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# Biopolymers from Polysaccharides and Agroproteins

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Chapter 6

# Biopolymer Additives for the Reduction of Soil Erosion Losses during Irrigation

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High molecular weight, synthetic polyacrylamides (PAM) are relatively large, water soluble polymers that are used increasingly by farmers to prevent erosion and increase infiltration during irrigation. A lab-scale erosion test was conducted to screen biopolymer solutions for a similar efficacy in reducing shear-induced erosion. In lab-scale mini-furrow tests, chitosan, starch xanthate, cellulose xanthate, and acid-hydrolyzed cellulose microfibrils, at concentrations of 20, 80, 80, and 120 ppm respectively, reduced suspended solids in the runoff water from test soil. None of these biopolymers, however, exhibited the >90% runoff sediment reduction shown by PAM at concentrations as low as 5 ppm. Preliminary field tests results showed that chitosan solutions were only marginally effective in reducing runoff from a 137m long furrow. There were indications that results were dependent on the length of the furrow. Erosion of some clay-rich soils from Northern California was reduced up to 85% by increasing the concentration of exchangeable calcium to >2.5mMole, with or without the addition of polymer additives.

Soil erosion threatens agricultural productivity and water through the loss of valuable "top-soil" and runoff of agricultural chemicals. U.S. row-crop farmers lose an average of 6.4 tons of soil per acre per year, despite being world leaders in practicing soil conservation (*1*). The EPA describes soil erosion as our greatest threat

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to water quality (*1*), a concern that is increased by evidence that chemical toxins readily pass from our waterways into the air (*2*).

Soil loss is especially significant during furrow irrigation because of the shear of flowing irrigation water, and because arid soils often are low in the natural polysaccharides that stabilize soil structure. Farmers could minimize erosion-induced soil losses by stringent use of settling ponds, sodded furrows, straw-bedded furrows, minibasins, soil stabilizers, and buried runoff pipes; however, these techniques are often too cumbersome or costly for adequate adoption.

Recently, an easy and effective tool has been added to these soil conservation measures -- adding small quantities of polyacrylamide copolymers, PAM, to the in-flowing water (*1,3-8*). Lentz *et al.* (*3*) added 5-20 ppm of high molecular weight, anionic PAM to irrigation water in the first several hours of irrigation, and reduced soil losses of a highly erodible soil up to 97%. This represented an ideological breakthrough in the use of soil conditioners. Rather than treat the "entire" 10 to 20 cm depth tilled surface layer of a field with hundreds of kilograms of polymer per acre, one only modifies the soil in contact with irrigation water. In irrigated agriculture the water itself is the PAM delivery means. For furrow irrigation, this translates to improved soil structure in the ~1-5 mm thick layer at the soil/water interface. Consequently, relatively small quantities of polymer are used (approximately 1 lb per acre per irrigation). Seasonal application totals range from about 2 to 8 lbs of polymer per acre per year.

The benefits of PAM have clearly been seen by farmers. Over a million furrow-irrigated acres were treated in 1998 (*9*). Although the method was introduced in Idaho, it has proven effective in an increasing number of diverse locations throughout the western US and in several countries overseas (*9,10*).

The successful use of PAM in irrigation water raises the question of whether there are other polymers that may have similar benefits. PAM has been used for decades as a flocculating agent -- for various food processing applications, to dewater sewage sludges, to remove heavy metals during potable water treatment, and to process industrial wastewater. PAM is widely recognized as a safe, cost-effective flocculating agent; yet, it is by no means the only flocculating agent available.

There are several reasons to explore other polymer additives. Environmental concerns have been raised about widespread PAM use in open agricultural environments – concerns that have been countered convincingly by experts in the field. PAM is a synthetic polymer that was designed to resist degradation, and is very stable (*11*). Environmental degradation rates are less than 10% per year via deamination, shear-induced chain scission and photo-sensitive chain scission (*11-13*). With such stability, there is some concern for potential accumulation. This concern is unfounded if PAM is used at the low concentrations recommended by the USDA (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 (*10*).

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, with minimal accumulation (9). 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 (*11-13*).

There is scientific and anecdotal evidence (*14*) that PAM efficacy varies with certain soil properties, including 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. The market price of PAM, ranging from about $2.50 - $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. Any reduction in price would benefit farmers. Finally, PAM is a synthetic polymer using a non-renewable monomer source from oil refining. It would be advantageous to derive an effective soil amendment from a renewable feedstock, especially from an agricultural waste stream. Not only do natural polymers generally degrade via relatively benign routes, they are often perceived to be safer by the public.

The general objective of this study was to screen a series of biopolymers to quantify their effectiveness as erosion retardants in irrigation water. Natural biopolymers, with potentially similar functional attributes as PAM, were selected specifically because of their environmental advantages (real or perceived). Biopolymer additives were screened using a lab-scale mini-furrow procedure to determine their potential efficacy in reducing erosion losses. The more promising formulations were tested in full field tests.

## Materials and Methods

*Polyacrylamides (PAM)*

Polyacrylamides from a variety of sources were used to establish parameters in the lab-furrow test and as a comparison of the biopolymer samples. PAM samples were generally random copolymers of acrylamide and acrylic acid, varying in molecular weight, charge type, charge amount, and relative solubility in water. A series of samples were provided by Cytec Industries of Stamford, CT, with the trademark, Magnifloc, and product codes 835A, 836A, 837A, 846A, 905N, 442C, 492C, and 494C. Cytec also provided several relatively short-chain samples specifically for this project. Samples were also provided by Allied Colloids, Suffolk, VA, and trademarked Percol (product codes 338, E24, and LT25). Additional PAM samples ranging in molecular weight from 40,000 to 15 million were purchased from Aldrich Chemical. Molecular weight and charge data were generally provided by the manufacturers.

*Cellulose and starch xanthates*

Cellulose xanthate was produced following the procedure of Menefee and Hautala (*15*) using Whatman filter paper #4 as a source of pure cotton. Starch

xanthates were produced according to Maher (*16*) with the following starch sources: Midsol 50 wheat starch (Midwest Grain Products, Inc., Atchison, KS), Hylon VII high amylose corn starch (National Starch and Chemical Corp., Bridgewater, NJ), and potato starch (Avebe, Princeton, NJ). The cellulose or starch was swollen by soaking in ~20% (w/w) aqueous NaOH. After decanting off excess NaOH, molar volumes of carbon disulfide were added with mixing, forming an orange sticky mass. After several hours of stirring, xanthates were diluted to a 2% solution (based on polysaccharide content), which presumably stopped the reaction and facilitated further dilution. The degree of substitution, ds, was estimated using a standard combustion method for sulfur content (*17*). The shelf life of xanthate is generally limited to several days, so samples were tested within 24 hours after production.

*Charged cellulose microfibrils*

Acid hydrolyzed cellulose microfibril suspensions were formed from cotton fiber (Whatman filter paper #4) following a procedure outlined by Revol *et al.* (*18*). Cellulose fibers were milled in a Wiley Mill to pass through a 40 mesh screen, added at 8% concentrations to ~60% sulfuric acid at 60°C, and stirred for 30 minutes. The reaction was stopped by adding excess water, and the samples were centrifuged and washed repeatedly (at least three times) until clean of salts and acid. According to previous reports (*18*), hydrolysis with sulfuric acid will create sulfate esters at the surface of the microfibrils. The procedure used here corresponds to a sulfonation level of 10%, i.e. a charge distribution of ~10% over the surface anhydroglucose units (or roughly 0.2 sulfate groups per $nm^2$).

*Chitosan*

Chitosan samples were provided by Vanson, Inc., Redmond, WA. In general, chitosan stock solutions were put into solution at high concentration by adding weak acid, lowering the pH to ~6.0. Before use, solutions were diluted and the pH was adjusted back to 7.0. This process was not required for a proprietary "water-soluble" chitosan provided by Vanson.

*Lab-Scale Mini-furrows*

Lab-scale furrows were created based on principles outlined by Stott *et al.* (*19*). Except where noted, the soil tested in the lab-furrow was a Zacharias gravelly clay loam soil obtained from Patterson, CA, a northern California farming community 90 miles south of Sacramento. This soil was chosen because it is typical of California's Northern Central Valley and because anionic PAM has been particularly effective in controlling its erosion (*11*). Soils were dried, sieved and re-moisturized to 18% (w/w) water contents and then formed into miniature furrows roughly 1/100th the size of a full furrow. That is, 1500g of moist soil was packed flat into a 2.5 x 2.5cm well cut into a 1m long bar. A furrow with dimensions 0.63 x 0.63cm was pressed lengthwise down the center of the packed soil, to create a mini-furrow. Test solutions were pumped down the furrow, set at an angle of 5°, at flow rates of 7mL/min. Water was collected at the lower end of the furrow and tested for solids contents. Sediment concentration was determined by measuring turbidity using a Shimadzu UV-Vis

UV1601 spectrophotometer, and calibrating turbidity with those from a set of pre-weighed soil dispersions. The relative suspended solids was determined for at least 5 replicate samples at each condition.

Multiple parameters affected the results of the furrow tests, including soil type, water flow rate, furrow slope, furrow length, and water purity. For example, if the flow rate was too high, not even PAM was effective in clarifying runoff. After some trial and error, conditions were selected so that results were reflective of the field tests results of Lentz *et al.* (*5*). Figure 1 compares the results of the furrow test with those from the field, showing the effect of PAM's molecular weight, MW, on its efficacy. For the lab-furrow test, >95% solids are removed (relative to control) and there is no molecular weight dependence above MW = 200,000. A similar trend is seen for field tests results, although the sediment levels are higher and the molecular weight dependence is apparent up to MW = 6million. Thus, the furrow test appears more "sensitive" than field test results, i.e. a positive result in the lab-furrow does not necessarily imply full effectiveness in the field. Such conditions were chosen to reduce the risk of missing polymers with potential (i.e. it was better to have false positive results).

*Field Tests*

Field furrow studies were conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, ID. The soil was a highly erodible Portneuf silt loam (coarse-silty, mixed, mesic, Durixerollic Calciorthid). The furrow had a slope of 1.5% and a length of 137m. Irrigation water was from the Snake River, with average electrical conductivity (EC0) of 0.5 $dSm^{-1}$ and sodium adsorption ratio (SAR) of 0.6 (*20*). Irrigation water was applied from individually regulated valves on gated pipe to conventionally prepared furrows between rows of silage corn. During the initial advance stage of irrigation, the water inflow rate was set at approximately 6 gal/min and polymer samples were metered into the flow at the top of each furrow via calibrated peristaltic injection pumps. Details of the irrigation and runoff monitoring procedure were described previously (*3,5*). Sediment content was measured at the end of furrows by collecting 1L of sample and measuring sediment using the Imhoff cone technique, and turbidity measurements (*21,22*).

## Results and Discussion

### Cellulose Xanthate, Starch Xanthate, and Cellulose Microfibrils

Cellulose and starch xanthates have been reported as soil stabilizers (*15, 23-25*) and in the removal of heavy metals from wastewater (*16,26*). Xanthates are promising because, like PAM, they carry a charge, they can dissolve or disperse readily in water, and they are available with large molecular weights. For example,

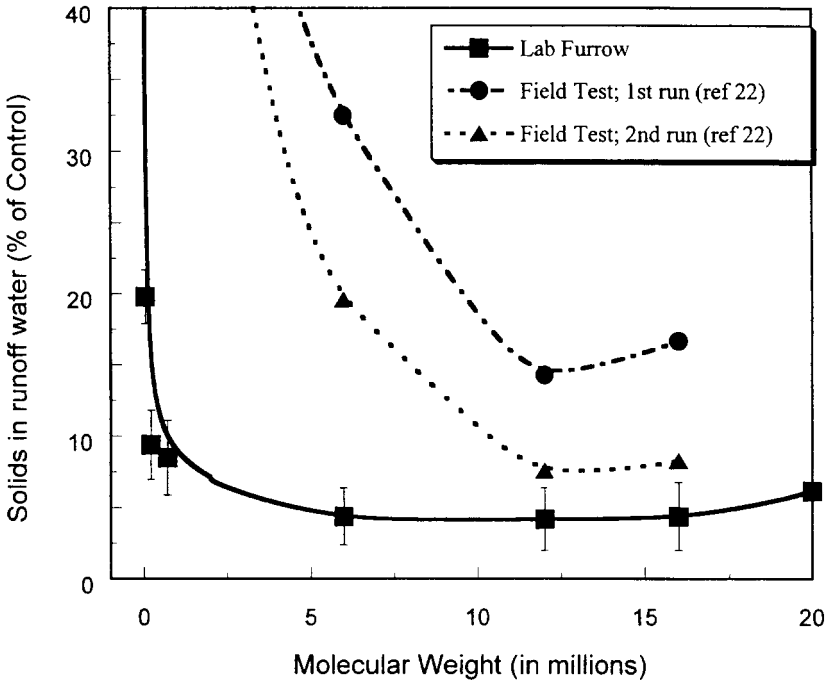


*Figure 1. Lab-scale furrow results compared with field test results highlighting the effect of molecular weight on the effectiveness of polyacrylamide, PAM, in controlling erosion-induced soil losses. Curves are drawn between data points in order to guide the eye.*

the molecular weight of the amylopectin component of a starch xanthate derivative is in the tens of millions, much greater than that of most PAMs.

Results of lab-scale furrow tests for cellulose xanthate samples are shown in Figure 2. Cellulose xanthate (degree of substitution, ds = 1.7) reduces soil runoff by more than 80% when it is applied at 80 ppm or greater. In comparison, PAM under the same conditions effectively reduces runoff at 10 and even 5 ppm to less than 3% of the control (or 97% sediment removal). Thus, PAM is significantly more effective than cellulose xanthate at concentrations only 1/8th those of the xanthates. Similarly high concentrations are required for starch xanthates produced from wheat, corn and potato starch (Table 1). Interestingly, there is no significant difference between xanthates from wheat, corn or potato, provided the ds is relatively high (ds > 0.38).

**Table 1. Soil sediment content in the runoff from lab mini-furrows comparing the efficacy of PAM with several polysaccharide derivatives.**

| *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); 10ppm | 0.99 ± 0.54 | 1.9 |
| Cellulose xanthate; 80ppm; (ds= 1.7) | 9.8 ± 2.2 | 19.3 |
| Wheat starch; 80ppm; (ds= 0.0) | 50.6 ± 6.7 | 98.6 |
| Wheat starch xanthate; 80ppm; (ds= 0.38) | 12.9 ± 5.8 | 25.0 |
| 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 |
| High amylose corn starch (Hylon VII) xanthate; 80ppm; (ds= 0.45) | 7.5 ± 1.8 | 14.5 |
| 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.

It is clear from Table 1 that charged polysaccharide derivatives such as cellulose and starch xanthate have some potential to reduce soil runoff during irrigation. Whether xanthates could compete with PAM in the market place, however, is not so clear. The main commercial use of xanthate is as an intermediate in the Viscose production of rayon fiber. Xanthates would generally cost less than PAM ($2.50 -

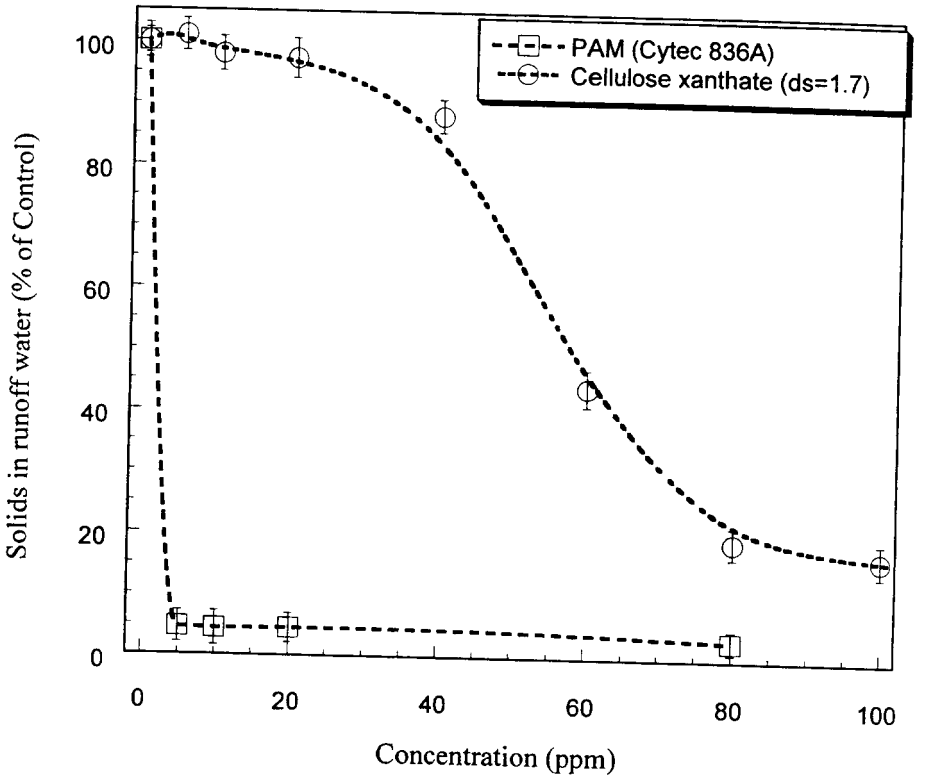


*Figure 2. The effect of polymer concentration on the sediment content of runoff water from lab furrow tests. The PAM had a MW = 16 million and charge density of 18% via randomly distributed acrylic acid groups.*

5.00 per lb). However, several major drawbacks of xanthate must be overcome. Their relative instability means that they have a shelf life of days or weeks. Meadows (*23,24*) developed strategies to extend the shelf life by removing the water, by storing at cooler temperatures, by storing in vacuum-sealed packages, and by adding dehydrating agents, such as CaO. More critical is the environmental impact of xanthate production. 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. Interestingly, the sulfur content of xanthates may give it an for sulfur deficient soils or highly calcareous soils. Sulfur could improve both the pH balance and micronutrient availability.

The most applicable conclusion from the data in Table 1 is that charged starch and cellulose derivatives have potential to reduce irrigation induced losses. With this in mind, acid-hydrolyzed cellulose microfibrils were tested using the lab-furrow procedure. Cellulose microfibrils are obtained during acid hydrolysis of pure cellulose, and are the basic crystalline unit of a cellulose fiber. The microfibrils studied here, which were derived from cotton, are rod-like crystallites with a length of 0.1-0.3 microns and a diameter of 5 nm (*18,27*). During acid hydrolysis, microfibrils gain a charge on their outer surface and become stable in water suspensions. Thus, 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 easy dispersion in water.

As outlined in Table 1, aqueous suspensions of cellulose microfibrils reduce the irrigation-induced erosion in lab-scale furrow experiments. Concentrations of at least 100 ppm were required to exhibit any significant reduction in runoff sediment, with a concentration of 120ppm 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 varying the source of cellulose. For example, sugar beet microfibrils are significantly larger than the fibers derived from cotton. In addition, it may be an advantage to add relatively high concentrations of cellulose back to arid soils to improve soil structure, without undue environmental concern. 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 and old clothing). Within the next several years, EPA laws will make it illegal for farmers in several Northwest states, including California, to burn their rice straw between seasons. Having value-added uses for such straws would be advantageous.

## Chitosan: Lab-scale and Field Tests

If production costs were no consideration, chitosan would have clear potential as an alternative to PAM. Chitosan has already established itself as a biodegradable

flocculating agent for removing heavy metals from plant water (*28*), for reducing suspended biological matter in municipal waste (*29*), and for clarifying swimming pool water in an "environmentally friendly" manner (*30*). The major drawback of chitosan is its market cost of at least $7/lb. This is as much as 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 mini-furrow results outlined in Table 2 show that highly deacetylated chitosan at 20ppm is as effective as PAM in reducing erosion-induced soil losses. With such favorable lab tests results, chitosan was further tested in a series of field tests at the USDA Northwest Irrigation and Soil Research Lab, Kimberly ID. In the field tests, chitosan did not reduce erosion induced soil losses relative to the control (see Table 2). The sediment concentration in the runoff water from chitosan treated furrows was, at best, an order of magnitude higher than that of PAM (although results for the chitosan furrows were highly variable). The only results significantly different from controls were for PAM (Cytec Magnifloc 836A), whereby 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. In the first 20 meters, the chitosan-treated furrows became green in color due, presumably, to algae build-up. In contrast, the control furrows or PAM-treated furrows did not gain a greenish hue during irrigation. Apparently, the flocculation aspect of chitosan works at least on a par with that of PAM. One explanation for the poor results for samples collected at the end of the 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. Such an explanation implies that the effectiveness of chitosan is dependent on furrow length.

Another explanation is that chitosan, lacking the size of the high molecular weight PAM, does not form a large stable soil/polymer network at the soil surface. Why does molecular weight effect the efficacy of PAM or PAM substitutes? The most common mechanisms invoked for polymeric flocculents is that of bridging. For polymer electrolytes, such as PAM, there is a combination of ionic and polymer bridging. Ionic bridging provides the attractive force between two like-charged entities; for example between two anionic monomers on the PAM chain or between PAM and a negatively charged soil particle. Polymer bridging occurs for large molecular weight polymers if segments of a single polymer chain can adsorb onto more than one particle. For such bridging, the non-adsorbed polymer chain segments must be long enough to exceed the minimum distance of close approach between particles, i.e. the sum of the thicknesses of the electrostatic double layers of the two approaching particles. At very high molecular weights, PAM would have a fully extended end-to-end distance of several microns, and would be able to form stable flocs with multiple soil particles. Ionic bridges further stabilize large flocs by

providing interaction between multiple polymer chains, and their associated bound particulates. Longer molecules increase the size of potential polymer/soil flocs.

Forming stable flocs may not be enough, though. Sojka (*10*) points out that the efficacy of PAM depends on two aspects of PAM's interaction with soil. PAM not only forms stable flocs with the soil suspended in water, but also interacts with the soil at the water/soil interface to create a network of PAM/soil aggregates. This network forms a thin protective coating 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 larger network, and thus be effective at very low concentrations (5-20 ppm in the irrigation water).

**Table 2. A comparison of polyacrylamide, PAM, (MW ~ 16 million, 18% anionic) and chitosan solution in controlling irrigation-induced sediment loss in a lab-scale[1] and a field furrow test.**

| | *Control (Tap Water)* | *PAM (10ppm)* | *Chitosan (10ppm)* | *Chitosan (20ppm)* |
|---|---|---|---|---|
| Lab Mini-Furrow Results[2] | | | | |
| Solids in runoff (mg/l) | 48.1[a] | 3.4[b] | 5.5[b] | 4.2[b] |
| Solids in runoff (% of control) | 100 | 7.1 | 11.4 | 8.7 |
| Field Test Results[2] | | | | |
| Sediment in runoff (kg/ha) | 38745[a] | 268[b] | 18981[a] | 24566[a] |
| Solids in runoff (% of control) | 100 | 0.7 | 49.0 | 63.4 |

1. No calcium was added to the irrigation water.
2. Results within a row with a different superscript are statistically different from each other.

## Calcium Effects

One of the interesting results of this study was the fact that improvements in soil runoff in the lab furrow test were achieved independent of the presence of PAM. To explore this result further, we utilized a soil from Davis, CA that did not respond well to PAM. As shown in Figure 3, calcium alone significantly reduced suspended solids in the runoff from this soil, although PAM and calcium still had a greater effect than

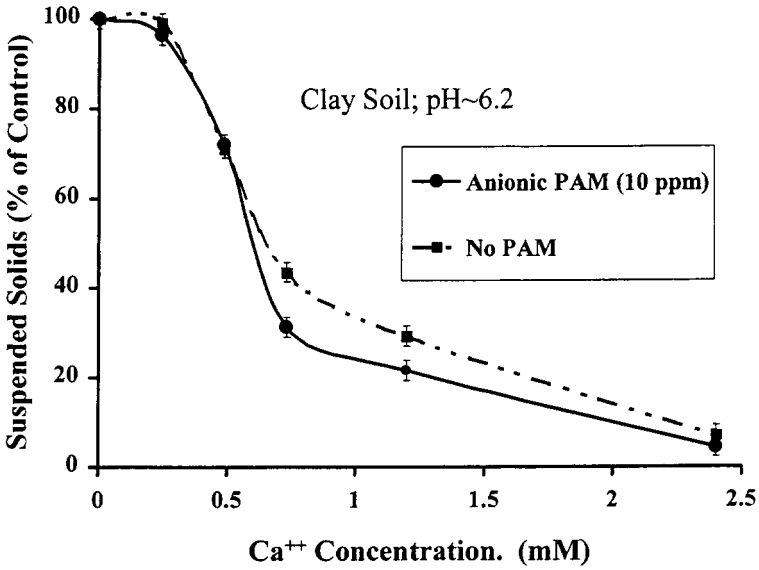


*Figure 3. The effect of added calcium on suspended solids in soil runoff from a lab-scale furrow test for water with and without PAM (MW~16 million, 18% anionic).*

calcium alone. A similar result was also reported by Wallace and Wallace (*7*), who noted that gypsum or other ions providing higher electrical conductances (*31*) also reduce erosion losses in clay-rich soils. The results in Figure 3 confirm their observations in a lab environment. Note, though, that this result is not necessarily universal. Many sources of irrigation water have a much higher electrical conductance than the tap water used here, with significantly higher levels of exchangeable calcium. Also, the benefit from added calcium is short term. Calcium must be added continuously to the irrigation water. In contrast, PAM can be added for a short period during an initial irrigation series, and provide a lasting effect for weeks without additional doses.

Calcium likely works by precipitating small tenuous floccules from turbid water. Flocs are held together by individual ionic bridges between clay particles. Calcium does not necessarily provide permanent structure to the soil. Floccules can easily be dispersed as they are bathed with water containing less calcium, thereby losing their ionic bridge during cation exchange.

With the addition of polymers, calcium plays an additional role in stabilizing flocs by providing ionic bridges between anionic polymers as well as between polymers and charged particles. As discussed above, the calcium double cation would interact with two separate anionic groups from potentially separate polymer chains, and create a larger, more stable polymer/soil aggregate.

## Conclusions

A lab-scale furrow test was utilized to test different polymer additives in irrigation water for their efficacy in reducing soil losses during irrigation. 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 10-16 times higher than for PAM, without even matching PAM's full efficacy. These polymers would not cost as much as the "high-grade" PAM employed here, so it is not clear that their high concentrations would automatically exclude them on an economic basis, especially if they are optimized for this application.

The results for chitosan solutions showed that, although lab tests are useful for screening potentially useful polymers for reducing erosion-induced soil losses, field tests, with longer furrows and potentially higher shear forces are required to fully assess polymer properties. In the lab mini-furrow test, chitosan solutions were very effective at controlling erosion-induced soil losses at concentrations approaching those used for PAM. However, in field tests, the effectiveness of chitosan was highly variable, with no clear improvement over controls. This could be because chitosan does not have the molecular size of PAM, preventing it from forming a large stable soil/polymer network at the furrow surface. Another possibility is that chitosan binds "too readily" with sediment and flocculates out of solution near the top of the furrow; an implication that its effectiveness depends on the length of the furrow.

Interestingly, the addition of calcium nitrate to irrigation water, with or without polymer additive, can reduce the amount of soil runoff for the clay-rich soils, and relatively pure water, encountered in Northern California. The addition of exchangeable calcium, however, would not have the long-term effect on soil structure exhibited by PAM.

Although PAM's efficacy was not reached in these tests, there is promise that biopolymers can play a role in reducing erosion-induced sediment loss, especially if their properties are optimized for their specific application. This study explored a very specific application, furrow irrigation. However, the performance of the biopolymers may already be in a range of efficacy to be tried in various other related uses. These include erosion reduction at construction sites and highways, "tackifying" straw beds (so they stay in place), and hydroseeding. In such applications, the costs of material are not the limiting restriction. The environmental advantages of degradable polymers derived from renewable sources may give these biopolymers a market edge.

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