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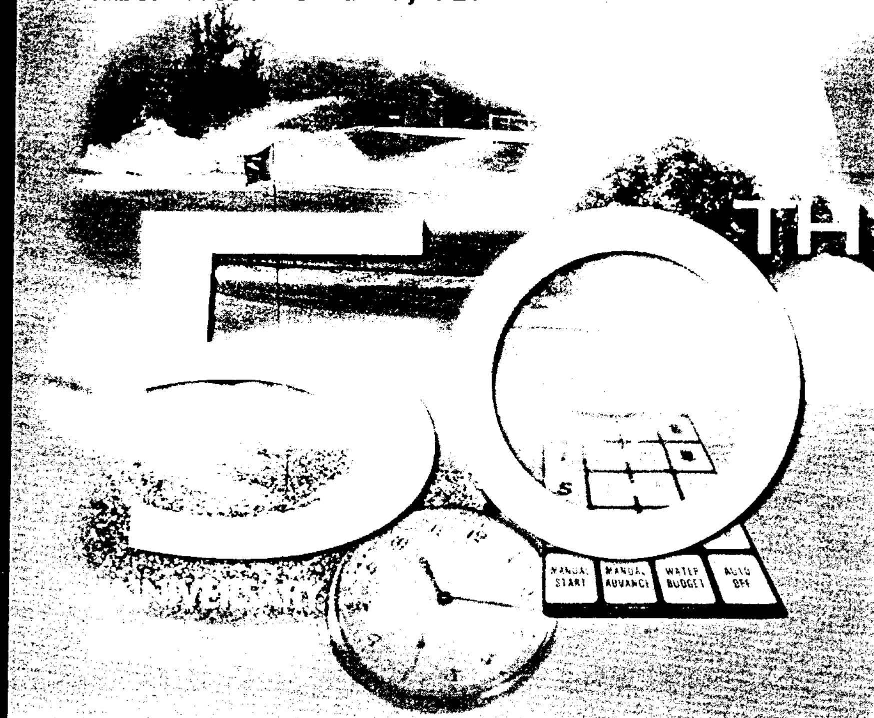

IRRIGATION ASSOCIATION

Polyacrylamide (PAM) - A One Million Acre Progress Report

R.E. Sojka[1], R.D. Lentz, D.L. Bjorneberg, J.K. Aase, J. Entry, D. Morishita, C.W. Ross and T. Trout

Water soluble polyacrylamide (PAM) was recognized in the early 1990s as an environmentally safe and highly effective erosion-preventing and infiltration-enhancing chemical, when applied in very dilute concentrations in 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). The mode of action involves surface soil structure stabilization and maintenance of pore continuity. A recommended conservation practice standard was published by NRCS in 1995 (Anonymous, 1995) and is being revised in 1999. It delineates considerations and specifies methodology for PAM-use. Commercial sales of erosion-preventing PAMs began in 1995. Approximately one million acres were treated in the United States in 1999. Extent of adoption of the practice outside the US is less certain, but interest is growing in several countries and continents. Key aspects of this PAM technology development are presented below.

Polymers were used in World War II for soil structure stabilization to hasten construction under sub-optimal conditions (Wilson and Crisp, 1975). The concept was adapted for agricultural use in the 1950s. The resulting literature of soil amendments is extensive. Early use of PAM and similar stabilizers sought to improve plant growth and prevent soil physical problems by stabilizing aggregates in the tilled zone. This required applying hundreds of pounds per acre of PAM via multiple spray applications and tillage operations. The high application rate requirement (cost), largely limited PAM use to high value crops and production systems such as nurseries. By the mid 1980s polymer costs had dropped and polymer formulations and purity had improved. Two cursory observations had noted greatly reduced sediment loss in runoff from soils irrigated with water containing small amounts of PAM (Paganyas, 1975; Mitchell, 1986). Development of an application strategy for practical and economical PAM use to control irrigation-induced erosion (Lentz et al., 1992) has opened the door for significant environmental benefit and provided an opportunity to greatly change several aspects of irrigation management.

PAM applied in irrigation water is irreversibly adsorbed onto the first few millimeters of soil encountered during infiltration (Malik et al., 1991). Because irrigation water itself is the application mechanism, delivery is highly efficient, PAM having only to stabilize the thin veneer of soil active in the erosion process. In contrast, stabilizing the plow-layer soil structure requires that the surface six to eight inches of soil depth across the entire field area be treated with PAM. Furrow irrigation application of PAM only treats about 25% of the surface area to a depth of about 1/16th of an inch. Thus high efficacy is achieved at only 1-2 lbs per acre of PAM applied per irrigation.

PAM Formulations: The terms *polyacrylamide* and *PAM* are generic terms, referring to a broad class of compounds. There are hundreds and perhaps thousands of specific PAM formulations, depending on polymer chain length and number and kinds of functional group substitutions along the

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[1]USDA Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793N-3600 East, Kimberly, ID 83341 Phone 208-423-5582, FAX 208-423-6555; Email <sojka@kimberly.ars.pn.usbr.gov>

chain. In erosion polymers, the PAM homopolymer is copolymerized. Spliced chain segments replace PAM amide functional groups with functional groups containing sodium ions or protons that 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. Typically one in five segments provide a charged site in this manner. The polyacrylamide formulations now used in irrigated agriculture are water soluble non-crosslinked (not gel-forming or cross-linked super water absorbent forms) anionic polymers with typical molecular weights of 12 to 15 Mg $mole^{-1}$ (or 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, and food processing and as a sticking agent in animal feed preparations.

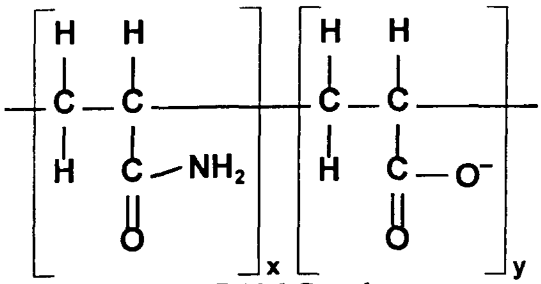

Figure 1 PAM Copolymer

Commercial PAM products available to farmers are most often of two types. The most commonly used product is a dry fine granular form of PAM, which is dissolved in water inflows or sprinkled in a dry patch on the ground near furrow inlets before water is let into the furrow. The second broad category of product formulation is a concentrated liquid emulsion of PAM and mineral spirits in aqueous suspension. These also include "inverse emulsions" that contain surfactant to help disperse the PAM when mixed with water. Emulsion formulations are more commonly used with sprinkler PAM application than in furrow irrigation (see below). Both granular materials and concentrates require substantial turbulence or agitation and high flow rate at the point of addition to water when attempting to dissolve PAM to reach a desired concentration. Detailed use considerations are given in several USDA-ARS Kimberly, ID publications and presentations accessible on the website <http://kimberly.ars.usda.gov/pampage.ssi>.

Erosion-fighting effectiveness in Furrow Irrigation: PAM's effectiveness as a flocculent and erosion-preventing irrigation water additive is due to its affinity for soil particles, largely via coulombic and Van der Waals attraction. These surface attractions enhance particle cohesion, stabilizing soil structure against shear-induced detachment and transport in runoff. If detachment does occur, PAM rapidly flocculates and settles particles from the transport stream. Since soil is negatively charged, attraction to negatively charged PAM requires scant amounts of divalent cations in the soil water, or in the water delivering PAM, to shrink the electrical double layer and bridge negative soil and PAM charge sites, thus enabling flocculation (Wallace and Wallace, 1996).

Careful use of PAM following the NRCS application standard (Anonymous, 1995) reduced runoff water sediment 94% in 3 yrs of studies (Lentz and Sojka, 1994). The 1995 NRCS standard calls for dissolving 10 ppm PAM in furrow inflow water as it first traverses a field (water advance), only. PAM addition is halted when runoff begins. The PAM adsorbed on the soil surface during the advance (typically the first 4-6 hrs of irrigation in production-sized fields) prevents erosion throughout a 24 hr irrigation. Amounts applied using this approach are typically 1-2 lbs/acre. PAM treatment is recommended whenever soil is disturbed before irrigation. If soil is undisturbed and no PAM is re-applied after an initial PAM-treated irrigation, erosion control is typically half, compared to the 2nd of two non-treated irrigations. Erosion control in subsequent irrigations can usually be maintained with less than 10 ppm PAM if the initial irrigation used the 10 ppm rate, e.g. using 5 ppm

PAM in the 2nd treated irrigation. In the Pacific Northwest, farmers and NRCS report that about 80% erosion control is common on farmers fields, where irrigation of disturbed soil is PAM-treated at 10 ppm but remaining irrigations of undisturbed soil are treated at lower rates. Seasonal PAM application amounts by farmers have typically been 3-5 pounds per acre depending on field conditions and crop (thus, number of cultivations and irrigations).

Advance Rate and Infiltration Effects: The advance rate of furrow irrigation streams is often slowed by PAM-use; this is particularly true for the first irrigation on newly formed or freshly cultivated furrows (Sojka et al., 1998a). Slower advance results from the higher infiltration rate of PAM-treated furrows compared to untreated furrows. Surface seals formed without PAM have low infiltration rates due to breaking of aggregates and dispersion of fine soil particles that plug soil pores. Pore continuity is better maintained when aggregates are stabilized by PAM. PAM macro-scale effects on viscosity-increase in solution delivery tubes greater than 10 mm in diameter are negligible at water temperatures between 15 and 30 C and until PAM concentration rises above about 400 ppm (Bjorneberg, 1998). However, apparent viscosity increases are significant in soil pores, 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 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). For much the same reason, infiltration enhancement is more transitory for furrows formed on wheel-tracks than on non-wheel track furrows (Sojka et al., 1998b). With PAM preventing erosion of furrow bottoms and sealing of the wetted perimeter, lateral water movement has been shown to increase about 25% compared to non-treated furrows, which can be a significant water conserving effect for early irrigations (Lentz et al., 1992; Lentz and Sojka, 1994). Farmers are usually advised to take advantage of PAM's ability to prevent erosion by increasing inflow rates two to three fold (compared to normal practices), thereby reducing infiltration opportunity time differences between inflow and outflow ends of furrows, and achieving more uniform water application rates (Sojka and Lentz, 1997; Sojka et al, 1998b). For greatest effectiveness, this practice must be coupled with flow rate reduction to least sustainable flow rates once runoff begins. For similar reasons coupling of PAM with surge flow irrigation appears to be a promising irrigation practice (Bjorneberg and Sojka, unpublished data).

Sprinkler Irrigation: Most studies of PAM applied through sprinklers have been bench-top studies or larger soil-box sprinkler studies (Ben Hur et al., 1989; Levy et al., 1992). Interest in use of PAM for sprinkler irrigation is increasing. Prevention of runoff/runon and ponding effects on stand establishment and the role of irrigation uniformity for precision sprinkler-application of water and chemicals is driving the interest more than erosion effects. In large soil box studies, PAM application rates as low as 2-4 lbs per acre reduced runoff 70% and soil loss 75% compared to controls (Aase et al., 1998). Effectiveness of PAM applied through sprinklers, however, is less dramatic and more variable than for furrow irrigation because of great differences in possible application strategies and system variables that affect water drop energy, the rate of water and PAM delivery, and possible application timing scenarios (Aase et al., 1998; Levin et al., 1991; Smith et al., 1990). Research has shown that only outer surfaces of large aggregates are stabilized by sprinkler applied PAM (Ben Hur and Keren, 1997), making PAM effectiveness compared to controls higher as drop impact energy increases (Levin et al., 1991; Smith et al., 1990). Flanagan et al., (1997a,b) found increased infiltration when sprinkling water at 10 ppm PAM, and attributed their results to reduced surface sealing. Because of water drop impact effects on surface sealing and the reality of treating 100% of the soil surface (as opposed to about 25% with furrow irrigation) PAM effects under sprinkler irrigation have proven more transitory, less predictable and often needing higher seasonal application totals for efficacy. Nonetheless, farmers who have concerns about water infiltration uniformity and runoff/ runon, particularly under center pivots and on variable slopes have begun to embrace the practice.

Environmental and Safety Considerations: Environmental and safety considerations of anionic PAMs have been thoroughly reviewed (Barvenik, 1994; Bologna et al., 1999; Seybold, 1994). Cationic PAMs and neutral PAMs can have toxicities warranting caution or preclusion from sensitive environmental uses. Anionic PAMs, the type specified by NRCS for controlling irrigation-induced erosion, are used extensively in the US for potable water treatment, for dewatering of 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. No significant negative impacts have been documented for aquatic, edaphic microorganisms, or crop species for PAM applied at recommended concentrations and rates Kaye-Shoemake (1998a,b). It should be noted that even at potentially harmful rates, when PAMs are introduced into waters containing sediments, humic acids or other impurities, the effects of the PAMs on biota are greatly buffered (Buchholz, 1992; Goodrich et al., 1991). Loss of PAM in runoff and return flows has also been studied. Lentz et al. (1996) developed a new 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 the lost PAM only travelled 300-1700 feet in waste ditches before being completely adsorbed on sediments in the flow or on ditch banks (Lentz and Sojka, 1996).

A second important environmental and applicator safety consideration is the need to use PAMs that contain less than 0.05% acrylamide monomer (AMD). AMD is a neurotoxin, but PAMs with these low AMD contents are entirely safe for sensitive uses when used as directed at low concentrations. PAM degrades in soil at rates of at least 10% per year as a result of physical, chemical, biological and photochemical reactions (Tolstikh, et al. 1992; Wallace et al. 1986; Azzam et al. 1983) and does not revert to AMD upon degradation (Mac Williams, 1978). Furthermore, AMD is readily 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) confirmed a large body of work showing that AMD is not absorbed by plant tissues, and apparently breaks down rapidly even when physically injected 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 reasonable care should be taken to avoid breathing dust and avoid exposure to eyes and other mucus membranes. PAM spills can be exceedingly slippery, especially if wet; PAM spills should be thoroughly cleaned with a dry absorbent and removed before attempting to wash down with water. Practical user considerations are numerous. Labels, website information and ARS and extension information should be consulted before embarking upon large scale use of PAM.

Recent Findings: In addition to reducing erosion and sediment in runoff from irrigated agriculture, PAM has been highly successful for reducing nutrients, pesticides, and biological oxygen demand of irrigation return flows (Agassi et al., 1995; Lentz et al., 1998). Recent research has also documented that broad categories of microorganisms carried across and among fields by runoff and return flows are also reduced by PAM in irrigation water (Sojka and Entry, 1999). Similar reductions occur for weed seed in runoff (Sojka and Morishita, unpublished data). All of these findings underscore the enormous potential for directly improving water quality of return flows as well as pointing to potential management improvements via PAM-use that ultimately may allow reduced use of pesticides. Promising new research has been intiated to investigate new classes of polymers synthesized from organic byproducts of agriculture and shell fish food processing which may supplement PAM for certain uses where enhanced biodegradability is needed or where bio-based chemistry is perceived to be an environmental benefit (Orts et al., 1999a,b)

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