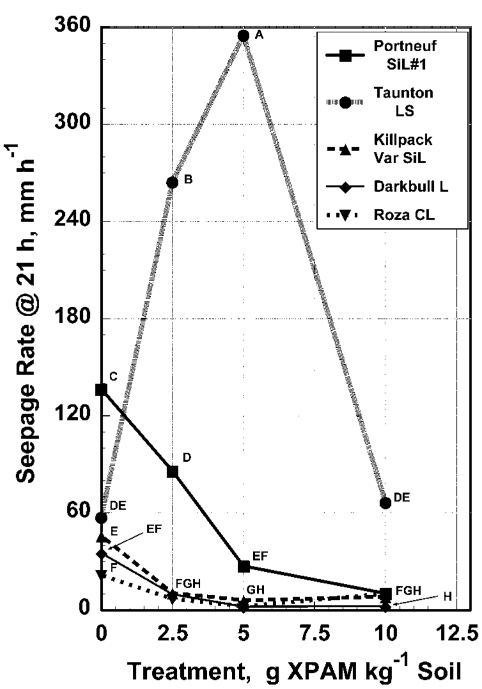

Fig. 4. Seepage rate of XPAM-treated soils in soil columns measured 21 h after water flow was initiated. Symbols followed by the same letters indicate no significant difference between soil and XPAM treatments, determined from confidence limits constructed on treatment means ($P \leq 0.05$).

Analysis was performed on the transformed data and mean values were back-transformed into the original units for reporting. Hence, values displayed in Fig. 5 are geometric means.

Experiement 2b: No transformations were used.

Experiement 2c: As in Exp. 1, seepage-rate values were transformed using the square root function before running the ANOVA. This improved the normality of error term distributions. Means were back-transformed to the original units for reporting.

Experiment 3: Miniflumes

The completely randomized design included three replications. An ANOVA on drainage parameters was conducted and confidence intervals on the treatment means were constructed using the SAS PROC GLM procedure at $P = 0.05$.

RESULTS AND DISCUSSION

Experiment 1: Evaluating XPAM Application Rate and Soil Type Effects

Soil type and XPAM rate significantly influenced the water seepage rate through soil columns ($P < 0.0001$). The interaction between soil type and XPAM rate was also significant ($P < 0.0001$). Thus, while increasing soil XPAM treatments tended to cause increasing seepage-rate reductions, the effect differed as a function of soil type. The seepage rate of soils followed similar patterns with time. At any given time, the seepage rate for a given soil generally was less for those with greater XPAM additions (Fig. 1). The exception to this pattern was Taunton loamy sand.

The seepage rate of untreated soils at 1 h responded to effects of soil texture and chemistry (Table 2). Taunton loamy sand exhibited the greatest seepage rate, followed by Portneuf silt loam;

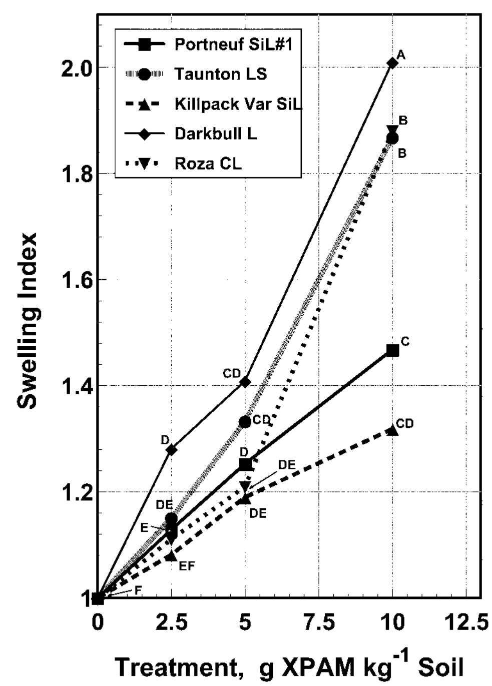

Fig. 5. Swelling index of XPAM-treated soils. The index was calculated as a ratio of soil column length at 1 h divided by the mean soil column length of the 0 g kg^{-1} XPAM soil treatment. Symbols followed by the same letters indicate no significant difference between soil and XPAM treatments, determined from confidence limits constructed on treatment means ($P \leq 0.05$).

then the two high-Na soils, Darkbull loam and Killpack Variant silt loam; and finally Roza clay loam. The intermittent additions of sediment applied to the untreated soil surfaces during the first 6 h of measurement produced a decline in the seepage rate at 5 h (Table 2) due to surface sealing (Segeren and Trout, 1991). Compared with each soil's 1-h seepage values, Taunton loamy sand experienced the greatest seepage-rate reduction at 5 h, 75%, while reductions ranged from 7 to 29% for the other untreated soils. The seepage rates of all untreated soils except Taunton loamy sand trended upward with time after sediment additions were curtailed (see 21- vs. 5-h rates, Table 2). This suggested that, in some cases, a continuing input of sediment is required to maintain the lower seepage rates attained during the initial sediment loading phase of the trial. The seepage rate of Taunton loamy sand continued to decline after the 5-h measurement.

The changes in seepage rate with increasing XPAM additions were similar at 1, 5, and 21 h after water flow was initiated (Fig. 2, 3, and 4). The one exception to this was Taunton loamy sand, which produced a strikingly different seepage vs. XPAM-rate pattern between 1-h and later measurement times.

The pattern of changing seepage rate with increasing XPAM additions took two general forms (Fig. 2, 3, and 4):

1. For Portneuf silt loam, Darkbull loam, Killpack Variant silt loam, and Roza clay loam soils, the seepage rate decreased curvilinearly with increasing XPAM, and the pattern was similar with time. At 21 h, the seepage rates of 10 g kg^{-1} XPAM treated soils were reduced 92% for Portneuf, 93% for Darkbull, 82% for Killpack, and 51% for Roza, relative to controls. Darkbull, Killpack, and Roza differed slightly from Portneuf in that addition of XPAM above the 5 g kg^{-1} treatment level provided no further reductions in seepage rate (Fig. 2, 3, and 4).
2. Taunton loamy sand exhibited a contrasting pattern: steep reductions in seepage rate with increasing XPAM were observed at 1 h, but at later times, seepage rates for 2.5 and 5 g kg^{-1} XPAM treated soils exceeded that of either 0 or 10 g kg^{-1} treatments (Fig. 1). The seepage rate of Taunton soils generally decreased with time, with the exception of the 5 g kg^{-1} XPAM treatment. The seepage rate of untreated Taunton soil declined more steeply with time than any other treatment, dropping from 440 to 57 mm h^{-1}. In comparison, the seepage rate of XPAM-treated Taunton soils either declined more slowly than the Taunton control or increased during the 21-h period. Such a pattern might occur if XPAM slowed or disrupted the self-sealing process, in which suspended sediment is drawn into soil pores during the extended infiltration period; however, no direct evidence of this effect was observed.

Factors Influencing XPAM Activity in These Soils

Stepwise regression models fitted the transformed seepage rate or seepage-rate reduction data to predictor variables including XPAM rate, soil swelling index, and soil characteristics. Water seepage rate through these soils was positively related to soil $CaCO_3$, sand concentration, and XPAM rate, and negatively related to soil SAR, clay concentration, and the square of XPAM (Table 3). The positive XPAM component in the seepage rate regression model resulted from flow enhancements that some XPAM treatments produced in Taunton loamy sand (see below). Note that $CaCO_3$ equivalent and SAR together explained 52.7% of the variability in seepage rate, while $(XPAM)^2$ and XPAM explained only an additional 11.4% of the variation. The reduction in seepage rate produced by a given XPAM treatment was positively related to the soil $CaCO_3$ equivalent, SAR, and $(XPAM)^2$ (Table 3); however, these factors together explained only 54% of the variability in seepage rate reduction.

Table 2. Seepage rates of control treatments for each soil in Exp. 1 (mean of three replicates).

Soil	XPAM treatment	Seepage rate 1 h	5 h	21 h
	g kg^{-1}	mm h^{-1}		
Portneuf silt loam no. 1	0	90.8	84.7	136
Killpack Variant silt loam	0	52.6	43.7	45.8
Darkbull loam	0	42.4	30.0	35.3
Taunton loamy sand	0	440	109	57.3
Roza clay loam	0	24.5	21.2	21.5

Soil Swelling and XPAM Relationships

Soil swelling began during initial saturation of the soil columns and continued, especially in XPAM-treated soils, throughout much of the monitoring period (Tables 4 and 5). The ANOVA indicated that both the soil column length and soil-swelling index increased with XPAM rate ($P < 0.0001$) and was significantly influenced by soil type ($P < 0.0001$). The interaction between these XPAM and soil factors was also significant ($P < 0.0001$), indicating that the relationship between soil swelling and XPAM rate differed among soils. Darkbull loam experienced the steepest rise in swelling index with increasing XPAM, followed closely by Taunton loamy sand, and Roza clay loam, and then by the silt loam soils, which as a group responded more conservatively (Fig. 5).

The relationship between soil swelling (in response to XPAM additions) and soil type was complex. Stepwise regression analysis

Table 3. Models derived from stepwise regressions fitting (seepage rate at 21 h)$^{1/2}$ or (seepage rate reduction at 1 h)$^{1/2}$ to predictor variables including XPAM rate, soil swelling index, and soil characteristics.

Variable†	Parameter estimate	Model R^2	$P > F$
	Seepage rate, mm h^{-1}‡		
Intercept	−87.936	–	0.005
$CaCO_3$	7.3795	0.358	0.002
SAR	−0.2274	0.527	<0.0001
XPAM × XPAM	−4.9544	0.600	<0.0001
Clay	−0.1296	0.643	0.0006
Sand	0.1105	0.672	0.001
XPAM	9.7823	0.713	0.009
	Seepage rate reduction		
Intercept	2.6218	–	<0.0001
$CaCO_3$	−0.04412	0.418	<0.0001
SAR	0.0030	0.508	0.002
XPAM × XPAM	0.1273	0.541	0.050

† $CaCO_3$ = concentration in soil (% w/w); SAR = sodium adsorption ratio; XPAM = concentration in soil (% w/w); sand (g kg^{-1}); clay (g kg^{-1}); XPAM × XPAM = quadratic term for XPAM.

‡ Calculated as the difference between seepage rate of untreated and treated values divided by the untreated values for a given soil.

Table 4. Soil column lengths, pore volumes, and cumulative pore volumes for treatments in Exp. 1 (mean of three replicates).

Soil	XPAM treatment	Soil column length			Final pore volume	Cumulative drainage	
		Prewetted	1 h	21 h		5 h	21 h
	g kg^{-1}	cm			mL	pore volumes	
Portneuf silt loam no. 1	0	6.8	6.7	6.9	58.1	4.3	19.6
	2.5	6.8	7.6	7.9	62.4	2.1	7.8
	5	6.8	8.4	8.9	63.6	1.1	3.3
	10	6.8	9.9	11.5	89.8	0.4	1.4
Killpack Variant silt loam	0	5.3	6.8	6.5	36.3	1.1	4.0
	2.5	5.3	7.3	7.1	54.2	1.2	3.8
	5	5.3	8.0	7.9	59.6	0.5	1.2
	10	5.3	8.9	9.5	78.1	0.3	1.3
Darkbull loam	0	5.4	5.7	5.6	36.0	4.5	17.3
	2.5	5.4	7.3	7.8	52.4	1.2	3.8
	5	5.4	8.0	8.3	56.0	0.7	2.1
	10	5.4	11.4	12.8	107.6	0.05	0.1
Taunton loamy sand	0	5.1	5.3	5.6	33.3	46.3	97.9
	2.5	5.1	6.1	7	46.6	30.8	120
	5	5.1	7.1	7.5	62.6	7.7	59.7
	10	5.1	9.9	10.6	96.8	1.4	3.9
Roza clay loam	0	6.1	6.0	6.0	44.2	2.4	12.2
	2.5	6.1	6.7	6.8	52.9	0.8	3.5
	5	6.1	7.3	7.4	59.1	0.3	1.3
	10	6.1	11.4	11	101.6	0.2	0.9

indicated that soil column length (after saturation) was positively related to XPAM, soil organic C, and EC (Table 6). On the other hand, the swelling index was positively related to XPAM and soil SAR, and negatively related to silt concentration. Thus for any given soil, the increase in swelling caused by XPAM was controlled largely by the XPAM rate, with minor influences by soil SAR, EC, and silt components. The effects of SAR and EC may be limited to an initial impact of soil chemistry on the soil solution, since continued irrigation of the soil column probably altered the soil solution chemistry with time. For a given soil, the swelling behavior of the soil–XPAM blend differed from that of XPAM alone with respect to soil EC effects. Johnson (1984) reported that water absorption and hence swelling of XPAM alone decreased with increasing EC of the water.

How Does XPAM Reduce Water Infiltration into Soils?

The added XPAM may have decreased the seepage rate by absorbing water and preventing its downward percolation, but longer term reductions probably resulted from XPAM effects on soil pore-size distribution. I hypothesized that XPAM particles distributed through the soil swelled as they absorbed water and compressed the intervening soil mass. Measured forces resulting from swelling hydrogel can exceed 100 kPa (Johnson et al., 2004), and are sufficient to cause consolidation of saturated soils (Spangler and Handy, 1982). The swelling XPAM applied compressive and shear stresses to the surrounding soil. The soil mass was constrained by the cylinder walls in the horizontal direction and partially constrained by the bottom screen and mass of overlying soil in the vertical direction. Thus, XPAM-induced stresses probably caused displacement and deformation of the intervening soil, which rearranged soil particles and reduced the volume and continuity of the large pores (Hillel, 1998). The variety of particle sizes present in these soils (except Taunton) would have enhanced the void-filling process that occurred due to compressive stress.

Note that increasing the XPAM application rate did increase the length and decrease the bulk density of the wetted soil columns. The decreased soil bulk density implies an increase in soil porosity, which appears to contradict the seepage reduction result. The increased bulk soil volume resulted from swollen XPAM gel masses, however, and not from an increase in the size or number of soil pores. This also indicates that hydrated XPAM gel is a poor conductor of water.

When amended with 2.5 and 5 g kg^{-1} XPAM, the seepage rate of Taunton, a coarse-textured soil with 880 g kg^{-1} sand and 70 g kg^{-1} clay, was increased relative to controls (Fig. 1). It is not clear what caused this response, although the duality of the pattern suggests that two mechanisms may be involved. For example, one may hypothesize that adding XPAM increased soil swelling, which produced an ongoing rise and deformation of the soil surface. This caused a continuing disruption of the surface seal, which develops in response to sediment added to the ponded irrigation water early in the period; however, increasing XPAM additions probably produced greater conductivity reductions within the soil matrix itself. Eventually the soil XPAM concentration reached a threshold level at which conductivity reductions within the soil matrix exceeded the infiltration-enhancing benefits of the swelling-induced seal disruption. Coarse-grained soils are only slightly compressible (Hillel, 1998), and their resistance to deformation is very low when saturated (Harris, 1971), which may explain why the Taunton loamy sand reacted differently to increasing XPAM additions than did other soils.

Table 5. Soil column lengths, pore volumes, and cumulative pore volumes for XPAM and NaCl treatments to Portneuf silt loam sample no. 2 soil in Exp. 2a (mean of three replicates).

NaCl treatment	XPAM treatment	Soil column length			Final pore volume	Cumulative drainage	
		Prewetted	1 h	21 h		5 h	21 h
g kg^{-1}		cm			mL	pore volumes	
0	0	7.1	7.2	7.2	54.0	5.2	26.9
	2.5	7.1	7.6	7.7	63.0	2.2	10.4
	5.0	7.1	7.8	8.3	68.6	1.5	5.3
1.7	0	7.1	7.3	7.3	57.7	2.2	9.6
	2.5	7.1	7.3	7.7	78.7	1.0	2.5
	5	7.1	7.8	8.5	86.2	0.8	1.6
5.1	0	7.1	7.2	7.3	57.5	2.3	7.3
	2.5	7.1	7.5	8.3	67.2	1.4	3.2
	5.0	7.1	7.9	8.6	72.4	0.6	2.3

Clearly, the soil-swelling index was a poor predictor of XPAM's seepage-rate impacts across all the soils tested in this experiment. Pearson's correlations indicated that seepage rate was weakly related to the swelling index in Taunton loamy sand and Roza clay loam soils (−0.21 and −0.11, respectively), but strongly related for the other soils (−0.66 to −0.82). The relationship broke down for soils with high sand content, which decreased the saturated soil's compressibility and resistance to the swelling XPAM, and in soils with higher clay and organic matter contents and smaller sand concentrations, which increased the soil fabric's resistance to XPAM swelling forces, at least at some treatment levels (Hamza and Anderson, 2005; Hillel, 1998), and stabilized the soil aggregates themselves against swelling and deformation.

Experiment 2: Influence of Sodium Chloride, XPAM Granule Size, and Treated Soil Depth

In Exp. 2a, ANOVA analysis on the log-transformed 21-h seepage-rate data indicated that both main effects, XPAM rate and soil NaCl concentration, were significant ($P < 0.0001$), but not the interaction ($P = 0.12$). The seepage rate of soils decreased with increasing NaCl concentration for all three levels of XPAM treatments. The salt effect was most pronounced for the 0 XPAM treatment at 21 h (Fig. 6). For example, as NaCl concentration increased from 0 to 5.1 g kg^{-1} in 0 XPAM soils, the water seepage rate declined from 132 to 21 mm h^{-1}, compared with a decline of 16.8 to 8.9 mm h^{-1} for 2.5 g kg^{-1} XPAM soils and a decline of 12.4 to 1.6 mm h^{-1} for 5 g kg^{-1} XPAM soil. In XPAM-free soils, added NaCl increased the SAR of the soil solution, which reduced the seepage rate (McNeal and Coleman, 1966) by decreasing pore diameters, either through clay swelling or dispersion (Pupisky and Shainberg, 1979) or aggregate slaking (Abu-Sharar et al., 1987). The effects of NaCl and XPAM treatments were additive. A 90% reduction in water seepage rate was achieved by either applying the combined 1.7 g kg^{-1} NaCl + 2.5 g kg^{-1} XPAM treatment or the 5 g kg^{-1} XPAM application alone.

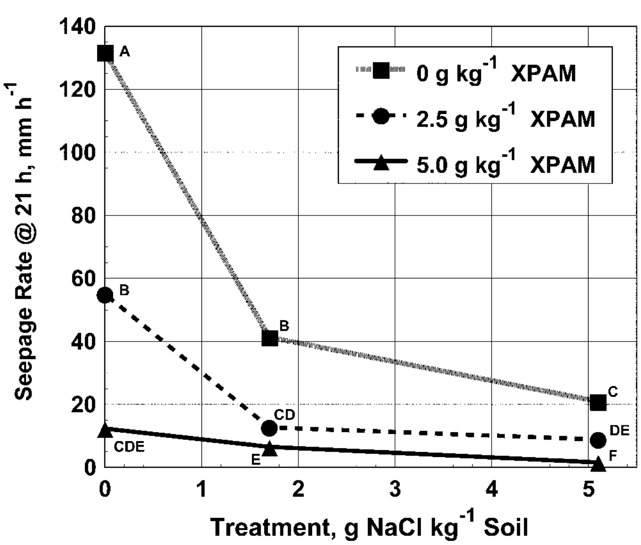

Fig. 6. Seepage rate of XPAM- and NaCl-treated Portneuf silt loam sample no. 2 soils in soil columns measured 21 h after water flow was initiated. Symbols followed by the same letters indicate no significant difference between XPAM and NaCl treatments, determined from confidence limits constructed on treatment means ($P \leq 0.05$).

Table 6. Models derived from stepwise regressions fitting soil column length and swelling index data to predictor variables including XPAM treatment and soil characteristics.

Variable†	Parameter estimate	Model R^2	$P > F$
	Soil column length, cm		
Intercept	4.8918	–	<0.0001
XPAM	4.1930	0.818	<0.0001
OC	0.4296	0.857	<0.0001
EC	0.1365	0.868	0.035
	Soil swelling index‡		
Intercept	1.0677	–	<0.0001
XPAM	0.7088	0.750	<0.0001
Silt	−0.00033	0.807	<0.0001
SAR	0.0021	0.842	0.0008

† XPAM = concentration in soil (% w/w); OC = organic carbon (g kg^{-1}); EC = electrical conductivity of a saturated extract (S m^{-1}); silt (g kg^{-1}); SAR = sodium adsorption ratio.

‡ Computed as a ratio of treated soil column length divided by the mean soil length of the untreated column of the same soil.

The soil swelling index increased with increasing XPAM rate ($P < 0.0001$) and increasing NaCl concentration ($P < 0.013$), although the interaction between these factors was not significant ($P = 0.57$). For the single soil tested here, the seepage rate decreased as soil swelling increased, although the relative change in swelling index was small (Fig. 7) compared with the corresponding change in seepage rate (Fig. 6). This increase in soil swelling with increasing NaCl concentration was congruent with previous observations that water adsorption by XPAM increases with increasing water SAR (Salem et al., 1991; Hussain et al., 1992).

A general comparison between results from Exp. 1 and 2 was made, although it was recognized that the Portneuf soils used in the two studies were not identical. The 21-h seepage rate for Portneuf no. 2, 0 g kg^{-1} NaCl treatments (Fig. 6) were generally less than values observed for identical Portneuf no. 1 treatments from Exp. 1 (Fig. 4). While the differences may not be significant, Portneuf silt loam no. 2 did contain more clay and less $CaCO_3$

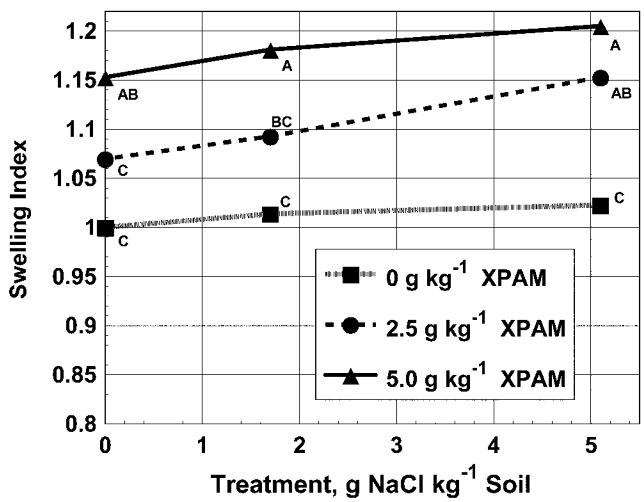

Fig. 7. Swelling index of XPAM- and NaCl-treated Portneuf silt loam sample no. 2 soils. The index was calculated as a ratio of soil column length in the polyvinyl chloride cylinder at 21 h divided by the mean soil column length of the 0 g kg^{-1} XPAM and 0 g kg^{-1} NaCl soil treatment. Symbols followed by the same letters indicate no significant difference between XPAM and NaCl treatments, determined from confidence limits constructed on treatment means ($P \leq 0.05$).

Table 7. Effect of XPAM granular size and rate on seepage rate and swelling index in Portneuf silt loam sample no. 2 soil columns 21 h after water flow began.

Granular size of XPAM treatment	Seepage rate at 21 h, mm h^{-1}			Swelling index		
	2.5 g kg^{-1} XPAM + 5.1 g kg^{-1} NaCl	5 g kg^{-1} XPAM + 5.1 g kg^{-1} NaCl	Mean	2.5 g kg^{-1} XPAM + 5.1 g kg^{-1} NaCl	5 g kg^{-1} XPAM + 5.1 g kg^{-1} NaCl	Mean
<300 µm	9.4	1.8	5.6 b†	1.14	1.19	1.16 a
200–800 µm	18.0	14.6	16.3 a	1.05	1.08	1.07 b
Mean	13.7 A‡	8.2 B	–	1.10 B	1.14 A	–

† Means followed by the same lowercase letter indicate no significant difference between treatments in each row, determined from confidence limits constructed on treatment means ($P = 0.05$).

‡ Means followed by the same uppercase letter indicate no significant difference between treatments in each column, determined from confidence limits constructed on treatment means ($P = 0.05$).

than Portneuf silt loam no. 1 (Table 1), conditions that should result in a decreased seepage rate for Portneuf no. 2, relative to no. 1 (Table 3). It was also noted that Portneuf no. 2 + NaCl treatments produced similar or less soil swelling than corresponding Portneuf no. 1 treatments without NaCl; yet Portneuf no. 2 treatments produced generally lower seepage rates than no. 1. This suggests that NaCl acts through a different mechanism than XPAM to inhibit seepage. The added NaCl caused a reduction in pore size by inducing clay swelling or dispersion and aggregate slaking, while the swelling XPAM acted via compressive forces to alter pore size and distribution (see above discussions).

The ANOVA results from Exp. 2b indicate that both main factors, XPAM granule size ($P < 0.002$) and XPAM rate ($P = 0.04$), significantly influenced the seepage rate of the soils. The interaction effect was not significant ($P = 0.39$). Thus, the soil water seepage rate decreased with decreasing XPAM granule size and increasing rate of addition (Table 7). Application of the <300-µm XPAM treatment produced a seepage rate of 5.6 mm h^{-1}, compared with 16.3 mm h^{-1} produced by the 200- to 800-µm XPAM application. Sohn and Kim (2003) reported that XPAM water uptake increased as polymer particle size decreased from 167 to 93 µm. The results for Portneuf soil corroborate their finding, to the extent that swelling was greater for the <300-µm XPAM treated soil than for the coarse XPAM treatment (Table 7). These results also support the concept that swelling-induced soil compression reduced the seepage rate.

In Exp. 2c, decreasing the thickness of a 5 g kg^{-1} XPAM and 5.1 g kg^{-1} NaCl treated soil layer did not significantly alter its capacity for reducing the water seepage rate through Portneuf silt loam soil ($P = 0.16$). At 21 h after the start of water flow, the average seepage rate was 2.3 mm h^{-1} for the 24-mm-thick XPAM-treated soil layer, 2.9 mm h^{-1} for the 48-mm layer, and 1.8 mm h^{-1} for the 71-mm layer. The average value across the three XPAM-treated thicknesses was 2.3 mm h^{-1}, which represented a 98% reduction in seepage rate compared with untreated soil.

Experiment 3: Application Uniformity in Miniflumes

The combined 5 g kg^{-1} XPAM and WSPAM treatment significantly decreased the "furrow-stream" advance period and reversed the drainage patterns observed in miniflumes, relative to controls (Table 8). The 2.5 g kg^{-1} XPAM treatment differed significantly from controls with respect to advance characteristics, and although water application uniformity measures for 2.5 g kg^{-1} XPAM were intermediate to those of controls and 5 g kg^{-1} XPAM + WSPAM treatment, differences were not significant.

The 5 g kg^{-1} XPAM + WSPAM treatment reduced the furrow-stream advance period 77% compared with controls (Table 8). The proportion of time required for "furrow streams" to advance to the miniflume midpoint, relative to the total advance time, was smaller for the treated furrows, 0.23, than for control furrows, 0.28. This suggested that the XPAM-treated soils along the inflow half of the furrow played an important role in reducing infiltration and increasing runoff there. The WSPAM may have also reduced drainage along the entire furrow via viscosity effects that slowed water transport through the mainly small pores present in the sieved soils used to fill the miniflume (Malik and Letey, 1992). The WSPAM generally does not have this effect in field furrows, especially newly formed ones, where large soil aggregates and clods create a greater number of large soil pores, which, when stabilized by the polymers, tend to promote greater infiltration rates and slower advance relative to untreated furrows (Lentz, 2003)

Table 8. Stream advance and drainage results from the miniflume study, Exp. 3.

Treatment†	Stream advance time		Drainage rate 20 min after drainage started			Drainage rate at 365 min after irrigation started			Cumulative drainage at 365 min after irrigation started		
	Half length	Full length	Inflow ½ section	Outflow ½ section	Spreading ratio‡	Inflow ½ section	Outflow ½ section	Spreading ratio	Inflow ½ section	Outflow ½ section	Spreading ratio
	— min —		— mL min^{-1} —			— mL min^{-1} —			— L —		
Control	7.9 a§	30 a	7.9 a	6.2 a	1.3 a	7.7 a	6.7 a	1.2 a	2.3 a	2.0 a	1.2 a
2.5 g kg^{-1} XPAM	4.3 b	18 b	1.7 b	1.3 b	1.3 a	0.83 b	0.75 b	1.1 ab	0.30 c	0.28 b	1.1 ab
5 g kg^{-1} XPAM + WSPAM	1.6 c	6.9 b	2.6 b	6.0 ab	0.42 b	3.4 b	3.9 b	0.89 b	1.3 b	1.4 a	0.89 b

† XPAM = crosslinked anionic PAM added to soil sublayer at inflow-end half of miniflume; WSPAM = water-soluble PAM added to irrigation water at 10 mg L^{-1} during stream advance only.

‡ Computed as the ratio of the inflow-half response value divided by that of the outflow half.

§ Means followed by the same lowercase letter indicate no significant difference between treatments in each column, determined from confidence limits constructed on treatment means ($P = 0.05$).

The 5 g kg^{-1} XPAM + WSPAM treatment significantly reduced the cumulative-drainage spreading ratio at 365 min: 0.89 compared with control furrows at 1.2 (Table 8). In controls, the drainage loss through the inflow half of the miniflume "furrow" exceeded that of the outflow half, while this pattern was reversed for treated soils. The drainage-rate spreading ratio determined shortly after percolation began was 1.3 for the control and 0.42 for the 5 g kg^{-1} XPAM treatment. Thus, the difference between the drainage-rate ratios of control and 5 g kg^{-1} XPAM treatments early in the "irrigation" was greater than at 365 min, when values were 1.2 vs. 0.89 (Table 8). This suggests that processes that promote water-application nonuniformity in both control and treated furrows were most effective during the early stages of the "irrigation."

The drainage differences between minifurrow inflow and outflow ends, especially at the end of the 6-h monitoring period (Table 8), were not as substantial as we observed in Exp. 1 for soil columns (Fig. 2) at equivalent application rates and measurement times. It is likely that the 0.5-cm-thick soil layer treated at the inflow end of the minifurrow (7.3% as thick as that in soil columns) was not thick enough for maximum drainage control. Other factors that may have influenced column vs. miniflume treatment efficacies were differences in (i) preconditioning, (ii) initial conditions (prewetted vs. dry), and (iii) water regimes (ponded vs. flowing).

Care must be taken when interpreting miniflume results and extending them to full-scale furrows. While the Manning's roughness coefficient for the miniflume channel and average shear of the flow compared favorably with those for full-scale furrows, stream flow velocities of minifurrow streams were smaller and advance ratios (irrigation time/advance time) greater than that of full-sized furrow streams (Lentz, 2003). The miniflume does not fully model the surface aggregate-breakdown and sealing processes that occur in full-scale furrows (Lentz, 2003). Despite these limitations, it is expected that treatment effects observed in the miniflume would transfer at some level of magnitude to field furrows.

Comparing Costs of Soil Sealing Treatments

The following cost determination assumes that XPAM treatments applied in the field would be (i) as efficacious as seen in the laboratory, (ii) applied only to the most amenable soils, and (iii) effective if added to a 20-mm-thick treated soil layer (as opposed to the 24-mm layer shown to be effective in Exp. 2c). Given the above, it is estimated that a 5 or 10 g kg^{-1} XPAM application to a 20-mm-thick soil layer would provide a >90% reduction in canal or pond seepage losses and incur a material cost of US\$0.65 to \$1.29 m^2. Material costs could be reduced if NaCl amendments were included or the treated layer was thinner. These costs compare very favorably with material costs of other soil liners and membranes: US\$13.98 m^2 for polyfiber reinforced shotcrete; US\$8.82 m^2 for 80-mil high-density polyethylene; US\$3.87 for 45-mil ethylene propylene diene monomer rubber; and US\$3.33 for linear low-density polyethylene with geotextile covering (Swihart and Haynes, 2003). Price comparisons were calculated based on year 2002 market values. No long-term evaluations of XPAM soil treatments were found in the literature, although Chen et al. (2003) observed XPAM to be effective for at least 2 yr in soils. Based on observations of XPAM's water absorbance activity in agricultural soils (D. DeBuff, personal communication, 2005), the effective lifespan of subsurface XPAM soil treatments is estimated to be between 3 and 7 yr, under conditions in which treated soils become seasonally dry. This compares to 10- to 50-yr lifespans for the other liners.

The costs associated with the use of XPAM in furrow-irrigated soils to attain uniform water application would depend on the thickness of soil treated, the concentration of XPAM used, the fraction of a total field treated, and the unit cost of XPAM. A minimal application would treat a 1.0-cm layer of soil with 2.5 g kg^{-1} XPAM, and treat only the soil in the irrigation furrows within the inflow half of the field. At the current price of XPAM (US\$6.60 kg^{-1}) the combined materials and application cost would be US\$296 ha^{-1}; however, if a single application to southern Idaho fields lasted 3 yr, the entire cost could be recovered from N-fertilizer savings alone. Nitrate-N leaching losses in furrow-irrigated Portneuf silt loam soils can be 120 kg N ha^{-1} yr^{-1} (Lentz et al., 2001). Thus, if NO_3–N leaching were prevented, the farmer would save US\$305 in N fertilizer costs during 3 yr (assuming a urea-N cost of US\$0.88 kg^{-1} [unpublished data, 2006]). The cost of XPAM applications to irrigation furrows appears to be relatively high; its practical use may ultimately depend on its as yet unproven durability in the field.

CONCLUSIONS

Cross-linked polyacrylamide hydrogel (XPAM) added to soils at the rate of 5 to 10 g kg^{-1} reduced water infiltration by as much as 87 to 94% relative to controls. The seepage-rate reduction was greatest in soils with more balanced distributions of particle size classes and least in soils with high sand fractions (>880 g kg^{-1}) or higher clay and organic C contents. In direct contrast to its effect on other soils, XPAM additions sometimes increased water infiltration into the coarse-textured Taunton soil. Soil swelling was strongly, negatively correlated with seepage rate in those soils most impacted by XPAM treatments. This may support the notion that shear and compressive stresses caused by the swelling of XPAM granules during water imbibition acted to displace and deform the intervening soil, alter soil pore structure, and reduce infiltration. This experiment could not distinguish, however, between the direct effects of XPAM swelling and potential correlated effects, such as the influence of XPAM on swelling or dispersion of soil particles.

The soil swelling response of soil–XPAM mixtures differed from that expected of XPAM or soil alone, and was positively related to XPAM and soil EC, SAR, and organic C and negatively related to soil silt content, although XPAM accounted for the majority of variation in swelling. If XPAM swelling is the active mechanism involved in this phenomenon, it may be possible to devise more efficacious seepage reducing treatments using hydrogels that have greater water absorption capacities. Thus, starch–polyacrylonitrile graft copolymers, which may absorb two to three times more water than XPAM (Johnson, 1984), should be considered for further testing. The starch polymer may degrade more rapidly in soil than XPAM, however, which could influence treatment durability.

The XPAM treatment potentially is an economical practice because the infiltration reduction produced did not decline with decreasing treated soil layer thickness. This study suggests that XPAM can be used to reduce soil water seepage losses in unlined conveyance structures and increase water application uniformity in irrigated furrows. Soils that don't respond to the XPAM amendments could be treated with alternative WSPAM applications (Lentz, 2003).

Further field-testing of XPAM treatments is warranted.

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