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Development of Best Management Practices for Turbidity Control During Rainfall Events at Highway Construction Sites using Polyacrylamide

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16. Abstract
The motivation for this project stemmed from AHTD's need to develop a treatment process for turbid water collected onsite in sedimentation basins at highway construction sites. These waters may have high turbidity that does not decrease appreciably with time, due to high particle stability and slow particle settling times. Through a series of lab- and field-scale experiments, the Project Team determined that PAM infused floc logs – acquired from Applied Polymer Systems (APS), Inc. – can be used in onsite sedimentation basins to reduce the turbidity of runoff waters by 95-99%. However, inline treatment (i.e., turbid water flowing over floc logs) was found to be ineffective, likely due to a lack of sufficient mixing between particles and the PAM. The selection of the particular type of floc log can be made based on results from standardized jar tests with soil samples from the active field sites. However, if jar tests are impractical in a given situation, multiple floc log types (i.e., APS 703d, 703#d, and 706) can be used in a single basin. An individual floc log ($70-$80 USD in 2016) is capable of treating at least 16,000 L (565 ft^3) of turbid water under the following conditions, which include (1) Floc log must be pre-soaked in water for 15 minutes prior to use in the sedimentation basin, (2) the floc log is submerged into the sedimentation basin containing the turbid water and rapidly mixed using a submersible pump of at least 15 minutes; one pump should be used for every 2,000 L (71 ft^3) of turbid water to generate adequate contact between the floc log and the particles causing the turbidity; mixing times should be increased proportionally for large water volumes, (3) following the rapid mixing period, the floc log is removed and turbid water is allowed to settle for at least 5 minutes without any mixing, (4) following the settling period, the low turbidity basin water can be released (or pumped) offsite into streams, ponds, or drainage ditches. The floc logs can be reused following cleaning to remove caked-on particles. This cleaning can be as simple as scraping and/or rinsing the floc logs and need not remove all particles. No limit to floc log reuse was found in this study.

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Turbidity, Polyacrylamide, Stormwater, Sedimentation Basin

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RESEARCH

Development of Best Management Practices for Turbidity Control During Rainfall Events at Highway Construction Sites using Polyacrylamide

PROJECT BACKGROUND AND OBJECTIVES

Highway construction sites are susceptible to erosion during rainfall events due to exposed soils that can be mobilized and transported into surrounding surface waters. In 2009, the USEPA regulated the turbidity of runoff waters leaving construction sites at 280 Nephelometric Turbidity Units (NTU) and violations of this water quality standard may result in fines of up to $37,500 per day (EPA, 2009). While as of March 6, 2014, the EPA withdrew the numeric turbidity limit and associated monitoring requirements found in 40 CFR 450.22(a) and 450.22(b), they may reinstate the 280 NTU turbidity limit in the coming years (EPA, 2014).
Without the implementation of turbidity control measures, stormwater discharged from AHTD construction sites can exceed 15,000 NTU. As such, there is a need to develop strategies to reduce the turbidity of these runoff waters.

Final Report – AHTD TRC 1403

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Abstract

The motivation for this project stemmed from AHTD's need to develop a treatment process for turbid water collected onsite at highway construction sites. These waters may have high turbidity that does not decrease appreciably with time, due to high particle stability and slow particle settling times. Through a series of lab- and field-scale experiments, the Project Team determined that PAM infused floc logs – acquired from Applied Polymer Systems (APS), Inc. – can be used in onsite sedimentation basins to reduce the turbidity of runoff waters by 95-99%. However, inline treatment (i.e., turbid water flowing over floc logs) was found to be ineffective, likely due to a lack of sufficient mixing between particles and the PAM. The selection of the particular type of floc log can be made based on results from standardized jar tests with soil samples from the active field sites. However, if jar tests are impractical in a given situation, multiple floc log types (i.e., APS 703d, 703#d, and 706) can be used in a single basin. An individual floc log ($70-$80 USD in 2016) is capable of treating at least 16,000 L (565 ft^3) of turbid water under the following conditions, which include (1) Floc log must be pre-soaked in water for 15 minutes prior to use in the sedimentation basin, (2) the floc log is submerged into the sedimentation basin containing the turbid water and rapidly mixed using a submersible pump of at least 15 minutes; one pump should be used for every 2,000 L (71 ft^3) of turbid water to generate adequate contact between the floc log and the particles causing the turbidity; mixing times should be increased proportionally for large water volumes, (3) following the rapid mixing period, the floc log is removed and turbid water is allowed to settle for at least 5 minutes without any mixing, (4) following the settling period, the low turbidity basin water can be released (or pumped) offsite into streams, ponds, or drainage ditches. The floc logs can be reused following

cleaning to remove caked-on particles. This cleaning can be as simple as scraping and/or rinsing the floc logs and need not remove all particles. No limit to floc log reuse was found in this study.

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1 Introduction

1.1 Motivation and Background

Highway construction sites are susceptible to erosion during rainfall events due to exposed soils that can be mobilized and transported into surrounding surface waters. In 2009, the USEPA regulated the turbidity of runoff waters leaving construction sites at 280 Nephelometric Turbidity Units (NTU) and violations of this water quality standard may result in fines of up to $37,500 per day (EPA, 2009). While as of March 6, 2014, the EPA withdrew the numeric turbidity limit and associated monitoring requirements found in 40 CFR 450.22(a) and 450.22(b), they may reinstate the 280 NTU turbidity limit in the coming years (EPA, 2014). Without the implementation of turbidity control measures, stormwater discharged from AHTD construction sites can exceed 15,000 NTU. As such, there is a need to develop strategies to reduce the turbidity of these runoff waters.

There are many erosion control measures that are used on highway construction sites, including rock check dams, straw wattles, mulching, silt fences, and retention basins (McLaughlin, 2010). However, the focus of this research was on assessing the efficacy of polyacrylamide (PAM) coagulants on turbidity reduction from stormwater runoff waters. Specifically, the Project Team focused on quantifying the impact of PAM type and dose and the importance of mixing conditions.

PAM is a compound formed by the polymerization of acrylamide and other connected monomers, which may contain additional functionalization (Barvenik, 1994). PAM is commercially available in three forms: dry, liquid emulsion, or entrained in a block or log. Dry PAM is available in a granular powder, which is then mixed with water to form a stock solution. Liquid PAM has already been mixed with water a predetermined concentration. Inverse emulsion PAMs are aqueous drops that include the polymer, which when mixed with water, release the PAM creating a more dilute solution (Barvenik, 1994). Flog Logs™ are semi-hydrated PAM designed for passive treatment of turbid water. As water flows over the Floc Logs, PAM is released which destabilizes the suspended particles, allowing them to form flocs that subsequently gravity settle from solution.

In terms of surface charge, PAM is cationic (positively charged), non-ionic (no charge), or anionic (negatively charged). The anionic and cationic PAM types have an associated charge density, which is the proportion of charged co-monomer expressed as a molar percentage. The use of PAM on construction sites has been limited to anionic PAMs due to their low toxicity to aquatic organisms, in contrast to cationic PAMs (Aly and Letey, 1988; Helalia and Letey, 1988; Seybold, 1994). The charge density is expressed as a mole ratio or weight percent of repeating monomer units. PAM acquires a charge when the amine ($-NH_2$) functional groups on the acrylamide are substituted with charged units, usually in the form of a salt or strong base. The charge density of PAM is classified as low (<10%), moderate (10-30%), or high (>30%), in accordance with the degree of amine substitution.

PAM is also classified by its molecular weight, which is associated with the polymer chain length (Green et al., 2000). It has been speculated that higher molecular weight PAMs flocculate particles more so than those with lower molecular weights, due to the longer polymer chains. However, PAM can experience conformal changes, such as polymer coiling, particularly at higher doses, which may offset benefits gained by longer chain lengths (Orts et al., 2002). The molecular weight of PAM is classified as low (<0.1 Mg mol^{-1}), medium (0.1-1 Mg mol^{-1}), high (1-5 Mg mol^{-1}), or very high (>5 Mg mol^{-1}).

Turbidity is a measure of the amount of light that is scattered by suspended (i.e., stabilized) particles in water. In 2009, the Environmental Protection Agency (EPA) proposed to regulate turbidity of runoff waters leaving construction sites at 280 Nephelometric Turbidity Units (NTU). Violations of this proposed water quality standard may result in monetary fines of the contractors and State agencies overseeing the construction.

Highway construction sites can be a source of turbid water during rainfall events due to their exposed soils, which can be mobilized and transported offsite and into surrounding receiving waters. There are many erosion control measures that are used on highway construction sites, including rock check dams, straw wattles, mulching, silt fences, and retention basins (McLaughlin and McCaleb, 2010). However, the use of best management practices (BMPs), such as silt fences and rock checks, can fail, leading to runoff water that can exceed 15,000 NTU from AHTD construction sites (ADEQ, 2010). As such, there is a need to develop improved BMPs to reduce the turbidity of these runoff waters.

There are three strategies commonly employed to manage turbid water generated on highway construction sites: turbidity prevention, inline treatment, and basin treatment. Prevention involves covering the exposed soil, typically by either seeding grass or other soft armoring methods. However, these techniques are typically applied after construction has been completed, and therefore treatment of turbid water is often required during the construction phase, which could last several months or years. Inline treatment involves reducing the turbidity of runoff water during a rain event without storage, prior to discharging offsite; this approach includes silt fences, fiber check dams, vegetative buffers, and Floc Logs. Basin treatment involves collecting and storing turbid water from a rain event in onsite basins and treating with a coagulant of PAM-based technology it before discharging offsite.

To prevent turbid water generation during construction, the preferred option is ground cover or soil stabilization. Shoemaker et al. (2012) showed that applying PAM directly to the bare soil surface reduced particle mobilization compared to using no PAM. Babcock and McLaughlin (2013) showed that applying PAM with straw ground cover reduced turbidity, but the form of application – wet or dry – may influence turbidity reduction during heavy rainfall events. Importantly, however, for a large construction site, it might not be feasible (or cost effective) to cover all exposed soil with PAM. Thus, BMPs for onsite turbid water treatment are needed.

Inline treatment materials for turbidity control include fiber check dams, fabric covered rock dam checks, jute matting, and Floc Logs. The use of fiber check dams or rock check dams covered with an erosion control blanket treated with granular PAM has been shown to be effective for turbidity control through multiple storm events (McLaughlin et al., 2009; Kang et al., 2013). Jute matting treated with granular PAM allows floc particles to adhere to the matting rather than relying on the flocs to settle out solution (Kang et al., 2014). Similarly, placement of an adequate number of Floc Logs within turbulent drainage streams potentially allows flocs to form and settle, although this application has not been tested on highway construction sites. All of these methods are considered to be passive treatment options because they do not require any mixing or pumping, but, as a result, are difficult to control due to imprecise dosing of PAM and insufficient or inconsistent mixing.

In basin treatment, PAM can be added as a liquid or in block form (i.e., as a Floc Log) and mixed with turbid water. However, the liquid PAM application requires careful dosing and pumping, which may be impractical (i.e., labor intensive) for onsite sedimentation basins. The use of Floc Logs may, on the other hand, only require rapid mixing for a predetermined amount of time to disperse the PAM throughout the basin, allowing flocs to form. The Floc Logs can potentially be reused, either in a given basin or in multiple basins at the construction site. For large amounts of rainfall, it may be difficult to store all of the runoff in sedimentation basins for long periods of time; therefore rapid treatment of turbid water is essential.

1.2 Objectives and Approach

The objective of this research is to develop PAM-based BMPs for turbidity control in runoff waters from highway construction sites. First, PAM properties were determined that facilitate turbidity reduction in stormwater runoff. Jar tests were done on 12 PAM types, which were selected to span a range of charge type and densities (0-50% for anionic PAMs and 20-100% for cationic PAMs) and molecular weights (0.1-28 Mg mol^{-1}). These results informed the experimental design of lab-scale hydraulic flocculation tests, in which two PAM types were assessed to determine the optimal PAM dose for subsequent field-testing and assess the impact channel baffling (i.e., hydraulic flocculation) on effluent turbidity. To facilitate implementation of the PAM-based BMPs, five commercially available Floc Log types were assessed in a series of laboratory- and field-scale experiments. Laboratory-scale jar tests were completed with six different types of clay to assess the impact of Floc Log type and soil type on turbidity reduction. Inline- and basin-scale sedimentation tests were completed at a test channel adjacent to the Cato Springs Research Center (CRSC, Fayetteville, AR) and during two rainfall events at AHTD construction sites on the Bella Vista Bypass.

2 Materials and Methods

2.1 Polyacrylamide Types and Preparation

Twelve commercially available types of PAM were selected for testing (Table 2-1), spanning ranges of molecular weight (0.1-28 Mg/mol) and charge density (0-100% molar charge). Five anionic PAM types were the focus of the research, although six cationic PAM types were also evaluated in the laboratory-scale jar tests, despite their known toxicity to aquatic life (Weston et al., 2009).

Table 2-1: Properties of the selected polyacrylamide (PAM) types

PAM Name	Charge Type	Charge Density (mol %)	Molecular Weight (Mg/mol)
APS #705	Unknown	Unknown	Unknown
Superfloc N300	Anionic	0	15
Superfloc A100	Anionic	7	7
Superfloc A100-HMW	Anionic	7	10-12
Superfloc A150	Anionic	50	15
Superfloc A150-HMW	Anionic	30	28
Superfloc C587	Cationic	100	0.1
Superfloc C591	Cationic	100	0.25
Superfloc C1594	Cationic	20	5-8
Superfloc C1596	Cationic	40	5-8
Superfloc C1598	Cationic	60	5-8
Superfloc 4516	Cationic	40	9-12

In addition, APS #705 (Table 2-1), was used in the Jar Testing only, and was a commercial blend of various different PAM types and had an unknown molecular weight and charge density (McLaughlin and Brown, 2006). The evaluation of anionic and cationic PAM types permitted inferences regarding the impact of surface charge on turbidity reduction. It was anticipated that the cationic PAM types would outperform the anionic types due to lower electrostatic repulsive forces with the negatively charged particles in the turbid waters.

Three methods were used to make the PAM stock solutions based on differences in surface charge (i.e., anionic vs. cationic) and the form in which it was received. The anionic

PAM types were received as crystalized powders and 0.1 g L^{-1} stock solutions were prepared in Milli-Q water by mixing at 200 rpm for approximately 30 minutes to ensure a stable PAM suspension. The cationic PAM types were received as either liquid-based polymers or oil-emulsion blends. For the liquid-based polymers, 0.1% stock solutions (v/v) were prepared in Milli-Q water by mixing at 200 rpm for 30 minutes. The oil-emulsion blends were repeatedly inverted in a bottle for a few minutes before adding 0.5 mL of this mixture to 99.5 mL of Milli-Q water (0.5% stock solution, v/v) and rapidly mixing the resultant solution for 3 minutes. Following 30 minutes of quiescent settling, this solution was diluted to 0.05% (v/v) in Milli-Q water.

2.2 Turbid Water Sources

Runoff water and soil samples from field sites were collected for use in the jar testing (Phase I). Runoff water was collected at an AHTD construction site located in Fayetteville, AR at the intersection of Crossover Road and Albright Road. The site had a detention pond to collect runoff water prior to being discharged to surrounding streams and the stormwater collection system. The water samples were collected using a bucket attached to a metal rod. The bucket was dipped midway into the pond and the collected water was transferred into 9-liter carboys for transporting back to the PI's lab at the UA and stored in a cold room at 4ºC until use.

The low volumes of runoff water available throughout Fall 2013 prompted other methods to be developed for the generation of turbid water. Soil collected from two AHTD construction sites in Fayetteville, AR was used to make a synthetic blend of runoff water. One site was at the location the runoff water was collected and the other site was at the intersection of Garland Avenue and Bel Air Drive. The collected soil was mixed with tap water at a concentration of 2 g L^{-1} by rapidly mixing at 200 rpm on a jar testing apparatus for 30 minutes. Soil samples were also mixed with raw water collected from the intake of the Beaver Water District drinking water treatment plant (Lowell, AR) to assess the effect of water type on turbidity.

Various soil types were also used to make synthetic runoff water to evaluate the effect of particle size on turbidity reduction following flocculation with PAM. All soil types were mixed with tap water with a targeted turbidity of at least 1,000 NTU. The soil collected at the two AHTD construction sites were classified as Arkansas Red Dirt. Three other soils – bentonite, kaolinite, and illite – were collected and used to make different blends of synthetic water. Bentonite was selected due to its expansive clay properties and large surface area. Bentonite was crushed and allowed to hydrate and dissolve into tap water at a concentration of 4 g L^{-1} prior to being rapidly mixed. Kaolinite, another clay soil, was mixed in tap water at a concentration of 2 g L^{-1}. The kaolinite remained suspended in the water more so than the bentonite (based on a visual assessment), likely due to its smaller particle size. Illite, an non-expansive clay, was mixed in tap water at a concentration of 4 g L^{-1}.

2.3 Jar Testing

2.3.1 Liquid PAMs

Jar tests were conducted on the natural and synthetic runoff waters and assessed for turbidity using a Hach 2100N Turbidimeter. For each test, 500 mL of sample water was measured into a 1-L rectangular jar and rapidly mixed for 5 minutes to produce a homogenous mixture prior to measuring the initial turbidity. Next, PAM was dosed to each jar between 0.1-80 mg L^{-1} by pipetting the PAM stock solution into the vortex of the rapidly mixing the sample. This was followed by periods of rapid mix (i.e., 5 minutes at 200 rpm), slow mix (i.e., 30 minutes at 60 rpm), and quiescent settling (i.e., 30 minutes), similar to others (Tobiason et al., 2000). The experimental matrix consisted of 12 PAM types (Table 2.1), five soil types, up to 10

PAM doses, and varying mixing conditions as described next. The turbidity of the supernatant was measured after the settling period to determine the effect of PAM type and dose and mixing conditions.

To more closely mimic field conditions, mixing and settling times were reduced in a second round of jar tests. Here, the rapid mix step was reduced to just 15 seconds and the slow mix and settling periods were shortened to 5 minutes. Additional tests were also run with no rapid mix step and slow mixing times of 1-, 3-, and 5 minutes followed by a 5 minute settling period.

2.3.2 PAM-based Floc Logs

Applied Polymer Systems (APS), Inc. provided a test kit containing samples of their APS 700 Series Floc Logs®. The test kit contained two cylindrical samples each of five commercially available types of anionic PAM-based Floc Logs: 703d, 703d#3, 706b, 707a, and 708x. The chemical composition of these Floc Logs is propriety information that is not released by APS. Each Floc Log sample was approximately 32 mm in diameter and 18-22 mm in length, and ranged in mass from 12.3-18.2 grams.

The soil used for the first round of jar tests was collected from a mound of soil at CSRC, which was excavated to construct the turbidity test channel. Prior to use in the jar tests, the soil was sieved through a #10 US Standard sieve to remove large particles and rocks that would rapidly settle out of solution.

Previous research showed that jar tests with tap water and Beaver Lake water were indistinguishable (Johnson, 2015), and thus tap water was used for convenience. For each jar test, 500 mL of tap water was measured into a 1-L rectangular jar. One gram of the sieved soil was added to the jar (2 g L^{-1}) and mixed at 200 rpm for 5 minutes to produce a homogenous mixture, after which the initial turbidity was measured. Turbidity measurements were taken during the rapid mix phase to ensure the mixture was homogenous and prevent the soil from settling. Due to the sponge-like consistency of some of the Floc Logs, small pieces that ranged in mass from a few milligrams to ~100 mg were separated by hand for use in the jar tests. The Floc Log pieces were added to the turbid water mixture at doses of 100-, 200-, and 300 mg, rapidly mixed (200 rpm) for 15 seconds, slow mixed (60 rpm) for 5 minutes, and settled for 5 minutes, prior to measurement of the final turbidity. Here, samples were taken from the spigot 30 mm from the bottom of the rectangular jars, with caution used to prevent disturbance of the underlying settled floc.

A second set of jar tests was completed with more uniformly sized pieces of each Floc Log. The same masses of 100-, 200-, 300-, and 400 mg were measured out and broken down by hand into pieces up to a maximum mass of ~15 mg. Following measurement of the initial turbidity as described previously, the pieces were added to the turbid water mixture, mixed, and settled prior to measurement of the final turbidity.

Based on the turbidity results from the jar tests, full-sized Floc Logs of type 703d and 703d#3 were acquired for field-testing. These Floc Logs were shaped like a trapezoidal prism and had a dry weight between 4.1-4.5 kg with dimensions of 30 cm (top length), 31 cm (bottom length), 16 cm (top width), 18 cm (bottom width), and a height of 7.5 mm.

Following an initial round a field testing, a third and final set of jar tests was completed with six source clays purchased from The Clay Minerals Society (Chantilly, VA): KGa-1b, PFI-1, SHCa-1, STx-1b, SWy-2, and SYn-1. Laboratory-scale jar tests were completed with each clay type and each of the five aforementioned APS Floc Log samples. The same jar testing procedure was followed as previously described. However, to achieve adequate initial turbidity, some of the clays were added at a concentration greater than 2 g L^{-1}. For example, the PFl-1 clay type at 2 g L^{-1} had an initial turbidity of 350 NTU. Therefore, the concentration for all clay types was increased to reach a minimum initial target turbidity of 1,500 NTU. The mass loadings for KGa-1b, PFI-1, SHCa-1, STx-1b, SWy-2, and SYn-1 were 2-, 10-, 8-, 8-, 4-, and 10 g L^{-1}, respectively. Next, 200 mg of Floc Log pieces were added to the turbid water mixture, rapidly mixed (200 rpm) for 15 seconds, slow mixed (60 rpm) for 5 minutes, and settled for 5 minutes, prior to measurement of the final turbidity of the supernatant.

2.4 Statistical Analyses

In the laboratory jar tests, a portion of the turbidity data were collected in triplicate ($n_i = 3$) and analyzed using Tukey's paired comparison with control method, following the approach described by Berthouex and Brown (2002). For each of *k* treatments and the controls (i.e., jars with no added Floc Log), the sample mean ($\overline{y_i}$) and variance (s^2) was calculated and used to determine the pooled variance using Equation 1:

$$s_{pool}^2 = \frac{(n_1-1)s_1^2+\cdots+(n_k-1)s_k^2}{n_1+\cdots+n_k-k} \text{ (Equation 1)}$$

Next, the confidence interval for the difference in two means was calculated, taking into account all possible comparisons of *k* treatments and control using Equation 2:

$$\overline{y_i} - \overline{y_j} \pm \frac{q_{k-1,v,\alpha/2}s_{pool}}{\sqrt{2}}\sqrt{\frac{1}{n_i}+\frac{1}{n_j}} \text{ (Equation 2)}$$

In Equation 2, $q_{k-1,v,\alpha/2}$ is the upper significance level of the studentized range for *k* means and *v* degrees of freedom in the estimate of the pool variance. Tabulated critical values (Harter, 1960) of $q_{k-1,v,\alpha/2}$ were used to calculate the two-sided 95% confidence interval. Differences in the treatment means were significant if they were larger than the confidence interval. A sample calculation for the confidence interval follows based on the data in Table 3-1.

From Equation 1 and values from Table 2-2,

$$s_{pool}^2 = \frac{(2-1)0.001452+(3-1)0.020849+(3-1)022728+(3-1)0.000793+(3-1)0.017877+(3-1)0.016351}{(2+3+3+3+3+3)-6} =$$

0.014422

Table 2-2: Sample data for calculation of the 95% confidence interval using the Tukey's paired comparison method

Floc Log type:	Control	703d	703d#3	706b	707a	708x
% Reduction in Turbidity	22%	47%	54%	57%	20%	24%
	27%	64%	80%	56%	33%	30%
		76%	80%	61%	47%	49%
Mean, $\bar{y}_i$	25%	62%	71%	58%	33%	34%
Variance, s_i^2	0.001452	0.020849	0.022728	0.000793	0.017877	0.016351
Measurements, n	2	3	3	3	3	3
Treatments, k	6					

The square root of the s_{pool}^2 is $s_{pool} = 0.12$ and v is the number of degrees of freedom, which is 17 for this example; with ν = 17, (k – 1) = 5, the number of treatments excluding the control, q is 2.922 (interpolated from Table 20.4 of Berthouex and Brown (2002)). Then, using Equation 2,

$$\bar{y}_i - \bar{y}_j \pm \frac{2.922}{\sqrt{2}} * 0.12\sqrt{\frac{1}{3} + \frac{1}{3}}$$

$$\bar{y}_i - \bar{y}_j \pm 20\%$$

Therefore, differences in the treatment means outside 20% were significant at the 95% confidence interval.

2.5 Particle Size Distribution Measurements

The particle size distributions of the six aforementioned source clays were measured with a Beckman Coulter Multisizer 4 Coulter Counter equipped with a 20-µm aperture. The operational range of this instrument is generally considered to be 2-60% of the aperture size, meaning particles between ~0.4-8 µm were counted. First, each of the clays were added to 200 mL of Millipore water and rapidly mixed for five minutes to create a homogeneous mixture. The mass loadings for KGa-1b, PFI-1, SHCa-1, STx-1b, SWy-2, and SYn-1 were 0.25-, 1.25-, 0.75-, 0.75-, 0.5-, and 1.25 g L^{-1}, respectively. From each mixture, 50 μL was transferred to 20 mL of electrolyte and measured with the Coulter Counter using an analytical volume of 100 μL. Each measurement was completed in triplicate.

2.6 Laboratory-scale Flocculation Tests

Phase II testing consisted for lab-scale flocculation tests, which utilized two 65 L rectangular flow-through reactors. The reactors were 75 cm long × 29 cm wide × 25 cm high, with an inlet port and outlet weir (see Figure 2-1). One reactor was equipped with 5 baffles, designed to enhance mixing and promote hydraulic flocculation and turbidity reduction. The other reactor had no baffles and acted as a control. To generate turbid water, kaolinite was used as preliminary testing showed higher initial turbidity in stock solutions compared to the soils collected from the AHTD field sites. The kaolinite was mixed with tap water at a concentration of 2 g L^{-1} in a 55-gallon bucket under constant mixing (see Figure 2-1). This particle concentration was selected to achieve an initial turbidity between 1,000-2,000 NTU.

The kaolinite-tap water mixture was pumped into each reactor using a peristaltic pump at a flow rate of 100 mL min^{-1}. The pumps were operated overnight to fill the 65-L reactors and, once full, continued at the same flow rate throughout the duration of the experiment. Samples for turbidity measurements were collected from the outlet weir and measured using the Hach 2100N Turbidimeter.

Figure 2-1: Photographs of the Phase II lab-scale hydraulic flocculation setup. (A) a 200 L bucket filled with tap water amended with 2 g L^{-1} kaolinite mixed at constant speed with a paddle controlled by a drill, (B) two 65 L flow through reactors (baffled reactor in the foreground), two peristaltic pumps (in the background) to supply the turbid water to the reactors, and a 9 L carboy containing PAM stock solution supplied to the reactors with a piston pump (to the right of the reactors), and (C) effluent of the two 65 L reactors.

Two PAM types were selected for Phase II testing, based on performance results from the Phase I jar tests. The PAMs selected were Superfloc N-300 and Superfloc A-100 (Table 2-1). These PAM types were dosed continuously throughout the seven-hour Phase II experiments at 1-, 5-, 10-, and 20 mg L^{-1} using a positive displacement piston pump at a flowrate of 10 mL min^{-1}. Turbidity measurements were taken every hour throughout the duration of the tests to assess the effects of PAM type, PAM dose, and reactor type (baffled or not baffled).

2.7 Channel Tests at the Cato Springs Research Center

The first round of field tests were conducted at the Cato Springs Research Center on a controlled field site adjacent to the building. A trench was excavated (12.2 m long, 1.2 m wide, and 1.2 m deep) with a backhoe and lined with a black plastic pond liner to help control natural erosion of the channel (see Figure 2-2). Experiments at these sites were designed to emulate lab-scale hydraulic flocculation tests and assess implementation techniques for PAM addition prior to testing on an AHTD construction site.

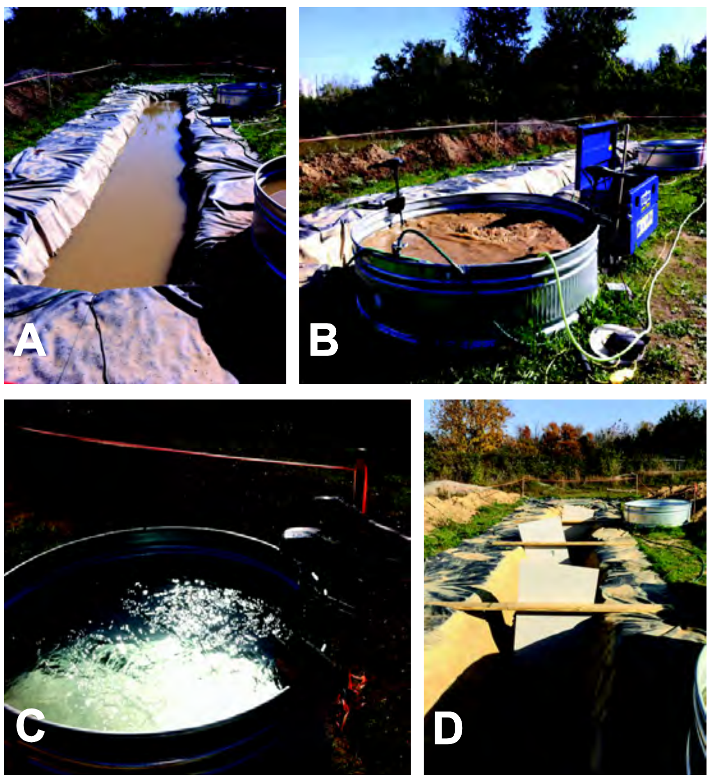

Figure 2-2: Photographs of the Phase III field site tests at the Cato Springs Research Center. (A) The excavated channel with a pond lined filled with turbid water (B) a 700 gallon stock tank with two trolling motors attached mixing tap water and 2 g L^{-1} of Arkansas Red Dirt; a submersible pump (not shown) supplied this mixture to the channel, (C) PAM stock solution made in tap water in a 400 gallon stock tank and mixed with two trolling motors, supplied to the channel at a PAM dose of 10 mg L^{-1} with a pond pump (not shown), and (D) baffle wall installation inside of the drained channel. Baffle walls were placed every ten feet from the influent to the effluent.

Turbid water for the Phase III experiments was generated on site. A 2,650 L (94 ft^3) stock tank was placed adjacent to the channel and filled with tap water. Soil that was excavated to create the trench was mixed into the tap water using two trolling motors, positioned to prevent soil settling in the stock tank. This soil-tap water mixture was pumped into the trench at 20 L min^{-1} using a heavy-duty submersible pump. Once the trench was full, the effluent was pumped into adjacent wetlands at 20 L min^{-1}.

2.7.1 Liquid PAMs

The PAMs used in these tests were the same selected for use in the lab-scale testing, Superfloc N-300 and Superfloc A-100 (Table 2-1). Each PAM was batched in a 1,500 L (53 ft^3) stock tank placed adjacent to the channel using tap water and mixed with trolling motors. The PAM stock solutions were prepared a concentration of 10 mg L^{-1}. To start a test, the PAM stock solution was pumped into the influent of the channel using a pond pump at a flow rate of 6 L min^{-1}. This continued for six hours with turbidity readings taken every hour at three locations along the trench (influent, mid-channel, and effluent).

A second round of tests at the Cato Springs field site was completed following the installation of baffles into the channel, dividing the trench into four 3-m long sections, which directed the water side-to-side along the length of the channel (see Figure 2-2). This was done to assess the impact of channel baffling on turbidity reduction at the field-scale.

The next round of experiments at the Cato Springs field site include the use of pre-manufactured PAM blocks, similar to those used by others (Tobiason et al., 2000). The use of PAM blocks could replace the need for pumping, and hence ease the implementation of the turbidity reduction strategies. The PAM blocks are available from SiltStop and are a composite form of mixed anionic polymer designed to release a dose of approximately 10 mg L^{-1}. The PAM blocks will be placed at the influent of the channel and upcoming tests will be completed to assess appropriate number of PAM blocks based on channel dimensions and approximate their replacement frequency to achieve adequate turbidity control.

2.7.2 PAM-based Floc Logs

Field tests were conducted at the CSRC using the turbidity test channel adjacent to the building. Here, an inline treatment experiment was conducted by pumping turbid water at a flowrate of 20 L min^{-1} into the channel using a heavy duty submersible pump and passing that water over Floc Logs suspended in the channel. The dimensions of the test channel were: 12.2 m long, 1.2 m wide, and 1.2 m deep. The channel was filled with turbid water to a height of 0.76 m; the calculated horizontal water velocity was 0.0219 m min^{-1} (0.019 cfs). Samples were taken at three locations: the front of the channel, middle of the channel, and end of the channel.

Figure 2-3: Photograph of four 703d type Floc Logs suspended in the turbidity test channel.

One control (no Floc Log) and two tests (with Floc Logs) were completed: the first test used one 703d Floc Log and second test used four 703d Floc Logs (Figure 2-3); the Floc Logs were placed between the sampling locations at the front and middle of the channel.

2.8 Sedimentation Basin Tests at the Cato Springs Research Center

Basin-scale jar test experiments were designed to be a large-scale version of lab-scale jar tests, and were performed using a circular 2,650 L (94 ft^3) stock tank (Figure 2-4). This application was intended to mimic treatment of turbid water collected in an onsite sedimentation basin.

Figure 2-4: Photographs of the basin-scale jar tests. (A) Photo of the Floc Log roped around a stake and suspended in the turbid water tank, (B) Photo of the stock tank filled with turbid water with the two trolling motors attached.

Turbid water was generated at the CSRC using tap water and the soil that was excavated to construct the turbidity test channel. To generate the turbid water, a 19 L bucket was filled with soil and transferred to the stock tank; three buckets of soil were transferred to the stock tank for every test. The stock tank used for this test was 240 cm in diameter and was filled with tap water to a height of 45 cm; therefore the tank was filled with approximately 2,000 L (71 ft^3) of tap water for every test.

Two trolling motors were used to mix the tap water and soil. The trolling motors were placed on opposite sides of the circular tank. Three mixing configurations were considered. The first was a circular configuration in which both motors faced the same direction, either clockwise or counter-clockwise. However, this resulted in a zone of low turbidity and mixing (assessed visually) in the center of the tank. In the second configuration, both motors directly faced one another. This created turbulent mixing, but would prove difficult to suspend the Floc Log in the center of the tank. In the third configuration, the motors were pointed at an angle to where one motor was mixing clockwise and the other counter-clockwise; this allowed the most turbulent area to be created on one half of the circular tank where the two flows intersected, rather than the center of the tank, while the other half was less turbulent. This third mixing configuration was chosen for all of the basin-scale jar tests.

For each of these jar tests, the soil and tap water was first rapidly mixed for 10 minutes, during which the trolling motors mixing configurations were constantly cycled to resuspend settled soil. Next, the trolling motors were set to the third mixing configuration, as described previously, for 5 minutes prior to measurement of the initial turbidity. After this mixing period, the initial turbidity was measured by taking a sample from near the top of the water surface. Given the high initial turbidity (> ~4000 NTU), samples were diluted at a 1:1 ratio in tap water prior to measurement.

To perform each basin-scale jar test, one APS Floc Log was center-anchored with a rope secured to a loop, allowing for it to be held in place. The rope was placed around a wooden stake in the ground; the Floc Log was placed in the stock tank and contacted with the turbid water for a selected duration (5-30 minutes). The trolling motors were left on for the duration of the test in an attempt to achieve adequate contact mixing with the Floc Log. Following this period, the mixers were turned off and the turbid water was allowed to settle for one hour. During this period, samples were taken every 5 minutes for a total of 12 samples for each test. Turbidity samples were taken from the supernatant near the top surface of the water. No samples were taken at mid-depth or near the bottom of the water column to prevent disturbing the settling flocs. The turbidity measurements at time zero, or immediately after the trolling motors were turned off, were discontinued because of the rapid settling that occurred within the first few minutes, which resulted in erratic turbidity measurements.

At the start of the one-hour settling period, the Floc Log was removed from the tank, cleaned with a brush to remove as much of the attached soil as possible, and air dried during the one-hour sampling. Following the completion of every test, the water was drained and the remaining soil was removed in preparation of the next test. Because the settled soil presumably contained PAM from the Floc Log, it was removed at the end of each test so as to not affect subsequent tests.

APS type 703d (which is white) and 703d#3 (which is blue) Floc Logs were used in the basin-scale jar tests at various mixing times (5-30 minutes) and with or without a presoaking period in a bucket of tap water. Other researchers (McLaughlin, 2004) have shown Floc Logs were less effective when initially dry. Therefore, a presoaking period was added to hydrate the exterior PAM prior to use. To determine the extent to which the Flog Logs were reusable, a single 703d#3 Floc Log was used in eight consecutive basin-scale jar tests, each 30-minutes in duration; the Floc Log was presoaked in tap water for 15 minutes prior to each test.

Figure 2-5: A single 703d#3 Floc Log placed inside of a cage container used for the eight consecutive basin-scale jar tests.

To offset the stress on the center-anchored rope within the Floc Log for the eight consecutive basin-scale jar test, the single 703d#3 Floc Log was placed inside of a cage container (Figure 2-5). A rope was looped through the cage and secured to the wooden stake in the ground.

Following the series of eight consecutive basin-scale jar tests, the Floc Log volume was measured by a water displacement method in an attempt to determine approximately how much of the Flog Log dissolved during the test. This volume was speculated to correlate to the number of treatment cycles possible for a single Floc Log, which could be used to estimate the volume of water treated. To measure the volume of the Floc Log, an overflow bucket was constructed and filled with tap water (Figure 2-6).

Figure 2-6: Photograph of the equipment used to measure the volume of the Floc Logs, which includes an overflow bucket (on the left), a catch bucket (center frame), and a graduated cylinder (on the right).

Three different Floc Logs were measured: one which was new and unaltered (a dry control), one which was new log but presoaked in tap water for 15 minutes (a wet control), and the one from the series of eight basin-scale jar tests. Each Floc Log was lowered into the overflow bucket allowing for the excess water to drain through the spout into the catch bucket. The volume of water in the catch bucket was measured using a graduated cylinder. Each volumetric measurement was completed in triplicate.

2.9 Field Tests at the Bella Vista Bypass

On June 18, 2015, Tropical Storm Bill brought 5.9 cm of rain to the Bella Vista Bypass construction site, which provided an opportunity to conduct a field test. Weather data was taken from National Weather Service using a station gage at the Bentonville Municipal Airport (KVBT) located 12 km from the field site. An ideal site location includes an active face with exposed soil to generate turbid water and a downstream basin to slow the turbid water and allow flocs to settle out. Because the Bella Vista Bypass was under construction during this study, locations were marked using GPS coordinates. While a number of locations were visited along the construction site by the research team prior to Tropical Storm Bill, a location at Latitude: 36.424475, Longitude: -94.314831 (Figure 2-7) was selected as the site test location because of aforementioned site features and a relatively small and shallow basin.

Figure 2-7: A picture taken from Google Maps®. The yellow-colored star located on the right side of the picture shows the approximate location where sampling took place.

Once the rainfall intensity increased and high turbid water was visually apparent, samples were taken in the absence of Floc Logs to get a baseline turbidity measurement. Samples were collected in 40 mL clear-glass vials and sealed with PTFE-lined screw top lids at two outflow locations downstream of the basin every 5 minutes for 30 minutes, for a total of 12 samples (6 from each outflow location). After the baseline measurements, wooden stakes were hammered into the ground centered within the inflow streams and two new APS 703d type Floc Logs were roped around the stakes, as shown in Figure 2-8.

Figure 2-8: Photograph of the APS 703d type Floc Log roped around a stake. Photo taken by Bryan Signorelli (AHTD) on June 18, 2015.

The Floc Logs were allowed to contact the turbid water for 30 minutes before beginning sampling at the two outflow locations every 5 minutes for 30 minutes.

Following the site testing, the sealed sample vials were taken back to the lab for analysis. Each vial was inverted multiple times to resuspend solids that had settled during transit. The turbidity of each sample was then measured using a Hach 2100N Turbidimeter, as described previously.

A second field test was conducted on November 17, 2015, in which the National Weather Service measured 7.3 cm of rainfall at the Bentonville Municipal Airport (KVBT) located 12 km from the field site. Prior to the field test, a jar test was completed using soil previously acquired from the test site to assess the suitability of the 703d and 703d#3 Floc Logs, with results showing 96% and 98% reduction in turbidity, respectively. The same location as the first field test – Latitude: 36.424475, Longitude: -94.314831 – was selected as the site test location. Samples were taken every 5 minutes for 30 minutes (6 samples) in the absence of Floc Logs at a single outflow location downstream of the basin to get baseline turbidity measurements. Next, wooden stakes were hammered into the ground and six APS 703d#3 type Floc Logs (new and used) were roped around the stakes. The approximate locations of the Floc Logs are shown in Figure 2-9.

Figure 2-9: A picture taken from Google Maps®. The yellow-colored star located on the right side of the picture shows the approximate location where sampling took place. The blue-colored stars show the approximate location of the placement of each 703d#3 Floc Log for the second field test.

The Floc Logs were allowed to contact the turbid water for 30 minutes prior to sampling at the outflow location every 5 minutes for 30 minutes. Following completion of this test, the sample vials were taken back to the lab, inverted multiple times to resuspend the solids, and measured for turbidity.

3 Results and Discussion

3.1 Liquid PAM

3.1.1 Jar Tests

The first round of jar tests was completed with runoff water samples collected from AHTD construction sites. The turbidity without PAM addition was between 500-600 NTU (Figure 3-1). Jar tests were completed with six PAM types under two mixing regimes: (1) high mixing, at PAM doses between 0.1-10 mg L^{-1} (Figure 3-1a) and (2) low mixing, at PAM doses between 0.1-20 mg L^{-1} (Figure 3-1b).

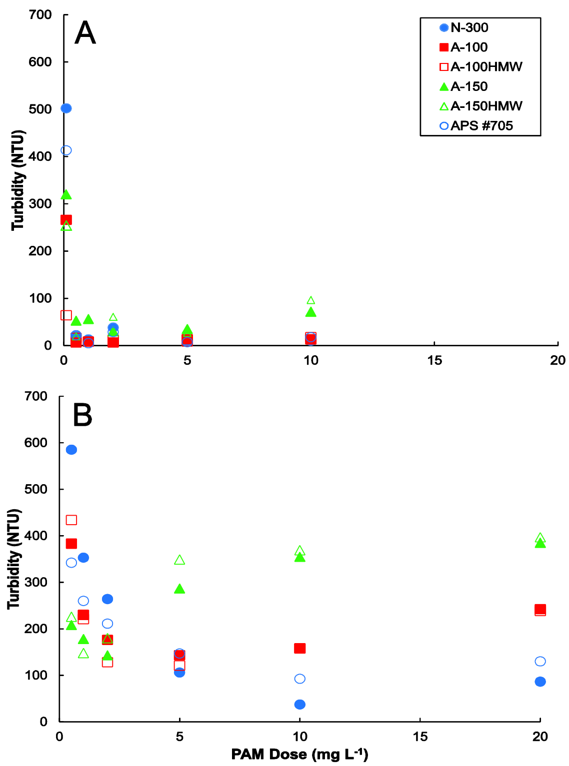

Figure 3-1: Turbidity of the supernatant following the Phase I Jar Tests with anionic PAMs using sample runoff waters collected from Highway 265. Mixing conditions were as follows: (A) high mixing which consisted of 5 min rapid mix at 200 rpm, 30 min slow mix at 60 rpm, and 30 min quiescent settling, (B) low mixing which consisted of 15 sec rapid mix at 200 rpm, 5 min slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.

Based on the findings of others (Sojka and Lentz, 1997), it was expected that PAM types with high molecular weight and low charge density would be the most effective for turbidity reduction. For the high mixing regime, turbidities of the supernatant were below 100 NTU for all PAM doses assessed, but were generally higher for A-150 and A-150HMW compared to the other PAM types. However, the turbidities were too low to facilitate comparisons based on PAM type. In comparison, for the low mixing regime, the turbidities were higher for each PAM type and dose, an expected result that indicates the importance of mixing. Furthermore, turbidities shown in Figure 3-1b for the PAM doses of 10- and 20 mg L^{-1} permitted the following inferences when compared to PAM properties (Table 2-1): (1) turbidities decreased as the PAM charge density decreased, with N-300 producing the lowest turbidity and (2) PAM molecular weight was not an important factor in turbidity reduction, as settled water turbidities of A-100 and A-100HMW were similar as were A-150 and A-150HMW. On balance, the results in Figure 3-1 indicate that settled water turbidities decreased with increased mixing and PAM types with low charge densities.

Next, jar tests were completed on waters generated by blending Arkansas Red Dirt with tap water (Figure 3-2a) and lake water (Figure 3-2b) with PAM doses between 0.5-20 mg L^{-1}. Similar to the results in Figure 3-1, supernatant turbidities decreased with (1) increasing PAM dose (up to ~5 mg L^{-1}) and (2) decreasing PAM charge density (see Table 2-1). No major differences were observed between water types, indicating tap water could be used in future tests, as a matter of convenience. At PAM doses of 10- and 20 mg L^{-1}, turbidities were similar for each PAM type (Figure 3-2), indicating there was no added benefit to increasing the dose beyond 10 mg L^{-1}.

To explain these results, it is helpful to consider the mechanism of PAM interaction with the soil particles. Flocculation of particles occurs when the polymer binds soil particles in suspension. Therefore, higher molecular weight polymers are generally more successful as they contain more binding sites for soil particles (Laird, 1997; Green et al., 2000), a result not apparent in this study.

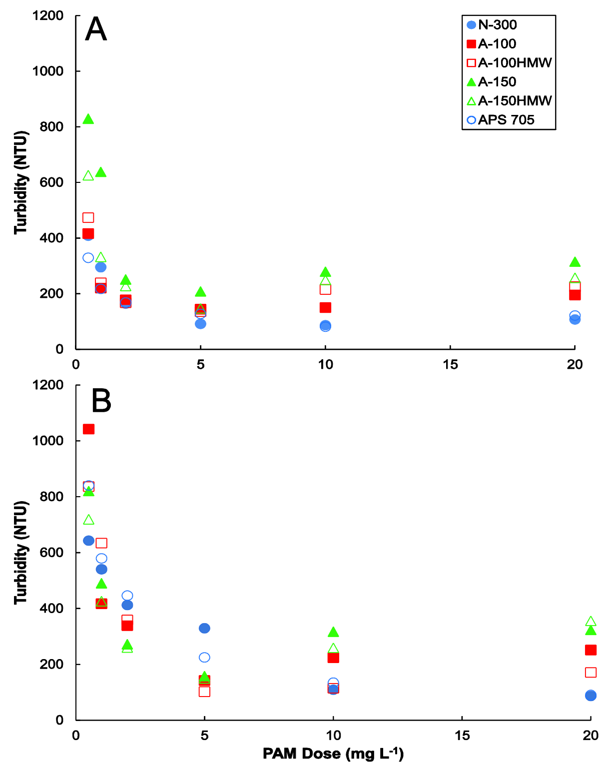

Figure 3-2: Turbidity of the supernatant following the Phase I Jar Tests with anionic PAMs using sample waters generated by blending Arkansas Red Dirt at 2 g L^{-1} with (A) tap water and (B) Beaver Water District intake water. Mixing conditions were as follows: 15 sec rapid mix at 200 rpm, 5 min slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.

Regardless, interparticle bridging is considered to be the predominant mechanism of PAM-soil flocculation. Bridging occurs when PAM is present in the aqueous phase, allowing many soil particles to attach to the polymer chain; however, beyond a certain PAM dose (~10 mg

L^{-1} in this study), interparticle bridging does not increase because of conformational changes in the PAM, such as polymer coiling (Helalia and Letey, 1988; Laird, 1997).

Charge type and density may also affect the binding mechanism. Nonionic, or neutrally-charged PAM, such as N-300 (Table 2-1), tends to coil in aqueous solution rather than form a chain (Theng, 1982; Helalia and Letey, 1988; Laird, 1997). This reduces its ability to bind with soil particles and, hence, entropy is the predominant binding mechanism (Theng, 1982). Polymer adsorption on clay tends to lead to desorption of solvent molecules, which increases the entropy of the solution. Though neutrally charged PAM tends to coil in solution, roughly 60% of nonionic polymer chains will extend in the aqueous phase, which allows for some particle bridging. In contrast, anionic PAMs tend to form chains due to intramolecular electrostatic repulsion. As a result, anionic polymers are generally more effective for the flocculation and stabilization of soil than nonionic or cationic polymers because of this extension (Laird, 1997). However, anionic polymers with charge densities greater than 40%, such as A-150 (Table 2-1), may coil around cations suspended in the soil solution (Malik and Letey, 1991). There are many proposed binding mechanisms to explain the interparticle bridging, largely based on clay content. Some of these include hydrogen bonding (Laird, 1997), anion exchange (Theng, 1982), ligand exchange (Aly and Letey, 1988), hydrophobic bonding, cation bridging, or van der Waals forces. The adsorption of most anionic PAM types to soil surfaces is commonly accredited to cation bridging because the cations present in solution act as a bridge between the anionic groups of the polymer and the negatively charged soil surfaces (Laird, 1997; Sojka and Lentz, 1997; Green et al., 2000; Orts et al., 2002). In terms of toxicity, anionic PAMs have been shown not to exert toxicity to freshwater amphipods to fathead minnows that were exposed to sediment treated with various doses of anionic PAM solutions for 96 hours (Weston et al., 2009).

The importance of the duration of the slow mixing regime for turbidity reduction was evaluated in the jar tests for the two top performing PAMs, N-300 and APS #705, and the poorest performing PAM, A-100HMW (Figure 3-3).

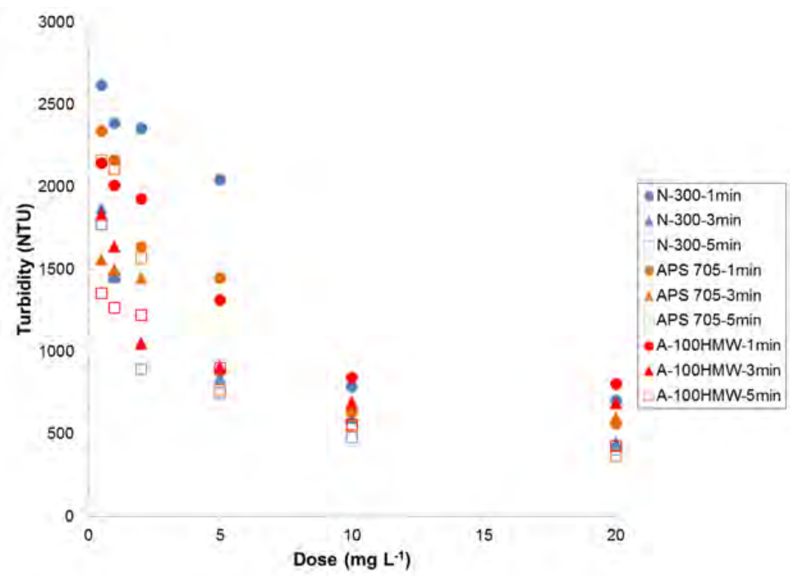

Figure 3-3: Turbidity of supernatant following the Phase I Jar Tests with anionic PAMs using sample waters generated by blending Arkansas Red Dirt with tap water at 2 g L^{-1}. Mixing conditions were as follows: no rapid mix, 1- (blue symbols), 3- (orange symbols), or 5 min (red symbols) slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.

Samples were mixed at 60 rpm for 1-, 3-, or 5 minutes and PAM doses between 0.5-20 mg L^{-1}. As expected, longer periods of slow mixing resulted in lower supernatant turbidities for all three PAM types tested, similar to the findings of other researchers (Lentz and Sojka, 1994). Mechanistically, longer slow mixing times result in the polymer extending further into solution, creating longer chains to bind to more soil particles in suspension. Figure 3-3 also shows minimal impact of PAM type at doses of 10- and 20 mg L^{-1}, in contrast with the results in Figures 3-1 and 3-2. This suggests that longer periods of slow mixing (~30 min) are needed to maximize particle binding with certain PAM types, such as N-300.

Despite toxicity concerns related to aquatic organisms (Sojka and Lentz, 1997), cationic PAMs were evaluated in the jar tests (Figure 3-4) at doses between 0.5-20 mg L^{-1}. Testing was done to determine the role of surface charge on supernatant turbidity.

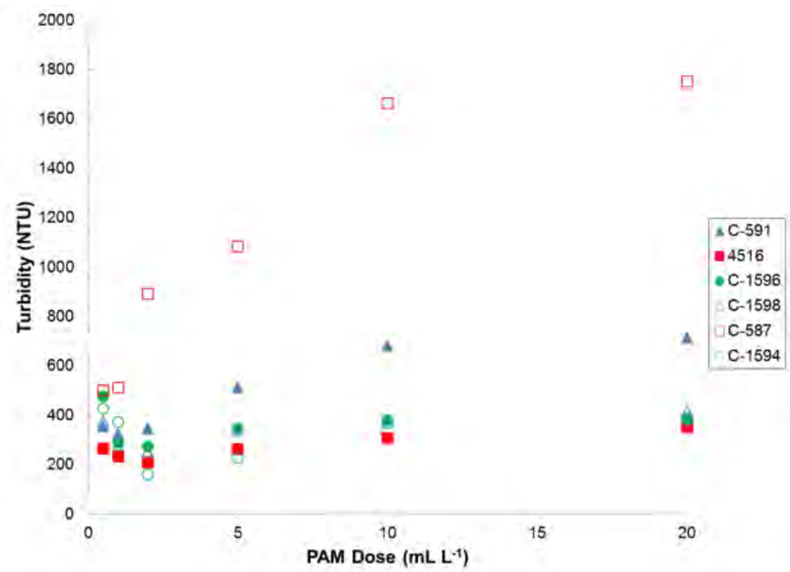

Figure 3-4: Turbidity of the supernatant following the Phase I Jar Tests with cationic PAMs using sample waters generated by blending Arkansas Red Dirt with tap water at 2 g L^{-1}. Mixing conditions were as follows: 15 sec rapid mix at 200 rpm, 5 min slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.

As shown in Figure 3-4, all six cationic PAM types tested were ineffective at decreasing supernatant turbidity across the range of doses evaluated. In general, cationic polymers bond through electrostatic or coulombic interactions (Aly and Letey, 1988), between positively charged ammonium groups on the polymer chain and the negative charged clay particles (Theng, 1982; Helalia and Letey, 1988). Compared to results in Figures 3-1 through 3-3, these results indicate that interparticle bridging, and not electrostatic interactions, was the dominant mechanism of PAM-particle binding.

3.1.2 Laboratory-scale Flocculation Tests

Two anionic PAMs – N-300 and A-100 – were selected for study in the lab scale flocculation tests. N-300 was chosen because it produced the lowest supernatant turbidities in the jar tests (Figures 3-1 and 3-2). A-100 was selected for comparison to N-300 to assess the importance of PAM type, specifically charge density, under the reduced mixing conditions expected in the lab-scale flocculation tests.

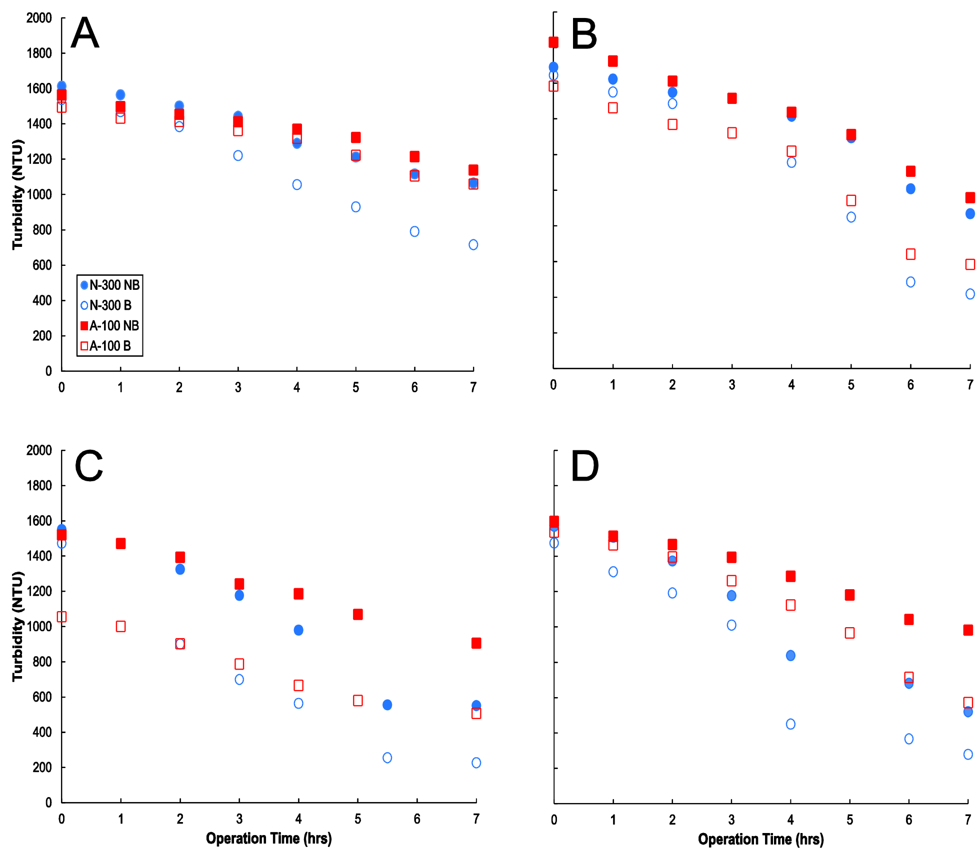

Figure 3-5: Turbidity of effluent waters in the Phase II Lab-scale Flocculation tests using water generated by blending 2 g L^{-1} kaolinite and tap water. The PAM types used were anionic Superfloc N-300 and Superfloc A-100 at doses of (A) 1 mg L^{-1}, (B) 5 mg L^{-1}, (C) 10 mg L^{-1}, and (D) 20 mg L^{-1}. NB denotes no baffling (closed symbols) and B denotes baffling (open symbols).

Kaolinite was used to generate the turbid water because of its relatively high turbidity at low PAM doses in the jar tests (~2,000 NTU, Fig. 3.5A). As shown in Figure 3-5, the time-dependent effluent turbidities were assessed as a function of PAM dose (1-. 5-. 10-, and 20 mg L^{-1}) and reactor baffling. These results indicate that baffling lowered the effluent turbidities (by up to 60%) for each PAM dose evaluated, indicating that the presence of baffles promoted hydraulic flocculation and settling of the kaolinite particles. Similar to the results from the jar tests, effluent turbidities decreased with increasing PAM dose, but there was no added benefit of increasing the PAM dose from 10- to 20 mg L^{-1} (Figure 3-5C and D). In terms of PAM type, effluent turbidities were generally lower with N-300 compared to A-100, indicating the importance of PAM type (specifically, lower charge density) in the lab-scale flocculators.

3.1.3 Field Tests at the Cato Springs Research Center

N-300 and A-100 PAMs were further evaluated in field-scale experiments at the Cato Springs Research Center. These experiments were performed at a PAM dose of 10 mg L^{-1} only, which was chosen based on the results of the lab-scale tests (Figure 3-5). Similarly, these tests were run with and without baffling to assess the impact of hydraulic flocculation at the field-scale on turbidity. All field tests were completed using Arkansas Red Dirt, which had lower initial turbidities compared to the lab-scale studies with kaolinite, ranging between 400-450 NTU (Figure 3-6A and C). Due to differences in the influent turbidities in the field-scale tests, influent-normalized plots (Figure 3-6B and D) were also presented to help interpret the impact of PAM type and channel baffling. These data show that the effluent turbidities were lower with N-300 compared to A-100 PAM, indicating the importance of PAM type at the field scale. For A-100, the presence of channel baffles decreased the normalized effluent turbidities from ~0.37 to ~0.22 (at an Operation Time = 6 hrs), indicating that baffling improved particle settling for this

PAM type. For N-300, these normalized values for the were less than 0.1 for both channel configurations, precluding an assessment of the impact of channel baffling; however, for samples taken from the Mid-Channel (Figure 3-6B and D), baffles decreased the normalized turbidities from ~0.19 to ~0.10 (at an Operation Time = 6 hrs), indicating that baffling similarly improved particle settling with N-300 as well.

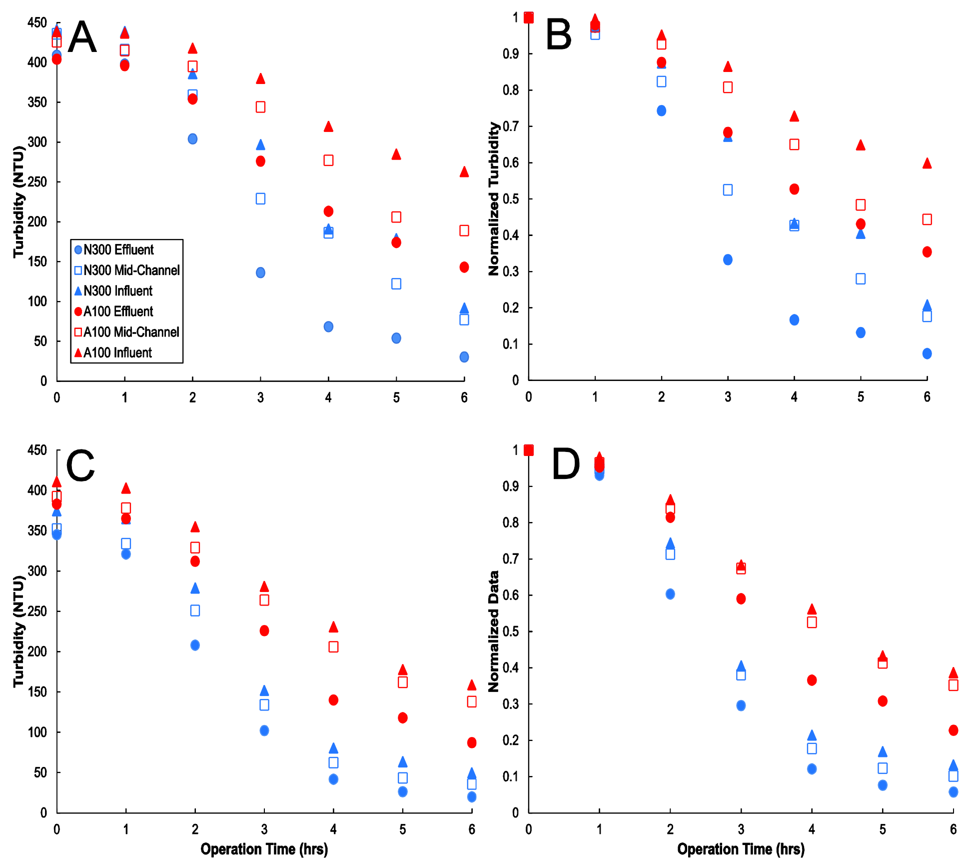

Figure 3-6: Turbidity of effluent waters in the Phase III Cato Springs Field Site Tests using water generated by blending 2 g L^{-1} of excavated Arkansas Red Dirt and tap water for the channel with (A) and (B) no baffles and (C) and (D) with baffles. The PAM types used were anionic Superfloc N-300 and Superfloc A-100 at a dose of 10 mg L^{-1}. Turbidity was measured at the influent, mid-channel, and effluent of the channel.

There are several other methods for achieving turbidity reduction in stormwater collected on construction sites, including rock check dams, silt fences, and sedimentation basins (McLaughlin and Brown, 2006). A study at the University of Texas evaluated silt fences for reducing turbidity and total suspended solids (TSS) of stormwater runoff at construction sites (Barrett et al., 1998). Their results indicated TSS removals of approximately 85%, which corresponded to a 2.9% reduction in turbidity. They concluded that silt fences were effective at trapping larger suspended sediment, but were unable to trap fines that disproportionately contributed to turbidity. A similar study in the Pacific Northwest found that silt fences only retained particles greater than 125 μm (sands and coarse silts) and retention ponds downstream of silt fences only retained particles greater than 10 μm in diameter (Tobiason et al., 2000). These results imply that chemical treatment, such as PAM application, or other erosion control barriers are necessary to catch the finer particles, a contention supported by others (Fennessey and Jarrett, 1994). This is particularly relevant to several AHTD construction sites, where the turbidity of runoff waters can exceed 15,000 NTU, presumably due to high concentrations of particles between 1-10 μm in diameter (EPA, 2009).

In terms of application procedures, PAM can be sprayed from a truck onto soil at construction sites to increase stabilization and promote turbidity control (Tobiason et al., 2000). Spraying PAM is generally preferably to pumping it because of its high viscosity and concerns related to shearing PAM particles during pumping, which may decrease its effectiveness (Bjorneberg, 1998).

PAM can also be applied by passive means, such as PAM blocks in which turbid water flows over the PAM, partially dissolving the polymer leading to particle flocculation and settling (Kang et al., 2013). McLaughlin and Brown (2006) tested PAM blocks exposed to different flows and sediment loads. They determined that turbidities were reduced between 50-80% under most conditions, however the blocks were less effective in colder weather need to be kept wet. These blocks are commercially available and can be comprised of several different PAM types, selected based on the soil type at the construction site. Applied Polymer Systems (APS) produces a variety of PAM blocks, however their usefulness for controlling turbidity in stormwater runoff at AHTD construction sites remains untested. In general, there has been very little published research on PAM blocks, but their potential ease of implementation and low maintenance makes them an attractive option for further testing.

3.2 PAM-entrained Floc Logs

3.2.1 Jar Tests

3.2.1.1 Round 1

The turbidity results for the first round of jar testing are reported in Table 3-1, organized by Floc Log type and dose (Ngo, 2015).

Table 3-1: Round 1 Jar tests: Turbidity reduction using non-uniformed pieces of Floc Log

Floc Log Type	Dose (mg/L)	Initial Turbidity (NTU)	Final Turbidity (NTU)	% Reduction
Control 1	0	1,713	1,337	22%
Control 2	0	2,224	1,616	27%
703d	206	1,859	989	47%
	408	1,993	722	64%
	606	2,357	577	76%
703d#3	200	2,306	1,060	54%
	406	2,354	460	80%
	607	2,433	491	80%
706b	203	2,335	997	57%
	403	2,180	958	56%
	605	1,937	747	61%
707a	201	2,005	1,608	20%
	405	2,405	1,601	33%
	605	2,413	1,290	47%
708x	209	1,639	1,244	24%
	400	1,869	1,312	30%
	609	1,885	970	49%

*Undissolved pieces of Floc Logs remained after the completion of each jar test

Tukey's tests were used to interpret the % Reduction data by grouping the Dose variable (Table 3-2). Compared to the controls (i.e., jars without added Floc Log pieces), Floc Log Types 703d, 703d#3, and 706b lowered the final turbidity, whereas 707a and 708x did not.

Table 3-2: Round 1 Jar tests: Tukey's test results

	Difference in the Means (%)*				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-25				
703d#3	-47	-9			
706b	-34	4	13		
707a	-9	29	38	25	
708x	-10	28	37	24	-1
* With 95% confidence, observed values outside ±20% are unlikely to be zero; negative values less than minus 20% indicate value in column is less than the corresponding row					

No differences in turbidity reduction were observed amongst 703d, 703#d, and 706b. However, as the sizes of the Floc Log pieces varied in these tests, a second round of jar tests was completed with more uniformly sized pieces.

3.2.1.2 Round 2

The turbidity results for the second round of jar testing are reported in the Table 3-3, organized by Floc Log type and dose. Again, Tukey's tests were performed on the % Reduction data by grouping the Dose variable (Table 3-4). Relative to the controls, all Floc Log Types lowered the final turbidity. Results from the Tukey's tests indicated that turbidity reductions with 703d and 703d#3 were higher than with 708x. However, no differences in turbidity reduction were observed amongst 703d, 703#d, 706b, and 707a; similarly, there were no differences between 706b, 707a, and 708x, a partially conflicting result. On balance, however, the results in Tables 3-2 and 3-4 indicate that selection of the appropriate Floc Log type is an important consideration to achieve turbidity reduction (Ngo, 2015).

Table 3-3: Round 2: Jar tests turbidity reduction using uniformed pieces of Floc Logs

Floc Log Type	Dose (mg/L)	Initial Turbidity (NTU)	Final Turbidity (NTU)	% Reduction
Control 1	0	1,992	1,457	27%
Control 2	0	1,889	1,371	27%
Control 3	0	1,848	1,370	26%
Control 4	0	2,010	1,510	25%
703d	203	2,079	669	68%
	400	1,936	343	82%
	605	2,260	399	82%
	806	2,296	371	84%
703d#3	208	2,179	570	74%
	402	2,373	413	83%
	606	1,846	302	84%
	807	1,973	250	87%
706b	200	2,198	946	57%
	408	1,863	490	74%
	607	2,046	455	78%
	806	2,114	481	77%
707a	205	1,839	1,119	39%
	403	2,271	1,114	51%
	604	2,096	501	76%
	802	2,061	553	73%
708x	209	2,079	1,534	26%
	405	2,307	1,593	31%
	609	1,906	426	78%
	803	2,260	724	68%

*Undissolved pieces of Floc Logs remained after the completion of each jar test

Table 3-4: Round 2 Jar tests: Tukey's test results

	Difference in the Means (%)*				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-53				
703d#3	-56	-3			
706b	-45	8	10		
707a	-34	19	22	12	
708x	-24	28	31	21	9

* With 95% confidence, observed values outside ±22% are unlikely to be zero; negative values less than minus 22% indicate value in column is less than the corresponding row

A third round of jar tests was completed to assess the relationship between soil type and Floc Log type.

3.2.1.3 Round 3

The turbidity results for the third round of jar testing are reported in the Table 3-5, organized by Clay type and Floc Log type. Tukey's tests were performed on the % Reduction data, which was collected in triplicate (Table 3-6a-f). The results in Table 3-6a for clay KGa-1b indicate that, compared to the controls (i.e., jars without added Floc Log pieces), 703d, 703d#3, 706b, and 707a lowered the final turbidity, whereas 708x did not. Further, no differences in turbidity reduction were observed amongst 703d, 703d#3, 706b, and 707a.

The results in Table 3-6b for clay PFl-1 indicate that, compared to the controls, all Floc Log Types lowered the final turbidity. Results from the Tukey's tests indicated no differences in performance amongst the five Floc Logs types.

The results in Table 3-6c for clay SHCa-1 indicate that, compared to the controls, none of the Flog Types lowered the final turbidity. However, 708x actually inhibited turbidity reduction compared to the controls (i.e., the turbidity increased in the presence of 708x). As a result, Tukey's tests indicated that turbidity reduction with 703d, 703d#3, 706b, and 707a were higher than that with 708x. However, no differences in performance were observed amongst 703d, 703#d, 706b, and 707a, and thus clays similar to SHCa-1 would not be amenable to flocculation by any of the APS Floc Logs types evaluated.

The results in Table 3-6d for clay STx-1b indicate that, compared to the controls, 703d and 703d#3 decreased the final turbidity whereas 706b, 707a, and 708x did not. However, 703d was equally as effective for turbidity reduction as 703d#3, 706b, and 707a, but better than 708x, a finding that is, in part, in conflict with the comparisons to the controls. Logically, turbidity reduction with 703d#3 was higher than 706b, 707a, and 708x and there were no differences in turbidity reduction amongst 706b, 707a, and 708x (Ngo, 2015).

Table 3-5: Round 3 Jar tests: Turbidity reduction results for the six clay types using the five Floc Log types

			Floc Log type				
Clay Type		**Control**	**703d**	**703d#3**	**706b**	**707a**	**708x**
	Initial	3,112	3,480	3,277	3,345	3,293	3,110
	Final	1,954	123	96.4	142	235	1291
	% Reduction	**37%**	96%	97%	96%	93%	58%
	Initial	3,305	3,154	3,455	3,489	3,610	3,177
KGa-1b	Final	2,512	136	104	185	315	670
	% Reduction	**24%**	96%	97%	95%	91%	79%
	Initial	3,511	3,312	3,009	3,275	3,339	3,501
	Final	1602	114	156	208	281	2,514
	% Reduction	**54%**	97%	95%	94%	92%	28%
	Initial	2,553	2,677	2,719	2,690	2,560	2749
	Final	721	47.6	36.6	37	80.3	95
	% Reduction	**72%**	98%	99%	99%	97%	97%
	Initial	2,810	2,797	2,748	2,799	2,575	2,524
PFl-1	Final	431	34.4	62	41.2	75.6	113
	% Reduction	**85%**	99%	98%	99%	97%	96%
	Initial	2,637	2,666	2,536	2,778	2,681	2,624
	Final	543	108	106	114	74.2	101
	% Reduction	**79%**	96%	96%	96%	97%	96%
	Initial	3,052	2,811	2,914	3,034	2,978	2,879
	Final	1,914	1,604	1,556	1,877	1,835	2,587
	% Reduction	**37%**	43%	47%	38%	38%	10%
	Initial	2,969	2,973	2,963	3,000	3,137	2,988
SHCa-1	Final	1,993	1,987	1,720	1,869	1,977	2,526
	% Reduction	**33%**	33%	42%	38%	37%	15%
	Initial	3,039	2,977	2,873	2,977	3,220	3,068
	Final	1,975	2,029	1,992	1,903	1,983	2,684
	% Reduction	**35%**	32%	31%	36%	38%	13%

Table 3-5 is continued on the next page

Table 3.5, continued

Clay Type		Control	703d	703d#3	706b	707a	708x
				Floc Log Type			
	Initial	3,192	3,160	3,174	3,188	3,144	3,152
	Final	2,124	1,157	1,054	1,672	1,764	1,443
	% Reduction	**33%**	63%	67%	48%	44%	5,4%
	Initial	2,907	3,068	3,156	3,099	3,029	3,171
STx-1b	Final	2,059	1,511	1,025	1,587	1,744	1,845
	% Reduction	**29%**	51%	68%	49%	42%	42%
	Initial	3,022	3,077	3,060	3,066	3,261	3,308
	Final	2,204	252	123	1,463	1,294	1,856
	% Reduction	**27%**	92%	96%	52%	60%	44%
	Initial	2,295	2,356	2,440	2,322	2,263	2,430
	Final	2,190	2,334	2,311	2,275	2,136	2,392
	% Reduction	**5%**	1%	5%	2%	6%	2%
	Initial	2,309	2,330	2,317	2,125	2,277	2,430
SWy-2	Final	2,195	2,056	2,204	2,074	2,182	2,337
	% Reduction	**5%**	12%	5%	2%	4%	4%
	Initial	2,187	2,172	2,230	2,186	2,173	2,193
	Final	2,104	1,737	2,148	2,112	2,000	2,117
	% Reduction	**4%**	20%	4%	3%	8%	3%
	Initial	1,607	1,680	1,608	1,734	1,685	1,737
	Final	696	729	663	826	674	721
	% Reduction	**57%**	57%	59%	52%	60%	58%
	Initial	1,605	1,626	1,599	1,706	1,689	1,390
SYn-1	Final	796	849	666	716	804	459
	% Reduction	**50%**	48%	58%	58%	52%	67%
	Initial	1,494	1,491	1,768	1,678	1,509	1,490
	Final	773	685	702	570	663	666
	% Reduction	**48%**	54%	60%	66%	56%	55%

On balance, therefore, 703d and 703d#3 performed better than the other Floc Log types for turbidity removal with clay STx-1b.

The results in Table 3-6e for clay SWy-2 indicate that, compared to the controls, none of the Floc Log types lowered the final turbidity. However, turbidity reduction with 703d was higher than 706b and 708x, but similar to 703d#3 and 707a. Further, there were no differences in turbidity reduction amongst 703d#3, 706b, 707a, and 708x and thus clays similar to SWy-2 would not be amenable to flocculation by any of the APS Floc Logs evaluated.

Table 3-6a: Clay KGa-1b Jar tests: Tukey's test results

KGa-1b	**Difference in the Means (%)***				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-58				
703d#3	-58	0			
706b	-56	2	2		
707a	-53	4	4	3	
708x	-17	41	41	40	37
* With 95% confidence, observed values outside ±21% are unlikely to be zero; negative values less than minus 21% indicate value in column is less than the corresponding row					

Table 3-6b: Clay PFl-1 Jar tests: Tukey's test results

PFl-1	**Difference in the Means (%)***				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-19				
703d#3	-19	0			
706b	-19	0	0		
707a	-18	1	0	1	
708x	-17	2	1	2	1
* With 95% confidence, observed values outside ±5% are unlikely to be zero; negative values less than minus 5% indicate value in column is less than the corresponding row					

Table 3-6c: Clay SHCa-1 Jar tests: Tukey's test results

SHCa-1	**Difference in the Means (%)***				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-1				
703d#3	-5	-4			
706b	-2	-1	2		
707a	-3	-2	2	-1	
708x	22	23	27	25	25
* With 95% confidence, observed values outside ±7% are unlikely to be zero; negative values less than minus 7% indicate value in column is less than the corresponding row					

Table 3-6d: Clay STx-1b Jar tests: Tukey's test results

STx-1b	Difference in the Means (%)*				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-39				
703d#3	-47	-8			
706b	-20	19	27		
707a	-19	20	28	1	
708x	-17	22	30	3	2
* With 95% confidence, observed values outside ±20% are unlikely to be zero; negative values less than minus 20% indicate value in column is less than the corresponding row					

Table 3-6e: Clay SWy-2 Jar tests: Tukey's test results

SWy-2	Difference in the Means (%)*				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-6				
703d#3	0	6			
706b	2	8	2		
707a	-1	5	-1	-3	
708x	1	8	2	0	3
* With 95% confidence, observed values outside ±7% are unlikely to be zero; negative values less than minus 7% indicate value in column is less than the corresponding row					

Table 3-6f: Clay SYn-1 Jar tests: Tukey's test results

SYn-1	Difference in the Means (%)*				
Floc Log Type	**Control**	**703d**	**703d#3**	**706b**	**707a**
703d	-1				
703d#3	-7	-6			
706b	-7	-6	0		
707a	-4	-3	3	3	
708x	-8	-7	-1	-1	-4
* With 95% confidence, observed values outside ±8% are unlikely to be zero; negative values less than minus 8% indicate value in column is less than the corresponding row					

The results in Table 3-6f for clay SYn-1 indicate that, compared to the controls, none of the Floc Log types lowered the final turbidity. Results from the Tukey's tests indicated no differences in performance amongst any of the Floc Logs types and thus clays similar to SYn-1 would not be amenable to flocculation by any of the APS Floc Logs evaluated.

3.2.1.4 Summary

Based on the Round 2 jar tests (i.e., tests with similarly sized Floc Log pieces), all five APS Floc Log types assessed lowered the final turbidity compared to the controls, but 708x was the poorest performing type and was not statistically better than 707a. Therefore, Floc Log types 703d, 703d#3, and 706b would be equally as effective for turbidity control with soil types similar to those at the CSRC (Ngo, 2015).

The Round 3 jar tests demonstrated that no single Floc Log type was suitable for turbidity control with all six clay types assessed. For clay types KGa-1b and PFl-1, multiple Flog Log types (703d, 703d#3, 706b, and 707a) were effective at lowering the final turbidity. In contrast, for clay types SHCa-1, SWy-2 and SYn-1, none of the five Floc Log types assessed lowered the final turbidity. As such, jar tests with field soil samples and multiple Floc Log types are recommended to assess their suitability for turbidity control.

3.2.2 Particle Size Distribution Measurements on Six Clay Types

To help explain the relationships between turbidity reduction and clay type in the Round 3 jar tests, PSDs were measured for each clay type before treatment with each Floc Log (Figure 3-7). These results show that KGa-1b had the largest PSD amongst the six clay types measured, but that PF1-1 had the lowest; the fact that these two clay types were removed with multiple Flog Log types (Tables 3.6a and 3.6b) while the other clay types were not suggests that particle surface charge, and not PSD, was the dominant flocculation mechanism in the jar tests. Future work should include zeta potential measurements of all soil types before and after treatment with the Floc Logs in addition to varying the Floc Log dose for each clay type to ensure adequate particle destabilization.

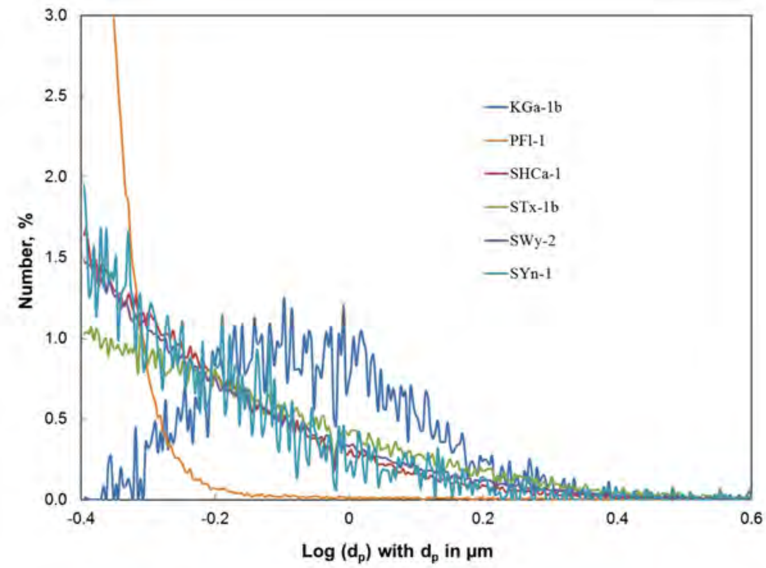

Figure 3-7: Particle size distribution of the six clay types assessed in the Round 3 jar tests

3.2.3 Field Tests at the Bella Vista Bypass

3.2.3.1 First Test

Many of the potential sites considered for the first field test had rock checks to slow water velocities, but only one site had a downstream basin to subsequently allow flocs to settle out. The site chosen (Figure 3-8) contained a basin that was followed by a sharp drop in elevation on the downstream end with a number of large rocks. For safety reasons, samples were collected further downstream, which may have allowed for changes in turbidity. Additionally, during the first field test, it became apparent that a low turbidity water stream from another inflow location was diluting the Floc Log-treated water flowing into the basin. This low turbidity flow was not apparent during the baseline turbidity measurements made prior to placement of the Floc Logs, and therefore the extent of dilution versus treatment is impossible to assess.

Table 3-7 shows the baseline (no Floc Logs) and treated water turbidity (two 703d Floc Logs) measurements; BL-E1 & FL-E1 were taken at the first sampling location and BL-E2 &

FL-E2 was taken further downstream. While there was a reduction in turbidity following placement of the Flog Logs (which occurred at 3:20 PM), it cannot be attributed to the Floc Logs due to the introduction of the aforementioned low turbidity water stream.

Figure 3-8**:** Photograph of the site chosen for the first field test. One inflow stream was from the left side of the photo, which enters the small and shallow basin. A second inflow stream is pictured in the background, which included a series of small basins with intermittent rock checks. Photo taken by Bryan Signorelli (AHTD) on June 18, 2015.

Table 3-7: Turbidity measurements during the first field test

Baseline Turbidity				**Treated Water Turbidity with Floc Log**		
Time	**BL-E1[a]**	**BL-E2[a]**		**Time**	**FL-E1[b]**	**FL-E2[b]**
2:45	1,695	1,470		3:50	707	555
2:50	1,601	1,307		3:55	613	525
2:55	2,060	1,729		4:00	556	485
3:00	1,729	1,632		4:05	495	438
3:05	1,403	1,200		4:10	449	404
3:10	934	1,061		4:15	404	344

*Finish placing Floc Logs at 3:20 pm

[a] BL-E1 is the baseline turbidity taken at the first effluent location, BL-E2 is the baseline turbidity taken at the second effluent location further downstream.

[b] FL-E1 is the Floc Log treated water turbidity taken at the first effluent location, FL-E2 is the Floc Log treated water turbidity taken at the second effluent location further downstream.

Additionally, the treated water turbidity was in excess of 300 NTU, which is above the EPA recommended limit for release from highway construction sites. As such, even if treatment was occurring due to the Floc Logs, it was not sufficient; therefore, the number of Floc Logs was increased to six for the second field test.

3.2.3.2 Second Test

The second field test occurred on November 17, 2015, at the site used previously (Figure 3-8). During the rainfall event, five upstream inflows combined into a single stream, which subsequently flowed into a series of basins. Six 703d#3 Floc Logs were placed within turbulent water locations (assessed visually) at each stream inflow in an attempt to achieve adequate coagulant dosing and mixing. This included placement of one 703d#3 Flog Log within each of the five inflow streams, and the sixth following the confluence of each inflow upstream of the basins. One inflow stream is shown in Figure 3-9 flowing over a 703d#3 Floc Log.

Figure 3-9: A stream inflow where a 703d#3 Floc Log was placed on a concrete ditch.

The baseline turbidity was lower in the second field test (~400 NTU, Table 3-8) compared to the first one (~1,500 NTU, Table 3-7). This was attributed to differences in rainfall duration prior to the baseline turbidity measurement, which, in the second test, was several hours longer and hence mobilized fewer particles during the baseline testing. Turbidity results in Table

3-8 were interpreted using Tukey's tests on the raw turbidity data. With 95% confidence, observed values outside ±205 NTU are unlikely to be zero; the mean difference between the baseline turbidity and Floc Log treated water was 92 NTU. Therefore, the Floc Log treatment did not lower the final turbidity.

Table 3-8: Turbidity measurements during the second field test

Baseline Turbidity			**Treated Water Turbidity with Floc Logs**	
Time	**BL-E3[c]**		**Time**	**FL-E3[c]**
8:45	425		10:20	305
8:50	400		10:25	304
8:55	398		10:30	278
9:00	359		10:35	274
9:05	347		10:40	265
9:10	310		10:45	260

*Started placing Floc Logs at 9:20 am and finish placing Floc Logs at 9:50 am

[c] BL-E3 is the baseline turbidity collected at a third effluent location, FL-E3 is the Floc Log treated water turbidity collected at the third effluent location.

Despite this result, the 703d#3 Floc Logs were confirmed to be effective with jar tests prior to the field test. Possible reasons for the relatively high treated water turbidities in the second field test (260-305 NTU) include insufficient dosing, mixing, and/or settling conditions. The contact mixing between the turbid water and Flog Logs cannot be determined accurately in the field. The series of basins and rock checks that had slowed the turbid water velocity in the first field test failed in the second test, allowing for high water velocities (Figure 3-10). In terms of selecting the appropriate number of Floc Logs (i.e., the correct coagulant dose for particle destabilization) for this mode of application, APS recommends one Floc Log for every 227-265 L min^{-1} (Price and Company, 2002). Future studies should include measurements of flow in the field and particle surface charge (i.e., zeta potential measurements) to calculate the required numbers of Floc Logs. However, based on the results from this test, it is likely that this number would be impractically large (i.e., several dozen Floc Logs per site for a storm of similar intensity and duration).

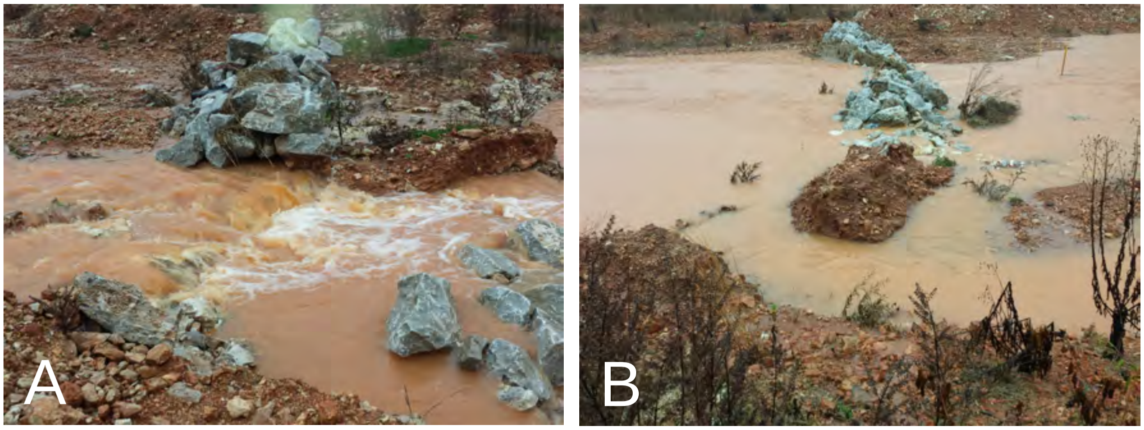

Figure 3-10: The overtopped rock check dams that separated the series of basins.

3.2.4 Inline Mixing Channel Tests

The turbidity test channel at the CSRC was used to mimic the field tests by pumping turbid water over a series of Floc Logs. The Floc Logs were placed at the front of the channel, after the influent sampling location. Turbidity was sampled at the mid-point of the channel (~6 m from the influent) and at the effluent (~12 m from the influent). Turbidity results are shown in Table 3-9 for a control condition (i.e., no Floc Logs) and two tests (the first with one Floc Log and the second with four Floc Logs).

Table 3-9: Turbidity measurements from inline mixing using the turbidity test channel

Test	**Sample Location**	**Time (hr)**	**0**	**1**	**2**	**3**	**4**	**5**
Control	Influent	**Turbidity (NTU)**	251	311	312	320	332	303
	Mid-Channel		241	254	262	289	328	292
	Effluent		231	254	253	275	292	310
One 703d Floc Log	Influent	**Turbidity (NTU)**	224	254	312	266	307	316
	Mid-Channel		174	182	188	201	182	247
	Effluent		174	174	173	205	201	170
Four 703d Floc Logs	Influent	**Turbidity (NTU)**	300	404	284	356	302	490
	Mid-Channel		169	164	170	240	292	293
	Effluent		173	156	166	178	257	301

Similar to the previous analysis procedures, these data were interpreted using Tukey's tests (Table 3-10). The results in Table 3-10 indicate that, compared to the control, the Floc Logs did not lower the final turbidity. Further, there were no differences in the final turbidity with either one or four Floc Logs.

Table 3-10: Inline Mixing Channel Tests: Tukey's test results

	Difference in the Means (NTU)*	
Floc Log Type	**Control**	**One 703d Floc Log**
One 703d Floc Log	-25	
Four 703d Floc Logs	-47	-9
* With 95% confidence, observed values outside ±337 NTU are unlikely to be zero; negative values less than minus 337 NTU indicate value in column is less than the corresponding row		

These results were attributed to insufficient dosing and/or mixing using this mode of operation, similar to that of the two field tests. Therefore, a series of basin-scale tests were undertaken to assess the performance of the Floc Logs as applied to turbidity reduction in onsite sedimentation basins.

3.2.5 Basin-scale Sedimentation Tests

3.2.5.1 Turbidity Reduction

The turbidity results for the basin-scale sedimentation tests with Floc Log types 703d and 703d#3 are reported in Table 3-11, organized by the duration of the rapid mix step (5-, 15-, or 30-min) and a binary variable, Presoak Time. This variable denotes whether the Floc Log was dry at the start of the test (i.e., Presoak Time = None) or had been presoaked in tap water for 15 min (i.e., Presoak Time = 15 min) prior to the sedimentation test (Ngo, 2015).

Turbidity reduction results in Table 3-11 were interpreted using Tukey's tests on the raw turbidity data by grouping the turbidity values at settling times between 5-60 minutes (Tables 3.12a-c). The impact of the rapid mix period on turbidity reduction is shown in Table 3-12a. These results indicate that rapid mix periods of 15- and 30-minutes decreased the final turbidity more so than the 5-minute period. Additionally, there was no difference in final turbidity between the 15- and 30-minute rapid mix periods. Therefore, a minimum rapid mix period of 15 minutes is recommended for every 2,000 L of turbid water to distribute the PAM throughout the basin and allow flocs to form.

Table 3-11: Turbidity reduction in the basin-scale sedimentation tests

Test number:	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
Floc Log Type:	703d	703d	703d#3	703d#3	703d	703d	703d#3	703d#3
Rapid mixing time (min)	5	5	15	15	15	30	15	30
Settling Time (min)	**Turbidity (NTU)**							
Initial Turbidity (NTU)[*]	>4,000[d]	3,317	>4,000[d]	>4,000[d]	2,041	1,584	2,402	2,938
5	2,823	1,326	2,452	147	545	256	88.1	295
10	2,461	998	2,144	146	414	122	85.7	182
15	1,956	872	1,857	143	354	110	79.9	180
20	2,041	847	1,947	141	349	109	77	182
25	1,633	740	1,833	137	322	106	76.8	177
30	1,698	717	1,470	135	282	104	74.4	171
35	1,525	689	1,512	134	279	102	74.6	160
40	1,476	616	1,520	133	274	96.7	74	169
45	1,152	593	1,308	134	267	93.9	72.6	159
50	1,205	595	1,388	132	269	92.9	72	156
55	1,121	522	1,262	132	238	95.9	70.6	154
60	1,065	499	1,166	129	253	93.6	70.7	156
Log Condition:	**Used[e]**	**Used[e]**	**New[f]**	**New[f]**	**Used[e]**	**Used[e]**	**Used[e]**	**Used[e]**
Presoak Time (min):	**None**	**15 min**	**None**	**15 min**	**None**	**None**	**None**	**None**

[*] Initial Turbidity (NTU) samples were measured prior to treatment with the Floc Logs
[d] Turbidity values listed as >4,000 were not diluted, so the actual turbidity may be greater than the turbidimeter maximum of 4,000 NTU
[e] Flog Log previously used in one or more tests
[f] Flog Log was new and had not been used in prior tests

The impact of presoaking the Floc Logs prior to use in the basin-scale sedimentation tests is shown in Table 3-12b. These results indicate that the 15-minute presoaking period decreased the final turbidity relative to no presoaking for both the 703d and 703d#3 Floc Log types. This result agrees with previous studies that show Floc Logs were more effective for turbidity reduction following a presoaking period (McLaughlin, 2004). As such, it is recommended that all Floc Logs used in the field be presoaked prior to use in sedimentation basins for turbidity reduction.

Table 3-12a: Basin-scale sedimentation tests: Tukey's test results comparing mixing duration

	Difference in the Means (%)*		
Test number:[g]	**#1**	**#5**	**#6**
		703d (white)	
Mix time (min)	5	15	30
	Used Floc Log No presoak	Used Floc Log No presoak	Used Floc Log No presoak
15	1,359		
30	1,565	205	

* With 95% confidence, observed values outside ±736 NTU are unlikely to be zero; negative values less than minus 736 NTU indicate value in column is less than the corresponding row

[g] Test number corresponds to the Test number in Table 3-11

Table 3-12b: Basin-scale sedimentation tests: Tukey's test results comparing Floc Log presoaking time

	Difference in the Means (%)*			
Test number:[g]	**#1**	**#2**	**#3**	**#4**
	703d (white)		**703d#3 (blue)**	
Mix time (min)	5	5	15	15
	Used Floc Log No presoak	Used Floc Log 15min presoak	New Floc Log No presoak	New Floc Log 15min presoak
703d, 5 min rapid mix, used, no presoak				
703d, 5 min rapid mix, used, 15 min presoak	929			
703d#3, 15 min rapid mix, new, no presoak	25	-904		
703d#3, 15 min rapid mix, new, 15 min presoak	1,543	614	1,518	

* With 95% confidence, observed values outside ±871 NTU are unlikely to be zero; negative values less than minus 871 NTU indicate value in column is less than the corresponding row

[g] Test number corresponds to the Test number in Table 3-11

Table 3-12c: Basin-scale sedimentation tests: Tukey's test results comparing Floc Log types 703d and 703d#3

	Difference in the Means (%)*			
Test number:[g]	**#5**	**#6**	**#7**	**#8**
	703d (white)		**703d#3 (blue)**	
Mix time (min)	15	30	15	30
	Used Floc Log No presoak	Used Floc Log No presoak	Used Floc Log No presoak	Used Floc Log No presoak
703d, 15 min rapid mix, used, no presoak				
703d, 30 min rapid mix, used, no presoak	205			
703d#3, 15 min rapid mix, used, no presoak	244	39		
703d#3, 30 min rapid mix, used, no presoak	142	-63	-102	

* With 95% confidence, observed values outside ±128 NTU are unlikely to be zero; negative values less than minus 128 NTU indicate value in column is less than the corresponding row

[g] Test number corresponds to the Test number in Table 3-11

The results from the Tukey's test related to Floc Log type is shown in Table 3-12c for 703d and 703d#3. These Floc Logs were compared under identical mixing conditions. The results in Table 3-12c indicate there was no difference in performance between the two Floc Log types. For the shorter rapid mix time (15 minutes), 703d#3 produced lower final turbidities, but at the longer rapid mix time (30 minutes), both Floc Log types performed similarly for turbidity reduction. Arbitrarily, the 703d#3 Floc Log was chosen for further testing to assess its effectiveness in successive basin-scale sedimentation tests designed to estimate the volume of turbid water treated with a given Floc Log.

3.2.5.2 Assessment of Floc Log Longevity

A basin-scale sedimentation test was completed eight times in succession with the same 703d#3 Floc Log in an attempt to determine its longevity in terms of volume of turbid water treated (Ngo, 2015). Control tests were also completed with the same experimental setup, but with no Floc Log, to assess the effectiveness of gravity settling alone on the turbidity reduction. The percent turbidity reduction data for the Control and Test conditions are shown in Figure 3-11, presented as a function of settling time (0-60 minutes).

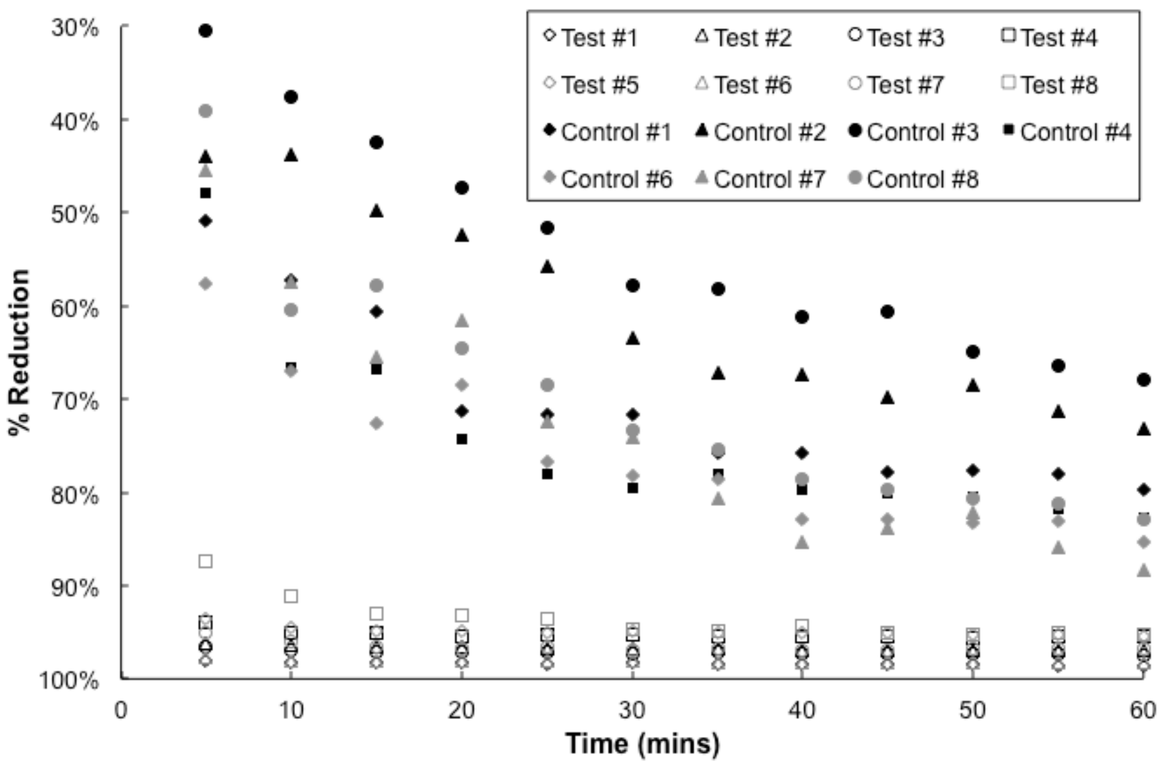

Figure 3-11: Percent turbidity reduction in the basin-scale sedimentation tests of the Control condition (i.e., no Floc Logs, closed symbols) and the Test condition (i.e., one 703#d Floc Log, open symbols). The Control and Test conditions were completed in succession to assess the reproducibility of the experiments.

At a settling time of 5 minutes, the % Reduction in turbidity of the Controls ranged from 30-58% and that of the Tests ranged of 88-98%; at a settling time of 60 minutes, the Controls ranged from 68-88%, and the Tests ranged from 95-99%. As such, the Floc Logs increased the overall extent and rate of turbidity reduction in the basin-scale sedimentation tests. Further, no decrease in turbidity reduction was observed over the course of the eight experiments in the Test condition, indicating a single Floc Log could treat more than 16,000 L (i.e., 8 tests of ~2,000 L each) of turbid water as long as the proper mixing conditions are achieved. On balance, the results in Figure 3-11 indicate the Floc Logs would be an effective tool to rapidly reduce turbidity in runoff waters collected in onsite sedimentation basins.

3.2.5.3 Volumetric Measurements

It was hypothesized that the volume of the Floc Log would decrease from one test to the next as the PAM from its surface dissolved. However, as shown in Table 3-13, the volume of the Floc Log in these tests increased over the course of the eight basin-scale sedimentation tests.

Table 3-13: Volumetric measurement of various conditions of 703d#3 Floc Logs

Log Type	**Volume of Floc Log (L)**			
	Triplicate Measurement			**Average**
New log	3.595	3.670	3.665	3.643
New log presoaked	3.745	3.765	3.830	3.780
Floc Log following the eighth Longevity test	4.170	4.175	4.230	4.191

Possible reasons include the absorption of water, entrapped air in the interior of the log, and soil adhered to the exterior of the log that could not be removed by brushing. APS contends that each Floc Log should be capable of treating 1.6 million liters (565,035 ft^3) of turbid water.

4 Conclusions

The objective of this research was to develop BMPs for the use of anionic PAM-based Floc Logs for turbidity control in runoff waters leaving highway construction sites. Storm water runoff can have turbidities of several thousand NTU due to exposed soil at construction sites leading to violations of the EPA proposed regulatory standard of 280 NTU (EPA, 2014) for waters leaving these sites. Floc Logs were assessed in a series of laboratory-scale jar tests, basin-scale sedimentation tests, and field tests at active AHTD construction sites. The major findings of this research were as follows:

- Based on the Round 2 jar tests (Tables 3-3 and 3-4), Floc Log types 703d, 703d#3, and 706b would be equally as effective for turbidity control with soil types similar to those at the CSRC.
- The Round 3 jar tests (Tables 3-5 and 3-6a-f) demonstrated that no single Floc Log type was suitable for turbidity control with all six clay types assessed. In fact, relative to the control condition, no turbidity removal was achieved with any of the five Floc Log types assessed for clays SHCa-1, SWy-2, and SYn-1. As such, jar tests with field soil samples and multiple Floc Log types are recommended to assess their suitability for turbidity control.
- PSDs were measured by Coulter Counter for the six clay types before treatment and, together with the Round 3 jar test results, indicate that particle surface charge, and not PSD, was the dominant flocculation mechanism in the jar tests (Figure 3-7). Future work should include zeta potential measurements of all soil types before and after treatment with the Floc Logs to determine the coagulant doses necessary to achieve adequate particle destabilization.

- Field test results showed little to no reduction in turbidity, despite that the Floc Log types used were confirmed to be effective in jar tests with the field soils. This was attributed to insufficient PAM dosing, mixing, and/or settling conditions in the inline treatment scenario attempted in the field.
- In the inline mixing channel tests at the CSRC, the Floc Logs did not lower the final turbidity (Tables 3-9 and 3-10). Similar to the field studies, these results were attributed to insufficient dosing and/or mixing using this mode of operation
- For basin-scale sedimentation, a minimum rapid mix period of 15 minutes is recommended for every 2,000 L (71 ft^3) of turbid water to distribute the PAM throughout the basin and allow flocs to form (Table 3-12a).
- Presoaking the Floc Logs in tap water for 15 minutes was found to increase turbidity reduction in sedimentation basin treatment (Table 3-12b).
- No decrease in turbidity reduction was observed in the Longevity Tests (Figure 3-11), indicating a single Floc Log could treat more than 16,000 L (565 ft^3) of turbid water as long as the proper mixing conditions are achieved. APS contends that each Floc Log should be capable of treating 1.6 million liters (565,035 ft^3) of turbid water.
- The results in Figure 3-11 indicate the Floc Logs would be an effective tool to reduce turbidity in runoff waters (~95-99% for the excavated soil at the CSRC) collected and treated in onsite sedimentation basins.

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