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TEMPERATURE, CONCENTRATION, AND PUMPING EFFECTS ON PAM VISCOSITY

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ABSTRACT. *As polyacrylamide (PAM) use in irrigated agriculture increases, new methods are being sought to accurately and automatically apply PAM with irrigation water. PAM is also beginning to be used in sprinkler irrigation. However, little information is available about flow characteristics of PAM solutions. This study was conducted to investigate temperature, concentration and pumping effects on viscosity of two agricultural PAM formulations: a dry powder and an inverse oil emulsion. Flow tests, using solutions prepared from the dry powder PAM, showed that viscosity decreased as flow rate increased for concentrations greater than 400 ppm. Thus, accurately predicting PAM viscosity at concentrations greater than 400 ppm is difficult because viscosity varies not only with concentration and temperature, but with flow conditions. Flow rate changes due to temperature fluctuations, however, should be minimal for the oil emulsion PAM over typical temperature ranges occurring under field conditions if tubing diameter is greater than 10 mm and tubing length is less than 1 m, which should be adequate for all surface irrigation applications. The two PAM products tested had similar viscosity relationships with temperature and concentration. PAM viscosity for solutions with concentrations < 24 ppm only increased about 5% relative to water for each 10 ppm increase in PAM concentration. Pumping a 2400 ppm PAM solution just once through a centrifugal pump reduced viscosity 15 to 20%; pumping five times reduced viscosity approximately 50%. The viscosity reduction is thought to result from breaking or shearing the PAM molecules, reducing its effectiveness to stabilize the soil surface and reduce soil erosion.*

Keywords. *Polyacrylamide, Viscosity, Temperature, Pumping, Irrigation, Erosion.*

Applying approximately 1 kg ha^{-1} of polyacrylamide (PAM) to irrigation water dramatically reduces soil erosion in furrow-irrigated fields (Lentz and Sojka, 1994; Lentz et al., 1992; Trout et al., 1995). As PAM is used by more irrigators, new techniques are being explored to accurately add PAM to irrigation water. Dry granular PAM must be added to turbulent water to be thoroughly dissolved. High concentration liquid PAM solutions tend to mix with irrigation water easier than granular PAM. One concern, however, is air temperature fluctuations changing high concentration PAM solution viscosity, resulting in unwanted flow rate changes. Higher concentration PAM solutions may also behave as non-Newtonian fluids (Ben-Hur and Keren, 1997), resulting in viscosity changes as flow conditions change at constant temperature. Information about PAM flow characteristics is needed if accurate, automated metering devices are going to be developed for applying liquid PAM to control erosion.

PAM has also been used with sprinkler irrigation to reduce runoff and soil erosion (Aase et al., 1998; Ben-Hur et al., 1989; Levy et al., 1992). However, pumping may shear PAM molecules, reducing its viscosity and possibly reducing the effectiveness of PAM to stabilize the soil surface. This study was conducted to learn more about viscosity changes of two agricultural PAMs as flow conditions, temperature, and concentration change.

MATERIALS AND METHODS

Two formulations of PAM were used for this study. Superfloc A836 is an 80% active ingredient (a.i.) dry powder with a molecular weight of 12 to 15 Mg mole^{-1} and a negative 18% charge density. This PAM is typically applied to irrigation furrows or mixed with irrigation water in the dry form, but sometimes a high concentration stock solution (e.g., 2400 ppm a.i.) is prepared and mixed with irrigation water. The second PAM tested was Pristine, a 30% a.i. inverse emulsion liquid, which is not diluted for field applications.

FLOW TESTS

Flow tests were conducted first to determine if Superfloc A836 behaved as a Newtonian fluid (i.e., constant viscosity at a constant temperature and concentration). Pristine was not used in flow tests because of difficulty handling this viscous fluid. An apparatus was constructed to supply a constant flow rate and to measure headloss along 2 m of 6.4 mm inside diameter tubing. The total head at each end of the tubing was measured by attaching identical tubing to a tee and mounting this tubing vertically on a meter stick. Six PAM concentrations (0, 100, 200, 400, 800, and 1920 ppm a.i.) were tested with at least four different flow rates. A Marriott siphon was used to supply a constant flow rate to the tubing. Flow rate was varied by changing the Marriott siphon elevation

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relative to the tubing. Actual flow rates used during a test were measured by recording depth change in the Marriott siphon with time. The maximum flow rate was chosen to maintain laminar flow in the tubing. The same Marriott siphon elevations were used for the six concentrations tested. Reynolds number varied from 1000 to 2000 for water and 0.2 to 7 for 1920 ppm Superfloc. A similar apparatus with 4.8 mm inside diameter tubing was also constructed. Only four PAM concentrations (0, 100, 400, and 1920 ppm a.i.) were tested in this apparatus. The maximum concentration tested (1920 ppm) was the typical stock solution concentration used for research studies at this location.

Kinematic viscosity was calculated for each flow rate and concentration using the following equation (Prasuhn, 1980):

$$v = \frac{gD^2 H_L}{32VL} \tag{1}$$

where v is kinematic viscosity ($mm^2\ s^{-1}$), g is gravitational constant ($mm\ s^{-2}$), D is diameter (mm), H_L is headloss (mm), V is average fluid velocity ($mm\ s^{-1}$), and L is tubing length (mm).

Shear stress, a function of headloss, was plotted against shear rate, a function of velocity and diameter, to determine if the Superfloc solutions were Newtonian fluids. The slope of the shear stress-shear rate line equals viscosity. The solution is a Newtonian fluid if the slope (i.e., viscosity) is constant for different flow conditions.

Shear stress was calculated by (Prasuhn, 1980):

$$\tau = \frac{g\rho}{4} \frac{D}{1000} \frac{H_L}{L} \tag{2}$$

where τ is shear stress ($N\ m^{-2}$) and ρ is fluid density ($kg\ m^{-3}$). Shear rate is the velocity distribution within the tubing and was calculated by (Prasuhn, 1980):

$$\frac{dV}{dr} = \frac{8V}{D} \tag{3}$$

where dV/dr is the shear rate (s^{-1}).

Miscellaneous headloss due to the tees on each end of the tubing was estimated by calculating the theoretical headloss for water in the 2-m long tubing and subtracting this value from the measured headloss for water (0 ppm). The miscellaneous headloss correlated linearly with the velocity head ($V^2/2g$). This correlation was used to adjust all other headloss measurements.

VISCOSITY TESTS

Kinematic viscosities of Superfloc A836 and Pristine were measured to determine temperature and concentration effects on viscosity. Both high and low concentration solutions of Superfloc were tested. High concentration Superfloc solutions were typical of concentrations used as bulk supply in the field (800 to 2400 ppm). Low concentration Superfloc solutions represent the typical concentrations used in irrigation furrows or applied through sprinkler irrigation systems (8 to 24 ppm). Only an undiluted sample and low concentration solutions of Pristine were tested because this product is not diluted prior to mixing with irrigation water. Furthermore, adding small amounts of water to Pristine removes the surfactant that surrounds the PAM molecules, resulting in a gelatinous PAM mass. Pristine is too viscous to work with at concentrations greater than approximately 3000 ppm.

A 2400 ppm a.i. stock solution of Superfloc was prepared by slowly adding PAM to tap water agitated with a propeller-type stirrer. The stock solution was diluted on a weight basis with distilled water to 800 and 1600 ppm. The 2400 ppm solution was also used to prepare a 24 ppm a.i. solution, which was diluted to 16 and 8 ppm a.i. for the low concentration solutions. A 24 ppm a.i. solution of Pristine was also prepared and diluted to 16 and 8 ppm.

To determine pumping effects on PAM viscosity, samples of 2400 ppm Superfloc stock solution were collected after being pumped through a centrifugal pump 1, 5, and 10 times. The pump outlet was connected to a 20-mm diameter polypipe with an open gate valve at the end.

Cannon-Fenske type viscometers were used to measure kinematic viscosity. Three viscometer sizes were required for the different PAM solutions, based on manufacturer recommendations. A no. 50 viscometer was used for low concentration solutions (8, 16, and 24 ppm) and a no. 150 viscometer was used for high concentration solutions (800, 1600, and 2400 ppm). The undiluted Pristine viscosity was measured with a no. 500 viscometer.

A water bath held the solutions at constant temperatures of approximately 10, 20, 30, and 40°C (±2°C) during each viscosity measurement. Measurements were repeated three or four times at each of the four temperatures. Copious amounts of water were flushed through a viscometer after a solution was tested at all four temperatures. Before testing a particular PAM solution, two samples of the solution were flushed through the viscometer. All viscosity measurements were conducted within a two-week period to reduce the possibility of PAM degradation.

Best fit equations relating temperature and PAM concentration to kinematic viscosity were determined for low and high concentration Superfloc, and low concentration and undiluted Pristine using a linear estimate function in a spreadsheet. Statistical comparisons were based on simple t-tests with $P = 0.05$.

RESULTS

FLOW TESTS

Flow test results showed that PAM solutions should be Newtonian when concentrations are less than 100 ppm and non-Newtonian when concentrations are greater than 400 ppm. The non-linear relationship between shear rate and shear stress for 1920 ppm Superfloc PAM solution indicates that it is not a Newtonian fluid (fig. 1). Based on power function exponents for combined data in table 1, both 1920 and 400 ppm solutions are non-Newtonian. If the exponents are not equal to one, the fluid is non-Newtonian because the line slope, which equals viscosity, changes with shear rate. The change in slope (i.e., viscosity) for the 1920 ppm solution illustrated in figure 1 means that PAM solution viscosity decreased as flow rate increased as shown in figure 2. The viscosity decrease probably occurred because polymer molecules

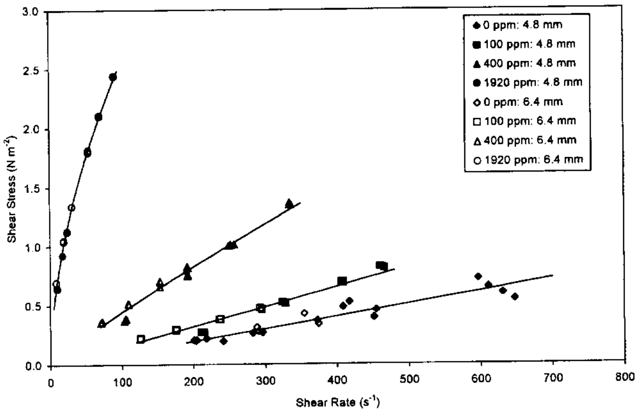

Figure 1–Shear rate-shear stress relationships for Superfloc solutions based on flow tests with 4.8 and 6.4-mm diameter tubing. Lines were calculated using equations for combined data in table 1.

Table 1. Exponents, coefficients, and coefficients of determination for best fit power functions* of shear rate–shear stress data from flow tests

Concentration (ppm)	a	b	R^2
	Combined Data		
0	1.0	0.00077	0.91
100	1.0	0.0013	0.96
400	0.90	0.0071	0.96
1920	0.56	0.19	0.99
	6.4 mm Diameter Tubing		
0	1.0	0.00098	0.90
100	0.89	0.0029	0.99
200	0.91	0.040	1.00
400	0.84	0.010	1.00
800	0.72	0.034	1.00
1920	0.52	0.22	1.00
	4.8 mm Diameter Tubing		
0	1.1	0.00055	0.90
100	1.4	0.00015	1.00
400	1.1	0.0023	1.00
1920	0.60	0.16	1.00

* Shear stress = b(shear rate)^a.

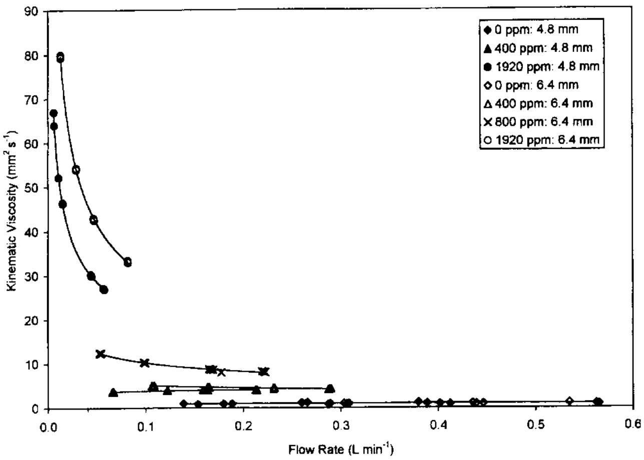

Figure 2–Kinematic viscosity relationships for Superfloc solutions based on flow tests using 4.8 and 6.4-mm diameter tubing. Lines are from a best fit power function.

tend to orient with laminar flow streamlines as shear rate increases (Ben-Hur and Keren, 1997; Eirich, 1956).

VISCOSITY TESTS

Second-order polynomial equations, with PAM concentration and temperature as independent variables, fit the viscosity data reasonably well for both high and low Superfloc concentrations (figs. 3 and 4). Coefficients of determination were greater than 0.99 for both equations. Separate equations were defined for low (< 24 ppm) and high (> 800 ppm) Superfloc concentrations (table 2) because Superfloc viscosity changed with flow conditions when concentrations were greater than 400 ppm. The high

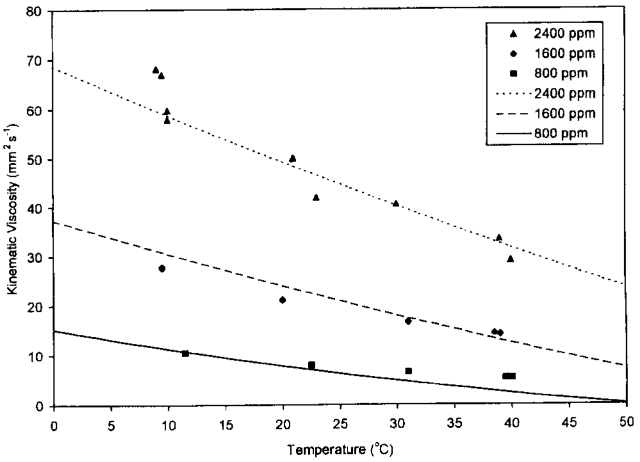

Figure 3–Viscometer measured kinematic viscosities for high concentration Superfloc solutions. Lines were calculated from best fit polynomial equation shown in table 2.

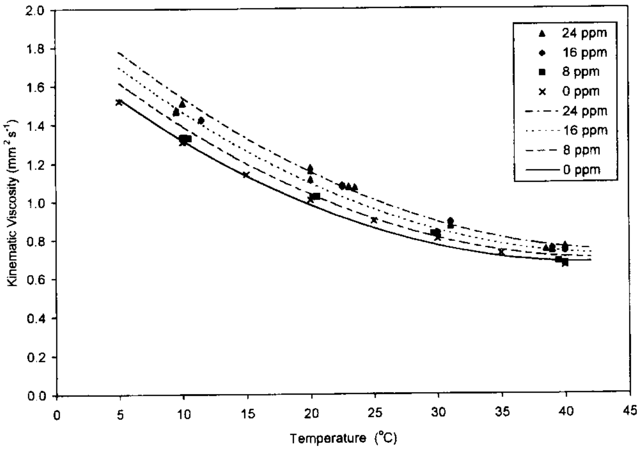

Figure 4–Viscometer measured kinematic viscosities for low concentration Superfloc solutions. Lines were calculated from best fit polynomial equation shown in table 2.

Table 2. Coefficients and constants for empirical equations* to calculate viscosity (mm^2 s^{-1}) from temperature (°C) and PAM concentration (ppm) from viscometer data

	a	b	c	d	e	f
High conc. Superfloc†	0.0022	–0.11	7.1E-06	0.011	–0.00038	2.1
Low conc. Superfloc†	0.00063	–0.054	3.0E-06	0.011	–0.00020	1.8
Low conc. Pristine†	0.00046	–0.046	–6.2E-05	0.012	–0.00013	1.8
Undiluted Pristine	0.11	14.	–	–	–	750

* Viscosity = a (temp)^2 + b(temp) + c(conc)^2 + d(conc) + e(conc)(temp) + f.

High concentration > 800 ppm and low concentration < 24 ppm.

concentration equation is only valid for flow conditions similar to those occurring in the viscometer because both temperature and flow rate affect viscosity of non-Newtonian, high concentration Superfloc solutions.

Both Superfloc and Pristine relationships at low concentrations differed little from water (figs. 4 and 5), although PAM solution viscosity was significantly greater ($P = 0.05$) than water viscosity at a given temperature. Viscosity values for water were taken from Prasuhn (1980). PAM solution viscosity only increased about 5% relative to water for each 10 ppm increase in PAM concentration. The small viscosity difference between water and a 10 ppm PAM solution, the concentration recommended by the Natural Resources Conservation Service for erosion control in furrow irrigation, indicates that decreased soil erosion is not solely due to greater viscosity of PAM treated irrigation water.

Only the low concentration Pristine equation had a negative coefficient for concentration squared (table 2), meaning the viscosity change decreased as concentration increased for a constant temperature. This might have resulted from measurement error or a fundamental difference in the concentration-viscosity relationship between Pristine and Superfloc, since the Pristine solutions contained dilute amounts of surfactant and petroleum distillates from the emulsification process.

Undiluted Pristine had approximately 10 times greater viscosity than 2400 ppm Superfloc PAM (fig. 6), but undiluted Pristine contains more than 100 times as much PAM (300,000 ppm). Increasing temperature from 20°C to 30°C decreases viscosity of 2400 ppm Superfloc about 20% (from 50 to 40 $mm^2\ s^{-1}$) and decreases viscosity of Pristine about 15% (from 510 to 430 $mm^2\ s^{-1}$). Such viscosity changes would probably affect PAM flow rate into an irrigation water source. However, calculating the exact magnitude of the flow rate change would be difficult because the viscosity changes with flow conditions, not just temperature. The headloss change due to temperature still could be estimated using the Darcy-Weisbach equation for headloss due to friction. This is only an estimate because the headloss equation is only valid for Newtonian fluids.

The Darcy-Weisbach equation for laminar flow conditions reduces to (Prasuhn, 1980):

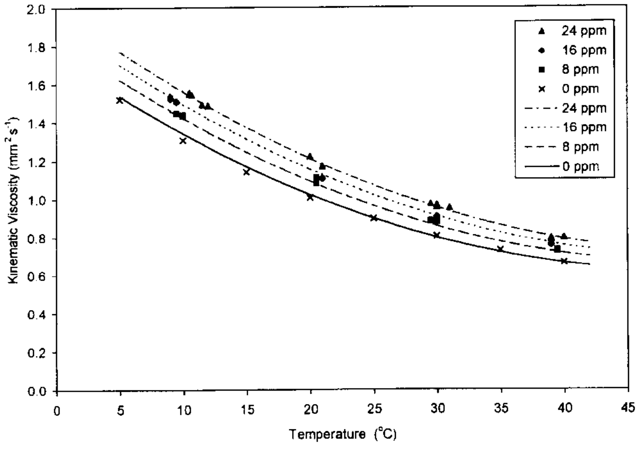

Figure 5–Viscometer measured kinematic viscosities for low concentration Pristine solutions. Lines were calculated from best fit polynomial equation shown in table 2.

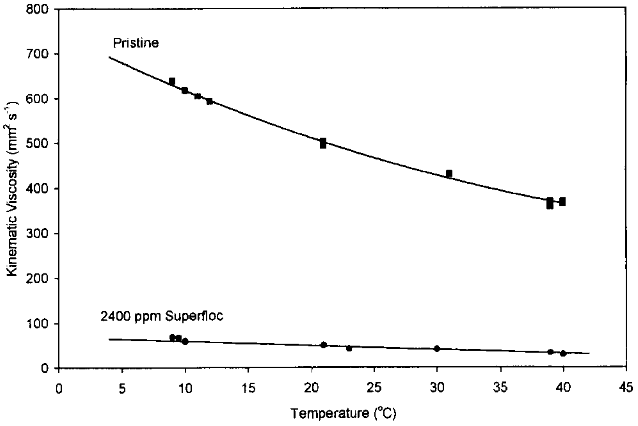

Figure 6–Viscometer measured kinematic viscosities for undiluted Pristine and 2400 ppm Superfloc. Line was calculated by best fit polynomial equation shown in table 2.

$$H_L = 1.154\,Q\,L\,D^{-4}\,v \tag{4}$$

where H_L is headloss (m), Q is flow rate ($L\ h^{-1}$), L is pipe length (m), D is pipe diameter (mm), and v is kinematic viscosity ($mm^2\ s^{-1}$). Friction headloss can be estimated as a function of temperature by combining the viscosity equation for undiluted Pristine from table 2 with equation 4:

$$H_L = Q\,L\,D^{-4}\,(0.126\,T^2 - 16\,T + 860) \tag{5}$$

where T is temperature in degrees Celsius. Adding Pristine at $5\ L\ h^{-1}$ to irrigation water flowing at $3000\ L\ min^{-1}$ results in the recommended 10 ppm PAM concentration. For 10-mm diameter tubing and $5\ L\ h^{-1}$ flow rate, the friction headloss per meter of tubing is 0.30 m at 20°C and 0.25 m at 30°C. This headloss decrease would be offset if the total head in the supply tank decreased 0.05 m during the time the temperature increased. Increasing the tubing diameter from 10 mm to 12 mm decreases the headloss change per meter of tubing from 0.05 m to 0.02 m. As long as the Pristine flow rate is less than $10\ L\ h^{-1}$ in 10 mm diameter tubing, the change in friction headloss would be less than 0.10 m per meter of tubing. These calculations show that Pristine flow-rate changes due to temperature should be minimal under field conditions.

Pumping 2400 ppm PAM once through a centrifugal pump significantly ($P = 0.05$) reduced PAM viscosity 15 to 20%. Viscosity was reduced 50 to 60% when the PAM solution was circulated through the pump five times. PAM solution viscosity was not significantly different between circulating the solution through the pump five and ten times (fig. 7). The viscosity reduction is thought to result from breaking or shearing the PAM molecules, which would reduce its effectiveness to stabilize the soil surface and to reduce soil erosion. Care should be taken to minimize pumping when designing PAM injection systems.

CONCLUSIONS

This study indicates how viscosity of agricultural PAM changes with temperature, concentration, pumping, and flow rates. At concentrations greater than 400 ppm,

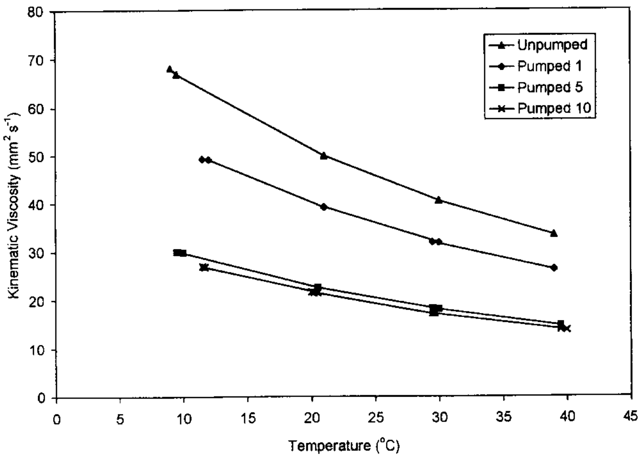

Figure 7–Pumping effects on viscometer measured kinematic viscosity. A 2400-ppm Superfloc solution was pumped through a centrifugal pump 1, 5, and 10 times.

Superfloc PAM was a non-Newtonian fluid meaning that viscosity changed with flow conditions. When PAM concentration was less than 400 ppm, Superfloc solutions behaved as Newtonian fluids. Accurately calculating PAM viscosity at varying concentrations, temperatures and shear rates is difficult and requires more thorough investigation than was conducted in this study. Viscosity estimates from this study, however, indicate that flow rate changes under field conditions should be minimal.

The two PAM products tested had similar viscosity relationships with temperature and concentration. Lower PAM concentration solutions had viscosities similar to water. The small difference in viscosity indicates that decreased soil erosion in PAM treated irrigation furrows is not solely due to the increased viscosity of the flowing water.

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