

Polyacrylamide: A Review of the Use, Effectiveness, and Cost of a Soil Erosion Control Amendment

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ABSTRACT

Soil degradation is a significant problem throughout the world. Use of soil amendments, including anionic polyacrylamide (PAM), is one of many options for protecting soil resources. Polyacrylamide has been the focus of a substantial amount of research in the 1990s. Our objective is to present a review of the recent findings and advancements in PAM work. As a soil conditioner PAM can be used to stabilize soil aggregates as well as flocculate suspended particles. Part of the attractiveness of PAM is its versatility. Polyacrylamide can be used in furrow irrigation where it reduces erosion and runoff while improving soil and water quality and water-use efficiency. In rain-fed agriculture and sprinkler irrigation, PAM is used to reduce surface sealing and crusting as well as erosion. Polyacrylamide is also used to stabilize steep slopes in construction, highway cuts, and other disturbed soils. The economics of PAM use can encourage its use in many instances and discourage its use in others. Polyacrylamide is very cost effective in furrow irrigation systems where it can be applied at low rates through the irrigation water. In construction applications, PAM reduces labor and material costs. Polyacrylamide can be cost effective in rain-fed agriculture under certain management regimes such as on soils highly susceptible to crusting and breaking the cycle of crusting-low organic residue production-crusting. As a soil conditioner, PAM is another tool that can be used to manage our soil resources.

INTRODUCTION

Soil physical properties greatly affect how the soil will function in the field. Infiltration rate and aggregate stability are listed amongst the most important soil quality indicators (Doran and Parkin, 1996). For agricultural uses, soil with good infiltration and stable aggregation is imperative. As infiltration decreases, runoff and erosion increase, thus degrading the soil. Good aggregation associated with high aggregate stability helps maintain adequate pore space for infiltration. Soil crusting, surface sealing, and compaction can inhibit seedling emergence. Raindrops can impact the soil with such force that it compacts the soil, causing a structural crust. Additionally, the impact of the rain and the rapid wetting of the soil cause slaking, disrupting the integrity of the soil aggregate. Once the soil aggregate has dispersed into smaller particles, the small particles can clog the pore spaces of the soil matrix. When this occurs, a thin seal develops which, when dry, becomes a hardened surface

crust, difficult for a germinating seed to penetrate (LeBissonnais, 1996; McIntyre, 1958; Shainberg and Singer, 1985).

In furrow-irrigated agriculture, the shear stress associated with running water detaches soil particles and deposits them farther down the furrow when the velocity decreases, creating a surface seal. The associated runoff and erosion cause both on- and off-site problems. Decreased infiltration rate is a severe problem and leads to increases in runoff, erosion, water use, nutrient losses and pollution, and decreased crop yields (Lentz et al., 1992).

Construction and development sites are other areas highly susceptible to erosion. Construction of urban areas, roads, and highways critically disturb the land. These areas are vulnerable to soil erosion before permanent vegetation can be re-established. Much of the time, these areas are on steep slopes and are left bare for extended periods. Both on- and off-site costs associated with erosion from construction activities are great. Costly repairs and reshaping of slopes as well as sedimentation and water pollution result in environmental and economic losses to the general public as well as the contractor.

Polyacrylamide (PAM) can stabilize soil structure but does not remediate poor soil structure. In the arid and Mediterranean climates of the world, PAM is being used quite effectively to stabilize soil structure, which leads to increased infiltration, reduction in water use, and reduced erosion on furrow irrigated fields (Lentz and Sojka, 1994; Lentz et al., 1996; Trout et al., 1995). Additionally, PAM can be used effectively in areas of rain-fed agriculture and sprinkler irrigation (Ben-Hur et al., 1989; Levy et al., 1992; Shainberg and Levy, 1994). After planting, PAM is sprayed on the soil either through the sprinkler irrigation system or directly on the soil via a high-pressure sprayer. Many researchers have shown that PAM can be used to maintain adequate infiltration under high intensity rainfall conditions (Levin et al., 1991; Shainberg et al., 1990; Smith et al., 1990), especially in the presence of electrolytes (Shainberg et al., 1990).

The objective of this paper is to present an overview of PAM use and application. It will include some of the recent findings in PAM work and focus on PAM use in furrow irrigation, rain-fed or sprinkler irrigation, and disturbed lands, including construction.

Polyacrylamide Characteristics

Polyacrylamide research for soil conditioning began in the 1950s. Yet, the most promising research has been

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Table 1. Soil physical and chemical properties.

Soil	Dominant clay mineral	Clay %	Total C %	OC [†]	CEC [†]	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	H ⁺
					cmol _c kg ⁻¹					
Heiden	Smectite	56.9	4.83	2.10	69.26	66.94	1.46	0.70	0.16	0.0
Fincastle	Mixed	16.0	0.82	0.82	10.83	6.71	3.38	0.21	0.07	0.46

[†] OC, Organic Carbon; CEC, Cation Exchange Capacity.

conducted in the last decade. Soil conditioners have been used for many years to stabilize soil aggregates. Natural soil polysaccharides and newer synthetic polymers have been researched extensively. Polyacrylamide is a water-soluble polymer with the ability to enhance soil stabilization. It is grouped in a class of compounds formed by the polymerization of acrylamide (Barvenik, 1994). Pure PAM is a homopolymer of identical acrylamide units. Polyacrylamide can be formulated with copolymers to give specific charges; the molecular weight can also be manipulated and generally ranges between a few thousand g mol⁻¹ to 20 Mg mol⁻¹ (Barvenik, 1994). Both molecular weight and charge give PAM its various characteristics.

Increasing the molecular weight increases the length of the polymer chain and the viscosity of the PAM solution. High molecular weight PAMs tend to be more effective than low molecular weight PAMs. A study by Levy and Agassi (1995) showed that the 20 Mg mol⁻¹ PAM performed better than the 200 kg mol⁻¹ PAM in reducing soil loss and maintaining infiltration rates. Current research using PAMs as soil conditioners focuses on high molecular weight (10-20 Mg mol⁻¹) anionic polymers (Fig. 1).

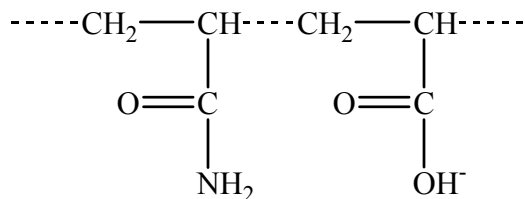


Figure 1. Molecular structure of anionic polyacrylamide.

The percent of sodium acrylate copolymerized in PAM is expressed as the charge density, which generally ranges from 2 to 40% for commercially available PAMs (Barvenik, 1994). Specifically, the charge density is the percent of acrylamide groups that have been substituted by sodium acrylate groups, generally termed percent hydrolysis. The ionic charge properties of PAM play an integral role in its adsorption to the soil. Michaels (1954) suggests that nonionic polymers are too tightly coiled to induce beneficial soil interactions. Likewise, a highly anionic polymer would have a very extended chain, as the negative groups would repel each other. Thus a medium anionic charge may be best. The terms high and medium are relative but suggest the mechanism of polymer behavior. Green et al. (2000) found that the effectiveness of a particular PAM formulation varied among soils of differing characteristics. They concluded that the charge density was the main factor affecting infiltration on clayey soils and that a charge density of 30% provided the greatest soil protection. On sandy soils, molecular

weight was the main factor affecting infiltration and molecular weight of 12 Mg mol⁻¹ worked most effectively. Cationic PAMs work well as flocculants, but as they are toxic to aquatic wildlife (Barvenik, 1994), their use as a soil amendment is extremely limited.

The way in which the polymer adsorbs to the soil is the key to its effectiveness as a soil amendment. Anionic PAM, being negatively charged like the clay surface, would be expected to experience repulsion from the negatively charged clay sites. However, it binds the negative sites through a process called cation bridging (Laird, 1997). Divalent cations are able to bridge the two negatively charged species together. Each positive charge of the divalent cation binds to one of the negative sites, either the clay surface or the anionic PAM. Hence, the presence of divalent cations, either in the PAM solution or on the clay surface, is imperative for effective soil stabilization (Laird, 1997; Shainberg et al., 1990).

Comparing flocculation rates of different PAM solutions emphasizes the importance of divalent cations in the soil-PAM system. As a demonstration, we prepared 10 mg L⁻¹ PAM solutions in deionized water and in 0.005 M CaCl₂ (tap water). Twenty g soil samples of Heiden clay and Fincastle silt loam (important physical and chemical properties of these soils are presented in table 1) were dispersed in 60 mL of deionized water and shaken over night. These samples were then introduced into 1 L columns of deionized water, tap water, PAM solution prepared in deionized water (10 mg L⁻¹) or PAM solution prepared in tap water (10 mg L⁻¹). We visually compared the flocculation rate of soil with deionized water and 0.005 M CaCl₂ with and without PAM at 10 and 30 seconds, and 5, 30, 60, and 120 minutes (Fig. 2). Soil in deionized water with and without PAM showed similar results with very little flocculation taking place throughout the entire time sequence. This demonstrates the ineffectiveness of PAM in the absence of divalent cations. In the presence of divalent cations (0.005 M CaCl₂) the soil in the PAM solution flocculated more rapidly than in 0.005 M CaCl₂ solution alone. After 120 minutes though, soil in the 0.005 M CaCl₂ solution without PAM had flocculated completely whereas soil in 0.005 M CaCl₂ with PAM was still slightly cloudy. This may have been due to the higher viscosity of the PAM-0.005 M CaCl₂ solution. For PAM to work effectively there must be a source of divalent cations (Laird, 1997). The divalent cation source may be in the PAM solution, in the soil, or through direct application to the soil (i.e. gypsum application). The Fincastle silt loam soil showed similar results as Heiden clay except that the flocculation was slightly slower. This was due to lower divalent cation content in the soil.

At an acid pH, though, anionic PAM can adsorb to the positive sites of variable charge surfaces that have under-

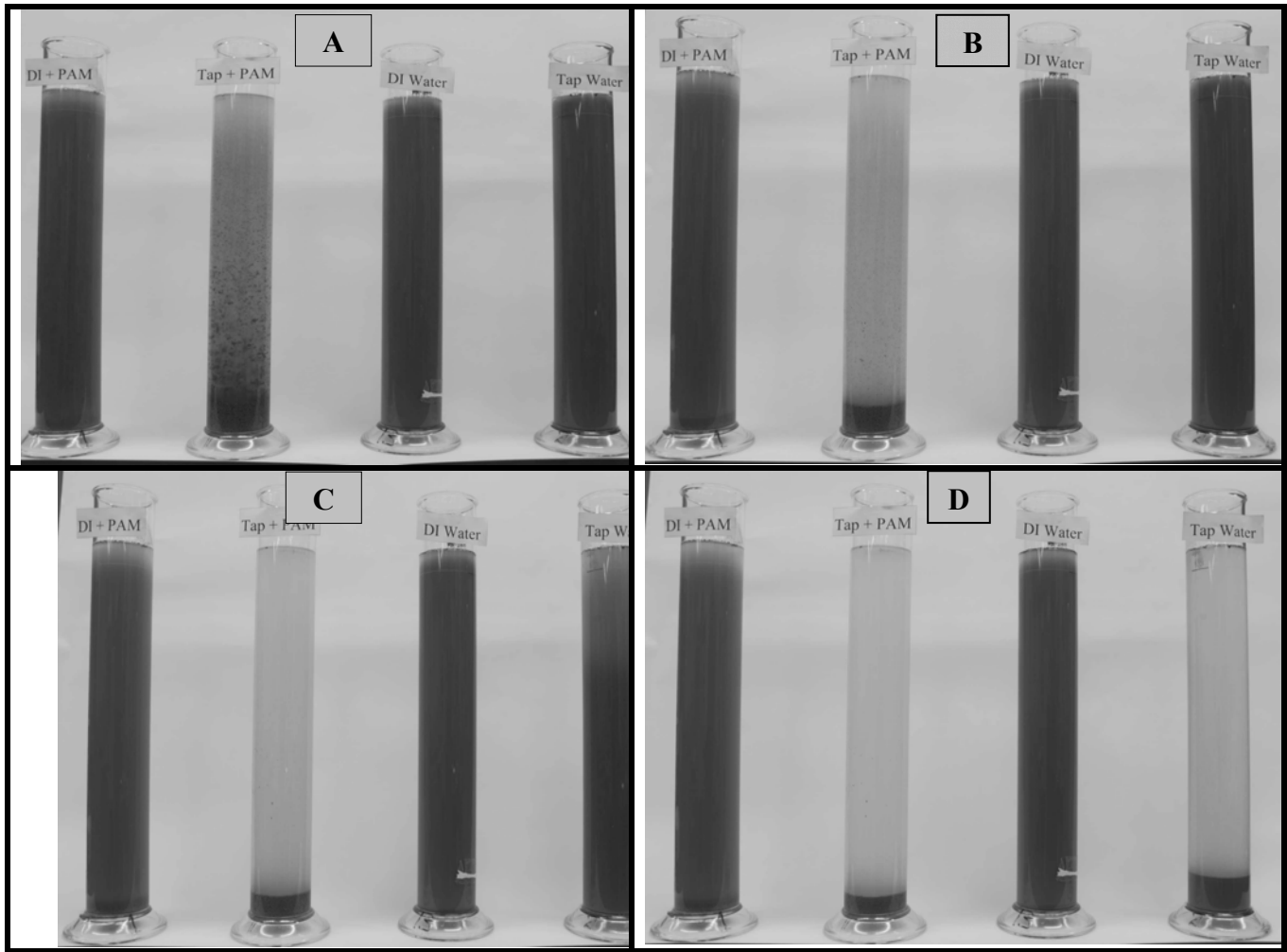


Figure 2. Flocculation of Heiden clay during a chronosequence where A is at 10 seconds from time of soil introduction; B is at 30 seconds; C is at 5 minutes; D is at 30 minutes. Treatments consist of solutions with and without PAM and with and without divalent cations present. DI + PAM= 10 mg L⁻¹ PAM in deionized water; Tap + PAM= 10 mg L⁻¹ PAM in 0.005 M CaCl₂; DI water= deionized water; Tap water= 0.005 M CaCl₂.

gone protonation (Theng, 1982). Adsorption of PAM to soil particles depends on both PAM and soil properties. Texture and clay type, organic matter content, and type of ions in the soil solution are the dominant soil properties affecting PAM adsorption while molecular weight, charge, and charge density are the main PAM properties involved (Seybold, 1994).

Increased effectiveness of PAM occurs when the treated soil is subjected to a drying cycle (Zhang and Miller, 1996). Nadler et al. (1992) found that after soils were subjected to a drying cycle, very few of the polymers experienced any desorption from the soil surface. Shainberg et al. (1990) found that complete drying of PAM and phosphogypsum treatments more than doubled the final infiltration values compared to incomplete drying. Drying induces inner-sphere complexes between the PAM and soil as well as van der Waals interactions (Shainberg et al., 1990). Thus a drying cycle causes the polymer chain to become irreversibly adsorbed to the soil.

Some of the characteristics of PAM pose some possible limitations. First, PAM solutions are viscous. This poses some problems for dissolving PAM in water and in applying PAM to the field if it is being sprayed. These limitations are being overcome as additional research is being conducted and means for more efficient application are being developed. Additionally, a single application of PAM is not a permanent or even a single season erosion control measure. It has been suggested that PAM is degraded by sunlight and mechanical breakdown (Wallace et al., 1986). Therefore a single application is only a temporary erosion control measure. This said, PAM is still very useful in controlling erosion when these limitations are understood and taken into account.

Use of Polyacrylamide as a Soil Conditioner

The versatility of PAM is one of the aspects that makes it attractive. Polyacrylamide can be used to control surface sealing and crusting, increase seedling emergence, reduce

runoff and erosion, as well as reduce fertilizer and pesticide losses. All these benefits help alleviate on-site and off-site pollution as well as costs. Additionally, PAM can be used on soils of different land-use including furrow irrigated and rain-fed agriculture, construction sites and road-cuts, mine spoils and other disturbed soils.

Polyacrylamide Use in Furrow Irrigation

Up to now the most applicable research has been conducted on the use of PAM in furrow irrigation (Sojka and Lentz, 1997). Here, PAM is used to increase infiltration and water quality while reducing erosion and water consumption. Early in PAM and other polymer research, researchers attempted to treat the entire plow layer (Sojka and Lentz, 1994). This proved labor intensive and costly so this line of research was essentially dropped. Researchers then discovered that only the soil surface needed to be treated since the surface is where soil sealing and erosion take place (Norton et al., 1993; Shainberg et al., 1994). With furrow irrigation, the treated area can be reduced to the furrow itself, reducing cost and labor. In fact, PAM can be applied directly with the irrigation water. Shainberg et al. (1994), using laboratory mini rill flumes, found that PAM application in the irrigation water at concentrations of >2.5 ppm prevented rill erosion at a 30% slope. They also found that, as with interrill erosion, rill erosion depends on the properties of the soil-water interface and not on the bulk properties of the underlying soil. Application rates of 5-20 ppm PAM in the irrigation water can reduce sediment loss by up to 98% in the initial irrigation (Lentz et al., 1992).

Lentz and Sojka (1994) found that PAM, under certain application strategies (10g m⁻³ during irrigation water furrow advance), reduced soil loss by 93%. Polyacrylamide treatments also improved water quality of tailwater discharge. They observed significant decrease in the amount of sediment, phosphates, nitrates, and biological oxygen demand in the tailwater. Infiltration rates were also improved. Trout et al. (1995) found infiltration rate to be enhanced by 30-110% over the control depending on application strategy. Polyacrylamide effectiveness in furrow irrigation results from PAM being applied in the initial pulse of water called furrow irrigation advance (Lentz and Sojka, 1994).

Polyacrylamide's effectiveness in furrow irrigation stems from the improvement in aggregate stability, which reduces detachment. Additionally, PAM has the ability to flocculate suspended clay and silt particles dispersed and transported by the flowing water (Sojka and Lentz, 1997). The result is increased porosity at the surface, decreased detachment, increased infiltration, higher water quality, and reduced water usage (Sojka and Lentz, 1997; Lentz and Sojka, 1994).

In furrow irrigation, PAM application is an economic soil and water conservation practice. The cost in PAM product is approximately US\$4 ha⁻¹ (according to year 2001 pricing and rate of 0.7 kg ha⁻¹) per application (generally 4 applications per season). Initial investment in injection machinery may be as much as US\$1500. Economic benefits include less furrow reshaping and cultivation, less retention pond construction and cleaning, and improved yield. In the arid areas of the world, less water usage is an incredible

economic as well as environmental benefit. Other environmental benefits include the obvious improvement in water quality due to reduced sediment outflow. Additionally, soil applied pesticides and fertilizers remain on the field as opposed to being washed away with the soil and runoff water.

Polyacrylamide Use in Rain Fed Irrigation (and Sprinkler Irrigation)

While PAM is being used in the field for furrow irrigation practices, it also has applicability to rain-fed agriculture and sprinkler irrigation. While sealing in furrow irrigation stems from the shear force of running water, sealing from raindrop impact evolves from 1) the impact of the drops on the soil surface and 2) the chemical dispersion of clays which then move into and clog the pore spaces (McIntyre, 1958). Soil sealing is affected by both soil and water characteristics including soil texture, mineralogy, pH, EC, organic matter content, rain intensity, electrolyte content, rainfall energy, etc. Many studies have been undertaken to determine PAM's applicability to rain-fed and sprinkler irrigated agriculture (Levy et al., 1992; Stern et al., 1992; Norton and Dontsova, 1998; Green et al., 2000). The majority of these studies have focused on PAM's effect on infiltration, runoff, and erosion.

Infiltration rates are affected by soil sealing. Application of PAM at a rate of 20 kg ha⁻¹ increased infiltration rates by 10 fold on susceptible loess soils, especially in the presence of electrolytes (Shainberg et al., 1990). Smith et al. (1990) found that addition of PAM at a rate of 20 kg ha⁻¹ resulted in increased final and cumulative infiltration by 7 to 8 fold compared to the control. Additionally, they observed decreased erosion by more than one order of magnitude compared to the control. Shainberg and Levy (1994) observed infiltration rates of soil applied with PAM and gypsum to had infiltration rates 10 times higher than the control. PAM effectiveness depends on charge type and density as well as molecular weight (Shainberg and Levy, 1994; Green et al., 2000).

PAM can be used effectively to control soil crust formation. This is dependent upon both PAM properties and soil properties. Clayey soils responded well to the charge density of the PAM while sandy soils responded more to the molecular weight of the PAM (Green et al., 2000). Therefore it is essential to take into account the soil properties in the selection of a PAM product in order to obtain optimum benefits.

The cost of PAM (US\$5 kg⁻¹) and cost of application defines where and when it can be used economically in rain-fed agriculture. Research has shown that a PAM application rate of 20 kg ha⁻¹ is effective for controlling erosion in many situations (Shainberg et al., 1990). This results in a cost of US\$100 ha⁻¹ for PAM product alone. Fortunately, PAM can be applied using general farm equipment that the farmer already owns. The application rate may need to be adjusted depending on the specific conditions. The economic benefits include increased yield due to increased seedling emergence and reduced erosion (both onsite and offsite costs). Depending on the crop and the soil management system, PAM may or may not be an economic alternative. For

certain crops on certain soils, PAM may be an economic alternative to other soil erosion and conditioning methods on a field scale. In other situations, PAM may be the best alternative for certain problem areas of a field and can be used quite effectively to alleviate soil sealing and subsequent erosion.

Environmental benefits include reduced soil loss, reduced pesticide and fertilizer runoff. This enhances both soil and water quality, both on site and off site.

Polyacrylamide use in Construction

Polyacrylamide is an alternative to traditional erosion control practices. Polyacrylamide use is very well suited for the construction industry where millions of dollars are spent to control erosion for short periods of time. Construction activities in the United States disturb hundreds of thousands of hectares annually (Troeh et al., 1991). With the disturbance comes the potential for severe erosion due to steep slopes, bare soil, and compaction.

Mulch application is the traditional method used to control erosion and promote vegetation establishment on construction sites. Due to high application cost, unavailability, and bulk, mulch may not be the best alternative in many cases (Wallace and Wallace, 1986). Additionally, mulches are generally ineffective once rills form (Meyer et al., 1972).

On steep slopes, PAM reduced runoff by more than 30% along with a reduction of sediment yield of more than 50% (Chaudhari and Flanagan, 1998). Additional benefits include decreased rilling, increased vegetation establishment, less reshaping of slopes, and reduced on- and off-site water pollution.

Due to necessary increase in application rate on steep slopes, PAM application on construction sites and other steep slopes costs more than on agricultural land. Even so, PAM application (including product cost at application rate of 80 kg ha⁻¹) will range from US\$265-550 ha⁻¹, which is much less than the cost of straw mulch product and placement (Flanagan and Chaudhari, 1999). Polyacrylamide provides substantial savings while controlling erosion and increasing vegetation establishment on construction sites. Using PAM in conjunction with other erosion control measures may also provide economical erosion control and warrants further investigation.

CONCLUSION

As a soil erosion control amendment, PAM is versatile, effective, and generally economical. In furrow irrigation, PAM protects the soil by reducing detachment and flocculating soil particles that do get detached. The increased infiltration results in less runoff and erosion as well as reduced water usage. Polyacrylamide is economical under certain conditions in rain-fed agriculture such as on soils used for high value crops as well as management of problem areas in a field. Polyacrylamide is effective in reducing runoff, erosion, and soil sealing. The construction industry has a great potential for PAM use. Whether used alone or in conjunction with other erosion control practices, PAM is both economical and effective in controlling erosion. The potential for PAM use in erosion control

continues to increase as researchers learn more about the properties of PAM and its interaction with soil.

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