Preventing Soil Erosion with Polymer Additives

William J. Orts[a], Robert E. Sojka[b], Gregory M. Glenn[a] and Richard A. Gross[c]

[a]USDA-ARS, Western Regional Research Center, 800 Buchanan Street, Albany, CA 94710
[b]USDA-ARS, Soil and Water Management Research Unit, 3793 N. 3600E., Kimberly, ID 83341
[c]Department of Chemistry/Chemical Engineering, Polytechnic University, Six Metrotech Center, Brooklyn, NY 11201

Abstract

The agricultural use of polyacrylamide, PAM, as an additive in irrigation water has grown rapidly since commercial introduction in 1995, with over 1 million acres treated in 1998. PAM provides both economic and environmental benefits by improving water infiltration and reducing up to 98% of erosion-induced soil losses — a yearly saving of tons of topsoil per acre. With as little as 5 ppm of PAM in the first irrigation water to run across the field, soil cohesion increases enough to prevent particle detachment and erosion. Stable soil/polymer flocs result from PAM's high molecular weight (typically > 12 million) and its affinity to soil via coulombic and Van der Waals attraction. Although water soluble linear PAM is the only class of commercial polymer presently used to reduce erosion during irrigation, other polymer additives have shown some potential. Biopolymers such as chitosan, starch xanthate, cellulose xanthate, and acid-hydrolyzed cellulose microfibrils reduce shear-induced erosion; however concentrations at least 6–10 times higher than PAM are required to obtain the > 90% runoff sediment reduction shown by commercial PAM. The application of PAM in agricultural irrigation water and potential biopolymer alternatives to PAM are discussed.

Keywords

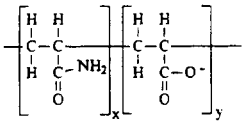
Polyacrylamide, PAM, soil erosion, polysaccharides, Xanthates, Chitosan, starch, cellulose

Introduction

Careful water management and modern irrigated farming techniques have allowed farmers in arid regions to obtain high crop yields on land that would otherwise be relatively unproductive. Considering that only 17% of the world's cropland is irrigated, it is remarkable that irrigated cropland accounts for over 30% of the worlds food crop in volume, and almost half of the world's crop value[1]. With irrigation, however, comes the age-old problem of erosion, a constant threat to agricultural productivity and our environment. For example, soil run-off from fields during furrow irrigation removes valuable topsoil at an average yearly rate of 6.4 tons per acre[2]. Additionally, soil carries residual agricultural chemicals from the fields into downstream waterways or other riparian surface waters. With accumulating evidence that chemical toxins, such as pesticides and herbicides, readily pass from open water into the air[3] there is an increasing need to prevent soil run-off.

Erosion problems are compounded by the fact that arid soils are generally low in the natural polysaccharides and organic acids that stabilize soil structure. Soil with little structure is easily disrupted and carried away by the shearing action of running water. One highly effective solution to this problem is to amend soil structure by adding conditioners, an array of synthetic and naturally derived polymers that improve soil cohesion[4–6]. Research on conditioners since their initial agricultural use in the 50's extended their effectiveness beyond field use to greenhouse applications, roadwork projects, and construction sites[6–8].

Throughout the 1970's and '80's, polyacrylamide or "PAM" emerged as a favored soil conditioner. PAM often refers to the family of polyacrylamide type polymers that include the homopolymer, as well as partially charged copolymers of acrylamide with acrylic acid (scheme 1). In its original mode of application, PAM was generally sprayed onto fields at rates as high as 450–1000 lbs/year and roto-tilled into the surface layer[5]. This technique was not embraced by farmers because of the initial costs of buying so much material. PAM use as a soil conditioner was generally reserved for research efforts, greenhouse work, high value horticultural or nursery crops, or for projects with unrestricted material costs.



Sheme 1 PAM: Poly(acrylamide-co-acrylic acid)

In the early '90's an ideological breakthrough in the use of soil conditioners was introduced — adding small quantities of PAM to the in-flowing water[1,9–15]. Lentz *et al.*[9] reduced soil losses of a highly erodible soil up to 97% by adding 5–20 ppm of

Polymer News, 1999, Vol. 24, pp. 406 – 413
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high molecular weight anionic PAM to irrigation water in the first several hours of irrigation. At these concentrations, polymer use for an acre is approximately 1.5 lb. per irrigation, with seasonal application totals ranging from about 3 to 8 lbs. per acre. This implies quite a saving from the cost of spraying the "entire" tilled surface layer (6 inch depth) of a field with hundreds of lbs per acre of soil conditioner. By adding PAM to the irrigation water, the water itself is the means of delivery; i.e. no extra application methods are required. Consequently, only the soil in contact with irrigation water is treated and is all that needs to be treated (see Figure 1a). For furrow irrigation, this translates to improved soil structure in the 1–5 mm thick layer at the soil/water interface. These several millimeters, however, are most critical in controlling erosion. One additional benefit of PAM is the improved water infiltration rates[16]. In PAM-treated fields, 15 to 50% more water is absorbed into soil sublayers, improving irrigation efficiency[17].

The benefits of PAM have clearly been seen by farmers. Agricultural PAM use has grown from treatment of 20,000 acres in 1995[1] to over 1 million acres in 1998. This represents an agricultural PAM market of ~6million lbs., roughly 2% of the total polyacrylamide market. Although agricultural PAM use was introduced in Idaho, it has proven effective in an increasing number of diverse locations throughout the western US and in several countries overseas.

With such widespread use, application of polymers to irrigation water merits further review. The purpose of this report is to describe the application of soil stabilizing polymers as irrigation water additives. The first part of this review discusses some of the functional attributes of PAM that make it effective in reducing erosion-induced losses and improving infiltration. This is followed by a brief outline of key environmental considerations of PAM use. The final part of this report discusses potential alternatives to PAM for agricultural applications. Since PAM is a synthetic polymer that was not designed to achieve both biodegradability and functional performance, this final section focuses on biodegradable biopolymers. Various biopolymers have potential to impart the primary functional attributes of PAM with the added advantage of more rapid biodegradability.

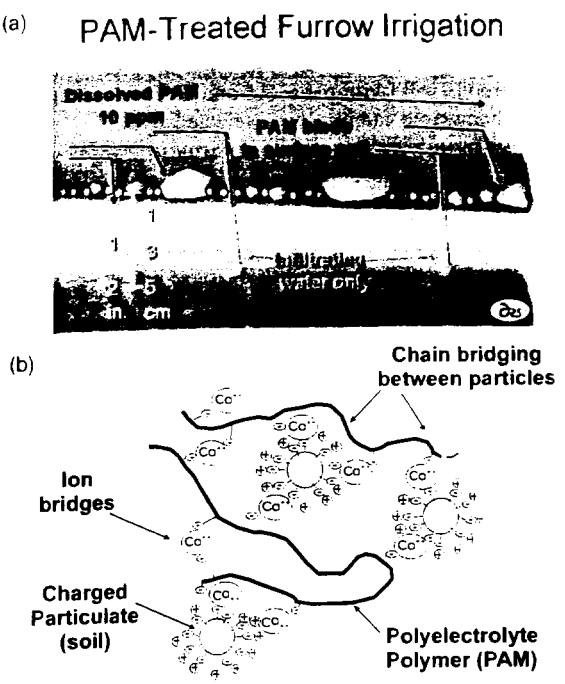


Figure 1 Schematic descriptions of the mechanism of PAM in controlling erosion-induced soil losses (a) at the water/soil interface (according to Sojka et al.1) and (b) at a molecular level. The high molecular weight of PAM molecules allows it to span between particles, while added ions, such as divalent calcium cations, form ionic bridges.

Functional Properties of PAM–Size and Soil Affinity

Typical erosion-preventing PAMs are very large polyelectrolytes, with molecular weights ranging from 12 to 17 million, and negative charge densities of ~18%. As mentioned above, anionic PAM is the random copolymer of acrylic acid with polyacrylamide (scheme 1). The molecular weight and charge of PAM contribute to essential practical characteristics of the molecule, such as size and shape, solubility in water, affinity to soil, and cost.

PAM forms large stable aggregates with soil via several mechanisms including chain bridging, ionic bridging, and charge neutralization (see Figure 1b). Chain bridging can occur for high molecular weight polymers if segments of a single polymer chain can adsorb onto more than one particle[18]. Adsorption can be the result of van der Waals interactions, dipole interactions, hydrogen bonding, or coulombic interactions. To effectively function by the bridging mechanism, the non-adsorbed loops and tails of the molecule must extend far enough into solution to exceed the minimum distance of close approach between the two entities. For charged entities, this distance is the sum of the thicknesses of the electrostatic double layers[19].

For anionic PAMs, chain bridging is affected by the confounding effects of size and charge. Figures 2 and 3 show the effectiveness of PAM in reducing soil run-off as a function of molecular weight (Figure 2) and charge density (Figure 3). Results are from field tests by Lentz and Sojka[20] and lab-scale mini-furrow experiments by Orts *et al.*[21]. Sediment levels in the run-off water (the y-axes) are reported based on a comparison between a polymer-treated furrow with that from a control furrow, one with no added polymer. Trends in Figure 2 show that molecular weight, MW, has a clear effect on sediment reduction of PAM up to at least 200K in the lab-scale experiments, and even higher in the field results. (Each of these samples had an anionic charge density of 18%) Above MW = 6 million, there is little significant improvement in erosion control.

The relative effectiveness of larger PAM molecules highlights the role of chain bridging in forming a stable soil/polymer network at the furrow surface. For PAM, with a molecular weight of 15 million, the stretched end-to-end chain length would exceed 10 microns, allowing it to easily span multiple aggregates in forming a stable network. Polyelectrolytic polymers, such as PAM, have the added advantage that the spatial extension of the loops and tails increases with increasing charge density due to repulsion of like-charged monomers. This increase in size, though, can be offset by the presence of counter ions, which provide shielding between groups. For example, neutron scattering results of 18% anionic, high molecular weight

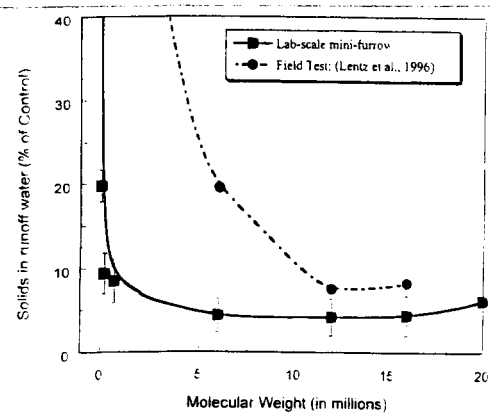


Figure 2 Lab-scale furrow results compared with field test results highlighting the effect of molecular weight on the effectiveness of polyacrylamide, PAM, in controlling erosion-induced soil losses (charge density is ~18% for all samples).

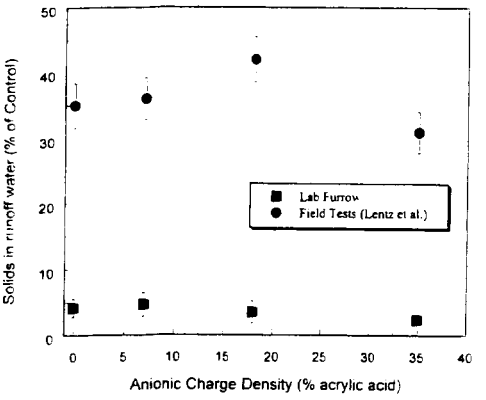


Figure 3 Lab-scale furrow results compared with field test results highlighting the effect of charge density on the effectiveness of polyacrylamide, PAM, in controlling erosion-induced soil losses (molecular weight is ~15million for all samples).

PAM in water shows that the radius of gyration of the chain in water decreases almost linearly with increasing concentration of calcium up to concentrations of over 100mM[22].

Differences between results from lab furrows and field furrows are not surprising, considering the experimental differences between tests. Field tests were run using a highly erodible Portneuf silt loam (coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcid), with furrows 8 inches wide, a slope of 1.5%, a length of 137 m and water flow rates of 6 gal/min[9]. In comparison, lab-scale furrows were roughly 1/100th the size of a full furrow; with lengths of 1.5 m, setting angles of 5°, and water flow rates of 7 mL/min. The lab soil, Zacharias gravelly clay loam soil obtained from Patterson, CA, was chosen specifically because anionic PAM has been particularly effective in controlling its erosion[23]. Despite differences between field tests and lab-scale tests, lab-scale furrows are useful because of the speed in which a wide array of samples and conditions can be preliminarily tested.

Figure 3 is a plot of the effect of the charge density of PAM on erosion control in the same field furrows[20] and lab-scale mini furrows[21] described above. (All of the samples had a MW of approximately 15 million). For either test, there is little significant difference between PAM with different charge density distributions – all work equally well. There are reports[20] that the efficacy of PAM in controlling erosion increases slightly with increasing charge density, but even that effect is subtle.

Clearly, coulombic attraction is not the only mechanism at work, considering how effectively neutral PAM controls soil losses in the field[20] and in lab experiments (represented by the first points of both curves in Figure 3). Such results imply that Van der Waals interactions for these very large polymers are sufficient to stabilize soil/polymer aggregates.

Interestingly, cationic PAM is also effective in reducing soil erosion, with the efficacy of high molecular weight, 20% cationic PAM roughly 85% that of anionic PAM. Cationic PAMs are generally not used because of the environmental concern that they can suffocate fish. Cations can bind with anionic sites on their gills[24-26], thereby impairing oxygen uptake.

Ionic bridging must also play a role in PAM/soil adsorption, considering that anionic PAM binds with soil, which generally consist of mostly negatively charged colloidal particles[27]. In ionic bridging, a divalent cation such as calcium interacts with anionic moieties from both PAM chains and soil. Ionic bridging is implied by the fact that the effectiveness of anionic PAM in reducing erosion losses increases with the addition of calcium[2,5,13,21,25].

Interestingly, reductions in soil runoff have been achieved by adding calcium to irrigation water in the absence of PAM[2,13,21]. An example of this behavior is outlined in Figure 4, in which a highly calcareous soil (with pH = 8.4 and a low concentration of soluble, exchangeable calcium) was selected specifically because it did not respond well to PAM treatment. Calcium alone significantly reduced suspended solids in the runoff from this soil, although PAM and calcium still had a greater effect than

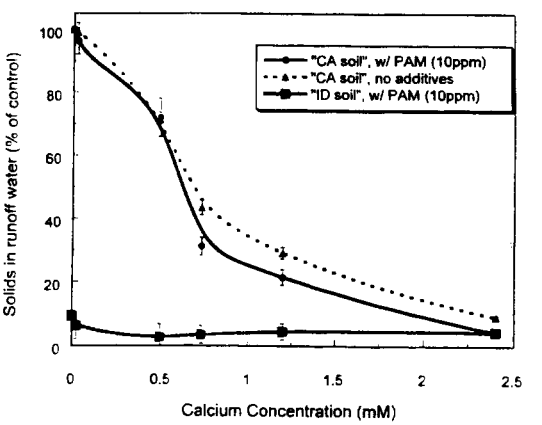


Figure 4 The effect of added calcium on suspended solids in soil runoff from a lab-scale min-furrow test for a Northern California soil low in exchangeable calcium, using water with (●) and without (▲) PAM. In contrast, calcium had little effect on an Idaho soil high in Ca (■). The PAM additive was 18% anionic with MW=16 million.

calcium alone. A similar result was also reported by Wallace and Wallace[15], who noted that exchangeable calcium (gypsum) or other ions that improve electrical conductances also reduce erosion losses in clay-rich soils. The results in Figure 4 extend their results to Northern California soil.

It is clear that calcium, in the form of gypsum or calcium nitrate fertilizer, can be a potential boon for controlling erosion and improving infiltration in soils low in exchangeable divalent base cations[2]. However, there are several notable differences between the application of calcium and polymers such as PAM. Calcium "salts out" sediment in run-off water by charge neutralization and ionic bridging, but it does not provide permanent structure to the soil. Flocs formed in the presence of calcium can be disrupted by bathing with water containing less calcium, in contrast to the more stable PAM/soil flocs. Erosion control by adding calcium alone is not universal, considering that erosion occurs in soil already rich in calcium. For example, in the mini-furrow experiments plotted in Figure 4, calcium reduced erosion in a Northern Californian soil, but had little effect on the Portneuf silt loam soil from Idaho, which is high in calcium carbonates. (see the dotted curve in Figure 4). Finally, the benefit from added calcium is short term – it must be added continuously to the irrigation water. In contrast, PAM can be added for a short time at the start of an irrigation series, and can often stabilize the furrow surface structure for weeks without additional doses[30]. It is apparent that calcium is most effective in soils or waters low in exchangeable calcium, such as found in parts of Northern California. These results suggest that calcium and polymer treatments in tandem may improve erosion control[13,21].

Environmental Issues Related to PAM in Irrigation Water

The successful use of PAM in irrigation water to reduce erosion and improve infiltration raises questions of its environmental impact and whether it is the "best" polymer for the application. PAM has been used industrially for decades – as a soil conditioner, for various food processing applications, to dewater sewage sludges, to remove heavy metals during potable water treatment, and to process industrial wastewater[26]. PAM is widely recognized as a safe, cost-effective flocculating agent.

Yet, environmental concerns have been raised about the widespread use of PAM in open agricultural environments; concerns that have been consistently countered by Soil Scientists studying PAM. PAM is a synthetic polymer that was designed to resist degradation, so long term accumulation is a possibility. Previously published research has suggested that environmental degradation rates are less than 10% per year via deamination, shear-induced chain scission and photosensitive chain scission[24,25,31-34]. It should be noted that these estimates were obtained under far less degradative environmental conditions than prevail in the surface few millimeters of soil, where PAM is predominately applied in the new technology. However, with the scant literature available, and with such stability indicated from early studies, concern has been expressed about accumulation[25]. This concern is unfounded if PAM is used at the low concentrations recommended by the USDA[35], i.e. 10 ppm in irrigation water flowing down the furrow in the first several hours. Applied under such guidelines, PAM does not leave the field in the runoff nor accumulate appreciably with time. For example, Figure 5 is a plot of the PAM buildup in soil applied constantly for 18 years

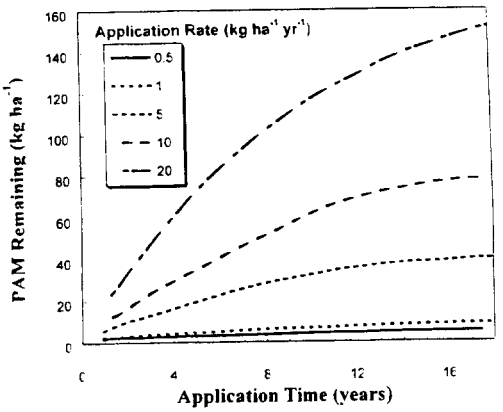


Figure 5 PAM buildup in soil over a period of time at different application rates.

for five different application rates, assuming a rate of degradation of 10% per year. USDA guidelines suggest an application rate of less than 5 kg ha^{-1} yr^{-1}, with accumulation of less than 10 kg ha^{-1} of PAM per decade (Note: a hectare, ha, is equivalent to 2.47 acres).

The other environmental concern is the fact that acrylamide, the monomer used to synthesize PAM, is a neurotoxin. Even low levels of monomer impurity in the product must be avoided. This issue has been suitably addressed by suppliers who provide PAM almost devoid of monomer (< 0.05%). The EPA recently reviewed the use of PAM with USDA and polyacrylamide industry scientists, and concluded that, at the concentrations recommended for use during furrow irrigation, PAM levels are acceptable and the presence of monomer in the environment is minimal[35]. Concern that the monomer may occur as a degradation product is countered by studies showing that the most likely route to degradation is early removal of the amine group from the polymer backbone[24,31-34].

There is increasing anecdotal[23] and scientific evidence[13,17,30] (such as the data in Figure 4) that PAM efficacy varies significantly with different soils. Variations in soil include sodicity, texture, bulk density, and surface charge-related properties. It would be beneficial to have a wide array of polymers with potentially different soil-stabilizing mechanisms, applicable to different soil types. Of course, any reduction in price would also benefit farmers. The market price of PAM, ranging from about \$3.00–\$5.00/lb, is high relative to many commodity polymers, such as polyethylene, polypropylene, and polystyrene. Treatment for one year can cost up to \$40 per acre, which is still cost competetive with conventional erosion abating technologies such as straw bales, settling ponds, and underground or drip irrigation systems[36]. An additional reason for exploring other polymers is that PAM is derived from non-renewable monomers from natural gas streams. There are potential environmental and marketing advantages to developing an effective soil amendment from a renewable feedstock, especially from waste streams, i.e. by-products from agriculture, the textile or paper industry, or seafood processing. Not only do natural polymers generally degrade via relatively benign routes; they are generally *perceived* to be safer by the public. Natural biopolymers derived from agricultural or natural by-products are discussed below specifically because of these advantages, and because of their similar

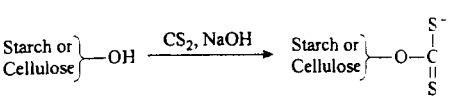
functional attributes to PAM — their large size, their affinity to soil, and their easy dispersion/solution in water.

Polysaccharide Alternatives to PAM

Erosion-resistant soil derives part of its stable structure from the interparticle cohesion provided by natural polysaccharides, lignin, and organic acids. Polyuronides and polysaccharides, natural products of decomposing organic material, are natural soil binders. When added to soils, such organic materials help to form stable aggregates that are readily infiltrated by water, do not erode as easily, resist formation of surface crusts, and improve soil aeration[37]. As early as 1952, Hendrick and Mowry[38] reported that polyuronic acid salts and sodium alginate are useful soil aggregate-forming substances. Smith *et al.*[39] showed that a number of modified agricultural materials such as carboxymethylcellulose and cellulose xanthates stabilized soil aggregates. Extension of this work by Weaver *et al.*[37] demonstrated that carboxymethyl starch, starch-g-poly(acrylic acid) and hydrolyzed starch-g-polyacrylonitrile were all useful for soil aggregation. In fact, hydrolyzed starch-g-polyacrylonitrile was applied in irrigation water as a PAM alternative[9], with an intriguing result. Starch copolymers did little to reduce erosion in the first irrigation. After settling and drying on the furrow bottom between irrigations, however, the starch copolymer seemed to "cure" and resist initial degradation, providing better post-application longevity of the erosion abatement effect than PAM. Perhaps aging and drying of treated furrows strengthened cohesive bonding between soil and starch copolymer. Considered below are several biopolymers with potential to act as PAM alternatives in irrigation water.

Cellulose and Starch Xanthate

Cellulose and starch xanthates have been reported to stabilize soil[40-43] and remove heavy metals from wastewater[44-45]. Xanthates are promising because, like PAM, they carry a charge, they dissolve or disperse readily in water, and they are available with large molecular weights. Xanthates obtain their affinity to soil through the addition of a charged carbon disulfide group (scheme 2) at hydroxyl positions on the glucan. The degree of substitution, ds, is an indicator of the number of charged groups per glucan monomer (with a maximum ds=3 corresponding to full substitution). Xanthate molecules are available with molecular weights potentially exceeding PAM, considering that molecular weight of the amylopectin component of a starch xanthate derivative is in the tens of millions.



Scheme 2: Starch or cellulose xanthate

Menefee and Hautala surface treated 20° sloped plots with cellulose xanthate solution (0.4%) by applying it to a surface depth of 0.5 cm. The sediment lost in runoff from adjacent untreated plots was over 500 times that from a treated plot. This work was extended to lab-scale mini-furrow tests in which the xanthates were added to the irrigation water[21]. Figure 6 is a plot of sediment run-off as a function of cellulose concentration in water. Cellulose xanthate (degree of substitution, ds = 1.7)

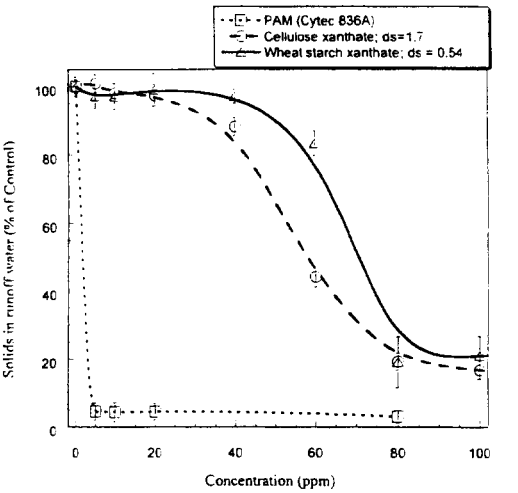


Figure 6 The effect of polymer concentration on the sediment content of runoff water from lab furrow tests for PAM and xanthate samples. The PAM had a MW = 16 million and an anionic charge density of 18%.

reduces soil lost in runoff by more than 80% when it is applied at 80 ppm or greater. In comparison, PAM added to irrigation water in similar furrows, reduces runoff by more than 97% at concentrations of *10 and even 5 ppm*. Thus, cellulose xanthate is almost as effective as PAM at concentrations ~8 times higher. Similarly high concentrations are required for starch xanthates produced from wheat, corn and potato starch (Table I). Interestingly, there is no significant difference between xanthates from wheat, corn or potato, provided the ds is relatively high (ds > 0.38).

The high concentrations of cellulose and starch xanthates required to match the efficacy of PAM in controlling erosion do not necessarily preclude xanthates from the market place. The main commercial use of xanthate is as an intermediate in the Viscose production of rayon fiber, with costs to industrial processors less than $1 per lb. In contrast, farmers pay $3.00–5.00

Table I Soil sediment content in the runoff from lab mini-furrows comparing the efficacy of PAM with several polysaccharide derivatives[21].

Additive[1]	*Soil Conc. in Runoff (mg/L)*[2]	*Soil conc. in runoff (% of control)*
Control (Tap Water)	51.5 ± 4.2	100
PAM (Cytec 836A); 10 ppm	1.0 ± 0.5	1.9
Cellulose xanthate; 80 ppm; (ds = 1.7)	9.8 ± 2.2	19.3
Wheat starch xanthate; 80ppm; (ds = 0.54)	9.4 ± 4.9	19.1
Potato starch xanthate; 80ppm; (ds = 0.47)	6.7 ± 3.1	12.9
Cellulose microfibrils; 120ppm	11.0 ± 4.8	21.3

[1] The soil used for this study had a pH of 7.5, exchangeable Ca of 7%, and ~5% organics. Calcium nitrate was added to the water, at a concentration of 10 ppm, to ensure ionic bridging.

[2] The standard deviations are reported based on 5 replicates per sample.

per lb for PAM, although costs are inflated by packaging in smaller lots, packaging in metering containers, and by marketing and distributing to a diffuse market place. It is not clear that xanthate would be significantly cheaper than PAM if it is introduced through the same distribution channels. With optimization of properties, xanthates could potentially compete on a cost per application basis.

However, several other drawbacks of xanthate must be overcome. Their relative instability means that they have a shelf life of only days or weeks. Meadows[41–42] developed strategies to extend the shelf life by removing water, by storing at cooler temperatures, by storing in vacuum-sealed packages, and by adding dehydrating agents, such as CaO.

The environmental concerns about xanthate production may be more difficult to overcome. The Viscose process for producing rayon fibers via xanthates is becoming increasingly obsolete because of the sulfur-based waste products generated during large-scale production. The washing process during production leaves large quantities of sulfur tainted water, which must be treated before it is returned to our waterways.

Once xanthates are deposited in the soil, they would be relatively safe in the environment. In fact, xanthate additives would degrade in a relatively benign mode, and may even provide benefits for sulfur deficient or highly calcareous soils. There is increasing evidence that conditioners such as PAM[46] or xanthate can play a critical role in maintaining mineral balance in soils.

Cellulose Microfibrils

Unlike most of the other polymers considered in this report, acid-hydrolyzed cellulose microfibrils have never been used as a soil conditioner or flocculating agent. They were tested in lab-scale mini-furrows[21] because they appear to possess the major attributes required for creating stable soil aggregates, i.e. a large size, an affinity to soil via a surface charge, and stability in aqueous suspensions. Cellulose microfibrils are the basic crystalline component of cellulose fibers, which are obtained during acid hydrolysis. The microfibrils studied here were derived from cotton by heating in 60% sulfuric acid for 30 minutes. Cotton microfibrils are rod-like crystallites with a length of 0.12–0.45 microns and a diameter of 5 nm[47–49]. Microfibrils gain a charge on their outer surface during acid hydrolysis, allowing them to disperse readily in water.

As outlined in Table I, cellulose microfibrils reduced the irrigation-induced erosion in mini-furrow experiments. Concentrations of at least 100 ppm were required to exhibit any significant reduction in runoff sediment, with a concentration of 120 ppm resulting in 78% reduction. In contrast, PAM (Cytec Magnifloc 836A) removed 98% of solids at a concentration of 10 ppm.

Despite the fact that relatively high concentrations of cellulose were required, the charged microfibrils are still promising for several reasons. As with starch xanthate, the charge distribution of the microfibrils has not necessarily been optimized. A wide range of charge density, charge type, and microfibril size can be obtained by optimizing reaction conditions and by varying the source of cellulose. For example, sugar beet microfibrils can be microns in length and 50 nm in diameter, significantly larger than the fibers derived from cotton. Larger microfibrils would stabilize larger soil aggregates by spanning between a greater number of particulates.

Cellulose microfibrils are attractive because they are readily available from various waste agricultural sources, such as wheat and rice straws, sugar beet fiber, and cotton wastes (including recycled cotton). Within the next several years, EPA mandates will prevent farmers in several Northwest states including California from burning rice straw between seasons. Having value-added uses for such straws would be advantageous.

Chitosan

Chitosan has already been introduced as an alternative to PAM in a range of applications. It has been used as a biodegradable flocculating agent for removing heavy metals from industrial waste water[50], for reducing suspended biological matter in municipal waste[51], and for clarifying swimming pool water in an "environmentally friendly" manner[52]. The major drawback of chitosan is its market cost of over $7/lb, about twice the price of PAM. Chemically, chitosan is similar to cellulose, with the hydroxyl in the 2-position replaced with a primary amino group. It has a net positive charge at neutral or acidic pH values and is available with reasonably high molecular weights.

Lab-scale mini-furrow results outlined in Table II show that highly deacetylated chitosan at 20ppm is as effective as PAM in reducing erosion-induced soil losses. With such favorable lab test results, chitosan was further tested in a series of field tests at the USDA Northwest Irrigation and Soil Research Lab, Kimberly ID[21]. In the field tests, chitosan reduced erosion-induced soil losses by, at best, half of the control (see Table II). The sediment concentration in the runoff water from chitosan treated furrows was an order of magnitude higher than that of PAM (although results for the chitosan furrows were highly variable). For PAM (Cytec Magnifloc 836A), sediment losses were reduced by 99% relative to controls.

Such poor comparative results, however, do not mean that chitosan had no effect on the irrigation. Observations of the furrows treated with chitosan revealed remarkable results in the first ~20 meters of the furrow. Chitosan acted as such an effective flocculating agent that it removed fine sediments, and even algae from the irrigation water. Consequently, the chitosan-treated furrows became green in color due to build-up of sequestered algae on the furrow bottom. In contrast, the control furrows or PAM-treated furrows did not gain a greenish hue during irrigation. Apparently, the flocculation aspect of chitosan

Table II A comparison of polyacrylamide, PAM, (MW ~ 16 million, 18% anionic) and chitosan solution in controlling irrigation-induced sediment loss in a lab-scale and a field furrow test.

	Control (Tap Water)	*PAM (10ppm)*	*Chitosan (10ppm)*
Lab Mini-Furrow Results[1]			
Solids in runoff (mg/l)	48.1[a]	3.4[b]	5.5[b]
Solids in runoff (% of control)	100	7.1	11.4
Field Test Results[2]			
Sediment in runoff (kg/ha)	38745[a]	268[b]	18981[a]
Solids in runoff (% of control)	100	0.7	49.0

[1] Results within a row with a different superscript letter are statistically different from each other.

works at least on a par with that of PAM. One explanation for the inability of chitosan to control erosion in a long furrow is that the chitosan binds so readily with sediment that it flocculates out of solution near the top of the furrow. It is not available to reduce sedimentation losses in the lower end of the furrow.

Chitosan lacks the size of the high molecular weight PAM, and may not be able to form a large stable soil/polymer network at the soil/water interface. Notably, in a PAM-treated furrow, very little sediment is stirred up in the water from the outset. Rather, a network forms immediately at the furrow surface that prevents shear forces from disrupting the surface structure and improves water infiltration efficiency. The very large molecular weights of PAM allow it to form a very large network, and thus be effective at very low concentrations (5–20 ppm in the irrigation water).

Summary–Future Applications of Polymers in Controlling Erosion

In summary, use of PAM for erosion control is a potent tool for reducing erosion and improving infiltration during irrigated agriculture. It has been shown to effectively halt furrow erosion on a variety of soils globally, preventing over half a ton of soil erosion on a field basis per ounce of PAM used[11]. The molecular weight, charge type and charge density of PAM all affect the capacity of PAM to mitigate irrigation-induce erosion, with molecular weights of at least 6 million required for best field results. The addition of calcium to irrigation water, with or without polymer additive, can reduce the amount of soil runoff for waters and clay-rich soils low in exchangeable calcium. Presumably, the addition of calcium stabilizes soil structure through the formation of ionic bridges, an effect that is not as long lasting as the soil stabilization exhibited by PAM.

Biopolymer alternatives to PAM, such as starch xanthate, cellulose xanthate, and acid hydrolyzed cellulose microfibrils each appear promising, with the ability to reduce soil runoff significantly. The effective concentrations of these derivatives, though, were 8–16 times higher than for PAM, without matching PAM's full efficacy. Chitosan solutions were very effective at controlling erosion-induced soil losses in lab-scale mini-furrows at concentrations approaching those used for PAM. However, in field tests the effectiveness of chitosan was highly variable, with limited improvement over controls. It appears that chitosan adsorbs too readily with sediment, and is depleted from solution near the top of the furrow. Perhaps chitosan does not have the molecular size or conformation of PAM, preventing it from forming a large stable soil/polymer network at the furrow surface.

It is surprising, considering that PAM technology has existed for soil stabilization and for water treatment since the 1950's, that it has taken until the mid 1990's for recognition of some of the other potential uses. However, now that the widespread attention has come to PAM via the success story with irrigation-induced erosion abatement, dozens of new uses for water quality protection and restoration in the environment are being recognized. The second wave of this breakthrough may be the expansion to these new classes of biopolymers. That is, although biopolymer additives did not reach PAM's efficacy in irrigation, there is evidence that biopolymers can reduce erosion-induced sediment loss, especially if their properties are optimized for their specific application. The performance of these biopolymers may already be in a range of efficacy for applications where PAM is finding inroads, but where material costs are not limiting. These include (i) erosion reduction at construction sites, along highway road cuts, and near waterways, (ii) application in "tackifying" straw beds (so they stay in place), (iii) use as a matrix material for fertilizer release, and (iv) applications in hydroseeding, where moisture is maintained around seeds during germination. The environmental advantages of degradable polymers derived from renewable sources may give biopolymers a market edge.

PAM can be applied during sprinkler irrigation but benefits are much less dramatic than with furrow irrigation[53]. Applying 2–4 lbs. of PAM per acre can reduce erosion and increase infiltration during the irrigation under some conditions. However, beneficial effects last for only one or two irrigations. Many questions are still unanswered about applying PAM through sprinkler systems.

Washington State's Department of Transportation Water Quality Program is in the process of evaluating PAM for its ability to stabilize soils and remove fine suspended sediments from storm water runoff at highway construction sites[54]. Storm water runoff is collected within wet detention ponds with sediment removed by the addition of PAM from a passive, non-mechanical dosing system. Many swine production operations keep the houses clean by flushing with water. Mechanical separation of manure solids and organic nutrients contained in the diluted wastewater is very inefficient — 5 to 20%. PAM was shown to be very effective for flocculating suspended solids and separating nutrients from flushing effluents[54].

Using PAM or a PAM alternative to control run-off from critical areas such as construction sites, highway cuts, manure fields, and water overflow sites may be more than an order of magnitude cheaper than present methods[55], such as building settling ponds, applying straw bales, etc. In these applications, the "natural" appeal of biopolymers may give them a distinct marketing edge.

Acknowledgements

The authors would like to thank Youngla Nam and Jim Foerster for their superior technical support, and Michael McElhiney, USDA Natural Resources Conservationist, Modesto, CA, for helpful discussions and for supplying characterized soil samples. The authors thank Ray Farinato of Cytec, Inc. for many helpful insights into the nature of PAM polymers, and for providing characterized samples. This work was partially supported by the Washington and Idaho Wheat Commissions under ARS agreement 58-5325-7-850.

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