RESEARCH & DEVELOPMENT

Optimizing Factors of Sediment Flocculation in Construction Site Runoff

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NCDOT Project 2015-16

FHWA/NC/2015-16

April 2018

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA/NC/2015-16</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Optimizing Factors of Sediment Flocculation in Construction Site Runoff</td><td>5. Report Date
April 19, 2018</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Richard A. McLaughlin and Detlef Knappe</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Departments of Crop & Soil Sciences
North Carolina State University
Campus Box 7620
Raleigh, NC 27695</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Analysis Group

1 South Wilmington Street
Raleigh, North Carolina 27601</td><td>13. Type of Report and Period Covered
Final Report
August 2015 – December 2017</td></tr>
<tr><td>14. Sponsoring Agency Code
2015-16</td></tr>
<tr><td colspan="3">Supplementary Notes:</td></tr>
</table>

16. Abstract

Runoff from construction sites has received increased interest because high levels of turbidity can adversely impact aquatic life in receiving streams. The current practice is to use polyacrylamide (PAM) to flocculate and settle suspended particles prior to release of the storm water into the environment. Not much, however, is understood about factors that control the interactions between PAM and soil particles. The goal of this study was to both identify the factors that lead to optimal turbidity reductions and determine the best screening method that can be applied on construction sites.

Soil from 22 counties in North Carolina were collected and tested for flocculation with 13 PAMs. These had charge densities from 0.0 to 30% and molecular weight in the ranges standard (STD), medium (SH), and high (VHM). During the preliminary screening, soil suspensions were prepared at 10 g/L and tested with PAM concentrations ranging from 1.0 to 250 mg/L. Upon hand shaking for 10 seconds and sedimentation for 30 seconds, the supernatant water turbidity was measured. Nonionic polymers were more effective in reducing turbidity than their anionic counterparts. PAM concentrations of 1.0 and 5.0 mg/L led to the lowest turbidities in all soils tested, and increasing PAM concentrations gradually resulted in increased turbidities. The effect of PAM molecular weight was found to be dependent on the charge density of the PAM in use. Larger turbidity reductions were observed in soils with higher clay and silt content relative to the sandy soils.

Using a jar tester, the soil suspensions were also mixed with PAM at different intensities (G = 48, 130, and 640 s-1) for periods of 20 to 600 seconds. The results indicated that mixing intensity plays a key role in the flocculation of sediments. Only G values of 130 and 640 s-1 resulted in measurable turbidity reduction compared to the hand shaking test. The highest turbidity reductions were achieved at G = 130 s-1. In contrast to the hand-shaking results, anionic PAMs were more effective at reducing turbidity than the nonionic one. This suggests that the choice of the most effective PAM also is dependent upon the screening method used. Increasing mixing time using the hand-shake test negatively affected the performance of the nonionic PAM with the soils with substantial clay and silt content. However, on the jar tester, an increase in mixing time resulted in reduced turbidity for all soils, regardless of the PAM used.

To evaluate the effectiveness of PAM on the field relative to the laboratory experiments, two 17-meter-long model ditches were constructed at the Sediment and Erosion Control Research and Education Facility (SECREF) of the Crop and Soil Sciences Department of North Carolina State University. Four PAMs having charge density 0, 3, 10, and 30%, respectively, were used. Following the flocculation tests, conducted with 0, 1, and 3 check dams installed across the channels, the anionic PAM with 3% charge density consistently achieved the highest turbidity reductions in all soils tested. This suggests that the jar tests may better predict PAM performances on construction sites, compared to the hand-shake method. Furthermore, no significant difference was found between the effects of 1 and 3 check dams on turbidity reduction in all soils used for the tests.

17. Key Words Flocculation, polyacrylamide, sediment, turbidity, construction site stormwater, coagulation	18. Distribution Statement

20. Security Classif. (of this page) Unclassified	21. No. of Pages 91	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Acknowledgments

Much of the work in generating the data for this report was done by graduate student Harold Hounwanou, MS candidate, Department of Civil, Construction, and Environmental Engineering, and technician Jamie Luther in the Department of Crop and Soil Sciences. Additional support was provided by a number of undergraduate students from NCSU, University of Texas, and Germany.

Executive Summary

A wide range of factors in the flocculation of suspended sediment were examined in this study with the goal to optimize these factors in the field. As has been demonstrated elsewhere, flocculation success, as measured by turbidity reduction, is a product of soil and flocculant properties and the physical processes involved. Soils from the Coastal Plain tended to be less reactive to the polyacrylamide (PAM) flocculants than Piedmont or Mountain region soils, although the latter had much higher turbidities. This may be a combination of minerology and particle size distribution, with much less clay and fine silt in the Coastal Plain but with a higher proportion of 2:1 clays which are difficult to flocculate. The optimal concentration of PAM for turbidity reduction was nearly always in the 1 – 5 mg L^{-1} range, and adding more often increased turbidity. The screening methods tested, a hand-shake method commonly used for construction site applications and a mechanical jar tester used in the water treatment industry, produced different results in some cases. However, the choice of method is unlikely to affect turbidity reduction in the field. Tests conducted with different mixing energies (time x paddle speed) suggested there was an optimal energy needed for maximum turbidity reduction and additional energy inputs were generally counterproductive. Tests in a simulated ditch usually produced similar turbidity reductions as in the laboratory, especially when at least one check dam was present. Coagulants commonly used in water treatment were much less effective than PAM and did not improve PAM performance when

introduced together. Some of these can also lower pH at the concentrations at concentrations where any effect was apparent, and much more material would be needed to apply these to runoff. There was some correlation between soil Ca and pH and turbidity reduction, but overall the current method of screening target soils with multiple PAMs appears to be the most effective approach to selecting a PAM for a project.

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Background

High erosion rates occurring during construction activities have recently received increased scrutiny. Each year, up to 5.4 x 108 Mg of sediment eroded from construction sites is discharged into the environment (Przepiora et al., 1998; U.S.EPA, 1993), resulting into highly turbid bodies of water. Increased levels of turbidity constitute a major water quality issue, which can diminish the aesthetic value of lakes and rivers and negatively affect the aquatic life (Przepiora et al., 1998). Excessive levels of suspended solids have been shown to cause gill damage and abrasion in fish (Clark et al., 1985). Furthermore, they can block sunlight from penetrating into the water and reduce the oxygen levels in slow-moving waters (Bartholomew, 2003). Fishing also becomes difficult, as fish can hardly see lures in turbid waters (Clark, 1985). In the drinking water treatment industry, a higher sediment load in raw water inevitably translates into higher treatment costs associated with the need of larger quantities of chemical coagulants and larger sedimentation basins (Clark, 1985).

In light of the negative impacts of highly turbid runoff, federal and state regulations now require that developers design and implement erosion and sediment control systems on construction sites (Przepiora et al., 1998). In addition, turbidity limits were set to attenuate the impacts of runoff discharged into surface waters. A numeric turbidity limit of 280 nephelometric turbidity units (NTU) for stormwater discharged from construction sites was imposed by the U.S. Environmental Protection Agency (U.S.EPA, 2009). Practically, compliance with such a value turned out to be arduous. Consequently, the limit was later challenged in court and withdrawn. Rounce et al. (2012) explain that respecting a numerical effluent limit may be particularly challenging for highway construction projects, since they often have many discharge locations. However, this challenge did not stop the State of North Carolina from enacting and enforcing one of the most stringent sediment and erosion control plans of the nation (Bartholomew, 2003; Burby et al., 1990). N.C. Administrative Code 15A NCAC 02B .0211 limits the turbidity of discharged water to 50 NTU for non-trout streams, 10 NTU for trout waters, and 25 NTU for lakes and reservoirs not designated as trout waters (NC DENR, 2002).

Therefore, best management practices (BMPs), such as temporary silt fences, silt ditches, and sedimentation basins are now well-established conventions. The purpose of such systems is to retain eroded sediments within the limits of construction sites (Kang et al., 2014c). And it has been demonstrated that they can prevent up to 90% of sediment from escaping the boundaries of development areas, depending on the influent particle size distribution (Bhardwaj & McLaughlin, 2008; Fennessey & Jarrett, 1994; Hayes et al., 2005; Kang et al., 2014c). Nonetheless, substantial levels of turbidity are still recorded in water discharged from these sediment control systems. During a twelve-month-long study, Przepiora et al. (1997) observed that turbidity of water discharged from two sedimentation basins in the North Carolina Piedmont region always varied between 120 and 3200 NTU. The reason is that finer sediment particles, responsible for high turbidity, settle very slowly and are very difficult to trap (Burby et al., 1990; Line & White, 2001). For instance, Line and White (2001) examined sediment discharge from three entrapment devices in North Carolina and found that they only retained 21 to 40% of clay and 43 to 72% of silt. Moreover, previous research actually showed that runoff containing more than 20% of soil particles finer than 20 µm would necessitate some form of chemical flocculation to meet the targeted discharge water quality (Fennessey & Jarrett, 1994).

Montgomery (1968) stated that addition of polyacrylamide (PAM), a synthetic, water-soluble polymer, to suspensions of fine particles promoted flocculation, leaving a clear supernatant after the flocs had settled. The prospective use of PAM to reduce turbidity levels in runoff from construction sites stemmed from its effectiveness in many other applications. Extensive research has proved the efficacy of PAM, particularly in the agricultural field. As a soil conditioner, it has been used to stabilize soil aggregates, reduce erosion and runoff in furrow irrigation, and minimize surface sealing in rain-fed agriculture (Ben-Hur et al., 1989; Green & Stott, 1999b; Green et al., 2000; Lentz et al., 1992; Lentz & Sojka, 1994; Levy et al., 1992; Mamedov et al., 2007). Due to its versatility, not only has PAM now emerged as an ideal candidate to help achieve discharge water quality goals on construction sites, but findings from recent research have also confirmed its potential in doing so.

McLaughlin and Bartholomew (2007) tested the efficacy of different PAM products at reducing turbidity in thirteen (13) soils collected from active construction sites around the State of North Carolina. Flocculation of five soils with all PAMs resulted in percent turbidity reductions north of 96%. However, two other soils showed increased turbidity for concentrations of anionic PAMs higher than 0.5 mg/L, whereas the remaining six soils displayed no linear response to flocculation with PAM. More recently, Rounce et al. (2012) analyzed PAM effectiveness at reducing turbidity in six runoff suspensions. The suspensions were prepared with soils collected at six Texas construction sites and were tested against different PAM products at concentrations ranging from 0.03 to 10 mg/L. They found that the neutral PAM, dosed at 10 mg/L, was very effective at lowering the turbidity of all the suspensions. As for the negatively charged PAMs, they were able to cause substantial turbidity reductions in only two soils when added at 1 mg/L. Additionally, when combined with conventional sediment and erosion control systems, PAM was able to further reduce turbidity to values lower than the ones obtained with the systems alone. Kang et al. (2014b) assessed the performance of three sedimentation basin configurations with and without PAM application. In all three cases, turbidity at the basin exit was significantly lowered when PAM was used. Application of PAM resulted in percent turbidity reductions higher than

88%, and they also observed that PAM performance was independent of basin configurations. In a rainfall simulation study, the performance of an excelsior erosion control blanket was also found to be greatly improved by PAM, regardless of the application method (Kang et al., 2014a).

Although PAM shows great potential at improving discharge water quality, there are still notable variabilities and inconsistencies in its performance. Research shows that many factors, such as PAM characteristics, play an important role in their effectiveness at flocculating soil particles. Here, a brief review of the background of polyacrylamide polymers is useful in shedding some light on the properties that may be key to the flocculation process.

Successful turbidity reduction in construction site runoff is dependent on the properties of both the soils and the PAMs used. Soil properties such as type, clay content, soil solution ionic strength, type of ions in solution, and pH are described as key to the process, while important PAM properties are type, amount of surface charge, polymer configuration, and molecular weight (Seybold, 1994). McLaughlin and Bartholomew (2007) performed a series of jar tests (hand-shake) to investigate the effect of these different properties on flocculation. They tested thirteen (13) different soils from construction sites in North Carolina with thirteen (13) different PAM products. They found that particle size distribution, extractable iron (Fe), soil mineralogy, calcium content, and pH influenced flocculation to various degrees.

Soil texture was described as an important factor in the efficacy of PAM at both controlling erosion and stabilizing soil aggregates (Green et al., 2000; Miller et al., 1998; Nadler et al., 1994). There is, however, little information on its importance in turbidity reduction. To our knowledge, the only known conjecture regarding the influence of soil texture on turbidity reduction was made by McLaughlin and Bartholomew (2007). For the sample of soils they analyzed, the effectiveness of PAM at decreasing turbidity seemed to worsen with increasing sand content. They concluded that sand might be a good indicator of PAM effectiveness for a given sample of soils.

Turbidity reduction in runoff from construction sites has also received a particular attention. However, most studies of the subject have focused on (1) finding the most effective PAM, (2) determining the best method of application of PAM, and (3) improving the performance of BMPs with PAM to lower runoff turbidity before its discharge into the environment (Babcock & McLaughlin, 2013; Bhardwaj & McLaughlin, 2008; Kang et al., 2014a; Kang et al., 2014c; Kang et al., 2013; McLaughlin & Bartholomew, 2007). Review of the literature uncovered only one study with an explicit emphasis on the effects of PAM characteristics on turbidity in construction site runoff. Rounce et al. (2012) experimented with the charge densities, 0, 10, 16, and 50%, and found that the nonionic PAM (0% charge density) led to the lowest turbidity values in all soils. In addition, a mixed polymer with undisclosed characteristics, APS 705, effectively reduced the turbidity of all soils suspensions. This polymer, which is presented in the

Materials and Methods section, has also been reported as being effective with soils difficult to flocculate with nonionic or anionic PAMs (McLaughlin & Bartholomew, 2007). Regardless of the domain of application, PAMs with higher molecular weight are consistently reported as being the most effective. The effectiveness of HMW PAMs is due to the longer chain's ability to extend and bridge a higher number of suspended particles.

To reduce erosion and control turbidity on construction sites, best management practices (BMPs) such as check dams have become standard practice. Check dams are hydrologic structures widely used across the world for sediment retention, water capture, groundwater recharge and carbon retention (Kang et al., 2013). On construction sites, they are typically installed across the ditches, where they help reduce the velocity of runoff, decrease its turbidity by trapping soil particles, and limit erosion (Hsieh et al., 2013; Kang et al., 2013; McLaughlin et al., 2009). Commonly made of large rock or gravel (traditional BMPs), check dams can also be built with other materials, such as geotextile-covered foam and wattles made of natural wood or coconut fibers (McLaughlin et al., 2009).

Several studies have highlighted the efficiencies of different types of check dams in reducing turbidity, particularly when they were combined with PAM. For instance, McLaughlin (2003) showed that sediment trapping efficiencies averaged 77% for check dams made out of large rocks, while those with gravel had an efficiency of almost 90%. Kang et al. (2013) tested three distinct check dams – rock check dam, excelsior wattle or fiber check dam, rock check dam covered with an excelsior erosion control blanket – with and without applied granular PAM. They observed that ditch effluent turbidity was reduced by more than 80% relative to check dams without PAM treatment. A field study conducted on two roadway projects in North Carolina also found benefits of combining PAM and fiber check dams to reduce turbidity runoff from construction sites (McLaughlin et al., 2009).

There have not been any studies which examined the influence of the number of check dams on turbidity removal. As a rule of thumb, check dams are usually installed along the ditch with the bottom of each check dam even with the top of the following one. Depending on the size of the construction project and the site conditions such as the slope of the terrain, this installation technique may lead to a relatively high number of check dams and, thus, increase the costs of erosion and turbidity control measures.

In this study, the potential factors which affect turbidity control in construction sites runoff are explored. The factors studied included soil texture, PAM concentration, PAM charge density and molecular weight, mixing time and intensity, and the screening method. In addition, a model ditch was used to measure the effects of check dams on flocculating turbid water.

The overarching goal was to study the factors involved in turbidity reduction in construction site runoff. Specific objectives included:

- Evaluating the effect of soil properties on effective flocculation with PAM;
- Examining the influence of PAM properties and concentrations on turbidity reduction;
- Determining the effect of mixing intensity and mixing time on turbidity reduction;
- Comparing turbidity reduction using the paddle-type jar test and the manual shaking methods.
- Selecting PAMs that provided successful treatment during laboratory analyses and evaluate their effectiveness on the field
- Determining the screening method – jar test or hand-shaking test – which best predicts PAM behavior on the field.
- Ultimately, the goal was to help determine which PAM products will effectively control turbidity on many construction sites across the State of North Carolina.

Methods:

Soil and PAM Analysis:

The North Carolina Department of Transportation (NCDOT) collected soil samples from active construction sites in twenty-two counties (Table 1). These soils had a range of textures and represented a wide variety of sediment sources encountered across the State of North Carolina. They were collected from layers of subsoil at unknown depths. Prior to the analyses conducted throughout this study, all soil samples were air-dried and ground until they passed through a 2-mm sieve. Soil samples will be designated in this study by the name of their respective county of origin.

Soil texture was determined in the Soil Physical Properties Laboratory of the North Carolina State University Crop and Soil Sciences Department using the hydrometer method (Gee & Bauder, 1979)(Table 1). Two samples of each soil were also provided to the Agronomic Services Division of the North Carolina Department of Agriculture & Consumer Services to determine nutrient and organic matter content.

Table 1: Percentages of sand, silt and clay, as well as textural analysis for each of the county soils collected for this study.

County of origin	% Sand	% Silt	% Clay	Texture
Bladen	97.8	1.90	0.30	Sand
Carteret	94.8	3.00	2.20	Sand

Brunswick	86.3	3.80	4.90	Loamy sand
Cumberland	87.3	5.70	7.00	Loamy sand
Gates	70.2	19.4	10.5	Sandy Loam
Vance	68.4	21.0	10.6	Sandy Loam
Buncombe	67.0	24.2	8.70	Sandy Loam
Guilford	65.8	23.4	10.8	Sandy Loam
Wilkes	62.0	19.6	18.3	Sandy Loam
Yancey	59.6	26.7	13.7	Sandy Loam
Durham	57.2	31.8	11.0	Sandy Loam
Watauga	55.5	36.3	7.80	Sandy Loam
Wake	55.0	26.2	18.8	Sandy Loam
Nash	54.4	29.8	15.7	Sandy Loam
Davie	50.4	33.5	16.1	Loam
Washington	48.2	29.2	22.6	Loam
Lee	34.9	44.4	20.7	Loam
Burke	29.9	51.5	18.6	Silt loam
Iredell	27.0	50.9	22.0	Silt Loam
Stokes	23.1	55.8	21.2	Silt loam
Chatham	12.0	37.3	50.7	Clay
Rowan	28.4	31.4	40.2	Clay

Thirteen PAMs were selected for initial screening for turbidity reduction (Table 2). A large variety of molecular weight and charge density characterized these polymers, which were obtained from SNF (Riceboro, GA, USA), with the exception of APS 705. The charge density varied from 0% to 30% molar charge, while the molecular weights (MW) evaluated fell in the categories Low or Standard (STD), Medium (SH), and High (VHM). Definitions of these MW ranges are provided by Barvenik (1994) as follows:

- Standard: < 105 g mol^{-1}
- Medium (SH): 105 – 106 g mol^{-1}
- High (VHM): > 106 g mol^{-1}

APS 705, a mixture of different PAM products manufactured by APPLIED POLYMER SYSTEMS (Woodstock, GA, USA), was also used. However, the PAMs included in the mixture are proprietary so are unknown to us, but are all anionic (Steve Iwinski, former APS owner, personal communication). All polymers tested were used in dissolved form. To obtain the dissolved form, granular PAM was mixed in distilled water for 24 hours at 0.5 g L^{-1}.

Table 2: PAM products tested and their respective characteristics.

PAM	Charge	Charge Density	Molecular Weight
FA 920	Nonionic	0%	Standard
FA 920 SH	Nonionic	0%	Medium
FA 920 VHM	Nonionic	0%	High
AN 905	Anionic	3%	Standard
AN 905 SH	Anionic	3%	Medium
AN 905 VHM	Anionic	3%	High
AN 910 VHM	Anionic	10%	High
AN 913 VHM	Anionic	13%	High
AN 923	Anionic	20%	Standard
AN 923 SH	Anionic	20%	Medium
AN 923 VHM	Anionic	20%	High
AN 934 VHM	Anionic	30%	High
APS 705	Unknown	Unknown	Unknown

Laboratory Testing:

A number of different tests were performed in the laboratory to examine the effect of each variable on turbidity. The primary variables tested were hand-shaken vs. jar tested (further details below), type of polyacrylamide, concentration of PAM, concentration of soil in solution, amount of time solution is left to rest, as well as how continued agitation and resting would affect the PAM's efficacy.

Turbidity for all samples was determined with an ANALITE NEP9000 nephelometer (McVan Instruments, Melbourne, Australia), and each soil-PAM combination was replicated three times with the average being reported. The majority of the readings were taken after 30 seconds of settling, and can be assumed as such, unless otherwise stated. This sedimentation period helps to minimize variations produced by turbulence in the suspensions and continued settling over time (Bhardwaj & McLaughlin, 2008).

Hand-shake Test:

The hand-shake test is a screening method used to determine the effectiveness of PAM products for reducing turbidity in soil suspensions. Its goal is to select the PAM product which rapidly reduces the murkiness of a specific soil suspension. The experimental procedure consists of adding a predetermined volume or amount of PAM to a clear container filled with a mixture of water and the soil of interest. The mixture PAM + soil suspension is then shaken manually for 10-20 seconds and left to settle for

30 seconds (Bhardwaj & McLaughlin, 2008). Upon sedimentation, the turbidity of the settled water is measured, and the PAM responsible for the lowest turbidity value is chosen for field treatment. For our analyses, clear 100-mL specimen cups were used (Figure 1). The soil suspensions were prepared at 10 g L^{-1}, and after PAM addition, the mixture was shaken for 10 s followed by 30 s of settling prior to turbidity measurement.

Figure 1: Two 120-mL specimen cups used in the hand shake test.

Jar Test

The jar tests in this study were implemented on a programmable jar tester (Model 7790-901B, Phipps & Bird, Richmond, VA, USA ; Figure 2). It is equipped with six square, 2-Liter beakers and six single-blade paddles, which can rotate at speeds ranging from 5 to 300 rpm and can be run continuously for up to an hour. For all tests conducted on the jar tester, the soil samples were mixed for 15 seconds to promote particle suspension before addition of PAM.

Figure 2: Phipps & Bird PB7790-901B jar tester used.

The impact of mixing intensity on turbidity removal was evaluated by varying the fluid shear and the mixing time in the jar tester. Typically called the average velocity gradient, fluid shear is a parameter used to describe turbulent mixing in a flocculation reactor (Saffman & Turner, 1956). Jar tests were conducted at three different rotational speeds, 50, 100, and 300 rpm, corresponding respectively to velocity gradient values of 48, 130, and 640 s^{-1}. Specific mixing times for each rotational speed were determined (Table 3) to keep the collision potential constant. The term collision potential, is a measure of the extent of flocculation in a reactor (Tse et al., 2011). In addition, increased mixing intensities may promote higher rates of collision between PAM molecules and soil particles, hence better flocculation and improved turbidity reduction performances.

Two PAM products, FA 920 (Chemtall Inc., Riceboro, GA, USA) and APS 705 (Applied Polymer Systems Inc., Woodstock, GA, USA) were used at 1 mg L^{-1} to flocculate the Wake County soil. Samples of soil suspension were prepared by adding 1 L of water to 10 grams of soil. Upon mixing, the residual turbidity was measured after settling for 30 seconds. The tests were conducted with three replications per test.

Table 3: Mixing times and resulting collision potential values evaluated

Collision Potential	**48 s^{-1}**	**130 s^{-1}**	**640 s^{-1}**
	seconds		
19200	400	148	30

38400	800	295	60
76800	1600	590	120
96000	2000	738	150
192000	4000	1477	300

Addition of Coagulants:

A number of coagulants were tested in conjunction with PAM for the purpose of turbidity reduction. These included $AlCl_3$, Poly $AlCl_3$, CaCl and $FeCl_3$ (40% w/v), all of which were tested at concentrations of 0, 1, 2, 5, 10 and 25 mg L^{-1}. The only soils used were from Carteret, Chatham, Durham and Wake counties, all of which were added at 10 g L^{-1}. $FeCl_3$ (40% w/v) was only tested on the Lake Wheeler soil. Four PAMs were included in this study: APS 705, FA 920, 913 VHM and a 50:50 mix between FA 920 and 913 VHM. These were each tested at concentrations of 0, 0.5 and 1 mg L^{-1}.

Effects of Increased Sedimentation Time:

Soil from Wake county was used in this study to determine the extent and rate of turbidity reduction when no mixing was performed after time zero. Similarly to other tests, all samples were hand-shaken for ten seconds, but instead of only reading turbidity at 30 seconds, turbidity was also measured at 30 minutes, 2 hours and 24 hours after initial mixing. Six PAMs were used in this study, including AN 913 VHM, AN 923, AN 923 SH, AN 923 VHM, APS 705 and FA 920. Thirteen PAM concentrations were tested for each PAM: 0, 0.25, 0.5, 0.75, 1, 2, 5, 7.5, 10, 25, 50, 100 and 250 mg L^{-1}. All tests used a soil concentration of 5 g L^{-1}.

PAM Effectiveness over Time and Repeated Agitation:

This section describes two separate but related tests, using a Piedmont (8) and a Mountain (13) soil from a previous project. APS 705 was used for both tests at concentrations of 0, 1, 5 and 10 mg L^{-1}. The first test evaluated suspension turbidity over a period of twenty days to determine if resuspended sediment produced similar turbidities over time. To initiate the test, PAM was added to all samples and shaken for 10 seconds, while the first reading of turbidity occurred after 30 seconds of settling (Day 1). This procedure was repeated on Day 2, Day 5, Day 10 and Day 20, with no additional PAM added to the sample.

The other test used the same PAM, PAM concentration and soils, but the suspension was repeatedly shaken after each measurement. This was to determine if the flocs would break up and the turbidity increase, or if more soil would flocculate with additional agitation. Similarly to the first test, PAM was added and the container was shaken for 10 seconds and then settled for 30 seconds before a turbidity measurement was taken. After recording the turbidity, the sample was immediately shaken again for 10 seconds, and the whole process repeated for a total of 5 measurements in succession.

Supernatant:

A test was conducted to determine if the smaller size fraction of the soil was more difficult to flocculate and settle than the whole soil. This was because in most cases, the larger size fraction (sand, large silt) is likely to settle quickly during the erosion process and the water being treated for turbidity will only have the finer fraction present. A laboratory test was performed using seven different soils (Burke, Chatham, Iredell, Durham, Wake, Vance and Rowan) and 4 PAMs (913 VHM, APS 705, FA 920, a mix of FA 920 and 913 VHM, as well as a control with no PAM added). All PAMs were tested at concentrations of 0.5, 1 and 5 mg L^{-1}, with 10 mg L^{-1} being added in for the FA 920 and 913 VHM PAM mixture. Initial soil concentration for all tests was 10 g L^{-1}. Thiswas shaken for 10 seconds and the supernatant was poured of at either 30 or 60 seconds later. The collected supernatant was then tested with the various PAMs and concentrations for turbidity reduction.

Field Testing: Simulated Ditches

This study was conducted at the Sediment and Erosion Control Research and Education Facility (SECREF) of the Soil Science Department at North Carolina State University. Four soils obtained in Wake, Lee, Burke, and Rowan counties were used for the testing. These soils represent a range of soil texture and mineralogy encountered in North Carolina. Four PAMs, FA 920, AN 905 VHM, AN 913 VHM, and AN 934 VHM were used in these experiments. The polymers were all high molecular weight (HMW) PAMs and had charge densities of 0, 3, 13, and 30%.   All were manufactured by SNF, Inc., Riceboro, GA, USA.

The experimental setup (Figure 3) consisted of:

- Two 17 m model channels sloped at 1% and 3%, respectively, using a platform made out of a series of three-foot-long wooden stakes; four 30 cm (12 in) PVC sewer pipes were halved longitudinally and used as the model channels.
- A 170 L tank used to mix the soil suspensions;
- An electric trolling motor (MotorGuide model T34, Attwood Marine, Lowell, MI) used to keep the soil particles suspended in the tank;

- Two 5.08 cm (2 inches) ball valves (Norwesco, Inc., St. Bonifacius, MN, USA) used to control the flow of soil suspensions out of the tank;
- Two 22.7 L tubs that received the soil suspension before its release into the channels. This is done in an upward movement from the bottom of the buckets to reduce the variation of the flow into the channels;
- A 5.08 cm (2 in) diameter discharge hose used as a connection between the tank and the buckets.

Figure 3: Experimental setup for the ditch simulator for field testing.

Turbid suspensions were generated by manually adding 1,700 g of each soil to 170 L of water in the tank to produce water with 10 g L^{-1} of sediment. This value matches concentrations tested in the lab and is within typical sediment concentrations recorded on construction sites in North Carolina (Line & White, 2001). The ditch simulations consisted of two series of experiments.

In the first set of tests, no check dams were used. The soils from Wake, Burke, and Rowan counties were flocculated with the four polymers as follows. During each run, the valve was opened halfway to release 57 L of soil suspension into the channel. Residence times were visually estimated using a dye and were 30 s and 24 s in the 1% and 3% channels, respectively. Considering the length of the ditches, 17 m, these correspond to flow velocities of 0.57 m s^{-1} and 0.71 m s^{-1}. One mg L^{-1} of each PAM was manually dosed at the entrance of the channels by slowly adding 114 mL of PAM solution prepared at 0.5 g L^{-1}. To ensure contact of PAM with the whole volume of soil suspension, dissolved PAM was added manually at approximate rates of 3.8 mL s^{-1} and 4.75 mL s^{-1} in the 1% and 3% sloped channels, respectively. Dosing the PAM at 1 mg L^{-}

[1] allowed for comparisons with results of laboratory testing performed at the same PAM concentration. For single runs, samples of suspensions (400 mL) were taken at the exit of the ditch simulator. The samples were swirled slightly, and turbidity was measured after 30 s of sedimentation. All soil and PAM combinations were replicated three times in each channel, for a total of 72 runs.

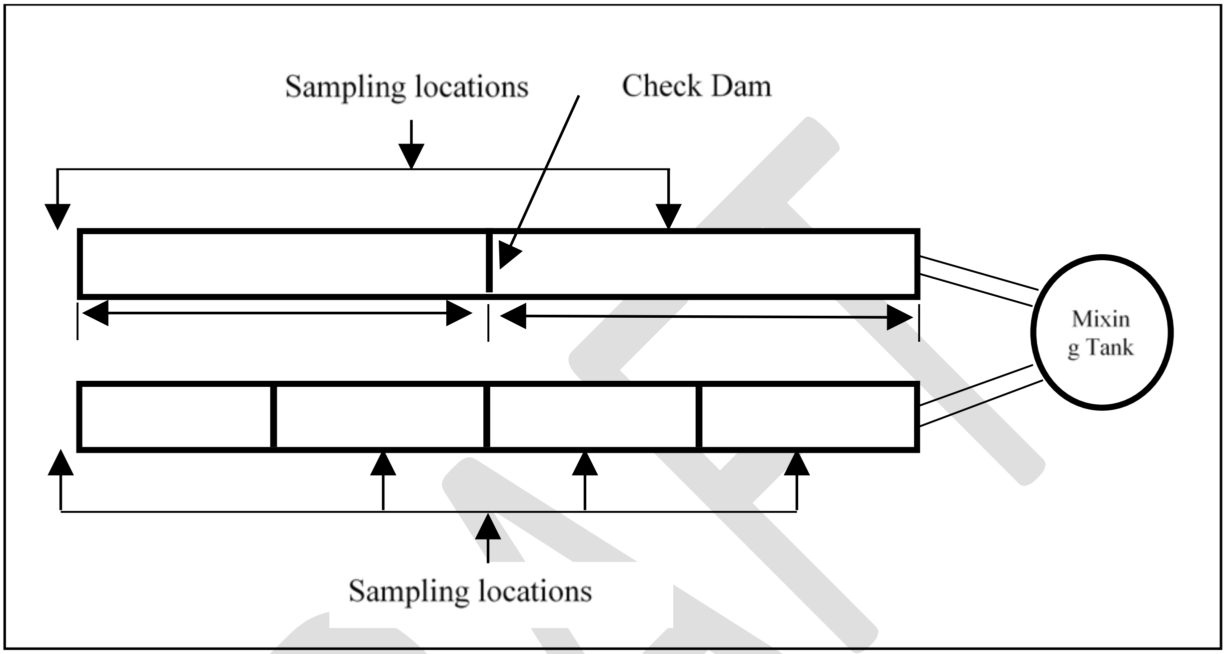

Figure 4: Schematic of Ditch Simulator showing sampling points for channels with one and three check dams.

In the second series of simulations, the impact of installing check dams across the ditches on turbidity was evaluated. The check dams were 30 cm long and 2.54 cm diameter foam insulation for water pipes. These were glued with silicone in the channels perpendicular to the flow (Figure 5). The experiments were conducted with either one or three check dams in both channels. The check dams were placed (1) halfway in the ditches at 8.5 m for one and (2) evenly spaced (5.67 m between) for three check dams. Soils from Wake, Lee, and Rowan counties and the anionic PAM AN 913 was used since this polymer was the most efficient at reducing turbidity in these soils in jar tests. Three runs were executed for each soil + PAM combination in both channels. Overall, thirty-six (36) runoff simulations were carried out. The PAM was introduced in the same manner as described above. The number of sampling points increased to 2 and 4 for one and three check dams, respectively (Figure 3.3) to monitor the progression of turbidity removal along the ditches. These changing turbidities along the channels and at their exit are presented in the results section. Before conducting these two series of experiments, the initial turbidity of each soil suspension was measured by executing three runs in the ditches without the addition of PAM. All samples collected throughout the field testing were swirled slightly prior to turbidity measurement, and turbidity was measured with an ANALITE NEP9000 nephelometer (McVan Instruments, Melbourne, Australia) after 30 seconds of sedimentation.

During the transition from one soil to the other, the mixing tank was disconnected from the experimental setup and thoroughly washed to remove remnants from the previous soil.

Figure 5: Experimental setup showing check dams in place across the simulated ditches.

In a final analysis, results of both these field experiments and laboratory testing are compared. For this purpose, flocculation tests were performed on the jar tester, prior to the field testing. Soil suspensions from Wake, Lee, Burke, and Rowan Counties were prepared at 10 g L^{-1} and dosed with 1 mg L^{-1} of various PAM products. Each soil + PAM combination was mixed at 100 rpm for 30 seconds, and turbidity was measured after settling for 30 seconds. Results of these jar tests helped determine which combinations of PAM and soil to test on the field. Comparison of both sets of results was used to determine which G*t value most closely predicts the ones achieved on the field.

Results

Coagulant Effects on Turbidity and Interactions with PAM

Several inorganic coagulants commonly used for water treatment were tested on four soils to determine their effectiveness in reducing turbidity. For the Carteret soil, which produced very little turbidity at the 10 g L^{-1} level tested, there was no clear response to increasing concentrations of any of the three coagulants test (Figure X). For the remaining three soils, all Piedmont sourced with turbidities in the 300-800 NTU range, the coagulants did appear to reduce turbidity (Figures 6-8). $AlCl_3$ had an optimal dose range in the 5-10 mg L^{-1} range and $CaCl_2$ had little response to concentration. $FeCl_3$ (anhydrous) was optimal at 25 mg L^{-1} for the Chatham soil and 1 mg L^{-1} for the others, although concentration effect was not pronounced. None of these ranges were statistically superior, however. $FeCl_3$ (40% w/v) was only tested on the Lake Wheeler soil and the lowest dose tested (10 mg L^{-1}) appeared to be the most effective.

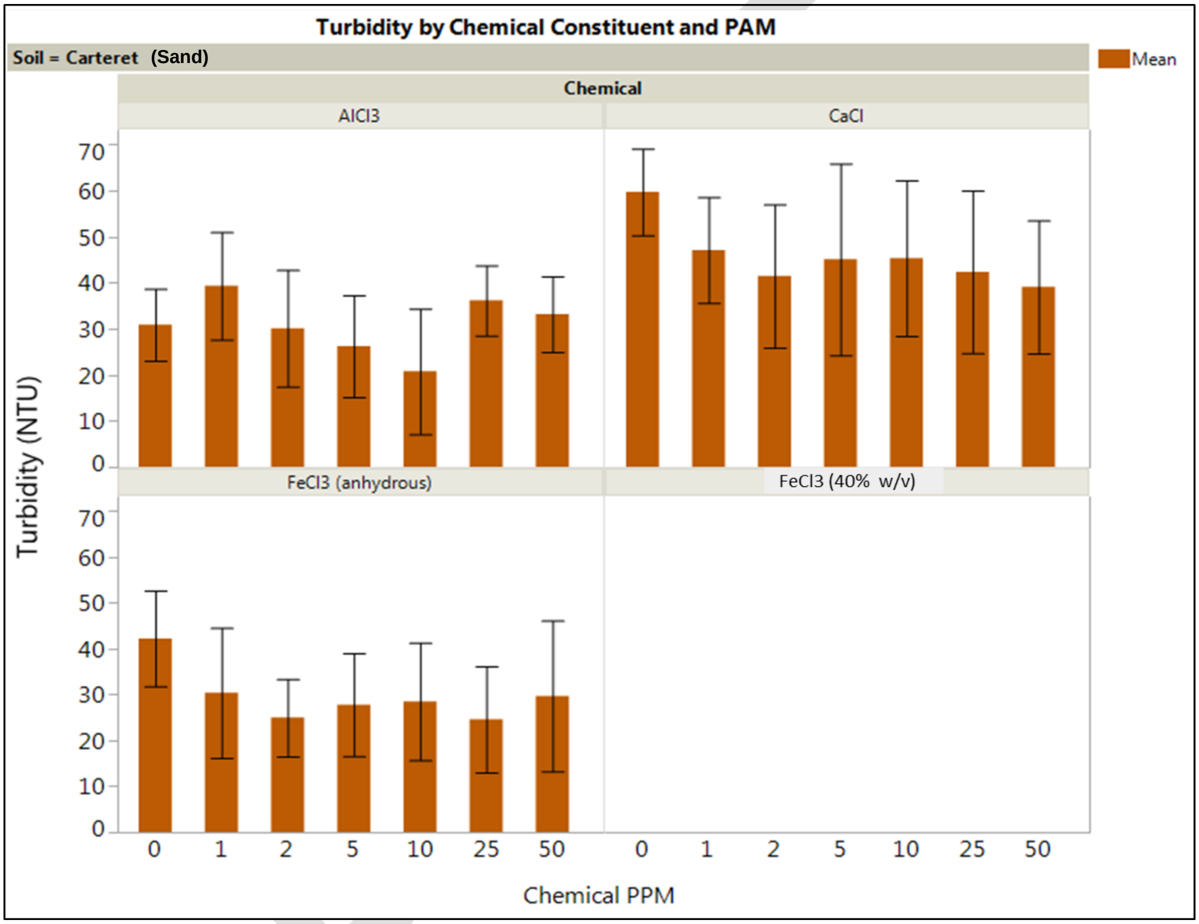

Figure 6: Effect of inorganic coagulants on turbidity for the Carteret soil (10 g L^{-1}). The $FeCl_3$ (40% w/v) was not tested on this soil.

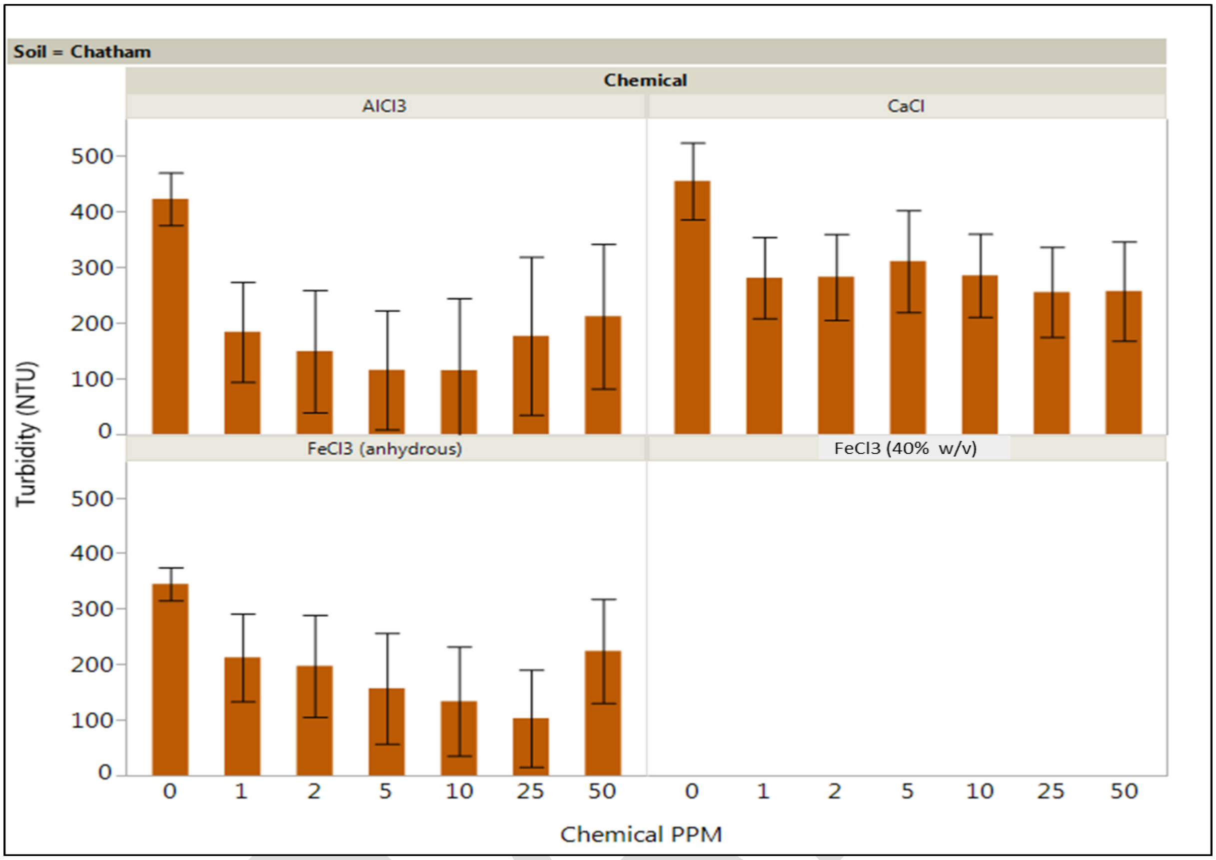

Figure 7: Effect of inorganic coagulants on turbidity for the Chatham (clay) soil (10 g L^{-1}). The $FeCl_3$ (40% w/v) was not tested on this soil

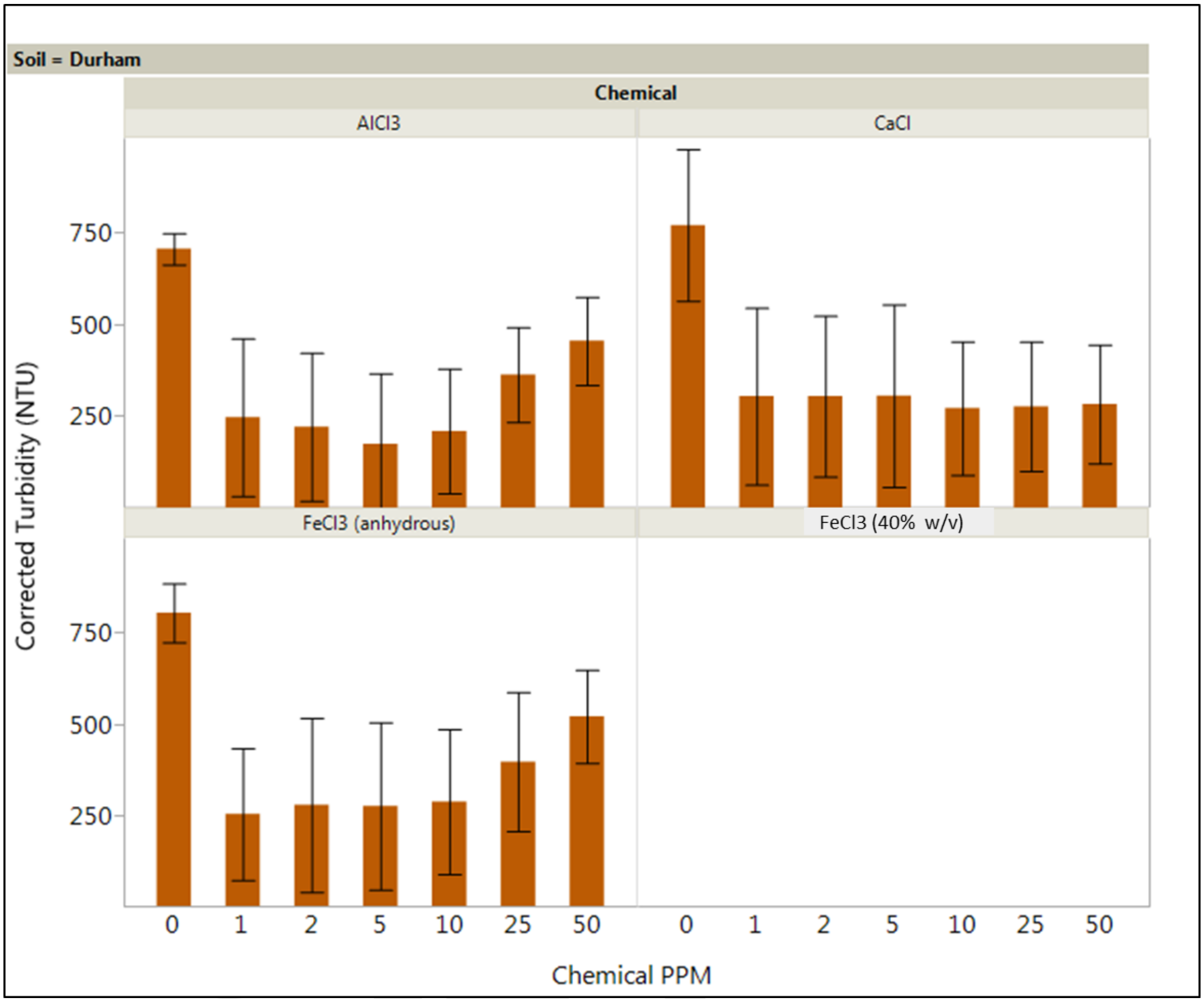

Figure 8: Effect of inorganic coagulants on turbidity for the Durham (sandy loam) soil (10 g L^{-1}). The $FeCl_3$ (40% w/v) was not tested on this soil.

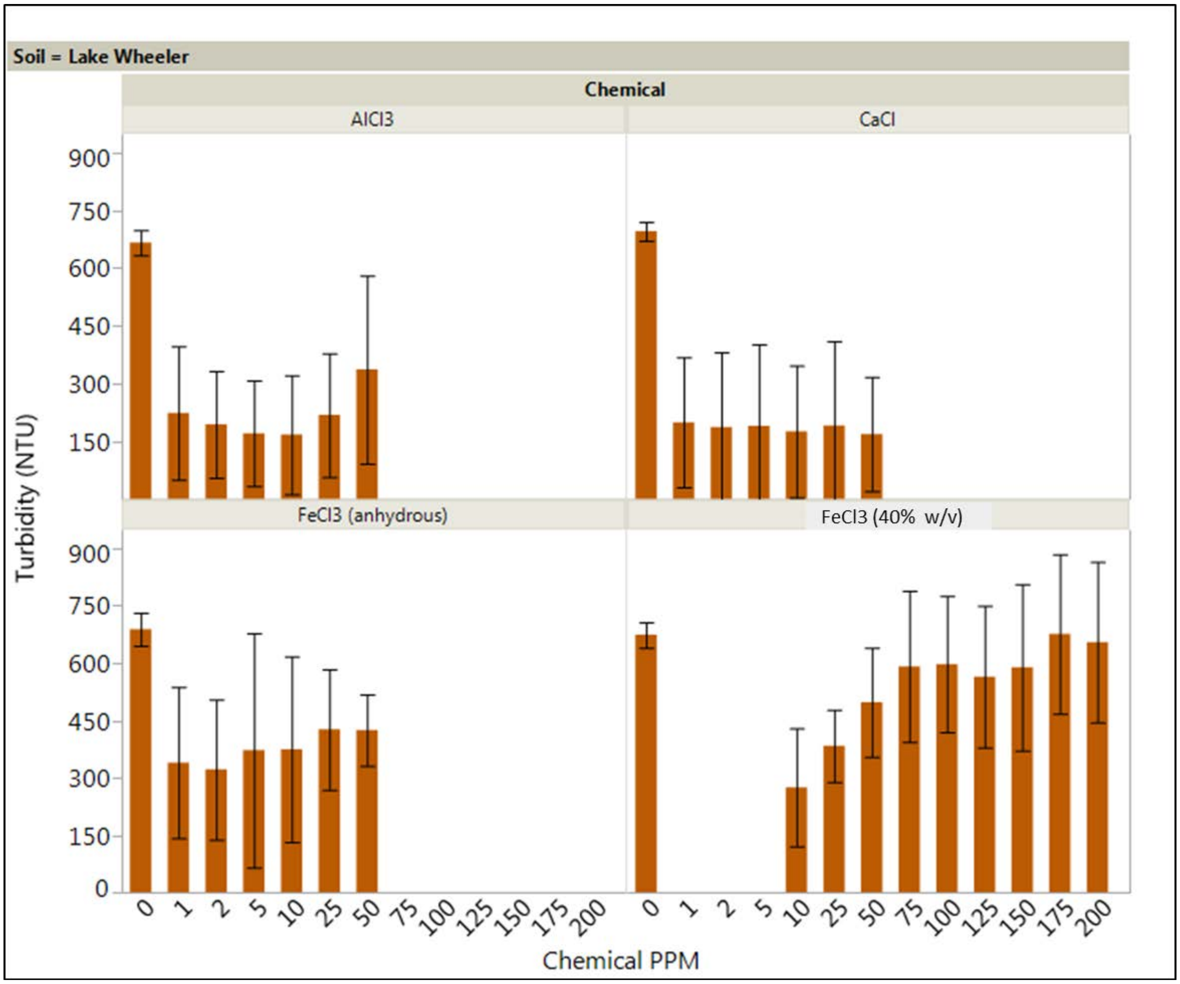

Figure 9: Effect of inorganic coagulants on turbidity for the Lake Wheeler (Wake Co.) soil (10 g L^{-1}).

Another question was whether the addition of a coagulant could reduce turbidity more than with PAM alone. A combination is often used in water treatment systems. We tested three soils with three PAMs, one combination of two PAMs, and a no PAM control with two coagulants at increasing concentrations. The PAMs were tested at either 0.5 or 1.0 mg L^{-1}, at the low end of the optimum treatment concentrations for turbidity reduction. For the Chatham County soil, the PAM treatments resulted in only minimal turbidity reductions, but adding $FeCl_3$ at 50-100 mg L^{-1} brought the turbidity down much further (Figures 9-10). The lowest turbidity achieved was about 50 NTU, and a combination of FA 920 PAM at 1.0 mg L^{-1} and $FeCl_3$ at 25 mg L^{-1} appeared to be the optimal treatment to reach that turbidity level. Exceeding 100 mg L^{-1} $FeCl_3$ sharply increased turbidity for most PAMs at both concentrations tested. The results were similar for $AlCl_3$ (Figures 11-12). In contrast, $CaCl_2$ did not have any clear impact on PAM effectiveness for this soil (Figures 13-14). The patterns of turbidity reduction with $FeCl_3$ or $AlCl_3$ and PAMs was very similar with the Durham County soil, with a somewhat lower range of effective concentration of 10-75 mg L^{-1} and turbidity rising above that level (see Appendix for results). $CaCl_2$ was also not effective.

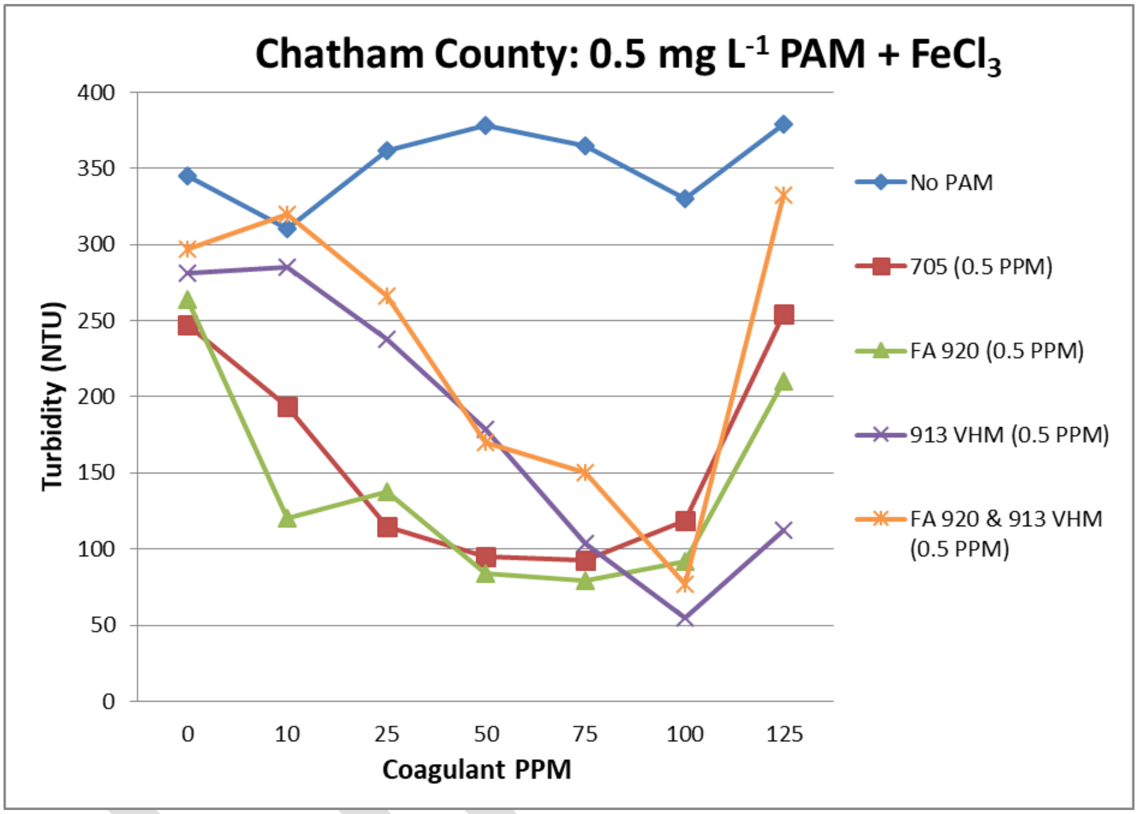

Figure 10: Effects of increasing concentrations of $FeCl_3$ on turbidity reduction by different PAMs at 0.5 mg L^{-1} for the Chatham County soil.

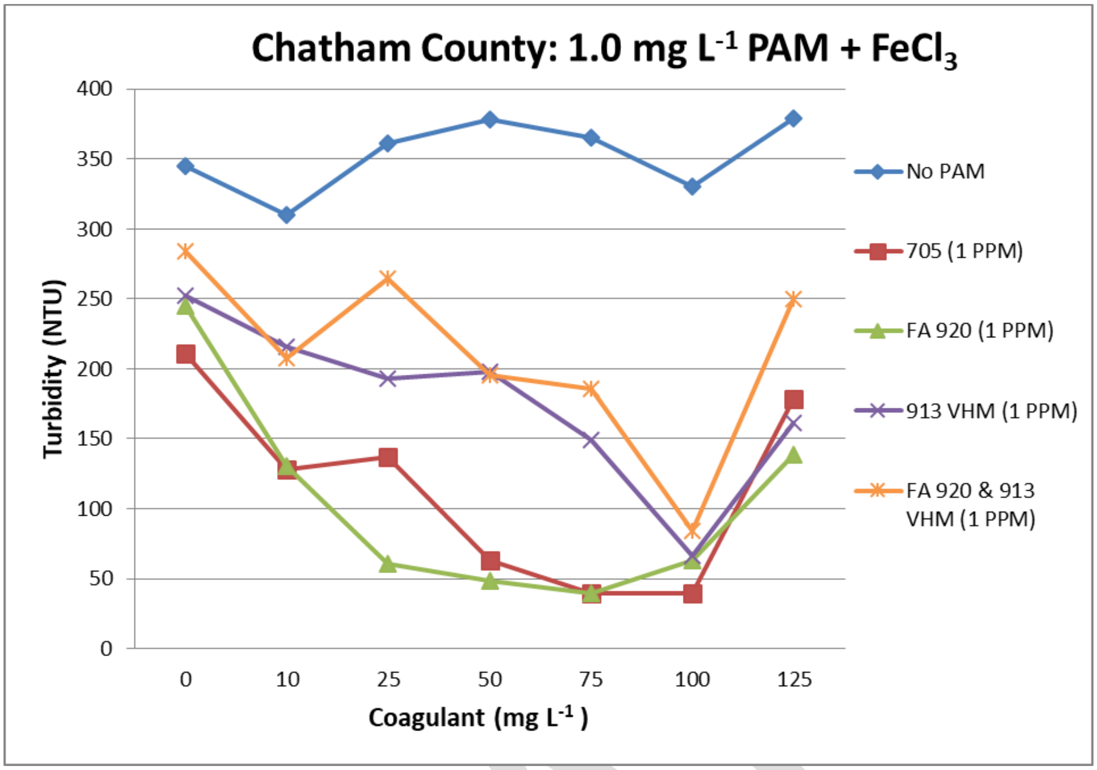

Figure 11: Effects of increasing concentrations of $FeCl_3$ on turbidity reduction by different PAMs at 1.0 mg L^{-1} for the Chatham County soil.

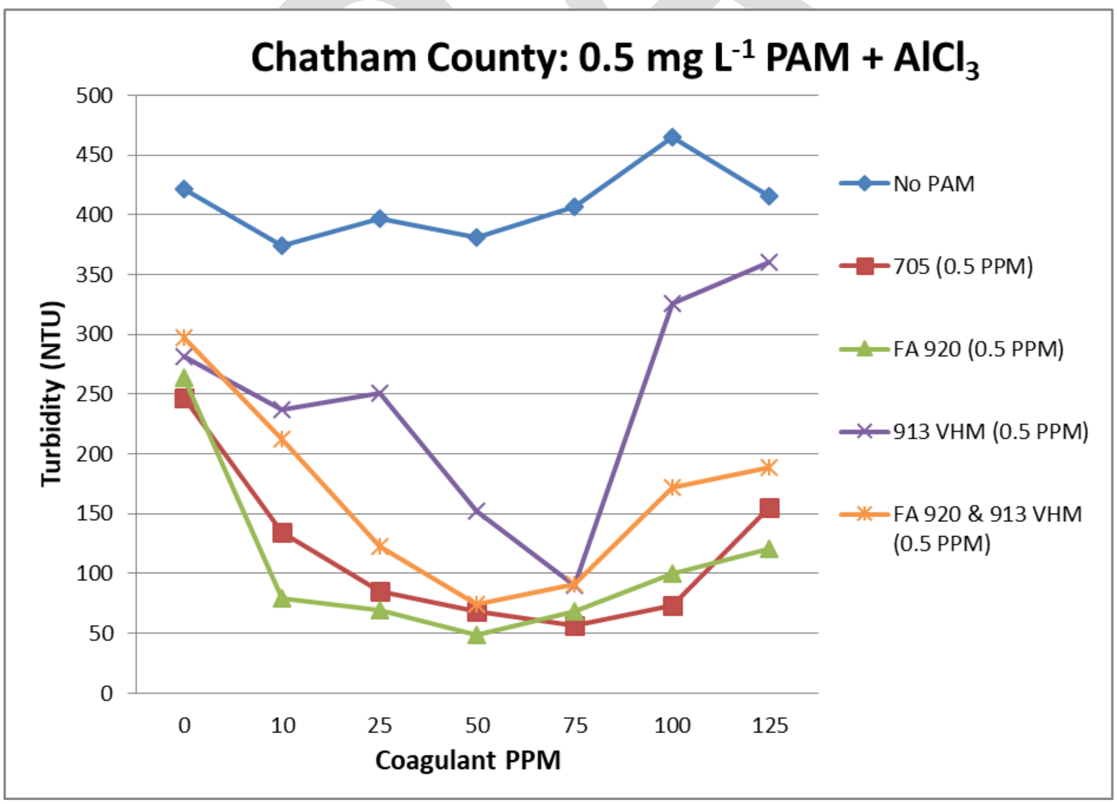

Figure 12: Effects of increasing concentrations of $AlCl_3$ on turbidity reduction by different PAMs at 0.5 mg L^{-1} for the Chatham County soil.

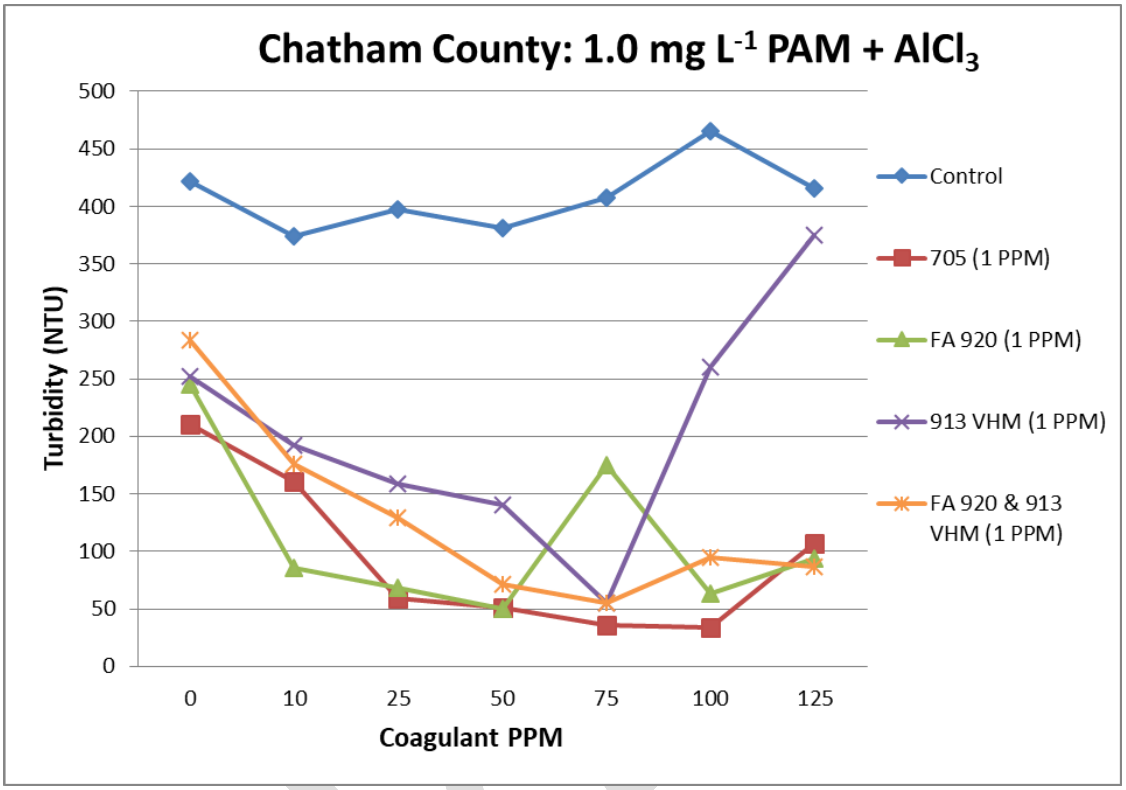

Figure 13: Effects of increasing concentrations of $AlCl_3$ on turbidity reduction by different PAMs at 1.0 mg L^{-1} for the Chatham County soil.

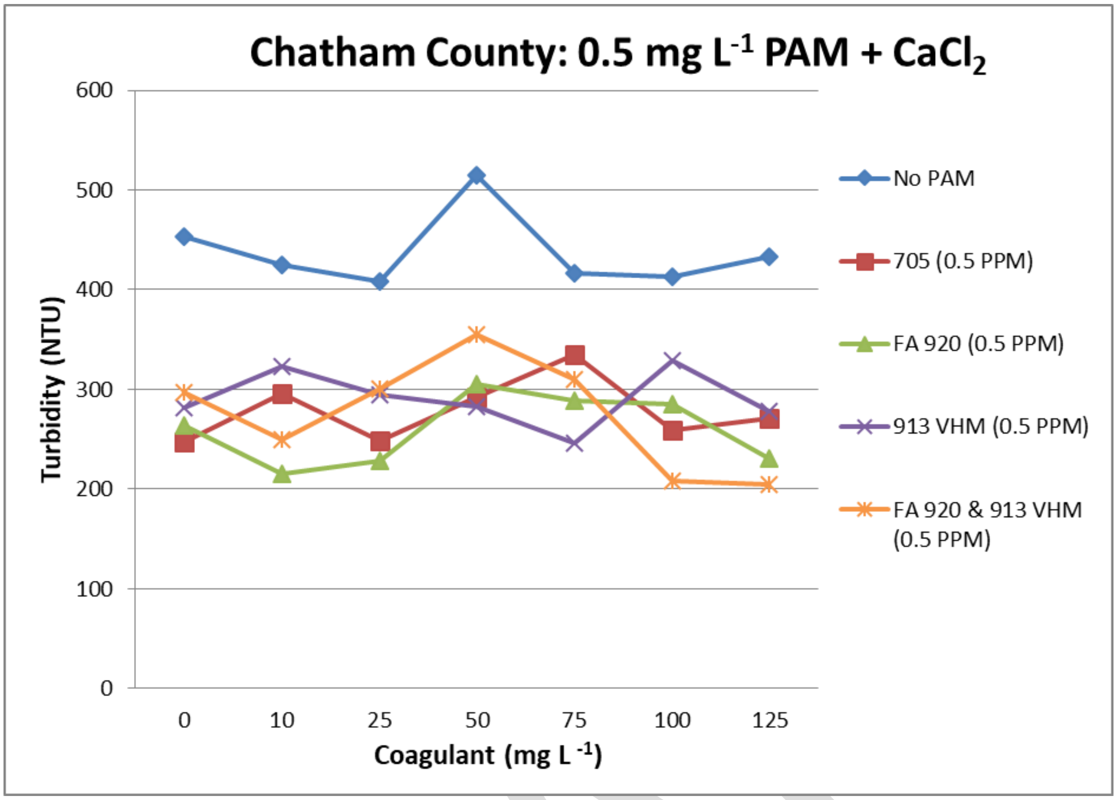

Figure 14: Effects of increasing concentrations of $CaCl_2$ on turbidity reduction by different PAMs at 0.5 mg L^{-1} for the Chatham County soil.

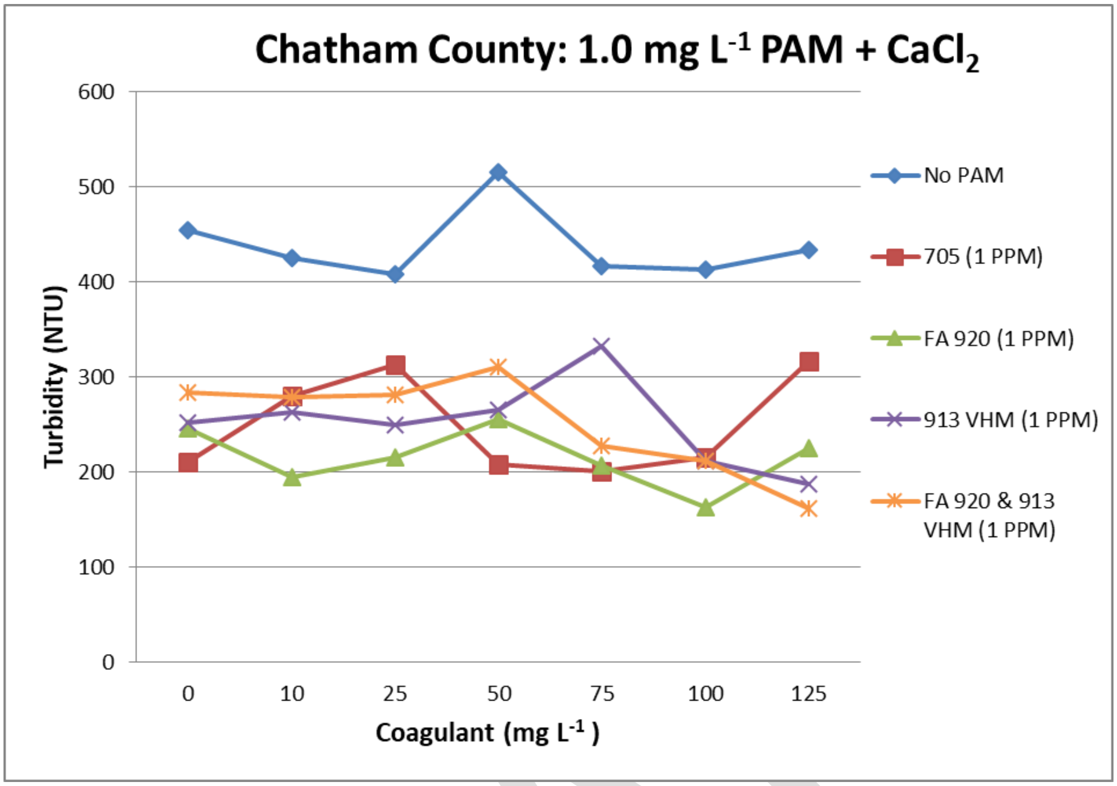

Figure 15: Effects of increasing concentrations of $CaCl_2$ on turbidity reduction by different PAMs at 1.0 mg L^{-1} for the Chatham County soil.

One problem with the use of either $FeCl_3$ or $AlCl_3$ is their effect on pH. In the 10 g L^{-1} soil suspension tested, the pH was reduced substantially at 25 mg L^{-1} and even more at 50 mg^{-1} (Figure 15). This could result in toxicity in the receiving waters, particularly if they had relatively low buffer capacity. In addition, these concentrations of coagulants would require very large amounts of material relative to the PAM.

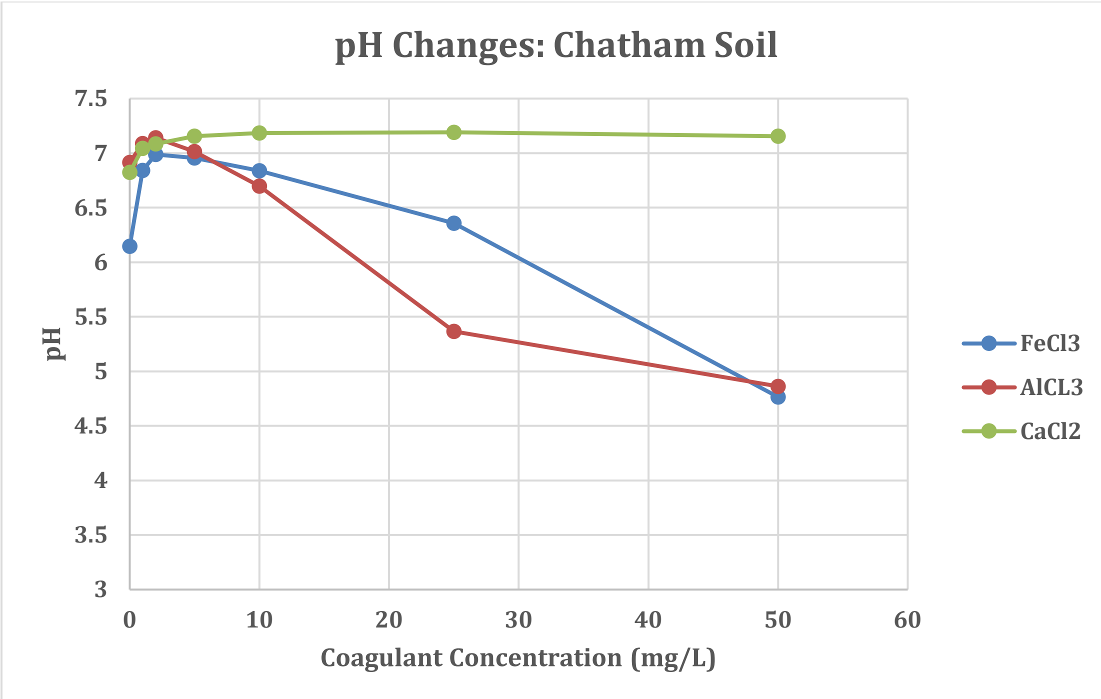

Figure 16: Effects of increasing concentrations of coagulants on pH of a suspension of Chatham soil.

Effects of Increased Sedimentation Time

Turbidity measurements on samples at 30 seconds, 30 minutes, 2 hours and 24 hours after PAM addition and mixing demonstrated the advantage of longer retention times. On average for all PAMs, samples tested after only 30 seconds showed significantly higher turbidity than those sampled at later times, with turbidity continuing to decrease with time (Figures 16-17). Additionally, turbidity was always highest when no PAM was added.   However, the general trend of increasing turbidity as the PAM concentration increases past the optimal dosage appears to be erased with increased settling time. The 30 min – 24 h samples were similar regardless of PAM concentration and all much less than the untreated control. This suggests the effect of overdosing is short-term, although at what point between 30 s and 30 min the turbidity becomes stable is not clear with these experiments.

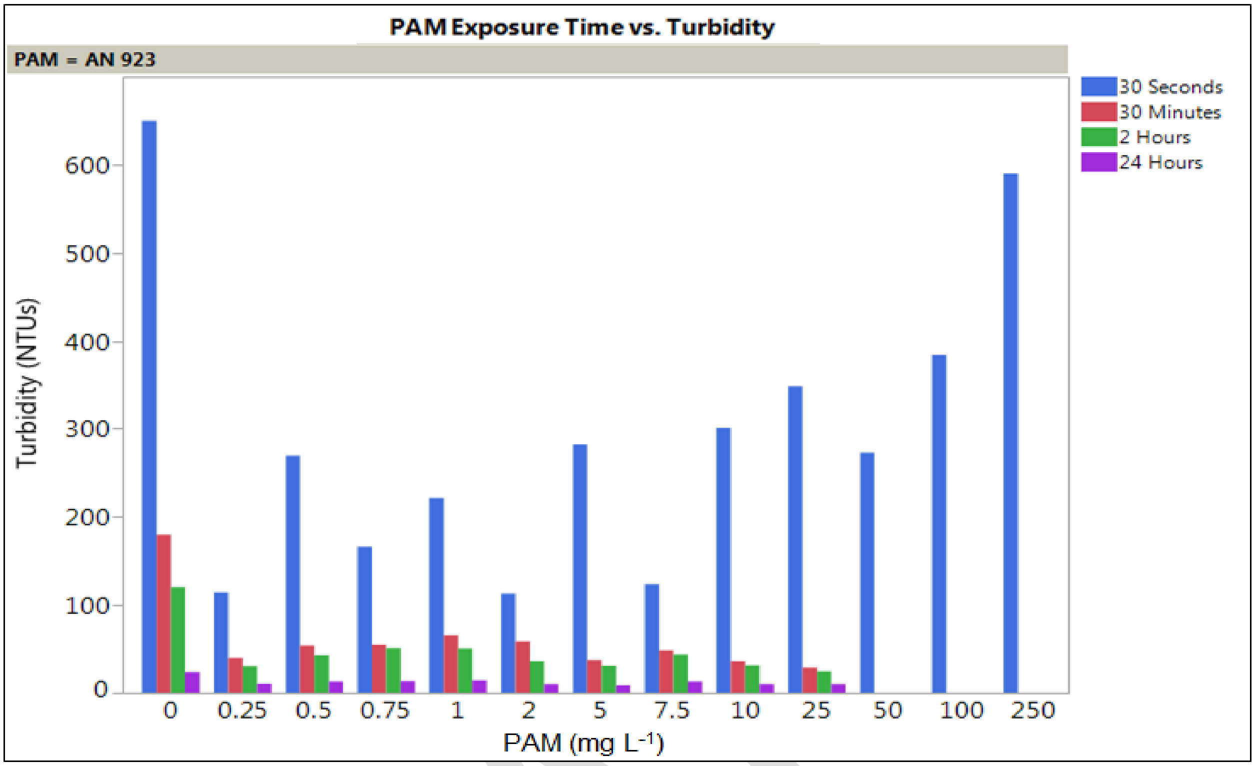

Figure 17: Effect of sampling time on turbidity at increasing concentrations when using AN 923. (Similar to AN 913 VHM, AN 923 SH, AN 923 VHM- now in Appendix)

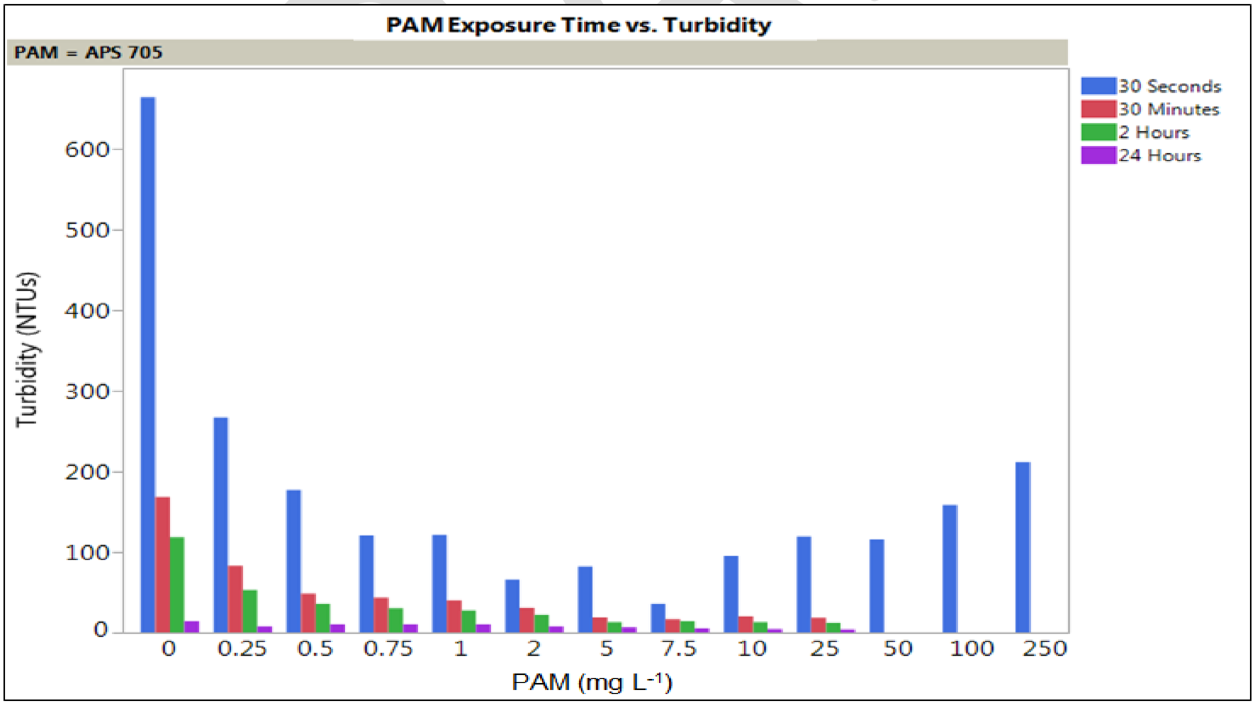

Figure 18: Effect of sampling time on turbidity at increasing concentrations when using APS 705. (Similar to FA 920- now in appendix)

PAM Effectiveness over Time and Repeated Agitation

The effects of sampling handling on the results of turbidity screening were examined for two conditions: repeated agitation prior to turbidity measurement and storage prior to measurement. Two soils from a previous project were tested, a Piedmont soil from Division 8 and a Mountain soil from Division 13. There were no obvious changes in turbidity for the Piedmont soil either when it was repeated shaken after PAM was added (Figure 18) or when the soil-PAM mixture was allowed to sit at room temperature for up to 20 days (Figure 19). The Mountain soil had a trend of reduced turbidity with repeated shaking at the 1 mg L^{-1} concentration, but not at higher concentrations (Figure 20). There was also some evidence that turbidity increased at days 10 and 20 for the mountain soil, but it remained well below the untreated controls (Figure 21). In general, these tests indicate that sampling handling does not greatly alter the turbidity reduction by PAM in hand-shake jar testing.

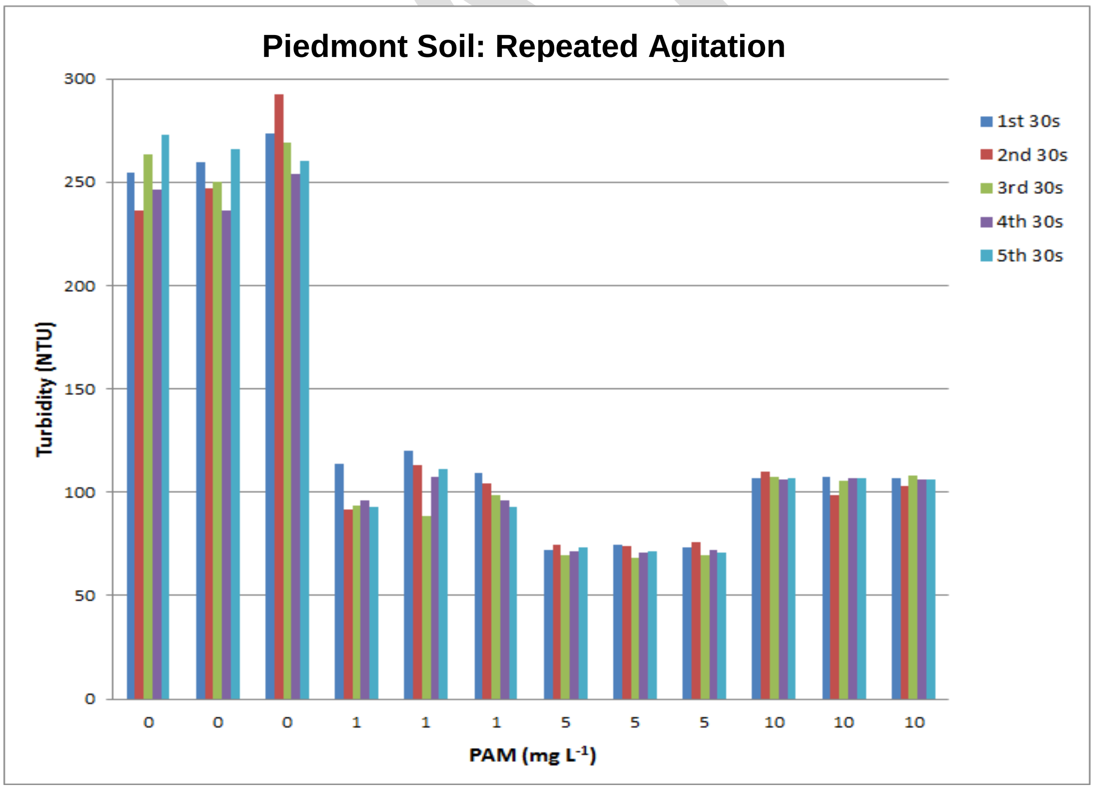

Figure 19: Effects of repeated shaking (10 s) and waiting (30s) on turbidity at increasing PAM (APS 705) concentration for the NCDOT Division 13 soil. Individual samples are shown to provide a visual measure of variability.

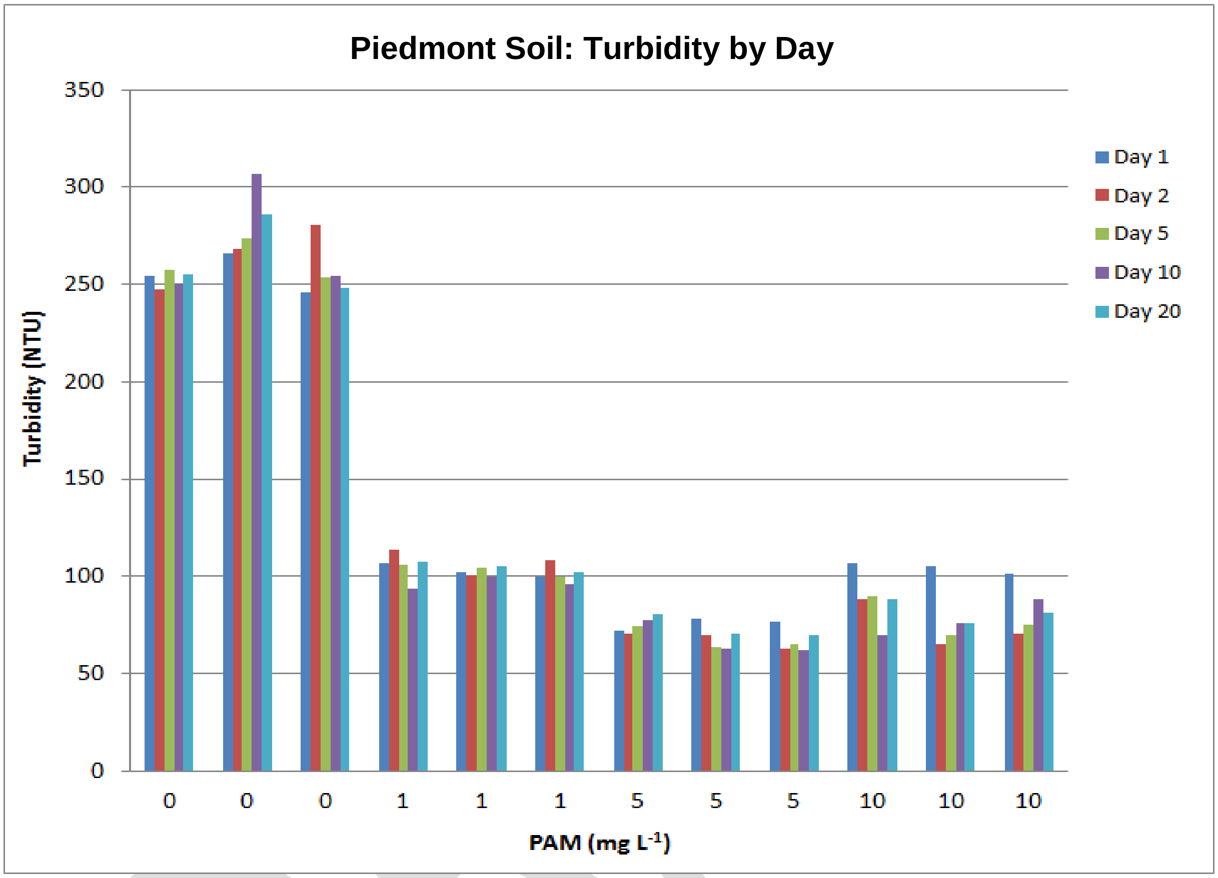

Figure 20: Effect of time on turbidity at increasing APS 705 concentrations for the Piedmont (Division 8) soil. Individual samples are shown to provide a visual measure of variability.

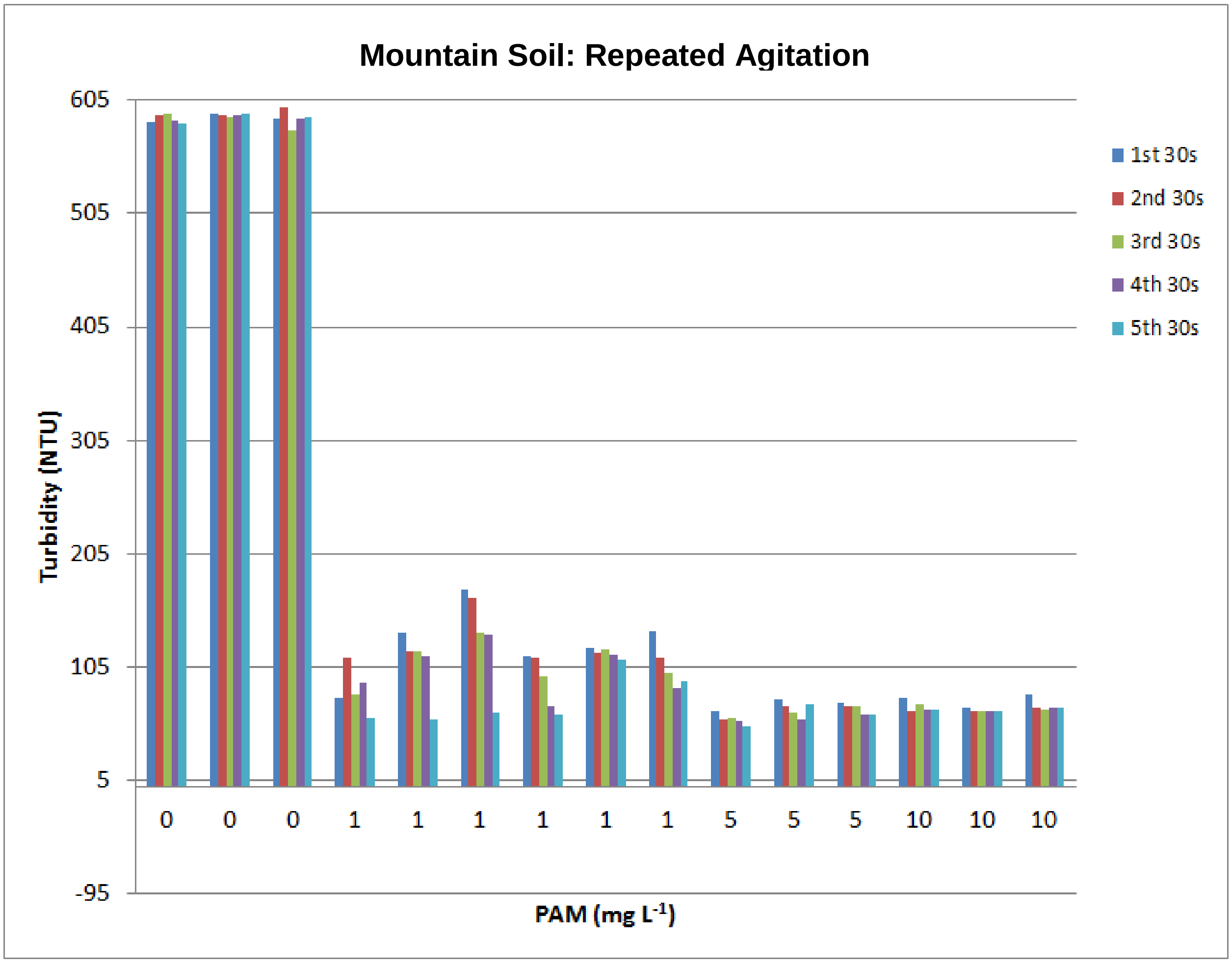

Figure 21: Effects of repeated shaking (10 s) and waiting (30s) on turbidity at increasing PAM (APS 705) concentration for the Mountain (Division 13) soil. Individual samples are shown to provide a visual measure of variability.

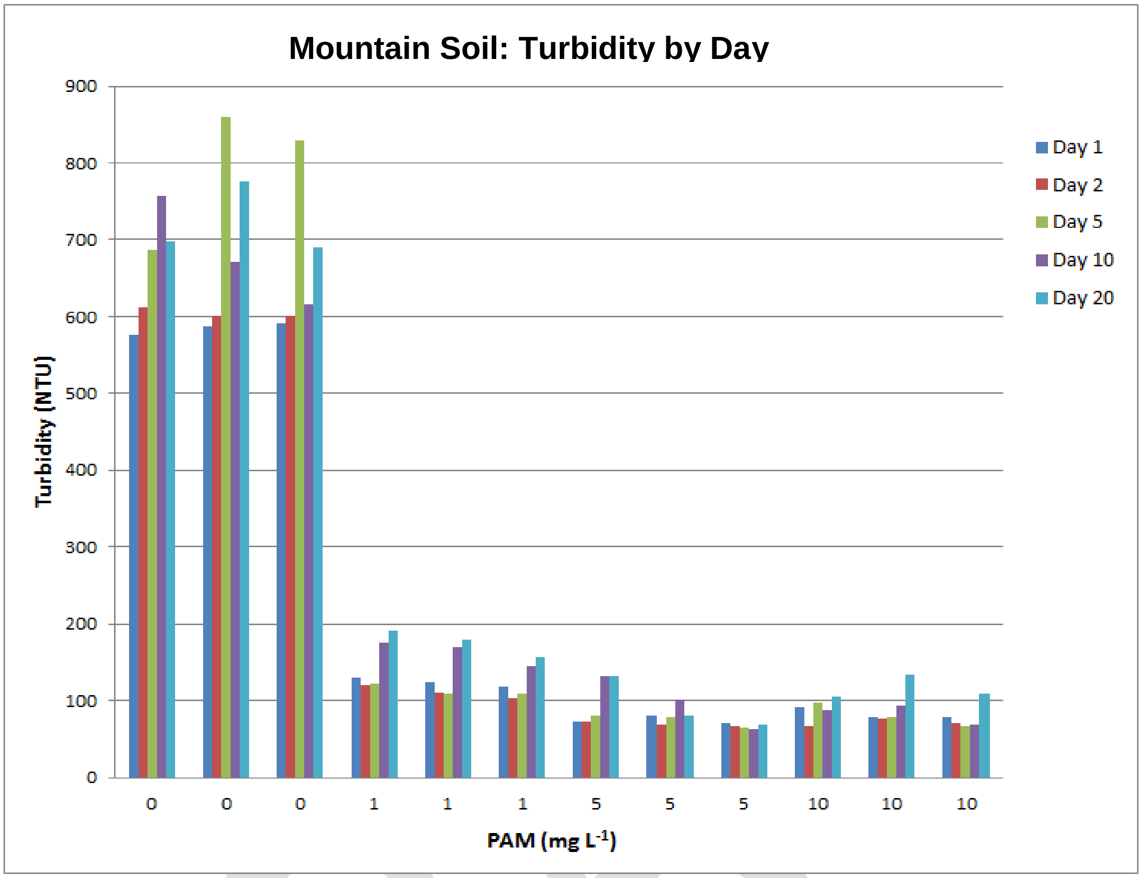

Figure 22: Effect of time on turbidity at increasing APS 705 concentration for the Mountain (Division 13) soil. Individual samples are shown to provide a visual measure of variability

Hand-Shaken vs. Jar Tested Results

The effects of different methods of screening PAMs for turbidity reduction were demonstrated to depend on the combination of PAM and soil. The typical method is a hand-shaken container with a short period of settling. However, in the water treatment industry this is usually done in a jar tester in which the suspension is stirred with a mechanical paddle at different speeds. While the testing covered all of the soils, the results for four are presented here as being representative of the different patterns of results for all of the soils. The results for the other soils are in the Appendix.

The first pattern of response is represented by the Wake County soil (Figure 22). When no PAM was added, generally the hand mixing method produced the highest turbidity. However, mixing by shaking reduced turbidity much more than the paddle stirring regardless of paddle speed. The next response pattern is represented by the Stokes County soil (Figure 23). In these cases, the hand-shaking method produced the highest turbidity with no PAM added. This also reduced turbidity the greatest, but the differences with the paddle mixing were not a clear. Some of the Coastal Plain soils had little response to PAM, regardless of mixing method, as represented by the Brunswick County soil (Figure 24). Finally, a number of soils had no pattern of turbidity produced with no PAM with mixing method, but the hand shaking reduced turbidity much more than paddle mixing (Figure 25).

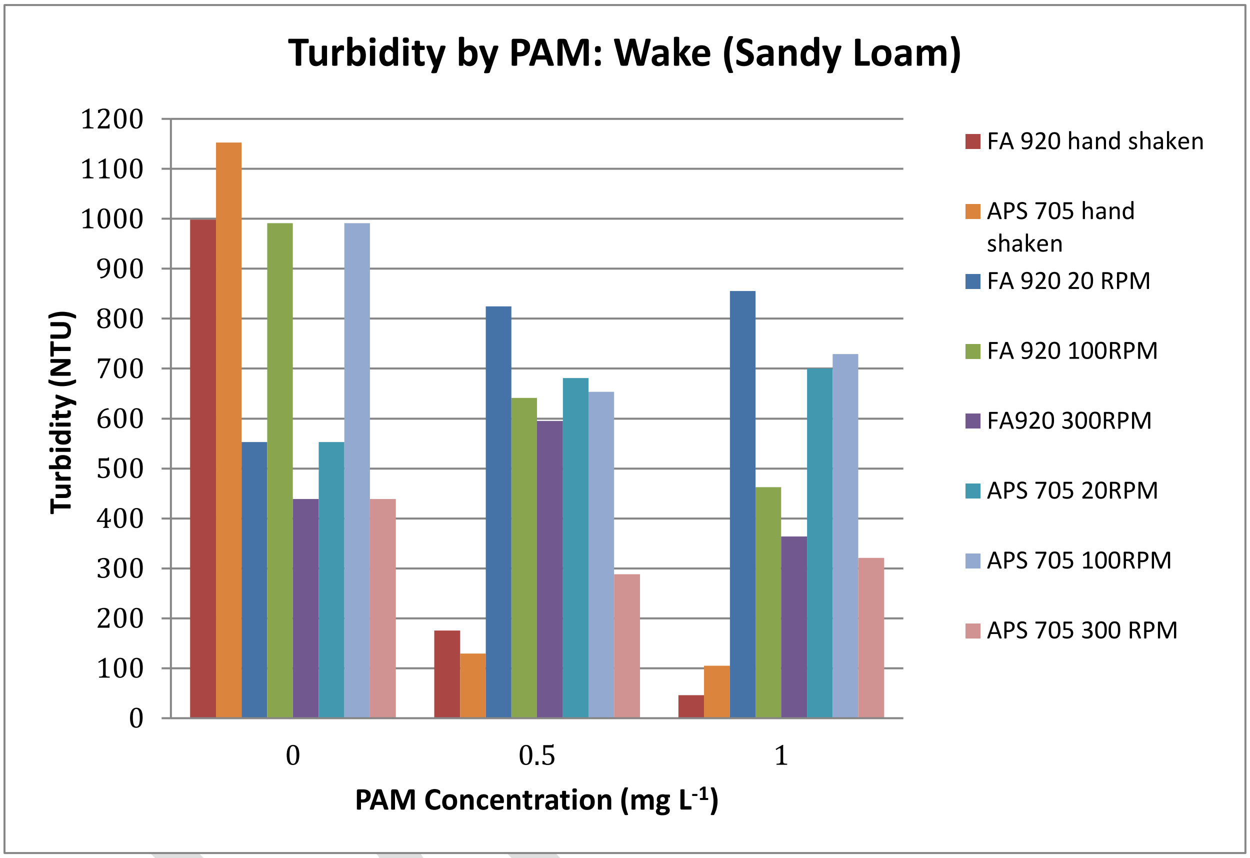

Figure 23: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Wake County soil, with a mixing time of 10 seconds for all samples. (Similar to: Iredell, Nash, Washington, Guilford, Burke, Rowan, Lee, Vance, Yancey, Chatham, found in Appendix).

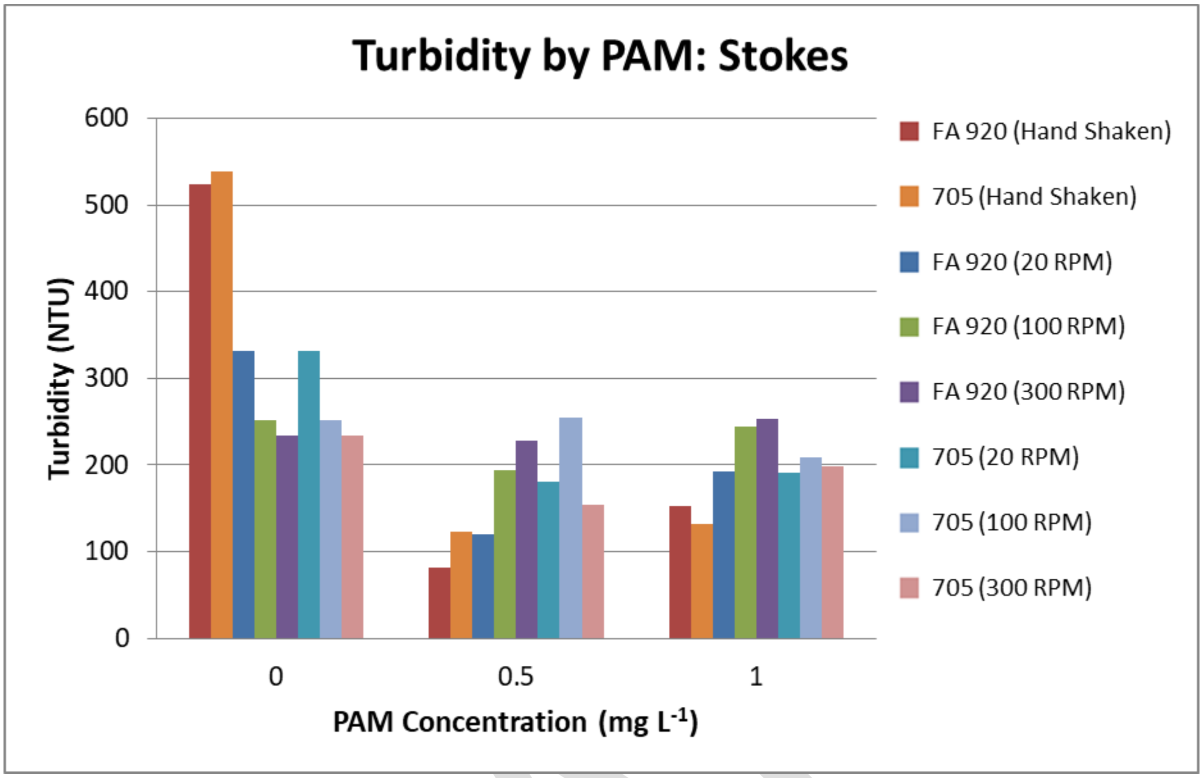

Figure 24: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Stokes County soil, with a mixing time of 10 seconds for all samples. (Similar to: Cumberland, Watauga and Wilkes, found in Appendix)

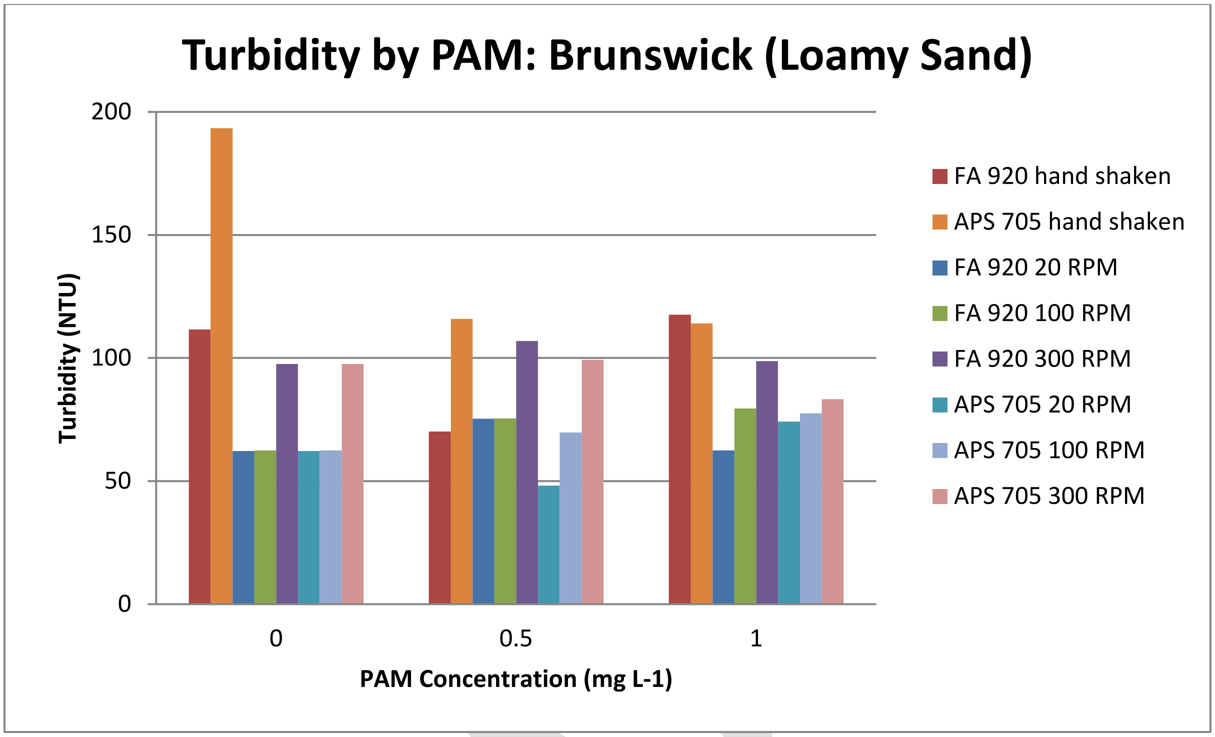

Figure 25: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Brunswick County soil, with a mixing time of 10 seconds for all samples. (Similar to Bladen, found in Appendix)

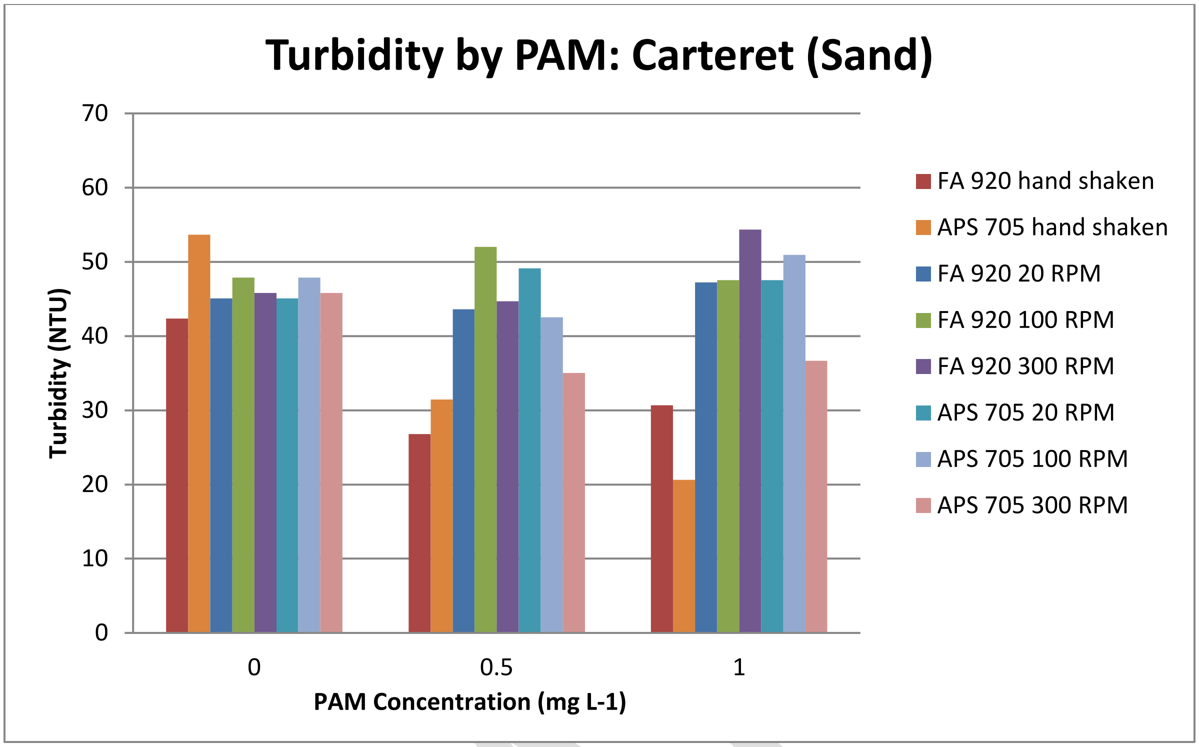

Figure 26: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Carteret County soil, with a mixing time of 10 seconds for all samples. (Similar to: Buncombe, Gates and Davie, found in Appendix)

Mixing Energy Effects

In the previous section, the effects of different mixing methods at 10 s was compared. The effect of imparting different amount of energy to the mixing process can also be compared. In this analysis, the mixing paddle speed and time were combined to produce an energy value, G*t, as explained in the Materials and Methods. Essentially, lower paddle speeds for longer periods would result in the same mixing energy as higher speeds for shorter periods. Tests using three PAMs on the Wake County soil suggest that for the same amount of energy, the middle paddle speed (100 rpm; 130 s^{-1}) is optimal (Figure 26). However, while this trend appears very clear, the effect of paddle speed on turbidity was not statistically significant due to high variability as indicated by the error bars.

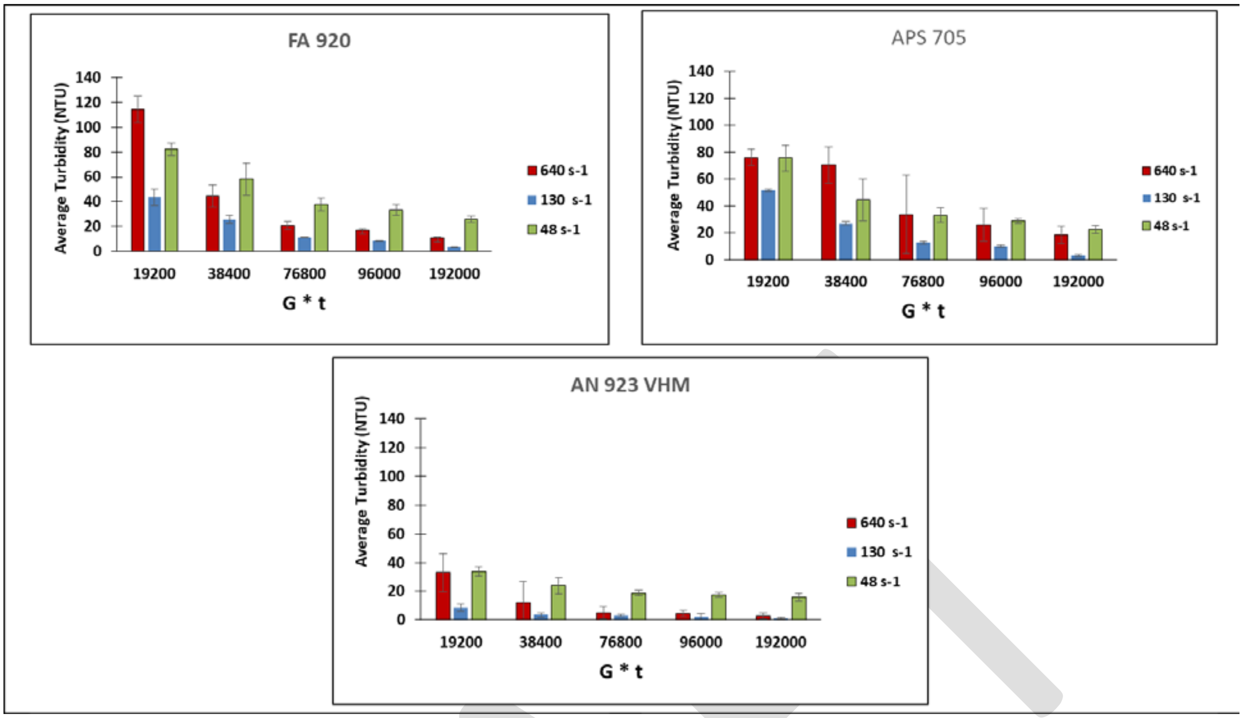

Figure 27: The effect of mixing energy (G*t) on turbidity reduction for the Wake County soil and three different PAMs at 1 mg L^{-1}.

The differences observed between turbidity reduction achieved at all three mixing intensities could be due to several reasons. It is likely that G = 48 s^{-1} may not have been strong enough to promote sufficient interaction between fine particles and PAM, thus the lower removals recorded in most cases. At G = 640 s^{-1}, the high shear may have caused floc breakage, leading to increased final turbidities compared to G = 130 s^{-1}. However, the increased turbidity removals with increased G*t seem to suggest that flocs break-up may be limited. Research has demonstrated that PAM desorption from soil particles is rare (Nadler et al., 1992) because it would be difficult for the molecular segments of PAM to be detached all at once (Seybold, 1994). Consequently, a more plausible explanation could be the decreased viscosity of PAM solution at high shear rates. Several studies have reported that increased shear rates resulted in a loss of viscosity, which, in turn, negatively affected flocculation performances (Henderson & Wheatley, 1987; Nagashiro & Tsunoda, 1977; Nakano & Minoura, 1978; Scott et al., 1996). The reduced viscosity is an indication of shearing of the PAM molecules, creating much shorter chains which may not be as effective.

Hand shake Tests

Increasing mixing time from 10 s to 60 s had variable impacts on turbidity depending on the soil (Figures 27 and 28). For three of the six soils, turbidity reduction decreased when dosed with FA 920 and shaken for 60 s compared to the 10 s shake. These soils contained more silt and clay than the remaining three soils. As for the sandy loam soils from Wake, Watauga, and Yancey Counties, though slight decreases in turbidity reduction were also recorded, this effect was not as pronounced and no significant differences ($p = 0.05$) were found between performances at 10 s and 60 s. In contrast, increasing mixing time did not affect the turbidity reduction by AN 923 VHM except for the Chatham soil, which had a significant ($p = 0.05$) increase in turbidity reduction from 64% to 80%.

The differences observed in the turbidity reduction for both PAMs possibly give an indication of the strength of the molecular bonds that may be formed with finer particles of a soil. Many researchers have attempted to explain the flocculation mechanisms of fine particles by both types of PAM, and many theories have been suggested (Aly & Letey, 1988; Ben-Hur et al., 1992; Laird, 1997; Nadler & Letey, 1989; Theng, 1982). The bonds formed between molecules of FA 920 and finer soil particles, hypothesized to be entropy driven, are disrupted during the 60s hand-shake test. This may have led to the decrease in turbidity reduction. The results of the jar test, presented next, also suggest that the differences observed between performances of both PAMs might be due to mixing intensity.

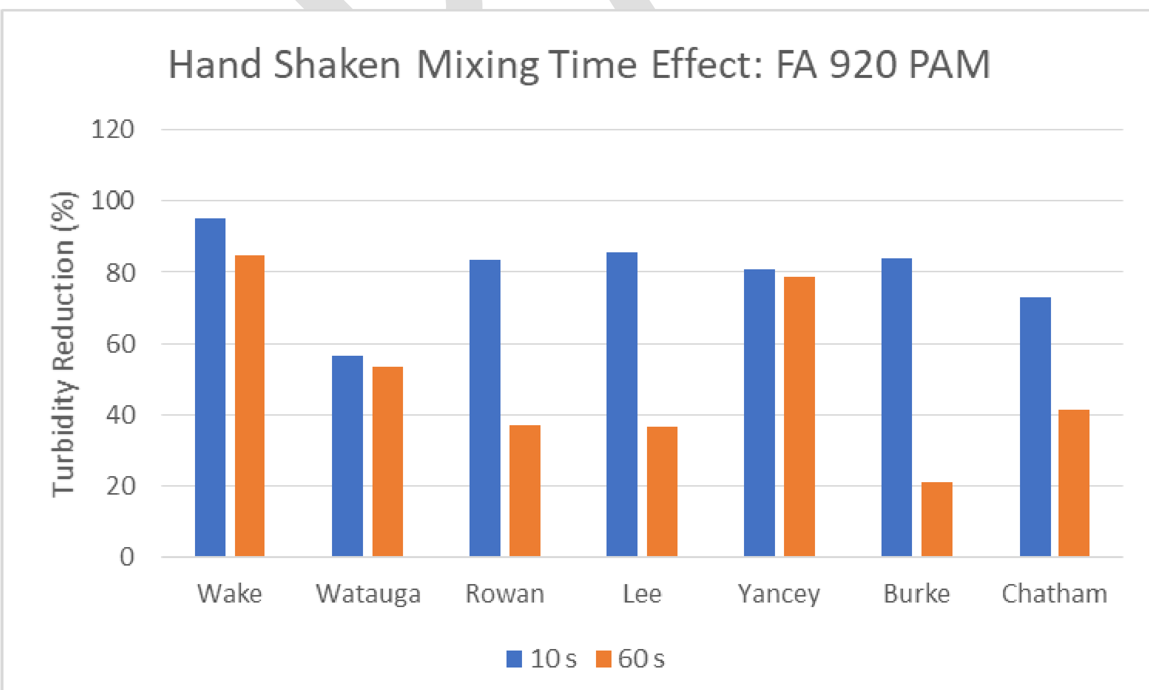

Figure 28: Effects of shaking time for the hand mixed samples for seven soils and the nonionic FA 920 PAM at 1 mg L^{-1}.

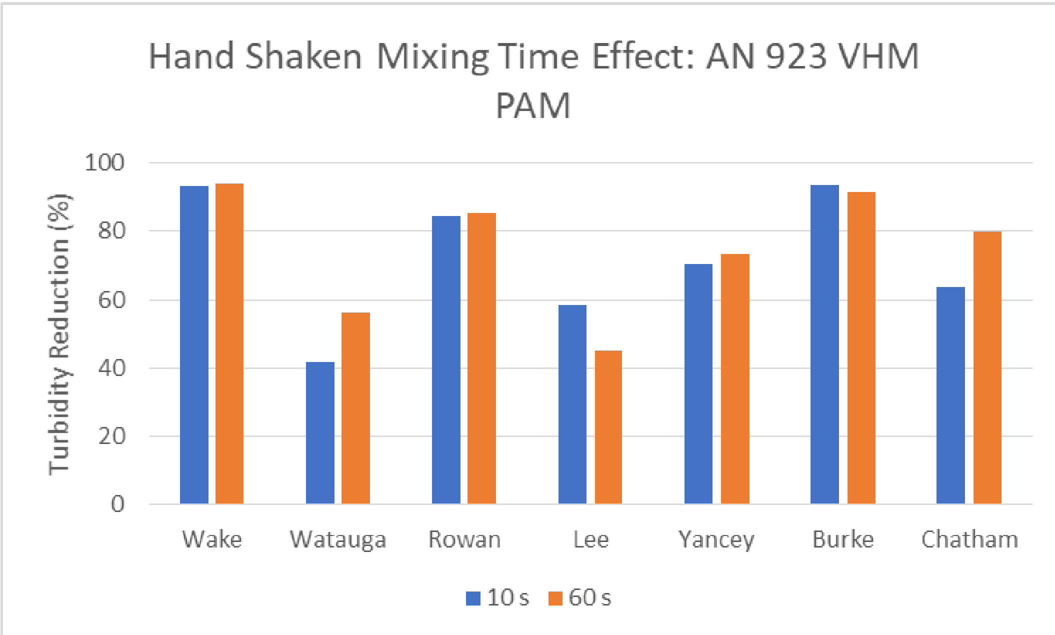

Figure 29: Effects of shaking time for the hand mixed samples for seven soils and the anionic AN 923 VHM PAM at 1 mg L^{-1}.

Field Testing: Simulated Ditches

PAM Performance without Check Dams

For the Wake Co. and Burke Co. soils, increasing the channel slope had no effect on turbidity reduction except for FA 920 and the Burke soil, which had lower turbidity with the higher slope (Figures 29 and 30). Compared to the jar tests, the turbidity reduction for the Wake Co. soil was similar except for the FA 920, which had lower turbidity in the channel. Turbidity reduction for the Burke soil was better in the jar tests, except for the FA 920 which had similar results in both the jar and channel tests. In contrast, the Rowan soil had much poorer turbidity reduction in the channel tests relative to the jar tests for all four PAMs (Figure 31). In addition, increasing the channel slope reduced the effect of the three anionic PAMs on turbidity reduction for this soil.

In the controlled environment provided in the laboratory, homogenous mixing allowed for increased interactions between a large number of soil particles and the PAM molecules. The resulting effect, increased aggregation, and thus, high turbidity removal, is especially strong when the silt loam and clay soils were flocculated with the negatively charged polymers. With these PAMs, turbidity reductions in the laboratory were significantly higher than the ones achieved during the ditch simulation tests. With the neutral PAM, however, results were dependent on the soil tested. In the sandy loam soil, lower turbidity removal was achieved in the lab compared to the field in both channels.

Previous investigation of the effect of mixing intensity on turbidity removal in the Wake County soil revealed that, for all G*t values evaluated, the lowest turbidities were achieved at G = 130 s^{-1}. However, a comparison shows some similarities between the results obtained at G = 640 s^{-1} and those of the field testing for the nonionic PAM. So, for simplicity purposes, only the values for this velocity gradient are presented (Figure 32). This analysis shows that the turbidities achieved with this PAM on the field fall within the range of turbidities achieved during the jar test at G*t = 6400 and G*t = 12800. Consequently, it may be plausible that for this PAM and this particular soil, turbidity reduction performances in the field could be predicted by running a G*t analysis on the jar test at G = 640 s^{-1}.

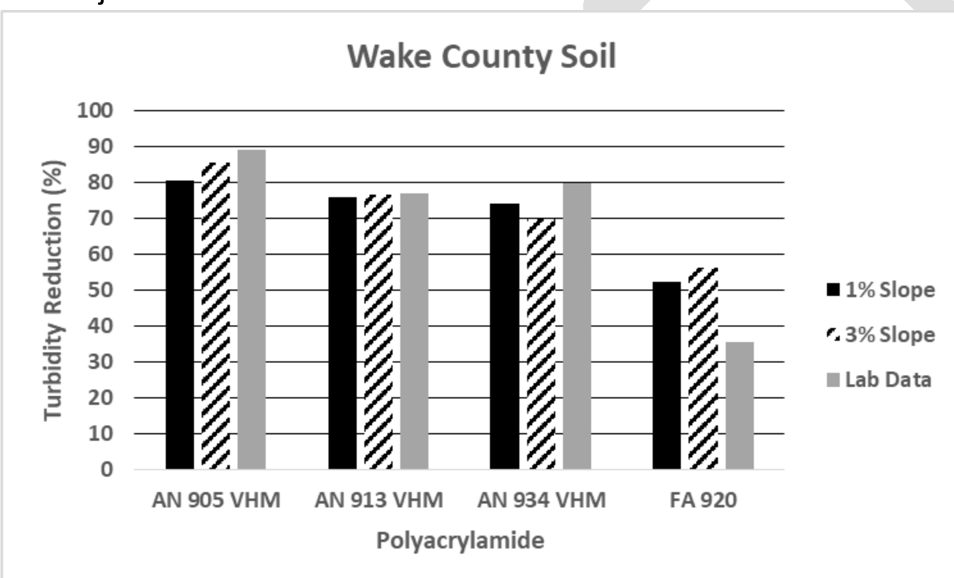

Figure 30: Turbidity reduction as a function of PAM type in the ditch simulator for the Wake County soil. The initial turbidity was 576 NTU.

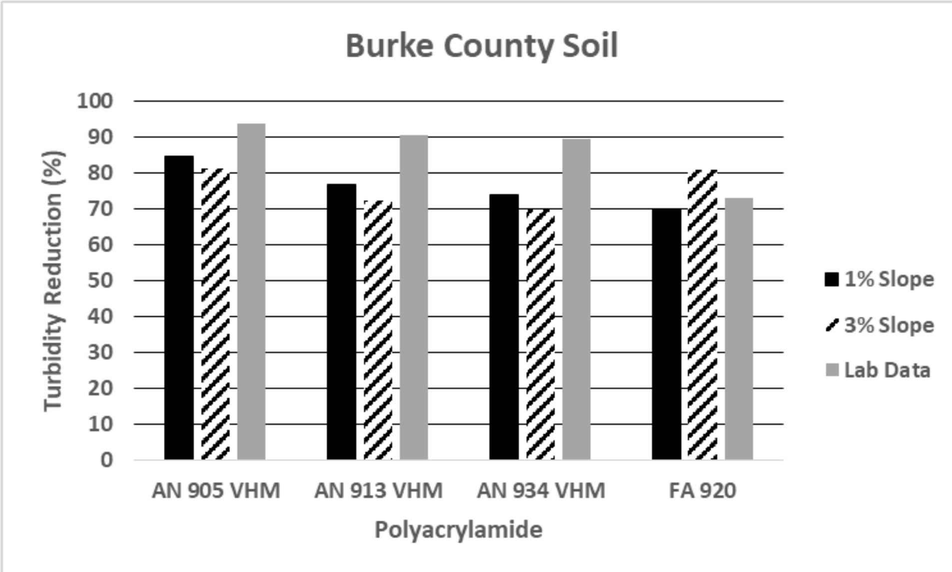

Figure 31:Turbidity reduction as a function of PAM type in the ditch simulator for the Burke County soil. The initial turbidity was 3,140 NTU.

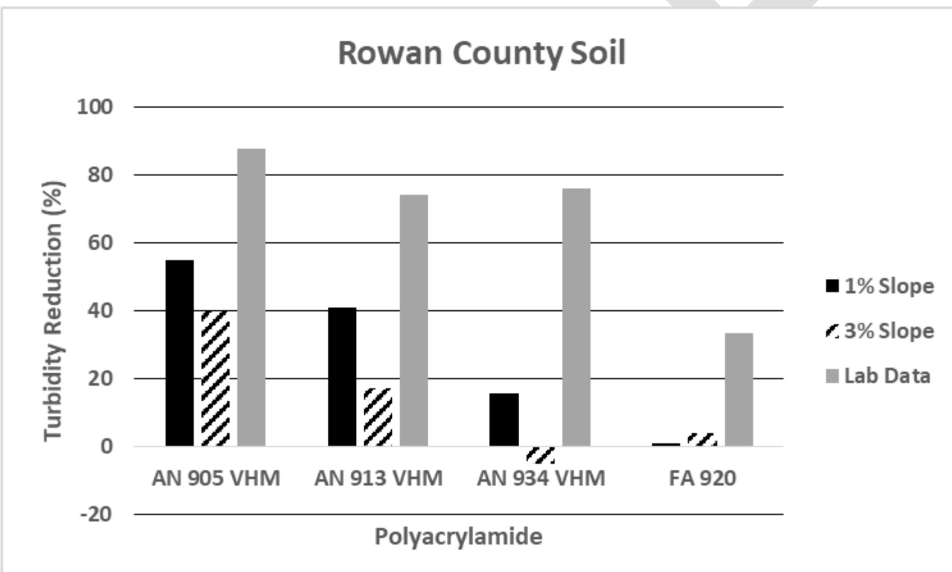

Figure 32: Turbidity reduction as a function of PAM type in the ditch simulator for the Rowan County soil. Initial turbidity was 913 NTU.

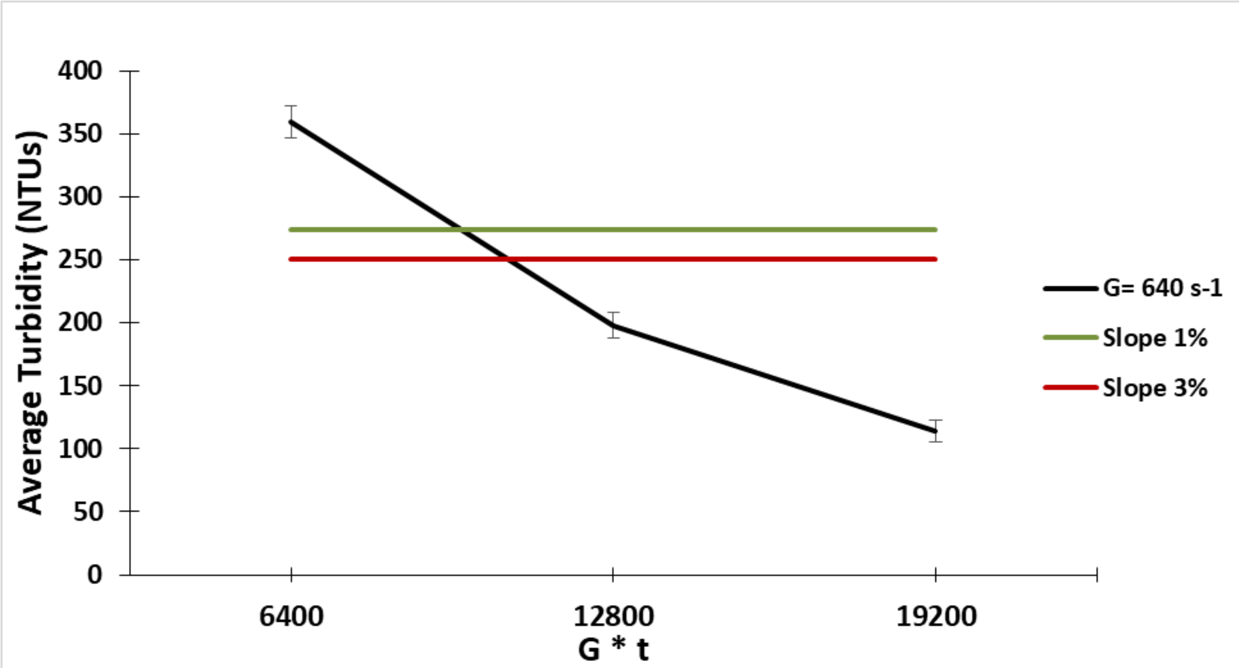

Figure 33: Comparison of turbidity reduction for the Wake Co. sandy loam soil with the FA 920 PAM in the jar mixer (black line) at different energy levels for stirring and that found in the simulated ditches at two slopes. The G*t values represent 10 s, 20 s, and 30 s stirring times.

Impact of Check Dams on Turbidity Removal

For the evaluation of the influence of check dams on turbidity removal, the anionic PAM, A3, was used. This polymer consistently achieved the lowest turbidities in all soils tested, both on the jar tester and in the ditch simulation tests. Introducing check dams into the ditches helped pool soil suspensions (Figure 33) and allowed for enhanced sedimentation of flocs formed. Therefore, turbidity was further reduced in all three soils tested in comparison to ditches without check dam. Furthermore, installing check dams in the ditches was particularly beneficial to the flocculation of soils with a large fraction of fine particles. For the clay soil from Rowan County, turbidity reduction increased from 55% to 88% in the 1% ditch with only one check dam installed. Similar results were observed in the loam soil of Lee County (65% to 87% reduction; Figure 34) and the sandy loam soil from Wake County (81% to 88% reduction, Figure 35). Comparable improvements in turbidity removal with the addition of check dams were also observed in the ditch installed at 3% slope.

Intuitively, one would expect better turbidity removal by increasing the number of check dams in the ditches. However, running the simulations with three check dams did not lead to results much different than the ones achieved with one check dam. Turbidity reductions remained within the same range in all three soils when the check dam number increased from one to three. No significant differences ($p = 0.05$) were found between the effects of one and three CDs in all three soils tested (Table 4). This suggests that there may not be a need to install many check dams to achieve substantial turbidity removals, unless there are additional flows entering the channel at multiple points. Changes in turbidity along the ditches lined with three check dams are also presented (Figures 36-38). Turbidities were measured after each check dam at four distinct sampling points. Generally, turbidity reduction gradually increased from one sampling point to the next. This observation was particularly pronounced when flocculating the clay soil from Rowan County in both channels. Pooling the suspension before each check dam allowed sufficient time for the fine particles to settle, thus improving the quality of the suspension. Check dams are primarily intended to reduce erosion in the ditch by slowing the flow, and this appears to also improve floc removal as well.

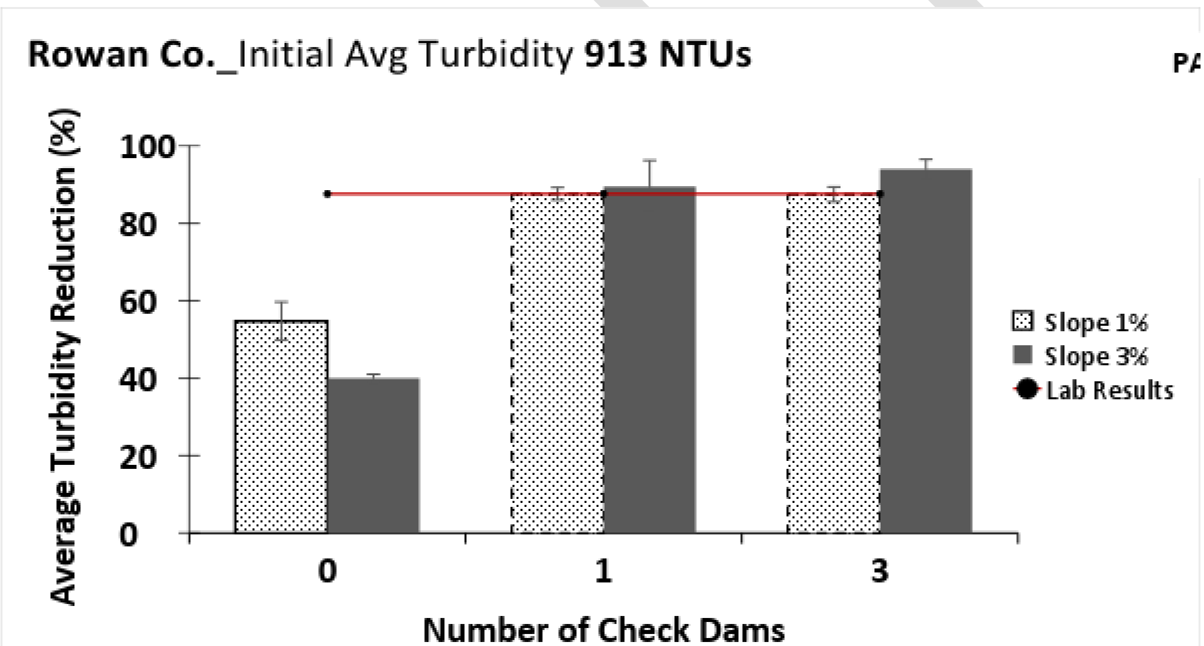

Figure 34:Turbidity reduction when using AN 905 VHM in the Rowan Co. clay soil suspension as a function of the number of check dams installed across the ditch simulator.

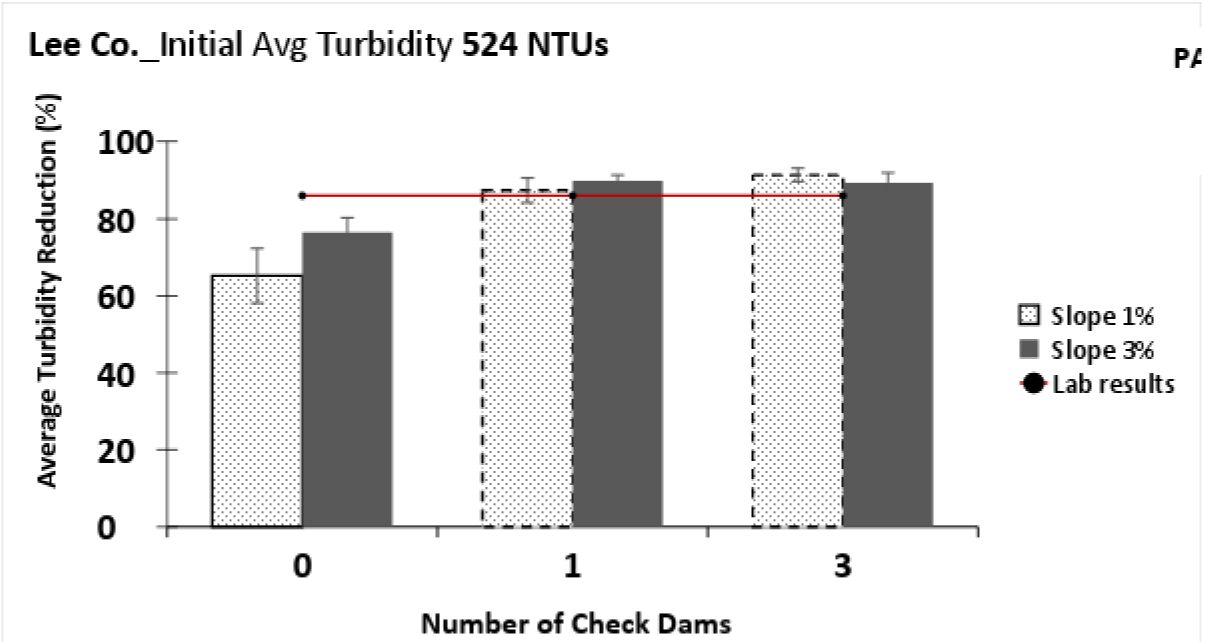

Figure 35:Turbidity reduction when using AN 905 VHM in the Lee Co. loam soil suspension as a function of the number of check dams installed across the ditch simulator

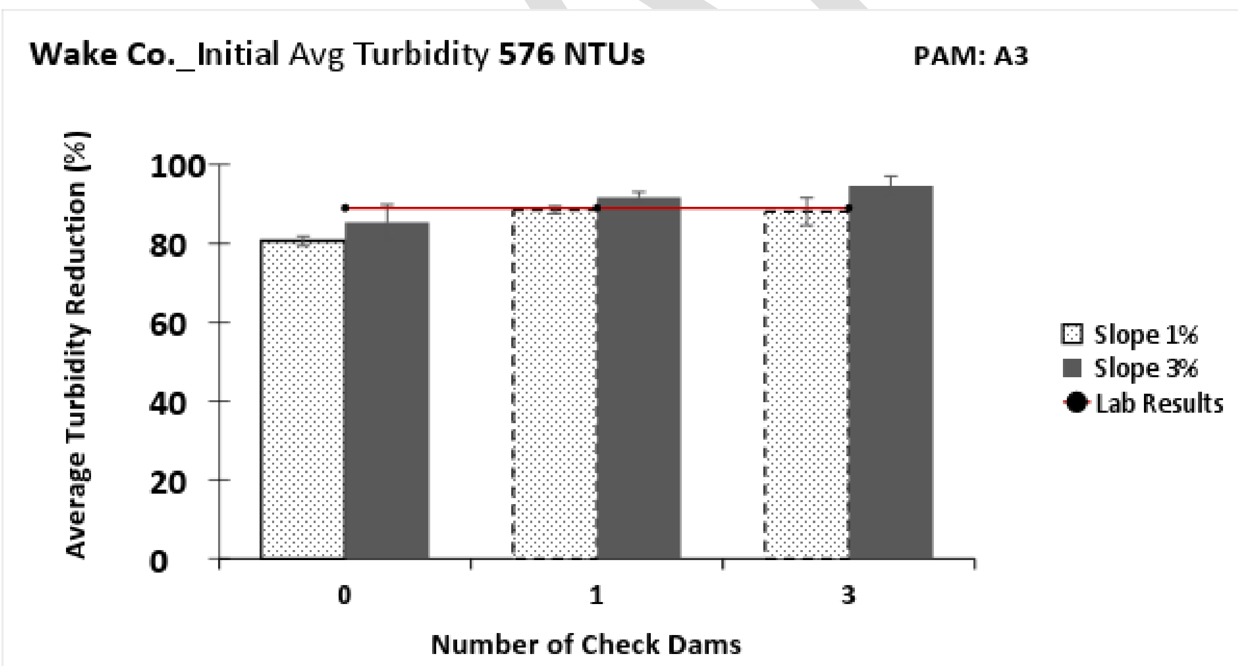

Figure 36: Turbidity reduction when using AN 905 VHM in the Wake Co. sandy loam soil suspension as a function of the number of check dams installed across the ditch simulator.

Table 4: Statistical analysis of turbidity reduction in the simulated ditches with 0, 1, or 3 check dames. Values in bold represent comparisons which were not significantly different ($p < 0.05$).

Summary of t-tests					
	1%			3%	
	Parameters compared	P-value		Parameters compared	P-value
Wake	1 CD vs 3 CD	**0.8500**		1 CD vs 3 CD	**0.1000**
	0 CD vs 1 CD	< 0.001		0 CD vs 1 CD	**0.0800**
	0 CD VS 3 CD	0.0300		0 CD VS 3 CD	0.0300
Lee	1 CD vs 3 CD	**0.1300**		1 CD vs 3 CD	**0.8200**
	0 CD vs 1 CD	0.0080		0 CD vs 1 CD	0.0050
	0 CD VS 3 CD	0.0030		0 CD VS 3 CD	0.0080
Rowan	1 CD vs 3 CD	**0.9200**		1 CD vs 3 CD	**0.3300**
	0 CD vs 1 CD	< 0.001		0 CD vs 1 CD	< 0.001
	0 CD VS 3 CD	< 0.001		0 CD VS 3 CD	< 0.001

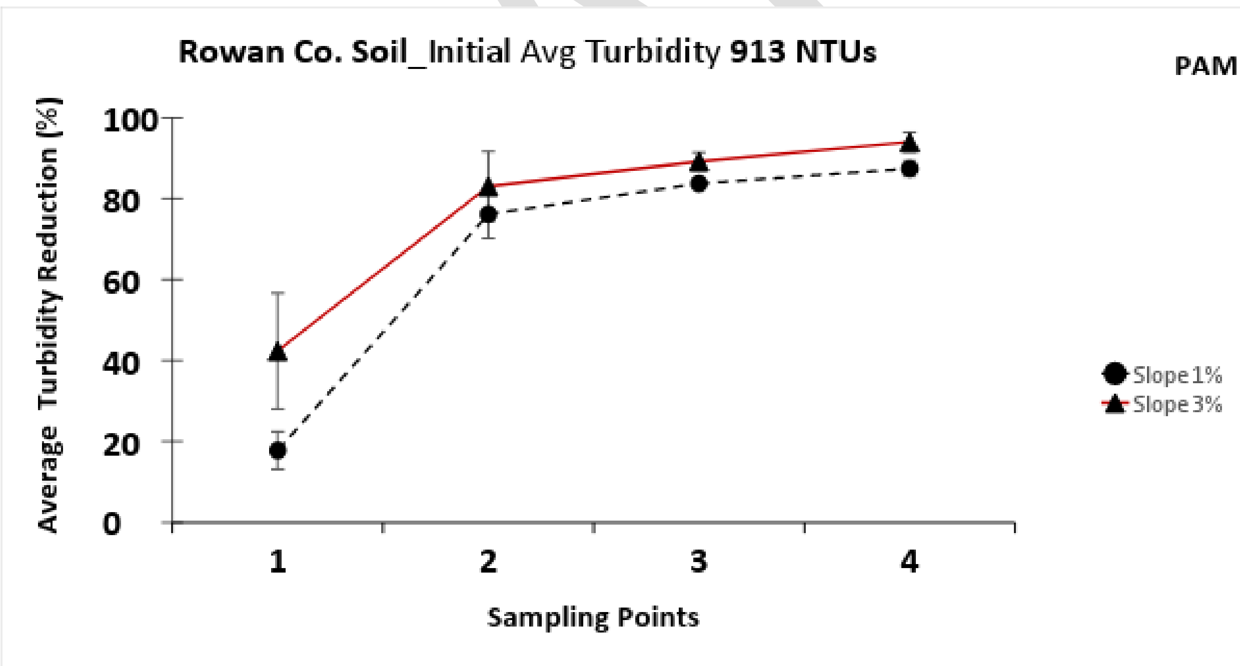

Figure 37: Turbidity reduction at each sampling point along the ditches for the Rowan Co. clay soil when using AN 905 VHM.

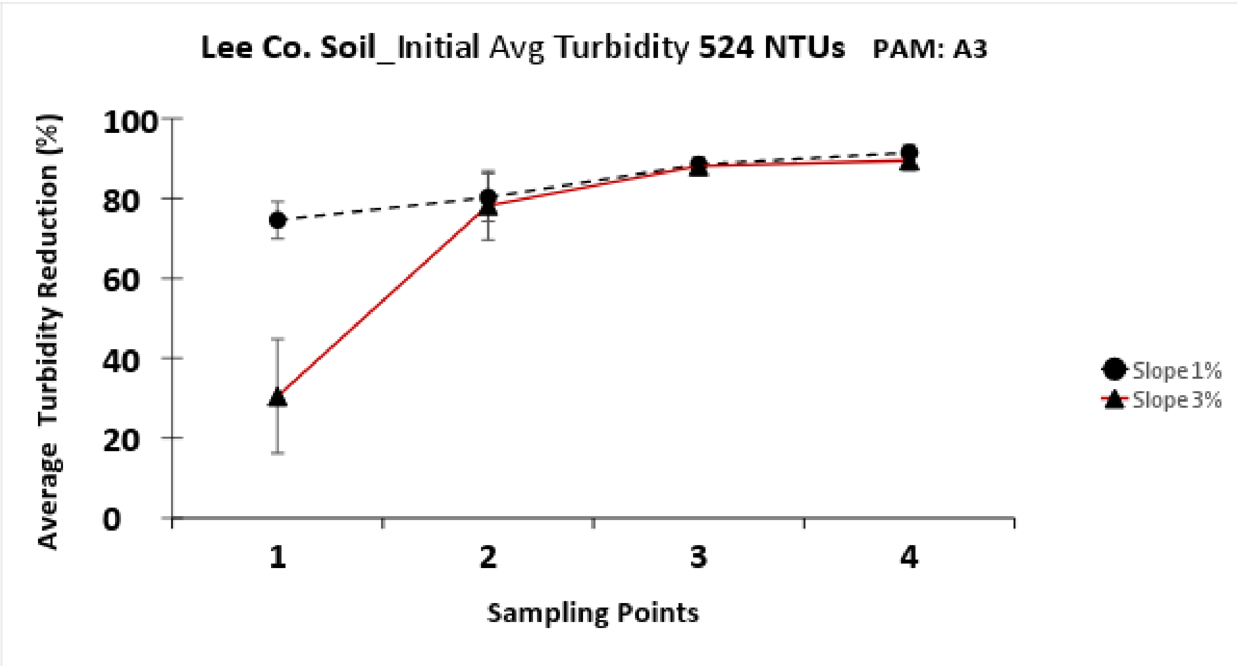

Figure 38: Turbidity reduction at each sampling point along the ditches for the Lee Co. loam soil.

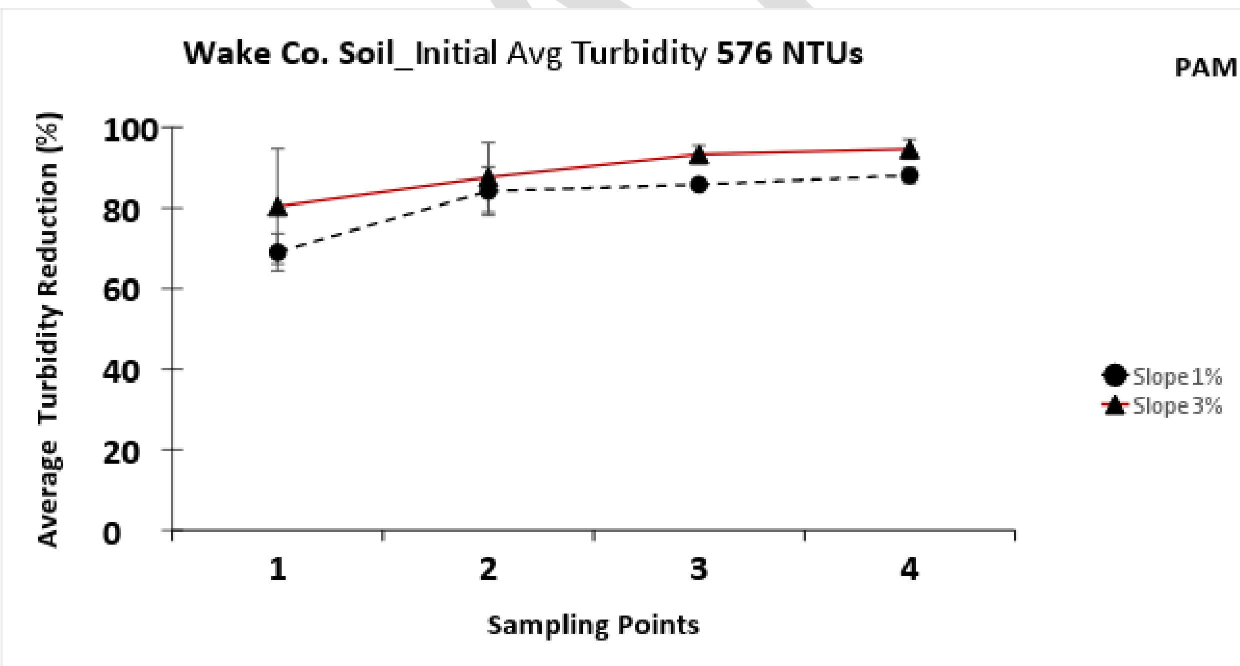

Figure 39: Turbidity reduction at each sampling point along the ditches for the Wake Co. sandy loam soil when using AN 905 VHM.

Conclusions

- The results presented show that flocculation performance with PAM is strongly dependent on the soil texture and mineralogy. Increased turbidity reductions were generally observed in the clay and silt soils from the Piedmont and Mountain regions, as opposed to the sandy soils from the Coastal region.
- Calcium content and pH of the soil suspensions used in this research did affect turbidity reduction.
- PAM concentrations of 1.0 and 5.0 mg/L resulted in the lowest turbidities in all twenty-two soils tested throughout these experiments; increasing PAM concentration up to 250 mg/L increased turbidity, particularly with the anionic PAMs.
- For the sample of soils analyzed, the effect of PAM molecular weight on turbidity reduction was not evident.
- Results indicated that the effect of PAM charge density on turbidity removal was dependent upon the screening method used. With the hand-shake test, the nonionic PAM led to the lowest turbidities, whereas the anionic PAM with charge density 3% was found to be more effective on the jar tester.
- PAM performances were also affected by the combination of the screening test and the mixing time used. Increasing mixing time while using the hand-shake test negatively affected the performance of the nonionic PAM. However, increasing mixing time on the jar tester improved turbidity reductions.
- The ditch simulations confirmed the results of the jar tests. The anionic PAM, AN 905, was more effective than the other polymers at decreasing the turbidity of the sample of soil suspensions used during the field testing
- The degree of effectiveness, however, varied from one soil to the other. Lower turbidity reductions were recorded in the clay soil in comparison to the sandy loam and silt loam soils used, highlighting the difficulty of PAM to rapidly flocculate fine particles.
- The introduction of check dams across the ditches proved to be an efficient method to attenuate this limitation. Installing check dams drastically increased the turbidity reduction recorded in the clay soil, from 40% to 89% in the 3% ditch simulator, for instance.
- The number of check dams did not affect the ability of AN 905 to flocculate the sample of soil suspensions used. Installing one or three check dams across the ditches resulted in comparable percent turbidity reductions in all three soils tested. With only one check dam, turbidity removal performances were comparable to results obtained in the controlled setting of the laboratory.
- It is important to note that these results may vary based on the shape and the length of the ditch used. So, a variation of these may help understand how the characteristics of the ditch used may affect PAM performances when a varying

number of check dams is installed. In addition, the point of introduction of PAM into the ditch could be the subject of investigation. In practice, granulated PAM is sprinkled over the check dams. But it is possible that addition of PAM into the ditch prior to the first check dam using a pump could further improve turbidity reduction performances in runoff from construction sites.

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Appendix

A1. Results of Full Screening Tests of All Soils

The following are graphs depicting the turbidity reduction for each PAM and concentration for individual soils.

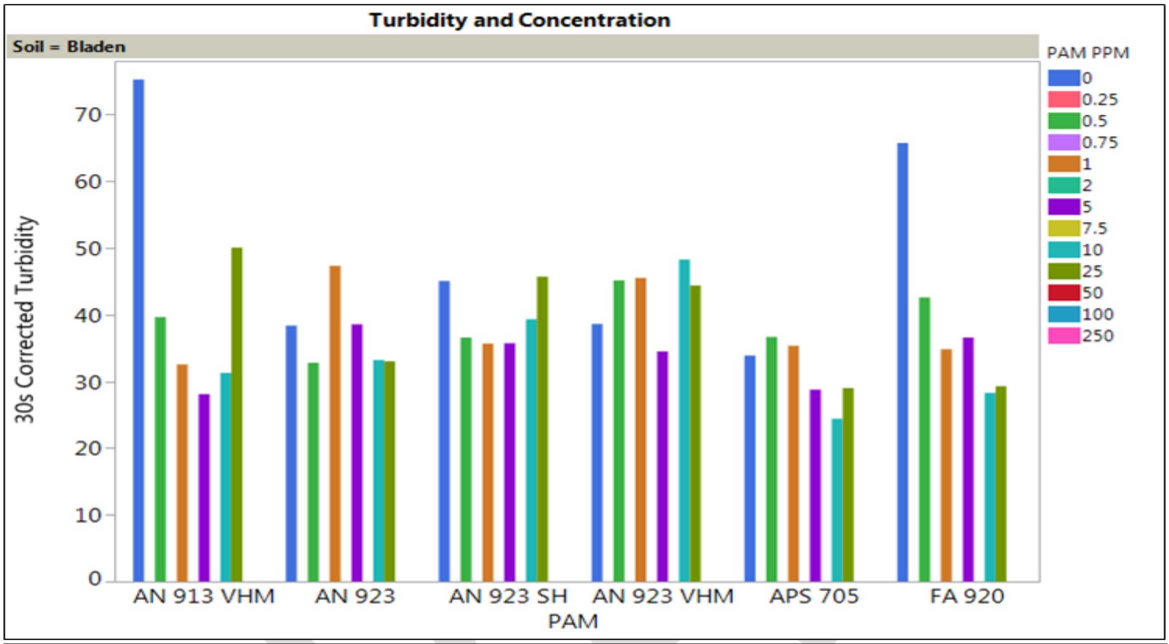


Figure A1: Effects of PAM concentration by PAM type for the Bladen county soil, a sandy soil, after resting for 30 seconds.

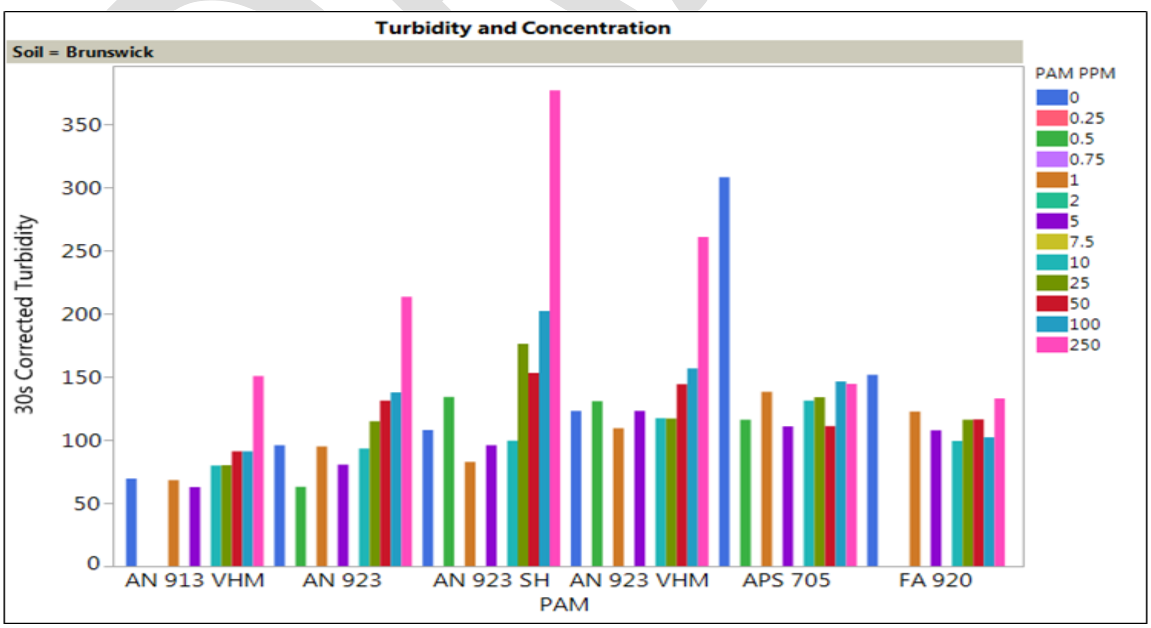


Figure A2: Effects of PAM concentration by PAM type for Brunswick County, a loamy sand, after resting for 30 seconds.

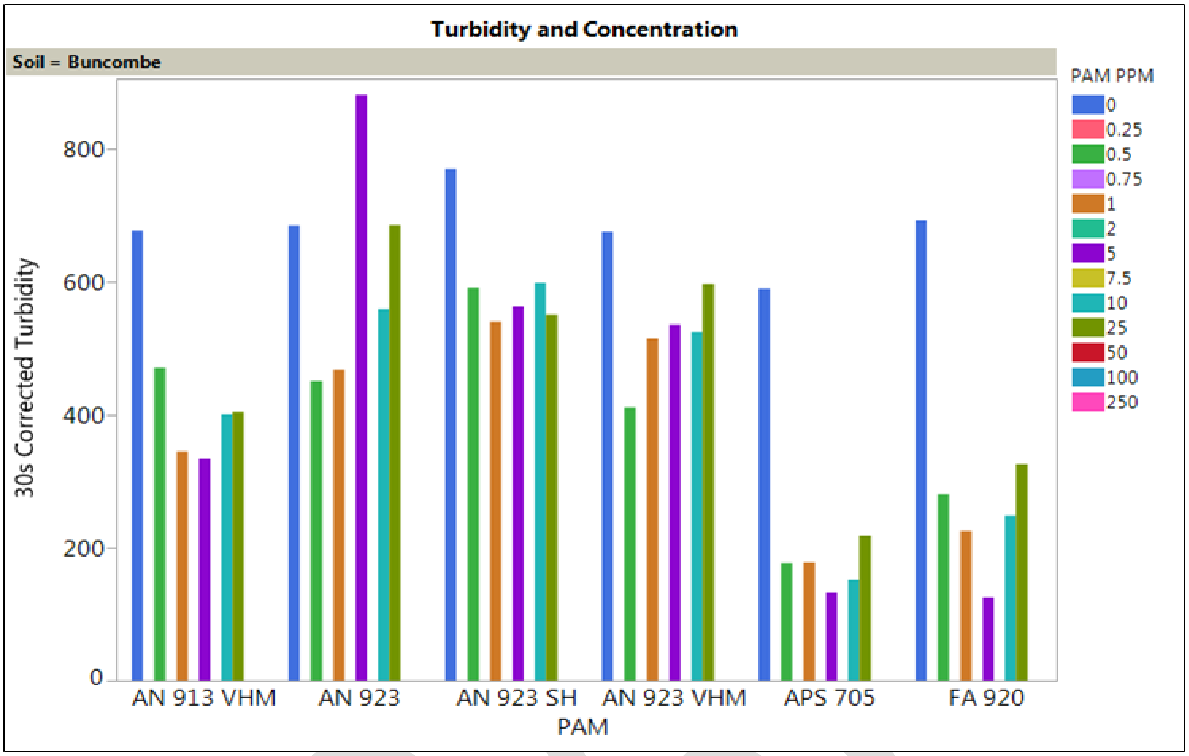


Figure A3: Effects of PAM concentration by PAM type for Buncombe County, a sandy loam, after resting for 30 seconds.

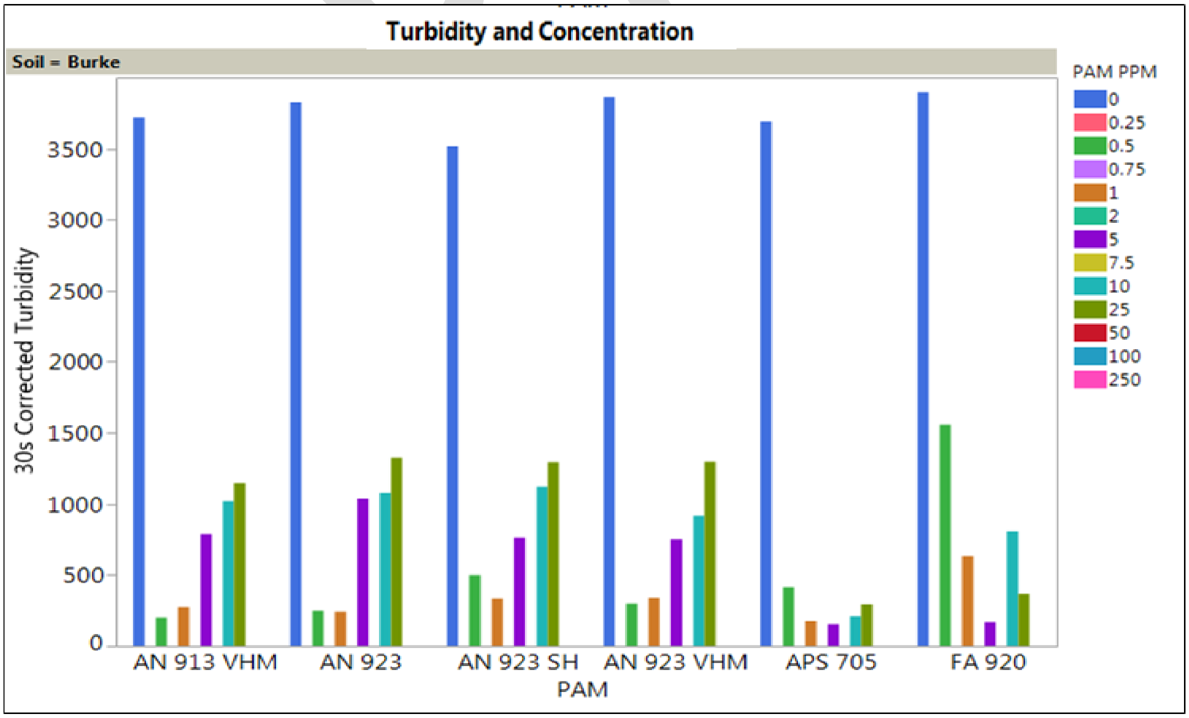


Figure A4: Effects of PAM concentration by PAM type for Burke County, a silt loam, after resting for 30 seconds.

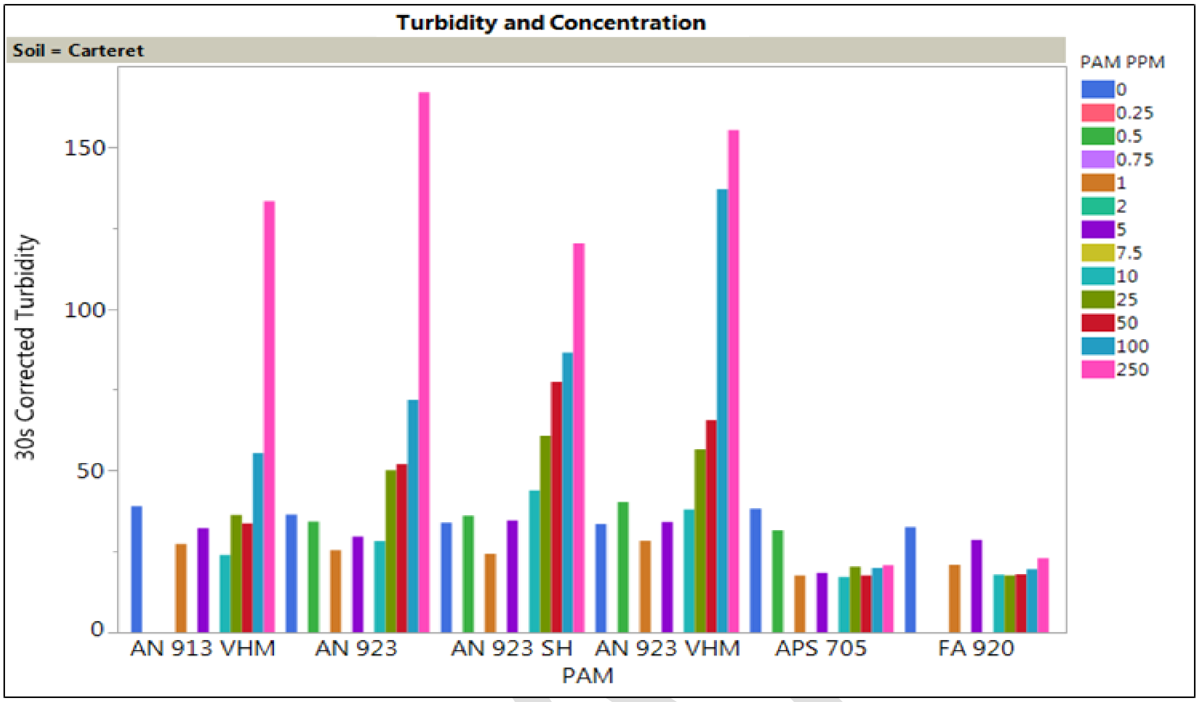


Figure A5: Effects of PAM concentration by PAM type for Carteret County, a sand, after resting for 30 seconds.

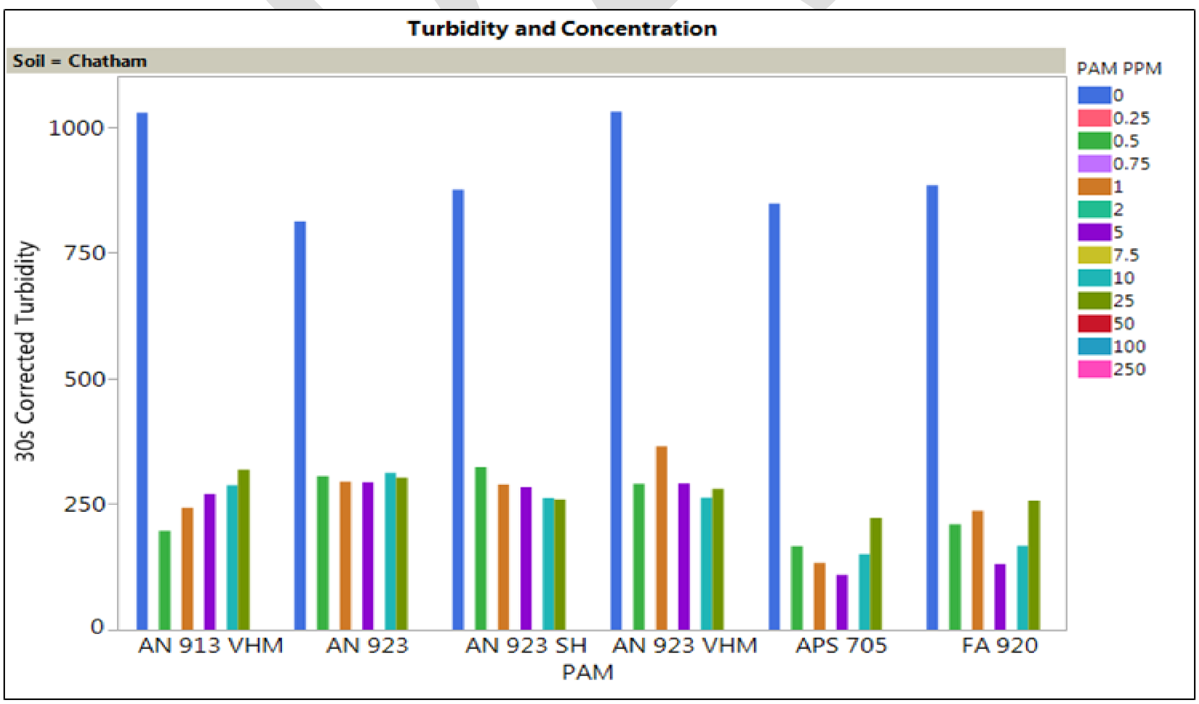


Figure A6: Effects of PAM concentration by PAM type for Chatham county, a clay, after resting for 30 seconds.

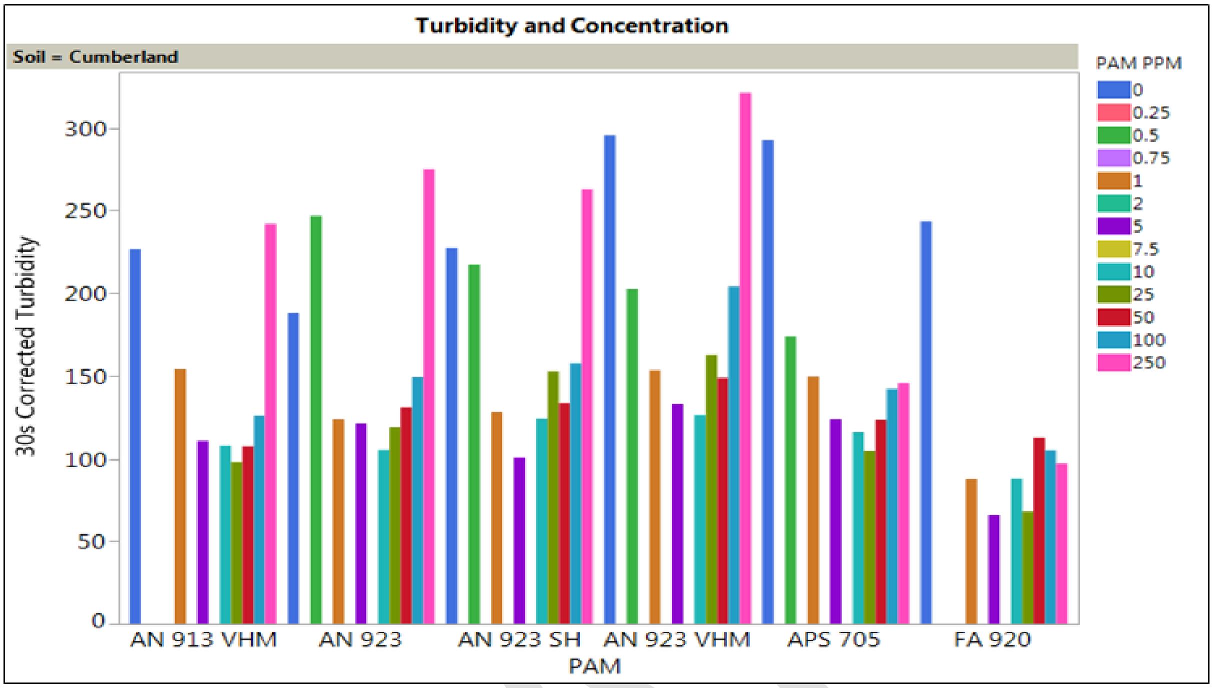


Figure A7: Effects of PAM concentration by PAM type for the Cumberland county soil after resting for 30 seconds.

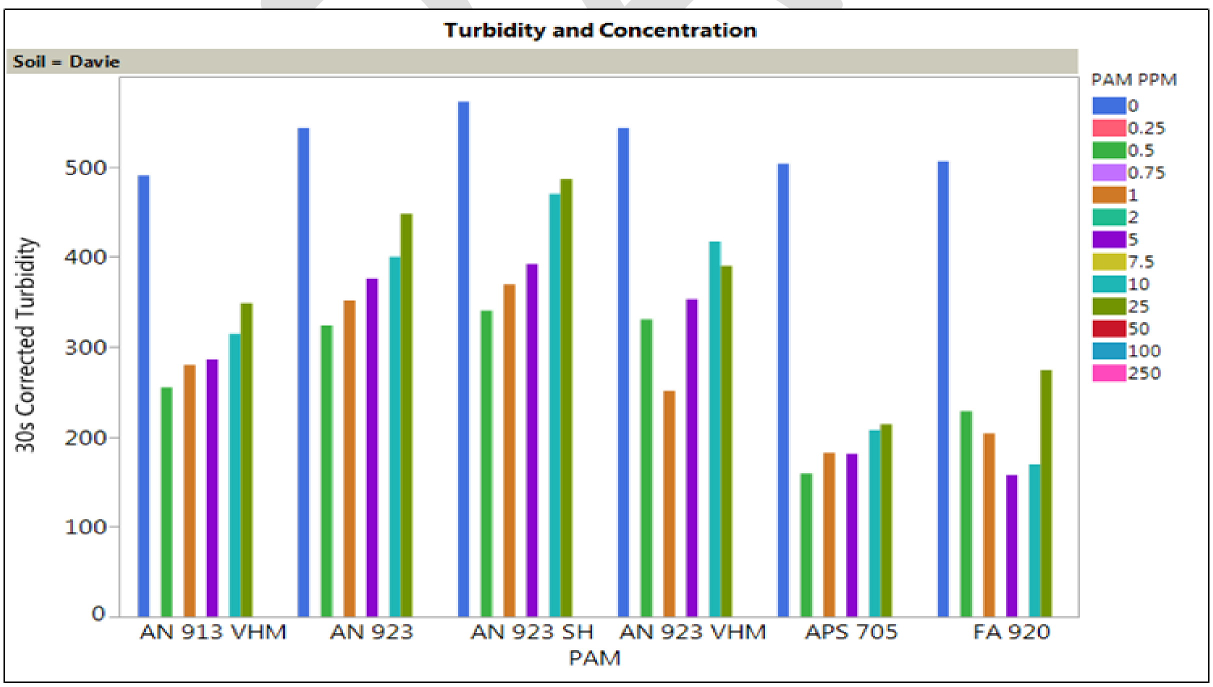


Figure A8: Effects of PAM concentration by PAM type for the Davie county soil after resting for 30 seconds.

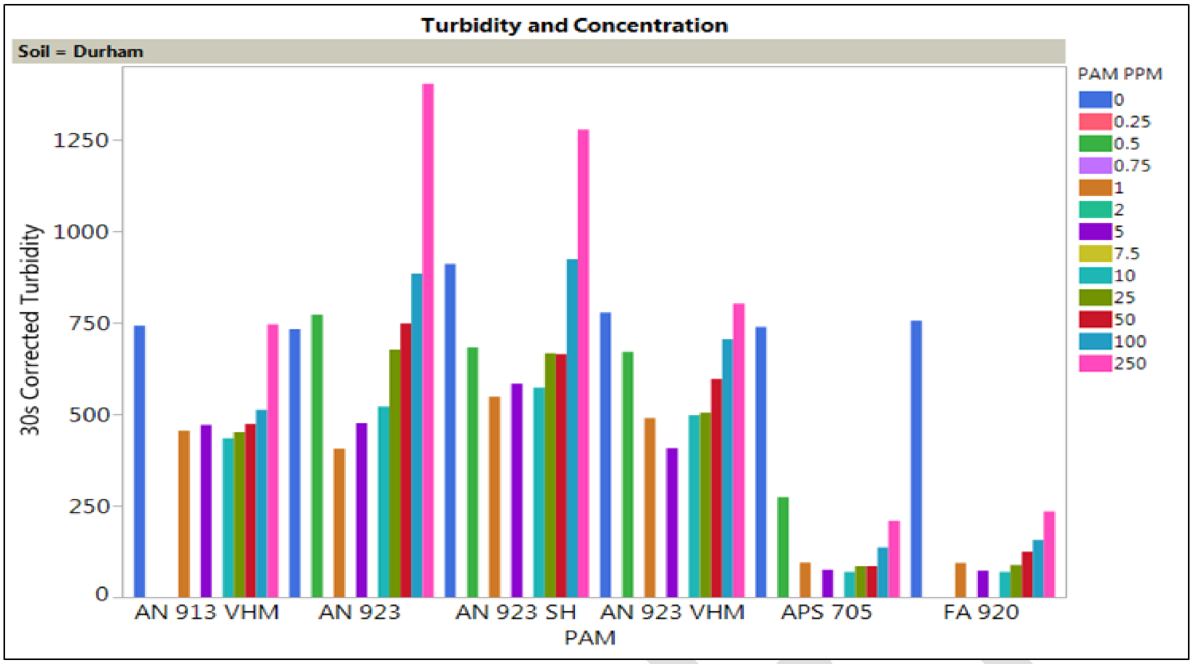


Figure A9: Effects of PAM concentration by PAM type for the Durham county soil after resting for 30 seconds.

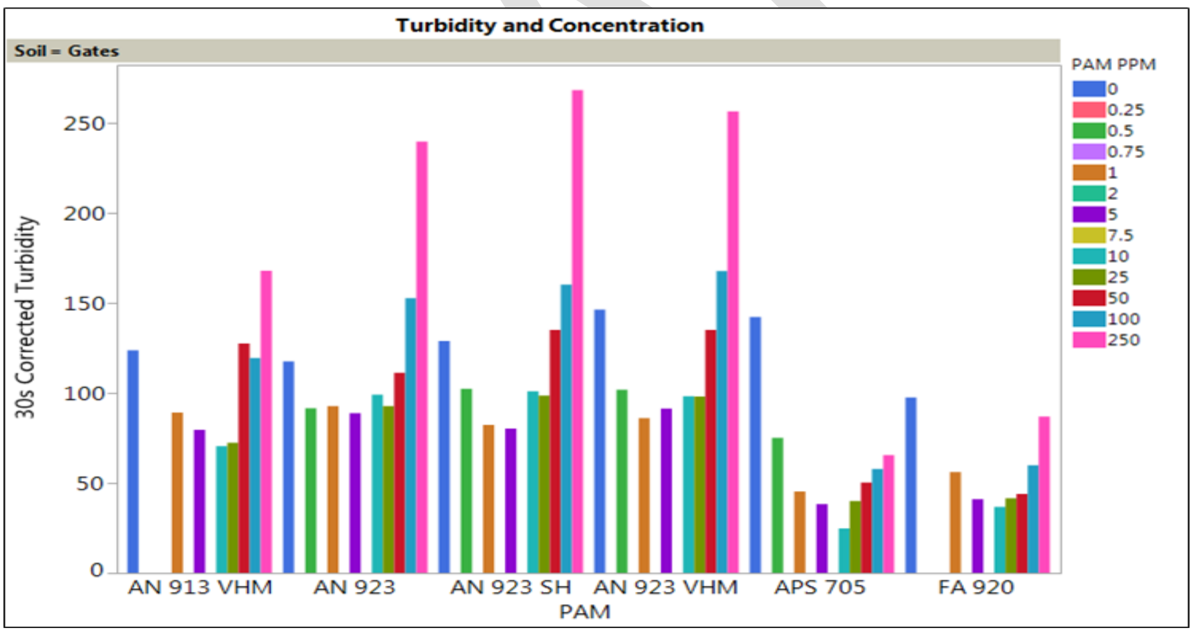


Figure A10: Effects of PAM concentration by PAM type for the Gates county soil after resting for 30 seconds.

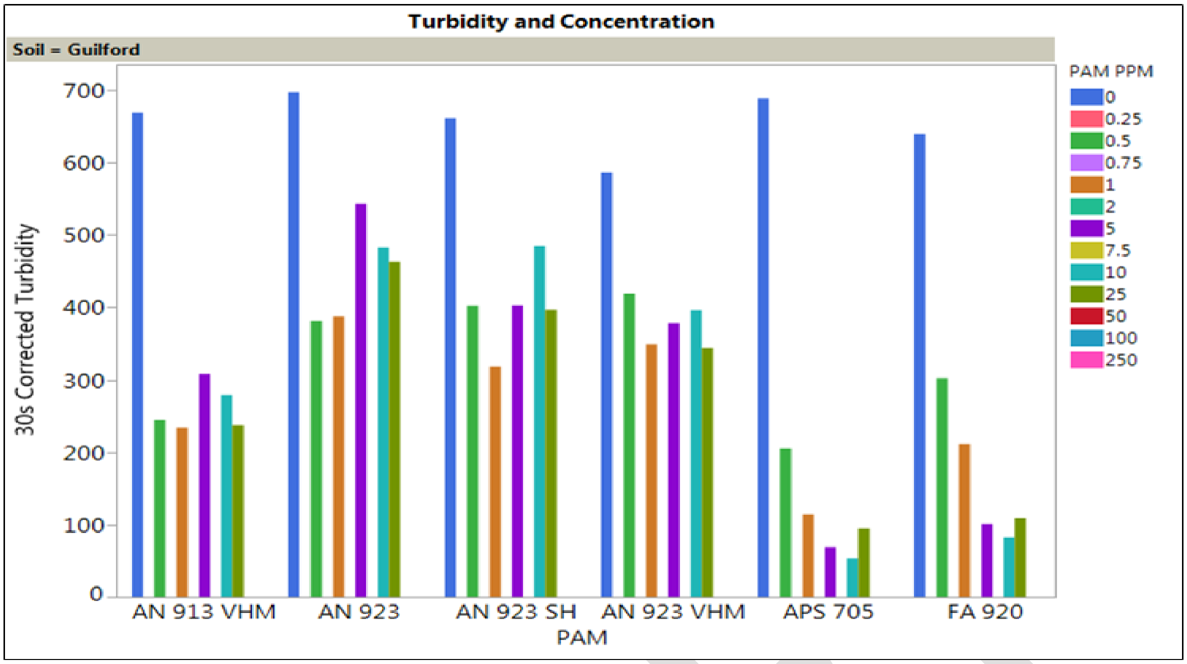


Figure A11: Effects of PAM concentration by PAM type for the Guilford county soil after resting for 30 seconds.

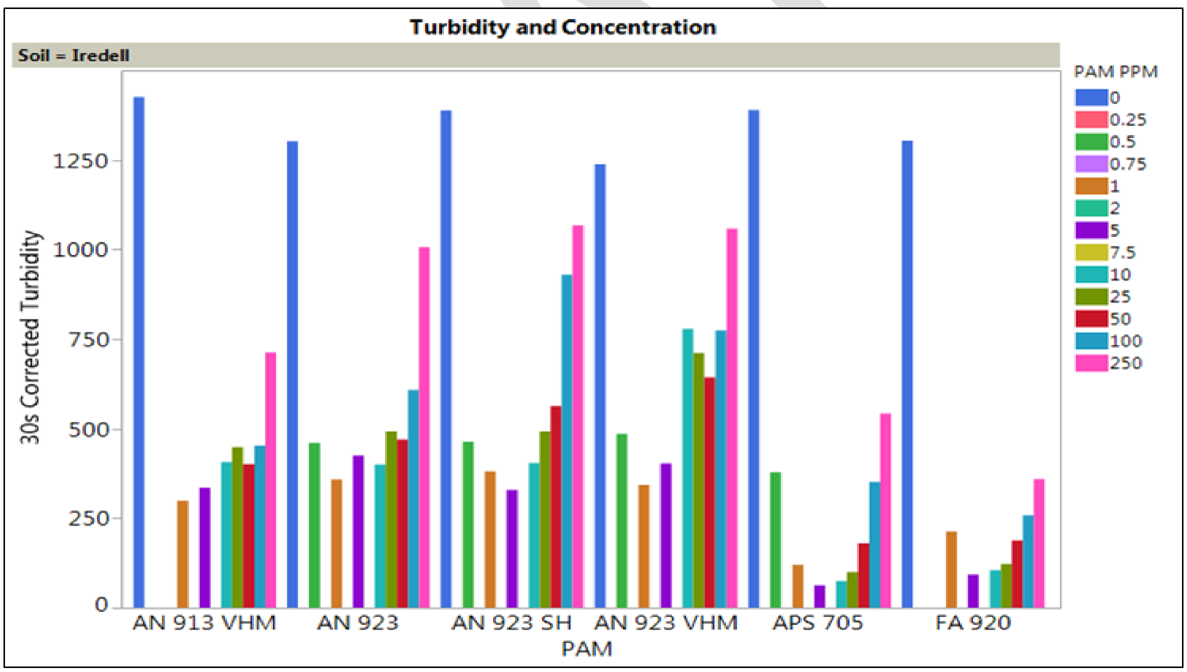


Figure A12: Effects of PAM concentration by PAM type for the Iredell county soil after resting for 30 seconds.

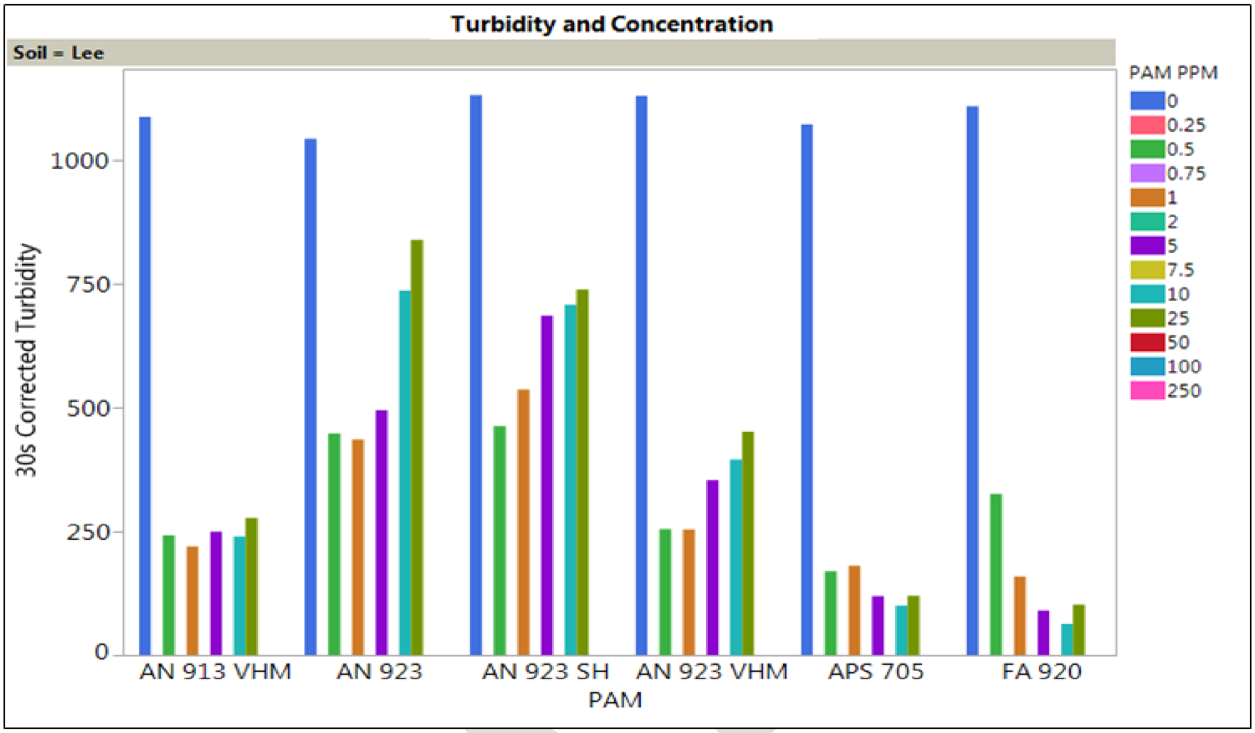


Figure A13: Effects of PAM concentration by PAM type for the Lee county soil after resting for 30 seconds.

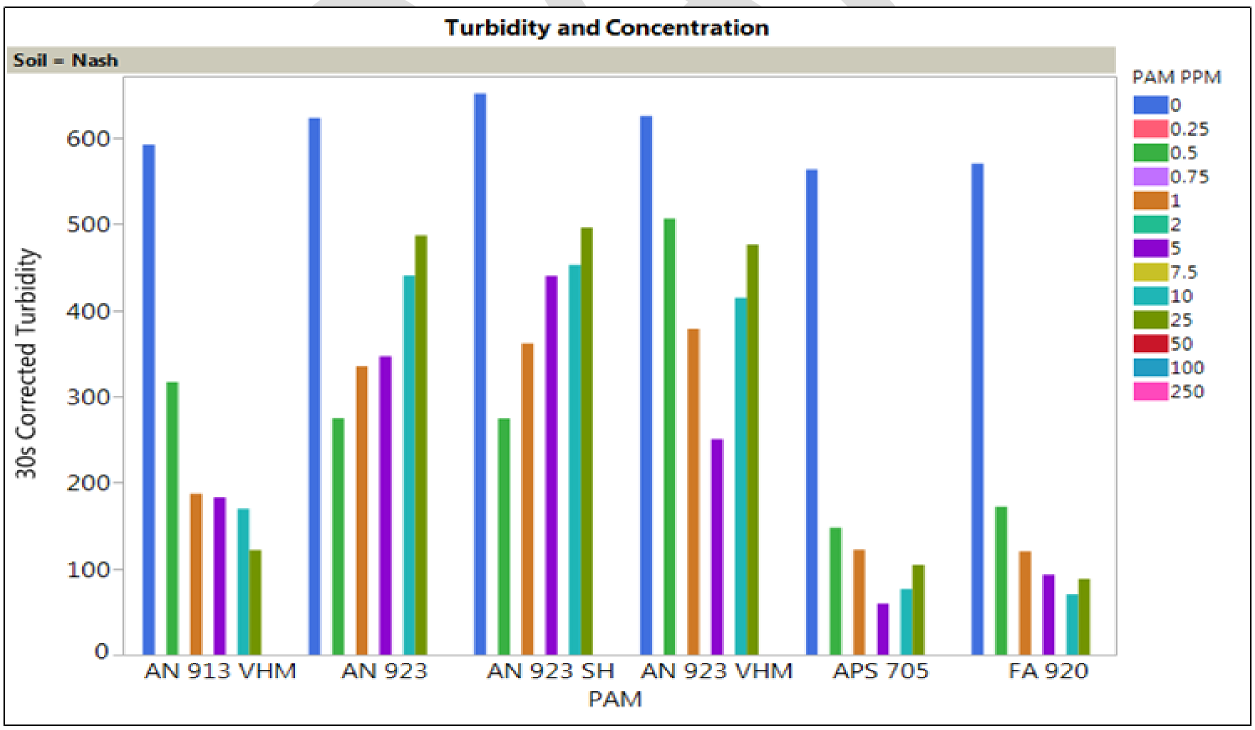


Figure A14: Effects of PAM concentration by PAM type for the Nash county soil after resting for 30 seconds.

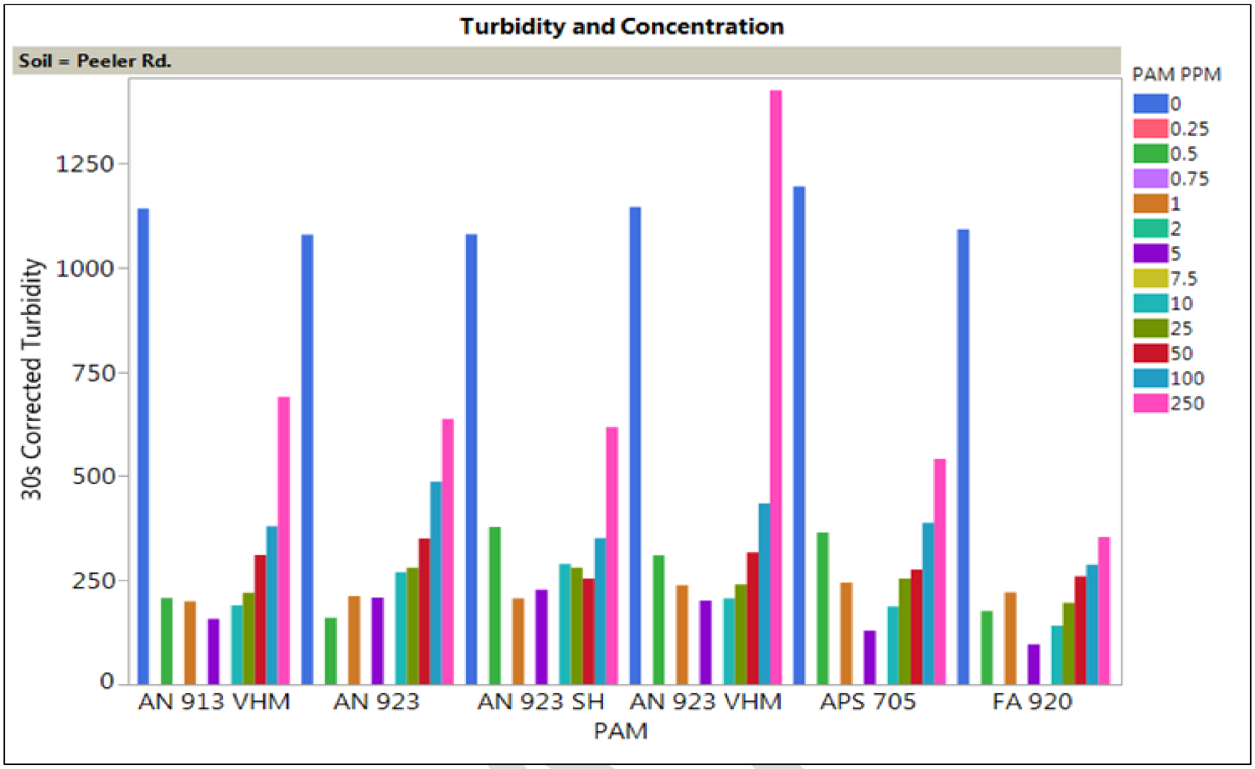


Figure A15: Effects of PAM concentration by PAM type for the Peeler Rd. soil (located in Rowan Co.) after resting for 30 seconds.

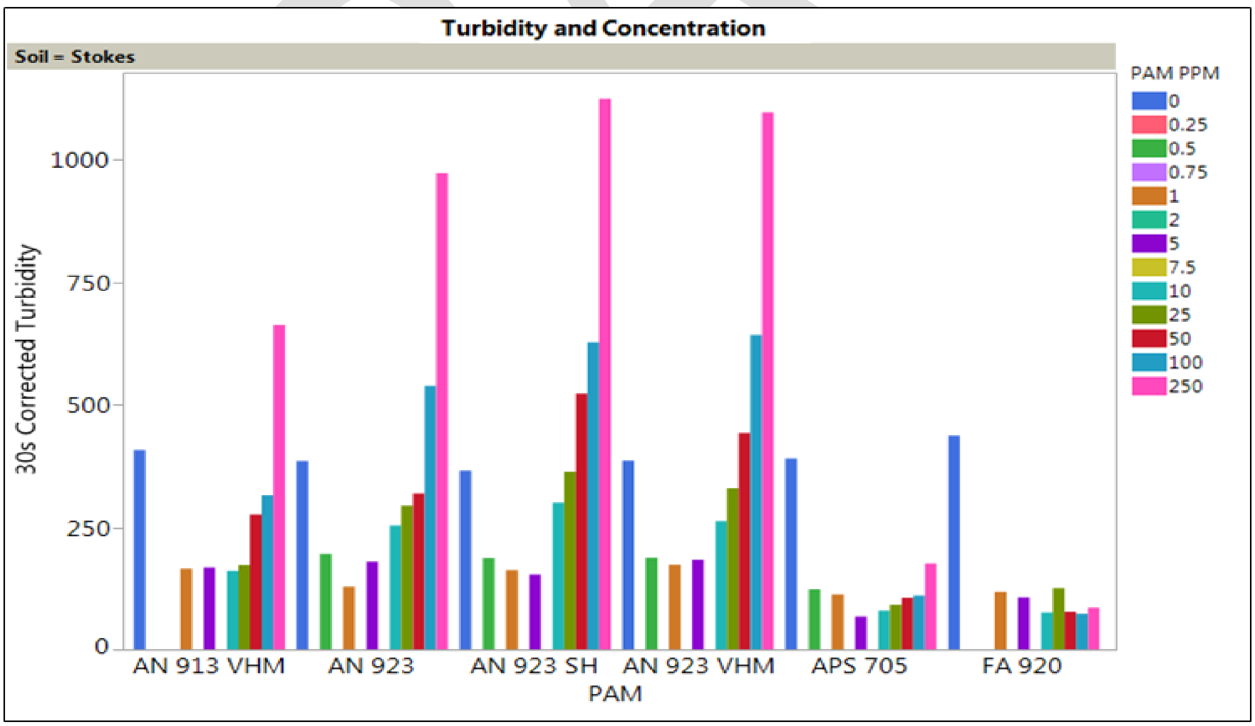


Figure A16: Effects of PAM concentration by PAM type for the Stokes county soil after resting for 30 seconds.

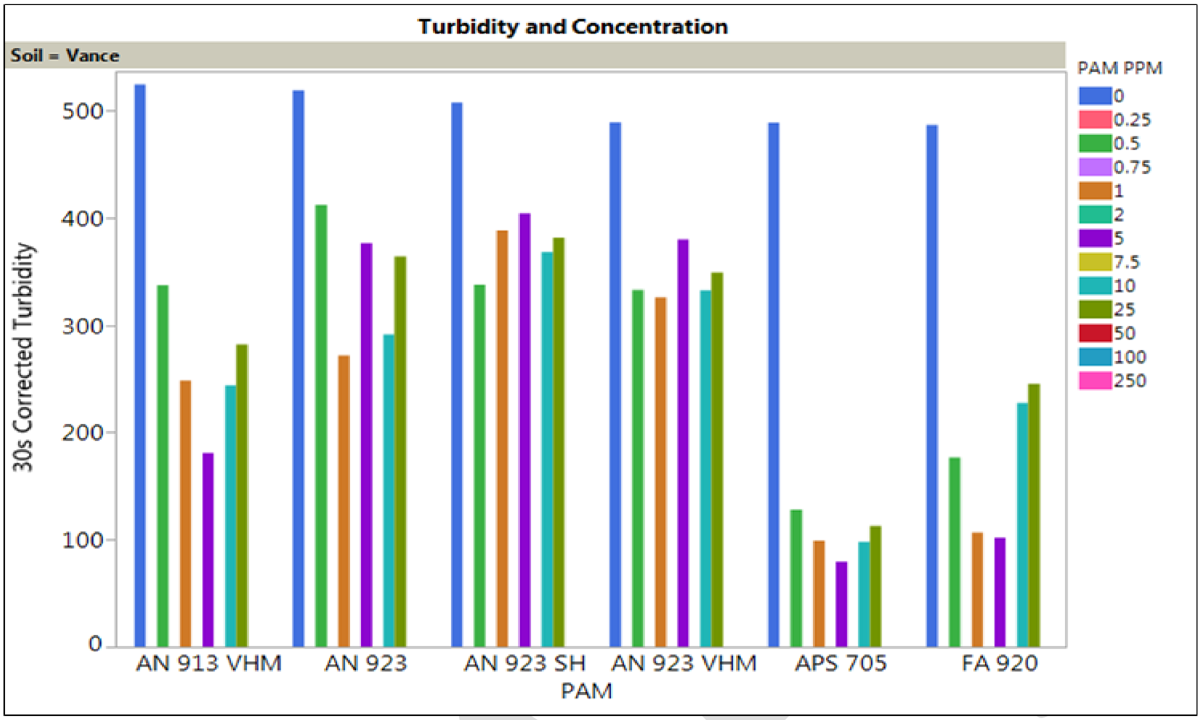


Figure A17: Effects of PAM concentration by PAM type for the Vance county soil after resting for 30 seconds.

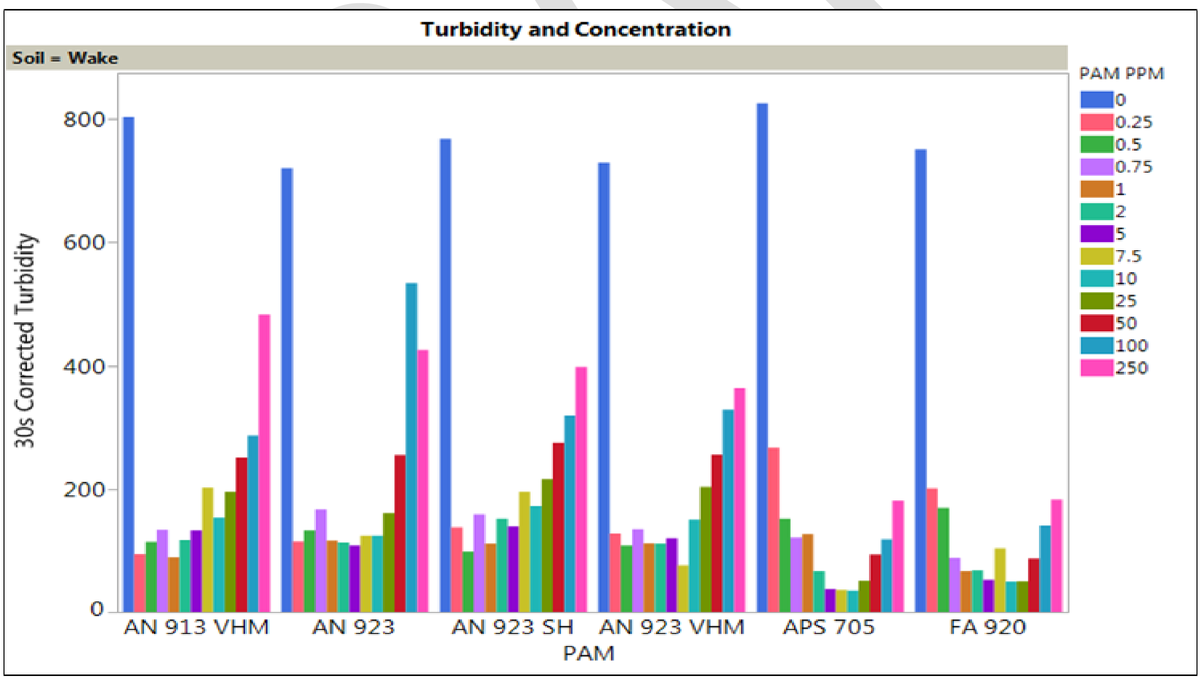


Figure A18: Effects of PAM concentration by PAM type for the Wake county soil after resting for 30 seconds.

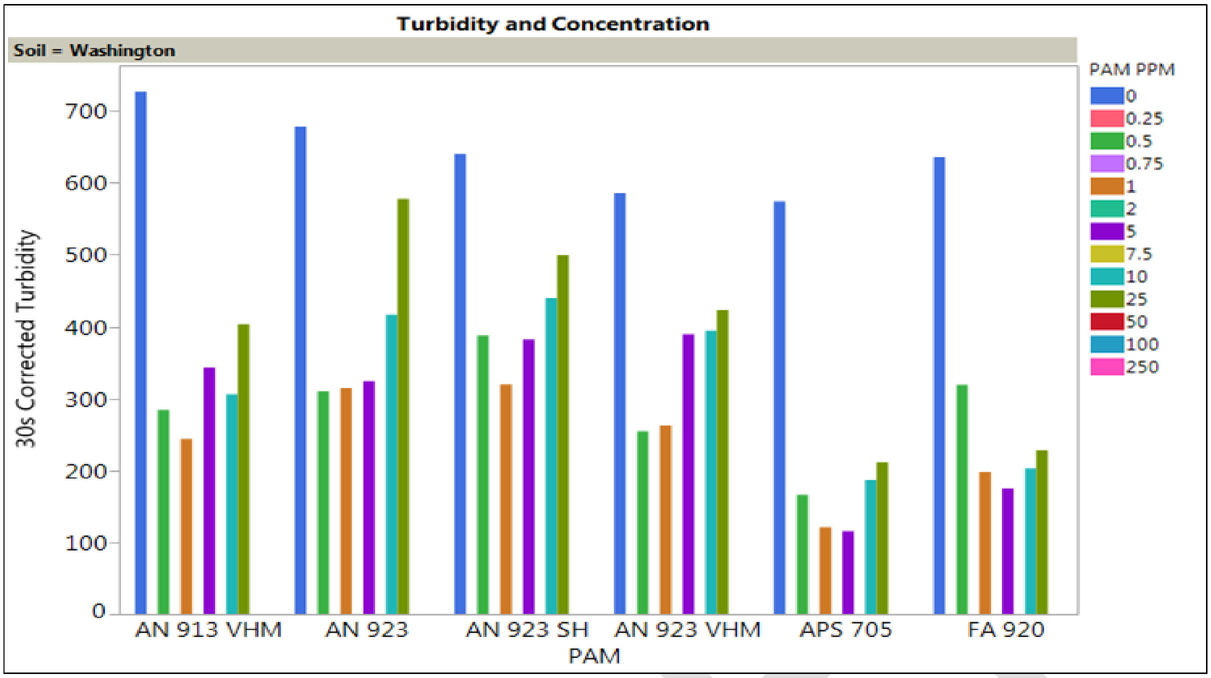


Figure A19: Effects of PAM concentration by PAM type for the Washington county soil after resting for 30 seconds.

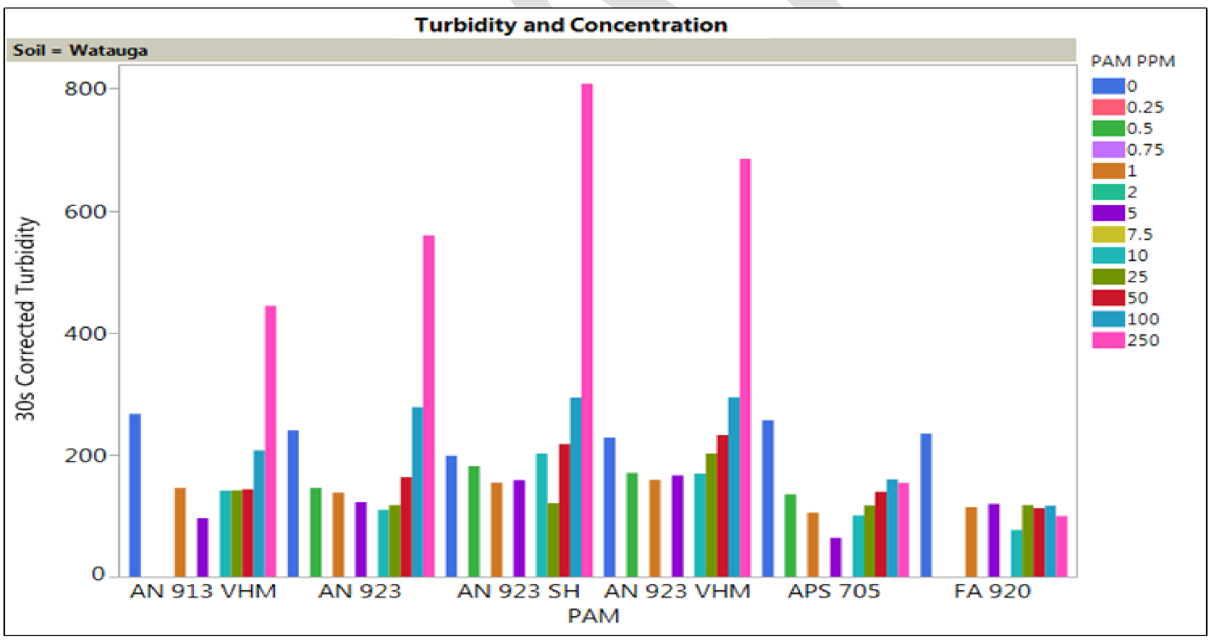


Figure A20: Effects of PAM concentration by PAM type for the Watauga county soil after resting for 30 seconds.

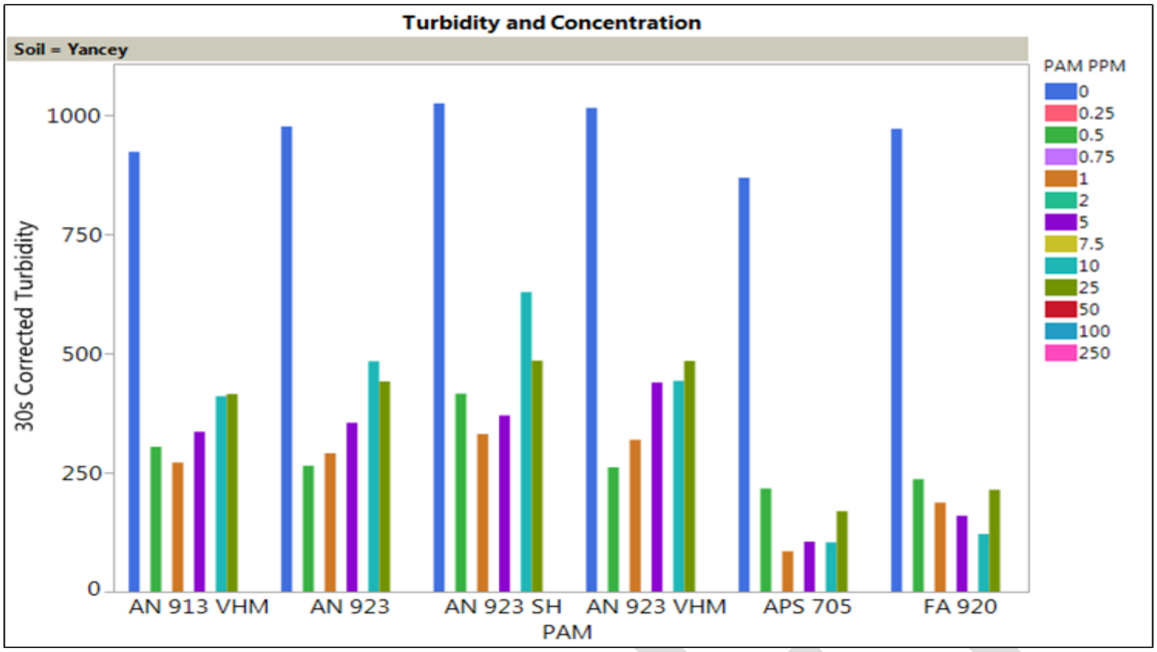


Figure A21: Effects of PAM concentration by PAM type for the Yancey county soil after resting for 30 seconds.

A2. Effects of PAM Concentration on Turbidity Over Time

The following graphs illustrate the effects of time on turbidity at different PAM concentrations.

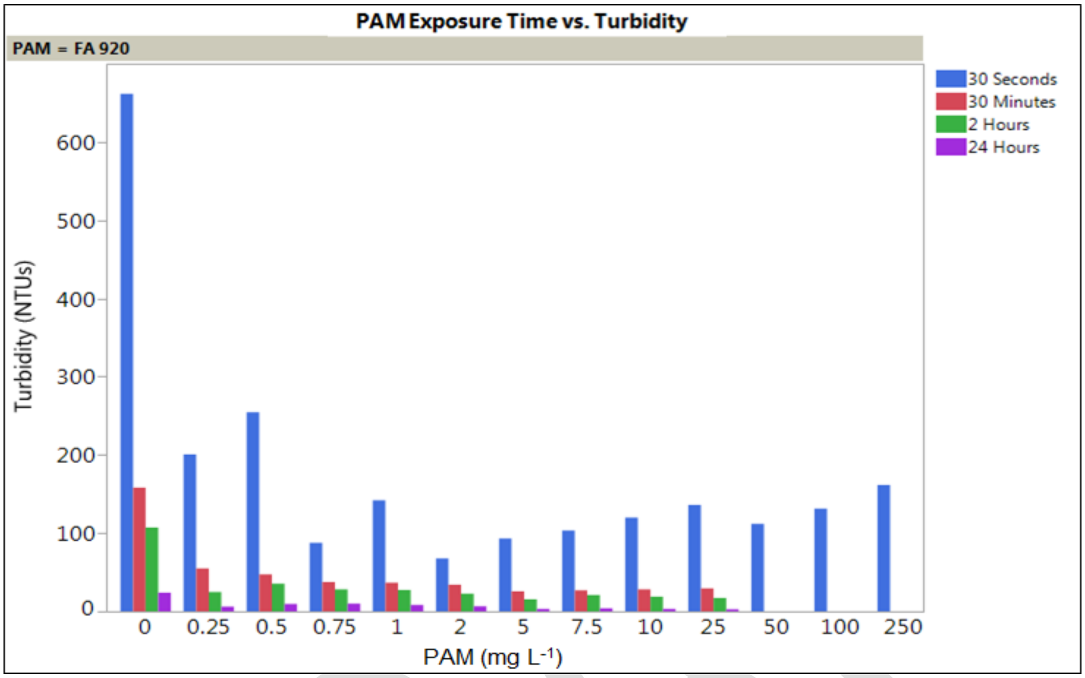


Figure A22: Effect of sampling time on turbidity at increasing concentrations when using FA 920.

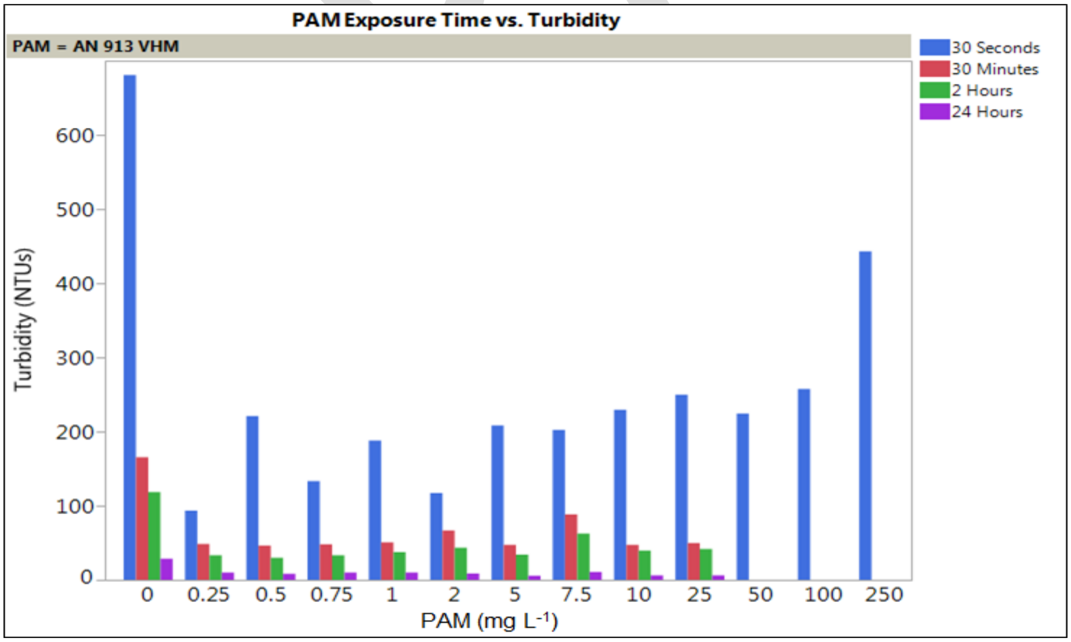


Figure A23: Effect of sampling time on turbidity at increasing concentrations when using AN 913 VHM.

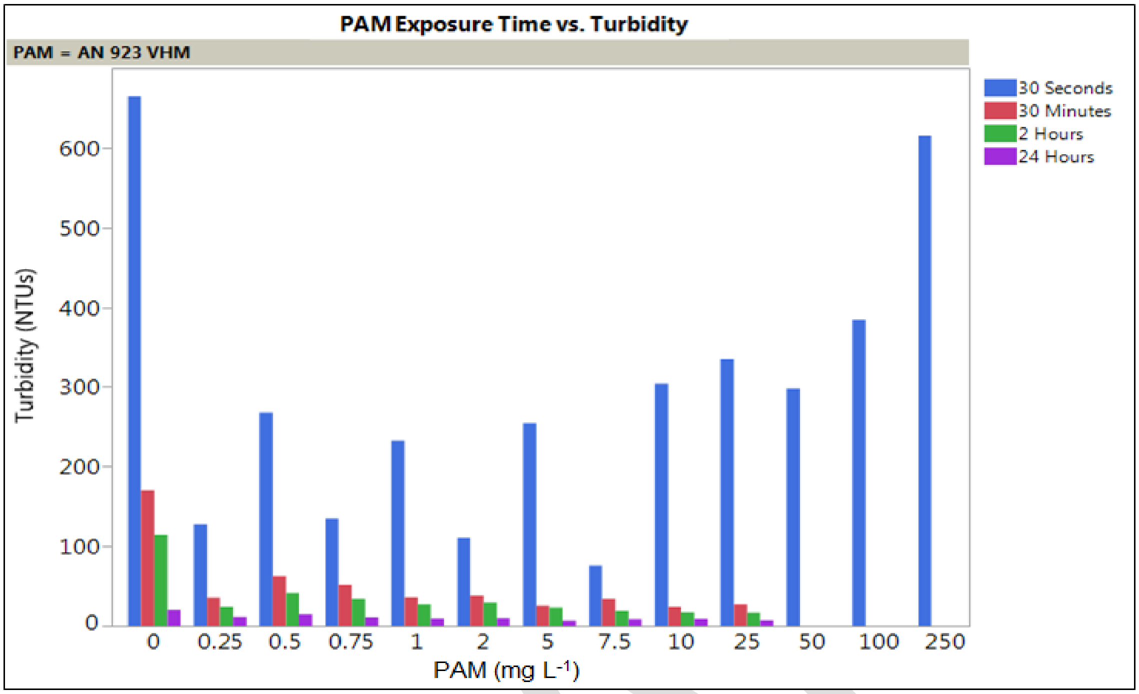


Figure A24: Effect of sampling time on turbidity at increasing concentrations when using AN 923 VHM.

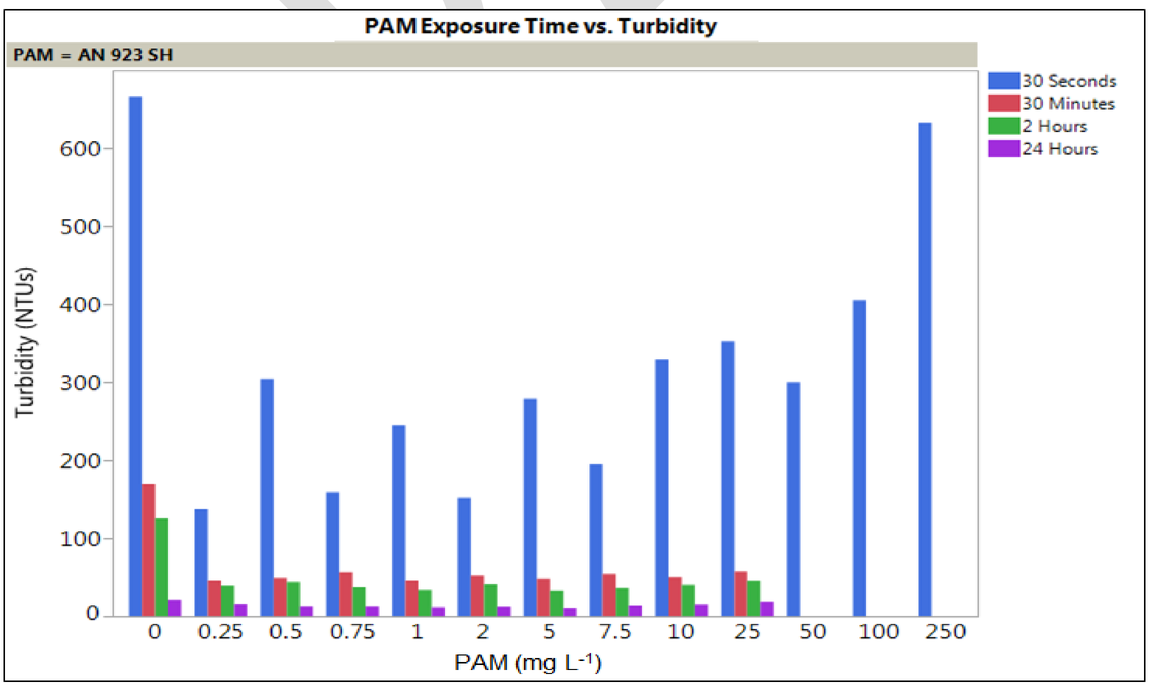


Figure A25: Effect of sampling time on turbidity at increasing concentrations when using AN 923 SH.

A3. Effects of Mixing Method on Turbidity Reduction

The following are the results of testing the effects of different mixing methods (hand vs. jar tester at different speeds) on turbidity reduction for various soil-PAM combinations.

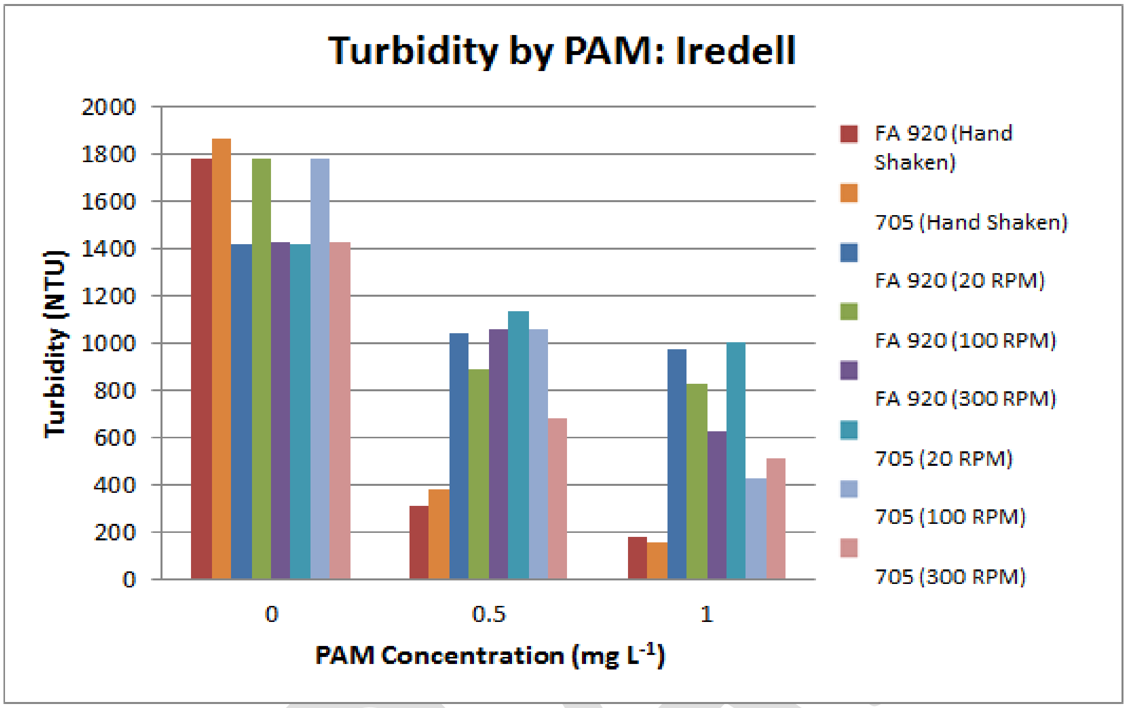


Figure A26: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Iredell County soil, with a mixing time of 10 seconds for all samples.

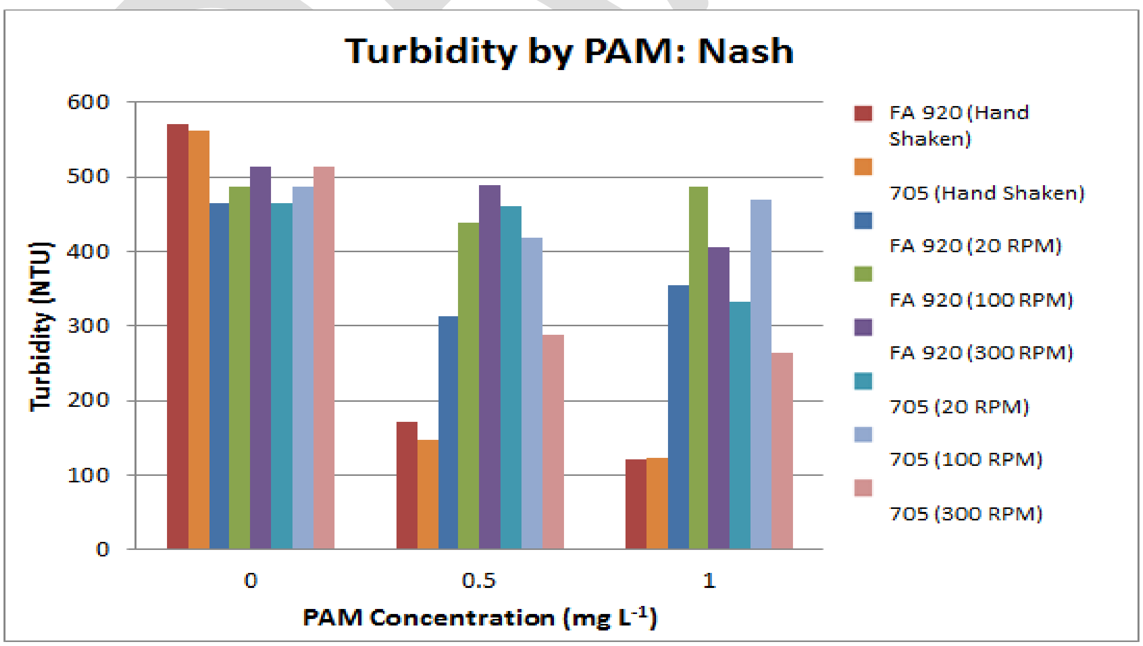


Figure A27: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Nash County soil, with a mixing time of 10 seconds for all samples.

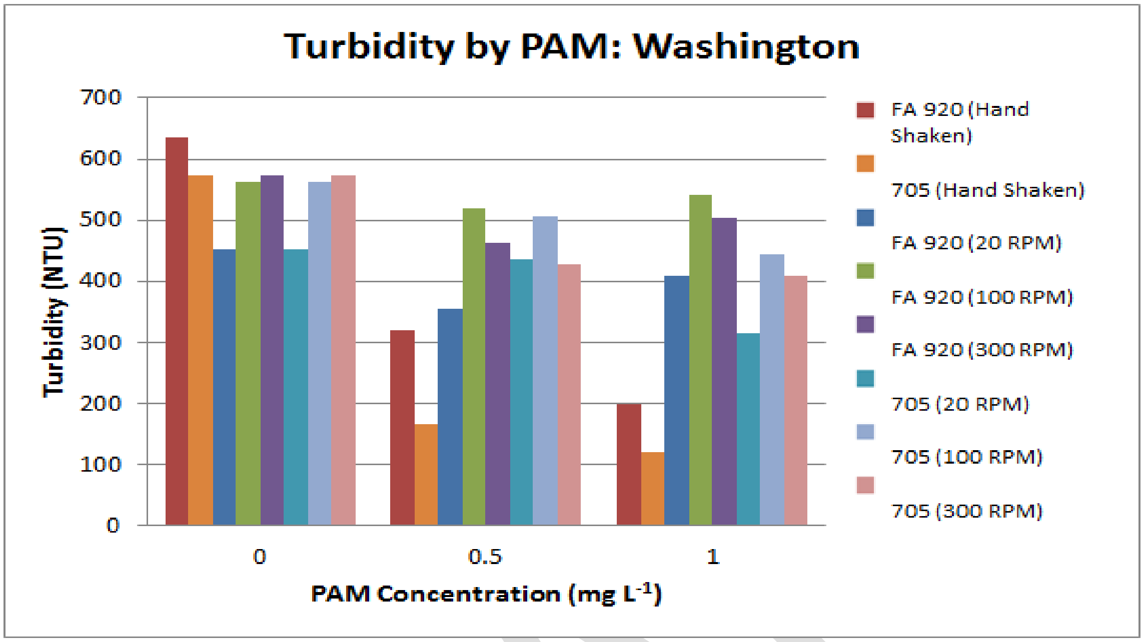


Figure A28: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Washington County soil, with a mixing time of 10 seconds for all samples.

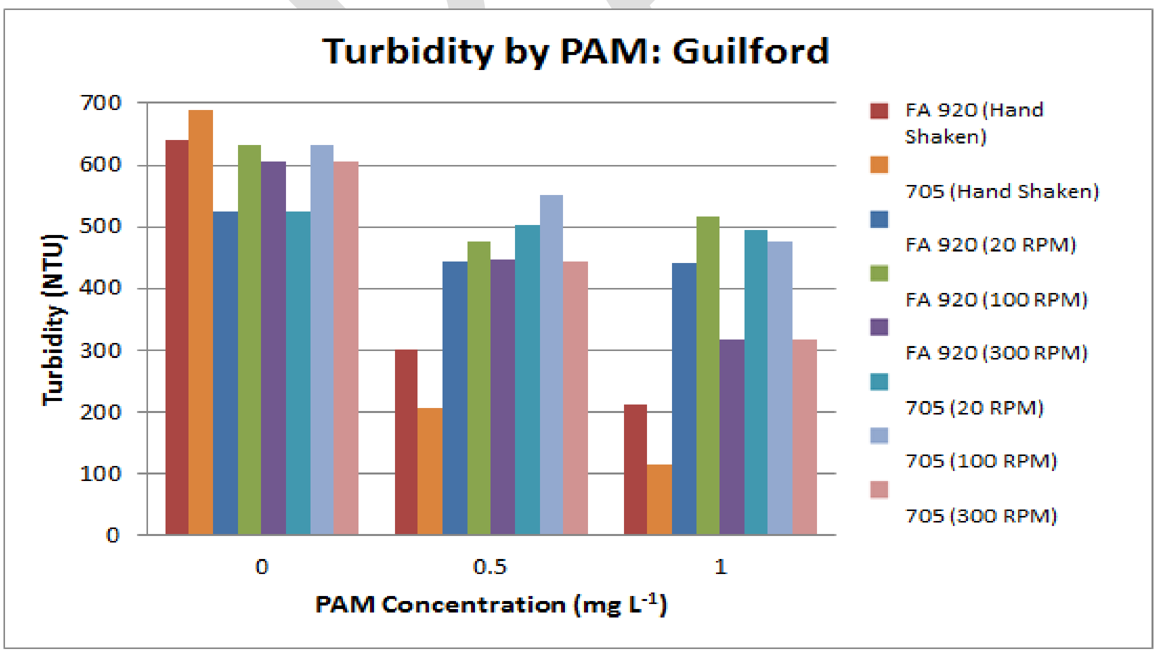


Figure A29: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Guilford County soil, with a mixing time of 10 seconds for all samples.

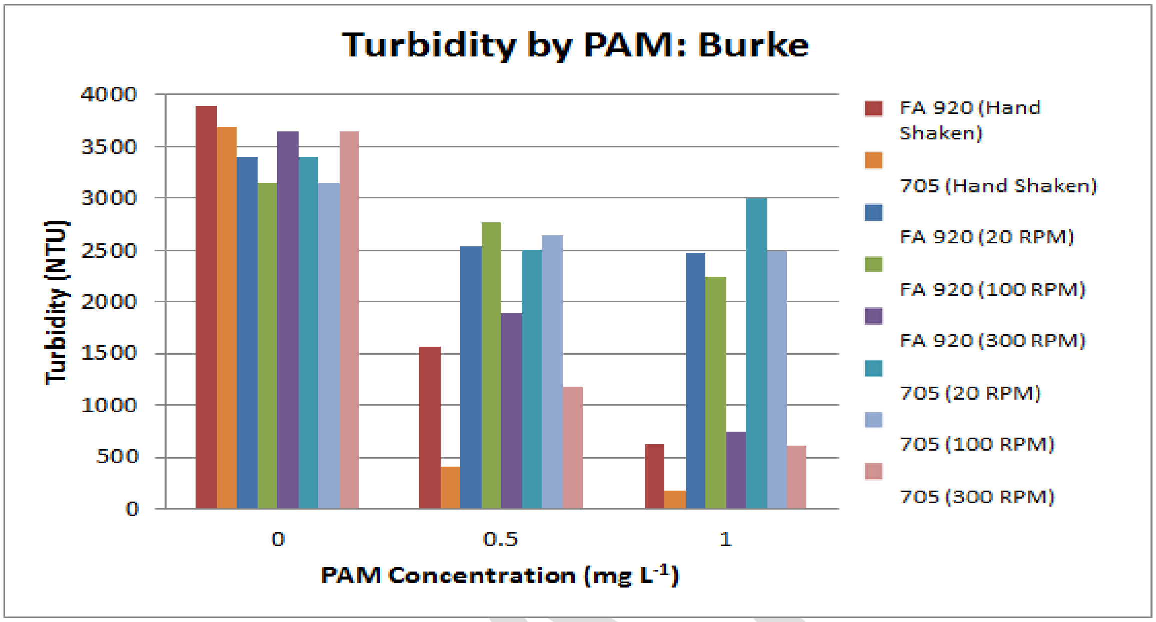
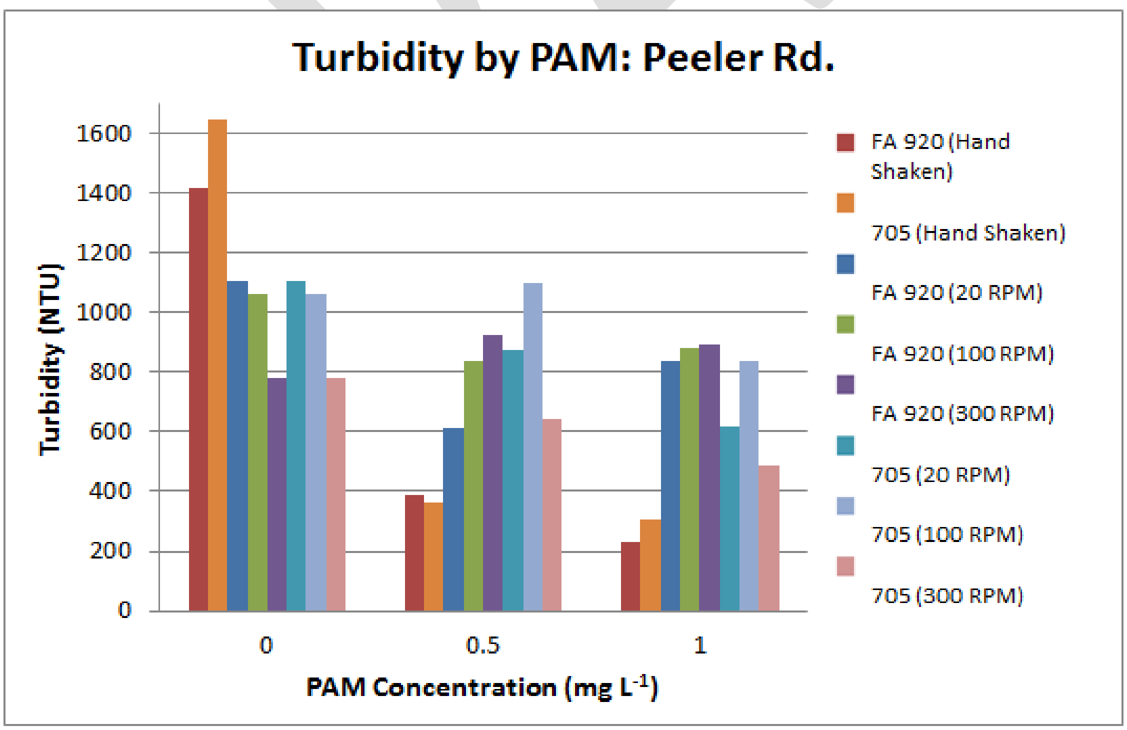
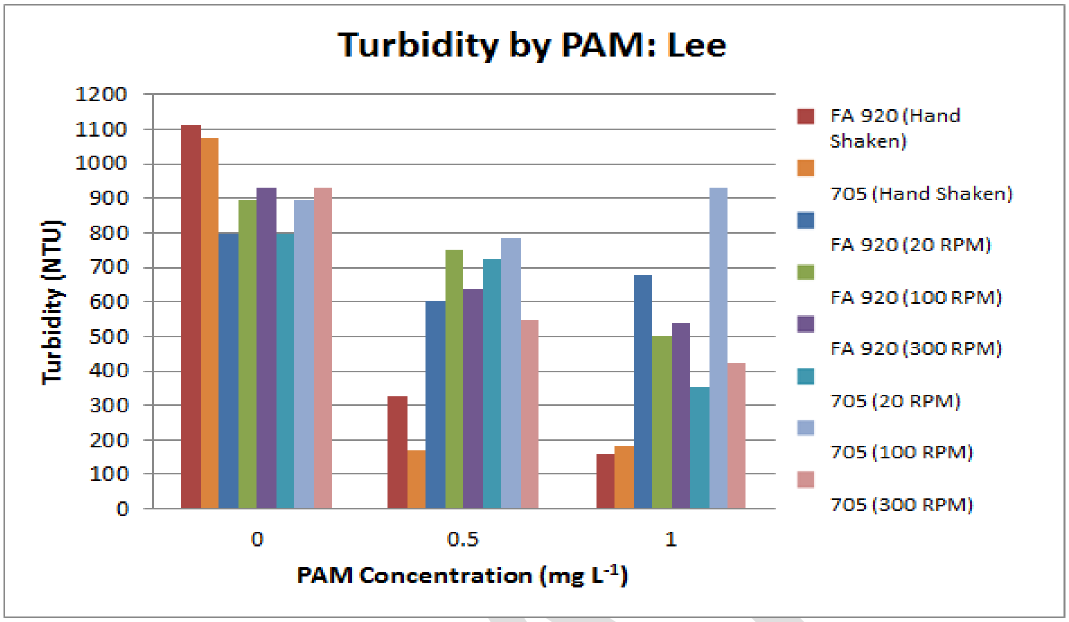


Figure A30: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Burke County soil, with a mixing time of 10 seconds for all samples.



<u>Figure A31:</u> Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Peeler Rd. soil, with a mixing time of 10 seconds for all samples.



<u>Figure A32:</u> Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Lee County soil, with a mixing time of 10 seconds for all samples.

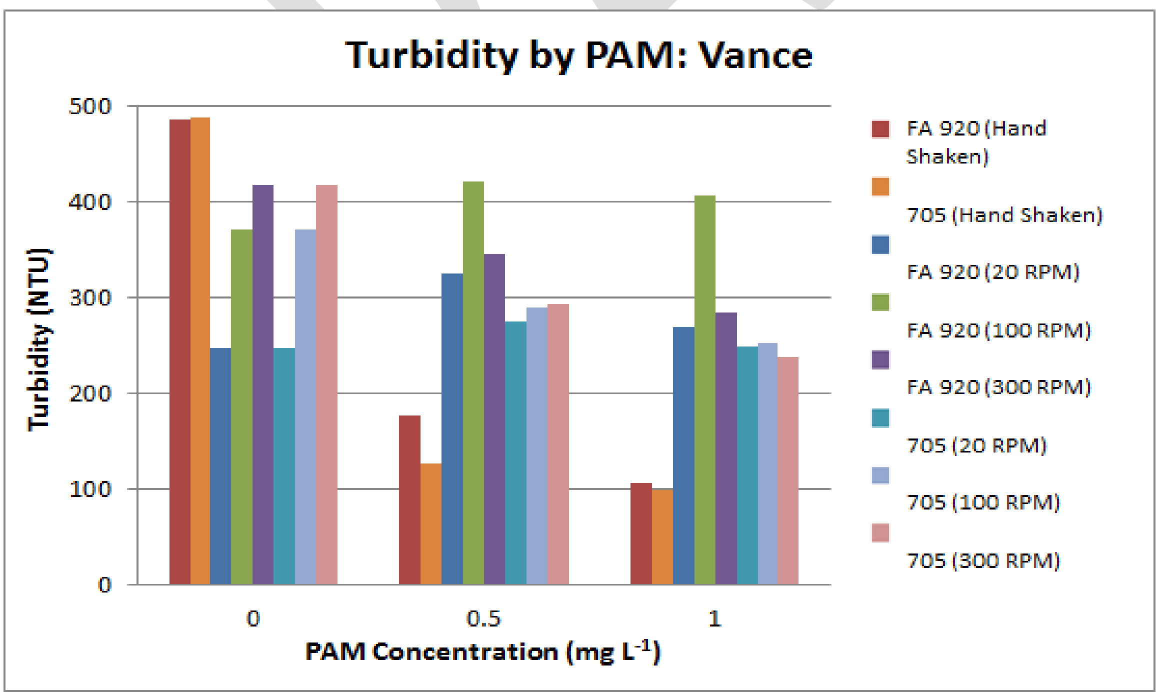


Figure A33: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Vance County soil, with a mixing time of 10 seconds for all samples.

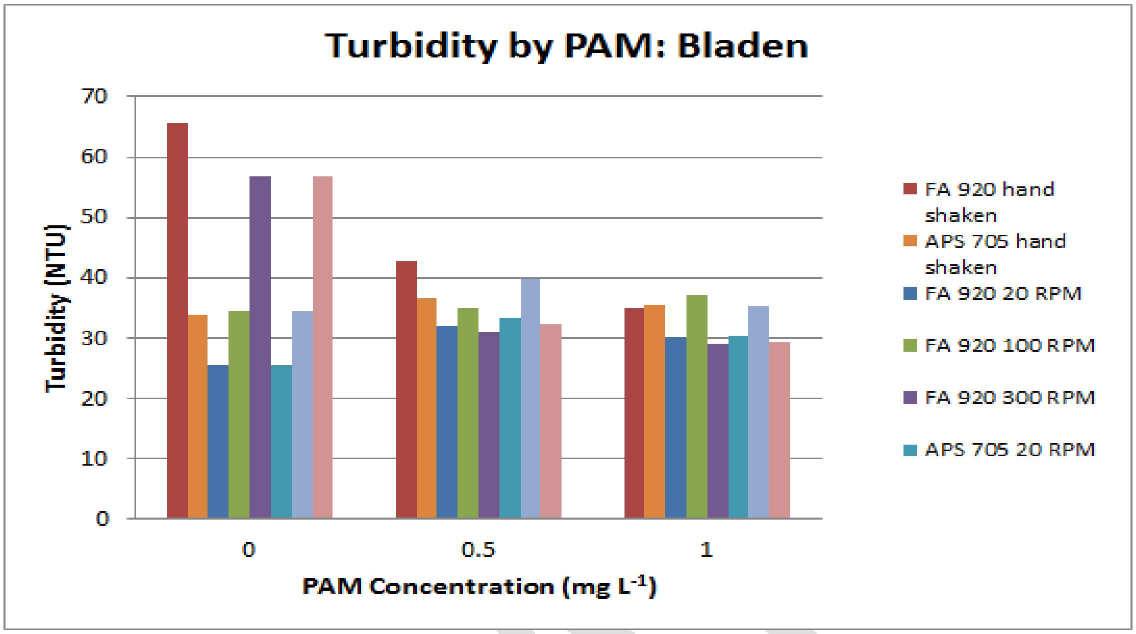


Figure A34: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Bladen County soil, with a mixing time of 10 seconds for all samples.

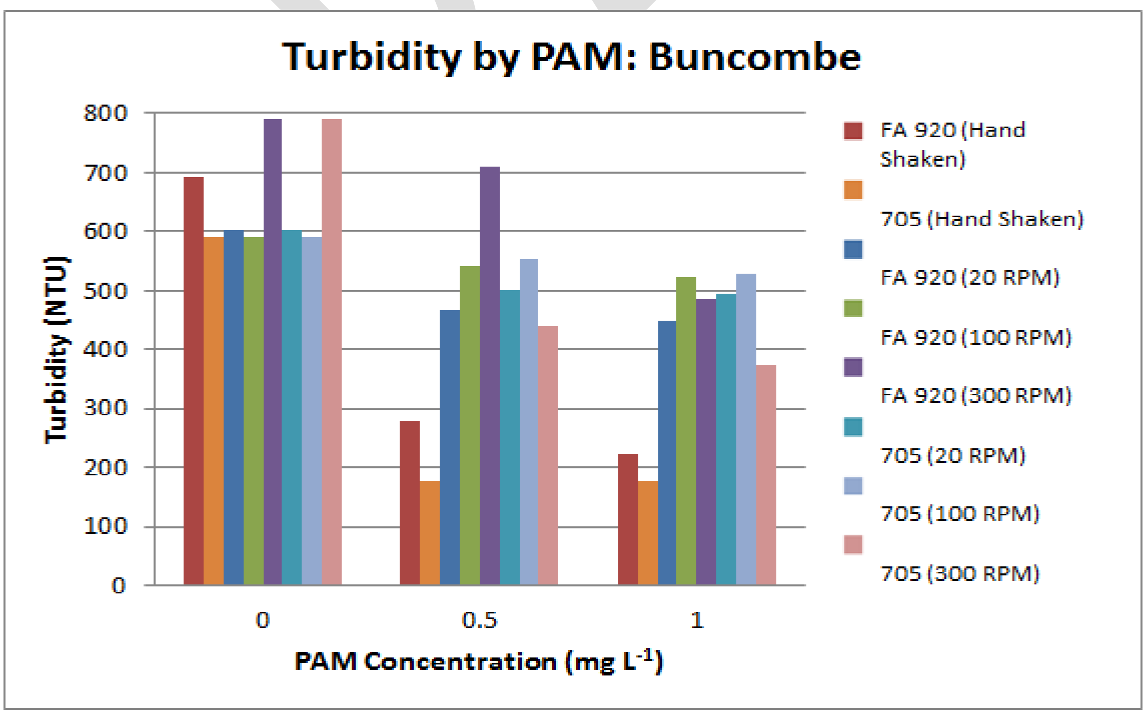


Figure A35: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Buncombe County soil, with a mixing time of 10 seconds for all samples.

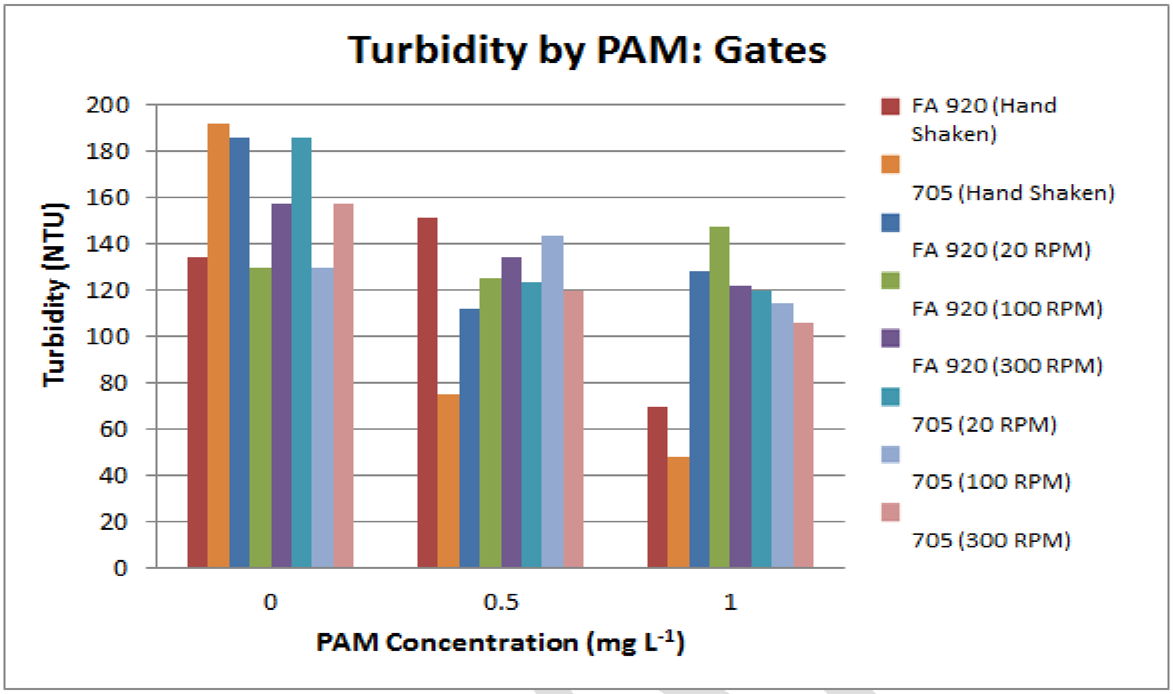


Figure A36: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Gates County soil, with a mixing time of 10 seconds for all samples.

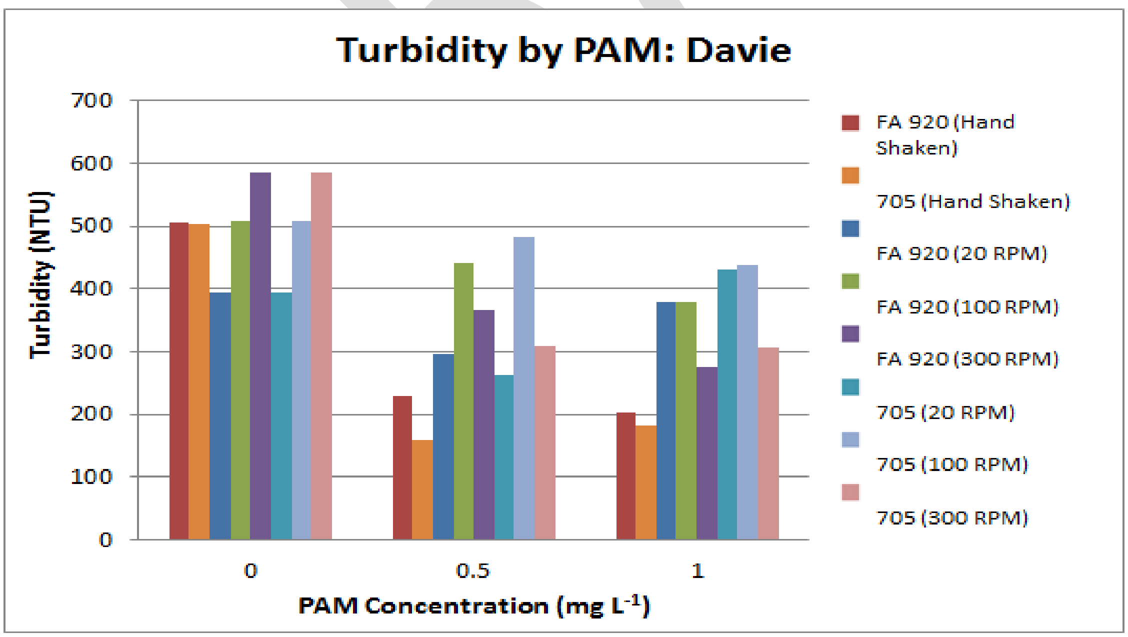


Figure A37: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Davie County soil, with a mixing time of 10 seconds for all samples.

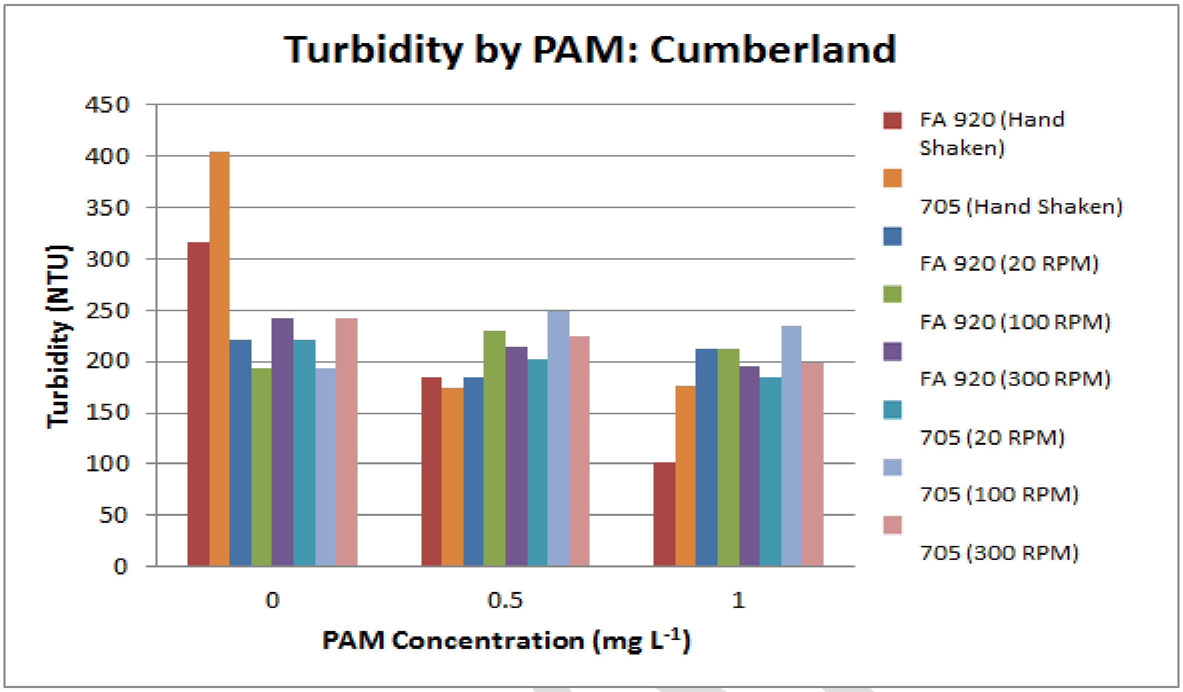


Figure A38: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Cumberland County soil, with a mixing time of 10 seconds for all samples.

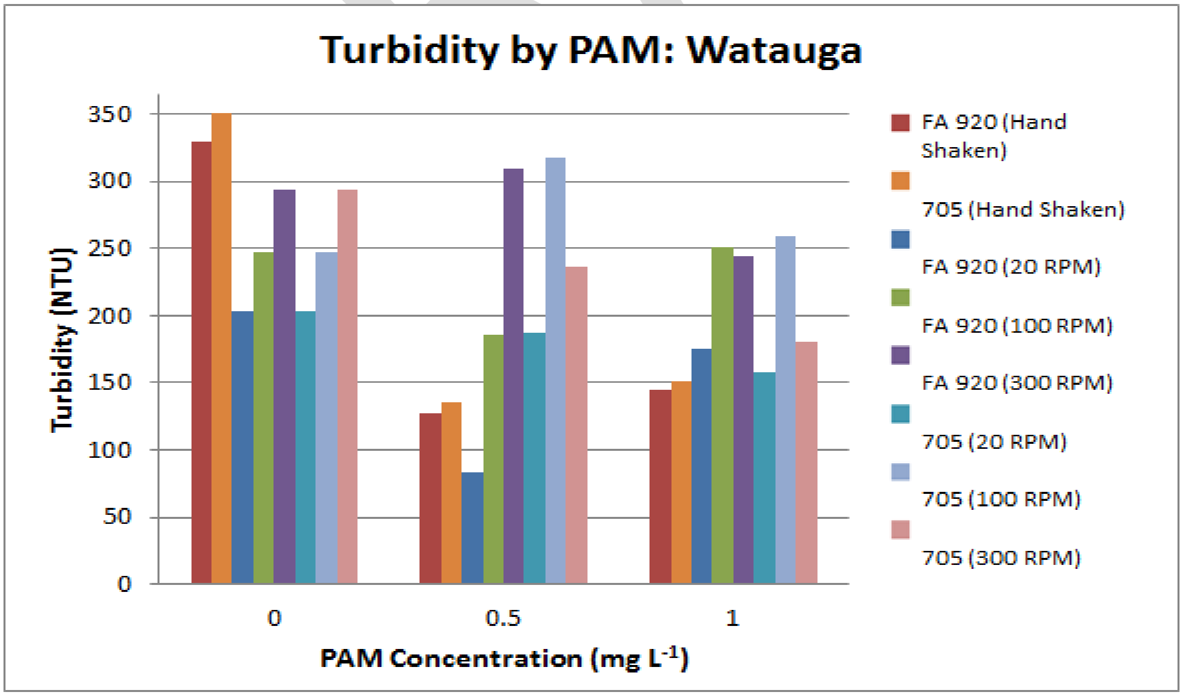


Figure A39: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Watauga County soil, with a mixing time of 10 seconds for all samples.

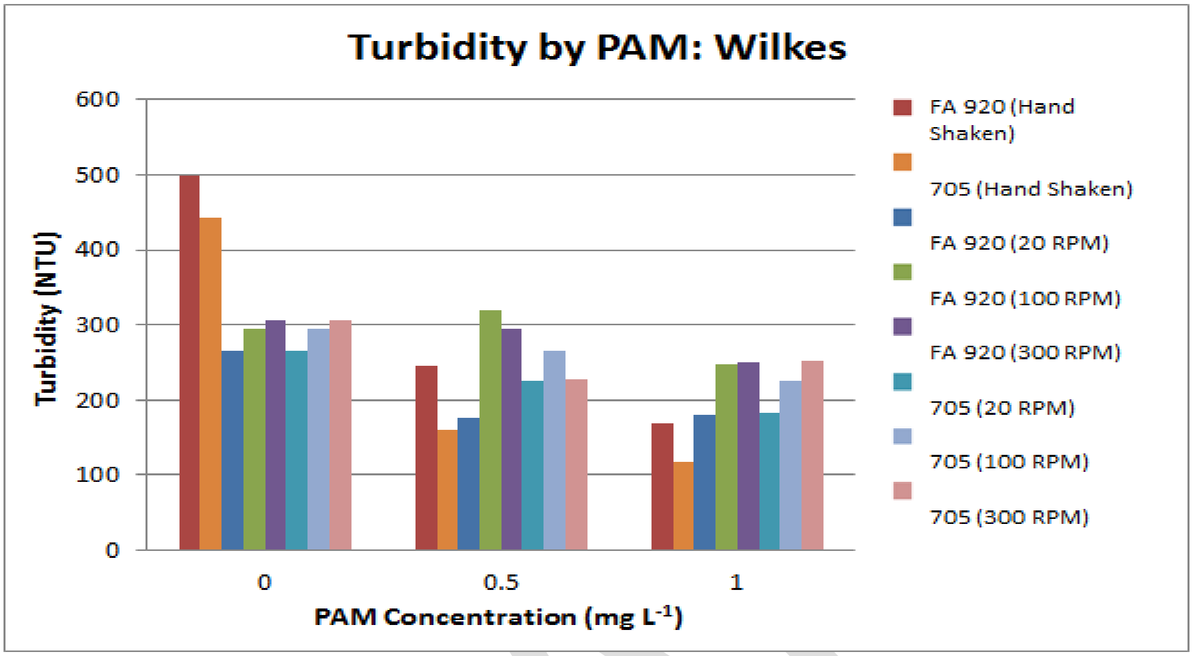


Figure A40: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Wilkes County soil, with a mixing time of 10 seconds for all samples.

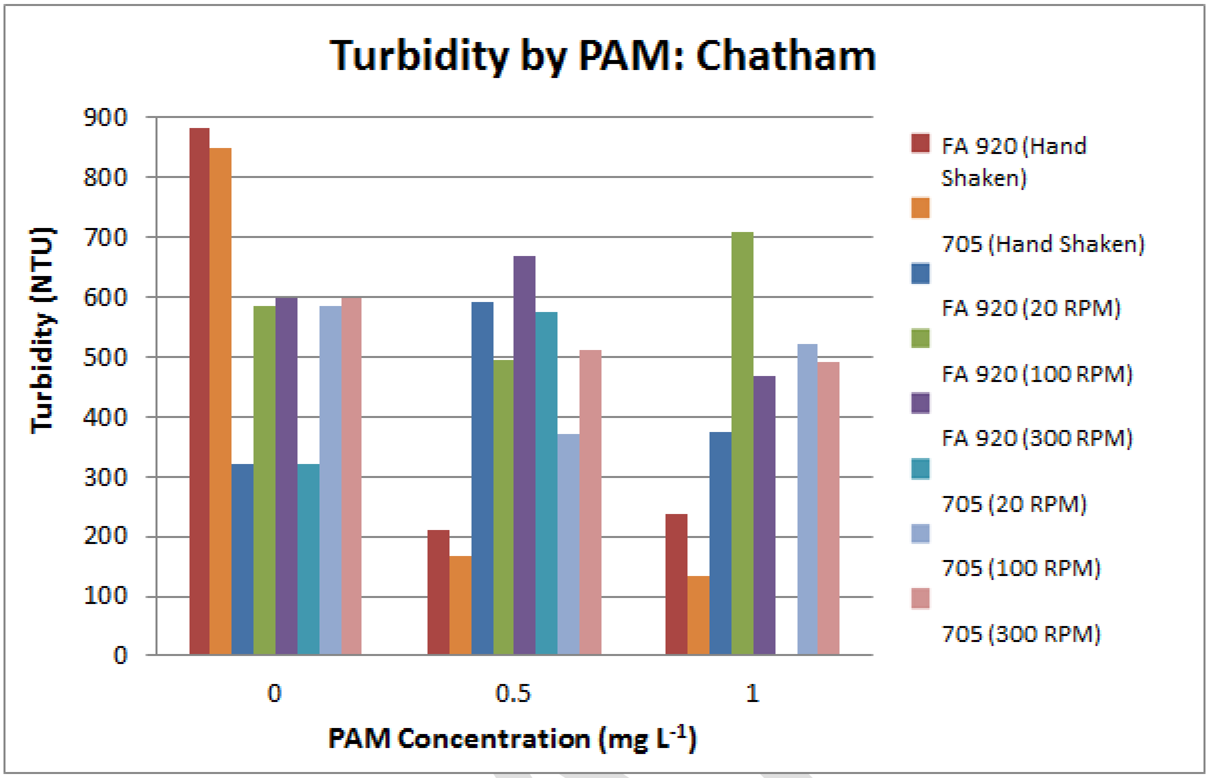


Figure A41: Comparison between hand-shaken and jar tested samples for each PAM and PAM concentration. This figure specifically shows results from the Chatham County soil, with a mixing time of 10 seconds for all samples.

A4. Effects of Settling on Turbidity and PAM

In this section comparisons were made between the turbidities of supernatants taken at 30 or 60 seconds. Seven soils were compared, three PAM concentrations and four different types of PAM, including one mixture. Burke County consistently showed the highest turbidity when comparing soils, and similarly for PAMs, the control or no PAM treatments were highest. There was no clear pattern of turbidity for the two settling times or their effects on turbidity reduction.

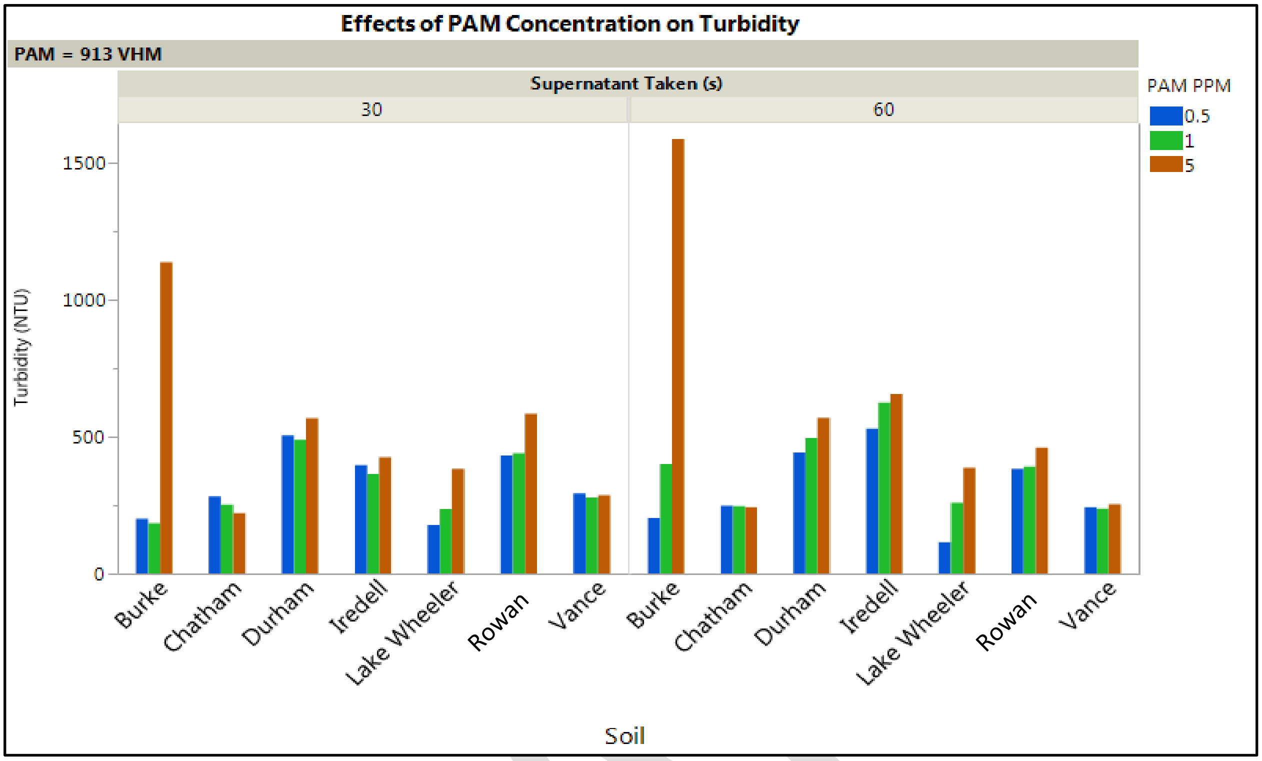


Figure A42: Turbidity comparison of 913 VHM supernatant samples taken at either 30 (left) or 60 seconds (right). Seven county soils are represented and three PAM concentrations.

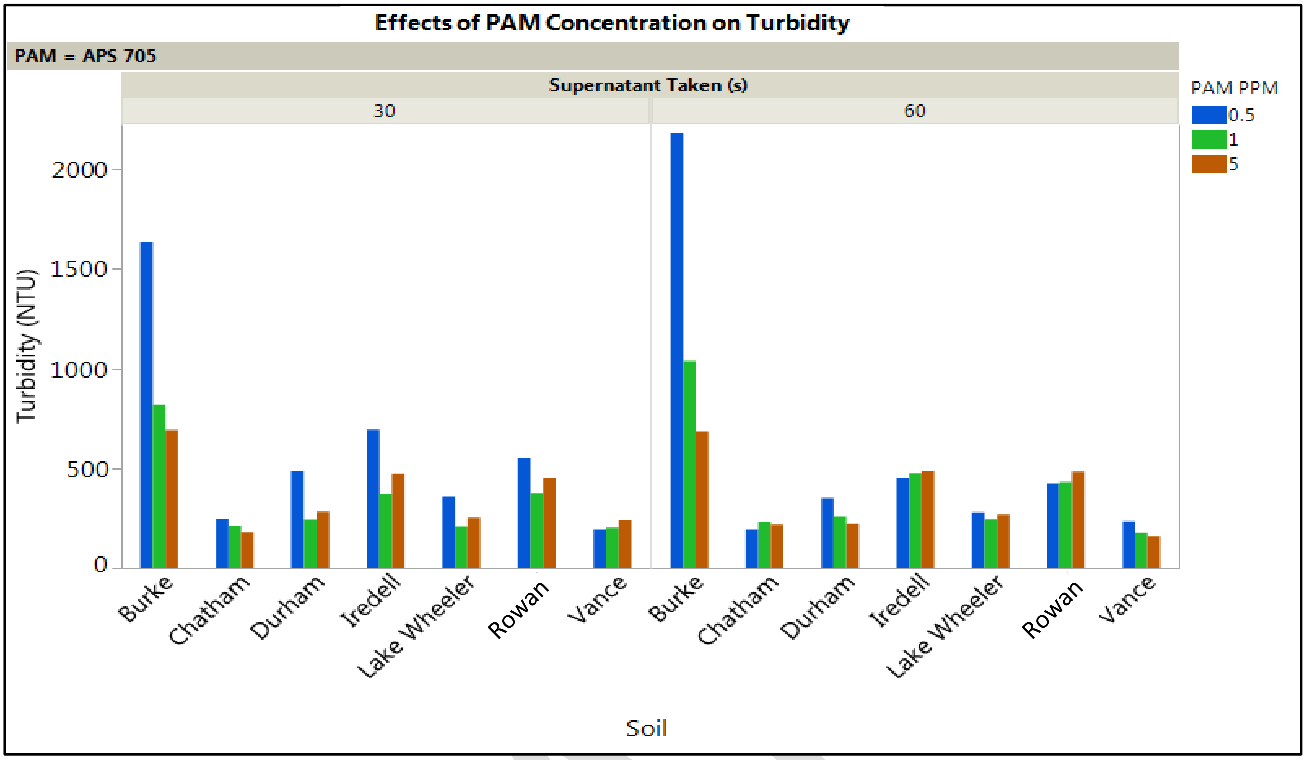


Figure A43: Turbidity comparison of APS 705 supernatant samples taken at either 30 (left) or 60 seconds (right). Seven county soils are represented and three PAM concentrations.

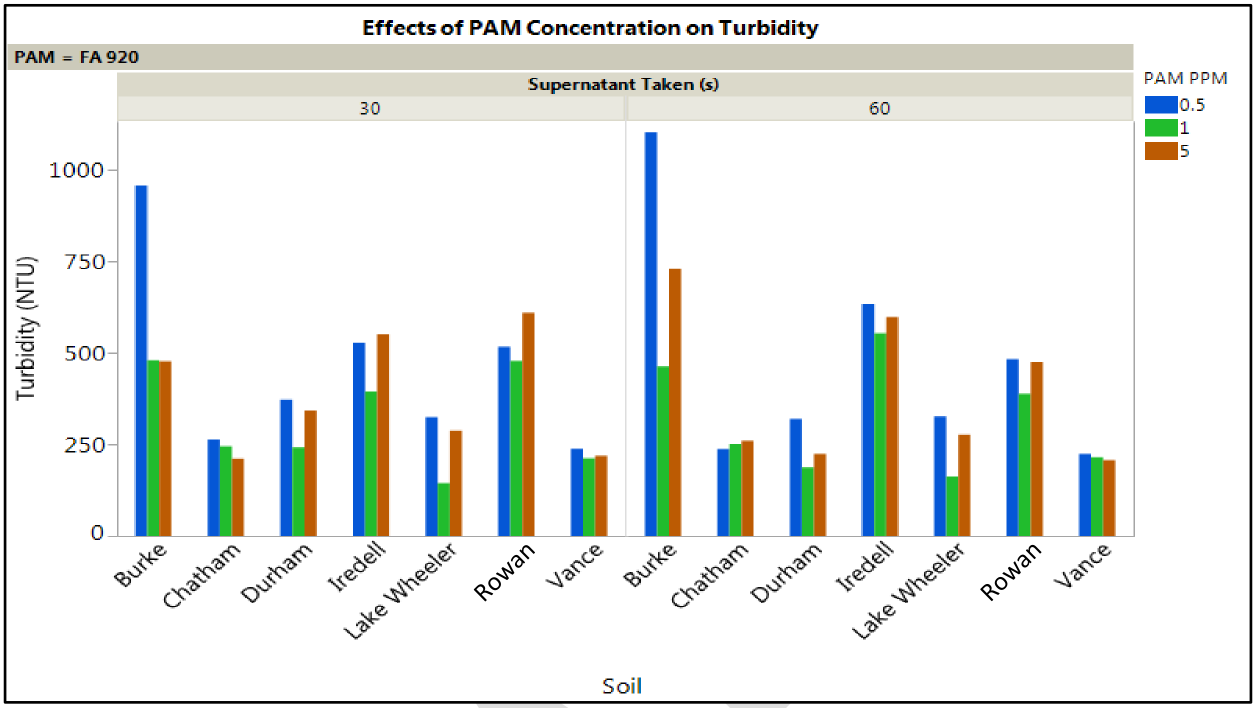


Figure A44: Turbidity comparison of supernatant samples taken at either 30 (left) or 60 seconds (right). No PAM was added, but seven county soils are compared.

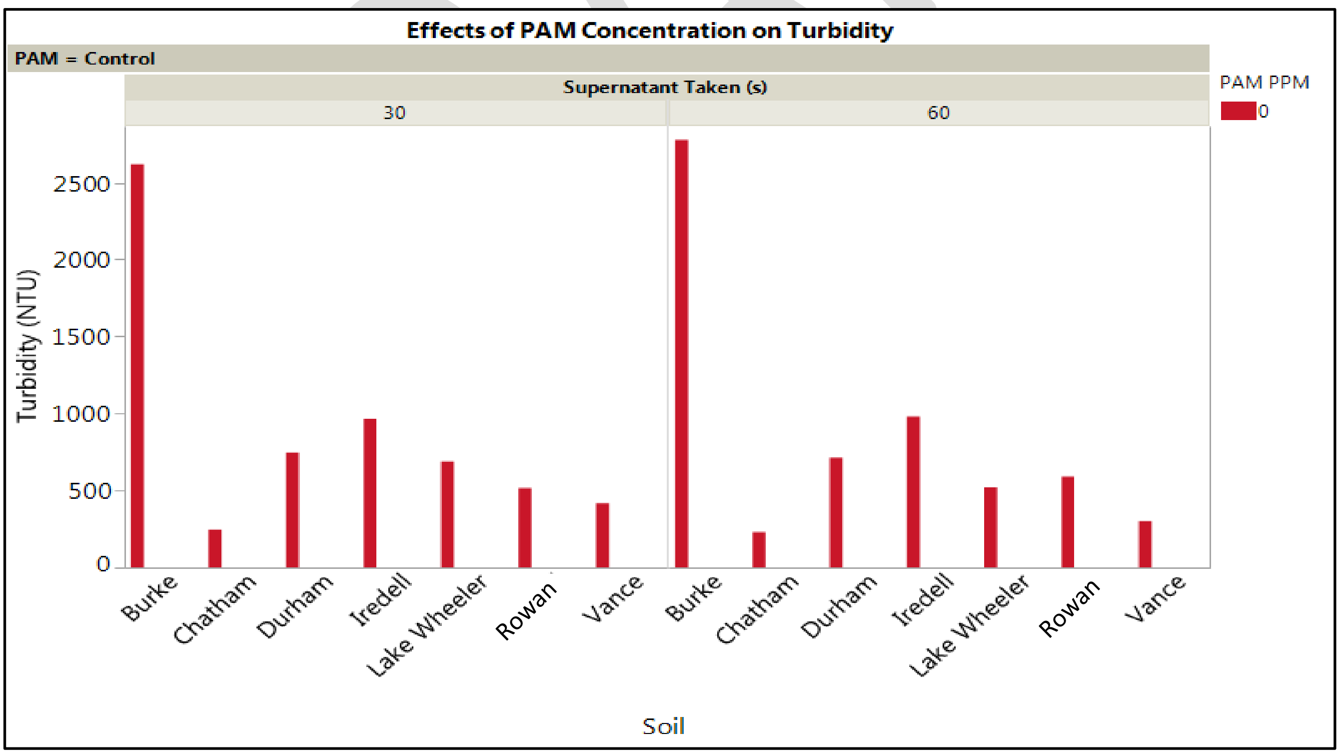


Figure A45: Turbidity comparison of FA 920 supernatant samples taken at either 30 (left) or 60 seconds (right). Seven county soils are represented and three PAM concentrations.

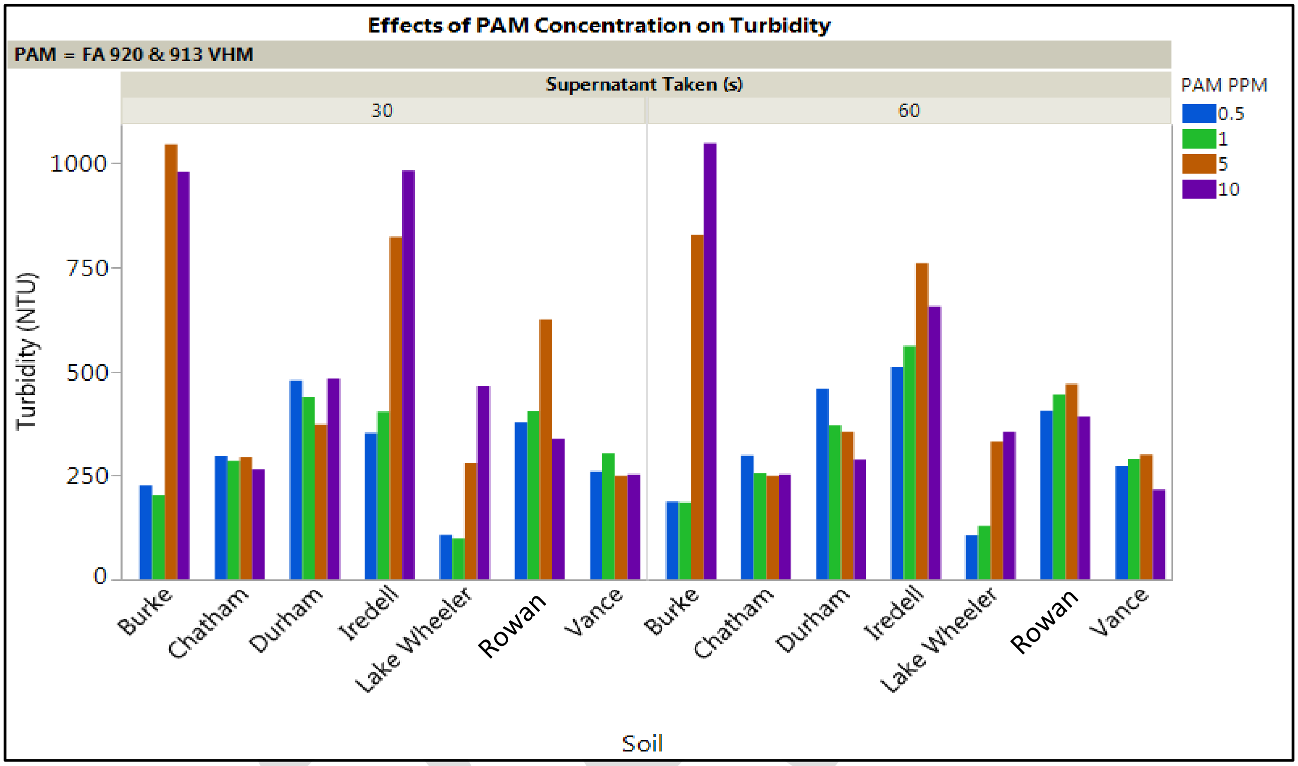


Figure A46: Turbidity comparison of FA 920 and 913 VHM (mixed) supernatant samples taken at either 30 (left) or 60 seconds (right). Seven county soils are represented and four PAM concentrations.