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

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

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science in Civil Engineering

by

Joanne Johnson  
University of Arkansas  
Bachelor of Science in Civil Engineering, 2013

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This thesis is approved for recommendation to the Graduate Council.

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## **Abstract**

In 2009, the United States Environmental Protection Agency (EPA) promulgated a national turbidity standard for runoff water leaving highway construction sites at 280 nephelometric turbidity units (NTU). Meeting this standard can be challenging as turbidities of runoff waters can exceed 15,000 NTU. The objective of this research was to assess polyacrylamide (PAM), a coagulant aid used in water treatment, to help meet the EPA turbidity regulation. Twelve commercially available PAM types were studied, selected on the basis of charge type (cationic, nonionic, anionic), charge density (0-100%), and molecular weight (0.1-28 Mg mol<sup>-1</sup>). Jar tests were conducted with runoff waters from AHTD construction sites and synthetically made formulations of tap water blended with bentonite, illite, kaolinite, and Arkansas Red Dirt. Jar tests were completed at PAM doses between 0.5-20 mg L<sup>-1</sup> and the turbidity of the supernatant was measured following a quiescent settling period. Results showed that anionic PAMs with low charge densities were most effective at reducing supernatant turbidities, likely due to enhanced interparticle bridging. Hydraulic flocculation tests were done with two PAM types in lab-scale continuous flow reactors and at a controlled field site. It was concluded that anionic PAMs at a dose of 10 mg L<sup>-1</sup> provided adequate turbidity reduction and that channel baffling induced hydraulic flocculation and further reduced effluent turbidities.

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# **1 Introduction**

## **1.1 Motivation and Background Information**

Highway construction sites are susceptible to erosion during rainfall events due to exposed soils that can be mobilized and transported into surrounding surface waters. The USEPA regulates 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). 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, impact of PAM type and dose was assessed along with the effect of channel baffling in promoting hydraulic flocculation.

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, or inverse emulsion. 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).

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<sub>2</sub>) 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 conformational 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<sup>-1</sup>), medium (0.1-1 Mg mol<sup>-1</sup>), high (1-5 Mg mol<sup>-1</sup>), or very high (>5 Mg mol<sup>-1</sup>).

## **1.2 Objectives and Approach**

The primary objective of this research was to elucidate PAM properties 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<sup>-1</sup>). 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 on effluent turbidity. Field-scale studies were completed to determine the efficacy of these two PAM types and the effect of channel baffling for turbidity reduction.



## 2 Methods and Materials

### 2.1 Polyacrylamide Types and Preparation

Twelve commercially available types of polyacrylamide (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). 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<sup>-1</sup> stock solutions were prepared in Milli-Q water (18.2 MΩ-cm) 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 Collection and Formulation of Synthetic Waters for Jar Testing**

Runoff water and soil samples from field sites were collected for use in the jar testing (Phase I). Runoff water was collected at an Arkansas Highway and Transportation Department (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 4°C 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<sup>-1</sup> 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 on 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  $4 \text{ g L}^{-1}$  prior to being rapidly mixed. Kaolinite, another clay soil, was mixed in tap water at a concentration of  $2 \text{ g L}^{-1}$ . 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, a non-expansive clay, was mixed in tap water at a concentration of  $4 \text{ g L}^{-1}$ .

### **2.3 Phase I- Jar Testing**

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  $0.1\text{-}80 \text{ mg L}^{-1}$  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 (Section 2.2), 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.

## **2.4 Particle Size Distribution**

The particle size distributions (PSDs) of the soils were measured using a Beckman Coulter Counter. The Coulter Counter was powered on and allowed to warm up for 30 min prior to use. Untreated samples of turbid water were screened by dilution with Isoton and assessed using 20- and 100  $\mu\text{m}$  apertures, similar to others (Reynolds et al., 2010). Isoton is a balanced electrolyte solution commonly used as a diluent for particle counting. It is used as a “blank” due to its low particle count, which is generally less than 50 particles per milliliter on a 100  $\mu\text{m}$  aperture. Each aperture can measure particle diameters within 2-60% of the aperture size, which is 0.5-12  $\mu\text{m}$  and 2-60  $\mu\text{m}$  for the two apertures, respectively. To measure the PSDs, various stock concentrations of the soil samples were prepared and added to cuvettes with 10 mL of Isoton (see Table 2.2). Bentonite and kaolinite samples were filtered through an 11 $\mu\text{m}$  Whatman filter to eliminate the clay particles that swelled excessively (based on a visual assessment). Each soil type was run in triplicate to determine an average PSD. The aperture was washed with Isoton between sample runs to ensure no carryover from previous measurements.

## **2.5 Phase II- Lab-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  $\times$  29 cm wide  $\times$  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  $2 \text{ g L}^{-1}$  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  $100 \text{ mL min}^{-1}$ . 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.

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 3.1). These PAM types were dosed continuously throughout the seven-hour Phase II experiments at 1-, 5-, 10-, and  $20 \text{ mg L}^{-1}$  using a positive displacement piston pump at a flowrate of  $10 \text{ mL min}^{-1}$ . Turbidity measurements were taken every hour throughout the duration of the tests turbidity to assess the effects of PAM type, PAM dose, and reactor type (baffled or not baffled).

## **2.6 Phase III-Field 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.

Turbid water for the Phase III experiments was generated on site. A 2,650 L 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  $20 \text{ L min}^{-1}$  using a heavy-duty submersible pump. Once the trench was full, the effluent was pumped into adjacent wetlands at  $20 \text{ L min}^{-1}$ .

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 stock tank placed adjacent to the channel using tap water and mixed with trolling motors. The PAM stock solutions were prepared a concentration of  $10 \text{ mg L}^{-1}$ . 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  $6 \text{ L min}^{-1}$ . 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.

Future 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  $10 \text{ mg L}^{-1}$ . 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.

**Table 2.1:** Properties of the selected polyacrylamide (PAM) types

| <b>PAM Name</b>    | <b>Charge Type</b> | <b>Charge Density (mol %)</b> | <b>Molecular Weight (Mg/mol)</b> |
|--------------------|--------------------|-------------------------------|----------------------------------|
| 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                             |

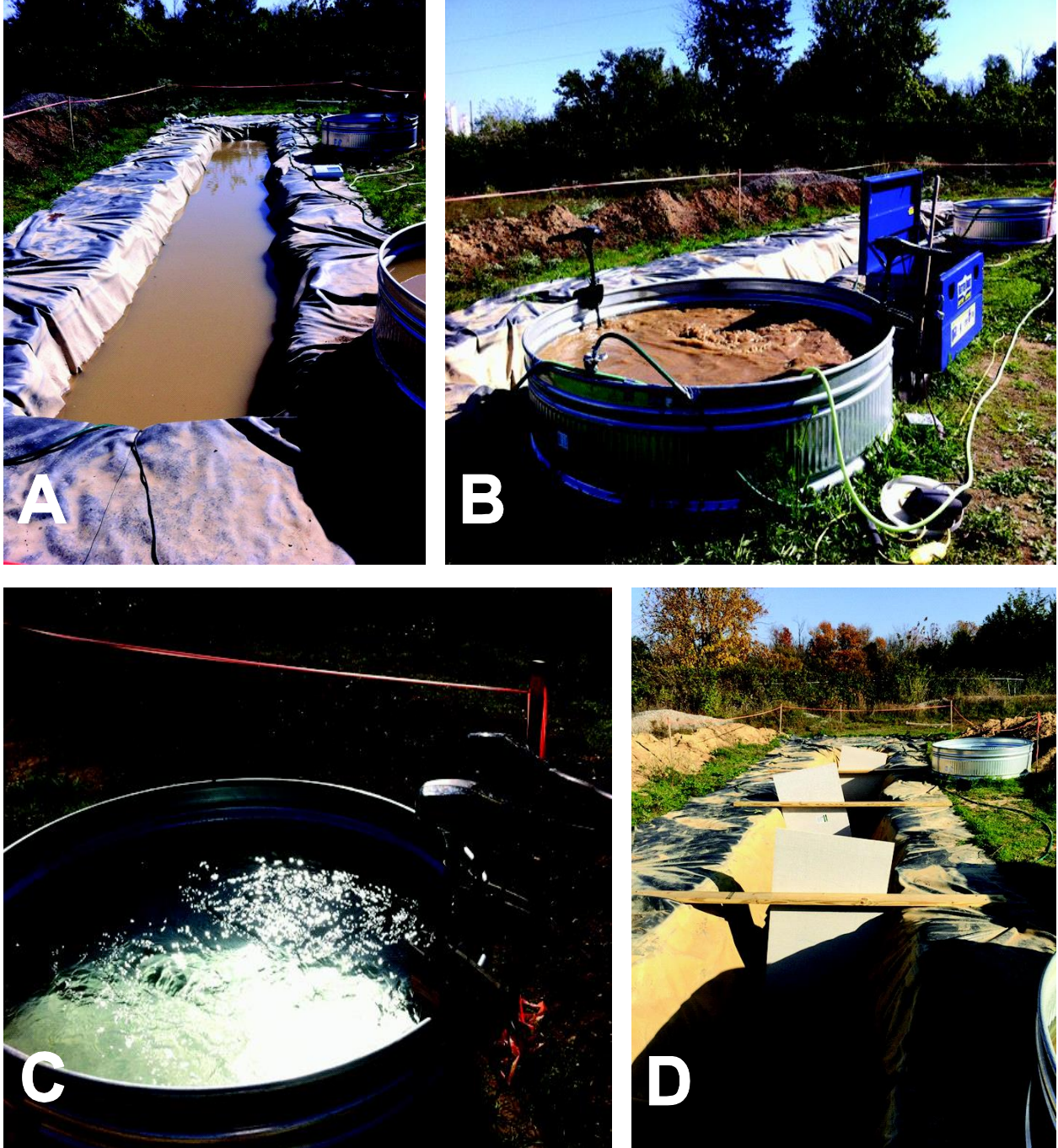
**Table 2.2** Conditions used for the particle size distribution tests with the Coulter Counter

| <b>Soil Type</b>  | <b>Stock Soil Concentration (g L<sup>-1</sup>)</b> | <b>Aperture Size (μm)</b> | <b>Isoton Volume (mL)</b> | <b>Volume of Stock Solution (μL)</b> | <b>Filtered</b> |
|-------------------|--|---------------------------|---------------------------|--------------------------------------|-----------------|
| Arkansas Red Dirt | 2  | 100                       | 10                        | 100                                  | No              |
| Bentonite         | 4  | 20                        | 10                        | 25                                   | Yes             |
| Illite            | 4  | 20                        | 10                        | 100                                  | No              |
| Kaolinite         | 2  | 20                        | 10                        | 25                                   | Yes             |





**Figure 2.1:** Photographs of the Phase II lab-scale hydraulic flocculation setup. (A) a 200 L bucket filled with tap water amended with  $2 \text{ g L}^{-1}$  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. Photos taken by the author.



**Figure 2.2:** Photographs of the Phase III field site tests at the Cato Springs Research Center. (A) The excavated channel lined and filled with turbid water (B) a 700 gallon stock tank with two trolling motors attached mixing tap water and  $2 \text{ g L}^{-1}$  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  $10 \text{ mg L}^{-1}$  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. Photos taken by the author.

### 3 Results and Discussion

#### 3.1 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 (Fig. 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<sup>-1</sup> (Fig. 3.1a) and (2) low mixing, at PAM doses between 0.1-20 mg L<sup>-1</sup> (Fig. 3.1b). Details of the mixing conditions are provided Fig. 3.1. 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 Fig. 3.1b for the PAM doses of 10- and 20 mg L<sup>-1</sup> 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 Fig. 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 (Fig. 3.2a) and lake water (Fig. 3.2b) with PAM doses between 0.5-20 mg L<sup>-1</sup>. Similar to the results in Fig. 3.1, supernatant turbidities decreased with (1) increasing PAM dose (up to

~5 mg L<sup>-1</sup>) 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<sup>-1</sup>, turbidities were similar for each PAM type (Fig. 3.2), indicating there was no added benefit to increasing the dose beyond 10 mg L<sup>-1</sup>.

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. 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<sup>-1</sup> 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 (Fig. 3.3). Samples were mixed at 60 rpm for 1-, 3-, or 5 minutes and PAM doses between 0.5-20 mg L<sup>-1</sup>. 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. Fig. 3.3 also shows minimal impact of PAM type at doses of 10- and 20 mg L<sup>-1</sup>, in contrast with the results in Figs. 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 (Fig. 3.4) at doses between 0.5-20 mg L<sup>-1</sup>. Testing was done to determine the role of surface charge on supernatant turbidity. As shown in Fig. 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 Figs. 3.1-3.3, these results indicate that interparticle bridging, and not electrostatic interactions, was the dominant mechanism of PAM-particle binding.

A final round of jar tests was done using N-300 PAM at doses between 0-20 mg L<sup>-1</sup> with runoff water made using different soil types, which included bentonite, illite, kaolinite, and Arkansas Red Dirt. As shown in Fig. 3.5a, the turbidities of the unamended soil solutions varied considerably, from bentonite at ~2,800 NTU to illite at ~200 NTU. Similar to previous results (Figs. 3.1-3.3), the turbidities of the supernatant decreased with increasing PAM dose up to ~10 mg L<sup>-1</sup>. The particle size distributions of the four soil-water mixtures were measured prior to PAM amendment (Fig. 3.5b), and indicated the three clays (bentonite, illite, and kaolinite) were monodisperse with a mean diameter of ~1 µm. This was an expected result given that clays have particles less than 2 µm. In contrast, Arkansas Red Dirt had particles as large as ~10 µm, indicating the presence of silts, which may improve the flocculation of clay particles through interparticle bridging (Rounce et al., 2012).

### **3.2 Lab 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 (Figs. 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. 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 Fig. 3.6, the time-dependent effluent turbidities were assessed as a function of PAM dose (1-, 5-, 10-, and 20 mg L<sup>-1</sup>) 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<sup>-1</sup> (Fig. 3.6C 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.

### **3.3 Field Tests**

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<sup>-1</sup> only, which was chosen based on the results of the lab-scale tests (Fig. 3.6). 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 (Figs. 3.7A and C). Due to differences in the influent turbidities in the field-scale tests, influent-normalized plots (Figs. 3.7B 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

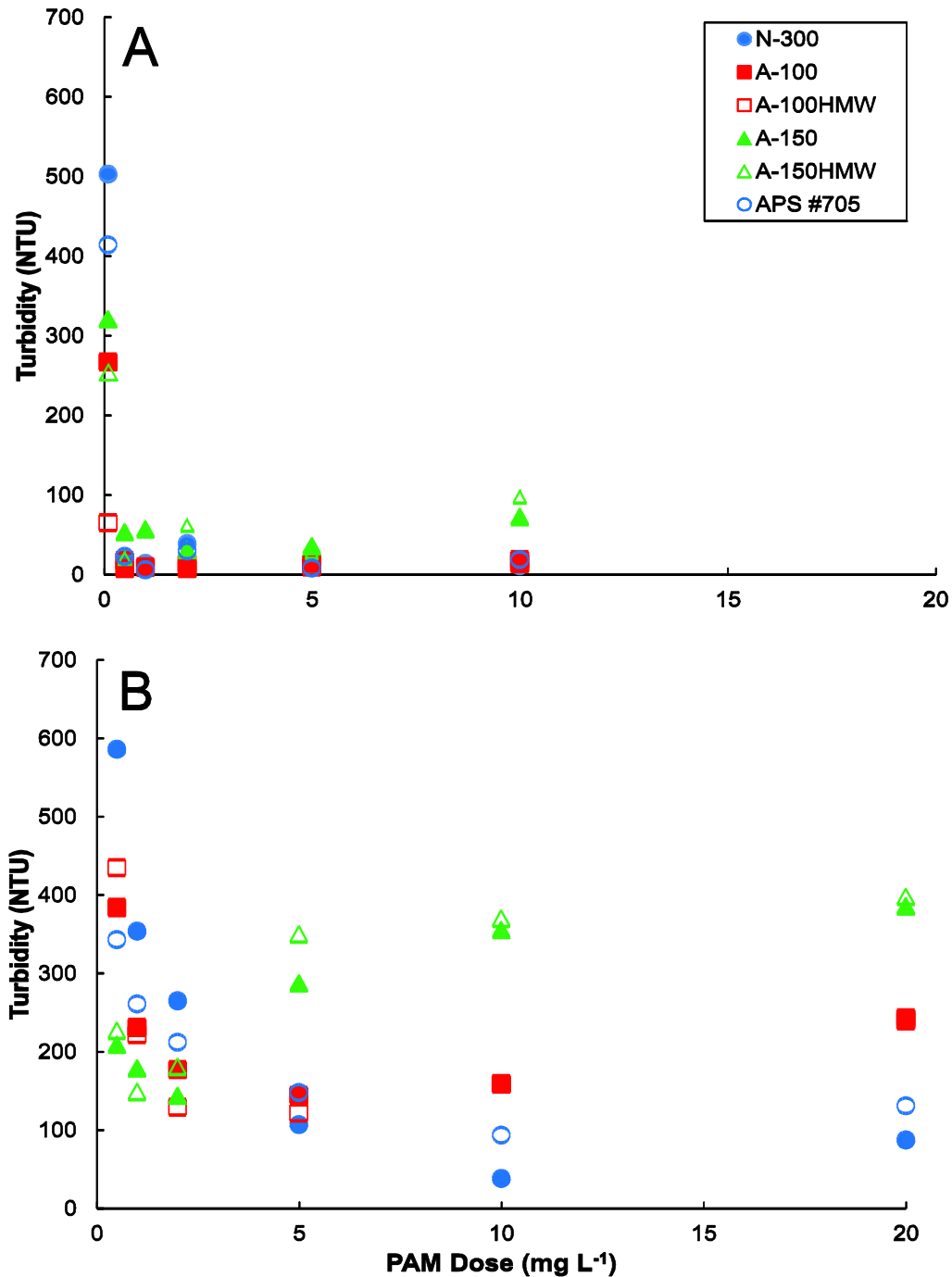
compared to A-100 PAM, indicating the importance of PAM type at the field scale. For A-100, the presence of channel baffles decreased the normalized effluent turbidities from ~0.37 to ~0.22 (at an Operation Time = 6 hrs), indicating that baffling improved particle settling for this PAM type. For N-300, 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 (Figs. 3.7B 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.

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  $\mu\text{m}$  (sands and coarse silts) and retention ponds downstream of silt fences only retained particles greater than 10  $\mu\text{m}$  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  $\mu\text{m}$  in diameter (EPA, 2009).

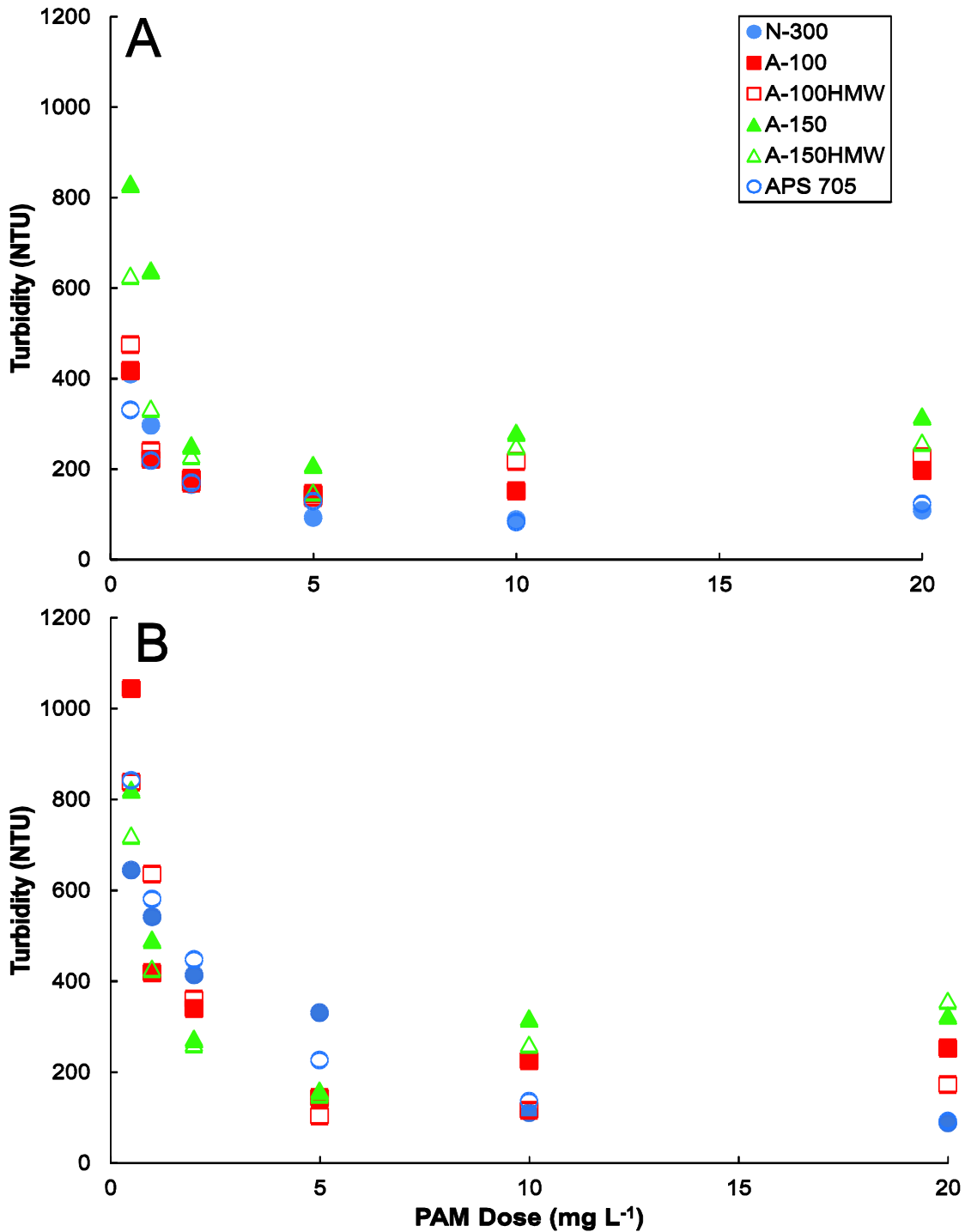


In terms of application procedures, PAM can be sprayed from a truck onto soil at construction sites to increase stabilization and promote turbidity control (Tobiason et al., 2000). Spraying PAM is generally preferable to pumping it because of its high viscosity and concerns related to shearing PAM particles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

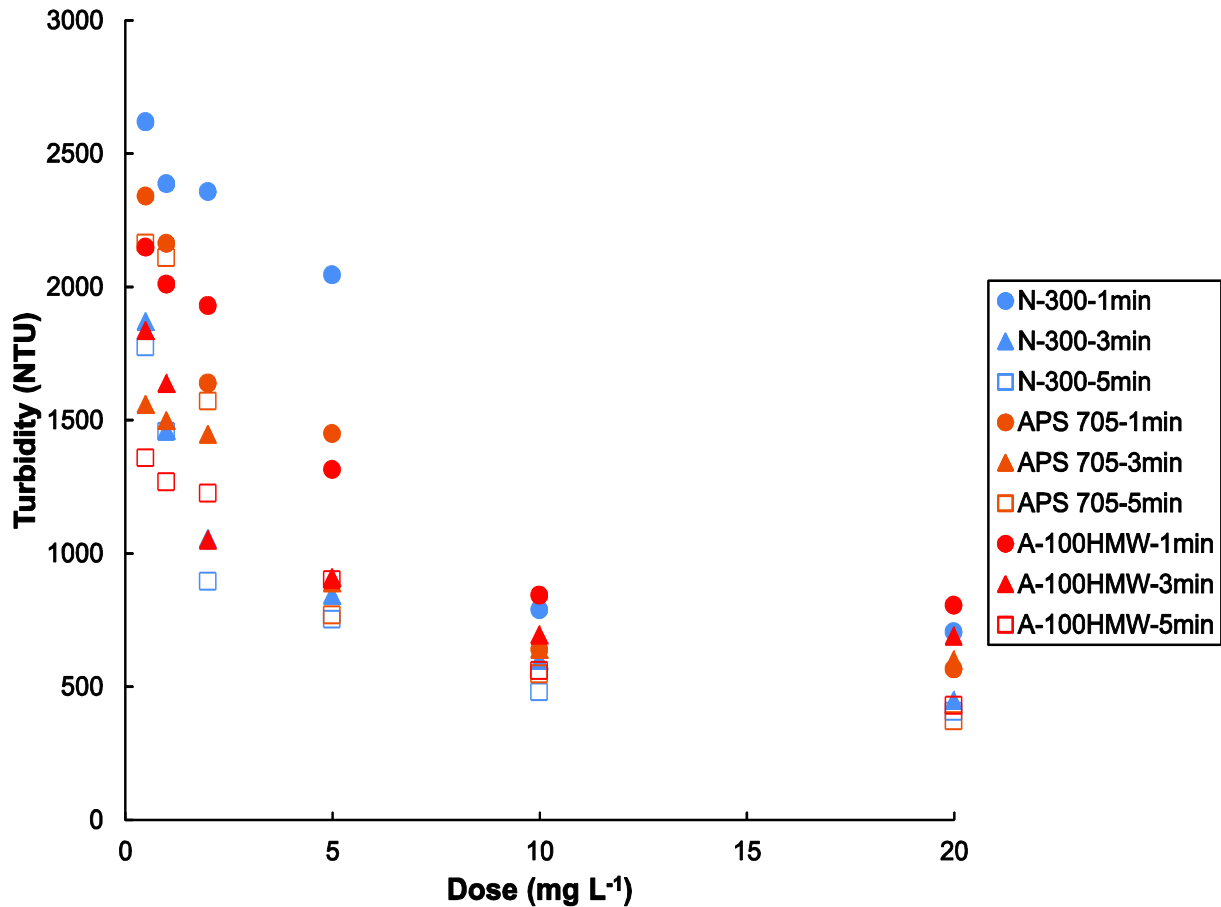
PAM can also be applied by passive means, such as PAM blocks in which turbid water flows over the PAM, partially dissolving the polymer leading to particle flocculation and settling (Kang et al., 2013). McLaughlin and Brown (2006) tested PAM blocks exposed to different flows and sediment loads. They 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.



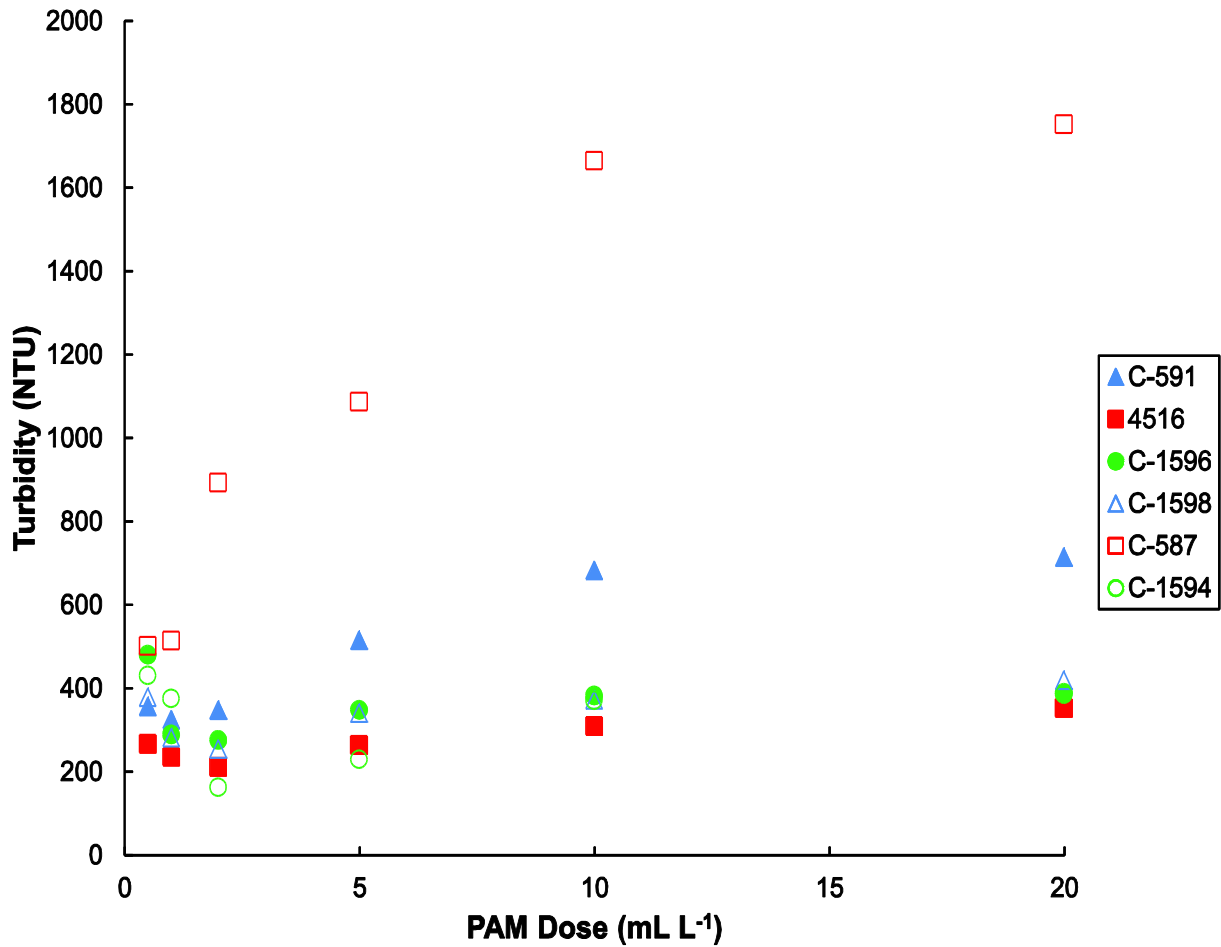
**Figure 3.1:** Turbidity of the supernatant following the Phase I Jar Tests with anionic PAMs using sample runoff waters collected from Highway 265. Mixing conditions were as follows: (A) high mixing which consisted of 5 min rapid mix at 200 rpm, 30 min slow mix at 60 rpm, and 30 min quiescent settling, (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.



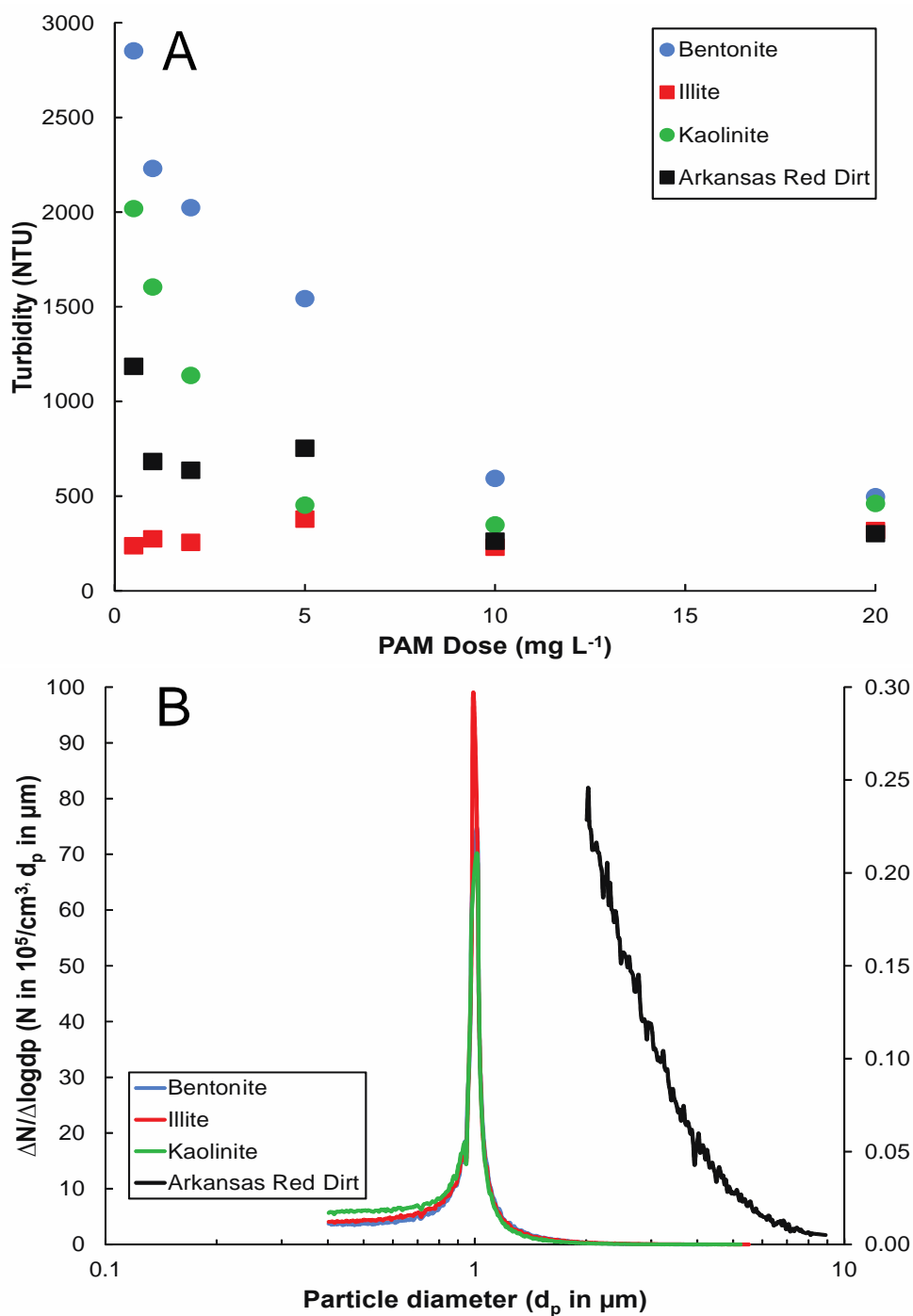
**Figure 3.2:** Turbidity of the supernatant following the Phase I Jar Tests with anionic PAMs using sample waters generated by blending Arkansas Red Dirt at 2 g L<sup>-1</sup> with (A) tap water and (B) Beaver Water District intake water. Mixing conditions were as follows: 15 sec rapid mix at 200 rpm, 5 min slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.



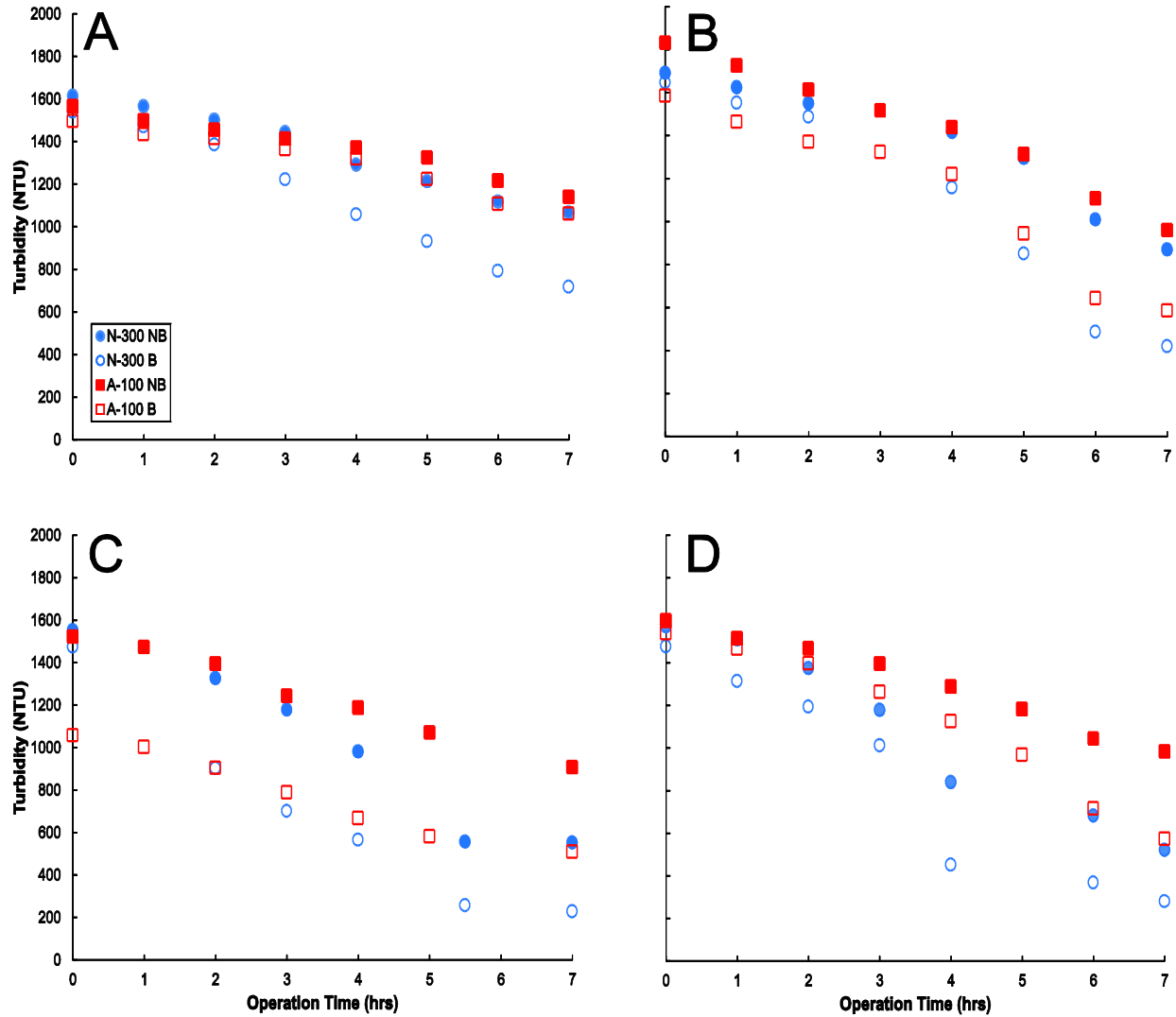
**Figure 3.3:** Turbidity of supernatant following the Phase I Jar Tests with anionic PAMs using sample waters generated by blending Arkansas Red Dirt with tap water at 2 g L<sup>-1</sup>. Mixing conditions were as follows: no rapid mix, 1- (blue symbols), 3- (orange symbols), or 5 min (red symbols) slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.



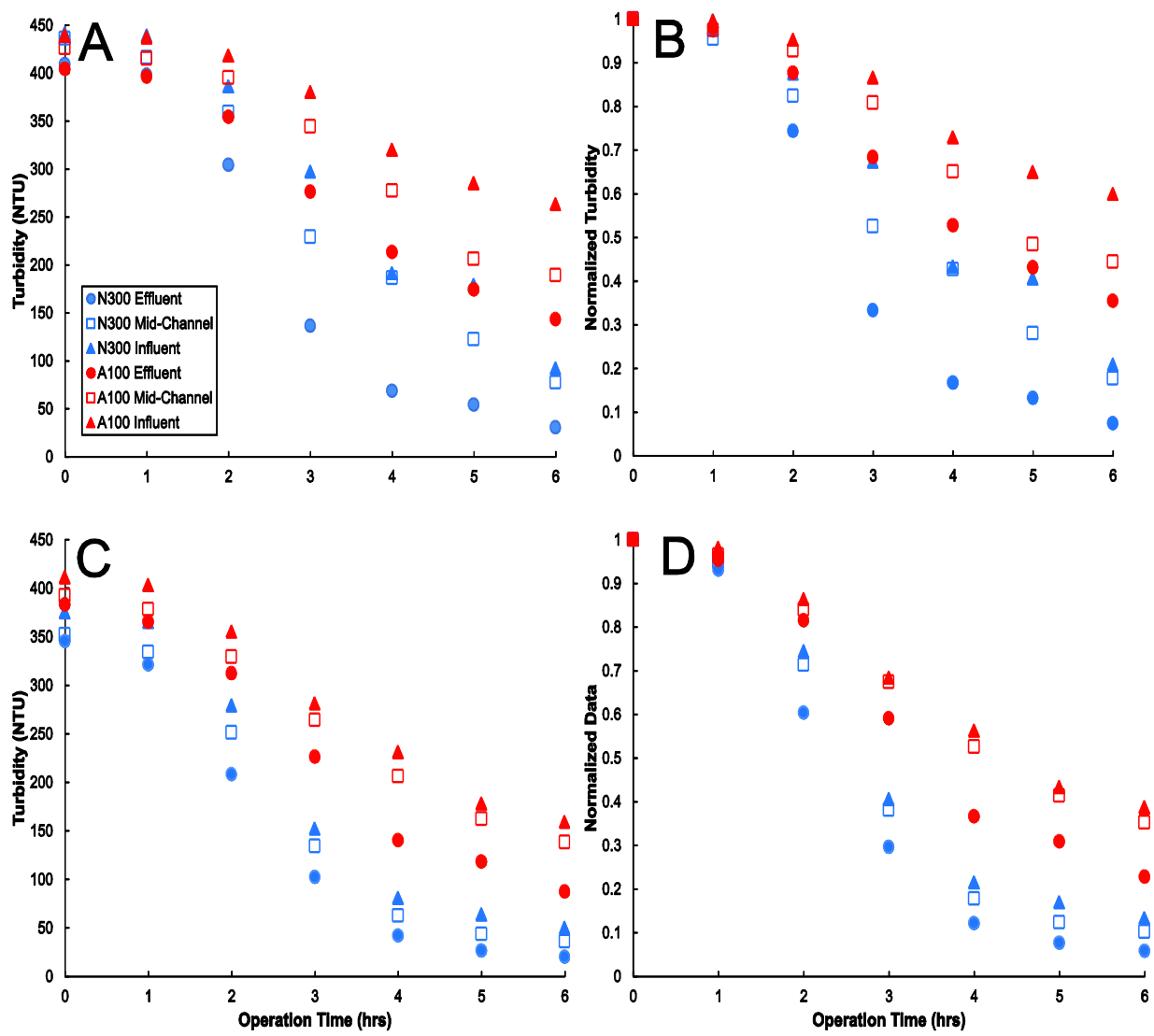
**Figure 3.4:** Turbidity of the supernatant following the Phase I Jar Tests with cationic PAMs using sample waters generated by blending Arkansas Red Dirt with tap water at  $2 \text{ g L}^{-1}$ . Mixing conditions were as follows: 15 sec rapid mix at 200 rpm, 5 min slow mix at 60 rpm, and 5 min quiescent settling; see Table 3.1 for a description of the PAM types.



**Figure 3.5:** (A) Turbidity of supernatant following the Phase I Jar Tests with Superfloc N-300 anionic PAM using sample waters generated by individually blending  $4 \text{ g L}^{-1}$  bentonite,  $4 \text{ g L}^{-1}$  illite,  $2 \text{ g L}^{-1}$  kaolinite, or  $2 \text{ g L}^{-1}$  Arkansas Red Dirt with tap 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. (B) Particle Size Distributions of soils used in the Phase I Jar Tests.



**Figure 3.6:** Turbidity of effluent waters in the Phase II Lab-scale Flocculation tests using water generated by blending 2 g L<sup>-1</sup> kaolin and tap water. The PAM types used were anionic Superfloc N-300 and Superfloc A-100 at doses of (A) 1 mg L<sup>-1</sup>, (B) 5 mg L<sup>-1</sup>, (C) 10 mg L<sup>-1</sup>, and (D) 20 mg L<sup>-1</sup>. NB denotes no baffling (closed symbols) and B denotes baffling (open symbols).



**Figure 3.7:** Turbidity of effluent waters in the Phase III Cato Springs Field Site Tests using water generated by blending 2 g L<sup>-1</sup> 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<sup>-1</sup>. Turbidity was measured at the influent, mid-channel, and effluent of the channel.



## 4 Conclusions

The objective of this research was to develop best management practices (BMPs) for the use of PAM to control turbidity in runoff waters at highway construction sites. These waters can exceed several thousand NTU due to heavy soil erosion during major rainfall events, well above the EPA regulation of 280 NTU (EPA, 2009). Several types of PAM with differing charge types, charge densities, and molecular weights were assessed for turbidity reduction in lab- and field-scale experiments. The optimal PAM type and dose was determined and the impact of channel baffling was quantified. The findings of our research were as follows:

- Anionic PAMs with lower charge density were more effective at decreasing the turbidity of runoff waters (Figs. 3.1 and 3.2) due to increased interparticle bridging.
- Cationic PAMs were ineffective at decreasing the turbidity of runoff waters (Fig. 3.4), suggesting that electrostatic interactions were an insignificant binding mechanism between the positively charged PAM types and negatively charged soil particles.
- The molecular weight of the anionic PAM types was not important for turbidity reduction (Fig. 3.1B), in contrast to other studies.
- The optimal PAM dose in the jar tests was  $\sim 10 \text{ mg L}^{-1}$  and insensitive to soil type and particle size (Fig. 3.5).
- In the lab-scale flocculation tests and field-scale experiments, channel baffling decreased effluent turbidities (Figs. 3.6 and 3.7), which was evidence of hydraulic flocculation.
- The optimal PAM type and dose was N-300 at  $10 \text{ mg L}^{-1}$  as determined in the lab- and field-scale experiments (Figs. 3.1, 3.2, 3.6, and 3.7). There was no benefit of increasing the PAM dose beyond  $10 \text{ mg L}^{-1}$  due to increased polymer coiling.

In January 2015, a site visit was coordinated with the AHTD and the resident engineer of the Bella Vista Bypass project in Northwest Arkansas. The purpose of the site visit was assess possible locations of erosion and sediment control measures for implementation of the PAM-based turbidity control measures. Two suitable sites were identified and testing is scheduled to take place in Spring and Summer 2015. Following this visit, it was determined that an active dosing system, such as the one tested at the Cato Springs field site, would not be feasible in the field. One study concluded that the construction of sedimentation basins with use of a PAM pumping system would account for 1.5% of total construction costs (McLaughlin, 2006). As such, future work is recommended on passive treatment systems with PAM blocks, which are designed to be placed upstream of sedimentation basins. The PAM is gradually released as water flows over the blocks and the subsequent sedimentation basins provide reaction time for PAM and sediment to flocculate. PAM blocks are an attractive option for further research because of its ease of implementation, but questions regarding their efficacy remain.

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