

# Polyacrylamide Molecular Weight and Charge Effects on Infiltration under Simulated Rainfall

V. Steven Green, D. E. Stott,\* L. D. Norton, and J. G. Graveel

## ABSTRACT

Soil sealing is a severe problem worldwide. Increased runoff and decreased seedling emergence cause on- and off-site problems affecting farmers and communities. One possible soil sealing control measure is the application of polyacrylamide (PAM). Little is known about the interaction of specific PAMs with soils of differing characteristics. This study was conducted to examine the relationship between different PAMs and soils of varying characteristics. We examined PAM charge densities (CD) of 20, 30, and 40% hydrolysis with molecular weights (MW) of 6, 12, and 18 Mg mol<sup>-1</sup>. The soils used were Heiden clay (fine, smectitic, thermic Udic Haplustert), Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult), and Fincastle silt loam (fine-silty, mixed, mesic Aeric Epiaqualf). Polyacrylamide (20 kg ha<sup>-1</sup>) was sprayed onto the soil in liquid form. Soil material was exposed to rainfall simulation in the laboratory. Infiltration rate was used as an indicator of soil surface sealing. Polyacrylamide increased infiltration rates on all three soils relative to the control. Twenty and 30% CD PAMs performed best in maintaining high infiltration rates on Heiden clay. The 12 Mg mol<sup>-1</sup> MW formulations worked best for Cecil sandy loam. Fincastle silt loam showed no preference for a particular PAM formulation. Polyacrylamide increased final infiltration rate by as much as 3- to 5-fold for these soils. Different PAM formulations provided differing degrees of soil protection, varying between soils. Understanding the interaction of different soils with various PAM formulations will enable PAM users to select the best PAM product for their soil conditions.

SOIL PHYSICAL PROPERTIES greatly affect how the soil will function in the field. Infiltration rate and aggregate stability are listed among the most important soil quality indicators (Doran and Parkin, 1996). For agricultural uses as well as construction site management, soil moisture recharge and stable aggregation are imperative. As infiltration decreases, runoff and erosion increase, thus degrading the soil. 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 great force, compacting the soil and creating a structural crust. Additionally, the impact of the rain and the rapid wetting of the soil cause slaking and dispersion of clays, thus disrupting the integrity of the soil aggregate. Once the soil aggregate has slaked and 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).

Different methods have been used to quantify the amount of sealing or crusting that takes place. These include measuring infiltration rates, using pocket and needle penetrometers, and percent seedling emergence. Infiltration rate measures the amount of water passing through the soil and is an indication of the total available pore space and pore conductivity. At the beginning of a storm event, infiltration rates of well-aggregated soil are relatively high. As rain impacts the soil and slaking and dispersion occur, structural and depositional seals develop, decreasing the amount of pore space. As the amount of pore space decreases, the infiltration rate decreases until the steady state infiltration of the sealed soil is reached, which will be less than that from reduction in soil water gradient alone (Levin et al., 1991). Hence, we can quantify surface sealing using infiltration measurements (Norton, 1987). Measuring the infiltration rate has the advantage of being able to monitor the sealing process through time.

Polyacrylamide (PAM) stabilizes soil structure but does not remediate poor soil structure (Cook and Nelson, 1986). In the arid and Mediterranean climates of the world, anionic PAM of high molecular weight (MW; 12–15 Mg mol<sup>-1</sup>) and low charge density (CD; 18–20%) 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 (MW 10–15 Mg mol<sup>-1</sup>; CD 20%) has been found to be effective in areas of rain-fed agriculture and sprinkler irrigation (Ben-Hur et al., 1989; Levy et al., 1992; Shainberg and Levy, 1994). Polyacrylamide is sprayed on the soil either through a sprinkler irrigation system or directly on the soil via a high-pressure sprayer. Many researchers have shown that high MW PAM can be used to maintain adequate infiltration under high intensity simulated rainfall conditions (Levin et al., 1991; Shainberg et al., 1990; Smith et al., 1990), especially in the presence of electrolytes (Shainberg et al., 1990).

Molecular weight of commercial PAM typically ranges from a few thousand g mol<sup>-1</sup> to 20 Mg mol<sup>-1</sup> (Barvenik, 1994). Increasing the MW increases the length of the polymer chain and the viscosity of the PAM solution. High MW PAM tend to be more effective for flocculation than low MW PAM (Linke, 1962). A study by Levy and Agassi (1995) showed that the 20 Mg mol<sup>-1</sup> PAM performed better than the 0.2 Mg mol<sup>-1</sup> PAM in reducing soil loss and maintaining infiltration rates. Current research using PAM as soil conditioners focuses on high MW (10–20 Mg mol<sup>-1</sup>) anionic polymers (Barvenik, 1994).

V.S. Green and J.G. Graveel, Dep. of Agronomy, Purdue Univ., 1150 Lilly Hall, West Lafayette, IN 47907-1150; D.E. Stott and L.D. Norton, USDA-ARS, National Soil Erosion Research Lab., 1196 Soil Building, West Lafayette, IN 47907-1196. Received 30 Aug. 1999. \*Corresponding author (destott@purdue.edu).

**Abbreviations:** CD, charge density; MW, molecular weight; PAM, polyacrylamide.

The amount of charge on a PAM is referred to as charge density (CD) or percent hydrolysis, which is the mole percent of charged comonomers in the anionic PAM. Charge density generally ranges from 2 to 40% for commercially available anionic PAM (Barvenik, 1994). From a practical viewpoint, the CD is the percentage of OH<sup>-</sup> groups substituted for acrylamide groups.

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. Counterintuitively, it does bind to some of the negative sites, primarily 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 bonds 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). At an acid pH, though, anionic PAM can adsorb to the positive sites of variable charged surfaces that have undergone 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). Unfortunately, many research papers only specify relative MW and CD as low, medium, or high and give only the range in which it belongs.

Many different molecular formulations of anionic PAM are commercially available. Unfortunately, very few of them have been examined and compared for use as soil amendments. Our objective was to examine systematically the influence of CD and MW of anionic polymers on the infiltration rate of various soils under rainfall simulation. We also planned to determine the best PAM formulation(s) for maintaining high infiltration and to determine whether the best PAM formulations are the same for different soils of varying characteristics (e.g., texture, mineralogy, etc.). We hypothesized that sandy soils will likely need a greater MW PAM than clayey soils as there are fewer adsorption sites on sandy soils. Charge density of 30% will likely be the optimum for these soils. Low charge (20%) will likely be too tightly coiled for adequate adsorption to clay sites. High charge (40%) will likely have too much polymer-particle repulsion for adequate adsorption. Different soils will likely have varying optimum PAM formulations for effective protection against soil seal and crust formation.

**Table 2. Soil chemical properties.**<sup>†</sup>

Soil	pH	ESP	g kg <sup>-1</sup>			CEC	Ca <sup>2+</sup>	cmol <sub>c</sub> kg <sup>-1</sup>			
			Total C	OC	Total N			Mg <sup>2+</sup>	K <sup>+</sup>	Na <sup>+</sup>	H <sup>+</sup>
Heiden	7.62	0.23	48.3	21.0	1.7	69.26	66.94	1.46	0.70	0.16	0.0
Cecil	4.98	0.81	4.7	4.7	0.6	6.17	3.41	0.69	0.34	0.05	1.68
Fincastle	5.58	0.65	8.2	8.2	1.1	10.83	6.71	3.38	0.21	0.07	0.46

<sup>†</sup> ESP, exchangeable sodium percentage; OC, organic carbon; CEC, cation exchange capacity.

**Table 1. Soil physical properties.**

Soil	MWD <sup>†</sup>	Sand	Silt	Clay
	mm			
Heiden	0.56	125	306	569
Cecil	0.51	707	159	134
Fincastle	0.36	140	700	160

<sup>†</sup> MWD, mean weight diameter of 1–2 mm aggregates.

## MATERIALS AND METHODS

### Soils

Three soils were used in this study. Heiden clay (fine, smectitic, thermic Udic Haplustert) was sampled from the USDA Grassland, Soil, and Water Laboratory field station at Reisel, TX; Heiden clay is dominated by smectite and calcite clays with some quartz (Reichert and Norton, 1994). Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult) was sampled from the USDA Southern Piedmont Conservation Research Center at Watkinsville, GA; it is dominated by kaolinite clays with some quartz and hydroxy-interlayer vermiculite (Reichert and Norton, 1994). Fincastle silt loam (fine-silty mixed, mesic Aeric Epiaqualf) was sampled from the Purdue University Agronomy Research Center at West Lafayette, IN; Fincastle silt loam, which is in association with Miami silt loam, has a mixed mineralogy and is composed of smectite, vermiculite, clay mica, and kaolinite (Norton et al., 1993). Soil material was collected from the top 10 cm of the Ap horizon at each site. Sample collection took place in August 1996 for Heiden clay and Cecil sandy loam and in August 1997 for Fincastle silt loam. Soil was air-dried, gently crushed to pass a 2.0-mm sieve, and stored at room temperature until packed in erosion pans.

Important physical and chemical soil properties were determined in the laboratory (Tables 1 and 2). Cation exchange capacity was measured by summing the extractable cations that were extracted with 2 M ammonium acetate at pH 7 and extractable acidity at pH 8. Calcium and Mg were measured by atomic absorption while K and Na were measured by emission spectroscopy. Total C and N were determined by dry combustion (CHN-600, Leco Corp., St. Joseph, MI). Organic C was determined by dry combustion after the carbonates were destroyed by acidification. Soil pH was measured on a 2:1 water slurry (deionized water:air dry soil). Aggregate mean weight diameter (MWD) was determined by wet sieving for 10 min (Kemper and Roseneau, 1986). Mean weight diameter was measured on the 1- to 2-mm size fraction with sieve sizes 1.0 and 0.2 mm. Particle size analysis was measured by the pipet method (Gee and Bauder, 1986).

### Infiltration

Interrill erosion pans, 0.14 m<sup>2</sup> (0.40 m long by 0.32 m wide) and 0.20 m deep, were packed with 0.14 m of gravel in the bottom and 0.03 m of sand in the middle to control water tension and facilitate infiltration measurements. Air dry soil (aggregates <2.0 mm) was packed in the top 0.03 m at specific bulk densities; Heiden clay was packed at 1.4 Mg m<sup>-3</sup>, Cecil

sandy loam at  $1.6 \text{ Mg m}^{-3}$ , and Fincastle silt loam at  $1.2 \text{ Mg m}^{-3}$ . Different soil bulk densities were used to simulate the bulk density commonly found in the field for the particular soil. An acrylic splashguard, 0.20 m in height, was placed on all sides of the erosion pans to reduce soil loss by splash erosion.

Upon treatment, the soil was prewetted from the bottom of the erosion pans by capillary action for 2 h with deionized water. The erosion pans were raised to a 5% slope and allowed to drain for 15 min while a 5-cm tension was held at the center of the pans to act as a watertable (Reichert and Norton, 1996). The 5-cm tension was maintained during the rainfall event. Rainfall, in the form of deionized water, was applied to the erosion pan soil at a rate of  $68 \text{ mm h}^{-1}$  for one h with a kinetic energy of approximately  $27.5 \text{ J m}^{-2} \text{ mm}^{-1}$  (Meyer and Harmon, 1979). The rainfall simulator was programmable and equipped with 80-150 VeeJet spray nozzles (Spraying Systems Co., Wheaton, IL). The simulator consisted of two troughs with three nozzles per trough. The nozzles were 1.1 m apart. The simulator nozzles were 2.4 m above the soil surface. The erosion pans were placed directly under the troughs, between the nozzles. Infiltration was measured at 5-min intervals during the rainfall event as drainage from outlets in the bottom of the pans.

### Treatments

Polyacrylamide (PAM; The Waterclear Co., Renton, WA) solutions were made by dissolving PAM (in crystal form) in  $0.005 \text{ M CaCl}_2$  and bringing to a 1-L volume. Polyacrylamide solutions were prepared in dilute  $\text{CaCl}_2$  in order to reduce chemical dispersion of the soil by deionized water and to add  $\text{Ca}^{2+}$  ions to the system to enhance cation bridging (Ben-Hur et al., 1989). Polyacrylamide solutions were prepared at a concentration of  $288 \text{ mg L}^{-1}$ . Such a dilute concentration was needed in order to be able to spray the high MW ( $18 \text{ Mg mol}^{-1}$ ) PAM solutions. The lower MW solutions were also diluted to this concentration in order to maintain consistency between treatments for statistical analysis, but in practice, can be more concentrated.

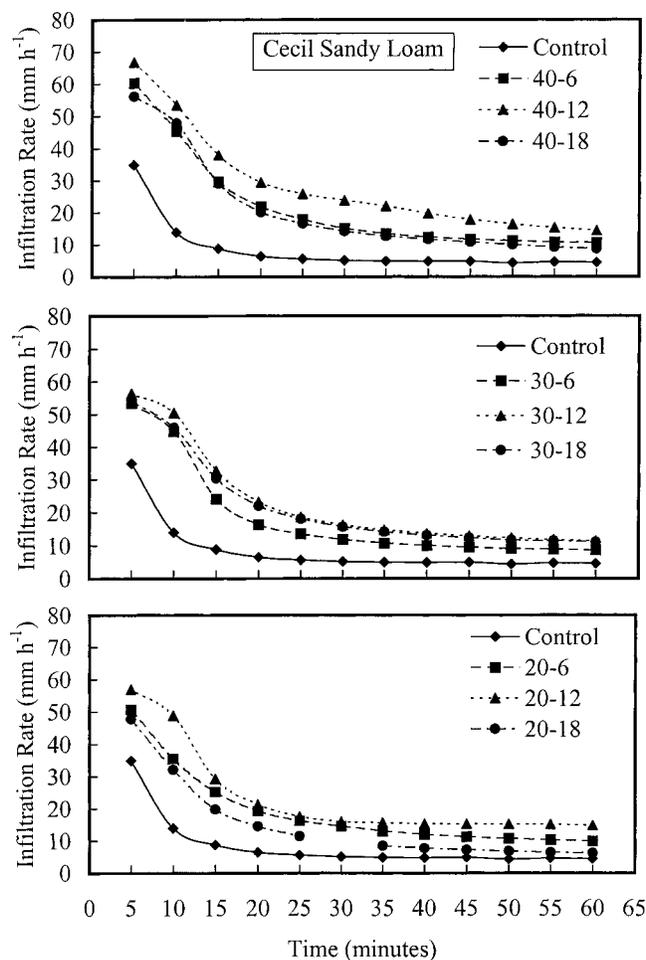
The soil surface in the erosion pan was sprayed with different PAM treatments at a rate of  $20 \text{ kg ha}^{-1}$ . Shainberg et al. (1990) found that dilute solutions of PAM at  $20 \text{ kg ha}^{-1}$  resulted in increased infiltration. Polyacrylamide treatments consisted of three CD (20, 30, and 40% hydrolysis) and three MW (6, 12, and  $18 \text{ Mg mol}^{-1}$ ) in all possible combinations for a total of 9 treatments plus a control consisting only of the  $0.005 \text{ M CaCl}_2$  solution. Polyacrylamide treatments are abbreviated as CD-MW (e.g., PAM of 20% CD and  $6\text{-Mg mol}^{-1}$  MW would be 20-6).

All amendments were sprayed on the soil surface in two 0.5-L applications, with a hand held compressed  $\text{CO}_2$  sprayer, separated by a 30-min interval between applications. The treated erosion pan soils were then left to air-dry 24 h under a gentle breeze from a fan as full air-drying results in more permanent binding of PAM to the soil (Shainberg et al., 1990).

All treatments were replicated twice in a randomized complete block, two-factor factorial design. Each block consisted of one replicate. The two factors of the factorial were MW and CD. Analysis of variance (ANOVA), included in SAS (SAS Institute, Inc., 1996 Windows Vers. 6.12), was used to determine significance of treatment vs. no treatment, CD, MW, and  $\text{CD} \times \text{MW}$ . Significant difference between treatment means was performed using Tukey's Honestly Significant Difference (HSD) procedure at  $\alpha = 0.05$ .

## RESULTS AND DISCUSSION

Infiltration rates decreased as amount of cumulative rain increased. The decrease in infiltration rates was



**Fig. 1.** Infiltration rate as a function of time with rainfall intensity of  $68 \text{ mm h}^{-1}$  on a Cecil sandy loam soil treated with PAMs of different molecular formulations. PAM treatments are abbreviated as charge density-molecular weight (CD-MW). This figure is a general representation of the trend for infiltration rates observed on all three soils.

due to the formation of a surface seal caused by the physical breakdown of aggregates and clay dispersion (LeBissonais, 1990; Norton, 1987). The use of soil material  $<2 \text{ mm}$  caused more rapid sealing than if we had used  $<4 \text{ mm}$  soil material. Clearly, all three soils experienced a similar trend in reduction in infiltration rate, as did the 10 treatments (9 PAM treatments plus the control) within each soil (Fig. 1). Since all three soils showed the same general infiltration trend, only one figure (Cecil sandy loam) is presented. Differences did appear, however, in the rate of decrease and in the final (steady state) infiltration rates (Tables 3, 4, and 5).

Final infiltration rates (FIR) varied greatly between soils with Heiden clay ranging from  $5.6$  (control) to  $23.7$  (PAM 30-6)  $\text{mm h}^{-1}$  (Table 3), Cecil sandy loam ranging from  $4.4$  (control) to  $14.8$  (PAM 20-12)  $\text{mm h}^{-1}$  (Table 4), and Fincastle silt loam ranging from  $2.0$  (control) to  $9.7$  (30-12)  $\text{mm h}^{-1}$  (Table 5). Susceptibility to seal formation occurred in the order Fincastle silt loam  $>$  Cecil sandy loam  $>$  Heiden clay. This is in accordance with other research, which has shown that soil texture (specifically the clay content) is one of the dominant factors

**Table 3. Effect of polyacrylamide molecular weight and charge density on final infiltration rate of Heiden clay. Treatment infiltration rates are the mean of two replicates.**

Charge density	Final infiltration rate				Mean†
	Molecular weight (Mg mol <sup>-1</sup> )				
	0	6	12	18	
%	mm h <sup>-1</sup>				
0	5.6	—	—	—	—
20	—	15.8	22.4	21.8	20.0
30	—	23.7	22.4	23.6	23.2
40	—	15.9	14.7	18.3	16.3
Mean‡	—	18.5	19.8	21.2	19.8§

Tukey's Honestly Significant Difference (HSD) for comparing any 2 treatment means; Tukey's HSD = 7.9.

† Mean averaged across the molecular weight and replicates, within charge density; Tukey's HSD = 3.6.

‡ Mean averaged across the charge density and replicates, within molecular weight; Tukey's HSD = 3.6.

§ Combined average of all PAM treatments.

in controlling seal formation (Ben-Hur et al., 1985). Heiden clay, having a high clay content (570 g kg<sup>-1</sup>) has a strong resistance to seal formation. Both Fincastle silt loam (160 g kg<sup>-1</sup> clay) and Cecil sandy loam (130 g kg<sup>-1</sup> clay) are close to the critical 200 g kg<sup>-1</sup> clay content described by Ben-Hur et al. (1985), which is the clay content at which soils are most susceptible to seal formation from rainfall. They observed a decrease in saturated hydraulic conductivity as clay content increased up to 200 g kg<sup>-1</sup> while an increase in clay content above 200 g kg<sup>-1</sup> resulted in an increase in saturated hydraulic conductivity. This is due to the stabilizing and cementing properties of clays. Soils with high clay content are cemented together from the clay bonds giving them better stability. Soils very low in clay do not have as much clay to disperse and cause a surface seal. Since Fincastle silt loam is closer to the 200-g kg<sup>-1</sup> clay content; we expected it to exhibit the most severe sealing, which it did.

Heiden clay responded to PAM treatment, with all treatments having greater FIR than the control. Infiltration rates for PAM treatments decreased gradually with time until steady state infiltration was reached near the end of the 1-h rainfall event. Infiltration rate for the control, however, decreased sharply within the first 30 min, gradually decreasing to a steady state. One of the PAM treatments (PAM 20-18) experienced infiltration rates equal to or in excess of rainfall amounts during the first 10 min of rainfall. This may have been due to incomplete drainage before initiation of rainfall for this particular treatment on this soil. Fifteen minutes may not have been enough time for complete drainage for this soil-PAM combination.

Polyacrylamide treatments resulted in FIR of 263 to 422% of the control. Charge density was the significant factor (Table 6) in the performance of the different PAM treatments on Heiden clay, whereas MW was not significant. The 20 and 30% CD treatments performed better than the 40% CD when MWs were averaged for each CD. No significant differences were found between the MWs. This is consistent with published data (Theng, 1979), which shows that high CDs can induce polymer repellence, thus restricting polymer coiling and reducing adsorption onto clay particles. Ben-Hur et al. (1992)

**Table 4. Effect of polyacrylamide molecular weight and charge density on final infiltration rate of Cecil sandy loam. Treatment infiltration rates are the mean of two replicates.**

Charge density	Final infiltration rate				Mean†
	Molecular weight (Mg mol <sup>-1</sup> )				
	0	6	12	18	
%	mm h <sup>-1</sup>				
0	4.4	—	—	—	—
20	—	9.9	14.8	6.3	10.3
30	—	8.5	11.3	11.0	10.3
40	—	10.6	14.4	8.7	11.2
Mean‡	—	9.7	13.5	8.7	10.6§

Tukey's Honestly Significant Difference (HSD) for comparing any 2 treatment means; Tukey's HSD = 9.5.

† Mean averaged across the molecular weight and replicates, within charge density; Tukey's HSD = 3.5.

‡ Mean averaged across the charge density and replicates, within molecular weight; Tukey's HSD = 3.5.

§ Combined average of all PAM treatments.

showed that as PAM charge density increased, adsorption onto montmorillonite clay decreased. They proposed that this was in part due to the potential barrier to penetration of high charge PAM into micro-aggregates as the coil size increases with increasing CD. Additionally, the high negative charge from the PAM and the high negative charge from the smectitic clay may have induced polymer-clay repellence resulting in decreased adsorption (Theng, 1979; Ben Hur et al., 1992).

All three MWs were represented in the top PAM performers. Research has shown that polymer MW is a key factor in the effectiveness of PAM on coarse textured soils, but not on fine textured soils (Levy and Agassi, 1995). Fine textured soils (high clay content such as Heiden clay) have a short distance between clay particles so even relatively short chain length polymers (low MW) can span the distance between the clay particles and bind them together.

The chemistry of the Heiden clay is also believed to have played an important role in PAM's efficacy in controlling seal formation. Heiden clay has a very high CEC (69.3 cmol<sub>c</sub> kg<sup>-1</sup>) with a large portion of that coming from Ca<sup>2+</sup> (66.9 cmol<sub>c</sub> kg<sup>-1</sup>). This provides numerous divalent cations to enhance the cation bridging process that is so important in PAM adsorption to soil (Laird,

**Table 5. Effect of polyacrylamide molecular weight and charge density on final infiltration of Fincastle silt loam. Treatment final infiltration rates are the mean of two replicates.**

Charge density	Final infiltration rate				Mean†
	Molecular weight (Mg mol <sup>-1</sup> )				
	0	6	12	18	
%	mm h <sup>-1</sup>				
0	2.0	—	—	—	—
20	—	8.9	7.7	6.1	7.6
30	—	6.8	9.7	7.5	8.0
40	—	8.1	7.0	6.0	7.0
Mean‡	—	7.9	8.1	6.5	7.5§

Tukey's Honestly Significant Difference (HSD) for comparing any 2 treatment means; Tukey's HSD = 4.0.

† Mean averaged across the molecular weight and replicates, within charge density; Tukey's HSD = 1.7.

‡ Mean averaged across the charge density and replicates, within molecular weight; Tukey's HSD = 1.7.

§ Combined average of all PAM treatments.

**Table 6. Analysis of variance for final infiltration rate.**

Source of variation	df	Heiden clay		Cecil sandy loam		Fincastle silt loam	
		MS†	Sig.	MS	Sig.	MS	Sig.
Block	1	15.66	NS†	0.46	NS	0.95	NS
Treatment	9	64.06	***	21.13	*	8.81	**
Control vs. PAM	1	363.80	***	68.78	**	55.24	***
MW‡	2	11.48	NS	39.75	*	4.38	*
CD¶	2	71.86	***	1.80	NS	1.40	NS
MW × CD	4	11.50	NS	9.56	NS	3.11	NS
Error	9	3.42		5.51		1.00	

\* \*\*, \*\*\* Significance at the 0.05, 0.01, and 0.001 probability levels respectively.

† MS, Mean square.

‡ NS, Not significant at the 0.05 probability level.

§ MW, Molecular weight.

¶ CD, Charge density.

1997). The divalent cations bind to both the negatively charged PAM and the negatively charged clay surface. The long chains of PAM are able to bind to several clay surfaces in this manner, thus stabilizing the aggregate.

Infiltration rates on Cecil sandy loam decreased rapidly with time and reached close to steady state infiltration within 40 min for all treatments except for the 40-12 treatment, which reached steady state infiltration, near the end of the hour. The control, however, reached near steady state infiltration within 25 min. Final infiltration rate for PAM treatments ranged from 141 to 335% of the control, yet only two treatments were significantly better than the control, with none of the PAM treatments being significantly different from each other (Table 4). The treatments performing better than the control were 20-12 and 40-12. Molecular weight was a significant factor influencing the performance of PAM on this soil (Table 6). The 12-Mg mol<sup>-1</sup> MW performed better than the 6- and 18-Mg mol<sup>-1</sup> MW. With the Cecil sandy loam soil having a small amount of clay (130 g kg<sup>-1</sup>), MW plays a major role in soil protection. Levy and Agassi (1995) hypothesized that the efficacy of lower MW polymers tends to be reduced, as the polymer may not be long enough to bridge adjacent clay particles on such a coarse textured soil. Additionally, the kaolinitic mineralogy has a low surface charge, thus reducing the number of reactive sites. The decreased efficacy of the greater MW (18 Mg mol<sup>-1</sup>) PAM may have resulted from the larger molecule having more difficulty penetrating the small pore spaces in the aggregates (Barraclough and Nye, 1979). If this were the case, however, we should have observed this in the other soils. This was not observed in the Heiden clay soil where the pore spaces would have been even smaller, yet it was observed in the Fincastle silt loam. Although this may be part of the puzzle, it does not adequately explain the phenomena observed. It may be that the CD, being the important factor for the Heiden clay, masked the phenomena of high MW, but is likely some other elusive characteristic. Additionally, the lower MW (6 Mg mol<sup>-1</sup>) molecule may have been too short to adequately bridge the distance between clay particles. We hypothesize, therefore, that lower MW polymers may be able to penetrate soil aggregates slightly more than higher MW polymers, but higher MW polymers are able to bridge longer distances. Thus a medium-size MW PAM may be necessary for optimum performance. For the Cecil

sandy loam soil, MW, not CD, was the major factor in controlling FIR and soil sealing.

Infiltration rates on Fincastle silt loam soil decreased rapidly with time and reached close to steady state within 40 min for all PAM treatments. The control reached near steady state within 30 min. Many treatments showed low initial infiltration rates (at 5 min) indicating rapid sealing or possibly some sealing from the application of the PAM treatments. Another possibility for the low initial infiltration rates is the inherent low infiltration capacity of Fincastle silt loam.

Final infiltration rate for PAM treatments on Fincastle silt loam ranged from 304 to 488% of the control. All treatments performed better than the control except PAM 40-18 (Table 5). The combination of high MW and high CD may have created such large coils as to make it difficult for the PAM to penetrate the soil aggregates. Interestingly, Fincastle silt loam showed the greatest percent increase in FIR over the control compared to the other two soils even though it showed the most susceptibility to sealing in its untreated state. Fincastle silt loam, having a medium texture and mixed mineralogy, showed no significant differences between PAM treatments. Additionally, no statistical differences were encountered for CD or MW by Tukey's procedure. However, the ANOVA detected a significant effect of MW at the 0.05 probability level (Table 6).

## CONCLUSION

Surface seals occurred on all three soils with all PAM treatments, but had different rates and extents of surface sealing. The addition of different PAMs resulted in differing degrees of soil protection. For the Heiden clay soil, all nine PAM treatments provided soil protection significantly above that of the control. Of the nine treatments, the 20 and 30% CD treatments performed better than the 40% CD treatments. This may be a function of clay mineralogy where the high charge of the smectite clays repelled the highly anionic PAMs of 40% CD and the micro-aggregate pore spaces are small, but this was not specifically examined in this study. Charge density was the main factor affecting the PAM performance for this soil. For the Cecil sandy loam soil, only two treatments were significantly better than the control, 20-12 and 40-12. The MW for Cecil sandy loam was a significant factor affecting PAM performance, with

12 Mg mol<sup>-1</sup> MW being the most effective. Eight of the PAM treatments resulted in a greater FIR than the control on the Fincastle silt loam soil.

Different soils had varying optimum molecular formulations of PAM for effective protection. No single PAM performed better than all of the others. The trend observed in this research indicates that CD of 30% provides the greatest protection for clayey soils (e.g., Heiden clay) while a MW of 12 Mg mol<sup>-1</sup> is highly effective for sandy soils (e.g., Cecil sandy loam). For an off-the-shelf type of PAM for general use, a CD of 30% associated with a MW of 12 Mg mol<sup>-1</sup> is a likely candidate. For specific situations and soil types, however, certain PAM formulations will work better than others. Understanding the interaction between PAMs of different molecular formulations and soils of varying physicochemical properties will enable soil managers to select the most effective PAM product for their specific soil properties and conditions, better conserving our soil resources. The interaction between soil type and PAM molecular formulations appears to be significant and warrants further investigation.

## REFERENCES

- Barraclough, D., and P.H. Nye. 1979. The effect of molecular size on diffusion characteristics in soil. *J. Soil Sci.* 30:29–42.
- Barvenik, F.W. 1994. Polyacrylamide characteristics related to soil applications. *Soil Sci.* 58:235–243.
- Ben-Hur, M., J. Faris, M. Malik, and J. Letey. 1989. Polymers as soil conditioners under consecutive irrigations and rainfall. *Soil Sci. Soc. Am. J.* 53:1173–1177.
- Ben-Hur, M., M. Malik, J. Letey, and U. Mingelgrin. 1992. Adsorption of polymers on clays as affected by clay charge and structure, polymer properties and water. *Soil Sci.* 153:349–356.
- Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and CaCO<sub>3</sub> content on water infiltration in crusted soil as related to water salinity. *Irr. Sci.* 6:281–294.
- Cook, D.F., and S.D. Nelson. 1986. Effect of polyacrylamide on seedling emergence in crust-forming soils. *Soil Sci.* 141:328–333.
- Doran, J.W., and T.B. Parkin. 1996. Quantitative indicators of soil quality: a minimum data set. p. 25–37. *In* J.W. Doran and A.J. Jones (ed.) *Methods for assessing soil quality*. SSSA Spec. Publ. 49. SSSA, Madison, WI.
- Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Kemper, W.D., and R.C. Roseneau. 1986. Aggregate stability and size distribution. p. 425–442. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Laird, D.A. 1997. Bonding between polyacrylamide and clay mineral surfaces. *Soil Sci.* 162:826–832.
- LeBissonnais, Y. 1990. Experimental study and modelling of soil surface crusting processes. p. 13–28. *In* R.B. Bryan (ed.) *Soil erosion—experiments and models*. Catena Verlag, Cremlingen, Germany.
- LeBissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* 47:425–437.
- Lentz, R.D., and R.E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. *Soil Sci.* 158:274–282.
- Lentz, R.D., R.E. Sojka, and D.L. Carter. 1996. Furrow irrigation water quality effects on soil loss and infiltration. *Soil Sci. Soc. Am. J.* 60:238–245.
- Levin, J., M. Ben-Hur, M. Gal, and G.J. Levy. 1991. Rain energy and soil amendments effects on infiltration and erosion of three different soil types. *Aust. J. Soil Res.* 29:455–465.
- Levy, G.J., and M. Agassi. 1995. Polymer molecular weight and degree of drying effects on infiltration and erosion of three different soils. *Aust. J. Soil Res.* 33:1007–1018.
- Levy, G.J., J. Levin, M. Gal, M. Ben-Hur, and I. Shainberg. 1992. Polymers' effects on infiltration and soil erosion during consecutive simulated sprinkler irrigations. *Soil Sci. Soc. Am. J.* 56:902–907.
- Linke, W.F. 1962. Polyacrylamide as a stock additive. *Tappi J.* 45:326–333.
- McIntyre, D.S. 1958. Soil splash and the formation of surface crusts by raindrop impact. *Soil Sci.* 85:261–266.
- Meyer, L.D., and W.C. Harmon. 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. *Trans. ASAE* 22:100–103.
- Norton, L.D. 1987. Micromorphological study of surface seals developed under simulated rainfall. *Geoderma* 40:127–140.
- Norton, L.D., I. Shainberg, and K.W. King. 1993. Utilization of gypsum amendments to reduce surface sealing in some humid soils of the eastern USA. p. 77–92. *In* J.W.A. Poesen and M.A. Nearing (ed.) *Soil surface sealing and crusting*. Catena Suppl. 24. Catena Verlag, Cremlingen-Destedt, Germany.
- Reichert, J.M., and L.D. Norton. 1996. Fluidized bed combustion bottom-ash effects on infiltration and erosion of variable-charge soils. *Soil Sci. Soc. Am. J.* 60:275–282.
- Reichert, J.M., and L.D. Norton. 1994. Aggregate stability and rain-impacted sheet erosion of air-dried and prewetted clayey surface soils under intense rain. *Soil Sci.* 158:159–169.
- SAS Institute. 1996. SAS user's guide: Statistics. Version 6.12 ed. SAS Inst., Cary, NC.
- Seybold, C.A. 1994. Polyacrylamide review: soil conditioning and environmental fate. *Comm. Soil Sci. Plant Anal.* 25:2171–2185.
- Shainberg, I., and G.J. Levy. 1994. Organic polymers and soil sealing in cultivated soils. *Soil Sci.* 158:267–273.
- Shainberg, I., and M.J. Singer. 1985. Effect of electrolyte concentration on the hydraulic properties of depositional crust. *Soil Sci. Soc. Am. J.* 49:1260–1263.
- Shainberg, I., D.N. Warrington, and P. Rengasamy. 1990. Water quality and PAM interactions in reducing surface sealing. *Soil Sci.* 149:301–307.
- Smith, H.J.C., G.J. Levy, and I. Shainberg. 1990. Water-droplet energy and soil amendments: effect on infiltration and erosion. *Soil Sci. Soc. Am. J.* 54:1084–1087.
- Theng, B.K.G. 1979. *Formation and properties of clay-polymer complexes*. Elsevier Scientific, New York.
- Theng, B.K.G. 1982. Clay-polymer interactions: summary and perspectives. *Clays Clay Miner.* 30:1–10.
- Trout, T.J., R.E. Sojka, and R.D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. *Trans. ASAE* 38:761–765.