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IRRIGATING WITH POLYACRYLAMIDE (PAM) - NINE YEARS AND A MILLION ACRES OF EXPERIENCE

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ABSTRACT

Polyacrylamide (PAM) has been available commercially since 1995 for reducing irrigation-induced erosion and enhancing infiltration. The first series of practical field tests was conducted in 1991. PAM used for erosion control is a large water soluble (non-crosslinked) anionic molecule (12-15 megagrams per mole) containing < 0.05% acrylamide monomer. In controlled field studies PAM eliminated, on average, 94% (80-99% range) of sediment loss in field runoff from furrow irrigation, with a typical 15-50% relative infiltration increase on medium to fine textured soils compared to untreated controls. Similar but less dramatic results have been seen with sprinkler irrigation. Under some conditions infiltration is unchanged or can even be slightly reduced, e.g. in sandy soils or where PAM application rates are very high. Results are achieved with per irrigation field application rates of about 1 kg per hectare, for furrow irrigation, and 2 to 4 kg per hectare for sprinkler irrigation. Cost of PAM is $7 to $13 per kg. Seasonal application totals vary from 3 to 7 kg per hectare. Farmer field sediment control has been around 80% of test plot results. Substantial runoff reductions have been documented for nutrients, pesticides, microorganisms, BOD, and weed seed. No adverse effects have been seen for soil microbial populations. Crop yields have not been widely documented, though evidence exists for yield increases related to infiltration improvement. High effectiveness, low cost, and ease of application, compared to traditional conservation measures, has resulted in rapid technology acceptance in the US and internationally. PAM-use for runoff water quality protection is one of the most potent new irrigation environmental technologies in the market place. New uses in construction and dryland erosion control are being developed rapidly. This paper discusses new insights and understanding of PAM-use and potential for future developments.

Keywords. Irrigation, Water quality, Erosion, Polymers, Pollution, Surface sealing, Infiltration

Introduction: In the early 1990s, water soluble polyacrylamide (PAM) was found to be an environmentally safe and highly effective erosion-preventing and infiltration-enhancing polymer when applied in very dilute concentration to furrow irrigation water (Lentz et al., 1992; Lentz and Sojka, 1994; McCutchan et al., 1994; Trout et al., 1995; Sojka and Lentz, 1997; Sojka et al., 1998a,b). PAM works by stabilizing soil surface structure and pore continuity. In 1995 NRCS published a PAM-use conservation practice standard (Anonymous, 1995) that will be available in revised form by 2000. The standard gives considerations and methodologies for PAM-use. Commercial sale of erosion-preventing PAMs began in 1995. About 400,000 ha were PAM-treated in the U.S. in 1999. Interest in and adoption of the practice is also growing outside the U.S. Key aspects of the PAM technology are presented below.

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Polymers were used in World War II to stabilize soil structure and hasten construction under sub-optimal conditions (Wilson and Crisp, 1975). The idea was adapted for agriculture in the 1950s (Weeks and Colter, 1952). The literature of polymeric soil amendments is extensive. Early agricultural use of PAM and other conditioners was aimed at preventing soil physical problems by stabilizing aggregates in the entire tilled zone, thereby improving plant growth. This required hundreds of kilograms per hectare of PAM applied via multiple spray applications and tillage operations. The high material and application costs limited PAM-use to high value crops, nursery operations, etc. By the 1980s polymer cost was less and polymer formulations and purity had improved. Two papers had noted reduced sediment in runoff when irrigating furrows after pretreatment with PAM (Paganyas, 1975; Mitchell, 1986). A practical low-rate application strategy for economical PAM-use to control irrigation-induced erosion was reported by Lentz et al. (1992). By greatly reducing sediment in return flows, significant environmental benefit resulted from the associated improvement of off-site water quality components. The reduction in erosion and increased infiltration in fine and medium textured soils has also provided an opportunity to reconsider several aspects of furrow and sprinkler irrigation management. PAM applied in irrigation water is irreversibly adsorbed by the first few millimeters of soil encountered during infiltration (Malik et al., 1991). Thus, PAM delivery in furrow irrigation streams is very efficient. PAM needs only stabilize the thin veneer of soil active in the erosion process. Whereas, earlier strategies of stabilizing plow-layer soil structure required treatment of 30 to 40 cm of soil depth across the entire field area. Furrow irrigation application of PAM treats only about 25% of the field surface area to a few millimeters depth. Thus, high efficacy is achieved with only 1-2 kg ha^{-1} of PAM applied per irrigation.

Erosion: PAM's floccule-forming and erosion-preventing abilities in irrigation water result from its attraction to soil particle surfaces, mainly via coulombic and Van der Waals forces. This helps stabilize soil structure against shear-induced detachment by enhancing particle cohesion, thereby preventing transport in runoff. The few particles that detach, are quickly flocculated by PAM, rapidly settling from the transport stream. Presence of Ca^{++} in the water helps shrink the ionic electrical double layer surrounding soil particles and bridges the negatively charged surfaces of soil particles and PAM molecules, enabling flocculation (Wallace and Wallace, 1996).

Use of PAM in furrow irrigation, following the NRCS application standard (Anonymous, 1995), reduced runoff water sediment by 94% in 3 yrs of studies (Lentz and Sojka, 1994). The 1995 NRCS standard calls for dissolving 10 g m^{-3} (10 ppm) PAM in furrow inflow water during the advance phase of the irrigation-- typically the first 4 to 6 hrs of a 24 hr irrigation in production-sized fields. PAM dosing is halted when runoff begins. The PAM applied during advance generally prevents erosion throughout a 24 hr irrigation. Net application amounts that result are typically 1 to 2 kg ha^{-1}. Lentz and Sojka (1999) reported that when applying PAM at a uniformly dosed inflow concentration, the effectiveness of PAM for controlling erosion or increasing infiltration varied with inflow-rate, PAM concentration, duration of furrow exposure, and total amount of PAM applied. They showed that on 1 to 2% slopes erosion control was comparable among three methods: 1) the NRCS standard, 2) application of 5 g m^{-3} during advance followed by 5 to 10 minutes of 5 g m^{-3} re-application every few hours, or 3) continuous application of 1 to 2 g m^{-3}. However, constant application of 0.25 g m^{-3} was about a third less effective at controlling erosion. Whether the PAM concentration in the irrigation stream was achieved by dissolving dry PAM granules or by using emulsified PAM liquid formulations to dose the water had no substantial effect on erosion control. An application strategy that has become popular with farmers is the "patch" application method. The patch method involves spreading dry PAM granules on an area-equivalent rate basis (based on furrow spacing and length) in the first meter of furrow below the inflow point. When water flows over this "patch" of dry granules, they gel into a thin mat that slowly dissolves during the course of the irrigation. Field-wide erosion and infiltration effects of the patch method are comparable to the NRCS standard approach of dosing at a set concentration in the advance stream (Sojka and Lentz, unpublished data); residual erosion control for subsequent non-treated irrigations is generally better with patch application than for flow dosing, since small areas of the patch are often still intact at the end of the treated irrigation, and these areas can provide small amounts of PAM in subsequent re-irrigations. The NRCS approach of advance flow dosing and the patch method each have advantages and disadvantages depending on specific field conditions and system requirements (Sojka et al., 1998c).

For effective seasonal erosion control, PAM treatment is recommended whenever soil is disturbed (loose and highly erodible) before irrigation. This includes pre-planting or pre-plowing irrigation. Using the NRCS standard method of dosing the advance flow, if soil is undisturbed between irrigations and PAM is not re-applied after an initial PAM-treated irrigation, erosion control from the residual PAM alone, is typically half as effective as retreatment with PAM. Erosion in subsequent irrigations can usually be controlled with less than 10 g m^{-3} PAM if the 10 g m^{-3} rate was used in the initial irrigation, e.g. using 5 g m^{-3} PAM in later treated irrigations (Sojka et al., 1998b). Farmers and NRCS in the Pacific Northwest report that about 80% seasonal erosion control is common on farm fields, where irrigation of newly formed furrows (disturbed soil) is PAM-treated at 10 g m^{-3} or using the patch method, but remaining irrigations of undisturbed previously irrigated furrows receive no additional PAM or are treated at lower rates. Seasonal PAM application amounts by farmers have typically been 3 to 5 kg ha^{-1} depending on field conditions and crop (thus, number of cultivations and irrigations).

Advance and Infiltration : The advance of furrow irrigation streams in fine or medium textured soils is often slowed when PAM is in the water, especially for the initial irrigation on freshly formed or cultivated furrows (Sojka et al., 1998a,b). This occurs because the infiltration rate of PAM-treated furrows is usually higher compared to untreated furrows in fine or medium textured soils. In medium and fine-textured soils surface seals form on untreated furrow bottoms due to the destruction of soil aggregates with rapid wetting, and the detachment, transport and redeposition of fine sediments in the furrow stream. Net infiltration on freshly formed PAM-treated furrows in silt loam soils is typically 15% more when irrigating with PAM-treated water. For soils with higher clay contents, comparative infiltration increases can be as high as 50% (Sojka et al., 1998a). Pore continuity is better maintained when aggregates are stabilized by PAM. This was demonstrated by Sojka et al. (1998a), who reported that infiltration at 40 mm soil water tension varied among irrigations over a range of 12.9 to 31.8 mm hr^{-1} for controls and 26.7 to 52.2 mm hr^{-1} for PAM-treated furrows and that infiltration at 100 mm tension varied from 12.3 to 29.1 mm hr^{-1} for controls and 22.3 to 42.4 mm hr^{-1} for PAM-treated furrows. Bjorneberg (1998) reported that PAM macro-scale effects on viscosity in solution delivery tubes greater than 10 mm in diameter are negligible at water temperatures between 15 and 30 C. Macro viscosity does not begin to rise until PAM concentration rises above about 400 g m^{-3}. However, in small soil pores, apparent viscosity increases are significant, even for the dilute PAM concentrations used for erosion control (Malik and Letey, 1992). PAM infiltration effects are a balance between prevention of surface sealing and apparent viscosity increases inside small soil pores. In fine textured soils, the more significant effect is the maintenance of pore continuity achieved by aggregate stabilization. In coarse textured soils, however, where little porosity enhancement is achieved with PAM, there have been reports of no infiltration effect or even slight infiltration decreases with PAM, particularly at higher PAM application rates (Sojka et al., 1998a). It follows that infiltration enhancement is more transitory for furrows formed on wheel-tracks than on non-wheel track furrows (Sojka et al., 1998b). Reduced surface sealing with PAM improves infiltration only until repeated wetting and drying begin to disrupt subsurface aggregates and/or deliver enough surface-derived fines to seal the few remaining subsurface pores which have already been partially reduced by compaction. Because PAM prevents erosion of furrow bottoms and sealing of the wetted perimeter, lateral water movement increases about 25% in silt loam soils compared to non-treated furrows (Lentz et al., 1992; Lentz and Sojka, 1994). This can be a significant water conserving effect for early irrigations. We have encouraged farmers to take advantage of PAM's erosion prevention properties to improve field infiltration uniformity. This can be done by doubling or tripling inflow rates, thereby reducing infiltration opportunity time differences between inflow and outflow ends of furrows (Sojka and Lentz, 1997; Sojka et al, 1998b). Once runoff begins, the higher initial inflows must be reduced to a flow rate that just sustains the furrow stream at the outflow end of the field. Initial observations suggest that coupling PAM with surge flow irrigation can be a beneficial irrigation practice (Bjorneberg and Sojka, unpublished data). With PAM in the water, enough sealing of the furrow occurs between surges to accelerate advance (although less than controls). However, the upper-field scouring associated with doubled flows (as is typical when surge valves are used) does not occur.

Sprinklers : The effect of PAM applied to soil via sprinkled droplets has been studied in laboratories on small trays (Ben Hur et al., 1989; Levy et al., 1992). Interest in using PAM for sprinkler irrigation is increasing, not as much for concern over erosion as because of PAM's potential to prevent runoff/runon problems and ponding effects on stand establishment and irrigation uniformity. Precision sprinkler-application of water and chemicals can benefit greatly by enabling infiltration exactly where water drops hit the soil, ensuring that water and chemical distribution are uniform. In large soil box studies, PAM application rates of 2 to 4 kg ha^{-1} reduced runoff 70% and soil loss 75% compared to controls (Aase et al., 1998). Effectiveness of sprinkler-applied PAM is less dramatic and more variable than for furrow irrigation because of spatial variations in water drop energy, rate of water and PAM delivery, and water/PAM application timing scenarios inherent in sprinkler systems (Aase et al., 1998; Levin et al., 1991; Smith et al., 1990). Ben Hur and Keren (1997) reported that PAM deposition was greatest on outer extremity of large aggregates. The effectiveness of PAM to prevent aggregate destruction becomes more apparent as drop impact energy increases (Levin et al., 1991; Smith et al., 1990). Flanagan et al. (1997a,b) reported increased infiltration when sprinkling water containing 10 g m^{-3} PAM, attributing the results to reduced surface sealing. Water drop impact and splash break down aggregates and seal 100% of a sprinkled soil surface (vs. about 25% with furrow irrigation). Thus, PAM effects under sprinkler irrigation have been more transitory, less predictable and have usually needed higher seasonal application totals for efficacy. However, farmers with sprinkler infiltration uniformity problems due to runoff or runon, e.g. with center pivots on steep or variable slopes, have begun to use PAM. Studies continue in order to document testimonial claims that PAM improves stands because of reduced ponding, crusting and damping off under sprinklers.

PAM Formulations: The terms *polyacrylamide* and the acronym *"PAM"* are generic chemistry vocabulary, referring to a broad class of compounds. There are hundreds of specific PAM formulations, depending on polymer chain length and the number and kinds of functional group substitutions along the chain. In erosion polyacrylamides, the PAM homopolymer is copolymerized. Spliced chain segments replace PAM amide functional groups with ones containing sodium ions or protons that freely dissociate in water to provide negative charge sites (fig. 1). In figure 1, chain segment X is the acrylamide formulation and segment Y indicates a dissociated altered segment leaving a negative charge site. In one of the most common classes of erosion-preventing PAM, one in five segments provide a charged site in this manner. The PAM formulations now used in irrigated agriculture are water soluble non-crosslinked (not gel-forming, not cross-linked super water absorbent) anionic polymers with typical molecular weights of 12 to 15 Mg $mole^{-1}$ (about 150,000 monomer units per molecule). These compounds are "off the shelf" polymers used as industrial flocculents. They are used extensively to hasten separation of solids from aqueous suspensions in sewage sludge dewatering, mining, paper manufacture, food processing and as a sticking agent in animal feed preparations. The choice of large anionic PAM conformations is largely for environmental and safety considerations (discussed below). Lentz et al. (2000a) reported that these properties also favored erosion control. They compared molecular weights of 4 to 7, 12 to 15, and 14 to 17 Mg

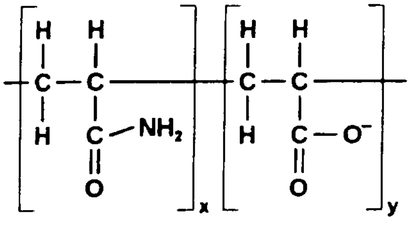

Figure 1 PAM Copolymer

mol^{-1}, neutral, positive and negative charges, and charge densities of 8, 19, and 35 %. The order of erosion control effectiveness in new furrows was anionic > neutral > cationic PAMs. Efficacy increased with charge density and molecular weight. Infiltration was favored, however, by lower molecular weights and medium to high charge density. Neutral and anionic PAMs enhanced infiltration over cationic PAMs. Charged PAMs increased infiltration of freshly formed furrows, but slightly decreased infiltration on re-irrigated furrows later in the season; neutral PAMs did not show this late season infiltration decrease on re-irrigated furrows.

Commercial anionic PAM products of moderate molecular weight are usually of two types. The most common product is a dry fine granular form. The granules are dissolved in water or sprinkled in a dry patch on the furrow bottom near the inlets before water is let down the furrow. The second formulation is a concentrated liquid emulsion of PAM and mineral spirits. This also includes "inverse emulsions" that contain a surfactant to help disperse the PAM when mixed with water. Emulsions are more commonly used with sprinkler than furrow irrigation. Both granular materials and emulsified concentrates require substantial turbulence or agitation and high flow rate at the point of addition to water in order to dissolve PAM to a target concentration. Detailed considerations for use are available on the website <http://kimberly.ars.usda.gov/pampage.ssi>.

Recent Findings: Broad categories of microorganisms carried across and among furrow-irrigated fields by furrow streams, runoff and return flows are also reduced by PAM in irrigation water (Sojka and Entry, 2000; Entry and Sojka, 2000). Similar reductions occur for weed seed in runoff (Sojka and Morishita, unpublished data). A recent study that measured water, nitrate and herbicide transport beyond the crop root zone, found that PAM-managed furrow irrigation did not affect field-wide season-long water and solute drainage losses, relative to non-treated furrows, when identical amounts of water were in all treatments but PAM treated furrows had doubled inflow rates until runoff initiation, followed by cutback irrigation (Lentz et al., 2000b). Studies in Australia, comparing the reductions of nutrients and pesticides among furrow irrigated cotton employing conventional tillage, conservation tillage or PAM found the greatest reduction of nutrients and pesticides in the PAM treated fields (Waters et al., 1999a,b). These new findings further underscore the enormous potential for directly improving water quality of irrigation return flows and point to potential management improvements via PAM-use that may ultimately help reduce pesticide use. Promising new research has begun investigating classes of copolymers synthesized from organic byproducts of crop agriculture and shell fish processing which may supplement PAM for certain uses where enhanced biodegradability is needed or where bio-based chemistry is a perceived environmental benefit (Orts et al., 1999, 2000).

Environment and Safety: Environmental and safety considerations of anionic PAMs have been thoroughly reviewed (Barvenik, 1994; Bologna et al., 1999; Seybold, 1994). The single most significant result of PAM use in the environment is its huge capacity to prevent erosion and improve surface water quality by reducing contamination of surface waters with sediment and other contaminants washed from eroding fields. PAM greatly reduces nutrients, pesticides, and biological oxygen demand of irrigation return flows (Agassi et al., 1995; Lentz et al., 1998). There are some specific environmental issues related to PAM charge type and PAM purity.

Cationic and neutral PAMs have toxicities warranting caution or preclusion from sensitive environmental uses, whereas anionic PAMs are safe when used at prescribed rates. Anionic PAM is specified by NRCS for controlling irrigation-induced erosion. Anionic PAMs are used extensively for potable water treatment, for dewatering sewage sludge, washing and lye pealing of fruits and vegetables, clarification of sugar juice and liquor, in adhesives and paper in contact with food, as thickeners and suspending agents in animal feeds, in cosmetics, for paper manufacturing, for various mining and drilling applications and various other sensitive uses. Negative impacts have not been documented for aquatic macrofauna, edaphic microorganisms, or crop species for PAM applied at recommended concentrations and rates Kay-Shoemake (1998a,b).

When PAMs are introduced (even at potentially harmful concentrations) into waters containing sediments, humic acids or other impurities, PAM effects on biota are greatly buffered due to PAM adsorption and deactivation associated with the suspended impurities (Buchholz, 1992; Goodrich et al., 1991). Loss of PAM into runoff and return flows was studied by Lentz et al. (1996). They developed a sensitive assay for PAM in irrigation water and determined that, because of PAM's high affinity for suspended sediments and soil in waste ditch streams, only 3-5% of the PAM applied left fields in runoff; furthermore, lost PAM only traveled 100 to 500 meters in waste ditches before being completely adsorbed on sediments in the flow or onto ditch surfaces (Lentz and Sojka, 1996). Ferguson (1997) reported on a watershed scale PAM test, where 1,600+ ha were irrigated using PAM-treated water for two weeks. On any given day, about half of the 40 farms in the study contributed runoff to the watershed's drainage, which collected in Conway Gulch, a tributary of the Boise River. Waste water from fields and the drain was analyzed for P, sediment, and PAM. About half of the water in the drain was field runoff. PAM was not found detrimental to the drain's water quality. PAM was detected in drainwater samples only twice (<0.8 g m^{-3}) during the entire monitoring exercise. PAM was found to be an effective sediment control practice that was well adopted by farmers and did not negatively impact the drain.

Another important environmental and applicator safety consideration is the need to use PAMs that contain <0.05% acrylamide monomer (AMD). AMD is a neurotoxin, but PAMs containing <0.05% AMD are safe, used as directed at low concentrations. In soil, PAM degrades at rates of at least 10% per year as a result of physical, chemical, biological and photochemical processes and reactions (Tolstikh, et al. 1992; Wallace et al. 1986; Azzam et al. 1983). PAM does not revert to AMD upon degradation (Mac Williams, 1978). Furthermore, AMD is metabolized by microorganisms in soil and biologically active waters, with a half life in tens of hours (Lande et al, 1979; Shanker et al., 1990). Bologna et al. (1999) showed that AMD is not absorbed by plant tissues, and apparently breaks down rapidly even when injected directly into living plant tissue. While the anionic PAMs used to control erosion are not toxic, overexposure can result in skin irritation and inflamation of mucus membranes. Users should read label cautions and take reasonable care not to breathe PAM dust and to avoid exposure to eyes and other mucus membranes. PAM spills become very slippery if wet. PAM spills should be thoroughly cleaned with a dry absorbent and removed before attempting to wash down with water. Do not apply PAM on or near roads. Practical user considerations are numerous. Labels, website, ARS and extension information should be consulted before embarking upon large scale use of PAM.

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