Scanning electron micrographs of polyacrylamide-treated soil in irrigation furrows

C.W. Ross, R.E. Sojka, and J.A. Foerster

ABSTRACT: Polyacrylamide (PAM) is used at rates of 1 to 2 kg ha^{-1} per irrigation on a half million hectares of United States irrigated farmland to prevent 94% of irrigation-induced erosion and to enhance infiltration by 15% to 50% on medium to fine-textured soils. The polyacrylamides used for this application are large (12 to 15 megagrams per mole), water-soluble anion molecules applied in the irrigation stream. Erosion prevention has been shown to result from stabilized soil structure in the 1 to 5 mm veneer of surface soil that regulates infiltration, runoff, and sediment loss on water application. We hypothesized that this could be confirmed from scanning electron micrographs (SEMs) of PAM-treated soil. Both untreated and PAM-treated soils form surface seals in irrigation furrows, but the stable surface structure of PAM-treated furrows is more pervious. This is thought to result from a greater number of continuous unblocked pores at the soil-water interface. SEMs of PAM-treated and untreated soil microstructures are presented from thin surface samples of Portneuf silt loam, collected from furrows immediately following an irrigation, and freeze-dried. SEMs of PAM-treated soil showed net or web-like microstructural surface coatings about 1 μm thick on soil mineral particles, giving a glue-like porous appearance. Individual strands of PAM were about 0.2 μm in diameter. Strands of PAM aggregated the soil by ensnaring and bridging mineral particles while untreated soil had poorly aggregated, unconnected particles. Thus, microstructural differences between PAM-treated and untreated soil from irrigation furrows were consistent with erosion and infiltration results.

Keywords: Irrigation-induced erosion, polyacrylamide, scanning electron microscopy, soil microstructure

The first practical field experiments using polyacrylamide (PAM) for erosion control in irrigated agriculture were conducted in 1991 (Lentz et al., 1992). PAM use was recognized by the U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) three years later (Anonymous, 1995) and commercial sales accounted for use on nearly a half million irrigated hectares by 1998. Numerous studies have verified the effectiveness of PAM for reducing erosion and enhancing infiltration. Lentz and Sojka (1994) and Sojka and Lentz (1995, 1997) demonstrated that 94% of sediment lost in runoff was prevented by using 5 to 20 g m^{-3} of PAM in the first water advancing across irrigated furrows, and then by irrigating with untreated water for the balance of the irrigation. Field furrow irrigation studies have shown typical net infiltration increases as compared to controls of 15% to 50% (increasing with clay content) with PAM treatment (McCutchan et al., 1994; McElhiney and Osterli, 1996, Trout et al., 1995). Field conditions can influence the magnitude of infiltration increase (Sojka et al., 1998a,b); compaction and coarse texture (sands) may show no infiltration increase, or even slight decreases. Data by Bjorneberg (1998) suggests that above the recommended maximum application concentration of 10 ppm, increased water viscosity could reduce infiltration. Similar but less dramatic erosion and infiltration results have been reported for sprinkler application (Aase et al., 1998; Ben-Hur, 1994; Levy et al., 1991).

In these and other studies, investigators have generally concluded that the mechanism by which PAM alters soil erosion, infiltration, and runoff is through alteration of soil surface seal formation (Shainberg et al., 1990, 1992; Smith et al., 1990). It is generally concluded that PAM-treated systems stabilize aggregates and preserve more pore continuity through the surface seals that result from the processes of wetting, detachment, dispersion, transport, and redeposition that accompany irrigation. Sojka et al. (1998b) documented increased aggregated stability of soil near the surface of furrow bottoms and sides.

The seals that result from PAM-treated furrows are more pervious to water than those seals without PAM treatment. Nearly double the infiltration at 40 and 100 mm water tension has been documented through surface seals formed with PAM treatment (Ross et al., 1996; Sojka et al., 1996; 1998a). Because the relative benefit of maintaining pore openings is greater with clays (clay soils seal more completely), the PAM infiltration effect tends to be greater in finer textured soils. In coarse-textured soils, where seals have minimal effect on the hydraulic conductivity of surface soil, PAM results in little or no increase in infiltration rates. If texture is coarse, and little soil is entrained in the flow and subsequently redeposited in seals, PAM can result in decreases in infiltration due to viscosity effects. Malik and Letey (1992) and Letey (1996), quantified an increase in effective viscosity of PAM-treated water moving through soil pores. The net infiltration effect of PAM treatment is the balance of pore continuity maintenance and effective viscosity.

The effect of PAM on soil systems is thought to result primarily from its beneficial impacts on soil aggregation, structural stability, and pore geometry. Furthermore, PAM is believed to surface adsorb in the first few millimeters of contact with soil (Malik et al., 1991).

We felt that the accumulated PAM applied in the field to soil surface seals via irrigation water might be visible at a microscopic level using scanning electron microscopy. Furthermore, since PAM applied in the field is more or less "sieved" from infiltrating water by the few millimeters of soil at the surface,

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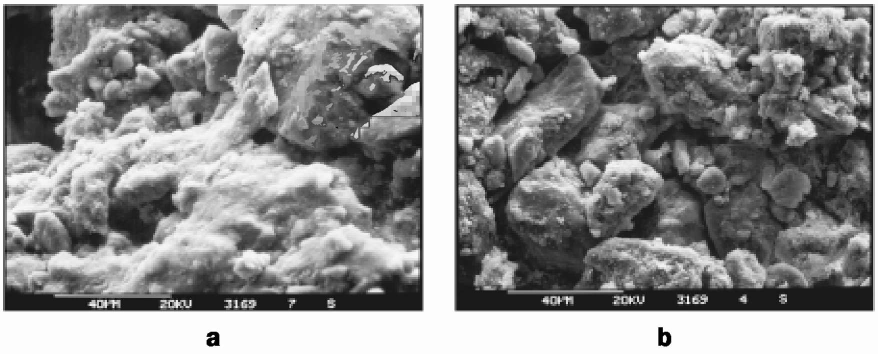
Figure 1

Comparative PAM-treated (a) and untreated (b) surface soil submicrostructures from irrigation furrows at a nominal magnification of 1500x. Note the glued-like porous appearance with PAM and poor visual microaggregation in the untreated soil.



we felt its accumulation might be denser and appear more net-like than in images of clay flocs. Images of PAM adsorbed on field-treated soil samples taken from furrow seals can also provide insight into PAM function and into its mode of soil structure stabilization at a microscopic level in irrigation furrows.

Scanning electron microscopy (SEM) allows direct observation of intact soil microstructures at a submicroscopic level (Eswaran, 1971; Smart and Tovey, 1981; Bisdom, 1983). Numerous SEM studies cited in literature have visually illustrated microstructures of soil aggregation at high magnifications beyond light microscopy (e.g.: Powers and Skidmore, 1984; Metzger and Robert, 1985; Sullivan and Koppi, 1987; Monreal and Kodama, 1997; Shepherd et al., 2001). Thus SEM provides a visual method to examine the physiochemical, submicrostructural behavior of PAM-treated soil. To obtain SEM images of adsorbed PAM, we collected surface samples from an experiment in which 20 g m^{-3} PAM treatments had been applied at each irrigation.

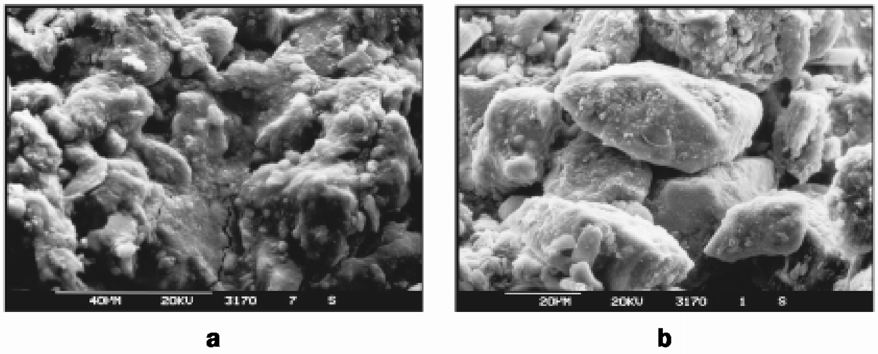
Methods and Materials

An irrigated field study was conducted near Kimberly, Idaho. The soil was Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids). This soil has low organic matter, typically 10 to 13 g kg^{-1}, and a moderate cation exchange capacity, typically 18 to 20 cmol(+) kg^{-1}. Soil pH is highly buffered (7.6 to 8.0), with a calcium carbonate equivalent of 2% to 8%. Electrical conductivity of saturated paste extracts ranges from 0.7 to 1.3 dS m^{-1}, with an exchangeable sodium percentage of 1.4% to 1.7%. Field slope was 1.0%.

The field had been plowed in the fall to 0.25 m depth. Fields were disked in the spring to 0.1 m depth and roller-harrowed. Irrigation furrows were created before the first irrigation using weighted 75° V-shaped furrow-forming tools. Furrows were approximately 0.1 m deep. Two irrigation treatments were imposed on this study: 1) irrigating with untreated water and 2) irrigating with water containing 20 g m^{-3} PAM applied during the first hour of each 8 to12 hour irrigation. Furrow lengths were short (12.2 m). Irrigations were by gravity flow delivered from spigotted pipe that allowed precise regulation of inflows. Water flowed in furrows and ran off into a tail ditch. Each irrigation alternated from wheel track (WT) to nonwheel (NW) furrows, with every other furrow in the field being either a wheel track or nonwheel furrow. Surface samples for SEM imaging were collected 12 hours after the tenth irrigation of the season. Samples were taken from WT furrows during the fifth irrigation of those furrows.

Figure 2

Comparative PAM-treated (a) and untreated (b) surface soil submicrostructures from irrigation furrows at nominal magnification of 2000x. A near complete coating of polyacrylamide compares with poorly bound, uncoated particles on untreated soil.



Irrigation water (0.5 dS m^{-1} EC, 0.4-0.7 SAR) was applied using gated pipe with flow-regulating spigots. Pipe manifolds allowed simultaneous delivery of untreated or PAM-treated water to individual furrows. Polyacrylamide (PAM) was Superfloc A836, provided by Cytec Industries, Wayne, New Jersey. This PAM has a molecular weight of 12 to 15 Mg mole^{-1} for approximately 150,000 monomer units per molecule, with a negative charge density of approximately 18%. The 20 g m^{-3} PAM concentration during advance was achieved by injecting 2400 g m^{-3} PAM stock solutions into manifolds via peristaltic pumps. Based on seasonal water application total, PAM application concentration, duration of application of PAM-treated water, net infiltration during application time, extent of wetted perimeter, and active ingredient content of applied PAM, we estimate that soil samples with PAM had a total undisturbed seasonal application of 2.24 grams of PAM per square meter of soil at the time of sampling. Because the soil samples for SEM imaging were obtained from within a meter of the treated inflow point, the PAM surface accumulation seen in the resulting SEMs represents a maximum surface density, whereas we would expect samples taken from near tail ditches to have less PAM visible at the soil surface.

We used a randomized strip plot design with four treatments and three replications. Treatments were PAM or no PAM and wheel track furrow or nonwheel track furrow. In soil sampling for SEM imaging, no attempt was made to distinguish wheel track or non-

Figure 3

High magnification (nominal 7400x) view of net or web-like polyacrylamide strands coating mineral particles (a) compared with uncoated grains from untreated soil (b). Individual strands of PAM appear to be about 0.1 μm in diameter.

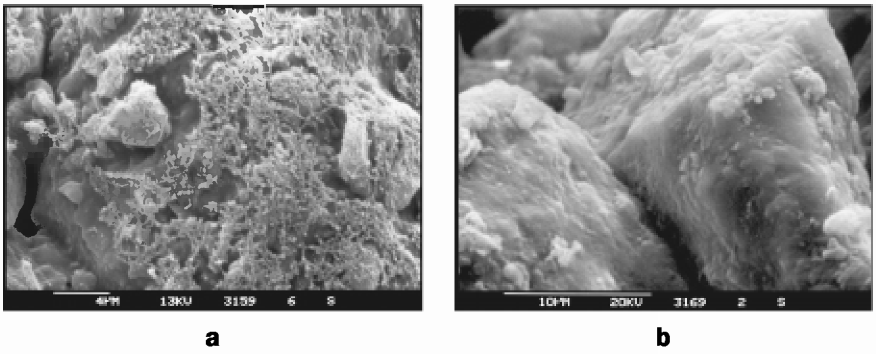


Figure 4

Net or web-like polyacrylamide surface coatings provide aggregation of mineral grains at the submicroscopic level (nominal magnification 1500x) in PAM-treated furrows. The semi-continuous coatings are about 1 μm thick.

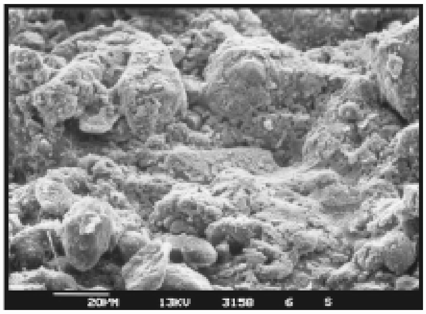
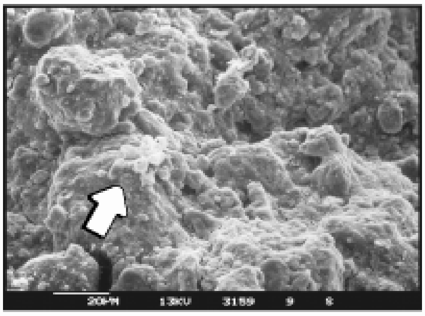


Figure 5

Net or web-like PAM coatings provide surface soil microstructural stabilization (nominal magnification of 1500x). A small cluster of microbial capsules, possibly fungal spores, appears to be ensnared in the PAM coating (middle left hand side).



wheel track furrows. Disks of surface soil 25 mm in diameter by 3 to 5 mm thick were randomly collected from the central areas of irrigation furrows immediately after an irrigation event by using a sharpened cork borer type tube.

Soil disks were freeze-dried from the field-wet state, using a method similar to that described by Humphries (1975), and mounted onto aluminum sample holders. The surfaces of soil disks were given a conductive coating of 10 nm carbon followed by 10 nm 60/40 gold/palladium before viewing in a Cambridge Stereoscan 250 Mark 3 scanning electron microscope.

Results and Discussion

Significant submicrostructural differences were observed between PAM-treated and untreated surface soil seals in the irrigation furrows. Comparative micrographs of PAM-treated and untreated soil are presented in Figures 1 through 3. Additional micrographs (Figures 4 through 5) from PAM-treated furrows further illustrate polyacrylamide-coated surface soil submicrostructures.

PAM-treated soil seals had semi-continuous net or web-like surface polyacrylamide coatings on mineral particles (Figures 3 and 4). Coatings were about 1 μm thick, giving a glued-like appearance (Figures 1, 2, and 5) at lower magnifications (1500×-2000×). Individual strands of polyacrylamide of about 0.2μm diameter, which form the webs, were distinguishable at higher magnifications (7400×) (Figure 3). The PAM-treated soil microsurfaces were porous, yet well aggregated. The submicrostructure of PAM-treated soil seals in the furrows would provide protective, yet pervious, coatings against disaggregation and dispersion of soil mineral particles in the irrigation stream. The micrographs also indicated polyacrylamide bridging between particles as a mechanism for coagulating or ensnaring soil particles into a temporary water-stable surface sealing structure. Laird (1997) proposed that cationic bridging was the major bonding mechanism between anionic PAM and clay particles, and possibly with hydrogen and hydrophobic bonding. These protective seals are generally most effective for only the irrigation where PAM is applied, but rapidly lose their effectiveness by the following irrigation. If PAM was not reapplied in the second irrigation, a loss of about half the erosion protection was observed (Lentz and Sojka, 1994) when irrigating a second time on a furrow within two weeks of the original PAM application. These polymers, and presumably their filamentous strands, are large enough to sustain mechanical failure if exposed to abrasion or shear. Drying and attendant soil shrinkage are believed capable of inducing such breakage. Others have noted that chemical, photochemical (ultraviolet [UV] exposure), and microbial processes also promote PAM degradation (Barvenik, 1994; Kay-Shoemake et al., 1998a,b). In these systems, where most of the

PAM is within a few millimeters of the soil surface, the ultraviolet effects are likely to be substantial between irrigations, especially before canopy coverage.

Figure 5 shows a small cluster of capsules of biological material, possibly fungal spores, ensnared in the polyacrylamide coating. This effect is consistent with the reported efficacy of polyacrylamide to remove microorganisms from irrigation runoff and from wastewater streams treated with polyacrylamide (Sojka and Entry, 2000; Entry and Sojka, 2000).

In contrast, untreated soil in the irrigation furrows was very poorly aggregated. These images show the paucity of organic material, or muscilages, available for binding of primary mineral particles in these soils. The predominate grain sizes in the images are silt and sand-sized particles. There is some evidence of mineral smears and flakes that may be carbonate salts or other transient mineral residues, whose binding effectiveness varies with water content. However, there was little evidence of durable particle adhesion or binding, via visible organic or mineral compound bridging, or any other soil aggregating mechanisms. The soil surface seals without PAM treatment had submicrostructures that would be prone to slaking and dispersion in the irrigation stream. This is consistent with the amount of irrigation-induced erosion and sediment runoff observed from untreated furrows, commonly 5 to 50 ton ha^{-1} y^{-1} soil losses (Lentz, and Sojka, 1996; Zhang and Miller, 1996). Seasonal erosion control of about 80% from PAM treatments on irrigated farm fields in the Pacific Northwest has been reported by Sojka et al. (2000).

Summary and Conclusion

Surface soil submicrostructures of PAM-treated and untreated irrigation furrows on a Portneuf silt loam were assessed by scanning electron microscopy. PAM-treated soil seals had semi-continuous net or web-like coatings of polymer on, and bridging between, mineral particles. This contrasted with poorly aggregated particles on untreated soil seals. Thin (about 1 μm), porous, surface soil veneers of protective polyacrylamide coatings accounted for soil stabilization against furrow irrigation erosion and improved infiltration rates. Unstable soil microstructures of surface soil seals on untreated furrows accounted for slaking and dispersion under irrigation, which leads to erosion losses and reduced infiltration rates.

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