APPLICATION OF POLYACRYLAMIDE TO ENHANCE SILT FENCE PERFORMANCE

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PERFORMANCE

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NOMENCLATURE

ANOVA	Analysis of variance
CRD	Completely randomized design
df	Degree of freedom
E	Flocculation efficiency
ha	Hectare
LC_{50}	Lethal concentration 50; defined as the concentration of a chemical which kills 50% of a sample population
LD_{50}	Lethal dose of 50; defined as the dose of a chemical which kills 50% of a sample population
LSD	Least significant difference
mmole	millimole
MS	Mean square
NTU	Nephelometric turbidity units
ppm	Parts per million
rpm	Revolutions per minute
Sec	Seconds
SS	Sum of squares
%SSC	Percentage suspended solid concentration
TC	Total corrected

CHAPTER 1

INTRODUCTION

1.1 Rationale for the Project

The concern to protect our planet's natural resources is steadily growing. Soil is one of the vital substances for human existence, and its conservation is important. Soil erosion not only depletes the productivity of soil but also produces sediment, a major pollutant. The sediment moving in streams and waterways not only increases the cost of water treatment, but it also reduces reservoir storage capacity through deposition. In addition, it modifies the stream systems and destroys the habitat of many of our desirable aquatic species (EPA 2001; Smith et al. 1992). In fact, in terms of quantity of pollutant, sediment is the largest polluter.

Agricultural, forestry, and construction industries contribute to accelerated erosion. The focus of this study is on erosion and sediment control in construction sites, a critical issue today. For example, construction activities account for about five percent of the nonpoint source (NPS) impacts to United States surface water (Morrow et al. 2003). Studies have shown that by removing the surface cover and disturbing the parent soil material, construction operations increase sediment yield by as much as 10,000 times as compared to undisturbed sites (Haan et al. 1994). Also, (Barrett et al. 1995) reported that soil losses from unprotected construction sites can be 150-200 tons per acre per year, while the average natural rate of erosion is approximately 0.2 tons per acre per year.

Erosion control strategies and practice vary by industry. The cost and feasibility dictate the soil conservation measures to be used. Environmental Protection Agency's (EPA's) stormwater regulatory program requires the use of Best Management Practice (BMPs) during and after construction to minimize erosion and sedimentation and to properly manage runoff for both stormwater quantity and quality. BMPs are a combination of management, cultural (e.g., strip cropping, contouring), new-structural (e.g., erosion control blankets, mulch), and conventional (ponds, silt fence) practices that the agricultural scientists, the government, or some other planning agencies decides upon to be the most effective and economical way of controlling such problems without disturbing the quality of the environment (Field 1997). Currently, silt fence is the most frequently used best management practice (BMP) technology, since it does not disturb large amounts of additional landscapes.

A silt fence is a temporary sediment barrier consisting of filter stretched across the down slope end of a drainage area. It is attached to supporting posts, anchored at the toe and, depending on the strength of the fabric used, reinforced with plastic wire or mesh backing. Silt fences trap sediment by intercepting and detaining small amounts of sediment-laden runoff from disturbed areas in order to promote sedimentation behind the fence (CASQA 2003).

In general, silt fence and sediment basins can trap only particles larger than 20 microns (DCR 2002). Thus, the suspended fine particles remain in the water column, requiring potentially complex and expensive methods to prevent violations and to remediate resulting downstream property and environmental damage. Trapping efficiency of the silt fence can be improved by flocculation of fine clay particles into larger aggregated particles with higher settling velocities. Clay flocculation can be induced by anionic polyacrylamides (PAM) in conjunction with divalent cations. (Flanagan et al. 2002) found that treatment with PAM plus gypsum (a source of divalent cation) reduced runoff sediment yield more than treatments with PAM alone.

1.2 Objectives

The specific objectives of this study are to:

- Evaluate the flocculation characteristics of three polyacrylamides (PAM) on silty clay loam soil and identify the best PAM for the soil, based on flocculation parameters measured.
- Study the process of flocculation on soil when PAM and the exchangeable cation (Ca^{++}) are used in combination.
- Determine the best concentration range of PAM and calcium ion in combination that yields high flocculation efficiency.

CHAPTER 2

LITERATURE REVIEW

2.1 Economic Cost of Soil Erosion and Conservation Benefits

Soil erosion is a major environmental and agricultural problem world wide. Productive agriculture and associated economic activities occur with good soil used intelligently and protected from erosion (Bennett 1957). On a worldwide basis, soil erosion rates are highest in Asia, Africa, and South America, averaging 30 to 40 tons ha^{-1} $year^{-1}$, and lowest in United States and Europe, averaging about 17 tons ha^{-1} $year^{-1}$. This loss of soil due to erosion and its consequences can cause tremendous problems to the economy, so much so that these costs may well outweigh the benefits of many development projects that create the problem. A recent pioneering study sponsored by United Nations agencies estimated the severity and cost of land degradation in South Asia with the shocking conclusion that India, Pakistan, Bangladesh, Iran, Afghanistan, Nepal, Srilanka, and Bhutan are losing at least US $10 billion annually as the result of losses resulting from soil degradation. This is equivalent to 2% of the regions gross domestic product (GDP), or 7% of its agricultural output (Khor 2005).

(Pimentel et al. 1995) have evaluated the erosion cost in the United States under three categories: energy costs, on-site costs, and off-site costs. For an average erosion rate of 7 tons ha^{-1} $year^{-1}$, they estimate that the on-site and off-site impacts of soil erosion and associated rapid water runoff require an additional expenditure of 1.6×10^6 kcal of fossil energy per hectare per year. This suggest about 10% of all the energy used in U.S agriculture today is spent just to offset the losses of nutrients, water, and crop productivity caused by erosion. The major on-site costs of erosion are those expended to replace the lost nutrients and water. In the United States, an estimated 4×10^9 tons of soil and 130×10^9 tons of water are lost from 160×10^6 ha of cropland each year. This translates into an on-site economic loss of more than $27 billion each year, of which $20 billon is for replacement of nutrients and $7 billon for lost water and soil depth (Troeh et al. 1991). The most significant component of this cost is the loss of soil nutrients.

Erosion not only damages the immediate agricultural area where it occurs, but also negatively affects the surrounding environment. "Off site problems include roadways, sewer, and basement siltation, drainage disruption, undermining of foundations and pavements, gullying of roads, earth dam failures, eutrofication of waterways, siltation of harbors and channels, loss of reservoir storage, loss of wildlife habitat and disruption of stream ecology, flooding, damage to public health, plus increased water treatment cost" (Gray and Leiser 1989). The cost of all off-site environmental impacts of U.S soil erosion is estimated to be about $17 billon per year. If off-site and on-site costs are combined, the total cost of erosion from agriculture in the United States is about $44 billion per year. (Pimentel et al. 1995) have also estimated that the total investment for U.S erosion control would be about $8.4 billion per year. Given that erosion causes about $44 billion in damages each year, a $8.4 billion investment is a small price to pay: For every $1 invested, $5.24 would be saved. This small investment would reduce U.S. agricultural soil loss by about 4×10^9 tons and help to protect the current and future food supply.

2.2 Polyacrylamide in the Field of Sediment and Erosion Control

The use of polyacrylamide (PAM) dates back to World War II, where it was used primarily as a soil conditioner to stabilize the soil structure (Sojka and Lentz 1996b). Scores of airfields and temporary roads have been constructed overnight with the aid of soil conditioners. Chemical soil conditioners stabilize the soil structure and prevent the hastily constructed landing fields from returning to mud wallows. This technology was then transferred to the agricultural arena in the early 1950s (Sojka and Lentz 1994), where its use has been primarily for soil structure stabilization in horticultural, agronomic and constructional applications. Soil amendment using PAM is one of the options to prevent soil erosion. PAM has also been used to stabilize soil structure, which leads to increased infiltration and reduced erosion (Green and Stott 1999). Hundreds of specific PAM formulations are available depending on the polymer chain length and the number and kinds of functional group substitutions along the chain.

In erosion-control polyacylamides, the PAM homopolymer is copolymerized. Spliced chain segments replace PAM amide functional groups with ones containing sodium ions or protons that freely dissociate in water to provide negative charge sites. As shown in Figure 1, the chain segment X is the acrylamide formulation and Y indicates a dissociated altered segment leaving a negative charge site. The PAM formulations now used in agriculture are water soluble non-crosslinked anionic polymer with typical molecular weights of 12 to 15 Mg mole^{-1}. PAM charge density expressed as the percent of sodium acrylate copolymerized generally ranges from 2 to 40% (Sojka et al. 2000).

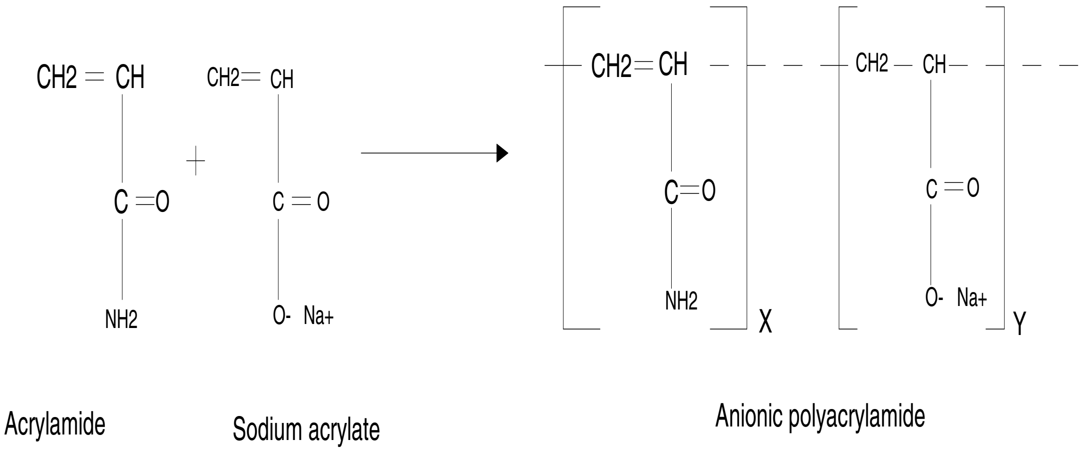


Figure 1: Copolymerization with Sodium Acrylate (Barvenik 1994)

When used as an erosion control product, anionic PAM reduces erosion and sedimentation by targeting the smallest soil particles such as fine silts, clays and colloidal materials (5-10 microns in size), which are difficult or impossible to control using conventional settling techniques. Anionic PAM uses two mechanisms to affect these difficult to address particles. It preferentially increases aggregation of these small particles to improve soil stability and prevent soil detachment in the first place, and decreases the settling time of particles to aid in their deposition within the site, thus improving runoff water quality. Additionally, anionic PAM can increase soil pore volume and permeability; thus, increasing infiltration and reducing erosion.

In a recent three-year efficacy study on construction sites (DCR 2002), anionic PAM provided up to 70% reduction in runoff-sediment, and was further improved when combined with conventional mulching and seeding measures. (David Bjorneberg et al. 1997) found that addition of PAM to soil in their experimental setup decreased runoff and soil loss by approximately 75%. (Lentz et al. 1992) reported that PAM provided a 94%

reduction in runoff-sediment in three years of testing. According to (Rao-Espinosa et al. 2000), the average reduction in sediment yield varies between 77%-93% in different modes of application of PAM.

Texture, clay type, organic matter content, and type of ions in the soil solution are the dominant soil properties affecting PAM adsorption, while molecular weight and charge density are the main properties of PAM. Charge density of 30% provides greater protection for clayey soil, while molecular weight of 12 Mg mol^{-1} are effective for sandy soils (Green et al. 2000). Polyacrylamide of 2% charge density has very little charge and would tend to form a tight coil, rather than a chain because the repulsive forces between negatively charged sites are not enough to hold the coil straight. A 40% charge density PAM would also tend to coil, especially in the presence of cations because the high negative charge has greater affinity toward the positively charged cations. Studies have suggested that a 30% charge density PAM is the maximum to avoid coiling and maintain the chain to produce larger flocs. The extended chain of 21% charge has more adsorption because more molecules extended from the surface when compared to higher charge density PAMs (Malik and Letey 1991). The behaviors of PAM at different charge densities are illustrated in Figure 2.

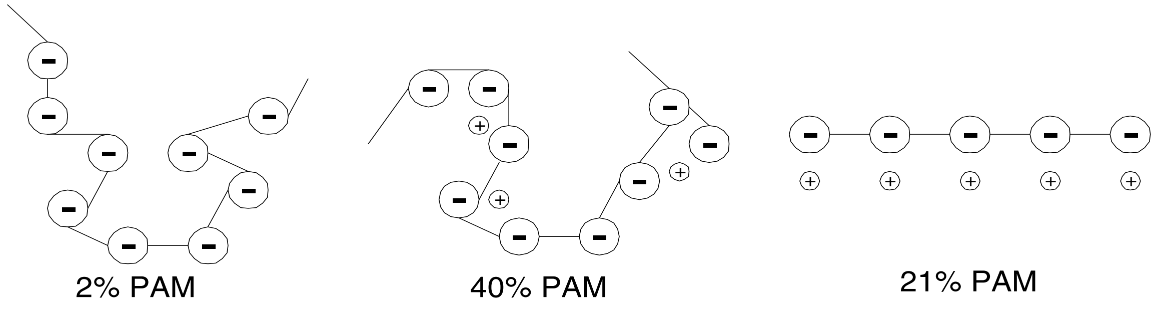


Figure 2: Orientation of PAM Structure at Different Charge Densities

2.2.1 Applicability

Anionic PAM is intended for use on areas that contain high amounts of fine silt, clay, or colloidal soils. Anionic PAM is generally applicable where the timely establishment of vegetation may not be feasible, is absent or inadequate, or where topographic conditions, construction activities, or other forces limit the utility of conventional temporary sediment control practices alone. Anionic PAM may be beneficial to the following activities/areas: staging areas, rough grading operations, balanced cut and fill earthwork, man-made or natural stormwater conveyances, haul roads, roadside ditches, soil stockpiles and borrow areas, phased projects, sites having a winter shut down, and other exposed areas that have not been adequately stabilized with vegetation (DCR 2002).

Some of the general considerations to be followed with the application of PAM are (DCR 2002):

1. PAM should not be over applied; excessive application of anionic PAM can lower infiltration rates or increase suspended solids in water. Application rates of anionic PAM above those suggested by the manufacturer will not provide additional effectiveness. More is not better!
2. Application of anionic PAM in pure form (75%-90% active polymer) is not to exceed 10 lbs acre^{-1} per single application event.
3. For anionic PAM to work effectively there must be a source of "divalent cations", gypsum ($CaSO_4.2H_2O$) is a common source. The divalent cation source may be in the anionic PAM mix, in the soil, or applied directly to the soil.

4. Care must be taken to prevent spills onto paved surfaces, as anionic PAM may be slippery. Gloves should be worn whenever handling anionic PAM and surfaces that contacted them.

2.2.2 Advantages and Limitations

Anionic PAM has several advantages. Specifically, it:

1. Improves the stability of soils to prevent soil detachment and provides quick stabilization where vegetation has yet to be established.
2. Promotes flocculation (reduces settling time) of smallest particles, and increases soil pore volume and permeability.
3. Does not interfere with construction machinery and activities.
4. Is convenient and easy to apply and can be stored along with other soil amendments (fertilizer, mulch, etc.).
5. Reduces windborne dust conditions, may prevent water quality damages (TSS, turbidity), eutrophication, habitat destruction, stream channel erosion, sedimentation, and related remediation costs.
6. Is economically beneficial in the long-term by requiring less mulch, and seeds.

Some of the limitations of anionic PAM are:

1. It is "soil-specific," so it requires site-specific testing that may take several days to complete.
2. Solubility is limited by its viscosity and requires an energy intensive process (mechanical mixing) for proper dissolution.

3. It enhances precipitation of fine sediments in downstream structures, and therefore, requires increased maintenance to remove sediments and PAM complex from basins.
4. Over use of PAM clogs soils and decreases infiltration.
5. It is not effective when applied to pure sand or gravel with no fines, and when applied over snow cover.
6. Application requires engineers to consider its impact on existing seeding, fertilizer, pond sizing, and other specifications.
7. Introduction to the natural environment draws public concern.

2.2.3 Toxicology and Regulations

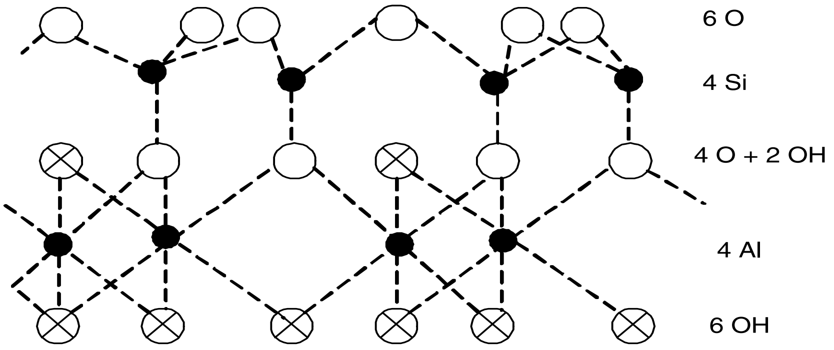
Environmental and safety considerations of anionic PAMs have been thoroughly reviewed (Barvenik 1994; Sojka et al. 2000). Cationic and neutral PAMs have toxicities warranting caution or preclusion from sensitive environmental uses, whereas anionic PAMs are safe when used at prescribed rates. These anionic PAMs exhibit a low order of toxicity to mammalian systems as they contain less than 0.05% of acrylamide monomer (AMD), a known genetic, reproductive and neural toxicant. Typically, monomer of this concentration does not cause toxic effects (Novaes and Berg 2003). In soil, anionic PAM degrades at the rates of at least 10% per year as a result of physical, chemical, biological and photochemical processes. Also AMD is metabolized by microorganisms in soil, in biologically active waters and is not absorbed by plant tissues (Sojka 2001). Dry anionic PAMs which are used in soil systems have a LC_{50} values greater than 100 mg L^{-1} for aquatic species and a LD_{50} value greater than 5 mg Kg^{-1} for mammalian systems. Moreover, human epidemiology studies demonstrated no association between unintentional exposure to PAMs and tumors; in addition, PAM's molecular dimension is too large to allow absorption via gastrointestinal tract (Barvenik 1994).

Anionic PAMs have gained a variety of Food and Drug Administration (FDA) approvals for specific direct and indirect food additive applications. They are used for scale control in sugar juice and liquor, washing, and assisting of lye peeling of fruits and vegetables. However, cationic polyacylamides have the danger of creating potential damage to aquatic life and have a LC_{50} value of 0.3-10 mg L^{-1}(Barvenik 1994). Thus, usage of PAM as a commercial product is governed by specific regulations (Barvenik et al. 1996; DCR 2002; Sojka and Lentz 1996a):

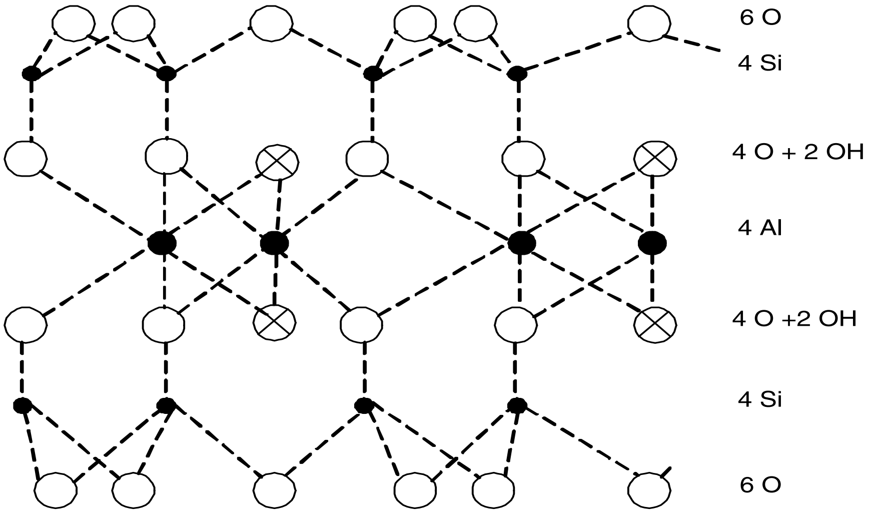
1. Cationic PAM shall not be used at any level because its toxicity to aquatic test species occurs at very low concentrations.
2. Anionic PAM mixtures shall have less than or equal to 0.05% free acrylamide monomer by weight as established by the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA).
3. Anionic PAM mixtures shall be non-combustible.
4. Users of anionic PAM mixtures shall obtain and follow all Material Safety Data Sheet (MSDS) requirements and manufacturer recommendations.

2.3 Properties of Clay

Clays are hydrous silicates or aluminosilicates and may broadly be defined as those minerals which dominantly make up the colloidal fraction of soils, sediments, and rocks (Theng 1979). The most prevalent clay minerals are the layered aluminosilicates. Their crystals are composed of two basic structural units, namely, a tetrahedron of oxygen atoms surrounding a central cation, usually Si^{4+}, and an octahedron of oxygen atoms or hydroxyl groups surrounding a larger cation usually Al^{3+} or Mg^{2+}. The tetrahedral are joined at their basal corners and the octahedral are joined along their edges by means of shared oxygen atoms. Thus tetrahedral and octahedral layers are formed as shown in the Figure 3.



Kaolinite (Non colloidal clay)



Montmorillonite (Colloidal clay)

Figure 3: Schematic Representation of the Structure of Aluminosilicate Kaolinite and Montmorillonite (Hillel 1982)

Colloidal clay such as montmorillonites decisively influences the physical behavior of the soil. Particularly, clay particles adsorb water on the edge as well as between the aluminosilicate layers and thus cause the soil to swell and shrink upon wetting and drying. Most of the clay-water systems are negatively charged and form an electrostatic double layer with exchangeable cations (Hillel 1982). According to (vanOiphen 1963), clay particles carry a net negative charge on their surface and a net positive charge on their edges, further they claim that clay particles are predominantly negatively charged because in a electrophoresis experiment the clay sols move toward the positive electrode.

2.4 The Process of Floc Formation

According to (Poirier 2001), the formation of flocs takes place in two steps. The first step is to destabilize the dispersion and coagulate the fine particles, which is generally done by the addition of positively charged species in appropriate quantities to neutralize the polarity on the suspended fine particles. The second step is the flocculation step, which takes place via polymer bridging. In polymer bridging, the polyelectrolytes are long chain molecules, which attaches to the small flocs formed by coagulation, thus building up into larger agglomerates.

(Laird 1997) described the phenomenon by a process called cationic bridging. Anionic PAM being negatively charged like the clay surface would expect to experience repulsion from the negatively charged clay sites. Counter institutively, it binds to some of the negative sites, primarily through a process called cationic bridging. Divalent cations are able to bridge the two negatively charged species together. Each positive charge of the divalent cation bonds to one of the negative sites, either the clay surface or the polymer to form larger agglomerates as shown in the Figure 4. Thus, the presence of cation such as Ca^{++} in solution is assumed to be important for flocculation.

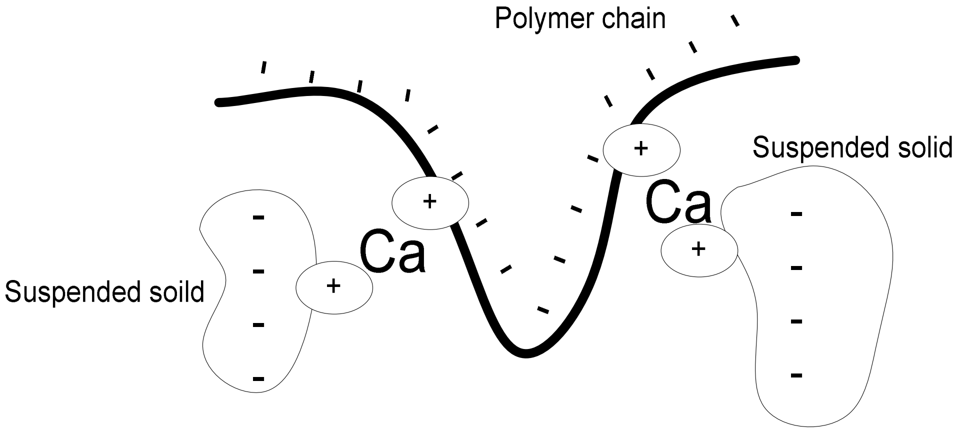


Figure 4: Cationic Bridging (Laird 1997)

2.5 Conventional Erosion Control Methods

The selection of erosion control methods should be based upon the nature of the construction activity and the conditions which exist at the construction site. According to EPA, the soil erosion and sediment control portion of the stormwater pollution prevention plan should:

1. Minimize the amount of disturbed soil.
2. Prevent runoff from offsite areas from flowing across disturbed areas, and slow down the runoff flowing across the site.
3. Remove sediment from onsite runoff before it leaves the site.

Some of the common methods of reducing erosion at critical sites include: temporary seeding, mulching, geotextiles, chemical stabilization and buffer zones (EPA 1992).

Temporary Seeding

Temporary seeding is the growing of short-term vegetative cover on disturbed site areas that may be in danger of erosion. The purpose of temporary seeding is to reduce erosion and sedimentation by stabilizing disturbed areas that will not be stabilized for long periods of time or where plant growth is not necessary or appropriate. Some of the advantages of temporary seeding are:

1. It is generally inexpensive and easy to do.
2. It establishes a plant cover fast when conditions are good and stabilizes soils better.
3. It is aesthetic and can provide sedimentation control.

Some of the limitations are:

1. It depends heavily on the season and rainfall rate for germination and growth of vegetation.
2. It may require extensive fertilizing which could cause problems with local water quality.
3. Seeded areas require protection from heavy use.

Mulching

Mulching is a temporary soil stabilization or erosion-control practice in which materials such as grass, hay, woodchips, wood fibers, straw, or gravel are placed on the soil surface. Besides stabilizing soils, mulching can reduce the velocity of storm water run off over an area. When used together with seeding or planting, mulching can aid in plant growth by holding the seeds, fertilizers, and topsoil in place, by helping to retain moisture. Some of the advantages of mulching are:

1. They provide immediate protection to soils that are exposed and that are subject to heavy erosion.

2. They require no removal because of natural deterioration of mulching and matting.

Some of the limitations of mulching are:

1. Mulch can be easily blown or washed away by runoff if not secured.
2. Some mulch materials such as wood chips may absorb nutrients necessary for plant growth.

Geotextiles

Geotextiles are porous fabrics known in the construction industry as filter fabrics, road rugs, synthetic fabrics, construction fabrics, or simply fabrics. Geotextiles are manufactured by weaving or bonding fibers made from synthetic materials such as polypropylene, polyester, polyethylene, polyvinyl chloride, glass and various mixtures of these. Some of the geotextiles are biodegradable materials such as mulch matting and netting. Netting is typically made from jute, other wood fiber, or cotton and can be used to hold the mulching and matting to the ground. Geotextiles, when used alone, can be used as matting. Matting is used to stabilize the flow on channels and swales. Geotextiles are also used as separators. For example, it is used as a separator between riprap and soil. This sandwiching prevents the soil from being eroded from beneath the riprap. Some advantages of geotextiles are:

1. They are relatively inexpensive for certain applications.
2. They are easy to install.
3. Design methodologies for the use of geotextiles are available.
4. A wide variety of geotextile to match specific needs are available.

5. They are capable of trapping 80-90% of larger particles like sand (Stevens et al. 2004).

Some of the limitations of geotextiles are:

1. If the fabric is not properly selected, designed, or installed, the effectiveness may be reduced drastically.
2. Many synthetic geotextiles are sensitive to light and must be protected prior to installation.
3. They may fail to trap fines (silt and clay) due to inadequate detention time and settling velocities. The trapping efficiency of silty clay loam soil was found to be 0-20 percent (Stevens et al. 2004).

Chemical Stabilization

Chemical stabilization practices, often referred to as chemical mulch, soil binder, or soil palliative, are temporary erosion control practices. Materials made of vinyl, asphalt, or rubber are sprayed onto the surface of the soil to hold the soil in place and protect against erosion from storm water. Some of the advantages of chemical stabilization are:

1. They can be easily applied to the surface of the soil.
2. They can be effective in stabilizing areas where plants will not grow.
3. They provide immediate protection to soils.

Some of the limitations of chemical stabilization are:

1. They can create impervious surface, which may in turn increase the amount and speed of storm water runoff.
2. They may cause harmful effects on runoff water if not used correctly.

3. They can be more expensive than vegetative cover.

Buffer Zones

Buffer zones are vegetated strips of land used for temporary or permanent water quality benefits. These zones are used to decrease the velocity of storm water runoff, which in turn helps to prevent soil erosion, decrease sediment transport, and allows deposition of suspended sediment. Some of the advantages of buffer zones are:

1. They provide aesthetic as well as water quality benefits.
2. They provide areas for infiltration, which reduces the amount, and speed of storm water runoff.
3. They provide areas for recreation.

Some limitations of buffer zones are:

1. They may not be cost effective to use if the cost of land is high.
2. They are not feasible if land is not available.
3. They require plant growth before they are effective.

2.6 Summary of Literature Review

Profound studies on the properties of polyacrlamides, properties of clay, process of flocculation and conventional erosion control methods have been made. Silt fence (geo textile fabric) is the most commonly used sediment control device in construction sites. Silt fence has showed poor performance in trapping fine particles, particularly silt and clay (Stevens et al. 2004). Trapping efficiency of silt fence can be improved by aggregating the fine particles with flocculants. PAM applied in conjunction with silt fence was has not been studied. The primary focus of this research is to evaluate the process of flocculation of fine particles with PAM and divalent cations when applied with the silt fence.

CHAPTER 3

MATERIALS AND METHODS

PAM can be applied in conjunction with silt fence to increase its performance. The newly designed apparatus and experimental procedures for flocculation studies as applicable to silt fence technology are briefly discussed in this chapter.

3.1 Soil Properties

Soil collected in the vicinity of Stillwater, Oklahoma was used to conduct flocculation experiments. As discussed in the literature review, silt fence showed poor performance in trapping fine particles, particularly silt and clay. Therefore loam soil, containing a high percentage of silt and clay, was used to conduct the experiments. Selected properties of the soil are listed in the Table 1. Soil analysis was done by the Soil Testing Laboratory at Oklahoma State University.

Table 1: Selected Soil Properties

Texture	Loam
% Sand	47.5
% Silt	30
% Clay	22.5
% Organic Matter	0.64
pH	6.2
Electrical Conductivity (µmhos/cm)	342

3.2 Soil Preparation for Flocculation Test

The particle size distribution of an undisturbed soil matrix is different from the particle size distribution of eroded sediment. The percentage of clay is found to be higher in eroded sediment (Haan et al. 1994). The following procedure suggested by (Jhon Sory Tapp 1981) was followed to get the sediment sample.

1. Large quantities of soil from the field were collected and air dried for several days.
2. The air-dried soil was then shredded with a soil shredder and oven dried to eliminate moisture.
3. The air dried soil was then passed though a hammer mill to break the soil lumps to approximately 1 mm size.
4. The ground soil was then sieved with a number 270 sieve with a mesh size of 53 microns. Particles passing through the sieve were collected and were dried again in the oven at 95^{o}C before sampling it for the tests.
5. After drying, a riffle splitter, as shown in Figure 5, was used to obtain a representative sample.
6. Soil sample obtained from the riffle splitter was mixed with lake water to prepare the sediment solution. Here, sediment solution prepared with lake water (lake Carl Blackwell, Stillwater, Oklahoma) is assumed to closely represent runoff from actual construction sites.

Size distribution of loam soil prepared by following the above procedure is listed in Table 2.

Table 2: Sieved Soil Properties

Texture	Silty Clay Loam
% Sand	12.5
% Silt	55
% Clay	32.5
% Organic Matter	0.64
pH	6.2
Electrical Conductivity (µmhos/cm)	1569

Figure 5: Riffle Soil Splitter

3.3 PAM Properties

Three types of PAM were considered in this study. They are Superfloc A110 (PAM10), Superfloc A120 (PAM 20), and Superfloc A130 (PAM30) from Cytec industries Inc., Carmel, IN 46032. The physical properties of PAM are listed in Table 3.

Due to toxicology regulations, flocculation experiment were conducted with anionic PAM only and three PAM's were chosen specifically for the silty clay loam soil based on a literature survey and for the reasons mentioned in Section 2.2.

Table 3: PAM Properties

PAM Type	**Molecular Weight Mgm mol^{-1}**	**Charge (%)**
PAM10	15	10
PAM20	15	20
PAM30	15	30

3.4 PAM Solution Preparation

Since PAM is not readily soluble in water, the following procedure was followed to prepare PAM solutions of the desired concentrations. Initially a one liter 2000 ppm stock solution was prepared and it was diluted to one liter of 10 ppm, 50 ppm and 100 ppm. The serial dilution process was followed because it is difficult to handle PAM at weights less than 2 grams and solution volumes greater than 1000 ml.

1. Two grams of PAM were weighed accurately on a high precision balance, and then transferred to a one liter volumetric flask.
2. A quarter of the volumetric flask was filled with de-ionized (DI) water and placed on a platform shaker (New Brunswick Scientific).
3. The shaker speed was set to 40 (mark in the instrument, has no units) and operated for 6 hours. At this point of time, PAM was found to be completely dissolved.
4. The volumetric flask was filled to 1000 ml to get a PAM stock solution of 2000 ppm.

5. The volumetric flask with diluted PAM solution was closed with a stopper and mixed thoroughly by inverted shaking.
6. The stock solution pH was monitored for subsequent runs to ensure that there was no major change in solution properties, as specified by (Lu et al. 2002; Wang and Chen 1997).

The 2000 ppm stock solution was diluted to 100 ppm, 50 ppm and 10 ppm. The procedure to prepare 50 ppm PAM solution is discussed below:

1. Accurately, 25 ml of the 2000 ppm stock solution was pipetted into a one liter volumetric flask containing 250 ml of DI water.
2. The pipette was washed thoroughly and the rinsed solution was poured back into the volumetric flask.
3. The volumetric flask was stirred gently and made to 1000 ml to get a PAM solution of 50 ppm.
4. Finally, the volumetric flask was closed with a stopper and mixed thoroughly by inverted shaking.

The above procedure was repeated with 50 ml and 5 ml of 2000 ppm stock solution to obtain 100 ppm and 10 ppm solutions. The 100 ppm, 50 ppm and 10 ppm PAM solutions were used to conduct jar test experiments. For example, to obtain a PAM concentration of 0.05 ppm in one liter of sediment, 5 ml of 10 ppm PAM solution was added to the jar containing one liter sediment solution.

3.5 $CaCl_2$ Solution Preparation

$CaCl_2$ solution was prepared on a molar basis. The molecular weight of $CaCl_2$ is 110.98 g/mole, so a 100 mmole solution was prepared by adding 11.1 g of $CaCl_2$ to 1000 ml of DI water. This 100 mmole solution was used to conduct experiments. For example, to obtain a $CaCl_2$ concentration of 5 mmole in one liter of sediment, 50 ml of 100 mmole $CaCl_2$ solution is added to the jar containing one liter sediment solution.

3.6 Jar Test

Jar testing is an important tool for determining the most effective PAM and the best dosing regime of PAM and divalent cations. A six-station compact laboratory mixer (Nova-Tech International Inc.) was used in this study. Paddle speed was controlled with a five switch-selectable and adjustable preset speed controller. The required paddle speeds at each of the switch positions were set before starting the test by adjusting the presets manually. The jar test apparatus is shown in Figure 6.

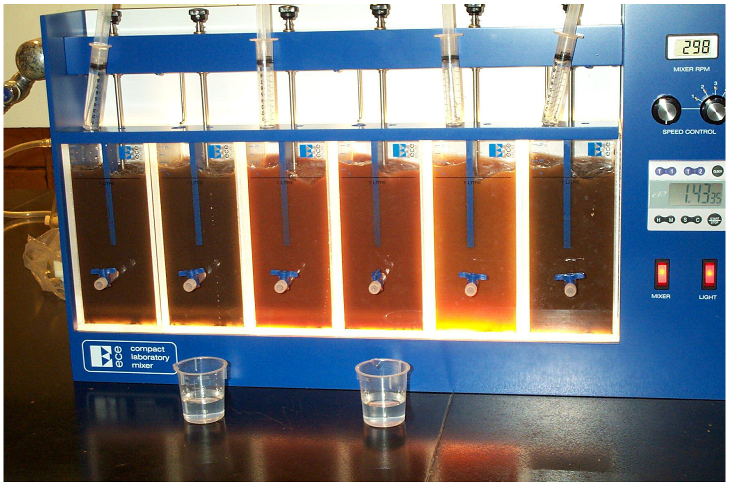


Figure 6: Jar Test Apparatus

A test procedure in compliance with (ASTM-D2035-80 1999)), with some modification, was followed. Mixing speed, flocculant mixing time and settling time called for in ASTM protocol were modified to conduct flocculation experiments for silt fence application. Initially the sediment solution was prepared by mixing the soil and water sample in the jar at 300 rpm for three minutes. This process was identified as the sediment preparation stage, and at the end of this stage, the sediment particles were thoroughly mixed and completely suspended in the jar. This could be observed visually by switching on the built in illuminator of the jar test apparatus. Next, the flocculants were dosed by reducing the mixer speed to 100 rpm, which is termed as the dosing intensity or flocculent mixing speed. The dosing intensity was selected based on visual observation of the sediment flow characteristics in the field. Selection of flocculent mixing time and settling time are discussed in Chapter 4 and Chapter 5. The flocculation test procedure was divided into three steps as A) pre-test, B) test and C) post-test procedures.

A) Pre-test Procedure

1. The jars and the respective soil sample dishes, dosing syringes and sampling bottles were labeled in sequence from 1 to 6.
2. The pH meter was calibrated before the test with standard solutions and the pH of lake water and the de-ionized water (DI) were measured and recorded.
3. The turbidities of the lake and DI water were measured with an NEP 160 turbidity meter.
4. The split soil sample obtained by riffle splitting apparatus was transferred initially to a pre-weighed metal dish, and the net weight of the sample in the dish was recorded to calculate the initial sediment concentration. The soil sample from the metal dish was carefully transferred to its corresponding numbered jar.
5. The metal dish was rinsed with lake water to make sure that all the particles in the dish were transferred to the jar.
6. The jar was then filled with lake water up to the 1 liter mark.
7. The procedure was repeated for other jars.

8. Paddle stirrers were lowered into the jars and the mixer was started.
9. The sediment mixing speed of 300 rpm, to prepare sediment solution, and the flocculant dosing intensity of 100 rpm, to aid flocculation, were pre-set to position 5 and 4, respectively, on the 5-position preset switch.
10. As soon as the entire soil sample was suspended in the water, the temperature of the sediment mixture was measured and recorded.
11. PAM dosing syringes were calibrated to deliver the required volume and labeled in the same sequence as the jars.
12. Syringes were filled with the required volume and type of flocculant and care was taken to eliminate any air bubbles in the syringe by tapping with a glass rod.
13. While the paddle stirrers were running, pH and turbidity of the sediment solution mixture was measured in each of the jars, and the readings were recorded.
14. Turbidity of the sediment solution mixture was measured three times in each jar and the average turbidity was calculated.
15. The dosing module was installed over the jars and the syringes were arranged to match the label numbers on respective jars. Figure 7 shows the picture of the dosing module installed on the jars.
16. Two timers with audible beeps were employed to indicate the end of dosing time and beginning of sampling time.
17. Paddle mixing speed for position 4 and 5 were double checked.
18. Sampling bottles for supernatant turbidity (500ml) and supernatant concentration (125ml), to be measured after the flocculation tests, were cleaned, dried, weighed, labeled and arranged in the sampling module as shown in Figure 7.

19. The sampling module was arranged in front of the jar test apparatus and care was taken to make sure that the label on the sampling bottle matched the label on the jars.

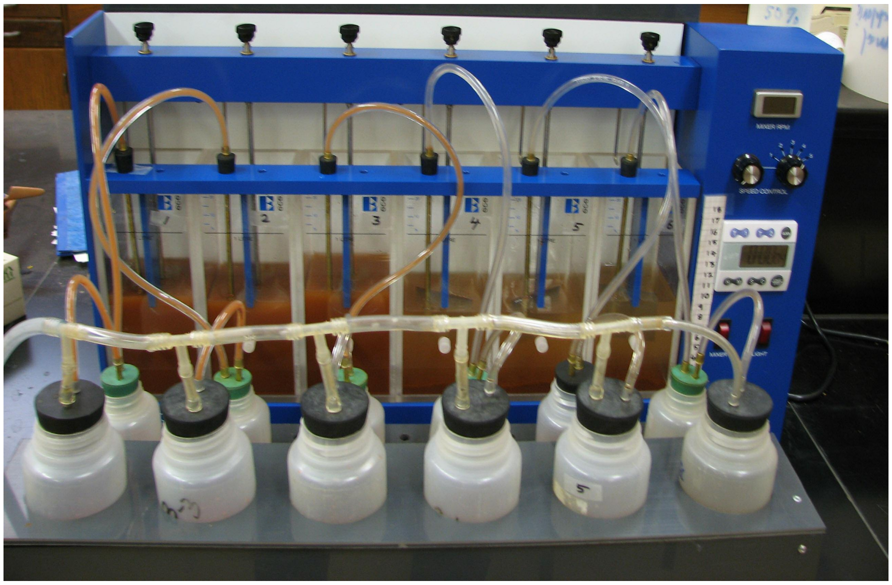


Figure 7: Sampling Device for Jar Test Experiment

20. The 500 ml and 125 ml sampling bottles for the respective jars were connected with plastic tubing and the tubing network was connected to a common vacuum line.
21. Copper tubes (connected to the plastic tubing from the 125 ml bottles) were inserted into the respective dosing module, after the flocculation test. To decant the supernatant, vacuum was applied to create suction in the both sets of bottles and draw supernatant from the respective jars into the bottles.
22. The depth of copper tubes used for sampling in the jars was checked for uniformity.

B) Test Procedure

1. Before starting the test procedure, all labels, vacuum lines, preset paddle speeds and timers were checked again.
2. The sediment and the lake water in the jar were mixed for three minutes at 300 rpm to prepare the sediment solution.
3. With two persons conducting the test, as soon as the soil particles were suspended in the sediment solution in the jar, one person changed the paddle speed to 100 rpm, by switching to position 4 on the pre-set switch, and immediately started dosing flocculant into the jars and the other person simultaneously started the two timers and helped the first person in dosing the flocculant.
4. The floc formation was observed and recorded.
5. When the first timer (30 seconds) started to beep, indicating the end of dosing time, the mixer was stopped and the sampling copper tubes were inserted into the respective dosing module.
6. The flocs at this point of time started to settle within the jar.
7. When the second timer (60 seconds) started to beep, vacuum was applied to the sampling device and the supernatant sample was decanted into the sampling bottle for further analysis.
8. The vacuum was applied until the supernatant level in the jar was below the copper tubing.

C) Post-test Procedure

Post-test procedure involved the measurement of the following response variables:

a) Supernatant Temperature

1. After collecting sufficient supernatant samples into the sampling bottles, the vacuum was turned off and the copper tubing from each of the jars was pulled out of the dosing module.
2. The temperature of the remaining supernatant in the jar was immediately measured and recorded.

b) Supernatant Turbidity

1. The turbidity of the supernatant sample collected in 500 ml sampling bottle was measured with the turbidity meter, continuously stirring with a magnetic stirrer.
2. Three readings were measured and recorded from each sample bottle.
3. Flocculation efficiency, E was calculated using Equation (1) (Vreysen et al. 2003).

$$E = \left(1 - \frac{T}{T_o}\right) \times 100 \tag{1}$$

where T is the turbidity of the supernatant, and T_o is the initial turbidity of the sediment solution measured during the pre-test procedure.

c) Supernatant pH

The pH of the supernatant sample, collected in the 125ml bottles, was measured with the pre-calibrated pH meter and recorded.

d) Supernatant Suspended Solid Concentration

1. The samples collected in 125 ml bottles were also used for the supernatant suspended sediment concentration measurement.
2. Using a syringe, 10 ml of the sample from the 125 ml bottle was drawn and passed through a 0.45 micron filter.

3. The sample passing through the filter was collected in pre-weighed metal dish.
4. The sample in the metal dish was evaporated and the dissolved solids correction factor was calculated.
5. The remaining sample in the 125 ml bottle was weighed and the level of sample was marked. The sample in the bottle was then dried and the suspended sediment concentration was calculated.
6. The initial sediment concentration before the test was calculated based on the measured weight of soil sample, during the pre-test procedure.
7. The ratio of suspended solid concentration of supernatant to the initial suspended solid concentration of the sediment solution was calculated, to get the percentage reduction in suspended solid concentration by flocculation process. The %SSC reduction is given by Equation 2.

$$\%SSC\,\mathrm{Re}\,duction = \left(1 - \frac{S}{S_o}\right) \times 100 \tag{2}$$

where S is the suspended solid concentration of the supernatant, and S_o is the initial suspended solid concentration of the sediment solution.

CHAPTER 4

EXPERIMENTAL DESIGN

The experimental strategy followed to determine the best flocculant and its optimum concentration range are discussed in this chapter. In this study, a sequential experimental approach was followed. Sequential experiments are applicable when a process consists of many steps with numerous factors at each stage. The incorporation of all factors of interest into one experiment would result in a study too large to conduct practically. However, by segmenting the analysis of the factors involved, a study of the first factor can be performed followed by a second study on a reduced number of factors (Peace 1993). In this study, the experimental problem was described by identifying the control factors and response variables, and then a sequential experimental schematic was developed to achieve the objective.

4.1 Experimental Problem Description

In examining any experimental process, what is being sought is a detailed understanding of the relationship between factors that can be changed in the process and their effects on the output of the process. Any condition or setting that can vary during a process is called an independent variable and any output or result of the process is termed a dependent variable. Independent variables are commonly referred to as control factors and dependent variables are known as responses (DelVecchio 1997). The problem under study can be described as follows:

Response Variables

The response variables to be analyzed in this study are:

- Flocculation efficiency (E)
- Percentage reduction in suspended solid concentration (%SSC)

According to (Tobiason et al. 2001), sediment particles responsible for turbidity are rich in clay and silt. Hence flocculation efficiency, based on turbidity and percentage suspended solid concentration reduction (%SSC), as an additional response variable, was measured to evaluate the flocculation process.

Control Factors

The control factors identified in this study are:

- Sediment concentration
- PAM type based on charge density
- PAM concentration
- Exchangeable cation concentration ($CaCl_2$ in this case)
- Mixing time
- Mixing speed (Dosing intensity)
- Sampling time

Change in sediment concentration would produce a change in response because the amount of PAM available for a specific sediment concentration will not be the same for different sediment concentration; hence, sediment concentration is one of the control variables in this study. As discussed in Section 2.2, flocculation with PAM is soil specific and the response would vary with different PAM type. Hence, PAM type based on different charge density was selected as a control variable in this study. Negatively charged anionic polyacrylamide binds with predominantly negatively charged clay particles due to the presence of net positive charge on its edges; however, the existence of divalent cations enhances flocculation due to the bridging phenomenon explained by (Laird 1997). Consequently, flocculation experiments were conducted with both anionic PAM and divalent cations. Change in PAM and exchangeable cation concentration would produce a change in response; thus, PAM and exchangeable cation concentration were also considered as control variables.

Solubility of $CaCl_2$ was found to be 74.5 grams per 100 grams of water. Gypsum and agricultural lime are slightly soluble in water and their solubility data are 0.209 grams per 100 grams of water and 0.1 gram/100 gram saturated solution (Perry and Green 1997). Since $CaCl_2$ is highly soluble in water, it can be easily prepared and quantified in the laboratory, and therefore, $CaCl_2$ was used as a source of divalent cations to conduct experiments.

Mixing time and mixing speed (dosing intensity) are anticipated to affect the response because a decrease in mixing time and/or mixing speed may not allow the sediment and flocculant to mix thoroughly. On the other hand, an increase in mixing time and mixing speed may break the flocs formed during flocculation process; thus, both were considered as control variables in this study. Finally, sampling time is also a control variable because an increase in sampling time enables more particles to settle and hence affect the response.

4.2 Experimental Sequence

The experimental procedure is divided into four steps and a sequential experimental approach was followed to conduct experiments. The schematic of sequential experimental approach is shown in Figure 8.

- Screening Test-I
- Screening Test-II
- Level-Selection test
- Factorial experiment

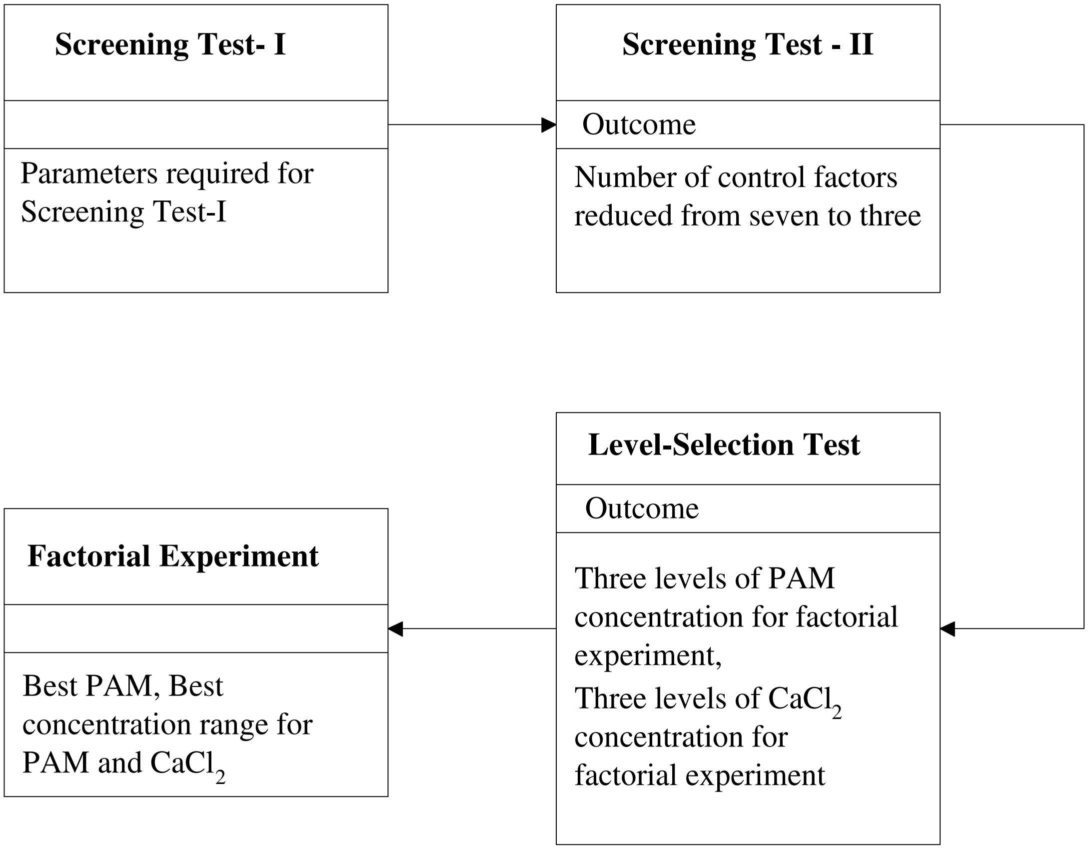


Figure 8: Schematic of Sequential Experiment Approach

As discussed in Section 4.1, the problem has seven control factors; this makes the experimental process very complex. For example, if all the factors were to be considered simultaneously, with three levels for each of the factor, a full factorial experiment would require: $3^7 = 2187$ experiments (Number of experiments = $\text{Level}^{(\text{Factor})}$), which is time consuming and not feasible.

To simplify the process, Screening Test-I and Screening Test-II were performed to eliminate factors that have little or no effect on the output of interest, thus reducing the list of control factors to a more manageable number to perform further experiments. Once the experiment was simplified, the level-selection experiments were performed to identify the number of levels and their quantitative values required at each level of the refined control factor. In the final step, a factorial experiment was conducted with the refined factors and their levels selected from previous steps. The detailed experimental procedure followed in each experimental step is discussed in further sections of this chapter

4.3 Screening Test-I

In Screening Test-I, jar test was conducted to determine the behavior of control factors namely: PAM type and PAM concentration. In this study, experiments were conducted with only one sediment concentration for silty clay loam soil. The choice of sediment concentration was based on rainfall simulation experiments conducted at varying slopes with sitly clay loam soil. From the simulation experiments, the average sediment concentration in the run off was found to be 25,000 ppm; hence, a sediment concentration of 25,000 ppm was selected to conduct further jar tests. It should be noted, however, that due to varying sediment flow characteristics, the sediment concentration and shear stress distribution will not be uniform over the entire construction site subjected to sediment control.

The test procedure followed here is in compliance with ASTM-D2035 (1999). The mixing speed and mixing time were modified from the ASTM protocol to conduct experiments with sediment. Here, the sediment mixing speed and mixing time were 300 rpm and 60 seconds, respectively. Since 300 rpm is the maximum speed the paddle could be operated, this speed was selected to mix the sediment completely. Also when the paddle is rotated at 300 rpm speed for 60 seconds the sediment is thoroughly mixed and suspended; this can be observed visually by switching on the built in illuminator. Once the sediment is mixed at 300 rpm for 60 seconds, PAM was dosed and the paddle was continuously operated at 300 rpm for 60 seconds for better mixing of PAM and sediment. Then paddle was operated at a reduced speed of 100 rpm for 60 seconds to enable smaller flocs formed to increase in size. If the paddle was continuously operated at 300 rpm, the flocs may break. So the speed was reduced from 300 rpm to 100 rpm. At this point of time, larger flocs are formed. To prevent these larger flocs from breaking, the paddle speed was reduced from 100 rpm to 20 rpm and operated for 30 seconds. After three stages of mixing, the treated sediment was allowed to settle for 5 minutes. Then the supernatant turbidity and sediment concentration were measured.

Based on the flocculation behavior of PAM type and PAM concentration interpreted from Screening Test-I, one PAM type and PAM concentration was selected for conducting Screening Test-II. Results obtained from Screening Test-I experiments are discussed in Section 5.1.

4.4 Screening Test-II

In Screening Test-II, jar test was performed to determine the significance of control factors, mixing time and sampling time. The significance of a specific control factor was analyzed based on response analysis, in which the response was measured by varying the factor under study with all the other factors kept constant. This study involved a total of seven control factors as mentioned in Section 4.1, five of which were kept constant in this experiment. They were:

- Sediment concentration
- PAM type
- PAM concentration
- $CaCl_2$ concentration
- Mixing speed (dosing intensity)

For this experiment, constant values of control factors PAM type and PAM concentration were selected based on the results of Screening Test-I. Experiments were conducted with only one mixing speed (dosing intensity) in this study. A speed of 100 rpm was selected as a representative mixing speed based on field observations. Regarding the $CaCl_2$ concentration, van Olphen (1963) found that divalent cations in the concentration range of 0.5 mmole to 2.0 mmole have higher flocculation power for the solution considered in his study. Since, the study involves a higher sediment concentration of 25000 ppm, $CaCl_2$ concentration of 3 mmole was selected for Screening Test-II.

Screening Test-II was conducted in two stages. In the first stage, the significance of mixing time was studied by varying mixing time with the other five control factors fixed. At this point, only six out of the seven control factors were considered. The seventh control factor, sampling time (whose significance to be determined in the second stage of Screening Test-II), was arbitrarily set to 30 seconds. Similarly, the significance of sampling time was studied by varying sampling time with the other five control factors fixed. Here, the seventh control factor, the mixing time, was selected from the first stage of Screening Test-II. The results of Screening Test-II are discussed in Section 5.2.

Results of Screening Test-II showed that mixing time and sampling time do not make significant difference in the flocculation characteristics; therefore, constant mixing time and sampling time were selected based on the results and kept constant while conducting further experiments. With the aid of Screening Test-I and Screening Test-II, the problem was simplified by reducing the number of control factors from seven to three; hence, the control factors in this problem were reduced to: PAM type, PAM concentration, and $CaCl_2$ concentration.

4.5 Level-Selection Test

Level-Selection tests were conducted to determine the number of levels and the quantitative values required at each level for the refined factors. Jar tests were conducted in two steps. In the first step, experiments were conducted with PAM, which is called PAM only-experiments. In the second step, experiments were conducted with $CaCl_2$, which is called $CaCl_2$-only experiments. Each of the three factors: PAM type, PAM concentration and $CaCl_2$ concentration requires at least three levels to study the effect of non-linearity of response variables; consequently, from the experimental data, three levels are inferred for each of the control factor. The experimental procedure followed in PAM-only and $CaCl_2$-only experiments are discussed as follows.

PAM-Only Experiment

In this experiment, jar tests were performed in compliance with the protocol discussed in Section 3.5. Experiments were conducted using each type of PAM by varying PAM concentration at suitable increments within the concentration range of 0-60 ppm. Based on the results, a response curve was generated. Figure 9 shows a hypothetical response curve that might be obtained from this experiment. Three levels of concentration representing high, medium, low concentration within the nonlinear region were selected from the response curve.

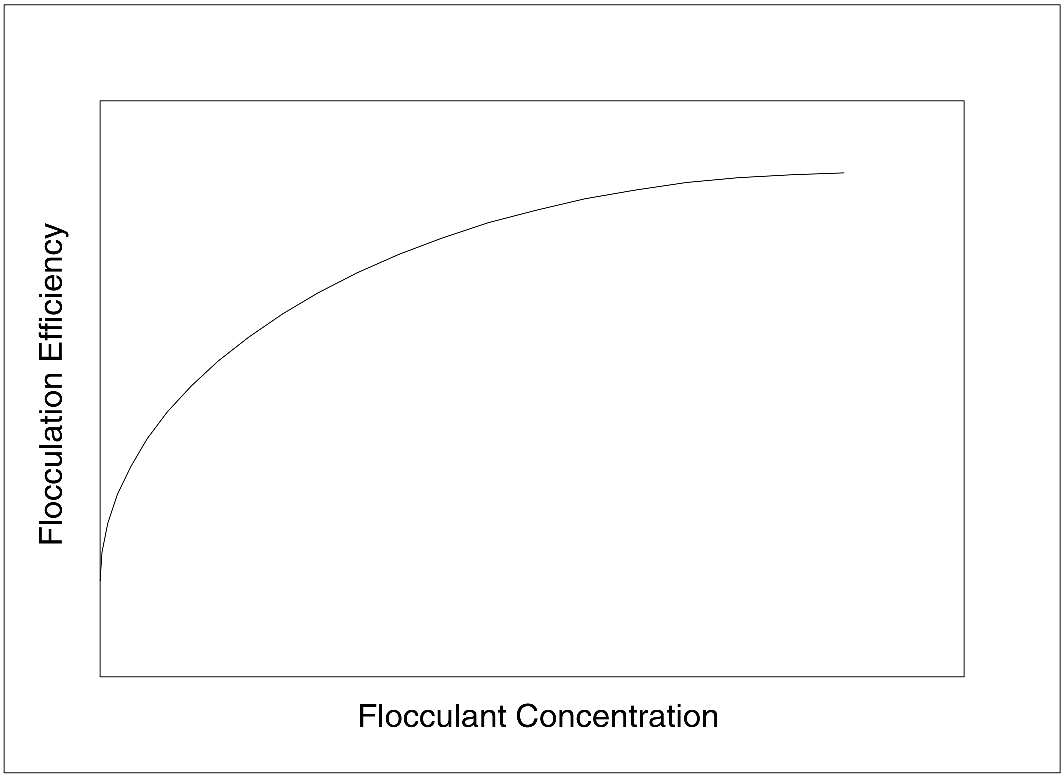


Figure 9: Typical Response Curve for Flocculation Process

$CaCl_2$-Only Experiment

In this experiment, jar test were performed in compliance with the protocol discussed in Section 3.5. Experiments were conducted by varying $CaCl_2$ concentration at suitable increments within a $CaCl_2$ concentration range of 0-25 mmole. Based on the results, a response curve was generated. Figure 9 shows a typical response curve that might be obtained from this experiment. Three levels of concentration representing high, medium, low concentration within the nonlinear region were selected from the response curve.

The three factors and their corresponding levels to be obtained from level-selection test are listed in Table 4. The three levels for the factor PAM type were selected as PAM10, PAM20, and PAM30 for the reasons mentioned in Section 2.2. Results obtained from Level-Selection tests are discussed in Section 5.3

Table 4: Level Chosen for Factorial Experiment

Level	**1**	**2**	**3**
PAM Type	PAM10	PAM20	PAM30
PAM Conc. (ppm)	Low	Medium	High
$CaCl_2$ Conc. (mmole)	Low	Medium	High

4.6 Factorial Experiment

The results obtained from the previous sets of experiments assisted in simplifying the problem to a three factor, three level experiment. Thus, a full factorial experiment requires only 27 experiments to study the flocculation characteristics for silty clay loam soil. The 27 experiments represent 27 different combinations of PAM type, PAM concentration and $CaCl_2$ concentration. The experimental protocol developed in Section 3.6 was followed to conduct a full factorial experiment. In the dosing part mentioned in Section 3.5, both the flocculants PAM and $CaCl_2$ were dosed simultaneously. Results obtained from these experiments are discussed in Sections 5.4 and 5.5

4.7 Factorial Experiment Analysis

As an experimental rule of thumb, nesting is required when qualitative factor level changes with its quantitative factor level (Kolarik 1995). In this study, PAM type is a qualitative factor nested with the factor PAM concentration.

Replication allows an easy estimate of the error associated within the factors. Since the experiments involve a significant amount of time and resources, only few of the experiments were repeated. If multiple replications are not made for each treatment combination, the error term cannot be estimated directly. In such cases, the higher order interactions may be pooled and used to estimate the experimental error term (Kolarik 1995). The three factor FAT-CRD (factorial arrangement of treatments-completely randomized design) model that represents the problem is given as:

$$Y_{ijkl} = \mu + A_i + B_{j(i)} + C_k + B_{j(i)}*C_k + A_i*C_k + \varepsilon_{l(ijk)}$$

where $i = 1, 2, \ldots, a$

$j = 1, 2, \ldots, b$

$k = 1, 2, \ldots, c$

$l = 1, 2, \ldots, n$

μ is the overall mean, Y_{ijkl} represents an observation. The A_i, C_k terms are main effect terms. $\varepsilon_{l(ijk)}$ is the pooled experimental error. Specifically, A measures the failure of the average response of the A levels to be the same when averaged over all levels of factor B and C. $B_{j(i)}$ is read as "B nested within A". $B_{j(i)}*C_k$, A_i*C_k are two-factor interaction terms. For example, the AC interaction term measures the failure of A or C to respond identically over all levels of A or C, averaged over factor B.

In this analysis, A is the PAM type, B is the PAM concentration, and C is the calcium chloride concentration. Statistical Analysis Software (SAS) was used to develop an analysis of variance (ANOVA) for estimating facor significance.

4.8 Settling Velocities

The study discussed in this section is based on visual observation, and these observations are casual and not quality controlled.

The size of flocs produced in Screening Test-I, Screening Test-II and factorial experiments were observed visually. For an experiment involving PAM and $CaCl_2$, the settling velocities of flocs were analyzed by conducting a batch-settling test. The procedure described in Section 4.3 was followed to conduct jar test experiment with PAM20 concentration of 2.5 ppm and $CaCl_2$ concentration of 3 mmole. The flocs along with the supernatant produced are poured into a sedimentation column of height 14 inches placed near horizontal position in order to prevent floc destruction. The suspension is allowed to settle after inverting the cylinder (slowly) five times. A clear liquid slurry interface was seen descending. The height of interface between clear liquid and suspended solids was observed at regular interval of time. Finally, the batch-settling test curve was generated by plotting the height of interface as a function of time. The results obtained form batch-settling test are discussed in Section 5.8

CHAPTER 5

RESULTS AND DISCUSSION

Experiments were conducted following the methods and design described in Chapters 3 and 4. The results obtained are presented and discussed in this chapter.

5.1 Screening Test-I

As a first task, jar tests were conducted to determine the behavior of PAM type and PAM concentration. Test procedures for Screening Test-I were discussed in Section 4.3.

As indicated by Figures 10 and 11, the flocculation efficiency and %SSC reduction increased with the PAM concentration up to about 2.5 ppm, and then both observables decreased with PAM concentration. There was no significant difference among the performance of the three PAMs; however, PAM20 concentration between 2.5 ppm and 3.5 ppm neither reduces the flocculation efficiency nor increases the supernatant suspended solid concentration (SSC) drastically. The other counterparts did show a major difference. For example, with reference to Tables A1, A2 and A3 in Appendix A, the flocculation efficiency of PAM 20 at 3.5 ppm is 89%, but for PAM10 and PAM30, the flocculation efficiencies are 74% and 84%, respectively. This indicates that PAM20 is stable at higher concentrations when compared to PAM10 and PAM30.

The flocculation behavior observed during the trial experiments revealed the following: The PAM concentration of 2.5 ppm is the threshold limit, after which the flocculation efficiency decreases and remains approximately constant. Also, PAM 20 is more stable at higher PAM concentration. Thus, PAM20 of concentration 2.5 ppm was selected for conducting Screening Test-II in the next step.

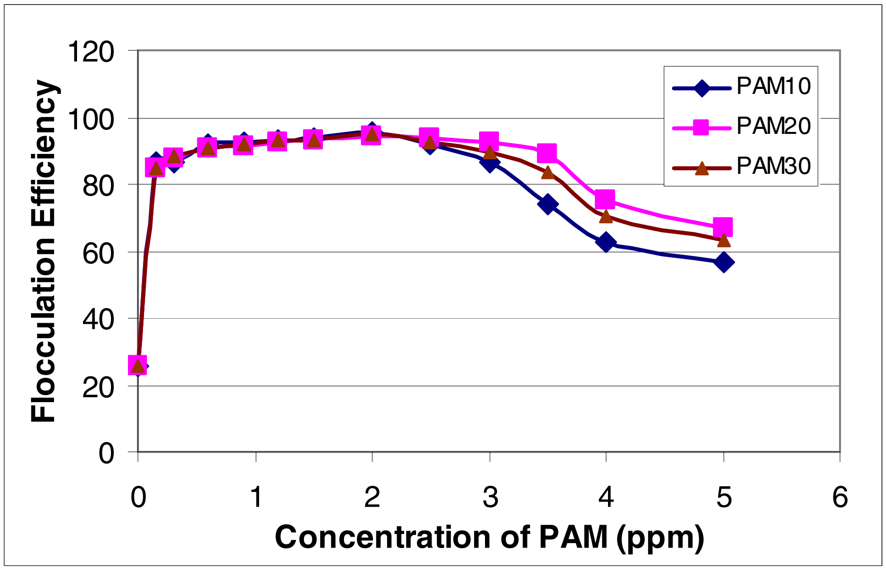


Figure 10: Flocculation Efficiency Response for Screening Test-I

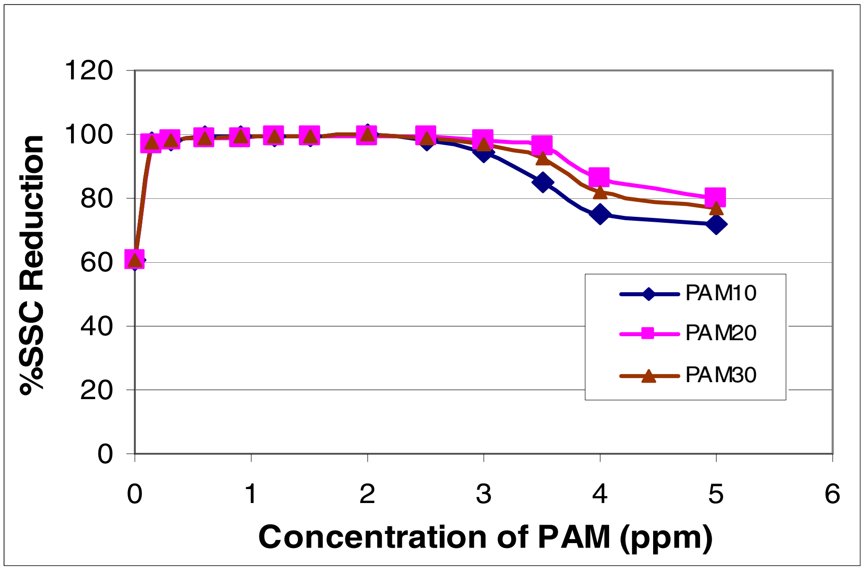


Figure 11: %SSC Reduction Response for Screening Test-I

5.2 Screening Test-II

The significance of the control factors, mixing time and sampling time were determined in Screening Test-II. Test procedure discussed in Section 4.4 was followed to conduct the experiments.

The experiments were conducted in two stages. In the first stage, the mixing time was varied and the response curve was generated using constant control factors and their values listed in Table 5. A constant sampling time of 30 seconds was used at this point, as discussed in Section 4.4. The change in response with increasing mixing time is represented graphically in Figure 12, and the same is listed in Table 5.

Table 5: Test Parameters for Screening Test - II

Control factor	**Value**
Sediment concentration	25000 ppm
PAM type	PAM 20
PAM concentration	2.5 ppm
$CaCl_2$ concentration	3 mmole
Mixing speed	100 rpm

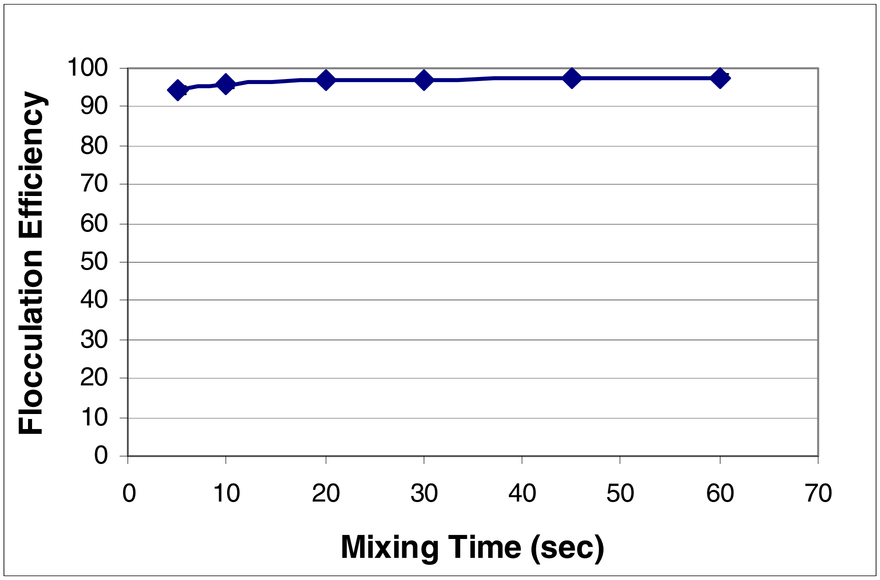


Figure 12: Effect of Mixing Time on Flocculation Efficiency

Table 6: Effect of Mixing Time on Flocculation Efficiency

Mixing Time (Sec)	Sediment Turbidity (NTU)	Supernatant Turbidity (NTU)	Flocculation Efficiency (%)
Run #1			
5	5720	421	93
10	5740	310	95
20	5700	190	97
30	5740	187	97
45	5690	184	97
60	5700	147	97
Run #2			
5	5700	273	95
10	5740	257	96
20	5720	150	97
30	5720	150	97
45	5730	150	97
60	5730	130	98

The results indicate that the change in flocculation efficiency is not significant in the mixing time range of 5-60 seconds. Therefore, a mixing time in the range of 5-60 would be appropriate in conducting our experiments. Moreover, field observations at a silt fence setup suggested that the runoff sediment would flow for approximately 30 seconds from the upstream to the downstream edge of the fence before it starts impounding behind the fence. Therefore, assuming that PAM would be applied at the upstream edge of the silt fence a mixing time of 30 seconds was chosen to conduct further experiments. The experiments were repeated two times. The results obtained from two runs are listed in Table 6.

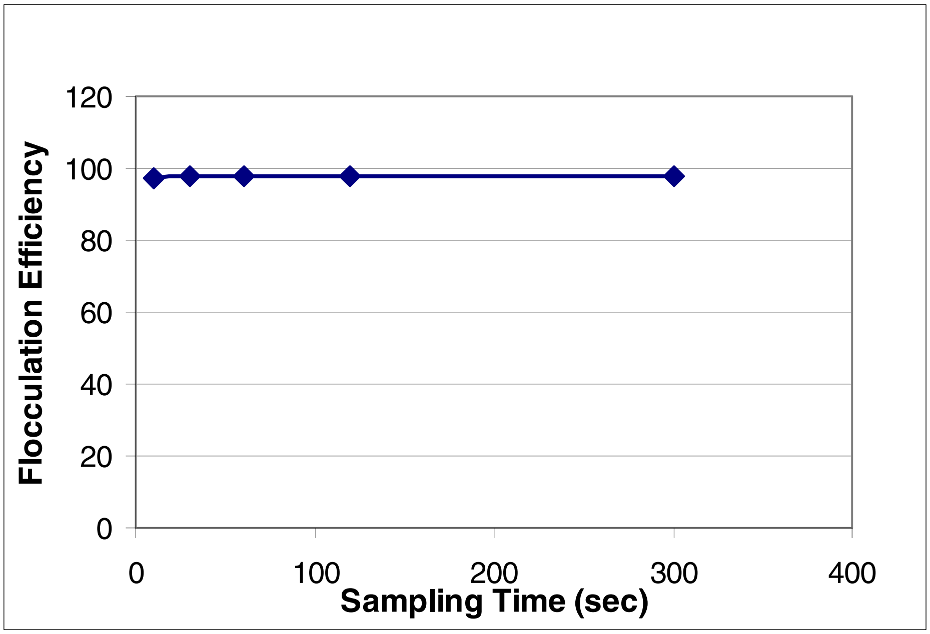
In the second stage, sampling time was varied and the response curve was generated using constant control factors with values as listed in Table 5. As discussed in

Section 4.4, a constant mixing time selected from the first stage of Screening Test-II was used at this point. The change in response with increasing sampling time is listed in Table 7, and the same is represented graphically in Figure 13

Table 7: Effect of Sampling Time on Flocculation Efficiency

Sampling Time (sec)	Sediment Turbidity (NTU)	Supernatant Turbidity (NTU)	Flocculation Efficiency (%)
Run #1			
10	5818	185	97
30	5867	146	98
60	5910	139	98
120	5837	136	98
300	5916	143	98
Run #2			
10	5861	167	97
30	5930	134	98
60	5916	138	98
120	5910	145	98
300	5939	130	98

Figure 13: Effect of Sampling Time on Flocculation Efficiency



The results indicated that within the range of 10-300 seconds there was no significant change in flocculation efficiency. Consequently, a settling time within the rage of 10-300 seconds would be appropriate. The experiments were also repeated two times. The results obtained from two runs are tabulated in Table 7.

This choice of sampling time was based on the dimensions of the jar used to conduct experiment (Figure 14) and Stoke's law mentioned in Equation 3.

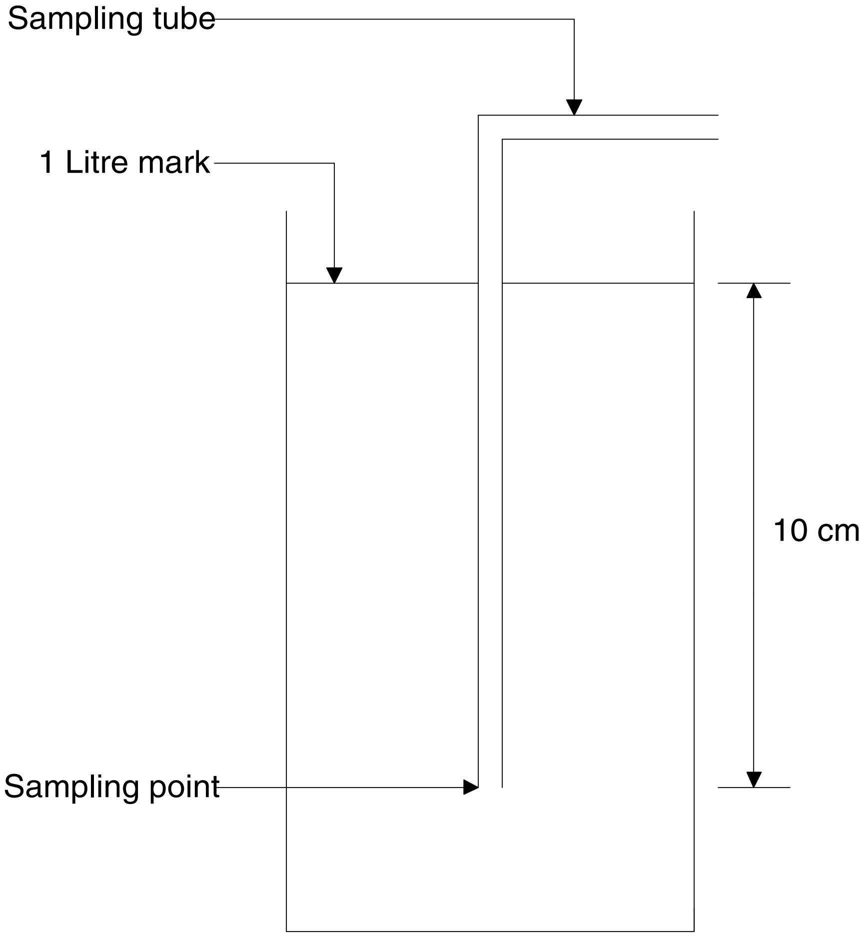


Figure 14: Dimension of Jar in Jar Test Apparatus

$$V_s = \frac{1}{18}\left[\frac{d^2}{v}(SG-1)\right] \tag{3}$$

where Vs is the settling velocity (cm/se), ν is the kinematic viscosity at 68°F (0.01003 cm^2/sec), g is the gravitational constant (980 cm/sec^2), and SG is the specific gravity (2.65).

Experiments were conducted with sediment solution having particles smaller than 53 microns. In the jar test apparatus, the sampling tube from the sampling module is located such that the sampling point is at 10 cm deep from the one liter mark of the jar (Figure 14). According to Stoke's law, a 53-micron particle takes approximately 40 seconds to reach the sampling point. Assuming particles greater that 53 microns were flocculated and if the settling time is 30 seconds, the sampling point at 10 cm deep would be free of flocculated particles. So a settling time of 30 seconds was selected for further experiment.

5.3 Level-Selection Test

Level-Selection tests were conducted to determine the number of levels and the quantitative values required at each level for the refined factors obtained from Screening Test-I and Screening Test-II. Test procedure discussed in Section 4.5 was followed to conduct experiments.

PAM-Only Experiments

Experiments were conducted with each PAM type as a flocculant; the flocculation efficiency and the percentage SSC reduction were measured. Tables A4, A5, and A6 in Appendix A present the results obtained for PAM10, PAM20 and PAM30, respectively. Figures 15 and 16 show the response, flocculation efficiency and percentage SSC reduction, respectively, for each PAM type at different increments of PAM concentrations. The results indicate that the flocculation efficiency and %SSC reduction increased with increase in PAM concentration at lower concentration range (0-10 ppm). Flocculation efficiency rises rapidly at 0.1 ppm and then increased slowly in magnitude up to 10 ppm. PAM concentration above 10 ppm caused the flocculation efficiency to remain approximately constant, up to 40 ppm. Further increase in PAM concentration from 40 ppm to 60 ppm decreased the flocculation efficiency. From the response curve, the choice of low level was fixed as 0.05 ppm based on the assumption that it may give better response when used in combination with $CaCl_2$. Accordingly, 5 ppm was selected as the medium level, which is in the region where the response was maximum, and 10 ppm was selected as the high level because it was the threshold point after which the response remains approximately constant.

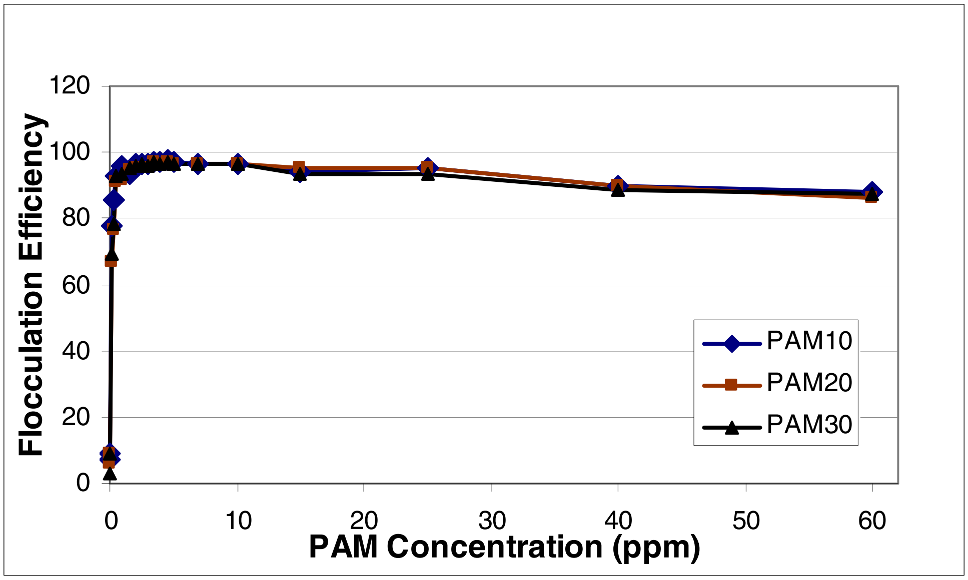


Figure 15: Effect of PAM Concentration on Flocculation Efficiency

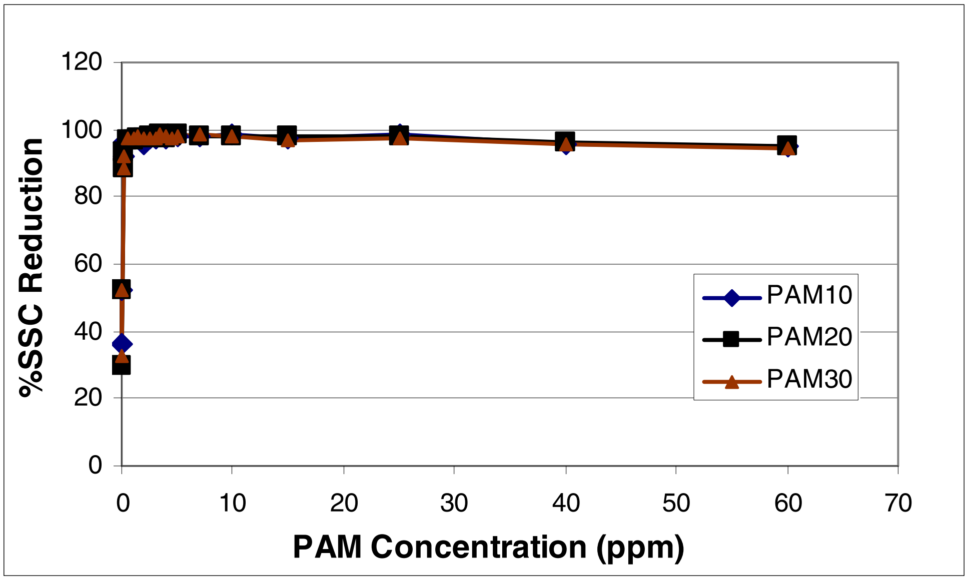


Figure 16: Effect of PAM Concentration on %SSC Reduction

Experiments were repeated two times for a few data points. The results obtained from two runs are listed in Table 8. From the results, it is obvious that the variability of flocculation efficiency and %SSC reduction are higher at low PAM concentration. This is due to the higher action based error introduced while preparing 0.05 ppm PAM solution. As listed in Table B2 of Appendix B, the amount of experimental uncertainty in preparing a 0.05 ppm PAM solution was 25% compared to only 5% for a 0.5 ppm solution.

Table 8: Repetition for PAM-Only Experiments

PAM Type	**PAM Conc. (ppm)**	**Flocculation Efficiency Run #1 (%)**	**Flocculation Efficiency Run #2 (%)**	**%SSC Reduction Run #1**	**%SSC Reduction Run #2**
PAM10	0.05	10	5	30	43
PAM10	0.5	91	95	95	97
PAM20	0.05	10	2	30	30
PAM20	0.5	93	89	97	96
PAM30	0.05	1	5	21	44
PAM30	0.5	95	90	98	97
Control	0	10	8	55	50

$CaCl_2$-Only Experiments

Table A7 of Appendix A presents the responses obtained for experiments conducted with $CaCl_2$ as a flocculant. The same results are illustrated graphically in Figures 17 and 18. The results showed that the change in responses was erratic in the $CaCl_2$ concentration range of 0.05-25 mmole considered in the experiment. From the results, it can also be inferred that beyond certain concentration, the response decreases with increase in $CaCl_2$ concentration.

Visual observation of $CaCl_2$-Only experiments showed that the flocs formed by $CaCl_2$ were very tiny compared to the size of flocs formed by PAM-Only experiment. Since the response curve was erratic, the concentration levels required to conduct factorial experiments were selected based on literature findings. van Olphen (1963) found divalent cations in the concentration range of 0.5 mmole to 2.0 mmole have higher flocculation power for the sol considered in his study. In this case, the low level was fixed as 0.5 mmole, the medium level was fixed to a value of 2.5 mmole (close to the one suggested by van Olphen (1963)), and the high level was fixed as 5 mmole. This is because at concentrations greater than 5 mmole the response decreases and remains approximately constant, as evident from Figures 17 and 18.

Experiments were repeated two times for a few data points. The results obtained from the two runs are listed in Table 9. The experimental uncertainties associated with the preparation of the $CaCl_2$ solution are discussed in Appendix B; moreover, Table B3 in Appendix B lists the expected percentage error for each of the $CaCl_2$ concentration data considered.

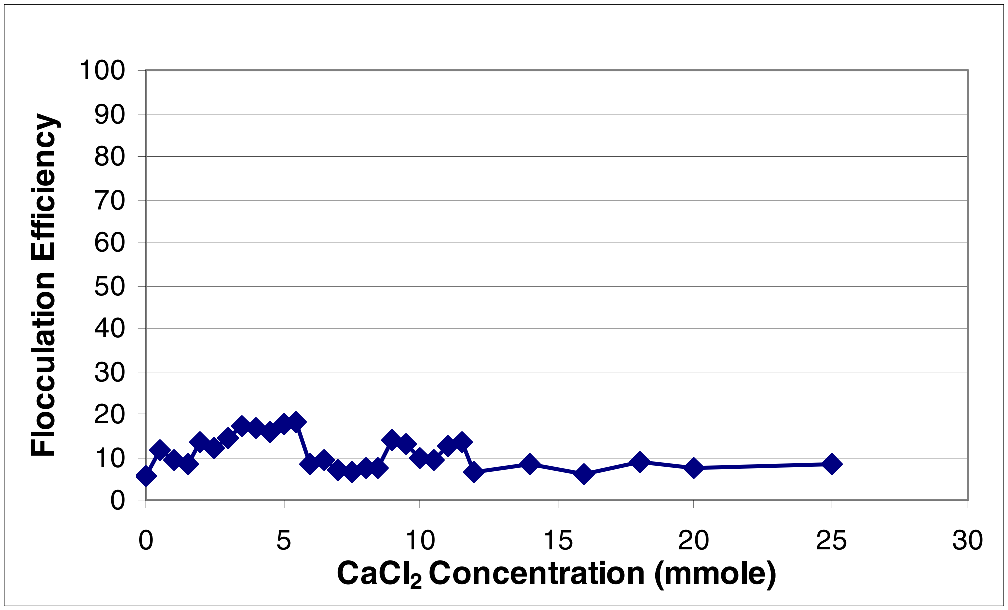


Figure 17: Effect of $CaCl_2$ Concentration on Flocculation Efficiency

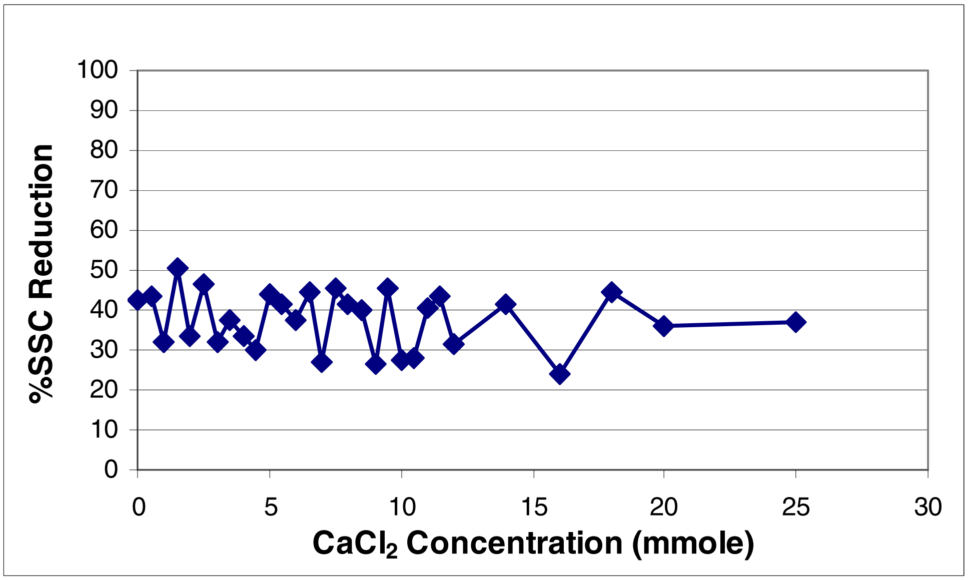


Figure 18: Effect of $CaCl_2$ Concentration on %SSC Reduction

Table 9: Repetition for $CaCl_2$-Only Experiment

$CaCl_2$ Concentration (mmole)	**Flocculation Efficiency Run #1(%)**	**Flocculation Efficiency Run #2 (%)**	**% SSC Reduction Run #1**	**% SSC Reduction Run #2**
0.5	11	12	44	42
2.5	12	13	46	45
5	18	8	44	30

From the Level-Selection test, three concentration values were selected for both PAM and $CaCl_2$ to conduct factorial experiment. Quantitative values inferred for three levels selected for each of the control factor from level selection test are listed in Table 10.

Table 10: Factor Levels Chosen for Factorial Experimentation

Level	**1**	**2**	**3**
PAM Type	PAM10	PAM20	PAM30
PAM Conc. (ppm)	0.05	5	10
$CaCl_2$ Conc. (mmole)	0.5	2.5	5

5.4 Factorial Experiment Results and Data Analysis

The three factors considered in this study were assigned as follows:

- Factor A is PAM type
- Factor B is PAM concentration
- Factor C is $CaCl_2$ concentration

Experiments were conducted for all possible combinations (3^3=27) of three factors and three levels of each factor mentioned in Table 10. In the factorial experiment, jar test experiments were conducted with both the flocculants PAM and $CaCl_2$ dosed simultaneously as mentioned in Section 4.6. The results based on flocculation efficiency and percentage SSC reduction responses are tabulated in Table A8 and A9. The results indicated that flocculation efficiency and %SSC reduction obtained in full factorial experiments are almost similar to PAM-Only experiments; however, visual observation showed that the flocs formed in factorial experiments are larger than flocs formed in PAM-Only experiments.

Experiments were repeated two times for nine data points. The results obtained from the two runs are listed in Table 11, which indicates that the variability of flocculation efficiency and %SSC reduction are higher at low PAM and $CaCl_2$ concentration. This is due to the higher error introduced while preparing 0.05 ppm PAM and 0.5 mmole $CaCl_2$ solutions. As mentioned in Table B2 and Table B3 of Appendix B, the percentage expected error for a factorial experiment in preparing 0.05 ppm PAM solution and 0.5 mmole $CaCl_2$ solutions are 5% and 5%, respectively; however, the percentage error in preparing 5 ppm, 10 ppm PAM solution and 2.5 mmole, 5 mmole $CaCl_2$ solutions are less, as evident from Table B2 and Table B3.

Table 11: Repetition for Factorial Experiment

Combination			**Flocculation Efficiency Run #1 (%)**	**Flocculation Efficiency Run #2 (%)**	**% SSC Reduction Run #1**	**% SSC Reduction Run #2**
PAM Type	**PAM (ppm)**	**$CaCl_2$ (mmole)**				
10	0.05	2.5	7	14	48	47
20	0.05	5	5	13	28	41
30	0.05	2.5	13	11	48	50
10	0.05	0.5	11	2	40	42
10	5	2.5	97	95	98	99
20	10	2.5	97	96	98	100
20	5	5	99	98	98	99
30	10	0.5	96	95	98	96
30	10	0.5	96	96	98	97

5.5 Data Analysis Based on Flocculation Efficiency

Inference Based on ANOVA Table and Main Effect Plots

An analysis of variance was conducted for the following hypothesis:

H_o: All responses are same

H_A: One of the responses is different

The ANOVA table was developed using the SAS software. Following are the results inferred from the ANOVA table (Table 12):

Table 12: ANOVA Table for Three-Factor Crossed and Nested CRD (Flocculation efficiency)

Source	Df	SS	MS	F-calc	P-value
TC	26 abcn-1	44885			
A_i	2 a-1	6.783	3.391	1.5	0.247
$B_{j(i)}$	6 a(b-1)	44284	7380.7	3263.4	0.0
C_k	2 c-1	17.682	8.841	3.909	0.037
Pooled Exp. Error	16	36.187	2.262		
$B_{j(i)}C_k$	12 a(b-1)(c-1)	26.151	2.179		
A_iC_k	4 (a-1)(c-1)	10.036	2.509		

- PAM type (factor A) is not significant (P=0.247); hence, PAM type does not affect flocculation efficiency. The same can be inferred from the main effect plot of A (Figure 19), where the response is same for all PAM types.
- PAM concentration (factor B) is significant ($P=8.061\times10^{-29}$); hence, PAM concentration affects flocculation efficiency. This is also evident from the main effect plot of PAM concentration (Figure 20), where the response increases with increase in PAM concentration;
- $CaCl_2$ concentration (factor C) is significant (P=0.0368); hence, $CaCl_2$ concentration affects flocculation efficiency. This is also evident from the main effect plot of $CaCl_2$ concentration (Figure 21). Close examination of Figure 21 show a little increase in response toward the medium level and reaches saturation toward the high level.

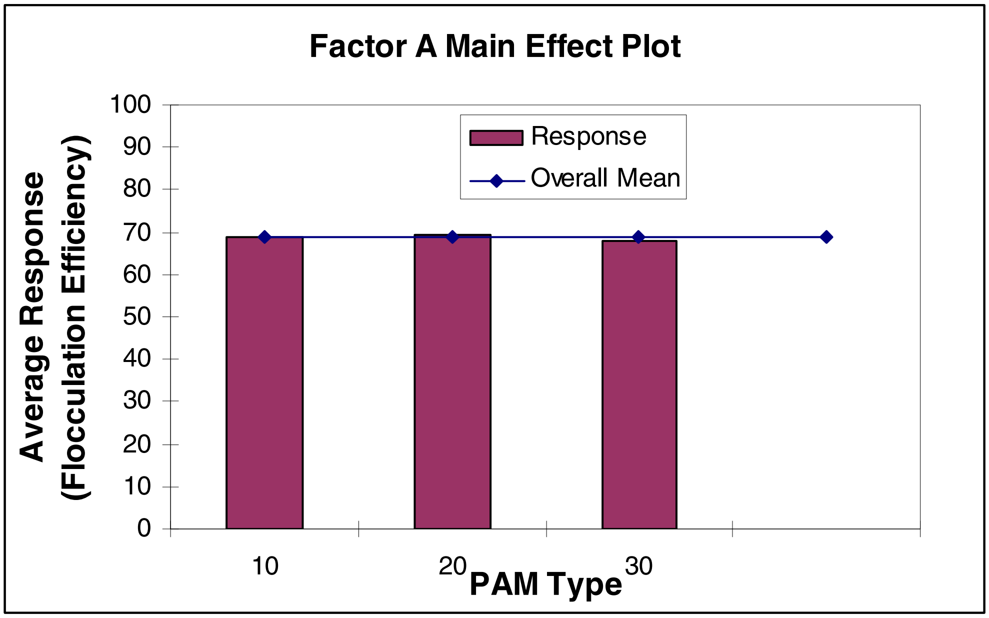


Figure 19: Main Effect for PAM type (Flocculation Efficiency)

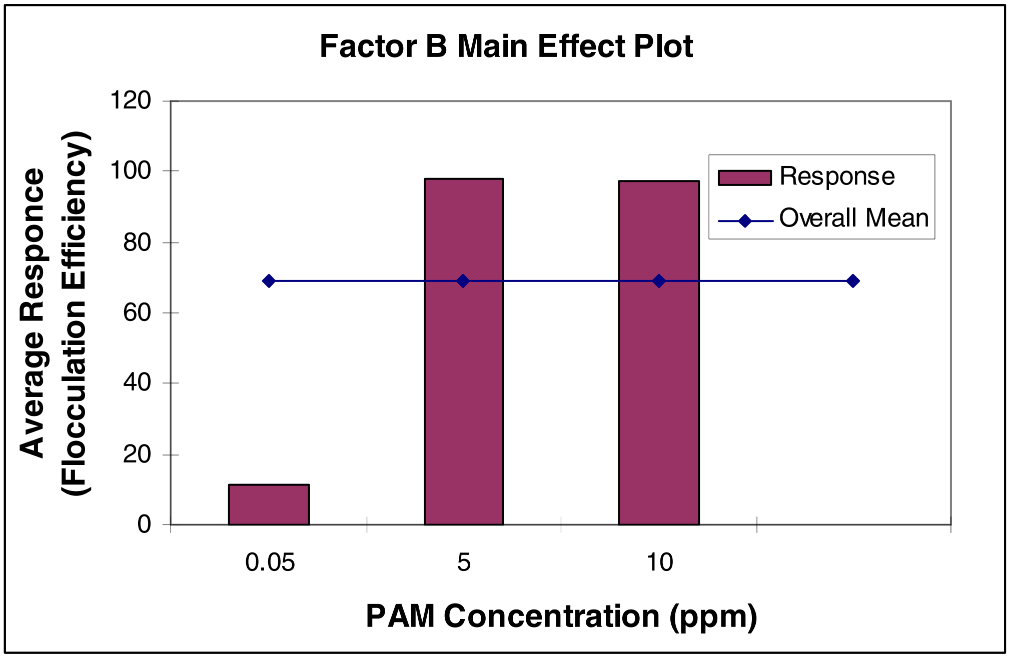


Figure 20: Main Effect for PAM Concentration (Flocculation Efficiency)

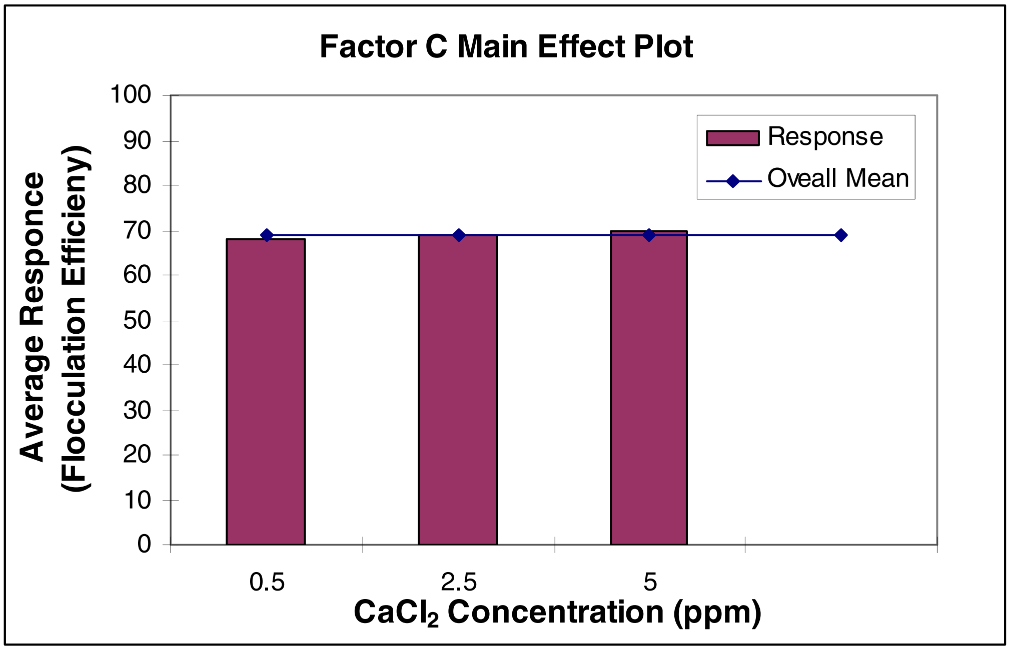


Figure 21: Main Effect for $CaCl_2$ Concentration (Flocculation Efficiency)

Inference Based on LSD Test

The test hypothesis for least significant difference (LSD) is as follows:

H_o: All the treatment effects are same

H_A: At least one treatment effect is different

LSD helps to determine the significant level of each factor considered in this experiment. Bold numbers in the table represents a 5% significance level. Since we assumed there is no interaction effect, LSD is not required for the interaction effects. Detailed explanation for the LSD data analysis based on flocculation efficiency is given in Appendix C. Following are the summary of results:

- Table 13 illustrates that the treatment effect of all PAM types are same.
- Table 14 indicates that there is a treatment difference between 0.05 ppm and 5 ppm; however, there is no difference between 5 ppm and 10 ppm. Hence, the PAM concentration operating range can be limited between 0.05 ppm and 5 ppm.
- Table 15 implies that there is a treatment difference between 0.5 mmole and 5 mmole, and there is no difference between 0.5 mmole and 2.5 mmole. In addition, there is no difference between 2.5 mmole and 5 mmole. Thus, the operating range of $CaCl_2$ concentration can be between 1.5 mmole to 3.5 mmole.

Table 13: LSD for Main Effect, PAM Type (Flocculation Efficiency)

Main Effect A

LSD **1.557**

			decreasing order (→)		
	A		PAM20	PAM10	PAM30
		Average	69.4	68.8	68.2
increasing	PAM30	68.2	1.226	0.676	
Order	PAM10	68.8	0.55		
(↓)	PAM20	69.4			

Table 14: LSD for Main Effect, PAM Concentration (Flocculation Efficiency)

Main Effect B

LSD **1.557**

			decreasing order (→)		
	B		5	10	0.05
		Average	97.8	97.4	11.2
increasing	0.05	11.2	***86.649***	***86.189***	
Order	10	97.4	0.46		
(↓)	5	97.8			

Table 15: LSD for Main Effect, $CaCl_2$ Concentration (Flocculation Efficiency)

Main Effect C

LSD **1.557**

			decreasing order (→)		
	C		5	2.5	0.5
		Average	69.8	68.8	67.8
increasing	0.5	67.8	***1.982***	0.979	
Order	2.5	68.8	1.003		
(↓)	5	69.8			

5.6 Data Analysis Based on %SSC Reduction

Inference Based on ANOVA Table, and Main Effect Plots

An analysis of variance was performed for the following hypothesis:

H_o: All responses are same

H_A: One of the responses is different

The ANOVA table was developed using the SAS software. Following are the results inferred from the ANOVA table (Table 16):

Table 16: ANOVA Table for Three-Factor Crossed and Nested CRD (%SSC Reduction)

Source	Df	SS	MS	F-calc	P-value
TC	26 abcn-1	20234.93			
A_i	2 a-1	50.130	25.065	2.608	0.115
$B_{j(i)}$	6 A(b-1)	19752.51	3292.086	342.574	1.06E-12
C_k	2 c-1	94.903	47.451	4.938	0.027
Pooled* Exp. Error	12*	115.318*	9.7*		
$B_{j(i)}C_k$	12 A(b-1)(c-1)	295.973	24.664		
A_iC_k	4 (a-1)(c-1)	41.409	10.352		

* Pooled experimental error is calculated based on the interaction terms: A*C and A*B*C obtained from three crossed factor ANOVA table.

- PAM type (factor A) is not significant (P=0.115); hence, PAM type does not affect %SSC reduction. The same can be inferred for the main effect plot of A (Figure 22), where the response is same for all PAM types.
- PAM concentration (factor B), is significant ($P=1.06\times10^{-12}$); hence, PAM concentration affects %SSC reduction. This is also evident for the main effect plot of PAM concentration (Figure 23).
- $CaCl_2$ concentration (factor C) is significant (P=0.0272); hence, $CaCl_2$ concentration affects %SSC reduction. This is also evident from the main effect plot for $CaCl_2$ concentration (Figure 24). Close examination of Figure 24 show a little increase in response toward the medium level and reaches saturation towards the high level.

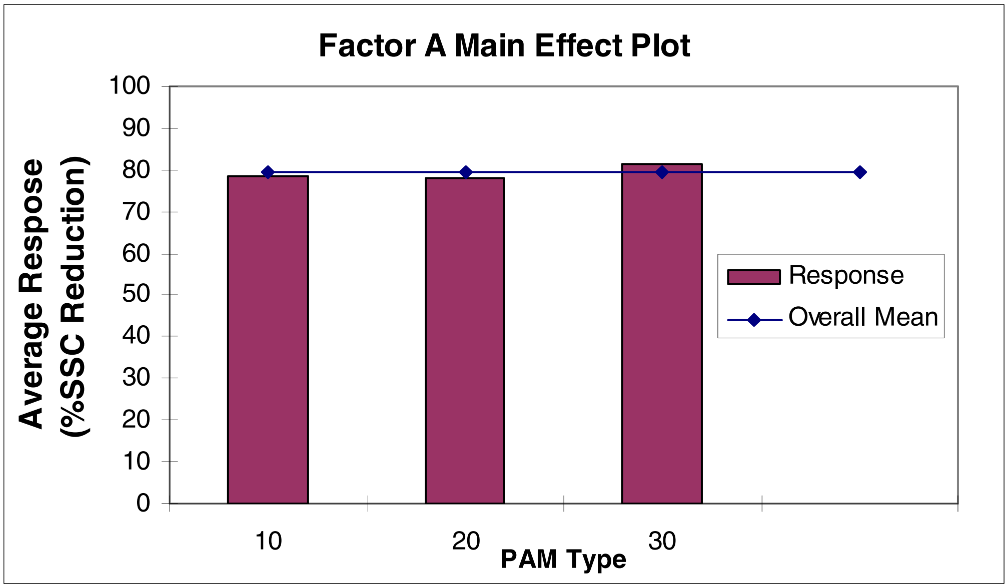


Figure 22: Main Effect for PAM Type (%SSC Reduction)

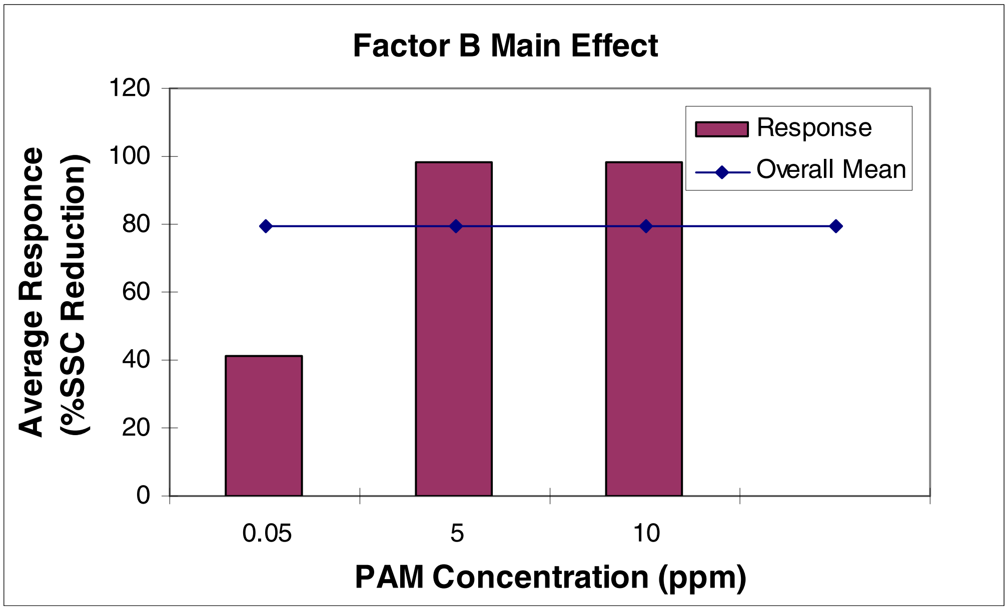


Figure 23: Main Effect for PAM Concentration (%SSC Reduction)

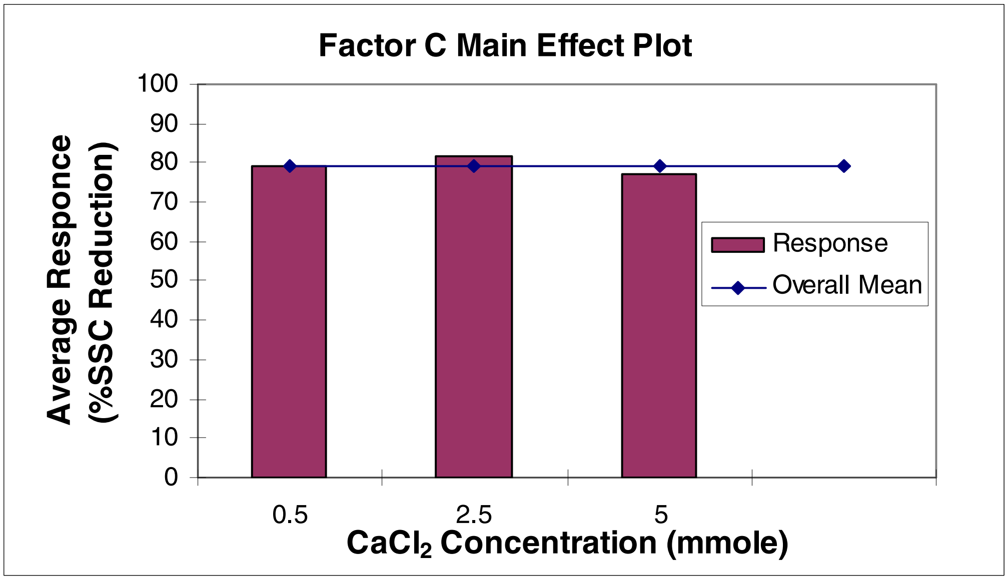


Figure 24: Main Effect for $CaCl_2$ Concentration (%SSC Reduction)

Inference Based on LSD Test

Least significant difference (LSD) test was conducted with the following hypothesis:

H_o: All the treatment effects are same

H_A: At least one treatment effect is different.

LSD helps to determine the significant level of each factor considered in this experiment. Bold numbers in the table represents a 5% significance level. Since there is no interaction effect, LSD is not required for the interaction effects.

- Table 17 illustrates that the treatment effect of all PAM types are same.
- Table 18 implies that there is a treatment difference between 0.05 ppm and 5 ppm; however, there is no difference between 5 ppm and 10 ppm. Hence, the PAM concentration operating range can be limited between 0.05 ppm and 5 ppm.
- Table 19 implies that there is a treatment difference between 0.5 mmole and 5 mmole, and there is no difference between 0.5 mmole and 2.5 mmole. In addition, there is no difference between 2.5 mmole and 5 mmole. Thus, the operating range of $CaCl_2$ concentration can be between 1.5 mmole to 3.5 mmole.

Table 17: LSD for Main Effect, PAM Type (%SSC Reduction)

Main Effect A
LSD 3.184

Decreasing order (→)

	A		PAM20	PAM10	PAM30
		Average	81.3	78.6	78.2
increasing Order (↓)	PAM30	78.2	3.077	0.418	
	PAM10	78.6	2.659		
	PAM20	81.3			

Table 18: LSD for Main Effect, PAM Concentration (%SSC Reduction).

Main Effect B
LSD 3.184

Decreasing order (→)

	B		5	10	0.05
		Average	98.5	98.4	41.2
Increasing	0.05	41.2	***57.271***	***57.177***	
Order	10	98.4	0.094		
(↓)	5	98.5			

Table 19: LSD for Main Effect, $CaCl_2$ Concentration (%SSC Reduction)

Main Effect C
LSD 3.184

Decreasing order (→)

	C		5	2.5	0.5
		Average	81.7	79.4	77.1
Increasing	0.5	77.1	***4.592***	2.269	
Order	2.5	79.4	2.323		
(↓)	5	81.7			

5.7 Summary of the Data Analysis

From the statistical analysis made for the two responses namely: flocculation efficiency and %SSC reduction, the following can be inferred:

1. Flocculation characteristics measured based on flocculation efficiency and %SSC reduction lead to similar interpretations.
2. Visual observation showed that, flocs formed in factorial experiments are larger compared to PAM-Only and $CaCl_2$-Only experiments.
3. The statistical analysis supports the inferences made by visual inspection.

5.8 Settling Velocities

The results discussed in this section are based on visual observation, and these observations are casual and not quality controlled.

When observed visually, no flocs were formed after dosing the flocculant ($CaCl_2$) in $CaCl_2$-Only experiments. Floc formation was observed in PAM-Only experiments after dosing the flocculant. Similar to PAM-Only experiment, floc formation was also observed in factorial experiments (Experiments conducted with PAM and $CaCl_2$). When the size of flocs formed in PAM-Only and $CaCl_2$-Only experiments are compared visually, the factorial experiments produced larger flocs compared to PAM-Only experiments. In addition, visual observations also suggested that the larger flocs settled within 10 seconds, and smaller flocs settled within 15-20 seconds in the 10 cm tall jar shown in Figure 14 of Section 5.2.

Batch-Settling Test

Batch-settling test was conducted following the procedure described in Section 4.8. The heights of interface at different time intervals were noted. Results obtained from batch-settling test are presented in Table 20. The batch-settling curve obtained by plotting the height of interface as a function of time is as shown in Figure 25.

Table 20: Results of Batch Settling Test

Height of Interface $\times10^{-2}$ (m)	Settling Time (sec)
35.56	0
33.02	2
30.48	4
27.94	7
25.40	10
22.86	13
20.32	16
17.78	19
15.24	23
12.70	27
10.16	32
7.62	36
5.08	41
2.22	47
1.91	60
1.59	92
1.27	148

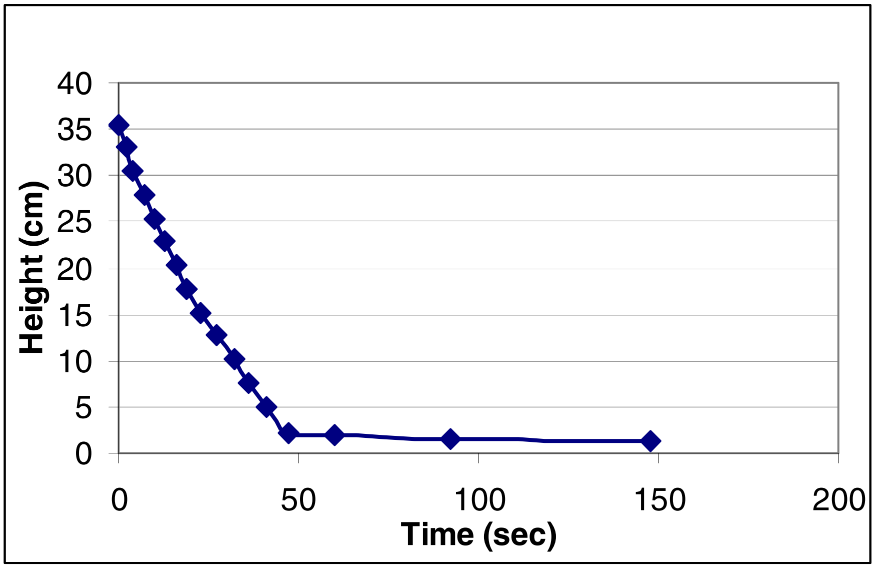


Figure 25: Height of Interface as a Function of Time

The results indicate that the interface settles with a higher settling velocity. As shown in Table 20 the interface descends approximately 33 cm (33×10^{-2} m) in 47 seconds.

5.8 First Order Economic Analysis for the Cost of PAM

Cost analysis performed for the application of polyacrylamide to silt fence technology is discussed in this section. A drainage area of 50×10 ft in Stillwater, with an annual average rainfall of 33 inches (Stillwater Fire Department 2006) was considered in this study. The plot area with a silt fence length of 10 ft is as shown in Figure 25.

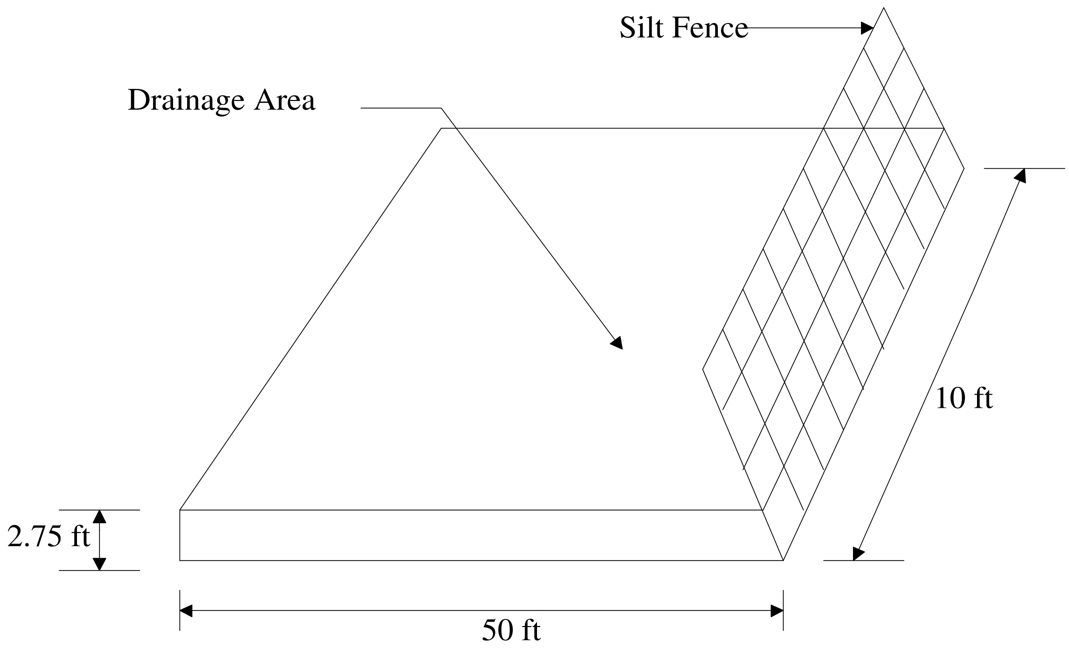


Figure 25: Typical Drainage Area Installed with Silt Fence

Cost Calculations

The following assumptions were made to estimate the cost of PAM required for one foot of silt fence:

- The plot area was assumed to have a silty clay loam soil with a uniform sediment concentration of 25000 ppm.
- A PAM concentration of 5 ppm was considered in this calculation. This was done to determine a maximum cost estimate based on the results given in Section 5.5, which showed that the operating range of PAM concentration for a 25000 ppm sediment solution is between 0.05 and 5 ppm per liter of sediment.
- PAM and the sediment solution in the drainage area were ideally mixed
- The cost involved for the mode of applying PAM to silt fence was ignored.

Based on the above assumptions, the cost for applying PAM was estimated to be $0.11 per foot of silt fence. The detailed cost estimation procedure is explained in Appendix D.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Flocculation experiments were conducted with three flocculants and exchangeable cations ($CaCl_2$ in this study) on silty clay loam soil. The effectiveness of flocculants and their combination with exchangeable cations were studied with the help of jar test experiments. The response variables of the experiment, i.e., flocculation efficiency and %SSC reduction, were analyzed statistically. Following are the conclusions drawn and recommendations based on this study.

6.1 Conclusions

- The three PAMs (flocculants): PAM10, PAM20, PAM30 considered for this study showed the same flocculation characteristics for the silty clay loam soil.
- PAM played a more vital role in increasing flocculation efficiency and %SSC reduction than $CaCl_2$ (exchangeable cations).
- The best operating range for PAM and $CaCl_2$ concentrations for desired flocculation efficiency and %SSC reduction were found to be 0.05-5 ppm and 1.5-3.5 mmole, respectively.
- After a threshold limit, the flocculation efficiency and %SSC reduction decreases with increase in PAM concentration. This supported the statement: “Application rates of anionic PAM above those suggested by the manufacturer will not provide additional effectiveness.”

6.2 Recommendations

The following are the recommendations of this study:

- In addition to flocculation efficiency and %SSC reduction, the size of the flocs should be determined to study the influence of $CaCl_2$ and to have a good understanding of the flocculation process.
- Jar test experiments should be performed for at least two more sediment concentrations to predict the flocculant requirement for different sediment concentration.
- Jar test experiments should be performed at different mixing speeds (dosing intensities) to determine the effect of mixing on flocculation process.
- Field experiments should be performed with anionic PAM and $CaCl_2$ to determine their effective application in real construction sites.

CHAPTER 7

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APPENDIX A

TABLES OF EXPERIMENTAL DATA

Table A1: Results of Screening Test-I (PAM10)

PAM 10						
PAM Conc. (ppm)	**Sediment Turbidity** (NTU)	**Supernatant Turbidity** (NTU)	**Flocculation Efficiency** (%)	**Sediment Conc.** (ppm)	**Supernatant Conc.** (ppm)	**% SSC Reduction**
0	6530	4858	26	25000	9910	60
0.15	6777	910	87	25000	660	97
0.3	6777	891	87	25000	500	98
0.6	6777	563	92	25000	200	99
0.9	6777	510	92	25000	200	99
1.2	6777	452	93	25000	140	99
1.5	6777	431	94	25000	140	99
2	6777	295	96	25000	60	100
2.5	6777	563	92	25000	500	98
3	6777	909	87	25000	1340	95
3.5	6777	1751	74	25000	3700	85
4	6777	2523	63	25000	6200	75
5	6777	2932	57	25000	7080	72

Table A2: Results of Screening Test-I (PAM20)

PAM 20						
PAM Conc. (ppm)	**Sediment Turbidity** (NTU)	**Supernatant Turbidity** (NTU)	**Flocculation Efficiency** (%)	**Sediment Conc.** (ppm)	**Supernatant Conc.** (ppm)	**% SSC Reduction**
0	6530	4858	26	25000	9910	60
0.15	6777	1020	85	25000	720	97
0.3	6777	823	88	25000	420	98
0.6	6777	627	91	25000	240	99
0.9	6777	584	91	25000	240	99
1.2	6777	489	93	25000	200	99
1.5	6777	481	93	25000	140	99
2	6777	389	94	25000	100	100
2.5	6777	429	94	25000	160	99
3	6777	504	93	25000	420	98
3.5	6777	753	89	25000	920	96
4	6777	1659	76	25000	3460	86
5	6777	2226	67	25000	5060	80

Table A3: Results of Screening Test-I (PAM30)

PAM30						
PAM Conc. (ppm)	**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**	**Sediment Conc. (ppm)**	**Supernatant Conc. (ppm)**	**% SSC Reduction**
0	6530	4858	26	25000	9910	60
0.15	6777	1017	85	25000	640	97
0.3	6777	808	88	25000	440	98
0.6	6777	621	91	25000	260	99
0.9	6777	559	92	25000	200	99
1.2	6777	471	93	25000	160	99
1.5	6777	460	93	25000	160	99
2	6777	364	95	25000	60	100
2.5	6777	491	93	25000	360	99
3	6777	707	90	25000	840	97
3.5	6777	1112	84	25000	1880	92
4	6777	2022	70	25000	4520	82
5	6777	2470	64	25000	5780	77

Table A4: Results of PAM-Only Experiment (PAM10)

PAM 10						
PAM Conc. (ppm)	**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**	**Sediment Conc. (ppm)**	**Supernatant Conc. (ppm)**	**%SSC Reduction**
0	5901	5340	9	25042	11350	52
0.05	5847	5279	7	25352	17726	36
0.1	5837	1291	78	25040	1917	92
0.25	5963	853	86	25043	994	96
0.5	6051	320	93	25040	749	96
1	6015	250	96	25039	577	98
1.5	5894	373	94	25043	676	97
2	5956	226	96	25036	1056	96
2.5	5912	215	96	25039	609	98
3	5895	191	97	25038	632	97
3.5	5952	186	97	25037	529	98
4	5913	176	97	25039	585	98
4.5	5874	150	97	25041	519	98
5	5959	172	97	25037	566	98
7	5953	201	97	25043	471	98
10	5889	192	97	25037	368	99
15	6015	363	94	25040	641	97
25	5971	291	95	25045	296	99
40	5907	597	90	25036	1099	96
60	5939	717	88	25038	1267	95

Table A5: Results of PAM-Only Experiment (PAM20)

PAM 20						
PAM Conc. (ppm)	**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**	**Sediment Conc. (ppm)**	**Supernatant Conc. (ppm)**	**%SSC Reduction**
0	5901	5340	9	25042	11350	52
0.05	5908	5303	6	25361	17855	30
0.1	5896	1954	67	25045	2814	89
0.25	5914	1377	77	25040	1657	93
0.5	6002	655	91	25035	975	97
1	6004	500	92	25042	836	97
1.5	5932	317	95	25038	634	97
2	5918	275	95	25036	685	97
2.5	5882	273	95	25039	570	98
3	5851	287	95	25037	623	98
3.5	5873	188	97	25039	273	99
4	5897	204	97	25039	578	98
4.5	5860	178	97	25037	561	98
5	5918	193	97	25043	402	98
7	5885	212	96	25042	529	98
10	5924	198	97	25040	501	98
15	5957	274	95	25040	565	98
25	5976	293	95	25043	527	98
40	5934	609	90	25047	886	96
60	5894	826	86	25044	1256	95

Table A6: Results of PAM-Only Experiment (PAM30)

PAM 30						
PAM Conc. (ppm)	**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**	**Sediment Conc. (ppm)**	**Supernatant Conc. (ppm)**	**%SSC Reduction**
0	5901	5340	9	25042	11350	52
0.05	6006	5718	3	25389	14158	33
0.1	5888	1807	69	25040	2909	88
0.25	5975	1308	78	25043	1937	92
0.5	6028	590	93	25040	809	97
1	5990	403	93	25034	634	97
1.5	5928	273	95	25036	441	98
2	5903	250	96	25035	699	97
2.5	5884	210	96	25042	694	97
3	5856	233	96	25046	649	97
3.5	5937	175	97	25040	363	99
4	5877	206	96	25044	513	98
4.5	5926	169	97	25039	699	97
5	5892	197	97	25039	555	98
7	5869	191	97	25034	290	99
10	5916	199	97	25038	497	98
15	5934	383	94	25036	730	97
25	5924	372	94	25037	716	97
40	5886	680	88	25044	1046	96
60	5909	736	88	25045	1422	94

Table A7: Results of $CaCl_2$-Only Experiment

$CaCl_2$						
$CaCl_2$ Conc. (mmole)	**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**	**Sediment Conc. (ppm)**	**Supernatant Conc. (ppm)**	**% SSC Reduction**
0	6050	5703	6	25038	14411	42
0.5	5972	5288	11	25039	14116	44
1	6003	5436	9	25040	16972	32
1.5	6017	5504	9	25037	12334	51
2	5993	5196	13	25037	16608	34
2.5	5962	5241	12	25039	13447	46
3	6012	5154	14	25040	17082	32
3.5	5973	4953	17	25038	15707	37
4	5958	4949	17	25038	16616	34
4.5	6005	5064	16	25038	17577	30
5	5967	4916	18	25037	13967	44
5.5	5964	4874	18	25039	14612	42
6	5982	5467	9	25039	15632	38
6.5	5958	5394	9	25038	13941	44
7	5910	5490	7	25039	18331	27
7.5	5931	5550	6	25039	13703	45
8	5923	5487	7	25037	14609	42
8.5	5946	5509	7	25039	14978	40
9	6050	5220	14	25039	18382	27
9.5	5972	5189	13	25039	13650	45
10	5973	5398	10	25037	18113	28
10.5	5994	5440	9	25037	18041	28
11	6016	5269	12	25039	14897	48
11.5	5997	5187	14	25037	14108	44
12	5974	5590	6	25038	17180	31
14	5980	5475	8	25040	14587	42
16	5855	5509	6	25040	19017	24
18	5917	5382	9	25039	13862	45
20	5905	5470	7	25038	16016	36
25	5914	5407	9	25039	15746	37

Table A8: Full Factorial Experiment Results Based on Flocculation Efficiency

Combination			**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency (%)**
PAM Type	**PAM Conc. (ppm)**	**$CaCl_2$ Conc. (mmole)**			
10	0.05	0.50	5916	5275	11
10	0.05	2.50	5899	5498	7
10	0.05	5.00	5861	5072	13
10	5	0.50	5905	151	97
10	5	2.50	5858	102	98
10	5	5.00	5946	61	99
10	10	0.5	5842	192	97
10	10	2.5	5870	97	98
10	10	5	5809	76	99
20	0.05	0.50	5854	5184	11
20	0.05	2.50	5825	5053	13
20	0.05	5.00	5874	5001	15
20	5	0.50	5876	168	97
20	5	2.50	5856	123	98
20	5	5.00	5827	84	99
20	10	0.5	5880	242	96
20	10	2.5	5865	175	97
20	10	5	5816	95	98
30	0.05	0.5	5836	5339	9
30	0.05	2.5	5827	5073	13
30	0.05	5	5841	5345	8
30	5	0.5	5817	211	96
30	5	2.5	5845	154	97
30	5	5	5828	91	98
30	10	0.5	5851	241	96
30	10	25	5845	165	97
30	10	5	5847	103	98

Table A9: Full Factorial Experiment Results Based on %SSC Reduction

Combination			Sediment	Supernatant	% SSC
PAM Type	PAM Conc. (ppm)	$CaCl_2$ Conc. (mmole)	Conc. (ppm)	Conc. (ppm)	Reduction
10	0.05	0.50	25379	15176	40
10	0.05	2.50	25386	13155	48
10	0.05	5.00	25365	18494	27
10	5	0.50	25359	532	98
10	5	2.50	25374	209	99
10	5	5.00	25316	400	98
10	10	0.5	25344	380	99
10	10	2.5	25352	162	99
10	10	5	25344	298	99
20	0.05	0.50	25374	15386	39
20	0.05	2.50	25379	13368	47
20	0.05	5.00	25352	18339	28
20	5	0.50	25356	442	98
20	5	2.50	25362	407	98
20	5	5.00	25349	415	98
20	10	0.5	25371	749	97
20	10	2.5	25325	581	98
20	10	5	25359	55	100
30	0.05	0.5	25341	13492	47
30	0.05	2.5	25387	13090	48
30	0.05	5	25362	13694	46
30	5	0.5	25373	542	98
30	5	2.5	25388	336	99
30	5	5	25368	145	99
30	10	0.5	25342	423	98
30	10	25	25379	542	98
30	10	5	25381	453	98

APPENDIX B

ERROR ANALYSIS

B1. Action Based Error Propagation for Experiments Involving PAM

The desired PAM concentration in sediment solution was obtained by a serial dilution procedure as discussed in Section 3.4. The following calculation provides estimates of the expected uncertainties in the desired PAM concentration in one liter of sediment.

Multivariate error propagation was employed in this analysis (Gasem 2006). The expected uncertainties in the instruments used to prepare PAM solutions are listed in Table B1, as supplied by the manufacturers.

Table B1: List of Instrument Precision

Description	**σ**
Kimax, class A 25 ml volumetric pipet	±0.03 ml
Kimax, class A 50 ml volumetric pipet	±0.05 ml
Kimax, class A 100 ml volumetric pipet	±0.08 ml
Pyrex, with life time red graduation line 1000 ml volumetric flask	±0.60 ml
Kimax, class A 50 ml measuring jar	±0.25 ml
Kimax, class A 250 ml measuring jar	±0.80 ml

Let C_1, C_2, and C_3 be the concentration of stock PAM solution, concentration of second diluted PAM solution, and concentration of PAM in sediment, respectively. Then by definition:

$$C_1 = \frac{M_1}{V} \qquad \text{B1}$$

$$C_2 = \frac{V_2 \times \frac{M_1}{V}}{V} = C_1\left(\frac{V_2}{V}\right) \qquad \text{B2}$$

$$C_3 = \frac{V_3 \times \left[\dfrac{V_2 \times \dfrac{M_1}{V}}{V} \right]}{V} = \frac{V_3 \times V_2 \times M_1}{V^3} = C_2 \left(\frac{V_3}{V} \right) \qquad \text{B3}$$

where M_1 is the mass of PAM (mg), V is the volume of water (liter),V_2 is the volume withdrawn from C_1 solution (liter), and V_3 is the volume withdrawn from C_1 solution (liter)

Propagating the error in C_3 (Gasem 2006), we get:

$$\sigma_{C_3}^2 = \left(\frac{\partial C_3}{\partial V_3} \right)^2 \sigma_{V_3}^2 + \left(\frac{\partial C_3}{\partial V_2} \right)^2 \sigma_{V_2}^2 + \left(\frac{\partial C_3}{\partial M_1} \right)^2 \sigma_{M_1}^2 + \left(\frac{\partial C_3}{\partial V} \right)^2 \sigma_V^2 \qquad \text{B4}$$

$$\left(\frac{\partial C_3}{\partial V_3} \right)^2 = \left(\frac{V_2 \times M_1}{V^3} \right)^2 \qquad \text{B5}$$

$$\left(\frac{\partial C_3}{\partial V_3} \right)^2 \times \frac{1}{C_3^2} = \frac{1}{V_3^2} \qquad \text{B6}$$

$$\left(\frac{\partial C_3}{\partial V_2} \right)^2 = \left(\frac{V_3 \times M_1}{V^3} \right)^2 \qquad \text{B7}$$

$$\left(\frac{\partial C_3}{\partial V_2} \right)^2 \times \frac{1}{C_3^2} = \frac{1}{V_2^2} \qquad \text{B8}$$

$$\left(\frac{\partial C_3}{\partial M_1} \right)^2 = \left(\frac{V_3 \times V_2}{V^3} \right)^2 \qquad \text{B9}$$

$$\left(\frac{\partial C_3}{\partial M_1} \right)^2 \times \frac{1}{C_3^2} = \frac{1}{M_1^2} \qquad \text{B10}$$

$$\left(\frac{\partial C_3}{\partial V} \right)^2 = \frac{9}{V^2} \left(\frac{V_3 \times V_2 \times M_1}{V^3} \right)^2 \qquad \text{B11}$$

$$\left(\frac{\partial C_3}{\partial V}\right)^2 \times \frac{1}{C_3^2} = \frac{9}{V^2} \qquad \text{B12}$$

$$\frac{\sigma_{C_3}^2}{C_3^2} = \frac{\sigma_{V_3}^2}{V_3^2} + \frac{\sigma_{V_2}^2}{V_2^2} + \frac{\sigma_{M_1}^2}{M_1^2} + \frac{9\sigma_V^2}{V^2} \qquad \text{B13}$$

Equation B13 was used to calculate the uncertainty of PAM concentration in sediment solution.

If the second dilution process is avoided, and a definite volume of stock solution is used to obtain the desired PAM concentration in the sediment solution, Equation B3 becomes:

$$C_3 = \frac{V_3 \times M_1}{V^2} \qquad \text{B14}$$

Consequently, the equation to calculate the uncertainty of PAM concentration in sediment solution is:

$$\frac{\sigma_{C_3}^2}{C_3^2} = \frac{\sigma_{V_3}^2}{V_3^2} + \frac{\sigma_{M_1}^2}{M_1^2} + \frac{4\sigma_V^2}{V^2} \qquad \text{B15}$$

The uncertainties estimated for each of the concentration data in PAM-Only experiment and factorial experiment are listed in Table B2.

Table B2: Uncertainty of PAM Concentration Values

C1 ppm	C2 ppm	C3 ppm	σC^2_3 ppm	σC_3 ppm	% Error
PAM-Only experiment					
2000	50	0.05	0.000156	0.0125	25.00
2000	100	0.1	0.000625	0.025	25.00
2000	50	0.25	0.000157	0.01251	5.00
2000	100	0.5	0.000626	0.02502	5.00
2000	100	1	0.000629	0.02508	2.51
2000	100	1.5	0.000635	0.02519	1.68
2000	100	2	0.000642	0.02534	1.27
2000	100	2.5	0.000652	0.02552	1.02
2000	100	3	0.000663	0.02575	0.86
2000	100	3.5	0.000677	0.02602	0.74
2000	100	4	0.000693	0.02632	0.66
2000	100	4.5	0.000711	0.02666	0.59
2000	100	5	0.000731	0.02704	0.54
2000	200	7	0.005795	0.07612	1.09
2000	200	10	0.009224	0.09604	0.96
2000	500	15	0.018658	0.13659	0.91
2000	500	25	0.02405	0.15508	0.62
2000	2000	40	0.064804	0.25457	0.64
2000	2000	60	0.067684	0.26016	0.43
Factorial experiment					
2000	10	0.05	6.27E-06	0.0025	5.01
2000	500	5	0.015962	0.12634	2.53
2000	500	10	0.016973	0.13028	1.30

B2. Action-Based Error Propagation for Experiments Involving $CaCl_2$

The desired $CaCl_2$ concentration in sediment solution was obtained by adding a definite volume of a stock $CaCl_2$ solution of known concentration as discussed in Section 3.5. The following calculation provides an estimate of the expected uncertainties for the desired $CaCl_2$ concentration in one liter of sediment. By a solution stochiometric balance:

$$m_1V_1 = m_2V_2 \quad \text{B16}$$

$$m_2 = \frac{m_1V_1}{V_2} \quad \text{B17}$$

where m_1 is the molarity of stock $CaCl_2$ solution (mmole), V_1 is the volume of stock solution added to sediment (liter), m_2 is the molarity of $CaCl_2$ in sediment solution (mmole), and V_2 is the volume of sediment solution.

Propagating the error in m_2, we get:

$$\sigma_{m_2}^2 = \left(\frac{\partial m_2}{\partial m_1}\right)^2 \sigma_{m_1}^2 + \left(\frac{\partial m_2}{\partial V_1}\right)^2 \sigma_{V_1}^2 + \left(\frac{\partial m_2}{\partial V_2}\right)^2 \sigma_{V_2}^2 \quad \text{B18}$$

$$\left(\frac{\partial m_2}{\partial m_1}\right)^2 = \left(\frac{V_1}{V_2}\right)^2 \quad \text{B19}$$

$$\left(\frac{\partial m_2}{\partial m_1}\right)^2 \times \frac{1}{m_2^2} = \frac{1}{m_1^2} \quad \text{B20}$$

$$\left(\frac{\partial m_2}{\partial V_1}\right)^2 = \left(\frac{m_1}{V_2}\right)^2 \quad \text{B21}$$

$$\left(\frac{\partial m_2}{\partial V_1}\right)^2 \times \frac{1}{m_2^2} = \frac{1}{V_1^2} \quad \text{B22}$$

$$\left(\frac{\partial m_2}{\partial V_2}\right)^2 = -\left(\frac{m_1 V_1}{V_2^2}\right)^2 \qquad \text{B23}$$

$$\left(\frac{\partial m_2}{\partial V_2}\right)^2 \times \frac{1}{m_2^2} = -\frac{1}{V_2^2} \qquad \text{B24}$$

$$\frac{\sigma_{m_2}^2}{m_2^2} = \frac{\sigma_{m_1}^2}{m_1^2} + \frac{\sigma_{V_1}^2}{V_1^2} + \frac{\sigma_{V_2}^2}{V_2^2} \qquad \text{B25}$$

As mentioned earlier m_1 is the molarity of stock $CaCl_2$ solution. To obtain $\sigma_{m_1}^2$, initially, the stock solution concentration was expresses in terms of mass/volume. Specifically, let C_1 be the concentration of $CaCl_2$ in terms of mass/volume, then:

$$C_1 = \frac{M_1}{V} \qquad \text{B26}$$

where M_1 is the mass of $CaCl_2$ (grams) and V is the volume of water added (liter).

Propagating the error in C_1, we get:

$$\sigma_{C_1}^2 = \left(\frac{\partial C_1}{\partial M_1}\right)^2 \sigma_{M_1}^2 + \left(\frac{\partial C_1}{\partial V}\right)^2 \sigma_V^2 \qquad \text{B27}$$

$$\left(\frac{\partial C_1}{\partial M_1}\right)^2 = \left(\frac{1}{V}\right)^2 \qquad \text{B28}$$

$$\left(\frac{\partial C_1}{\partial M_1}\right)^2 \times \frac{1}{C_1^2} = \frac{1}{M_1^2} \qquad \text{B29}$$

$$\left(\frac{\partial C_1}{\partial V}\right)^2 = \left(\frac{M_1}{V^2}\right)^2 \qquad \text{B30}$$

$$\left(\frac{\partial C_1}{\partial V}\right)^2 \times \frac{1}{C_1^2} = \frac{1}{V^2} \qquad \text{B31}$$

$$\frac{\sigma_{C_1}^2}{C_1^2} = \frac{\sigma_{M_1}^2}{M_1^2} + \frac{\sigma_V^2}{V^2} \qquad \text{B32}$$

Therefore,

$$\sigma_{m_1}^2 = \frac{\sigma_{C_1}^2}{(Molar - mass)^2} \qquad \text{B33}$$

The uncertainties estimated for each of the concentration data in PAM-Only experiment and factorial experiment are listed in Table B3.

Table B3: Uncertainty of $CaCl_2$ Concentration Values

C_1 **g/l**	**m_1** **mmole**	**m_2** **mmole**	**σm_2^2** **mmole**	**σm_2** **mmole**	**%** **Error**
$CaCl_2$-only experiment					
11.1	100	0.5	0.00063	0.025	5.01
11.1	100	1	0.00063	0.025	2.52
11.1	100	1.5	0.00065	0.025	1.69
11.1	100	2	0.00066	0.026	1.29
11.1	100	2.5	0.00068	0.026	1.04
11.1	100	3	0.00071	0.027	0.89
11.1	100	3.5	0.00074	0.027	0.77
11.1	100	4	0.00077	0.028	0.69
11.1	100	4.5	0.00081	0.028	0.63
11.1	100	5	0.00085	0.029	0.58
11.1	100	5.5	0.0009	0.03	0.54
27.8	250	6	0.00423	0.065	1.08
27.8	250	6.5	0.00429	0.065	1.01
27.8	250	7	0.00435	0.066	0.94
27.8	250	7.5	0.00441	0.066	0.89
27.8	250	8	0.00448	0.067	0.84
27.8	250	8.5	0.00456	0.068	0.79
27.8	250	9	0.00464	0.068	0.76
27.8	250	9.5	0.00472	0.069	0.72
27.8	250	10	0.00481	0.069	0.69
27.8	250	10.5	0.0049	0.07	0.67
27.8	250	11	0.005	0.071	0.64
27.8	250	11.5	0.0051	0.071	0.62
55.5	500	12	0.01692	0.13	1.08
55.5	500	14	0.01739	0.132	0.94
55.5	500	16	0.01793	0.134	0.84
55.5	500	18	0.01854	0.136	0.76
55.5	500	20	0.01923	0.139	0.69
55.5	500	25	0.02125	0.146	0.58
Factorial experiment					
11.1	100	0.5	0.00063	0.025	5.01
11.1	100	2.5	0.00068	0.026	1.04
11.1	100	5	0.00085	0.029	0.58

APPENDIX C

LSD ANALYSIS

C1. LSD Analysis for Flocculation Efficiency

LSD analyses were based on the procedure described in Kolarik (1995). Table C1 represents the full factorial experiment results based on flocculation efficiency.

Table C1: Full Factorial Experiment Results Based on Flocculation Efficiency

Combination			**Sediment Turbidity (NTU)**	**Supernatant Turbidity (NTU)**	**Flocculation Efficiency* (%)**
PAM Type	**PAM Conc. (ppm)**	**$CaCl_2$ Conc. (mmole)**			
10	0.05	0.50	5916	5275	10.83
10	0.05	2.50	5899	5498	6.80
10	0.05	5.00	5861	5072	13.46
10	5	0.50	5905	151	97.44
10	5	2.50	5858	102	98.25
10	5	5.00	5946	61	98.97
10	10	0.5	5842	192	96.71
10	10	2.5	5870	97	98.34
10	10	5	5809	76	98.69
20	0.05	0.50	5854	5184	11.45
20	0.05	2.50	5825	5053	13.25
20	0.05	5.00	5874	5001	14.86
20	5	0.50	5876	168	97.15
20	5	2.50	5856	123	97.91
20	5	5.00	5827	84	98.55
20	10	0.5	5880	242	95.88
20	10	2.5	5865	175	97.02
20	10	5	5816	95	98.37
30	0.05	0.5	5836	5339	8.52
30	0.05	2.5	5827	5073	12.94
30	0.05	5	5841	5345	8.49
30	5	0.5	5817	211	96.37
30	5	2.5	5845	154	97.36
30	5	5	5828	91	98.44
30	10	0.5	5851	241	95.88
30	10	25	5845	165	97.17
30	10	5	5847	103	98.24

*For LSD analysis the flocculation efficiency data corrected to two decimal place was used. In Table A8 of Appendix-A the flocculation efficiency data was rounded off to whole numbers

Tables C2, C3 and C4 are formed by grouping the flocculation efficiency values from Table C1 under PAM10, PAM20, and PAM30 corresponding to PAM and $CaCl_2$ concentration.

Table C2: Full Factorial Experiment (Flocculation Efficiency, PAM10)

		PAM10		
PAM(ppm)		**0.05**	**5**	**10**
$CaCl_2$ (mmole)	**0.5**	10.83	97.44	96.71
	2.5	6.8	98.25	98.34
	5	13.46	98.97	98.69

Table C3: Full Factorial Experiment Results (Flocculation Efficiency, PAM20)

		PAM20		
PAM (ppm)		**0.05**	**5**	**10**
$CaCl_2$ (mmole)	**0.5**	11.45	97.15	95.88
	2.5	13.25	97.91	97.02
	5	14.86	98.55	98.37

Table C4: Full Factorial Experiment (Flocculation Efficiency, PAM20)

		PAM30		
PAM (ppm)		**0.05**	**5**	**10**
$CaCl_2$ (mmole)	**0.5**	8.52	96.37	95.88
	2.5	12.94	97.36	97.17
	5	8.49	98.44	98.24

C2. Calculation of mean

The LSD table in Chapter 5 is formed by calculating the mean for each factor PAM type, PAM concentration, and $CaCl_2$ concentration. The mean value for PAM10 is obtained by calculating the mean of responses corresponding to PAM10. Similarly, the mean values for the other factors were also calculated.

Mean of flocculation efficiency for PAM10:

$$\frac{10.83+6.80+13.46+97.44+98.25+98.97+96.71+98.34+98.69}{9}=68.83$$

Mean of flocculation efficiency for PAM20:

$$\frac{11.45+13.25+14.86+97.15+97.91+98.55+95.88+97.02+98.37}{9}=69.38$$

Mean of flocculation efficiency for PAM30:

$$\frac{8.52+12.94+8.49+96.37+97.36+98.44+95.88+97.17+98.24}{9}=68.16$$

Mean of flocculation efficiency for 0.05 ppm PAM concentration:

$$\frac{10.83+6.8+13.46+11.45+13.25+14.86+8.52+12.94+8.49}{9}=11.18$$

Mean of flocculation efficiency for 5 ppm PAM concentration:

$$\frac{97.44+98.25+98.97+97.15+97.91+98.55+96.37+97.36+94.44}{9}=97.83$$

Mean of flocculation efficiency for 10 ppm PAM concentration:

$$\frac{96.71+98.34+98.69+95.88+97.02+98.37+95.88+97.17+98.24}{9}=97.37$$

Mean of flocculation efficiency for 0.5 mmole $CaCl_2$ concentration:

$$\frac{10.83+97.44+96.71+11.45+97.15+95.88+8.52+96.37+95.88}{9}=67.80$$

Mean of flocculation efficiency for 2.5 mmole $CaCl_2$ concentration:

$$\frac{6.8+98.25+98.34+13.25+97.91+97.02+12.94+97.36+97.17}{9}=68.78$$

Mean of flocculation efficiency for 5 mmole $CaCl_2$ concentration:

$$\frac{13.46+98.97+98.69+14.86+98.55+98.37+8.49+98.44+98.24}{9}=69.79$$

C3. LSD for PAM Type

The LSD table for the factor PAM type is formed by ordering the mean values calculated for PAM 10, PAM20 and PAM30 in a decreasing order from left to right and in an increasing order from top to bottom, as shown in Table C5. The LSD value 1.557, for a 5% level significance shown in Table C5, was calculated as:

$$LSD_{0.05}=t_{0.025,16}\sqrt{\frac{2MS_{err}}{n}} \qquad \text{C1}$$

where MS_{err} is the pooled experimental error value taken from Table 11 of Chapter 5, the value 16 is the degree of freedom for the pooled experimental error obtained from Table 11, and n is the number of data points considered for each factor (in this case n=9).

The value 1.226 in Table C5 is the difference between 69.38 and 68.16, the value 0.676 is the difference between 68.832 and 68.16, and the value 0.55 is the difference between 69.38 and 68.83 of Table C5, respectively.

Table C5: LSD for Main Effect, PAM Type (Flocculation Efficiency)

Main Effect A
LSD **1.557**

decreasing order (→)

	A		PAM20	PAM10	PAM30
		Average	69.38	68.83	68.16
increasing	PAM30	68.16	1.226	0.676	
Order	PAM10	68.83	0.55		
(↓)	PAM20	69.38			

Based on Table C5, the values 1.226, 0.676 and 0.55 are less than the LSD value determined; therefore, there is no significant difference among PAM10, PAM20 and PAM30 on the response flocculation efficiency.

C4. LSD for PAM Concentration

Similar to the procedure discussed to obtain the LSD table for PAM type, a LSD table for PAM concentration is developed as shown in Table C6.

Table C6: LSD for Main Effect, PAM Concentration (Flocculation Efficiency)

Main Effect B

LSD **1.557**

			decreasing order (→)		
	B		5	10	0.05
		Average	97.83	97.37	11.18
increasing	0.05	11.18	***86.65***	***86.19***	
Order	10	97.37	0.46		
(↓)	5	97.83			

As indicated by Table C6, the bold values 86.65 and 86.19 are greater than the determined LSD value 1.557. This implies that there is a difference between PAM concentration 0.05 ppm and 5 ppm, and 0.05 ppm and 10 ppm regarding flocculation efficiency. Also the value 0.46 is less than 1.557. This suggests that there is no difference between PAM concentration 5 ppm and 10 ppm regarding flocculation efficiency. Therefore, the best PAM concentration range lies between 0.05 ppm and 5 ppm, concentration above 5 ppm produced the same response as that of 5 ppm.

C5. LSD for $CaCl_2$ Concentration

Similar to the procedure discussed to obtain the LSD table for PAM type, a LSD table for PAM concentration is developed, as shown in Table C7.

Table C7: LSD for Main Effect, $CaCl_2$ Concentration (Flocculation Efficiency)

Main Effect C
LSD **1.557**

			decreasing order (→)		
	C		5	2.5	0.5
		Average	69.79	68.78	67.80
increasing	0.5	67.80	***1.982***	0.979	
Order	2.5	68.78	1.003		
(↓)	5	69.79			

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Based on Table C6, the bold value 1.982 is greater than the determined LSD value 1.557, this implies that there is a difference between $CaCl_2$ concentration 0.5 mmole and 5 mmole regarding flocculation efficiency. The values 0.979 and 1.003 are less than 1.557; hence, there is no difference between 2.5 mmole and 5 mmole, 0.5 mmole and 2.5 mmole $CaCl_2$ concentrations. Therefore, the best $CaCl_2$ concentration range lies between 1.5 ppm and 3.5 ppm. Similarly, LSD analyses were performed for %SSC data listed in Table C8.

Table C8: Full Factorial Experiment Results Based on %SSC Reduction

Combination			Sediment Conc. (ppm)	Supernatant Conc. (ppm)	% SSC* Reduction
PAM Type	**PAM Conc. (ppm)**	**$CaCl_2$ Conc. (mmole)**			
10	0.05	0.50	25379	15176	40.20
10	0.05	2.50	25386	13155	48.18
10	0.05	5.00	25365	18494	27.09
10	5	0.50	25359	532	97.90
10	5	2.50	25374	209	99.18
10	5	5.00	25316	400	98.42
10	10	0.5	25344	380	98.50
10	10	2.5	25352	162	99.36
10	10	5	25344	298	98.82
20	0.05	0.50	25374	15386	39.36
20	0.05	2.50	25379	13368	47.33
20	0.05	5.00	25352	18339	27.66
20	5	0.50	25356	442	98.25
20	5	2.50	25362	407	98.39
20	5	5.00	25349	415	98.36
20	10	0.5	25371	749	97.05
20	10	2.5	25325	581	97.71
20	10	5	25359	55	99.78
30	0.05	0.5	25341	13492	46.76
30	0.05	2.5	25387	13090	48.44
30	0.05	5	25362	13694	46.01
30	5	0.5	25373	542	97.86
30	5	2.5	25388	336	98.68
30	5	5	25368	145	99.43
30	10	0.5	25342	423	98.33
30	10	25	25379	542	97.86
30	10	5	25381	453	98.22

*For LSD analysis the %SSC reduction data corrected to two decimal place was used. In Table A9 of Appendix A the %SSC reduction data was rounded off to whole numbers.

APPENDIX D

FIRST ORDER ECONOMIC ANALYSIS FOR THE COST OF PAM

D1. First Order Economic Analysis for the Cost of PAM

If the average annual rainfall is 33 inches over a plot area of 50×10 ft, the volume of water accumulated in one year would be:

$$33 inches \times \left(\frac{1}{12}\right) ft \times 50 ft \times 10 ft = 1375 ft^3$$

The plot area was assumed to have a silty clay loam soil with a uniform sediment concentration of 25000 ppm. Results from Section 5.5 showed that the operating range of PAM concentration for a 25000 ppm sediment solution is between 0.05 and 5 ppm per liter of sediment. To have a maximum estimate of PAM concentration, 5 ppm was considered in this calculation.

If PAM and the sediment solution in the drainage area was ideally mixed, the amount of PAM required to treat 1375 ft^3 of 25000 ppm sediment solution is given as:

$$1375 ft^3 \times 28.316 \left(\frac{liter}{ft^3}\right) \times 5 \left(\frac{ppmPAM}{litre}\right) = 194.7 \times 10^3 \, ppmPAM$$

Consequently, the required PAM concentration is approximately 195 grams/ liter.

The cost of PAM supplied by Cytec industries Inc., Carmel, IN 46032 on April 27, 2006 is \$2.50/lb. Thus, the cost of PAM required to treat 1375 ft^3 of 25000 ppm silty clay loam sediment solution is:

$$2.5 \left(\frac{\$}{lb}\right) \times \frac{1}{453.59} \left(\frac{lb}{grams}\right) \times 195 grams = \$1.07$$

As indicated in Figure 25 the drainage was installed with a silt fence length of 10 ft. Therefore, application of PAM costs \$0.11 per foot of silt fence.

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