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Laboratory studies to examine the impacts of polyacrylamide (Pam) on soil hydraulic conductivity

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LABORATORY STUDIES TO EXAMINE THE IMPACTS OF POLYACRYLAMIDE (PAM) ON SOIL HYDRAULIC CONDUCTIVITY

By

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ABSTRACT

Laboratory Studies to Examine the Impacts of Polyacrylamide (PAM) on Soil Hydraulic Conductivity.

By

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Polyacrylamide (PAM) is being suggested as a new technology to reduce seepage losses in unlined irrigation canals. The goals of this thesis were to quantify the optimum concentrations of PAM and suspended sediment (SSC) that would reduce K_{sat} to the greatest extent, and to better understand the mechanisms contributing to reduced K_{sat}. Testing was conducted using a constant head method in soil columns (15 cm length, 6.35 cm diameter). An unbalanced multi-factorial design was used with experimental variables including soil type (#70 mesh sand, C33 sand, loam soil), PAM concentration (5, 10, 20, 40 lbs/ca), and SSC (0, 150, 300 ppm). Results show that PAM reduced K_{sat} 40% to 98% in sandy soils, but reductions were less in loam. Adding suspended sediment reduced K_{sat} 8-11 times versus PAM alone. Mechanisms that reduced K_{sat} included higher viscosity from dissolved PAM, creation of a separate and distinct PAM layer, and the plugging of larger soil pores. Significance of these mechanisms was found to be a function of experimental conditions.

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CHAPTER 1

INTRODUCTION

Water is a precious commodity in the western United States. It has been estimated by the U.S. Geological Survey (USGS) (1990) that as much as 50 percent of the water flowing through irrigation canals is lost due to seepage through the bottoms of the unlined canals. In order to help conserve water resources, the U.S. Bureau of Reclamation (USBR) is evaluating the use of polyacrylamide (PAM) as a means of sealing unlined irrigation canals.

PAM is an ultra-high molecular weight polymer that has been widely used in industry for over 50 years. PAM has been used for numerous applications that range from food processing to well drilling to wastewater treatment. In agricultural practices, PAM is perhaps most commonly used to stabilize irrigation furrows by improving soil aggregate structure, which allows more uniform infiltration rates along the furrows. This practice has become standardized by the U.S. Natural Resources Conservation Service (NRCS) using their Conservation Practice Standards for erosion control (Spofford and Pfeiffer, 1996).

However, an alternative impact of adding PAM to soil water is a reduction in infiltration rate. Previous laboratory research showed that higher concentrations of PAM will begin to decrease infiltration in soil (Malik and Letey, 1992; Nadler et al., 1994; Letey, 1996; Lentz, 2003; and Ajwa and Trout, 2006). Using these results, scientists and water users suggested that PAM could be used as a means to reduce water loss due to seepage in unlined irrigation canals. If effective as a tool for reducing water loss, water managers and stakeholders would benefit in two key ways. First, irrigation water would likely travel greater distances down the canal, supplying a larger number of users who need the water for irrigation. Second, the water conservation would allow canal managers to reduce the time interval between water releases to individual water users, thus providing more water during the irrigation season. In both cases, PAM as a water conservation tool would provide the means for farmers and ranchers to be more successful in their endeavors, directly impacting consumers at a regional and/or national level.

If PAM is to be widely used as a canal sealant, many questions need to be answered, including the benefits of using PAM as a water conservation tool, as well as possible health and environmental concerns associated with the use of PAM. This latter issue stems from the presence of the monomer acrylamide (AMD), which is used to make PAM. AMD is a known animal carcinogen and mutagen (i.e., the compound alters DNA which is then passed on to offspring). During the polymerization process that creates PAM, from 0.025% to 0.05% of residual AMD remains as part of the PAM molecule (Sojka et al., 1998a). To date, very little is known about the transport characteristics of PAM and AMD. It is thus important to understand PAM and AMD transport through soil and the factors that affect their movement. Assuming that health and/or environmental risks of PAM usage can be managed properly, leading to approval of PAM usage by USBR, the next goal would be to develop a list of standards for how PAM should be used in field applications. Finding the optimum concentration of PAM needed to achieve the desired reduction in seepage losses without using excess PAM is a key consideration in this study and the larger PAM research program. With optimization, unnecessary release of PAM and its associated monomer AMD into the environment can be minimized.

To better understand the use of PAM as a canal sealant, the U.S. Bureau of Reclamation (USBR) has sponsored a cooperative research program that includes groups within USBR, the Desert Research Institute (DRI), the University of Nevada, Las Vegas (UNLV), and the University of Nevada, Reno (UNR). The study is quite broad, including numerous laboratory and field experiments to understand how to maximize effectiveness of PAM, and an environmental risk characterization that considers both ecological and human toxicological risks.

For the research conducted in this study, the hypothesis is that PAM can be used to decrease saturated hydraulic conductivity of soil material, thus decreasing water loss due to infiltration. The main objectives in this study are to (1) evaluate to what extent PAM effects hydraulic conductivity and infiltration rates of a soil and (2) better understand the physical mechanisms that are leading to the decrease in infiltration. For this second goal, this study considers three possible physical mechanisms that reduce seepage, including (1) PAM-treated water is more viscous than untreated water, thus reducing the infiltration rate; (2) PAM physically plugs large soil pores, especially in coarser grained canal sediments; and (3) PAM itself becomes a low-conductivity layer when treating finer-grained soils. The information gained from this research will be vital for predicting the effectiveness of PAM application in unlined canals, when field conditions (suspended sediment concentration, soil type and PAM concentration) are known, and for developing the standards needed for PAM use as a sealant.

This thesis is divided into chapters that present different aspects of the study. Chapter 2 is a literature review that discusses past work related to PAM use. Chapter 3 describes in detail the methods and techniques used for the experiments in this study. Chapter 4 provides the results from the testing, and Chapter 5 presents final conclusions and future recommendations.

CHAPTER 2

LITERATURE REVIEW

The study and use of PAM has changed and broadened greatly over time. A literature search for PAM will most likely bring up articles related to electrophoresis and DNA research. Although PAM has had such varied uses, as related to this study, PAM research has focused on three main themes: (1) soil erosion control, (2) increasing infiltration in soil, and (3) decreasing infiltration in soil. While these studies are closely related to the work conducted in this study and provide a foundation for the work presented here, none have clearly hit upon the goals of this study.

The precursor to PAM was polyacrylonitrile developed by the Monsanto Chemical Company in the early 1950s. It was marketed as a soil conditioner under the trade name Krilium. Krilium was used the same way as modern day PAM; specifically, it was used for decreasing furrow erosion and increasing aggregate stability. The benefits of Krilium use on crop yield were published by Bear (1952). Although Krilium was effective, about 200 pounds per acre was needed for soil conditioning, or approximately two orders of magnitude more than the amount of modern day PAM needed for the same purpose. The product was marketed in 1953, but due to its cost of $2.00 per pound (equivalent to $15.00 in 2006, inflationdata.com) and the high amounts required, the product had limited success.

2.1 Soil Erosion Control

In 1988, Helalia and Letey used cationic PAM in laboratory tests to increase soil structure and permeability under simulated rain fall events. They also found in these tests that inter-rill erosion was decreased. Lentz et al. (1992) hypothesized that PAM could be used to increase the cohesiveness of soil at the surface and therefore be used to decrease erosion. Several studies focused on the ability of the compound to decrease erosion in irrigation furrows (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka et al., 1998b). These studies were, for the most part, field-based tests performed in irrigation furrows, where irrigation water was treated with anionic PAM prior to release into the furrows. The variables in these experiments included the concentrations of PAM, the number of applications, and whether the applications were continuous or intermittent.

The results from the studies showed PAM to be very successful at decreasing erosion as well as being cost effective. A concentration of 10 ppm was found to be ideal for reducing erosion. From the results of these studies, the use of PAM as an erosion control agent in furrow irrigation became an NRCS interim conservation practice standard in 1995 and later in 2001 the interim status was removed to become a true standard (NRCS, 2001). As will be described in the next section, in addition to decreasing erosion, these investigators found that low concentrations of PAM could also increase infiltration rates within the furrows.

2.2 Increasing Infiltration in Soils

The previous work, as well as research by Sojka et al. (1998c) showed that concentrations between 5 and 10 ppm of PAM will actually increase infiltration rates and hydraulic conductivity in soil. In furrow irrigation environments, the mechanism for PAM increasing infiltration is due to the maintenance of soil structure. PAM has cohesive properties that binds soil particle together. This cohesiveness helps maintain aggregate stability. The addition of water with PAM concentrations below 10 ppm increases the soil structure by maintaining aggregate stability and keeping soil pores from collapsing. Without the addition of PAM, flowing water disturbs soil structure, causing the aggregates to slake, thus collapsing the larger pores through which water would preferentially flow.

Because flow through capillaries is proportional to the pore radius to the fourth power, keeping open the larger pores can greatly increase the potential for water to flow through a porous media.

2.3 Decreasing Infiltration in Soils

Numerous papers have been written that suggest that increases in viscosity from PAM addition explain the decrease in infiltration/conductivity in soil. Even very small amounts of PAM can have significant impact on viscosity, and in turn the ability of fluids to move through soil. Used at concentrations above 10 ppm, PAM has been shown to lead to decreased infiltration and conductivity (Malik and Letey, 1992; Nadler et al., 1994; Letey, 1996). Letey (1996) described quite simply the mechanism for the decrease in infiltration/conductivity in soil, when PAM solutions exceeding 10 ppm concentrations are applied. He described viscosity (η) as a governing factor in the equation for hydraulic conductivity (K) that could be influenced by PAM:

$$K_{sat} = \frac{\kappa \rho g}{\eta}$$

where, κ is the intrinsic permeability (L^2) of the soil, ρ is the fluid density (M/L^3), g is the gravitational constant (L/T^2), and η is the kinematic viscosity of the fluid (L^2/T). The parameters k and g are unaffected by PAM addition In theory, the fluid density (ρ) will be affected by the addition of PAM by a very slight amount and thus is considered negligible. The only parameter in the equation that PAM does affect significantly is the kinematic viscosity of the solution. Increasing the dynamic viscosity will reduce the ability of the solution to flow through the porous media, and therefore reduce the hydraulic conductivity. The increase in infiltration due to the maintenance of pore structure is opposed by the increase in viscosity as PAM concentration increases. A finite point exists where the benefits of maintaining pore structure are outweighed by the increased viscosity of the PAM solution. Although pore structure is maintained, the increased viscosity of the fluid will begin to decrease infiltration/conductivity.

A study by Lentz (2003) showed not only that PAM could decrease infiltration, but how this application could be used. He discussed how PAM could be used to decrease the rate of infiltration at the inflow end of a furrow, relative to the outflow end. In furrow irrigation, water on the inflow side has more time to infiltrate than water on the outflow side. By decreasing the infiltration rate at the inflow side it is possible to get a more uniform infiltration rate throughout a furrow. Lentz (2003) even mentions how PAM might be used to reduce seepage in unlined irrigation canals.

One of the tests conducted by Lentz (2003) showed how PAM could be used in a ponded environment such as an irrigation pond or canal. Lentz discusses that adding enough PAM to treat the amount of water needed to fill a canal would be cost prohibitive. He instead suggests lining the canal surface prior to filling the canal with water as an alternative. Lentz (2003) tested this idea by applying 20 ml of a 1000 ppm PAM solution to a 12.6 cm^2 surface area soil column and then allowing the solution to dry. With this method, 0.020 g of PAM was applied to 12.6 cm^2, or 0.0016 g/cm^2. The results from this test showed that PAM could decrease conductivity by 60% in silt loam soils and > 90% in clay loam soils.

Although this application method is shown to be affective at decreasing infiltration in a canal environment without using an exorbitant amount of PAM, this method may not be cost effective in terms of the logistics needed to apply PAM in this manner to 10's or even 1000's of miles of canals. The amount of PAM used by Lentz (2003) (0.0016 g/cm^2) is 3.5 times higher than the highest concentrations used in our study (0.00045 g/cm^2 or 40 lb/ca). The real importance of Lentz's 2003 study is that it shows that PAM can be used to decrease infiltration rates and hydraulic conductivity without relying on the change in water viscosity to achieve the reduction. As used by Lentz (2003), the PAM was basically creating a seal at the soil water interface, decreasing the ability of water to infiltrate. The specific mechanisms for the reduction are not fully explained, but two possibilities include, (1) the hydrated PAM molecule penetrated some small distance into the soil causing the pores to be clogged, or (2) the hydrated PAM created a less permeable layer directly on top of the soil. The magnitude and importance of these two mechanisms may depend on the soil texture.

2.4 PAM Formulation

PAM polymers can be categorized into three distinct types: cationic, non-ionic, and anionic.

Several different studies (e.g., Deng et al., 2006) have shown that cationic PAM is very effective at causing flocculation of sediment. Fine particles of sediment such as clays generally posses a negative charge due to the broken edges of the crystal lattice (Hillel, 1998, p. 75-78). Cationic PAM with a positive charge thus attracts the negatively charged sediment. This attraction between the positively-charged PAM and the negatively-charged particles causes the particle to accumulate into larger floccs that eventually become too heavy to remain suspended in the water column and settle.

A major drawback of cationic PAM is that the molecule adheres to negatively charged fish gills. When excessive amounts of cationic PAM build up on the gills, the fish eventually dies of asphyxiation (Mason et al., 2005).

Nonionic PAM has neither a positive nor negative charge. A recent study done by Deng et al. (2006) showed that anionic PAM has flocculation/dispersion an effect somewhere between that of anionic and cationic forms of PAM.

Anionic PAM, with its negative charge, has not been shown to be harmful to fish because the negative charge does not adhere to the fish gills. Depending on the chemistry of the water where PAM is used, anionic PAM can cause flocculation or can cause sediment to be repulsed and held in suspension longer. In the experiment by Deng et al. (2006) using distilled water, PAM was shown to disperse the sediment, holding it in suspension longer. Anionic PAM cannot cause flocculation of sediment unless cations such as Ca^{2+} or Mg^{2+} are present in the water. Lu et al. (2002) stated that the presence of divalent cations in the water phase shrinks the electrical double layer and bridges the negatively-charged sites of soil and PAM. The Ca^{2+} or Mg^{2+} thus act as a bridge between the negatively-charged PAM and negatively-charged particles. Without the presence of bridging cations, the anionic PAM will not flocculate the sediments. Fortunately water found in natural environments tends to contain the cations needed for anionic PAM to cause flocculation.

2.5 PAM as a Flocculation Agent

Because of logistical ease, adding dry PAM to a flowing canal seems to be a more commonly used application method. A problem with this method is that, in theory, adding dry PAM to water flowing in an operational canal will just create a weak PAM solution. The key to this application method is understanding how PAM settles from the solution to the bottom of the canal. Numerous manuscripts have been published that show PAM to be a strong flocculation agent; for this reason, PAM has been used extensively in wastewater treatment for decades. PAM works when charged, hydrated PAM molecules attract suspended sediment present in the water column, creating larger particles or "floccs." These floccs eventually becomes too heavy to remain suspended in the water column and fall to the bottom. The presence and or addition of sediment or other particulate matter could thus greatly increase the effectiveness of PAM.

It is hypothesized in our study that flocculation of PAM and sediment on the soil surface can decrease infiltration rates and hydraulic conductivity by creating a lower-conductivity layer on top of the soil. This process would be analogous to physical crusts that form on soil surfaces, sealing the surface against water infiltration (Hillel, 1998, p.

227-228). By sealing the surface and decreasing infiltration at the interface, the effective conductivity of the entire soil system is decreased.

In contrast to the explanation that relies on the increase in viscosity to reduce infiltration, the flocculation mechanism does not require higher concentrations (i.e., greater than 10 ppm), nor does it require any changes in viscosity in the water column. In fact, when flocculation does occur, it is expected that both the sediment and the PAM are removed from the water column, thereby maintaining viscosity levels similar to water. Given the large volume of water in the canal, and that PAM can begin to flocculate sediment at concentrations below even one ppm, the flocculation mechanism for decreasing seepage in the canals seems to be a more reasonable as well as possibly a more efficient mechanism.

CHAPTER 3

METHODOLOGY AND DATA DESCRIPTION

Several different types of tests were conducted to answer the questions in this study, increasing in complexity from simple mixing studies to soil column Ksat testing. Chapter 3 is an overview of the experimental standards used for the experiments as well as a discription of the purpose and design for each type of experiment.

3.1 Experimental Standards

The experimental standards chapter describes the specific type of PAM, test solution, and sediment used for all experiments, as well as the types of soil used for the soil column testing.

3.1.1 PAM Formulation Used in Experiments

The specific PAM polymer used for these experiments is TACK Dry distributed by Precision Polymer Corporation of Greeley, Colorado. It is an anionic, straight-chain, non-cross linked polymer with a molecular weight of approximately 18 Mg/mole.

3.1.2 Composition of Test Solution

Recent studies (i.e., Wallace and Wallace, 1996; Lu et al., 2002; Deng et. al., 2006) and preliminary test results have shown that cations need to be present in the test solution for the anionic PAM to flocculate sediment. Therefore, for all of the PAM experiments conducted for this study, we used a 0.005 M $CaSO_4$ test solution augmented with 0.3g/L thymol as an anti-microbial agent. This standard test solution is described by Klute and Dirksen (1986, p.692-693). When converted to the mass of individual ions, 0.005 M $CaSO_4$ equals 200 ppm Ca^{+2}, which corresponds well to values attained from measurements taken in several canals in the Grand Junction area, where PAM field scale testing (unrelated to this study) was conducted over the summer of 2006 (Susfalk et al, 2006). Those results showed that canal samples contained 71, 196, and 234 ppm of Ca^{+2}. In addition to Ca^{+2} the canal samples also contained 22, 89, and 128 ppm of Mg^{+2}, and 38, 189, and 294 ppm of Na^{+}. Lu et al. (2002) stated that divalent cations are 28 times more effective at enhancing PAM sorption than monovalent cations. Although divalent cations are more effective than monovalent cations, Lu et al. (2002) also stated that "the amount PAM sorption increased significantly as the total dissolved salts (TDS) increased." Testing with various cation concentrations could be a consideration for future testing.

3.1.3 Suspended Sediment

Suspended sediment was used in most of the laboratory experiments to more closely replicate conditions in operational canals. The amount of sediment held in suspension is termed the suspended sediment concentration (SSC), and is calculated as the mass in grams of sediment contained in one liter of water. The SSC will vary in the canals due to the slope and parent material of the canal, as well as the amount of water passing through the canal. The SSC usually changes with the seasons and storm events.

Another common measurement related to the presence of sediment in water is referred to as turbidity. Turbidity is not a concentration of mass, but rather is related to the clarity of the water. Turbidity is measured using a turbidimeter and is given in

Nephelimetric Turbidity Units (NTU). A turbidimeter measures the opacity of the water to light. A turbidity measurement can be affected by the amount, color, and size of the sediment present in a sample, as well as the presence of coloring agents such as iron oxide and organic acids. Because of these interferences, a direct relationship between SSC and turbidity often does not exist. Nonetheless, it is possible to correlate SSC to NTU for a given set of water samples, but this correlation is not exact and may not hold true for water samples from different sites with different characteristics. Due to the more labor intensive nature of an SSC measurement, turbidity can be a useful tool for estimating SSC, as long as a reasonable correlation has already been established.

Two sources of sediment were used for the laboratory experiments. The first source was derived from soil collected in Grand Junction, Colorado, and the second was kaolinitic material purchased from a vendor in Georgia. Sediments derived from soil were obtained by mechanically sieving dry soil from Grand Junction through 120- and 45-micron sieves. The 45-micron sieve was chosen because fines were needed in the silt and clay ranges (i.e., < 50 micron). Two five-gallon buckets of soil produced approximately 120 g of fine sediment in the silt and clay size ranges. Particle size analyses of the sediment gave us a ratio of approximately 80% silt size particles and 20% clay size particles.

Discussion with other project scientists raised concerns about the use of the sediment from Grand Junction. Specifically, it was felt that the 80% silt content in the sediment was too high, leading to a low charge density and relatively low reactivity with PAM. Based on suggestions and discussions with Drs. Frank Mangravite (Public Works Management, Inc., Morris Plains, NJ) and Rick Lentz (USDA-ARS, Kimberly, ID), both of whom are on an external PAM Peer Review Panel organized by DRI, it was decided that a more reactive material with uniform grain size should be used. Thus, for future experiments, we chose to use a kaolinite clay for our experiments. Kaolinite was chosen because it has the lowest charge density of the clays, providing a conservative reactive material for PAM experiments. Also, kaolinite has been in recent PAM experiments (Deng et al., 2006), All kaolinite (type Huber 80 kaolinite) was purchased from the J.M. Huber Corporation, Macon, Georgia. Laboratory experiments (K_{sat} testing, and flocculation jar tests) were carried out using the Huber 80 kaolinite clay.

3.1.4 Description of Soil Material

Three different soils were chosen to test PAM efficiency at decreasing infiltration these include; (1) an engineered #70 mesh washed silica sand (obtained from a local home improvement store) used as a control, (2) a natural C33 sand collected from Grand Junction, Colorado, and (3) a loam collected from Grand Junction, Colorado. Material was treated by spreading and air drying, sieving through a screen with 2 mm openings to remove larger stones and other material, and then homogenizing the material with a small shovel. Soil was then packed into 20-L buckets with lids for storage and future usage. Because the engineered (#70 mesh) sand was already homogenized at time of purchase, no additional treatment was done.

Soil physical and hydraulic properties were also determined on all three soil materials. Soil samples were analyzed for particle size using the Laser Light Scattering technique (Digisizer, Micromeritics, Norcross, GA) at the Soil Characterization and Quaternary Pedology Laboratory at the Desert Research Institute in Reno, NV. Tables 3.1a-c are the particle size distributions for the soils used in the experiments.

Table 3.1a: Particle size analysis for #70 mesh sand.

Sieve Name	Aperture Size (μm)	Cumulative Volume Passed (Percent)	Volume Frequency (Percent)	Cumulative Volume STD (6 tests)
No. 25	710.0	100.0	0.0	0.0
No. 50	300.0	79.8	20.2	1.2
No. 120	125.0	11.2	68.6	0.3
No. 270	53.0	2.0	9.2	0.1
No. 635	20.0	1.2	0.7	0.0

Table 3.1b: Particle size analysis for C33 sand.

Sieve Name	Aperture Size (μm)	Cumulative Volume Passed (Percent)	Volume Frequency (Percent)	Cumulative Volume STD (4 tests)
No. 12	1700.0	75.5	0.0	0.0
No. 25	710.0	68.5	7.0	1.5
No. 50	300.0	22.3	46.3	1.2
No. 120	125.0	5.2	17.0	0.4
No. 270	53.0	3.2	2.0	0.3
No. 635	20.0	2.5	0.7	0.3

Table 3.1c: Particle size analysis for Loam soil.

Sieve Name	Aperture Size (μm)	Cumulative Volume Passed (Percent)	Volume Frequency (Percent)	Cumulative Volume STD (5 tests)
No. 25	710.0	100.0	0.0	0.0
No. 50	300.0	88.7	11.3	1.0
No. 120	125.0	52.1	36.7	1.6
No. 270	53.0	33.4	18.7	0.9
No. 635	20.0	25.4	8.0	0.7

3.1.5 Establishing PAM Concentration per Surface Area or Volume

An interesting and difficult part of the PAM project has been to determine the PAM concentrations used for the experiments. The difficulty lies in how PAM concentrations are expressed in the field, which is done by areal coverage of the canal (i.e., pounds PAM per canal acre, or lb/ca), not in mass of PAM per volume of water (i.e., mg/L or ppm). Areal coverage may be an awkward way of describing a concentration, but for this purpose, mass per surface area is more appropriate method. Using a volume based concentration can result in significant differences in the mass of PAM that actually settles to the surface of the canal. For example, assuming that PAM will flocculate and settle to the bottom, if a target PAM concentration of 10 ppm is needed in the canal, but the volume is increased 10 times, the fluid concentration would remain the same, but the areal coverage at the bottom of the canal would be 10 times higher. Using a mass per surface area concentration, the amount of PAM reaching the bottom of the canal is independent of the volume of water in the canal.

Typical PAM usage in the field will likely be done by farmers, ranchers and other non-scientists. Field applications have traditionally used the English units of pound per canal acre (lb/ca), which is defined as the product of the wetted perimeter of the canal and the length of the canal required equal one acre of surface area. For the K_{sat} experiments conducted in this study, the unit of lb/ca was converted to metric system units of g/cm^2, where the conversion of 1 lb/ca equal 1.121 x 10^{-5} g/cm^2. The surface area of the soil columns used in laboratory experiments is 31.67cm^2. Therefore, multiplying this area by 1.121 x10^{-5} g yields a mass of PAM of 3.55x10^{-4} g, equivalent to 1 lb/ca.

This value is then multiplied by the number of lbs/ca needed for the experiment (i.e., 5, 10, 20, 40, etc.). Thus, the mass of PAM is known, as well as the surface area coverage. Depending on the height of the water column used in the experiment (described below), the PAM concentration in ppm can be calculated. For our soil column tests, we have a surface area of 31.67 cm^2 and a water column height of 15 cm, yielding a volume of 0.475 L. The mass of PAM used to achieve 5, 10, 20, and 40 lbs/ca is thus equivalent to 4, 8, 16, and 32 ppm PAM. The concentration in ppm from the soil column tests was used as the basis for the Flocculation Jar Testing described in section 3.3.

3.2 Experiment 1: PAM Application Test

Tests were performed to find out if application methods of polyacrylamide (PAM) make a difference in its ability to flocculate suspended sediments from turbid water. The experimental variable in this test was the manner in which PAM was added to the test columns. These test data were not quantifiable, but the empirical information gained was very informative as to how PAM works, and was important to the experimental design of subsequent laboratory experiments. Attempts were made to quantify the flocculation tests using a hydrometer; unfortunately, the PAM interfered with the hydrometer and rendered the unusable.

Five 1-L graduated cylinders were used for the experiment. Each cylinder contained equal amounts of fines and PAM, but varied in the way the PAM was applied to the cylinder. A stock solution of PAM was made by adding 1 gram of PAM to one liter of D.I. water. The stock was mixed with a magnetic stirrer for approximately 20 minutes. After a few minutes, when the solution became too viscous to maintain a vortex, solution was then moved and stirred with a propeller type mixer at 300 rpm for approximately 15 minutes, after which the PAM appeared to be completely in solution (PAM lumps or powder were not evident).

Suspended sediment concentration was kept at 3g/L for each column, with fine-grained material added to the water column separately. Fines were obtained as described above.

PAM was added to the column as described below:

Cylinder 1 - 100 mL of 1000ppm stock solution was added to 900 mL of D.I. water. The cylinder was then vigorously stirred again to make a weaker 100 ppm solution.

Cylinder 2 - Similar to Cylinder 1, 100 mL of stock solution was added to 900 mL of D.I. water, but the stock solution was not mixed into the water. Rather, the 100 mL of PAM solution was allowed to remain a gelatinous mass within the 900 mL of turbid water.

Cylinder 3 - 0.1 g of dry PAM crystals was applied to 1 liter of water in the cylinder.

Cylinder 4 - 0.1 g of dry PAM crystals was hydrated with 10 mL of D.I. water for 5 minutes, and then added to 990 mL of water in the cylinder.

Cylinder 5 - used as a control with equal mass of fines, but no PAM added.

3.3 Experiment 2: Flocculation Jar Test

Flocculation tests were conducted to observe, and quantify if possible, the reactivity of PAM and suspended sediment under different experimental conditions. The variables for the flocculation/jar test included PAM concentration in ppm and sediment concentration in ppm/NTU. PAM concentrations were 0.5, 1, 2, 4, 8, 16, and 32 ppm. Sediment concentrations were 0, 20, 60, 110, 203 and 368 ppm (25, 75, 150, 300, and 600 NTU).

Courtesy of Dr. Jaci Batista (UNLV, Department of Civil and Environmental Engineering), a Flocculation Apparatus (Phipps and Bird PB-700 Series), also known as a jar tester, was used to uniformly stir dry granular PAM into solution. The jar tester is used in many wastewater treatment applications to find the optimum flocculating dose for waste water treatments. In 1 L of test solution with suspended sediments mixed in, dry PAM granules were added while the apparatus stirred at 100 RPM for 5 minutes. This stirring period allowed the PAM to fully hydrate. The apparatus was then slowed down to 30 RPM and allowed to stir for 15 minutes so that the PAM flocculates could grow and settle.

After the stirring was complete, a pipette was used to vigorously stir the beaker back into a homogenous mixture, and for collecting the sample for analysis. The end of the pipette was cut to have about a 7-mm opening, preventing exclusion of the flocculates. Approximately five pipette loads were needed to fill a 15-mL cell (Hach Chemical Co., Loveland, CO)

Turbidity measurements were performed in attempts to quantify the ability of PAM to flocculate sediments from a water column under the given experimental conditions. For each turbidity analysis, the Hach cell was shaken by hand to suspend the flocculates prior to placement into the turbidimeter (Model 2100P). The first reading (used as the initial time) was immediately taken after the cell was in place. Turbidity readings were taken from the same cell over time until equilibrium was reached. Laboratory observations showed that the larger flocculates fell quickly, thereby changing turbidity rapidly early in the experiment, but that turbidity changes tended to taper toward the end. Thus, turbidity measurements were taken every 30 seconds after the initial reading for the first three minutes, every minute up to six minutes, and then every two minutes until equilibrium was reach. For most tests equilibrium was reached at approximately 20 minutes.

3.4 Experiment 3: Hydraulic Conductivity Testing

The purpose of the K_{sat} testing is to quantify how the application of PAM will affect the ability of water to infiltrate through the soil surface. From the results of these experiments, it is possible to find the most efficient use of PAM, or the optimum ratio of percent reduction divided by the mass of PAM used. The experiments were conducted using a constant head setup, based on designs by Klute and Dirksen (1986, p. 694-700). The factors for the soil column testing include PAM concentration (5, 10, 20, and 40 lbs/ca), suspended sediment concentration (0, 150, 300 ppm), and soil types (engineered (#70 mesh) sand, C33 sand, and loam soil). As described in section 3.1.5, using the known dimensions of our water column 5, 10, 20, and 40 lbs/ca is equivalent to 4, 8, 16, and 32 ppm PAM.

The experimental setup (Figure 3.1) for these experiments consisted of six main parts:

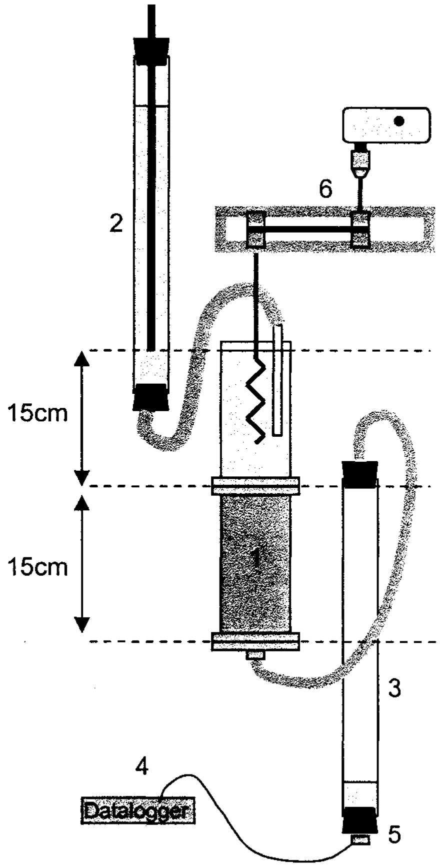


Figure 3.1: Schematic diagram showing parts of K_{sat} experimental setup.

Column (1) - The column is made of two parts; a soil column and a water column. The use of columns makes volume calculation easy. For these experiments, 7.62 cm outside diameter pressure cells were used (Soil Measurement Systems, Tucson, AZ.). The column material used in the pressure cell is made of non reactive cast acrylic (6.35 cm inside diameter by 15 cm long). Using these dimensions yielded a column volume of 475 cm^3.

Marriotte (2)_- The Marriotte system is a simple but very important part of the setup. Using gravity and a siphon tube, it maintains a constant head in the water column.

Collector (3) – Acrylic tubing of 3.18 cm inside diameter was used to collect outflow during the experiment. At the base of the collector, a 1 psi pressure transducer (Honeywell Microswitch PX26-001GV) was inserted through a stopper to record water height with time. Using the water height measurement and known inside diameter, the outflow volume was calculated.

Datalogger (4) and pressure transducers (5) - A datalogging system with calibrated pressure transducers was used to collect and store data for these experiments. A Campbell Scientific 21x Datalogger (Ogden, UT) was used for the data collection. The datalogger was programmed to take measurements from the three replicate columns every 10 seconds. The data collected on the datalogger was downloaded to a personal computer for further processing using a Microsoft Excel spreadsheet. The transducers were calibrated by correlating pressure transducer responses in volts to known values of hydrostatic head. All transducers used were calibrated with an $R^2 > 0.99997$.

Agitator (6) - To simulate water moving in the channel a stirring system was incorporated into the design.

3.4.1 Soil Column Preparation

To determine how much soil is needed to fill the soil column, a target bulk density was chosen that might be expected to be found in an undisturbed natural environment. Though density varies from location and soil type, the C33 soil at the Grand Junction field area is known to have a field bulk density of 1.7 g/cm^3, which we used for the target density of both the C33 and the engineered (#70 mesh) sand for our columns. Due to its finer texture and higher porosity, the loam was packed at a bulk density of 1.5 g/cm^3.

To obtain soil water content, an arbitrary amount of soil is weighed, and then placed in an oven at 105°C for 24 hours to drive off moisture. The soil is then weighed again to determine the amount of moisture in the original sample. Gravimetric water content is then calculated as:

(mass moist soil – mass oven dry soil)/(mass oven dry soil)

The air dried engineered (#70 mesh) sand, C33 sand, and loam soil were found to have gravimetric water contents of, respectively, 0.0015, 0.0027, and 0.0087. The known water contents were then factored in as a percent of the total mass of oven dry soil needed for the soil columns. For the engineered (#70 mesh) and C33 sands packed to a bulk density of 1.7 g/cm^3, 807.6 g of oven dry soil is needed, and 712.58 g is needed for the loam soil given a bulk density of 1.5 g/cm^3. To account for the moisture that exists in the air dry soil, an additional 0.15%, 0.27%, and 0. 87% of the oven dry mass needs to be added for the materials being tested.

Preliminary tests were conducted by packing columns using a hydraulic press. One of the most important, but often over looked parts of laboratory soil column testing is how soil columns are packed. Lebron and Robinson (2003) reported that more variability in experimental results can come from differences in soil packing then from the variable being tested. To increase the consistency of bulk densities between cores, we first opted to use a hydraulic press. Instead of adding small amounts of soil to the column and hand packing until the required volume was filled, the column could be filled with the predetermined mass of soil, and then compressed in a single ‘lift’ using the hydraulic press until the given volume was filled. Compressing the soil to the correct density all at once left no layering and provided a more consistent distribution of density throughout the column. This method is substantially better than traditional hand packing in terms of speed, ease, and, most importantly, consistency. Unfortunately, uniformly packing dry soil into columns does not always translate into consistent saturated water contents, as will be discussed below.

All column experiments were done on saturated soil material. Soils were saturated using the method described by Klute and Dirksen (1986). Although all procedures were followed, inconsistencies were observed in the level of saturation between the replicate columns. For example, for soil with a bulk density of 1.7 g/cm^3, a fully saturated column should have a volumetric water content of 0.36. However, our columns recorded volumetric water contents of between 0.30 and 0.35. This small difference in volumetric water content caused large differences in the K_{sat} measurements between replicates, where higher water contents corresponded to higher K_{sat} and vice versa. Because the relationship between water content and K_{sat} is a nonlinear, normalizing the data for water content was difficult. Therefore, we chose an alternative means of packing soils columns for subsequent tests.

The new method of packing the soil column was done while the column and soil were placed under water. The “waterpacking” was done by using the same method as the dry packing. A tubing and funnel apparatus (Figure 3.2), with a predetermined amount of soil, was used to swirl the soil into the column.

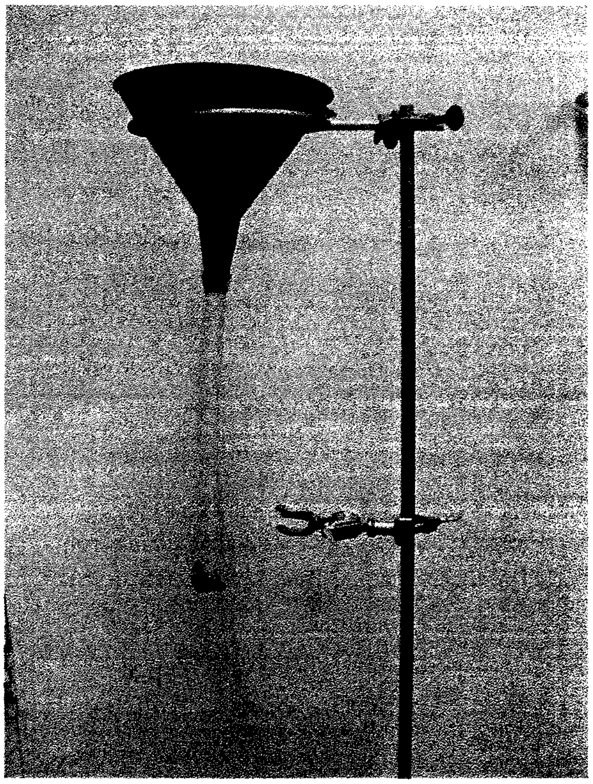


Figure 3.2: Funnel setup used to pack soil columns.

Approximately 2 cm of water was added to the column and soil was swirled in until an insufficient amount of water covered the soil surface. At this point, water was again added the process was repeated. Approximately four to five repetitions of this process was needed to fill each column.

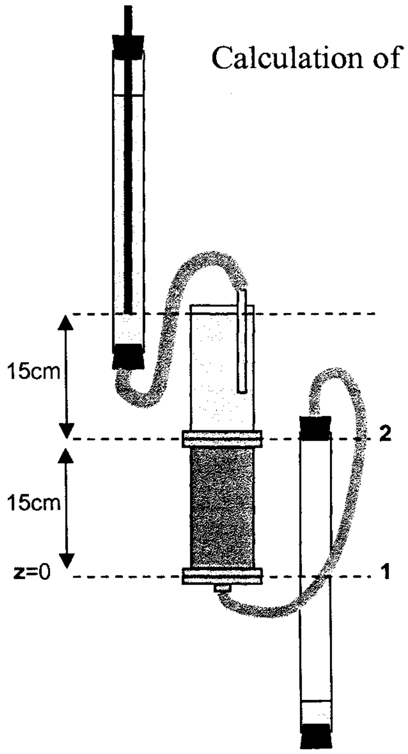
Unlike dry packing the water already present in the column helped the particles settle more tightly together and thus it was not necessary to compact the column using a press. A simple tap on the side of the column was usually enough to reach the desired bulk density. No apparent particle size segregation occurred from packing, and the method was more time efficient because the packing and saturation were completed simultaneously.

3.4.2 Calculation of Hydraulic Conductivity

Pressure transducer output was transferred to Excel spreadsheet format, and was then converted from voltage output to height of water, using the transducer-respective calibration equations. Knowing the area (A_c) of the collector column and the height of the water within the collector column (h_c), outflow volume (V) could be easily calculated over time (t). Results of discharge (Q) were then divided by the cross-sectional area of the soil core, yielding the Darcy velocity (q) or flux:

$$q = -K\left(\frac{\partial H}{\partial z}\right)$$

where K is hydraulic conductivity, H is total head, and z is the length of the region of interest (Figure 3.3). In this application, K is the unknown parameter we seek to quantify.



Calculation of hydraulic gradient

	z	p	H
1	0	15	15
2	15	15	30

$$\frac{H_2 - H_1}{z_2 - z_1} = \frac{30-15}{15-0} =$$

$$\frac{\Delta H}{\Delta z} = \frac{15}{15} = 1$$

Gradient = 1

Figure 3.3: Diagram and calculations of hydraulic gradient for soil column testing.

3.4.3 Application of PAM to Water Column

Some time was spent developing the most appropriate method of applying the dry PAM to the water column. The goal was to develop a method that most closely replicated the natural environment in a flowing canal. An early method was to stir the dry PAM in an orbital shaker, with 100 ml of test solution to dissolve the PAM crystals. The PAM solution was then applied to the 375 ml of test solution already present in the water column and the K_{sat} was started.

Two different variations of this method were tested in terms of turbidity: (1) PAM solution was added to water column containing turbidity, (2) turbidity was added to beaker and shaken in the orbital shaker while the PAM crystals dissolved.

Both methods of PAM turbidity interaction had drawbacks in terms of realism. Method 1 did not appear to flocculate the suspended sediment. Once the PAM solution was added to the water column, the suspended sediment would not sufficiently contact the PAM and react with it. Using method 2, the suspended sediment completely flocculated within the beaker, but when the mixture was added to the water column, the PAM flocculates did not evenly cover the surface of the soil column. The PAM flocculates were very large and, instead of creating a continuous layer, the flocculates were sparsely distributed as individual clumps.

To get the most realistic flocculation, it was decided that the dry PAM should be added directly to the water column and stirred in-situ to allow dissolution and flocculation to happen gradually. We hypothesized that using this method would create smaller floccs that would be more evenly distributed on top of the soil column. A stirring device was designed and fabricated to stir three replicate columns at the same rotational speed (Figure 3.4). Dye tests were performed to qualitatively identify the revolutions per minute that would replicate the threshold between turbulent and non-turbulent flow. The results indicated that 130 rpm most closely replicated conditions in a flowing canal.

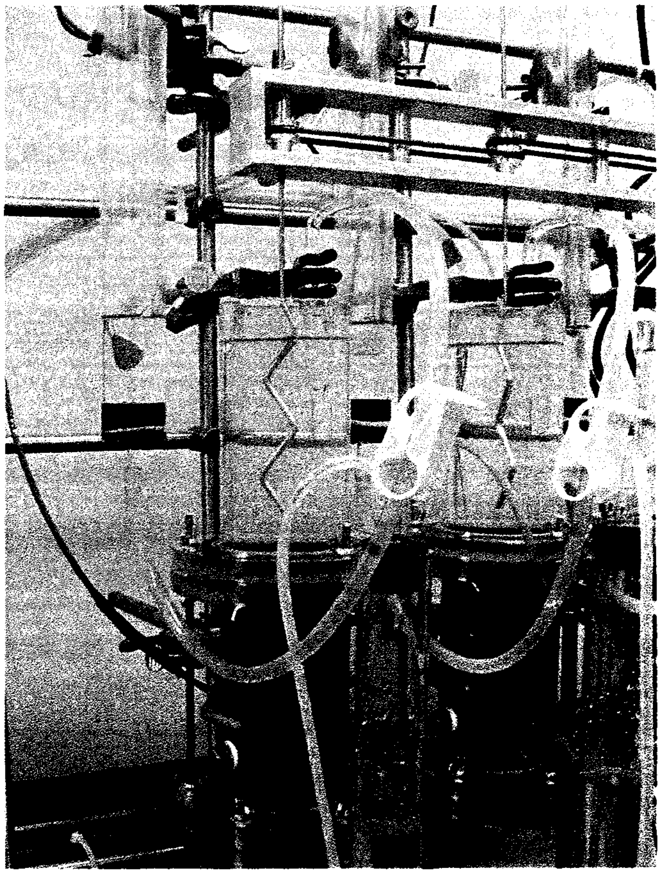


Figure 3.4: Stirring device used for soil column testing.

3.4.4 Viscosity Measurements

To identify the significance of each mechanism to reduce hydraulic conductivity, samples of the test solution remaining in the columns after the K_{sat} experiments were tested for viscosity. Viscosity measurements were performed using a viscometer (Cannon-Fenske Routine Type Viscometer #50 for Transparent Liquids) as shown in

Figure 3.5. The viscometer operates by measuring the time in seconds for the meniscus of a specific amount of fluid to move from a higher etched line on the apparatus to a lower etched line. The time is then multiplied by the calibrated viscometer constant. The value attained is the kinematic viscosity in centistokes (cSt) or mm^2/s.

Figure 3.5: Canon-Fenske Routine type Viscometer used for viscosity measurements.

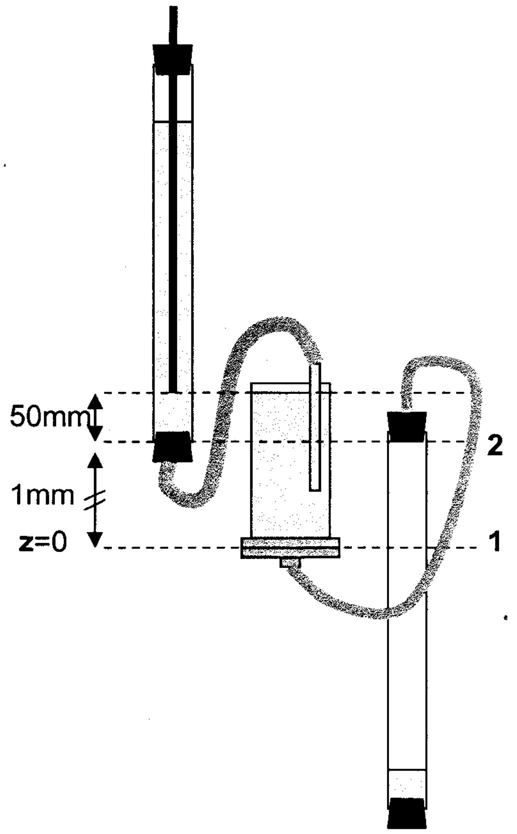
The viscosity of fluids is very temperature dependant and the change in viscosity with temperature is a non-linear function. The calibration constant of the viscometer varies slightly with temperature; this effect is minimal and is accounted for. To account for the measurement variability due to temperature for each experiment, the viscosity of the PAM solutions were compared relative to deionized water of the same temperature.

3.5 Experiment 4: Filter Material Testing

The fourth set of lab experiments were conducted using water columns and silk filter mesh. Filter media tests were carried out in to verify how much impact PAM alone, with no soil interaction, has on reducing K_{sat}. The filter material tests were carried out using the same procedures and the same PAM and sediment concentrations as the soil column tests.

Nitex Bolting Cloth from Wildco (Buffalo, NY) was chosen as the filter material used. Nitex Bolting Cloth is a woven nylon material with consistent aperture size. From an empirical test, a cloth with a 20-micron aperture was chosen for the filter material experiments.

To calculate K_{sat} for the filter material test an arbitrary thickness of 1 mm is assumed for the PAM and filter mesh together. The filter mesh material had such a high flow rate that the hydraulic head level had to be decreased from 15 cm to 5 cm for the Marriotte system to maintain a constant head level. Figure 3.6 shows the schematic and calculation of gradient used for the filter media experiments.



	z	p	H
1	0	1	1
2	1	50	51

$$\frac{H_2-H_1}{z_2-z_1}=\frac{51-1}{1-0}=$$

$$\frac{\Delta H}{\Delta z}=\frac{50}{1}=50$$

Gradient = 50

Figure 3.6: Diagram and calculations of hydraulic gradient for PAM filter media testing.

3.6 Statistical Methods

Statistical methods were applied to the soil column data to verify if significant differences existed between treatments. Triplicate K_{sat} measurements using the same soil type and same SSC, but varying PAM concentration were compared to one another using a comparison wise test. The data was run through Statistical Analysis Systems (SAS) software (Cary, NC) using the general linear model (GLM) procedure and Duncan's Multiple Range Test. The test compares all pairs of means, including within and between treatments. The test is initiated by first comparing the largest and the smallest mean within a treatment (e.g., largest and smallest K_{sat} for different PAM application rates using #70 mesh sand and 150 ppm SSC) and uses a studentized range statistic to determine significance (Montgomery, 2001). The test then compares the largest mean and the second-smallest mean, and so on, until all comparisons are completed.

CHAPTER 4

DATA ANALYSIS

4.1 Experiment 1: PAM Application Test

When the PAM application test was initially run, flocculation with sediment did not occur. It appeared that the columns containing PAM were in fact holding sediment in suspension longer than the control. It was discovered by chance why PAM was not having any effect on flocculation. The lack of flocculation was due to the use of distilled water in the experiments. After running another PAM/sediment column with tap water instead of distilled water, flocculation of sediment occurred immediately. In hindsight this made sense, the difference between the distilled water and the tap water is the calcium carbonate present in the tap water. In the distilled water the negatively charged PAM and negatively charged sediment repulsed each other causing dispersion, whereas calcium in the tap water acted as a bridging cation

When tests were performed again using tap water all columns containing PAM flocculated sediment. The pre-hydrated PAM and PAM solution worked faster, but once the PAM in all cylinders had the chance to hydrate all application methods worked equally well.

4.2 Experiment 2: Flocculation Jar Test

As indicated in Section 3, all suspended sediment was composed of kaolinite clay. To approximate the turbidity found in full scale canals, we sought a relationship between NTU and SSC for the kaolinite clay. Though no direct conversion between NTU and SSC is typically available, especially in natural waters where colloids and other coloration can influence the turbidity, Figure 4.1 shows a good relationship between kaolinite clay concentration and turbidity when clay is mixed in test solution.

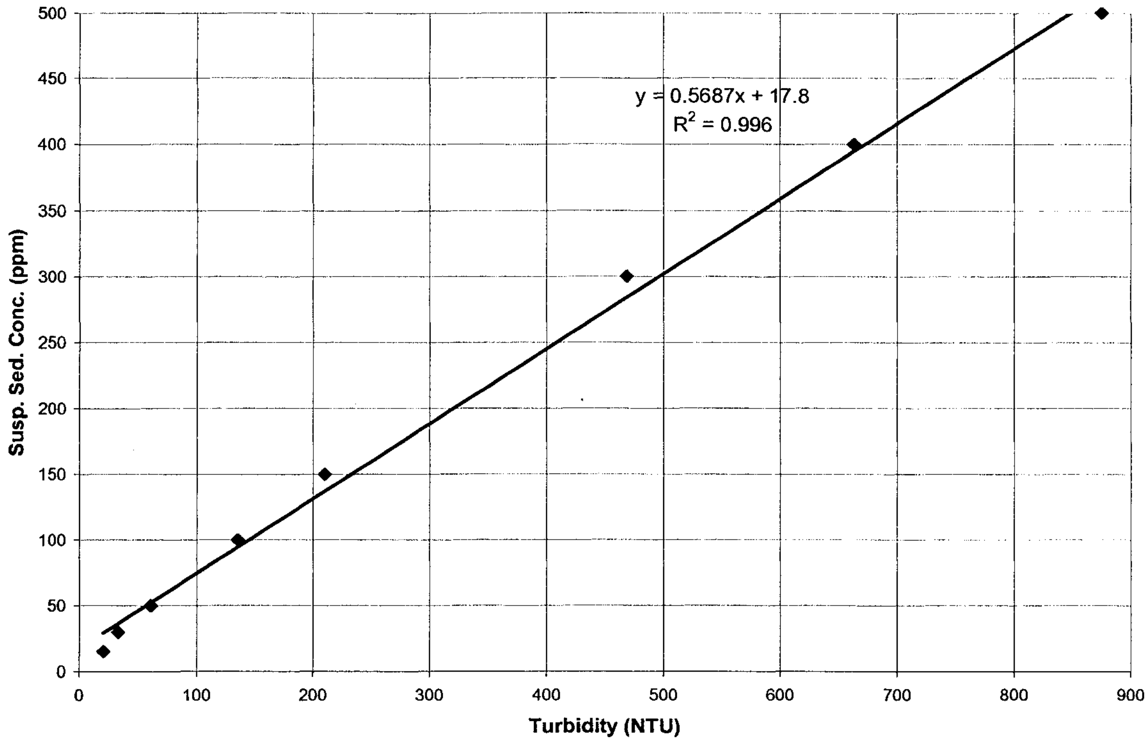


Figure 4.1: Correlation of suspended sediment concentration (SSC) to turbidity (NTU). Symbols are the data and the line represents the regression equation.

Once this relationship was established, the jar testing was initiated. Figures 4.2a-c show the results of the jar tests for PAM concentrations ranging from 0 - 32 ppm (0.5, 1, 2, 4, 8, 16, and 32 ppm) for suspended sediment concentrations of 20, 60, 110, 203 and 368 ppm (25, 75, 150, 300, and 600 NTU), and how the turbidity changed as a function of time. Note that NTU values were slightly lower, though consistent from test to test, when PAM was added to the solution.

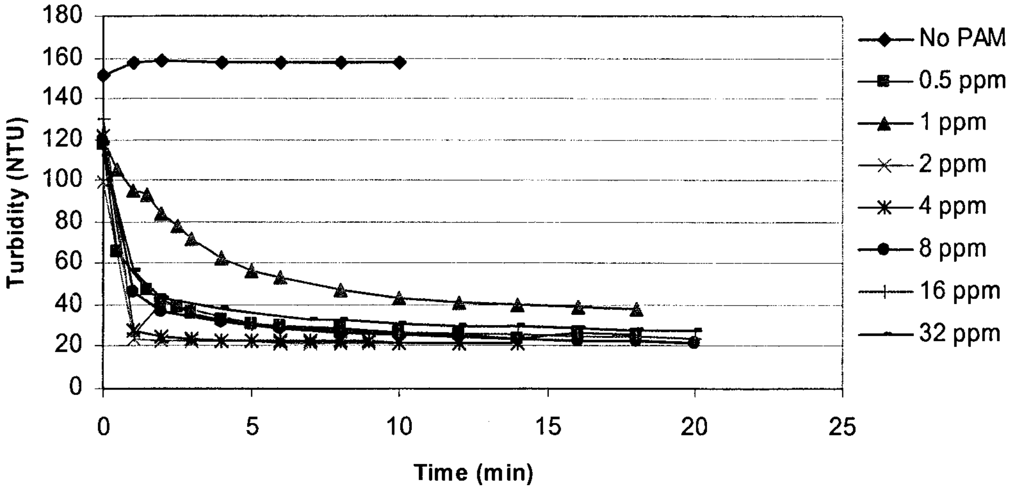


Figure 4.2a: Results of mixing tests for 110 ppm SSC (corresponding to 150 NTU) as a function of time and PAM concentration. Note different scales on the y-axes for other graphs in Figure 4.2

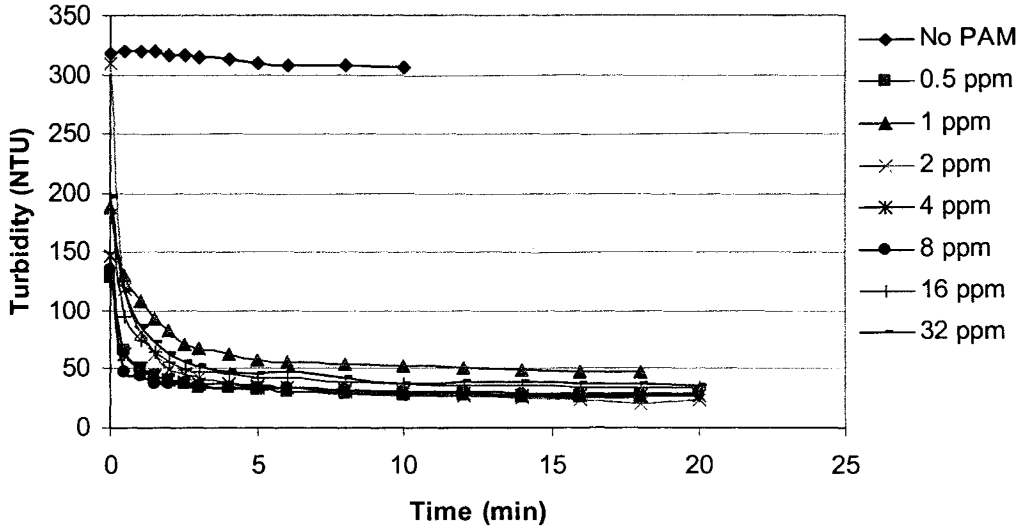


Figure 4.2b: Results of mixing tests for 203 ppm SSC (corresponding to 300 NTU) as a function of time and PAM concentration. Note different scales on the y-axes for other graphs in Figure 4.2.

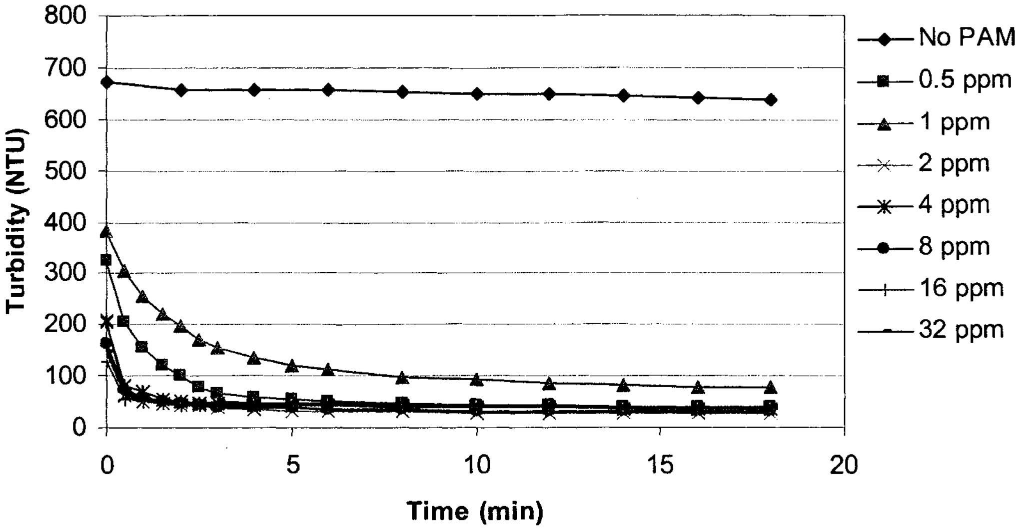


Figure 4.2c: Results of mixing tests for 368 ppm SSC (corresponding to 600 NTU) as a function of time and PAM concentration. Note different scales on the y-axes for other graphs in Figure 4.2.

Figure 4.2 shows the significant reactivity of PAM and kaolinite, as seen by the rapid reduction in turbidity. In each case without PAM added to the water column, very slight reductions in turbidity were seen, indicating that the kaolinite remained suspended in solution. The clay was acting as a colloid and not settling to the bottom of the column, as would heavier particles. Even small amounts of PAM, as low as 0.5 ppm, resulted in almost immediate settling of kaolinite as flocculates. We noted that flocculates were visibly seen falling through the water column within the first 30 seconds.

In terms of ability to flocculate kaolinite, using a higher concentration of PAM was not necessarily more effective. In all experiments, it appeared that the 2 and 4 ppm concentration of PAM flocculated sediment faster than did lower or higher concentrations. With lower SSC/turbidity levels, the higher concentrations of PAM (16 and 32 ppm) flocculated sediment rather poorly. The effectiveness of PAM to flocculate sediment declined with increasing levels of PAM. This result is likely due to the increased viscosity of the fluid in the column, which created additional resistance to settling of the flocculates. As sediment levels were increased, the larger (and heavier) flocculates began to settle more quickly, though the PAM solution at 4 ppm concentration was still most effective. Even at the low concentrations of 0.5 and 1.0 ppm PAM, sediment flocculation still occurred, although not as effectively as the higher concentration (2 and 4 ppm) treatments. When PAM concentrations exceeded 1.0 ppm, the turbidity reached approximate equilibrium conditions in the water column within five minutes. Final turbidity values settled on approximately 20 NTU for each experiment, regardless of the initial value or the PAM concentration.

As stated in Section 3, the original intent of these experiments was to quantify the reactivity of PAM and suspended sediment. However, because the readings for the turbidimeter took approximately 12 seconds to complete, flocculates in the treated water columns fell too rapidly for the meter to record a true time zero reading. This affected our ability to quantify the reactivity rates between PAM and suspended sediment, though qualitative observations were possible.

4.3 Experiment 3: Hydraulic Conductivity Testing

The combinations of soil type (three textures), PAM concentrations (4 levels plus control), suspended sediment (2 levels plus control) and triplicate measurements of each combination yielded a total of 135 experiments (Appendix A). Each experiment resulted in a time series of cumulative flux as a function of time, with the long-term (steady-state) flux expressed as a hydraulic conductivity. Rather than showing all individual plots of the output here, several representative graphs are included and discussed below. Mean values are also discussed below

Figures 4.3a-c are representative graphs from individual tests with the #70 mesh sand, C33 sand, and loam soil, using the same treatment of 40 lbs/ca PAM and 300 ppm SSC. The graphs show both cumulative flux in cm/sec and K_{sat} in cm/sec with time. Figures 4.3a and 4.3b, corresponding to the two sandy materials, exhibit very similar characteristics (note the difference in the y axis). In both cases, outflow is high at the beginning of the experiment and begins to taper off after approximately 300 seconds or 5 minutes into the experiments. After five minutes the flux begins to decrease over time until a steady state is reached at approximately 60 minutes.

Figure 4.3c show a more linear cumulative flux, with a slope that changes very little with time. Explanation for the change in flux will be discussed in greater detail below.

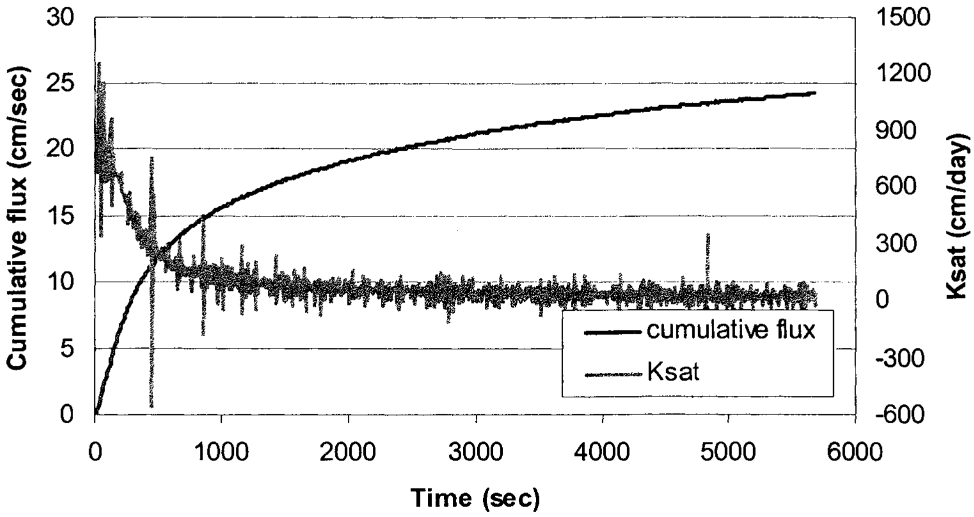


Figure 4.3a: Representative sample from the PAM soil column testing. Graph shows the cumulative flux and K_{sat} for the #70 mesh sand with 40 lbs/ca PAM and 300 ppm SSC.

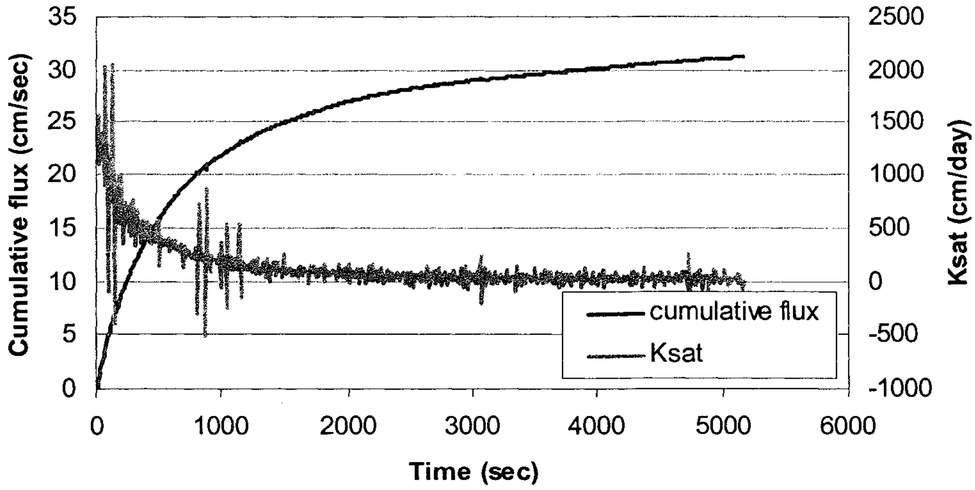


Figure 4.3b: Representative sample from the PAM soil column testing. Graph shows the cumulative flux and K_{sat} for the C33 sand with 40 lbs/ca PAM and 300 ppm SSC.

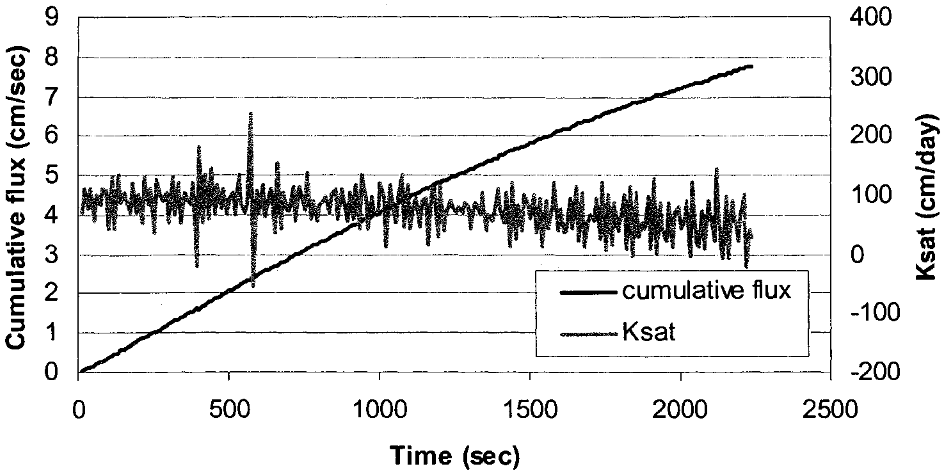


Figure 4.3c: Representative sample from the PAM soil column testing. Graph shows the cumulative flux and K_{sat} for the loam soil with 40 lbs/ca PAM and 300 ppm SSC.

Taking the mean of the steady-state K_{sat} results from triplicate experiments for each treatment combination, and plotting the means as a function of PAM and suspended sediment concentrations allow for a direct comparison of impact. Figures 4.4a-c show the saturated hydraulic conductivity values for the #70 mesh sand, C33 sand, and loam soil, respectively, after PAM treatment. Error bars are the range of data, and letters above the bars represent statistical differences between treatments of PAM concentration for each treatment of SSC (i.e., similar letters above treatments with different SSC are not related).

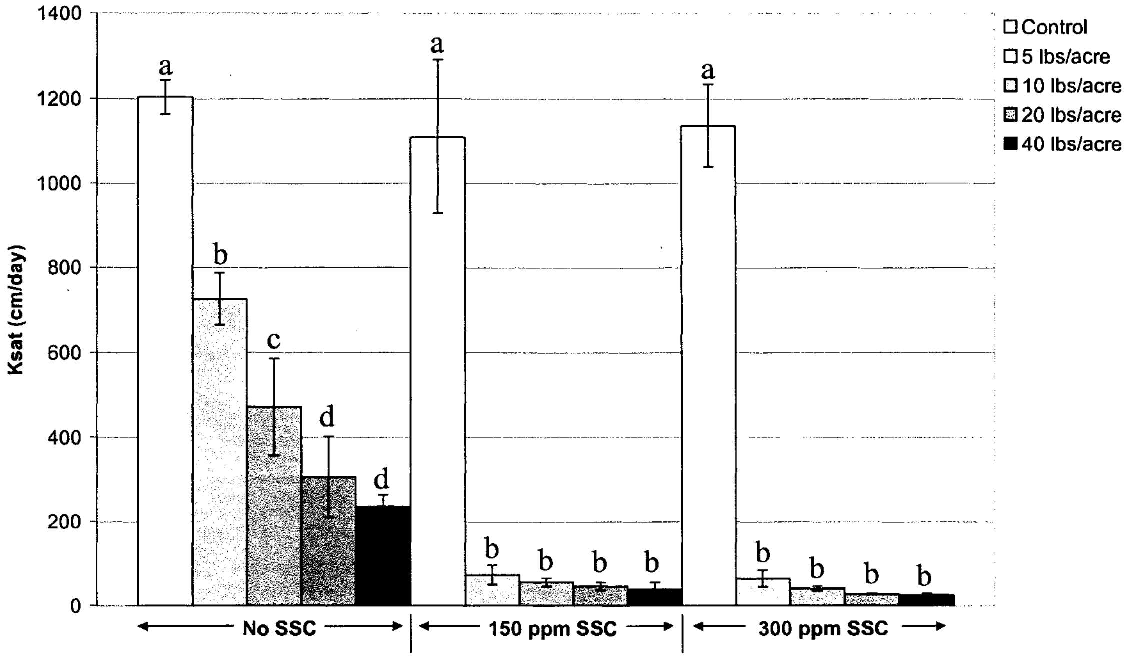


Figure 4.4a: Comparison of K_{sat} for treatments performed on #70 mesh sand.

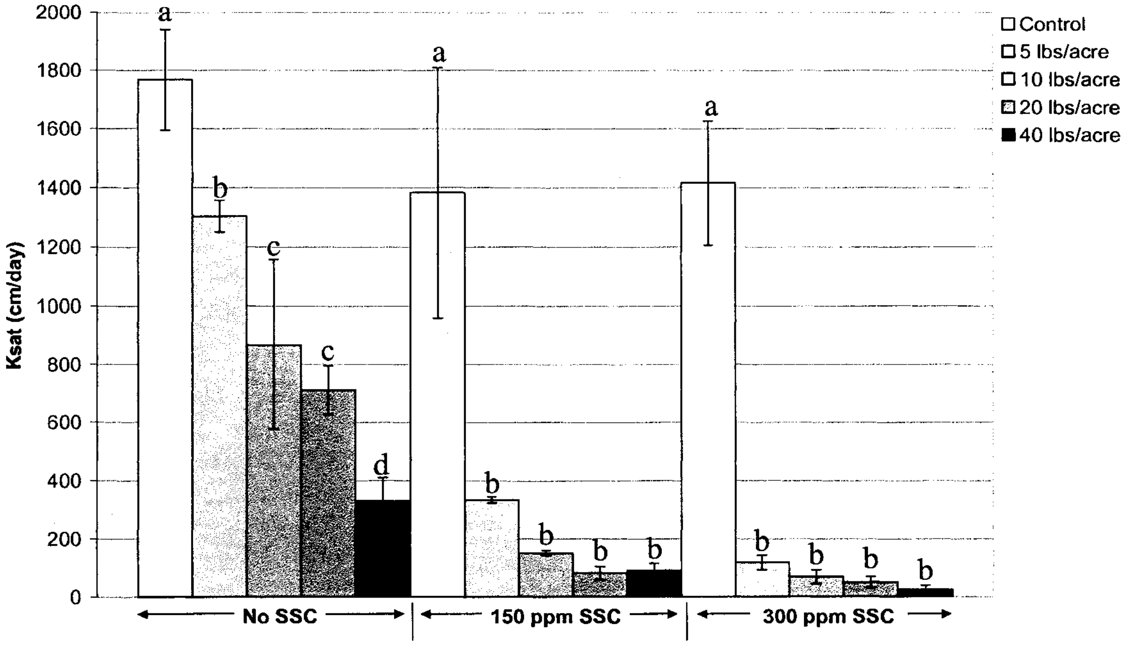


Figure 4.4b: Comparison of Ksat for treatments performed on C33 sand.

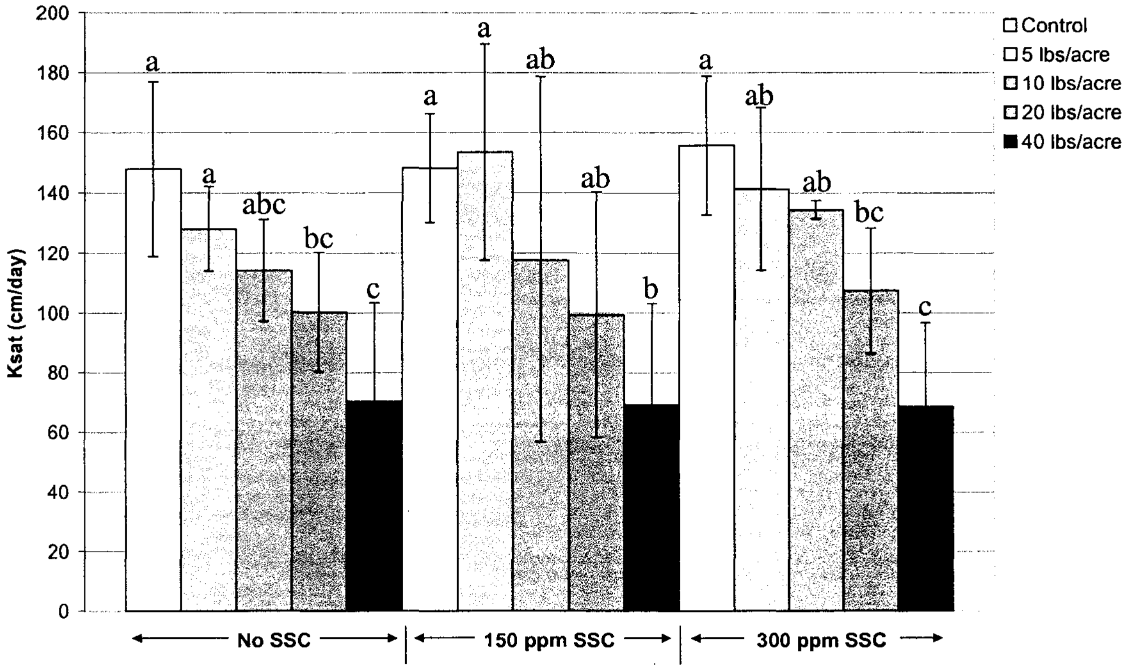


Figure 4.4c: Comparison of Ksat for treatments performed on loam soil.

The results without any treatment (no PAM, no SSC), show wide differences in K_{sat} between the three soils. The C33 sand, typically used for concrete, has the highest K_{sat} and the loam has the lowest K_{sat}. Values of K_{sat} did not change significantly for any soil when suspended sediment alone (no PAM) was added to the solution. When PAM was added to the solution (no SSC) in increasing concentrations, the results show significant decreases in K_{sat} for the #70 mesh and C33 sands, but only a decreasing trend in K_{sat} was observed for the loam soil.

The reduction of K_{sat} for the sandy material when no SSC was added (Figures 4.4a-b) is most likely a combination of increasing viscosity of the solution, which is described in more detail below, and the settling of PAM "fish-eyes," which are the colloquial name for hydrated PAM molecules. In this latter case, the molecules were likely carried downward to the soil surface during the experiment, where they sorbed to the soil surface and/or plugged larger soil pores. With respect to the results of PAM addition without SSC in the loam soil (Figure 4.4c), the results showed a decreasing trend in K_{sat}, but the trend was not statistically significant ($p=0.05$). The increased viscosity can explain the reduction in K_{sat}, but apparently the smaller pore sizes in the loam soil were not plugged by the PAM molecules as they settled onto the soil. Thus, some reduction in K_{sat} for the loam soil was observed through PAM addition, but the treatment was not as effective.

The PAM treatment was observed to be much more effective when PAM and SSC were used in combination. When sediment was not present (SSC = 0), the decrease in K_{sat} of the #70 mesh sand appeared to be more gradual with increasing concentrations of PAM (Figure 4.4a). When PAM was applied at 5 lb/ca, plus the addition of 300 ppm SSC, a decrease in K_{sat} of more than 11 times greater than PAM alone (62 versus 726 cm/day) was observed. This increase in efficiency decreased with the higher PAM concentrations used. For example, when using a PAM application of 40 lbs/ca with 300 ppm SSC, K_{sat} of the #70 mesh was 9.5 times lower than using PAM alone. This increase in efficiency was also observed for the 150 ppm SSC treatment, where an 8 to 10 fold reduction in conductivity was observed, versus PAM alone.

With respect to the loam soil, Figure 4.4c shows reductions in K_{sat} for PAM treatments with and without suspended sediment. When suspended sediment is absent, though a trend is evident for most treatments, a significant reduction in K_{sat} was recorded only at the maximum rate tested (i.e., 40 lbs/ca). PAM application with 150 ppm SSC produced similar results to PAM alone, only at the highest concentration of PAM tested was there a significant difference from the control. However, when SSC was present at the highest level tested (300 ppm), PAM concentrations of 20 and 40 lbs/ca resulted in statistically significant reductions in K_{sat} from the control. For all combinations of PAM and SSC, the reductions in K_{sat} were between 0% and 56% regardless of the presence of SSC.

The efficiency of PAM to reduce K_{sat} was calculated by dividing the percent reduction for the PAM treatment by the amount of PAM used in lbs per canal acre (Figure 4.5a-c). For example, in the #70 mesh sand experiments (Figure 4.5a), 5 lbs/ca of PAM and test solution with 300 ppm SSC caused a 94% reduction in K_{sat}. The 94% reduction was divided by 5 lbs/ca of PAM for an efficiency of 18.8. When PAM concentration was increased to 40 lbs/ca and 300 ppm SSC a 98% reduction in K_{sat} was

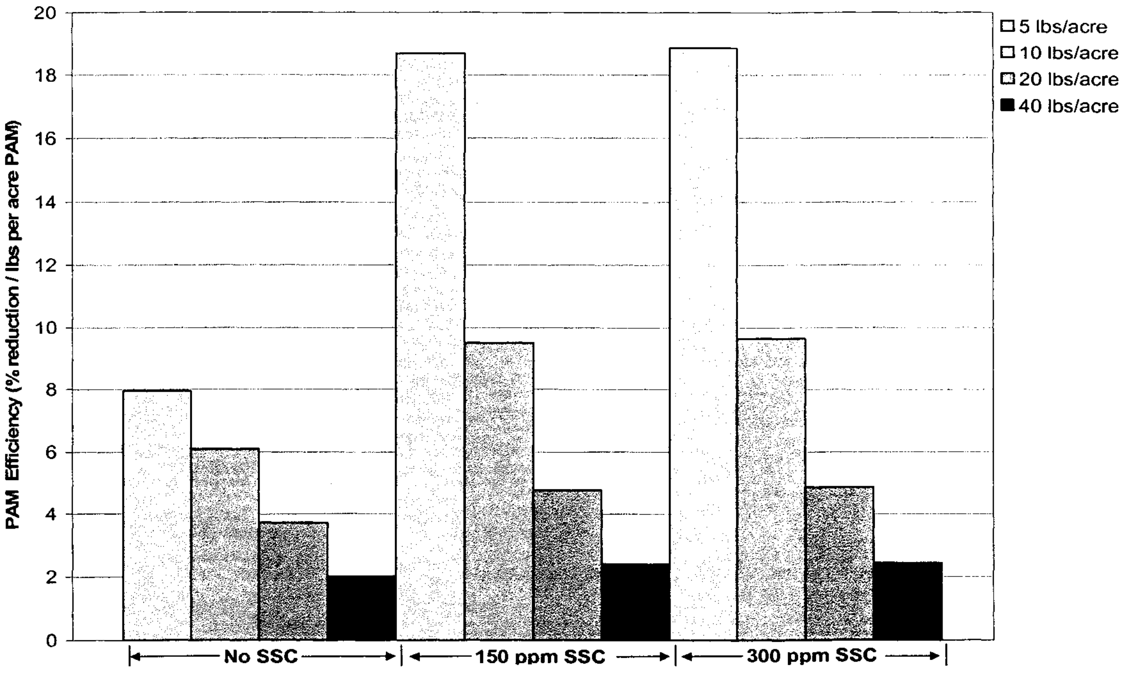


Figure 4.5a: Comparison of efficiency for PAM treatments using #70 mesh sand.

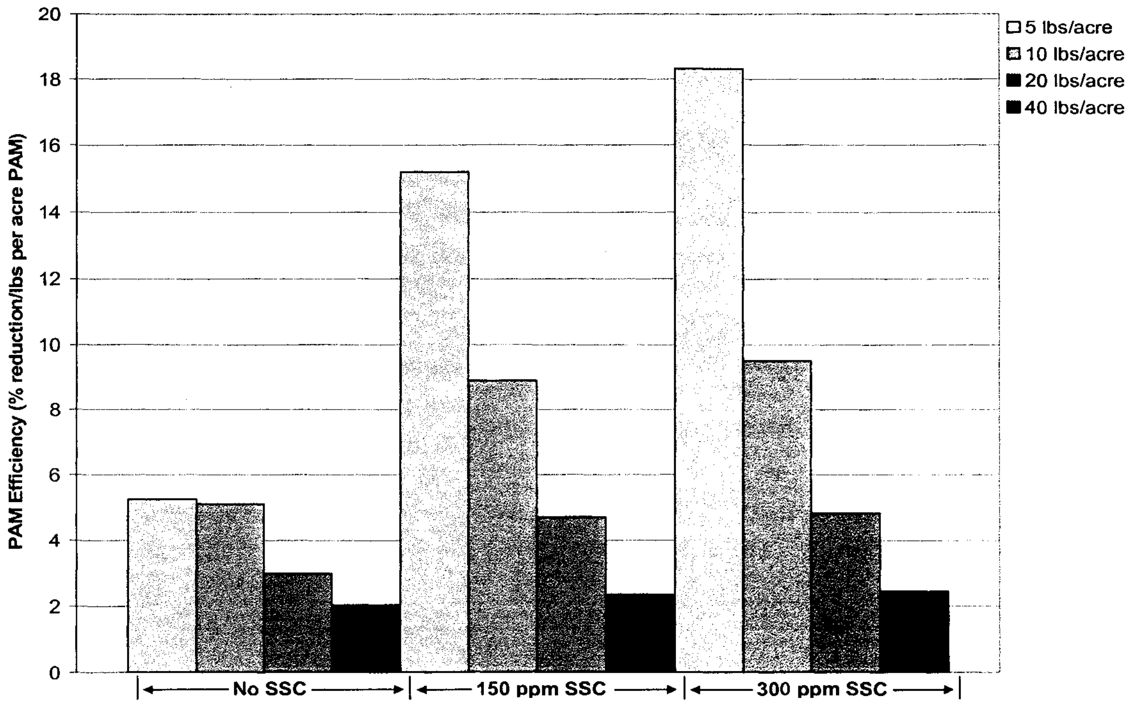


Figure 4.5b: Comparison of efficiency for PAM treatments using C33 sand.

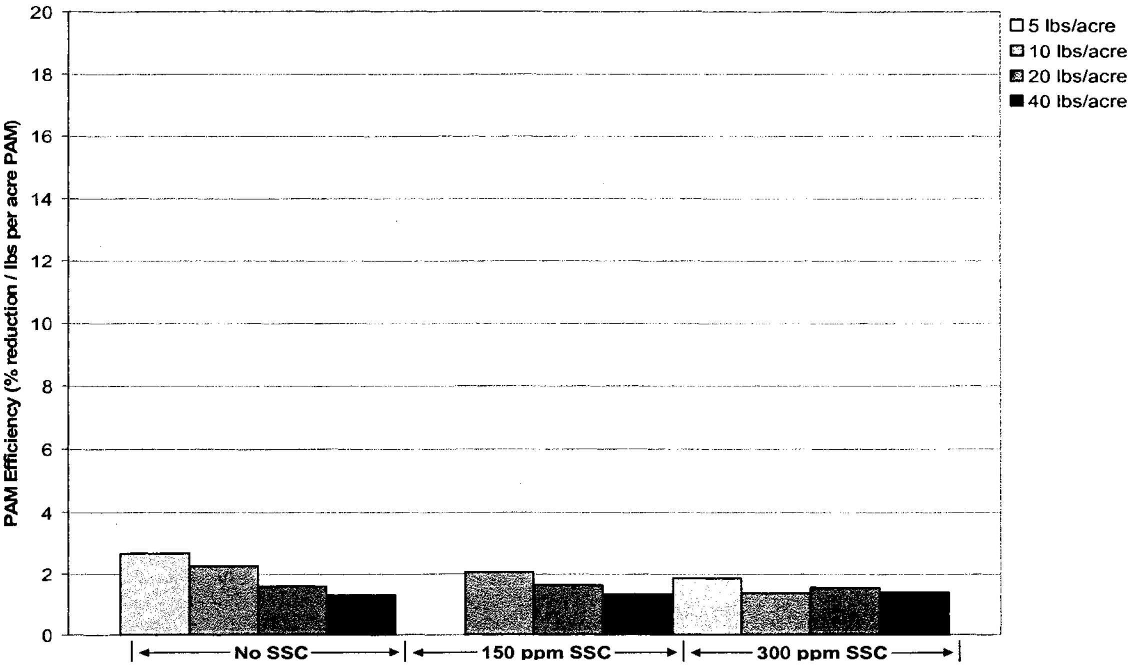


Figure 4.5c: Comparison of efficiency for PAM treatments using loam soil.

achieved, yielding an efficiency of 2.45. In the C33 sand, the efficiency values for the same treatments were 18.2 and 2.45, respectively. Thus, although the 40 lbs/ca application caused a greater reduction over the 5 lbs/ca application, the 4% additional reduction in K_{sat} required an eight-fold increase in the amount of PAM. In the loam soil (Figure 4.5c), PAM is shown to be inefficient at all concentrations used. The results in Table 4.1 highlight the capability of PAM as a sealant, and also the relatively small amount of PAM needed to effectively reduce K_{sat}. Therefore, results from the soil column K_{sat} tests support the original hypotheses that (1) PAM can be used to decrease infiltration, and (2) the presence of suspended sediment can increase the efficiency of PAM use.

Table 4.1: Average K_{sat} values, percent reduction from the respective controls, and efficiency for all treatments.

	#70 Mesh Sand				**C33 Sand**				**Loam Soil**			
Treatment	PAM	K_{sat}	Red.	PAM	PAM	K_{sat}	Red.	PAM	PAM	K_{sat}	Red.	PAM
	(lbs/ca)	(cm/d)	%	Eff.	(lbs/ca)	(cm/d)	%	Eff.	(lbs/ca)	(cm/d)	%	Eff.
Test solution only	0	1204	0	NA	0	1767	0	NA	0	148	0	NA
	5	726	39.7	7.9	5	1304	26.2	5.2	5	128	13.4	2.7
	10	471	60.9	6.1	10	867	50.9	5.1	10	114	22.7	2.3
	20	306	74.6	3.7	20	711	59.8	3.0	20	100	32.2	1.6
	40	236	80.4	2.0	40	331	81.3	2.0	40	70	52.5	1.3
150 ppm SSC	0	1110	0	NA	0	1384	0	NA	0	148	0	NA
	5	73	93.5	18.7	5	334	75.9	15.2	5	154	-3.6	-0.7
	10	55	95.0	9.5	10	152	89.0	8.9	10	118	20.6	2.1
	20	46	95.9	4.8	20	84	94.0	4.7	20	99	33.0	1.7
	40	39	96.5	2.4	40	82	94.1	2.4	40	69	53.3	1.3
300 ppm SSC	0	1136	0	NA	0	1415	0	NA	0	156	0	NA
	5	64	94.4	18.9	5	119	91.6	18.3	5	141	9.3	1.9
	10	40	96.5	9.6	10	70	95.1	9.5	10	134	13.7	1.4
	20	28	97.6	4.9	20	51	96.4	4.8	20	107	31.0	1.6
	40	25	97.8	2.4	40	26	98.2	2.5	40	69	55.9	1.4

4.3.1 Effect of Viscosity

As discussed in Chapter 2, numerous papers (Malik and Letey, 1992; Nadler et al., 1994; Letey, 1996) have been written suggesting that increases in viscosity from PAM addition explain the decrease in infiltration/conductivity in soil. Even very small amounts of PAM can significantly increase viscosity, and in turn affect the ability of fluids to move through soil. In our laboratory experiments when suspended sediment was not present, the change in viscosity of the solution was hypothesized to be primarily responsible for the decrease in K_{sat}. If no sediment is present in the water column for flocculation to occur, it is likely that more PAM stays in suspension rather than settling to the soil surface where it would be most effective. To examine whether PAM is remaining in solution during the tests, an aliquot of solution was analyzed with a viscometer at completion of the tests. The viscosities of these aliquots were compared to the viscosity of deionized water of the same temperature. Figure 4.6 shows, with no sediment present, an increase in the relative viscosity as PAM concentration is increased.

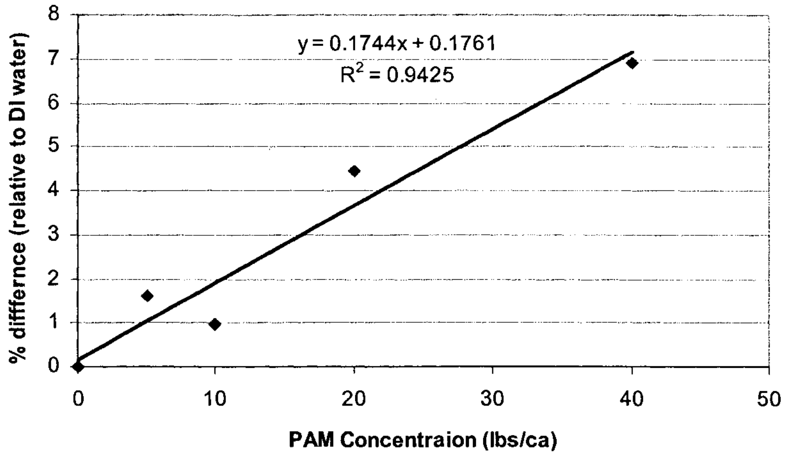


Figure 4.6: Correlation of relative viscosity to PAM concentration for experiments using #70 mesh sand and no SSC.

At the maximum PAM concentration of 40 lbs/ca, a difference in viscosity of 7 % was recorded. An increase in the viscosity from the addition of PAM could explain the reduction in K_{sat}, but a 7% increase in viscosity would not be enough to explain the full extent of the K_{sat} reductions seen in the tests. Figure 4.7 shows the effect that the change in viscosity alone should have on K_{sat}.

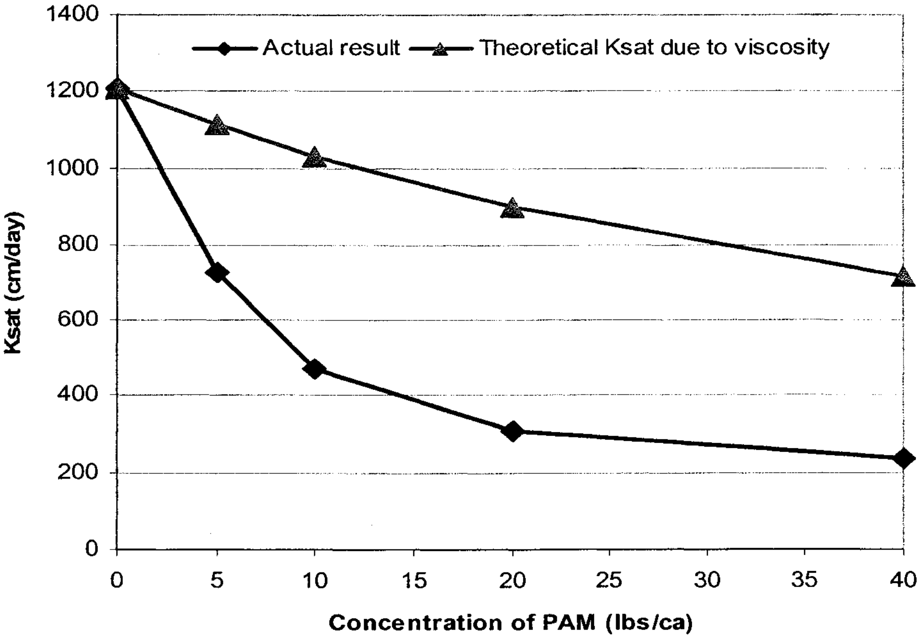


Figure 4.7: The figure shows actual K_{sat} results from the #70 mesh sand with PAM and no sediment, and the theoretical K_{sat} results for the effects of viscosity alone.

The theoretical K_{sat} value attributed to change in viscosity was derived by using the relationship attained in the Figure 4.8. The kinematic viscosity of test solution was divided by the viscosity values for the PAM concentrations of 4, 8, 16, and 32 ppm (equivalent to 5, 10, 20, and 40 lbs/ca). The relative differences in viscosity between test solution and PAM solutions were 0.992, 0.855, 0.747, and 0.596, respectively. The actual

K_{sat} of the #70 mesh sand was then multiplied by the relative viscosity values, to get the change attributed to viscosity alone. This approach is equivalent to correcting the hydraulic conductivity for viscosity, as shown:

$$K_{sat} = \frac{\kappa \rho g}{\eta}$$

where κ is the intrinsic permeability (L^2), r is the bulk density of the fluid (M/L^3), g is the acceleration constant (L/T^2) and η is the kinematic viscosity (L^2/T).

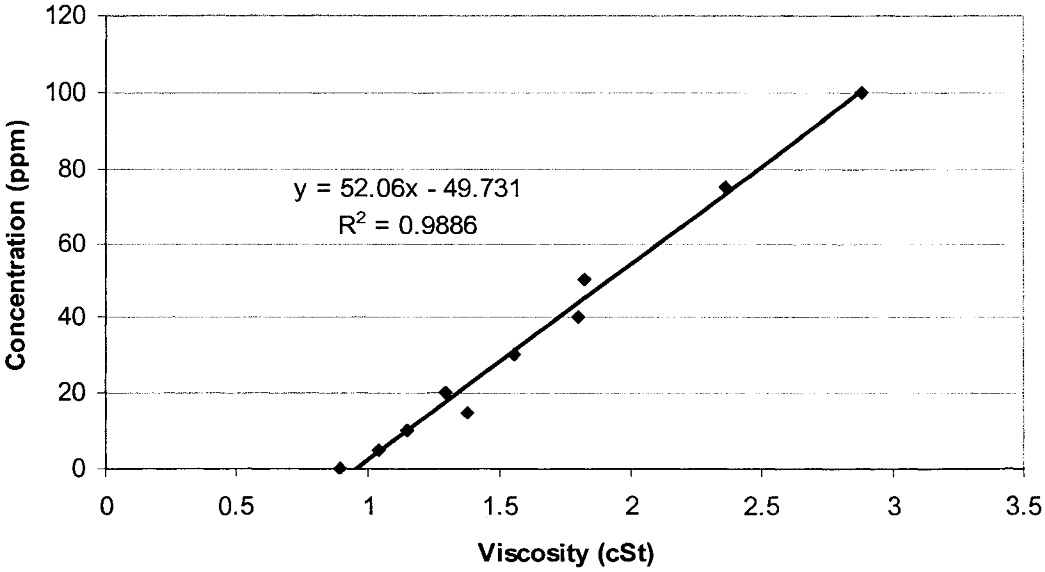


Figure 4.8: Correlation of viscosity to PAM concentration (ppm) at 25°C.

Figure 4.7 shows that a substantial difference exists between the theoretical K_{sat}, due to viscosity change alone, and the actual K_{sat} values measured with the column studies. With no suspended sediment present, the test results show a difference of 34, 54, 66, and 67% from what could be expected from viscosity alone. Although no suspended sediment was present to flocculate PAM from the water column, which was continuously stirred in the column, PAM would still have contacted the soil surface with the likelihood of sorbing and causing the greater reduction in K_{sat} than could be expected from increased viscosity alone. As previously discussed, even without suspended sediment the reduction in K_{sat} can be attributed in some extent to change in viscosity as well as PAM adhering to and sealing the soil surface.

In addition to comparing the viscosity of the test solution remaining after the experiments are complete to that of deionized water, an attempt was also made to predict the concentration of PAM in solution from change in viscosity. This was done by establishing a regression curve between viscosity, measured from the viscometer, and the PAM mass added to the solution. The correlation was done by measuring viscosity of 10 solutions with known PAM concentrations at a standard laboratory temperature of 25°C (Fig. 4.7). The R^2 value of 0.9886 indicated a good fit to the data; however, a standard error of 3.666 ppm PAM concentration means that low, residual concentrations of PAM remaining in the water column may not be quantifiable using this method.

Although a good correlation exists between solution viscosity and PAM concentration, two problems were identified with accurately estimating the concentration of PAM left in solution from a viscosity measurement.

(1) Viscosity readings are greatly affected by temperature. Although care was taken to accurately measure room temperature during all experiments, temperature variations between room temperature and solution temperature were possible.

(2) The regression model for solution viscosity to PAM concentration has a standard (predictive) error of 3.7 ppm; thus, for most cases, the model lacks the precision to accurately measure low PAM concentrations.

During the laboratory experiments, the only sample to exceed the standard (predictive) error limit of 3.7 ppm was the combination of a PAM application rate of 40 lbs/ca and no SSC, where an estimated PAM concentration of 4.3 ppm was left in solution. Nonetheless, although the correlation lacks the resolution to estimate low concentrations, it is still helpful in showing that most of the PAM has been removed from the solution. For the soil column K_{sat} testing the initial PAM inputs were 4, 8, 16, and 32 ppm (5, 10, 20, and 40 lbs/ca).

4.3.2 Surface Seal versus Pore Clogging

In experiments with SSC, for all three soil types, a thin layer of PAM was observed on the soil layer at the completion of the experiments (Figure 4.9 is an example of the PAM layer).

Figure 4.9: An example of the PAM/sediment layer on top of the soil at completion of the experiments. The layer has been disturbed to show contrast between the PAM/sediment layer and the darker C33 sand beneath.

Though the layer of PAM and sediment was seen for all three soils types, the decrease in conductivity was more pronounced in the two coarse-grained soils. Moreover, not only were the decreases in K_{sat} greater for the sands than for the loam, compared to their respective controls, but the absolute value at the end of the experiments were lower as well. Using the highest PAM application rate of 40 lbs/ca and the highest SSC of 300 ppm, the percentage decrease in K_{sat} was 98%, 98%, and 56% for the #70 mesh sand, C33 sand, and loam soil, respectively. The final K_{sat} values for this same treatment were 25, 26, and 69 cm/day. If the PAM and sediment are sealing the soil like a soil crust, then the magnitude of K_{sat} for the sands should be no lower than those observed for the loam soil. The laboratory results clearly show differences in the magnitude of the K_{sat} values after PAM treatment. A possible explanation for this phenomenon is that the PAM/sediment layer is not only sorbed to the upper soil surface, but it is partially penetrating into the larger pores of the coarser soils. Because the #70 mesh and C33 sands have larger pores than the loam soil, it is likely that the flocculates are able to penetrate and clog pores resulting in a more effective decrease in K_{sat}. To further examine this possibility, a targeted series of experiments were conducted on filter material with a uniform pore size distribution in the fine to medium pore range.

4.4 Filter Material Test

4.4.1 K_{sat} results

The K_{sat} results for the PAM and filter material tests are presented in Figure 4.10, using the same graphing style as used to show the soil column experiments.

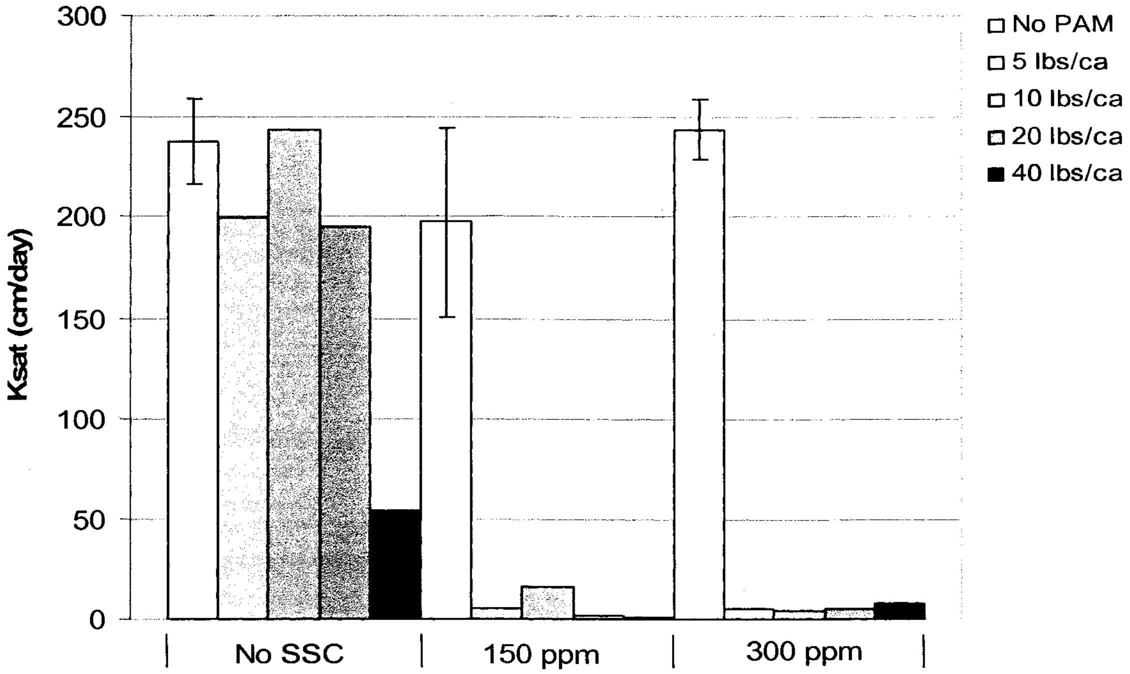


Figure 4.10: K_{sat} data for filter media tests.

Unlike the soil column experiments that used a unit gradient for calculation of K_{sat}, the filter material test used a gradient of about 50. With such a high gradient, there was some concern that movement of water across the PAM layer would be turbulent, resulting in non-Darcian flow. This type of flow condition would render use of Darcy's equation invalid, and under estimate K_{sat} values for our filter material experiments.

To address this concern, we examined whether the flow conditions in our experimental setup exceeded a Reynolds number (R_n) of 1. The equation (Fetter, 2001, p. 123-124) and example calculation are shown below:

$$R_n = dq\rho/\mu$$

$$R_n = (20x10^{-6}\,m)(0.004\,m/s)(1000\,kg/m^3)/8.9x10^{-4}\,kg/m\cdot s = 0.09$$

where d is the pore diameter of the filter material (d=20 μm), q is discharge velocity, ρ is density of fluid, and μ is fluid viscosity. The results indicate that R_n is less than one; thus, we can infer that we have laminar flow and Darcy's law is applicable for calculation of K_{sat}.

The filter material tests verify that PAM alone can decrease K_{sat}, with a good linear fit representing K_{sat} as a function of PAM concentration ($r^2 = 0.840$) (Figure 4.11). Similar trends were observed from both the soil column and filter material tests; specifically, (1) sediment alone has very little effect on decreasing K_{sat}, (2) increasing PAM concentration decreases K_{sat}, and (3) the addition of sediment increases the effectiveness of PAM much greater than PAM alone.

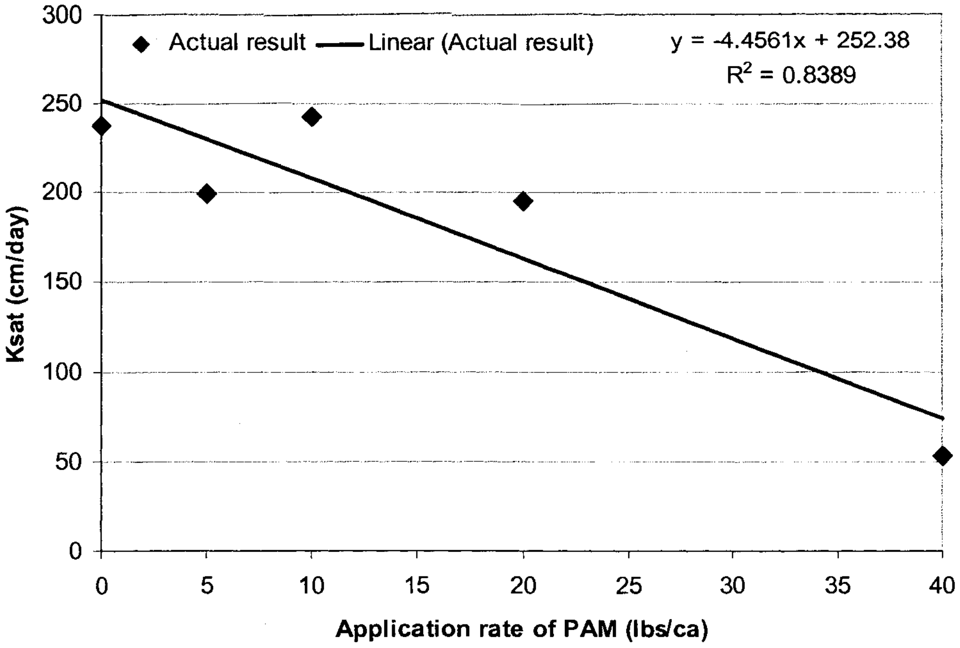


Figure 4.11: Linear regression of K_{sat} results from PAM filter material test without suspended sediment. Symbols are the data and the line is the regression model.

4.4.2 Addition of sediment

The reduction in K_{sat} from the PAM and suspended sediment, when mixed together, is more evident with the mesh filter media, than when using soil columns. As shown in Figure 4.10, it is clear that adding sediment leads to significantly higher seepage reduction. Only the tests with no PAM and varying SSC were performed with replicates. Using those test results, it was possible to verify that no statistical difference existed between the concentrations of sediment and K_{sat} reduction, when PAM is not present. These results are consistent with the size differences between the silk mesh filter material (20 micron openings) and the kaolinite clay (<2 microns in diameter). As a result, the clay is not likely to build up on top of the mesh material to create a less permeable layer.

Figure 4.10 shows that the addition of sediment and PAM can reduce K_{sat} between 7 to 55 times greater than PAM alone, depending on the concentrations of PAM and kaolinite. The use of the filter material provided a unique means to isolate the physical processes of crust development and pore clogging. Unlike in soil, which can trap sediment within larger pores and eventually reduce flow, particles with diameters smaller than the openings of the filter material will pass through, most likely not affecting the flow. Once sediment was added to the PAM solution and allowed to flocculate, very rapid and significant reductions in K_{sat} were observed. The very similar K_{sat} reductions, regardless of the treatments that contain PAM and sediment, indicate that a threshold size flocculate of PAM and sediment could initiate pore plugging.

4.4.3 Hydration Period

PAM requires some amount of time to hydrate before it can effectively reduce K_{sat}. Knowledge of hydration period is a key parameter in PAM field application, especially given the distance traveled in the canal water before reacting with the sediment and settling to the canal bottom. To estimate the hydration period, we examined more closely the time series of outflow from the filter material experiments, to see if slope breaks could signal a change in hydration status of the PAM flocculate.

Figures 4.12a and b are examples from soil column and filter material tests respectively. Both show three distinct phases of hydration. In Phase I, PAM is not hydrated and has no affect on decreasing flux. During Phase II, PAM is hydrating, reacting with sediment and is beginning to decrease flux. In Phase III, PAM has been completely hydrated and the column outflow rate has reached a state of dynamic equilibrium. The highest amount of K_{sat} reduction occurs in this phase.

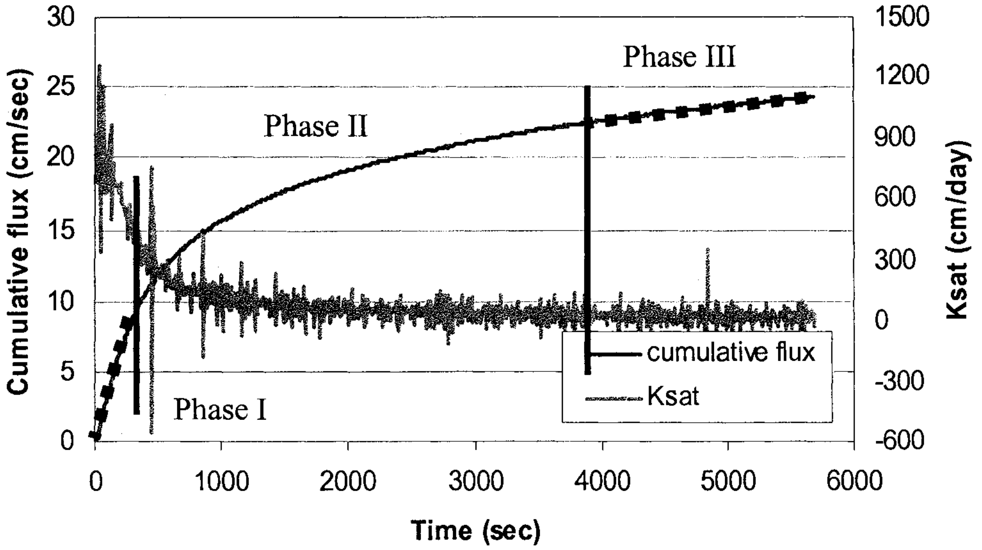


Figure 4.12a: Three different phases of hydration. Test performed on #70 mesh sand with 40 lb/ca PAM and 300 ppm SSC.

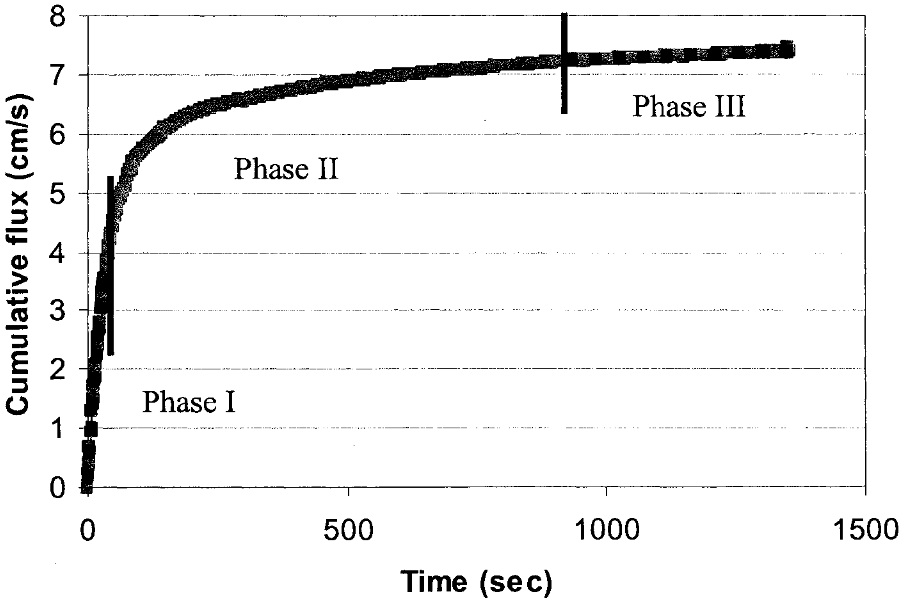


Figure 4.12b: Three different phases of hydration. Test performed on filter media with 40 lb/ca PAM and 300 ppm SSC.

In many cases, the time needed to complete the experiments was less than 120 seconds, so that repeated experiments were needed to examine longer hydration periods. In these cases, the flow-through rates (i.e., cumulative flux versus time) were essentially uniform and the fluxes themselves could be compared on a single graph. However, as the PAM and suspended sediment concentrations increased, the time needed to complete the experiments took longer than the individual hydration periods being studied. In these cases, and using the example shown in Figure 4.12a, first derivatives were calculated at times corresponding to the hydration period, using the equation:

$$slope_{t} = \frac{flux_{t+10\,s} - flux_{t-10\,s}}{time_{t+10\,s} - time_{t-10\,s}}$$

where t + 10s and t - 10s are time periods 10 seconds before and after the time of interest (i.e., 20 second regression window). The slopes were then used to plot fluxes as functions of time for different hydration periods and for different treatment combinations of PAM and SSC. The plots in Figures 4.13a-d were generated for PAM concentrations of 5, 10, 20, and 40 lbs/ca with no suspended sediment. In the case of 5 lbs/ca, the initial hydration periods (0 and 5 minutes) show no difference in slope, which would indicate that hydration has not yet affected PAM enough to reduce flux. At the 10 minute period, the flux is decreasing, thus indicating the beginning of when PAM hydration is leading to a reduction in flux. By 40 and 60 minute period, the PAM hydration appears to have reached a maximum level, at least as it affects seepage reduction. As the PAM concentration increased from 5 lbs/ca to 40 lbs/ca, the time needed to fully hydrate the PAM molecule also increased, as did the seepage reduction. The results show that hydration period to fully reach equilibrium can vary from about 10 to 60 minutes depending on the amount of PAM applied.

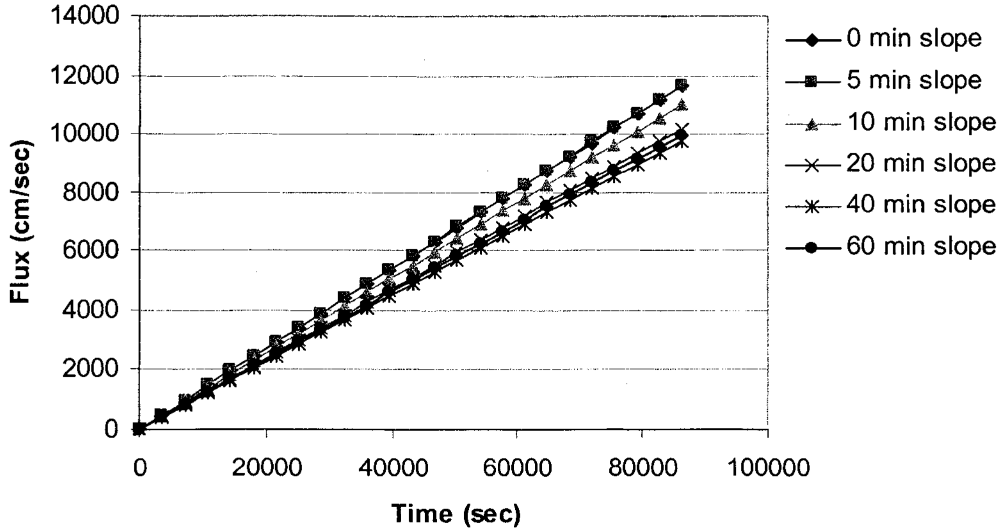


Figure 4.13a: The effects of hydration on 5 lbs/ca PAM, with no SSC.

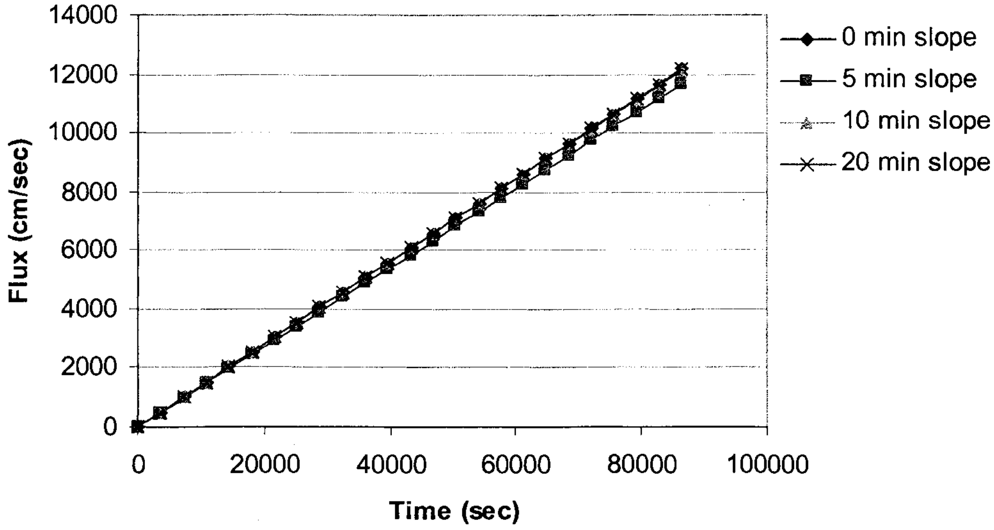


Figure 4.13b: The effects of hydration on 10 lbs/ca PAM, with no SSC.

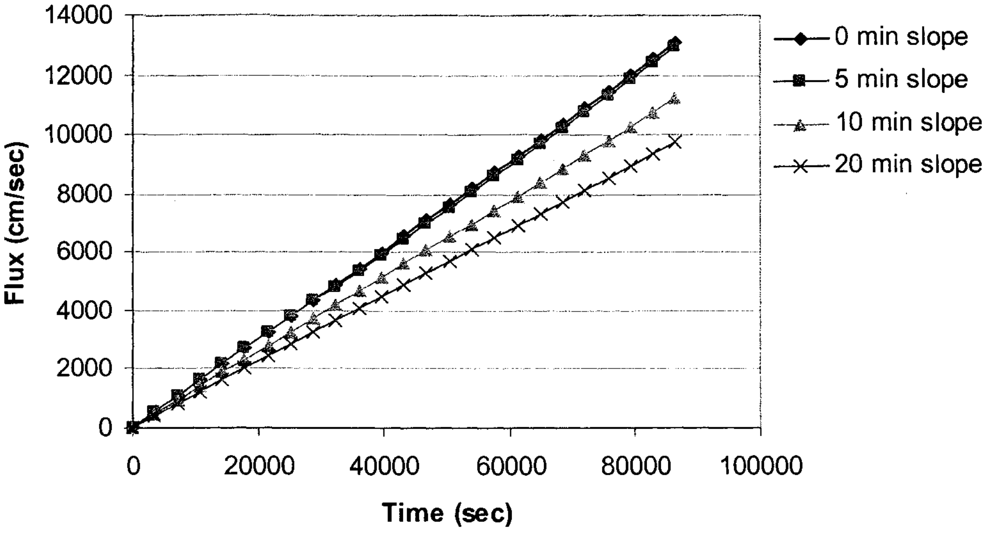


Figure 4.13c: The effects of hydration on 20 lbs/ca PAM, with no SSC.

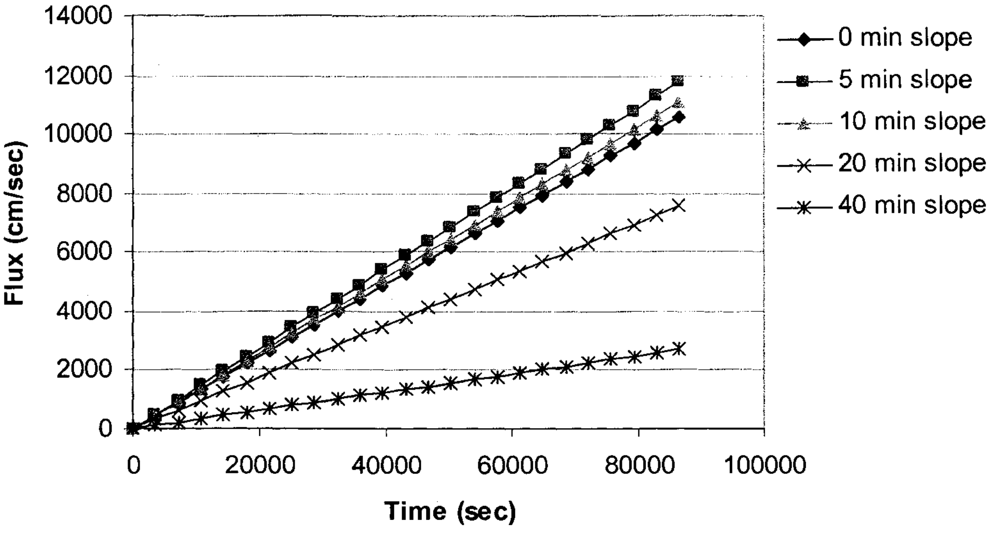


Figure 4.13d: The effects of hydration on 40 lbs/ca PAM, with no SSC.

Figures 4.14a-d are time series showing flux as a function of time for the same PAM concentrations as used in Figures 4.13a-d, but experiments used to generate Figures 4.14a-d were conducted at the highest turbidity level of 300 SSC. With SSC present most columns showed little change with hydration period of 5 minutes, but in most cases, the flow reached an abrupt steady state at approximately 7.5 minutes. Although steady state in terms of flux was reached very quickly, the PAM may not be fully hydrated. In these cases, sufficient time has been reached for PAM hydration to flocculate enough sediment to clog the pores of the filter media, even though the PAM molecule may still be hydrating.

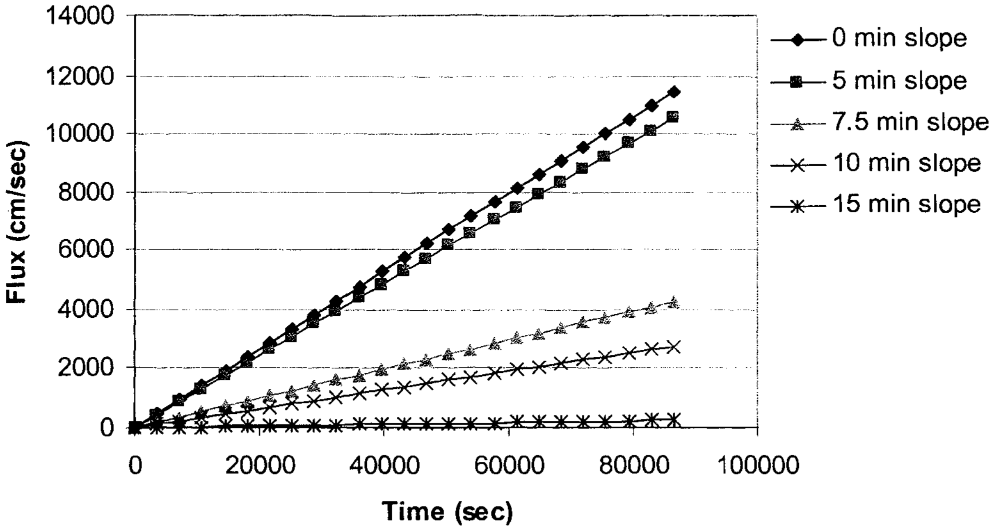


Figure 4.14a: The effects of hydration on 5 lbs/ca PAM, with 300 ppm SSC

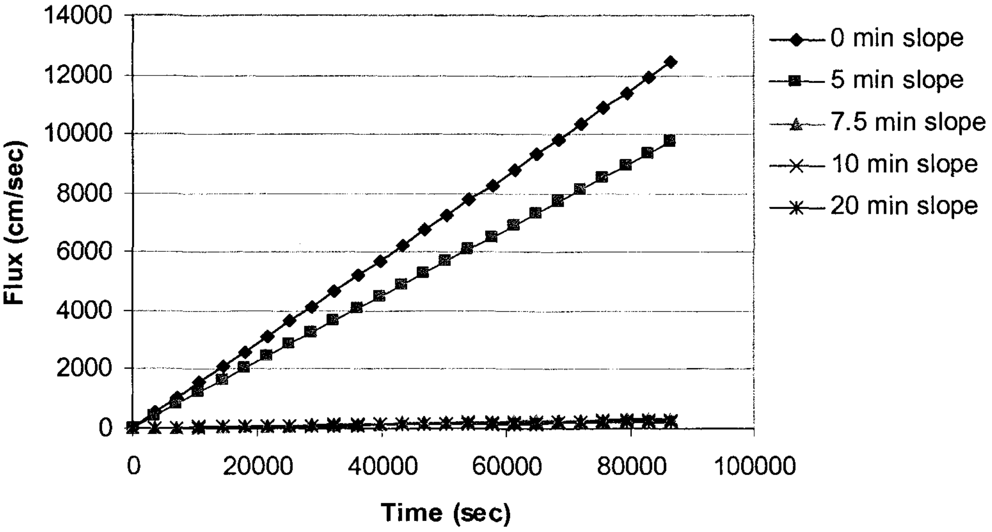


Figure 4.14b: The effects of hydration on 10 lbs/ca PAM, with 300 ppm SSC.

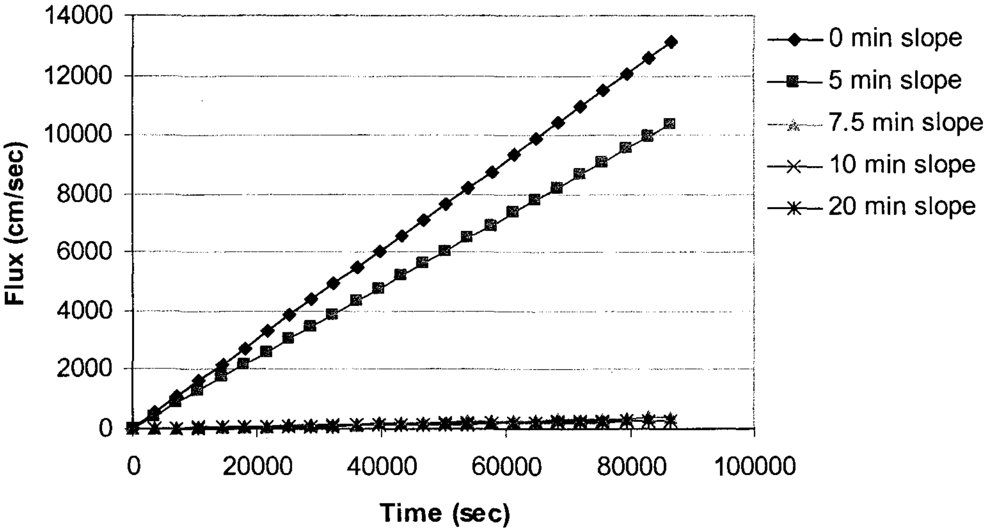


Figure 4.14c: The effects of hydration on 20 lbs/ca PAM, with 300 ppm SSC.

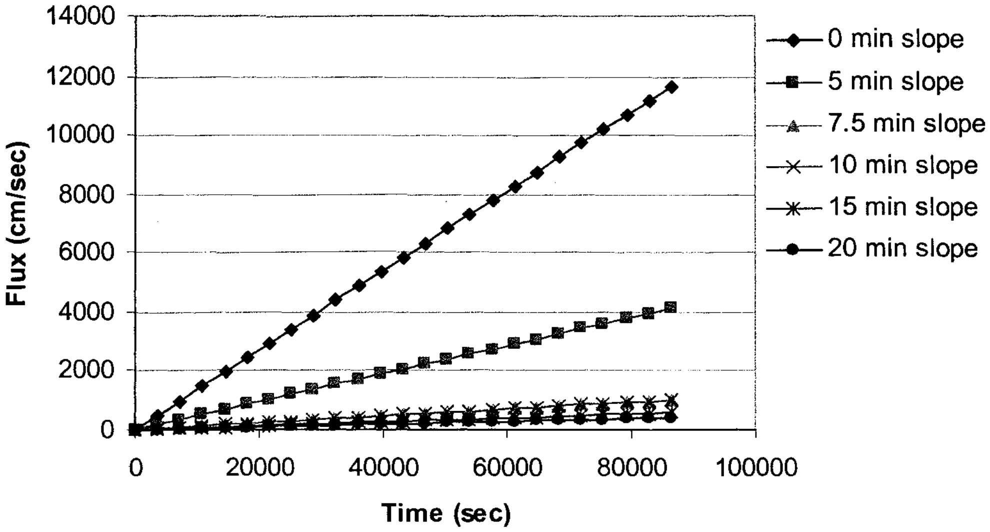


Figure 4.14d: The effects of hydration on 40 lbs/ca PAM, with 300 ppm SSC.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

For the research conducted in this study, our hypothesis was that PAM could be used to decrease saturated hydraulic conductivity (K_{sat}) of soil material, thus decrease water loss due to infiltration. The main objectives of this thesis were to (1) evaluate the extent to which PAM affected hydraulic conductivity of soil material, and (2) better understand the physical mechanisms that lead to the decrease in K_{sat}.

Laboratory tests, conducted to achieve the goals, relied on the use of acrylic columns and pressure cells. In some experiments, the apparatus included soil columns and in other experiments, the apparatus included only the end plates of the cells; these were done to examine water flow through filter media without soil. The results of the experiments with soil columns showed a large range of PAM effectiveness depending on the PAM concentration, suspended sediment concentration, and type of soil.

Results showed that increases in PAM concentration alone (i.e., without any suspended sediment) had the ability to decrease conductivity in all the soils tested. For example, when PAM was at the maximum level tested (40 lbs/ca), K_{sat} reductions of 80%, 81%, and 52% were observed for the #70 mesh sand, the C33 sand and the loam soil, respectively. The reduction in K_{sat} with increasing PAM concentration was found to be gradual, indicating that part of the K_{sat} reduction could be due to increases in viscosity alone.

When sediment was added to the solution and allowed to flocculate with PAM, the two components together were more efficient than with either component tested alone. For example, K_{sat} values measured for the #70 mesh and C33 sands were found to be 1,204 and 1,767 cm/day without any treatment. With a treatment of 5 lbs/ca of PAM and no sediment K_{sat} values of 726 and 1,304 cm/day were attained. These values correspond to reductions in K_{sat} of 40% and 26%. However, when PAM at 5 lbs/ca was mixed with suspended sediment at 300 ppm, the final K_{sat} values were 62 and 116 cm/day, corresponding to reductions of 94% and 92%. Therefore, PAM mixed with suspended sediment led to an 11-fold increase in K_{sat} reduction versus PAM alone. The results also showed that in the #70 mesh and C33 sands, when suspended sediment was present, increases in PAM concentration above 5 lbs/ca had vary little effect on further reducing K_{sat} (94% versus 98% reduction for PAM concentrations of 5 lbs/ca and 40lbs/ca, respectively). The results indicate that less PAM is needed in the presence of suspended sediment to reduce K_{sat} (i.e., the treatment is more efficient). The results also indicate that treatment options reduced K_{sat} only to a certain degree, and that further addition of the compound did not lead to lower K_{sat}.

The results showed that application of PAM to the loam soil was not as effective at reducing $K_{sat,}$ than with the sandy material. Reductions in K_{sat} ranged from 0 to 56% Although PAM did not appear to be as successful on finer textured soil, fine-textured soils already have a low K_{sat} and likely would not be considered a high-enough seepage area to warrant treatment with PAM. Therefore, PAM is better suited for coarse-grained material where water loss to seepage is already a greater problem.

For the second goal in this study, we examined three possible physical mechanisms that reduce seepage, including: (1) increase in the solution viscosity from the addition of PAM, (2) PAM/sediment flocculates forming a seal on top of the soil, and (3) PAM/sediment flocculates partially penetrating and clogging soil pores as well as forming seal on top. We hypothesized that each mechanism could be responsible for a decrease depending on the experimental conditions.

From viscosity testing (Figure 4.7), increases in PAM concentration were shown to correlate to increased solution viscosity, which in turn decreases K_{sat}. Thus, for a test solution of dissolved PAM but without suspended sediments (i.e., no PAM flocculates), reduction of K_{sat} would be due to change in viscosity alone. However, just the settling of the hydrated PAM can cause a reduction in K_{sat} (Figure 4.6), which indicates that K_{sat} reduction could be due to a combination of increased viscosity and flow through the PAM layer itself (Figure 4.6). When suspended sediment is present, the combination of these processes further reduces the K_{sat}.

It is evident from the experimental results (see Figure 4.9 for example) that seals can form when PAM is combined with suspended sediment. Results discussed in Section 4.3.2 support the theory that PAM can plug larger pores in coarser-grained material, in addition to creating a surface seal. The coarser-grained soils showed greater reductions in K_{sat}, as well lower absolute values than the loam soil.

The information gained from this research will be vital for predicting the effectiveness of PAM application in unlined canals, when field conditions (suspended sediment concentration, soil type and PAM concentration) are known, and for developing the standards needed for PAM use as a sealant. However, as with any laboratory experiments, the laboratory conditions do not completely simulate conditions in a full-scale canal. For example, the experiments were conducted in column tests that limited water movement through the soil/water interface to the vertical direction, though a stirring mechanism was used agitate the solution. In a field situation, lateral movement would be present that would prevent the vertical settling of flocculates onto the canal bottom. Also, because the Marriotte system of water application replaces only the water lost to seepage through the column, the viscosity of the test solution could be higher than in a canal, where water is constantly being flushed through the system. Nonetheless, as shown through field experiments (conducted as part of the larger PAM program), seepage reduction can approach 100% when field conditions allow.

5.2 Recommendations

During the nearly two years of laboratory experimentation on PAM, many variables were tested; unfortunately, questions of how field conditions affect PAM efficiency still need to be answered. For example, though PAM, dissolved divalent cations, and suspended sediment are needed for PAM to work most efficiently, any of the three components could be a limiting factor. However the experiments conducted in this study held constant the cation concentration of the test solution. PAM may work to a greater or lesser extent depending on the amount and types of cations that are present in the water, or the sodium adsorption ratio (or the relative amounts of univalent to divalent cations present in the test solution), since cations act as a bridge between PAM and sediment. Without cations present in the water, any addition of PAM could essentially be wasted.

The amount of PAM needed to seal unlined canals may also depend partially on the size of the sediment present in the canal waters, and the morphology of the sediment. For example, platey (clay) material may have higher charge density than does a similar-sized silt particle, and thus would be more reactive with PAM. Also, when PAM reacts with larger particles with higher mass, the resulting flocculate would be heavier and potentially more likely to settle, than would a flocculate containing finer-grained suspended sediment.

Finally, due to limitations of laboratory-scale testing, it is highly recommended that field scale tests be continued.

APPENDIX

Exp. #	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Soil	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand	#70 Sand
Concentration	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.
SSC	No SSC	No SSC	No SSC	No SSC	No SSC	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L
Column 1	1170	760	524	227	226	1296	66	67	47	35	1228	49	44	27	21
Column 2	1194	656	549	412	214	1100	98	52	36	27	1147	56	41	27	26
Column 3	1248	762	340	280	268	933	54	47	55	56	1033	87	35	29	29
Avg Ksat	**1204**	**726**	**471**	**306**	**236**	**1110**	**73**	**55**	**46**	**39**	**1136**	**64**	**40**	**28**	**25**
STD	40	61	114	95	28	182	23	10	9	15	98	20	5	1	4
CV	0.033	0.084	0.242	0.311	0.120	0.164	0.310	0.185	0.205	0.375	0.086	0.317	0.121	0.035	0.143

Exp. #	#28	#29	#30	#31	#32	#33	#34	#35	#36	#37	#38	#39	#40	#41	#42
Soil	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33	C33
Concentration	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.
SSC	No SSC	No SSC	No SSC	No SSC	No SSC	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L
Column 1	1800	1331	1192	717	386	1617	341	148	81	103	1585	111	76	62	16
Column 2	1753	1337	633	791	240	893	321	162	62	109	1179	148	43	30	21
Column 3	1530	1243	775	624	366	1641	338	146	107	66	1483	100	90	62	41
Avg Ksat	1796	**1304**	**867**	**711**	**331**	**1384**	**334**	**152**	**84**	59	**1415**	**119**	**70**	**51**	**26**
STD	2060	53	290	84	79	425	11	9	23	71	211	25	24	19	13
CV	1664	0.040	0.335	0.118	0.240	0.307	0.032	0.057	0.270	**82**	0.149	0.209	0.343	0.366	0.513
	1767									23					
	176									0.280					
	0.099														

Exp. #	#55	#56	#57	#58	#59	#60	#61	#62	#63	#64	#65	#66	#67	#68	#69
Soil	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam	Loam
Concentration	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.	No PAM	5 lb.	10 lb.	20 lb.	40 lb.
SSC	No SSC	No SSC	No SSC	No SSC	No SSC	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.15g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L	0.3g/L
Column 1	98	113	95	123	107	169	210	166	119	125	182	160	131	94	48
Column 2	141	131	129	84	44	138	182	138	106	77	145	180	135	132	57
Column 3	138	140	118	94	60	137	134	49	44	42	140	139	137	97	101
Avg Ksat	177	**128**	**114**	**100**	**70**	**148**	149	**118**	71	85	**156**	139	**134**	**107**	**69**
STD	161	14	17	20	33	18	123	61	92	35	23	126	3	21	28
CV	173	0.111	0.153	0.200	0.468	0.121	123	0.519	164	51	0.148	103	0.025	0.196	0.413
	148						**154**		**99**	**69**		**141**			
	29						36		41	34		27			
	0.197						0.232		0.416	0.486		0.188			

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