ABSTRACT

HOUNWANOU, OBATAYO HAROLD. Optimizing Factors of Sediment Flocculation in Construction Sites Runoff. (Under the direction of Dr. Detlef Knappe and Dr. Richard McLaughlin).

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 molar charge densities from 0 (nonionic) to 30% (anionic) and molecular weights of $<10^5$ Da (standard), $10^5–10^6$ Da (medium) and $>10^6$ Da (high). During 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 turbidity of the supernatant 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 dependent on the charge density of the PAM. Larger turbidity reductions were observed in soils with higher clay and silt content relative to the sandy soils.

Using a jar tester, soil suspensions were mixed with PAM at different intensities ($G = 48, 130, \text{ and } 640 \, s^{-1}$) and times (20 to 600 seconds). Only $G$ values of 130 and 640 s$^{-1}$ resulted in similar turbidity reduction compared to the hand shaking test, demonstrating that mixing intensity plays a key role in the flocculation of sediments. 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 nonionic PAM when using the jar tester. Thus, the choice of the most effective PAM is also dependent on 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, with the jar tester, an increase in mixing time resulted in lower turbidity for all soils, regardless of the PAM used.

To evaluate the effectiveness of PAM in 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 densities of 0, 3, 10, and 30% were used. Field tests were 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, which concurred with the jar tests results in the laboratory. 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.
Optimizing Factors of Sediment Flocculation in Construction Sites Runoff

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering

Raleigh, North Carolina
2018

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DEDICATION

To
Lauren, for her unbelievable patience and sacrifices
My parents, for loving and encouraging me
  Marinelle and Wellborn
  Michael and Sandy
  Samuel
BIOGRAPHY

Obatayo Harold Hounwanou was born and raised in the coastal city of Cotonou in Benin (West Africa). He earned a master’s degree in water resources engineering from the University of Abomey-Calavi in his home country. After teaching for a year at the same university, he embarked on a long-dreamed-of journey to North Carolina State University in the United States. He joined the department of Civil, Construction, and Environmental Engineering where he undertook graduate studies under the direction of Dr. Detlef R.U. Knappe in collaboration with Dr. Rich McLaughlin of the Department of Crop and Soil Sciences.
ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my research advisors, Dr. Detlef Knappe and Dr. Rich McLaughlin, for their patience, their listening ears, and their understanding throughout the journey that led to the completion of this thesis. Numerous life challenges and changes arose along the way, and many times, I could not begin to imagine a light at the end of the tunnel. But, as many times, they have picked me up and pointed me into the right direction. I am forever thankful to both.

The implementation of the research project that led to the results presented in this thesis could not have been possible without the help of many people. I am grateful to:

- Jamie Luther, for her invaluable assistance, both in the lab and on the field throughout the span of the project; for her friendship and support;
- Christopher Niewoehner, for his expertise and guidance in constructing the experimental setup of the field testing;
- Alex, Maria, Blake, Ally, and Ashlyn, for helping me perform a great deal of lab experiments.
- William, Faith, Matthew, and Azaria, of the North Carolina School of Science and Mathematics, who were instrumental in collecting the field data.

My gratitude also goes to the professors who encouraged and inspired me during the two years spent at NC State: Drs. Morton Barlaz, Detlef Knappe, Francis De Los Reyes, Joel Ducoste, Chris Frey, Joseph DeCarolis, Andrew Grieshop, and Downey Brill.

Amie, Clark, Amanda, Catalina, Jonathan, Catherine, Joe, Zach, Josh, Ling, Brita, Fausto, Hillary, and Arpit, for walking the graduate school path with me through both its challenges and rewards. Thank you so much for the friendship, the insights, and the support.

Renée Howard, for her friendship and for being the best graduate services coordinator any graduate student could ever dream of.
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Chapter 1: Introduction

1. Overview of the Problem

High erosion rates that occur during construction activities have received increased scrutiny. Each year, up to $5.4 \times 10^8$ Mg of sediment eroded from construction sites is discharged into the environment (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 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). 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 proved 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 > 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 a biodegradable 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 reveals 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.

2. PAM Background

The term PAM designates a group of chemical compounds formed by the polymerization of repeating identical units of acrylamide (Barvenik, 1994). These polymers are characterized by their molecular weight (MW), their charge density (CD), and their net charge. The MW of PAM can be made to vary from a few thousands to tens of millions g mol$^{-1}$ (Barvenik, 1994; Bolto, 1995; Bolto & Gregory, 2007). As the MW of PAM is increased, the polymer chain is lengthened and solutions of PAM become more viscous (Green & Stott, 1999b; Seybold, 1994). The charge density is the degree of negative or positive charge carried by the polymer (Bartholomew, 2003) and is expressed as mol ratio, mol % or weight % of the repeating units (Barvenik, 1994). Based on their charge density, PAM products are generally grouped in three categories: nonionic, anionic, and cationic. In anionic PAM, the degree of hydrolysis defines the charge density, whereas in cationic PAM it is defined by the percent of positively charged units in the polymer (Bartholomew, 2003; Green & Stott, 1999b).
Nonionic PAMs are formed by the polymerization of repeating units of acrylamide (Figure 1.1). Despite being referred to as “nonionic,” these PAMs have a slight anionic charge (1-3%) due to hydrolysis of some acrylamide units during manufacture (Barvenik, 1994; Bolto & Gregory, 2007). Nonionic PAMs are used for different applications. In the paper and pulp industry, they are employed for the clarification of wastewater (Barvenik, 1994). They are also used as flocculant aids to primary coagulants such as aluminum and iron salts during the clarification of potable water (Bolto, 1995).

Anionic PAMs can be produced using different chemical pathways. They can be manufactured via hydrolysis of nonionic PAM with a strong base (Barvenik, 1994). Here, the charge density of the PAM can be adjusted by controlling the quantity of strong base added. But most commonly, they are manufactured by copolymerization of acrylamide and acrylic acid or a salt of acrylic acid, as presented in Figure 1.2 (Barvenik, 1994). Anionic PAMs have a wide range of applications. Thickening and dewatering of concentrates and tailings in the mineral and coal industry, well cementing in the petroleum industry, clarification, thickening and dewatering of wastewater sludge, and the clarification of potable water are just a few processes where anionic PAMs are heavily used (Barvenik, 1994). The last few decades have also seen an increased use of anionic PAMs in erosion and sediment control applications (Bartholomew, 2003; Orts et al., 1999). High molecular weight, linear, moderately anionic PAMs have been found to be effective
as a soil conditioner for erosion control in irrigation furrows and construction sites (Sojka et al., 2007).

As for cationic PAMs, they are employed in processes such as clarification of drinking water, sludge dewatering, paper manufacture, and as coating resins (Barvenik, 1994; Goodrich et al., 1991). However, cationic PAMs have toxic effects on aquatic life and are not currently used for erosion and turbidity control applications. (Bartholomew, 2003; Barvenik, 1994; Goodrich et al., 1991; Lentz & Sojka, 1994). Thus, they are not discussed in this thesis.

![Copolymerization of acrylamide and sodium acrylate to form anionic PAM](image)

Figure 1.2. Copolymerization of acrylamide and sodium acrylate to form anionic PAM (Barvenik, 1994).

For erosion and sediment control applications, the technique used to introduce PAM in stormwater runoff is one of the elements paramount to successful turbidity reduction (Kang et al., 2014c). PAM is used either in dry or dissolved form, suggesting two methods of application: passive and active. The active system is a small-scale water treatment plant which features a flocculant pumping system and a filtration system (Kang et al., 2014c). Widespread adoption of this system is limited for many reasons. As one can imagine, such a water treatment plant is costly to setup, operate, and maintain (Kang et al., 2014c; U.S.EPA, 2009). Furthermore, Bjorneberg (1998) found that pumping liquid PAM sheared its molecules. This resulted in up to 50% reduced viscosity and reduced PAM effectiveness at flocculating soil particles.
The passive system uses solid blocks or granules of PAM that are introduced in channels or sprinkled over check dams. As the turbid runoff flows downhill over the solid PAM, flocculation of suspended particles occurs (Kang et al., 2014c). Although research in soil application previously demonstrated that PAM was most effective when dissolved in water prior to treatment (Lentz & Sojka, 1994; Nadler et al., 1994), this passive system appears to be more attractive, as it is inexpensive and easier to implement. Findings from recent research have also bolstered the use of the passive dosing system. Relative to untreated runoff, turbidity was reduced by 58 to more than 80% when granular PAM was applied to check dams or straw wattles (Kang et al., 2014a; Kang et al., 2013; McLaughlin et al., 2009).

3. PAM Flocculation Mechanisms

Many researchers have focused their effort on understanding the mechanisms through which polymers such as PAM bind soil particles. Particular attention has been accorded to fine particles, since polymers largely interact with the clay fraction of soils (Seybold, 1994). Flocculation takes place when a polymer molecule binds multiple soil particles. This process is generally referred to as “particle bridging” Successful flocculation of suspended soil particles can occur with high molecular weight (HMW) polymers (Green et al., 2000; Gregory & O'Melia, 1989; Laird, 1997; Orts et al., 1999; Theng, 1982). Increasing the MW of polymers results in longer chains of molecules capable of bridging multiple soil particles. Regarding charge density, successful adsorption of polymers to clay particles has been found to decrease in the order cationic > nonionic > anionic (Aly & Letey, 1988; Ben-Hur et al., 1992). However, ionic polymers are generally more effective flocculants than their nonionic counterparts (Laird, 1997). The reason is that, in aqueous systems, ionic polymers are extended as a result of electrostatic repulsion, whereas nonionic polymers tend to coil on themselves, shortening the length of their molecules (Laird, 1997; Theng, 1982).

Cationic, nonionic, and anionic PAMs have been reported to have distinct flocculation mechanisms. Similarly to salts, cationic PAM interacts with soil particles via charge neutralization by adsorbing to negatively charged clay particles through electrostatic forces (Aly & Letey, 1988; Ben-Hur et al., 1992; Theng, 1982). Aly and Letey (1988) observed that cationic polymers tend to both coagulate and flocculate suspended particles, first, by decreasing interparticle repulsion and, second, by forming bridges between clay particles. Several theories have been proposed with
respect to the mechanisms through which nonionic PAMs and soil particles interact. Emerson (1960) and Greenland (1963) first suggested that nonionic PAM was adsorbed to suspended particles through hydrogen bonds. This theory was later invalidated by Farmer (1971), who proved through infrared spectroscopy analyses that basal oxygen on the surface of clays was very weak and incapable of forming hydrogen bonds. Theng (1982) and Ben-Hur et al. (1992) later proposed that adsorption of nonionic PAMs to suspended particles is driven by Van der Waals forces.

The flocculation mechanisms of anionic PAM have also been subject of debate and extensive research. Being negatively charged, anionic PAM would be expected to be repelled by negatively charged surfaces of clay (Green & Stott, 1999a). Yet, different types of anionic PAM have repeatedly been proven to be efficient flocculating agents of clay particles. Adsorption of negatively charged PAM has often been attributed to a process called “cation bridging” (Aly & Letey, 1988; Ben-Hur et al., 1992; Green & Stott, 1999a; Laird, 1997; Orts et al., 1999; Theng, 1982). Divalent cations, such as Ca$^{2+}$, act as bridges between the carboxyl groups of the polymer and the negatively charged clay surfaces. This mechanism was eventually challenged by Peng and Di (1994). They surmised that adding multivalent ions should enhance flocculation of clay particles. Then, they increased Ca$^{2+}$ and Al$^{3+}$ content by adding CaCl$_2$ and AlCl$_3$ to kaolinite suspensions and found that clay flocculation decreased. Peng and Di (1994) went on to propose hydrogen bonding as the adsorption mechanism between anionic PAM and clay particles. Hydrophobic bonding between the carbon backbone of PAM and the basal surface of kaolinite was also proposed as binding mechanism by Laird (1997).
4. Objectives

A careful review of the literature reveals that the efficacy of PAM is dependent on the polymer formulations, the soil properties, and the intended type of application. For instance, anionic PAM having a 20% charge density and molecular weight $10^{-15} \times 10^6$ Da was most effective for soil (loamy sand and sand) stabilization and amendment (Malik & Letey, 1991; Seybold, 1994; Shainberg et al., 1990). Much of the previous work pertaining to turbidity control on construction sites has focused on improving the performance of traditional BMPs with PAM products (Babcock & McLaughlin, 2013; Bhardwaj & McLaughlin, 2008; Kang et al., 2015; Kang et al., 2014b; Kang et al., 2014c; Kang et al., 2013; McLaughlin et al., 2009). However, there is still limited information concerning the properties of both PAM and soil suspensions as well as mixing properties that optimize flocculation.

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

1. evaluate the effect of soil properties on flocculation effectiveness of PAM;
2. examine the influence of PAM properties and concentrations on turbidity reduction;
3. determine the effect of mixing intensity and mixing time on turbidity reduction;
4. Compare turbidity reduction using the paddle-type jar test and manual shaking methods.
5. Select PAMs that provided successful treatment during laboratory analyses and evaluate their effectiveness on the field
6. Determine the screening method – jar test or hand-shaking test – that best predicts PAM behavior on the field.

Ultimately, the goal was to help determine which PAM products will effectively control turbidity on many Department of Transportation construction sites across the State of North Carolina.
5. References


Goodrich, M.S., Dulak, L.H., Friedman, M.A., Lech, J.L. 1991. Acute and long-term toxicity of water-soluble cationic polymers to rainbow trout (ONCORHYNCHUS MYKISS) and the


Chapter 2: Potential Factors Affecting Turbidity Reduction

1. Introduction

Successful turbidity reduction in construction site runoff is dependent on the properties of both the soils and the PAMs used. Soil properties include soil type, clay content, soil solution ionic strength, type of ions in solution, and pH. Important PAM properties include type, 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) 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 soils they analyzed, the effectiveness of PAM for 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.

Many studies have investigated the influence of PAM characteristics on the effectiveness of flocculation in different applications. In the mineral industry, PAM has been used successfully to reduce turbidity in tailings. Tailings are waste residues resulting from minerals processing activities. Nasser and James (2006) studied the effect of PAM charge density and molecular weight on tailings laden with kaolinite particles. They found that increasing charge density from 10% to 35% increased the turbidity of the suspension compared to the control, suggesting that a lower charge density PAM might be more effective. Green et al. (2000) performed a similar study, focusing on infiltration under simulated rainfall. Their investigation of three different charge densities – 20, 30, and 40% – determined that anionic PAM with 20% hydrolysis was the most effective at preventing erosion and increasing infiltration. These results are in agreement with findings from many other studies pertaining to agricultural applications (Ben-Hur et al., 1989; Green et al., 2000; Lentz et al., 1992; Levy et al., 1992; Malik & Letey, 1991; Shainberg et al., 1990; Stern et al., 1992; Yu et al., 2003).
Turbidity reduction in runoff from construction sites has also received 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.

Cation bridging is hypothesized to be the main mechanism through which anionic PAM binds soil particles (Aly & Letey, 1988; Bartholomew, 2003; Laird, 1997). Nadler and Letey (1989) suggested that soils with divalent exchangeable cations, particularly, would lead to better flocculation with PAM. This theory was later substantiated by Laird (1997) who saturated clay suspensions with both Ca$^{2+}$ and Na$^+$ and observed that greater flocculation occurred in Ca$^{2+}$-saturated suspensions. More recent research suggested that the importance of divalent cations, such as Ca$^{2+}$, in flocculation with PAM may depend on soil mineralogy. Calcium had a significant correlation with turbidity reduction in soils with kaolinite dominance (McLaughlin & Bartholomew, 2007). This behavior was not observed in soils with smectite or vermiculite dominance.

Peng and Di (1994) studied the effect of pH on the flocculation of kaolinite suspensions with anionic PAM (30% charge density and 7 x 10$^6$ Da). They found that PAM was most effective when pH was in the range 5 to 7. Flocculation was slightly less effective at higher pH values up to 9 but was ineffective at pH below 5. The authors attributed the inefficacy of PAM at pH lower than 5 to the protonation of its carboxyl groups, which resulted in loss of its anionic character. At
pH values ranging from 7 to 9, precipitation of calcium and aluminum hydroxides on the functional groups of PAM may have led to poor flocculation. It is also possible that clay surfaces may have become more negative, increasing repulsion of anionic PAM (Bartholomew, 2003). Although they did not perform a formal study of the effect of pH on flocculation, Rounce et al. found that the dosages of PAM they tested – 0.03 to 10 mg/L – had no effect on pH of soil suspensions.

In this chapter, the potential factors that affect turbidity control in construction site 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.

2. Materials and Methods

2.1. Materials

2.1.1. Soils

The North Carolina Department of Transportation (NCDOT) collected soil samples from active construction sites in twenty-two counties (Figure 2.1). These soils had various characteristics (Tables 2.1 & 2.2) 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 were 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 Crop and Soil Sciences Department at North Carolina State University using the hydrometer method (Gee & Bauder, 1979). Two samples of each soil were also provided to the Agronomic Services Division of the North Carolina Department of Agriculture & Consumer Services, where average values of the following characteristics were determined:

- calcium, magnesium, phosphorus, potassium, sulfur, copper, and zinc content using the volumetric soil testing procedure (Tucker, 1984),
- humic matter (HM) content of the soils using a method proposed by Mehlich (1984b),
- cation exchange capacity (CEC) employing the Melich-3 procedure (Mehlich, 1984a).

Results from the soil characterization are shown in Tables 2.1 & 2.2.
Table 2. Nomenclature of soils collected and their respective characteristics

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<th>CEC (meq/100cc)</th>
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<th>P (mg/L)</th>
<th>K (mg/L)</th>
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<td>27.0</td>
<td>50.9</td>
<td>22.0</td>
<td>Silt Loam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stokes</td>
<td>23.1</td>
<td>55.8</td>
<td>21.2</td>
<td>Silt loam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chatham</td>
<td>12.0</td>
<td>37.3</td>
<td>50.7</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rowan</td>
<td>28.4</td>
<td>31.4</td>
<td>40.2</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1.2. Polyacrylamide Products

The effectiveness of thirteen PAM products (Table 2.3) was assessed in this study. A large variety of molecular weight and charge density characterized these polymers. The charge density ranged 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:

- STD: < 10^5 g mol\(^{-1}\)
- Medium (SH): 10^5 – 10^6 g mol\(^{-1}\)
- High (VHM): > 10^6 g mol\(^{-1}\)

APS 705, a mixture of different PAM products from APPLIED POLYMER SYSTEMS, Inc., was also used. However, the PAMs included in the mixture are proprietary, 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 tap water for 24 hours at 0.5 g L\(^{-1}\). For simplicity, polymers were identified by their respective charge, charge density, and molecular weight throughout the rest of this thesis (Table 2.3). For instance, the high molecular weight anionic PAM AN 905 VHM with charge density 3% is denominated A3-H.
<table>
<thead>
<tr>
<th>PAM</th>
<th>Charge</th>
<th>Charge Density</th>
<th>Molecular Weight</th>
<th>Nomenclature Adopted</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA 920</td>
<td>Nonionic (N)</td>
<td>0%</td>
<td>Standard</td>
<td>N</td>
</tr>
<tr>
<td>FA 920 SH</td>
<td>Nonionic (N)</td>
<td>0%</td>
<td>Medium</td>
<td>N-M</td>
</tr>
<tr>
<td>FA 920 VHM</td>
<td>Nonionic (N)</td>
<td>0%</td>
<td>High</td>
<td>N-H</td>
</tr>
<tr>
<td>AN 905</td>
<td>Anionic (A)</td>
<td>3%</td>
<td>Standard</td>
<td>A3</td>
</tr>
<tr>
<td>AN 905 SH</td>
<td>Anionic (A)</td>
<td>3%</td>
<td>Medium</td>
<td>A3-M</td>
</tr>
<tr>
<td>AN 905 VHM</td>
<td>Anionic (A)</td>
<td>3%</td>
<td>High</td>
<td>A3-H</td>
</tr>
<tr>
<td>AN 910 VHM</td>
<td>Anionic (A)</td>
<td>10%</td>
<td>High</td>
<td>A10-H</td>
</tr>
<tr>
<td>AN 913 VHM</td>
<td>Anionic (A)</td>
<td>13%</td>
<td>High</td>
<td>A13-H</td>
</tr>
<tr>
<td>AN 923</td>
<td>Anionic (A)</td>
<td>20%</td>
<td>Standard</td>
<td>A20</td>
</tr>
<tr>
<td>AN 923 SH</td>
<td>Anionic (A)</td>
<td>20%</td>
<td>Medium</td>
<td>A20-M</td>
</tr>
<tr>
<td>AN 923 VHM</td>
<td>Anionic (A)</td>
<td>20%</td>
<td>High</td>
<td>A20-H</td>
</tr>
<tr>
<td>AN 934 VHM</td>
<td>Anionic (A)</td>
<td>30%</td>
<td>High</td>
<td>A30-H</td>
</tr>
<tr>
<td>APS 705</td>
<td>Proprietary (P)</td>
<td>Proprietary</td>
<td>Proprietary</td>
<td>P</td>
</tr>
</tbody>
</table>

2.2. Methods

2.2.1. Hand-shake Test

The hand-shake test is a screening method used to determine the effectiveness of PAM products at reducing turbidity in soil suspensions. Its goal is to select the PAM product that rapidly reduces the turbidity of a soil suspension. The experimental procedure consisted of adding a predetermined volume or amount of PAM to clear 120-mL specimen cups filled with a mixture of water and the soil of interest to the 100-mL mark (Figure 2.2). The soil suspensions were prepared at 10 g. L⁻¹. The PAM + soil suspension was then shaken manually for 10 seconds and left to settle for 30 seconds (Bhhardwaj & McLaughlin, 2008). Upon sedimentation, the turbidity of the settled water was 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. The soil suspensions were prepared at 10 g L⁻¹, and after PAM addition, the mixture was shaken for 10 seconds.
2.2.2. Jar Test

Jar tests were conducted on a programmable jar tester (Model 7790-901B, Phipps & Bird, Richmond, VA, USA; Figure 2.3). It was 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. The experimental design for each specific test conducted on this instrument is presented later in this chapter. For all jar tests, soil samples were mixed for 15 seconds to promote particle suspension before addition of PAM.
2.2.3. Turbidity Measurement

Turbidity was determined with an ANALITE NEP9000 nephelometer (McVan Instruments, Melbourne, Australia; Figure 2.4), and each soil-PAM combination was replicated three times (3 replicate jars) with the average being reported. Each reading was taken upon 30 seconds of sedimentation. This helps minimize variations produced by turbulence in the suspensions (Bhardwaj & McLaughlin, 2008).
2.2.4. Experimental Design

2.2.4.1. Influence of soil characteristics on turbidity removal

Determining the effects of soil characteristics on turbidity reduction involved testing all 22 soils with six PAM products representing a range of characteristics. The polymers used were the nonionic PAM N (Chemtall Inc., Riceboro, GA, USA), the anionic PAMs A20, A20-M, A20-H and A13-H (Chemtall Inc., Riceboro, GA, USA), and the mixed polymer P (Applied Polymer Systems Inc., Woodstock, GA, USA).

Flocculation tests were conducted using the hand-shake screening test. First, 10 g L\(^{-1}\) of soil suspensions were prepared by adding one gram of soil to 100 mL of water in a 120-mL specimen cup. The initial turbidity of each soil suspension was measured in three control specimen cups after 10 s shaking and 30s settling. Then, each PAM was dosed at 1 mg L\(^{-1}\) by adding 0.2 mL of a 0.5 g L\(^{-1}\) PAM solution to the soil suspensions, amounting to a matrix of 22 x 6 x 3 = 396 specimen cups. This concentration was selected as it was near optimal in earlier testing (Bartholomew, 2003), and this was confirmed by dose-response tests conducted described below. The mixture was again shaken for 10 s and the turbidity measured after 30 s. Tests of each soil-PAM combination were replicated three times and the average was calculated for comparisons with the average of the controls.

2.2.4.2. Influence of PAM characteristics on turbidity removal

To evaluate the influence of PAM concentration on turbidity reduction, soils from Wake, Watauga, Iredell, Stokes, Rowan, Carteret, Durham, Brunswick, Gates, and Cumberland counties were selected to represent a wide range of soil properties. Suspensions were prepared at 10 g L\(^{-1}\) and tested with PAM doses of 1, 5, 10, 25, 50, 100, and 250 mg L\(^{-1}\). The PAM products used were N, A20, A20-M, A20-H, A13-H (Chemtall Inc., Riceboro, GA, USA), and the mixed polymer P (Applied Polymer Systems Inc., Woodstock, GA, USA). These were selected to represent varying charge densities and molecular weights. Upon hand-shaking for 10 seconds, turbidity was measured at 30 s. The average value of three replications was reported for analysis.

Intramolecular electrostatic repulsion extends the chain of anionic polymers, making it easier to bind multiple suspended soil particles (Bartholomew, 2003). So, we hypothesized that...
the higher the charge density of an anionic PAM product, the more effective it should be at reducing turbidity. The effect of PAM charge density on turbidity removal focused on six soils from Chatham, Stokes, Burke, Durham, Gates, and Lee Counties. Six PAMs having charge densities ranging from neutral to 30% were selected from the VHM (high) molecular weight category (Table 2.4). One liter of each soil suspension was prepared at 10 g L\(^{-1}\), and PAM was dosed at 1 mg L\(^{-1}\). Soil suspensions and PAM were then mixed at 100 rpm on a six-paddle jar tester. These experiments were conducted on the jar tester as it allowed for control of both the mixing intensity and the mixing time. In previous testing, the results of which are presented later in this thesis, 100 rpm led to the lowest turbidity values and was consequently chosen for this set of experiments. After three minutes of mixing, the turbidity value was measured 30 seconds after the impellers had stopped revolving. The experiment was repeated three times, and average final turbidity values were used for analysis.

Table 2.4. PAM products used to evaluate the effect of charge density on turbidity reduction

<table>
<thead>
<tr>
<th>PAM</th>
<th>Charge</th>
<th>Charge Density</th>
<th>Molecular Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-H</td>
<td>Nonionic</td>
<td>0%</td>
<td>High</td>
</tr>
<tr>
<td>A3-H</td>
<td>Anionic</td>
<td>3%</td>
<td>High</td>
</tr>
<tr>
<td>A10-H</td>
<td>Anionic</td>
<td>10%</td>
<td>High</td>
</tr>
<tr>
<td>A13-H</td>
<td>Anionic</td>
<td>13%</td>
<td>High</td>
</tr>
<tr>
<td>A20-H</td>
<td>Anionic</td>
<td>20%</td>
<td>High</td>
</tr>
<tr>
<td>A30-H</td>
<td>Anionic</td>
<td>30%</td>
<td>High</td>
</tr>
</tbody>
</table>

As for the influence of PAM molecular weight, the experiments focused on the three MW ranges, Standard, Medium, and High, for three PAMs, N, A3, and A20. Overall, nine PAM products (Table 2.5) were used at a concentration 1 mg L\(^{-1}\). One-liter suspensions of three soils from Rowan, Durham, and Burke Counties, respectively, were prepared at 10 g L\(^{-1}\). These tests
were conducted with the jar tester at 100 rpm for three minutes and turbidity was measured after 30 s settling. The tests were replicated three times.

### Table 2.5. PAM Products used to evaluate effect of PAM MW

<table>
<thead>
<tr>
<th>Increasing Molecular Weight</th>
<th>Increasing Charge Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>A3</td>
</tr>
<tr>
<td>N-M</td>
<td>A3-M</td>
</tr>
<tr>
<td>N-H</td>
<td>A3-H</td>
</tr>
</tbody>
</table>

2.2.4.3. Effect of mixing intensity on turbidity removal

The impact of mixing intensity on turbidity removal was evaluated by varying the fluid shear, $G$, and the mixing time, $t$, in the jar tester. Typically called the average velocity gradient, $G$ is a parameter used to describe turbulent mixing in a flocculation reactor (Saffman & Turner, 1956):

$$G = \sqrt{\frac{\bar{\varepsilon}}{\nu}}$$  \hspace{1cm} \text{(Equation 1)}$$

where $\bar{\varepsilon}$ is the average turbulent energy dissipation rate and $\nu$ is the kinematic viscosity of the fluid. The average turbulent energy dissipation rate between two points A and B is calculated using the following equation:

$$\bar{\varepsilon} = \frac{h}{\tau} \left(\frac{\text{Energy dissipation from point A to point B}}{\text{time required for fluid to travel from point A to point B}}\right)$$

Jar tests were conducted at three different rotational speeds, 50, 100, and 300 rpm, corresponding, respectively, to velocity gradient ($G$) values of 48, 130, and 640 s$^{-1}$. Specific mixing
times for each G value were determined (Table 2.6) to keep the product G*t constant. The term G*t, known as the collision potential, is a measure of the extent of flocculation in a reactor (Tse et al., 2011). It is a parameter commonly used in the design of hydraulic flocculators in water treatment plants. This analysis is based on the assumption that any combination of G and t that gives the same product should work equally well (Tse et al., 2011) and lead to similar turbidity reduction performances. 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.

Three PAM products, N, A20-H, and P were used at 1 mg L\(^{-1}\) to flocculate Wake County soil. Samples of soil suspension were prepared by adding 1 L of tap 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>
<thead>
<tr>
<th>G (s(^{-1}))</th>
<th>(48 \text{ s}^{-1})</th>
<th>(130 \text{ s}^{-1})</th>
<th>(640 \text{ s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G*t) (-)</td>
<td>Mixing Time (seconds)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19200</td>
<td>400</td>
<td>148</td>
<td>30</td>
</tr>
<tr>
<td>38400</td>
<td>800</td>
<td>295</td>
<td>60</td>
</tr>
<tr>
<td>76800</td>
<td>1600</td>
<td>590</td>
<td>120</td>
</tr>
<tr>
<td>96000</td>
<td>2000</td>
<td>738</td>
<td>150</td>
</tr>
<tr>
<td>192000</td>
<td>4000</td>
<td>1477</td>
<td>300</td>
</tr>
</tbody>
</table>

2.2.4.4. Effect of mixing time on turbidity removal

It is possible that increasing the mixing time would allow for extended interaction between PAM molecules and soil particles, which could help achieve higher turbidity removals in runoff. So, to better understand the influence that mixing time could have on turbidity removal, mixtures of soil suspensions and PAMs were agitated for 10 and 60 seconds using the hand-shake test. Six
soils from Wake, Watauga, Yancey, Burke, Chatham, and Rowan Counties were prepared at 10 g L\(^{-1}\) and flocculated with two PAMs, N and A20-H. The analysis was also carried out on the jar tester. Here, the Wake County soil was tested with the same PAMs and mixed for 10, 30, 60, 120, 150, and 300 seconds at 300 rpm.

For hand shake and jar tests, the turbidity of the supernatant was measured after the suspension was left to settle for 30 s. Three replicates were performed for each combination of PAM and soil, and the average percent turbidity reductions were calculated. These results were used for a comparative analysis of both screening methods.

2.2.4.5. Influence of screening method on choice of PAM

One-liter suspensions of soils from Wake, Burke, and Rowan counties were prepared at 10 g L\(^{-1}\) and flocculated with two PAM products, N and A20-H. The soil suspensions were dosed at a concentration of 5 mg PAM L\(^{-1}\). This concentration was chosen because it led to the lowest turbidity values in the Rowan and Burke County soils during the preliminary analyses. As for the Wake County soil, 1 mg L\(^{-1}\) and 5 mg L\(^{-1}\) of either PAM led to statistically comparable results.

Both screening tests were conducted for this analysis. During the hand-shake test, suspensions were mixed for 10 seconds. To allow for comparison, the mixture soil suspension + PAM was also mixed for 10 seconds with the jar tester at 100 rpm. Residual turbidity of the supernatant was measured after sedimentation for 30 seconds in both cases.
3. Statistical Analyses

Statistical analyses of the data collected throughout these experiments were conducted using JMP (version 14; SAS Institute, Cary, NC, USA). Multivariate regression analyses were conducted to determine significant effects of soil properties at a probability level of 0.05 using the Standard Least Squares model. For each PAM, the overall model used for this analysis was:

\[ \text{Reduction Efficiency} \% = \text{Intercept} + A \times (HM) + B \times (Density) + C \times (CEC) + D \times (pH) + E \times (\text{Phosphorus}) + F \times (\text{Potassium}) + G \times (\text{Calcium}) + H \times (\text{Magnesium}) + I \times (\text{Sulfur}) + J \times (\text{Manganese}) + K \times (\text{Zinc}) + L \times (\text{Copper}). \]

Twenty-two (22) data points corresponding to the number of soils collected were used for each parameter (soil property). The backwards selection method was implemented to remove progressively the least important covariates (soil properties) which did not have a significant effect on the turbidity reduction efficiencies observed throughout the flocculation tests. The most significant soil properties are then presented along with their respective partial $R^2$ in the results section. Simple t-test analyses were also performed using the DATA Package in Microsoft Excel 2016 to evaluate the difference between the effects of various parameters investigated all throughout this research project.
4. Results and Discussion

4.1. Influence of Soil Characteristics on Turbidity Removal

The shake method was used to test six PAMs for turbidity reduction for all twenty-two soils. On average, the highest reduction efficiencies (> 70%) were generally achieved in the sandy loam, silt loam, and clay soils, regardless of PAM type (Table 2.7). Lower efficiencies (<45%) occurred in the loamy sand and sandy soils. These soils had a sand content higher than 80%, and, typically, had low initial turbidity (less than 150 NTU at 10 g L\(^{-1}\)). A closer look at the results obtained with just the clay and silt loam soils reveal that the highest turbidity removal efficiencies were recorded in the ones that had the highest sand content. It is possible that for soils with a large fraction of fine particles, such as the ones from Chatham or Iredell County, there needs to be a certain quantity of coarser particles for effective flocculation and settling to take place. Montgomery (1968) stated that PAM “integrates finer particles with coarser particles” to form flocs that easily fall out of suspension. Nevertheless, the disparity of results obtained from one soil texture to the other suggests that this parameter may not be the only factor affecting turbidity reduction in construction site runoff.

The calcium (Ca) bridging mechanism set forth by many researchers (Aly & Letey, 1988; Ben-Hur et al., 1992; Laird, 1997; Nadler & Letey, 1989) suggests that soils with a high concentration of Ca would be easier to flocculate with the negatively charged polyacrylamides. Consequently, one would expect high turbidity reduction efficiencies in soils with high Ca content when the anionic PAMs were used as flocculating agents. Although the soil from Durham County had the highest Ca content (3352 mg L\(^{-1}\)), turbidity reduction efficiencies varied from 27% to 49% for this soil with the six PAMs (Table 2.7). However, with a Ca content of only 116 mg L\(^{-1}\) the soil from Rowan County had reduction efficiencies ranging from 79% to 85% with the same anionic PAMs. Consequently, for this sample of soils, there was no strong evidence that Ca content alone could explain the results obtained during the flocculation tests.

Peng and Di (1994) observed that the flocculation of kaolinite with anionic PAM was strongly dependent on pH, with the optimal range being between 5 and 7. Though our study did not focus on the mineralogy of the sample of soils used, many of the soils had a pH value within the optimal range. However, no correlation (p >>0.05) was found between the turbidity reduction with the anionic PAMs and the pH of the soils (Table 2.8).
The samples from the five Coastal Plain counties (Bladen, Carteret, Brunswick, Cumberland, Gates) were generally harder to flocculate than those of the Piedmont and Mountain areas of North Carolina. This is consistent with previous work (McLaughlin and Bartholomew, 2007) and, given the poor correlation with pH or Ca content, also suggests that mineralogy is a major factor in the flocculation process. The Coastal Plain soils tend to be sandier with mixed mineralogy and the clay fraction may contain considerable montmorillonite (McLaughlin and Bartholomew, 2007), an expanding 2:1 clay which may be more difficult to flocculate (Ben-Hur et al., 1992; Laird 1997). The Durham soil was poorly flocculated by the anionic PAMs despite high Ca, but these soils are also dominated by montmorillonite clays.

Further investigation, through a series of regression analyses, reveal that the significant explanatory variables (soil properties) at the p = 0.05 level vary dependent upon the PAM being used. When flocculation was performed with the nonionic PAM, N, turbidity reduction results were found to be significantly explained ($R^2 = 0.93$) by eight distinct soil properties (K, CEC, Ca, P, pH, sand content, density, and Mg) with the potassium content (K) explaining 72% of the variability observed in the results (Table 2.9). The equation of the regression model for N was:

\[
\text{Reduction Efficiency (\%) = 92.8 + 43.3 \times (Density) - 8.50 \times (CEC) - 11.6 \times (pH) - 0.30 \times (Phosphorus) + 0.32 \times (Potassium) + 0.06 \times (Calcium) + 0.06 \times (Magnesium) - 0.32 \times (\%) Sand.}
\]

The variability observed in the results with the mixed PAM, P, were attributed to three soil properties (p < 0.05). K, P, and Zn contents explained 36%, 25%, and 20% of the variability observed within all soils tested, respectively (Table 2.10). The overall $R^2$ was 0.44, indicating that these covariates were not enough to explain the variability observed in the reduction efficiencies obtained with the mixed polymer, P. The prediction equation for this model was: Reduction Efficiency (\%) = 50.7 + 0.58 \times (Potassium) - 5.51 \times (Zinc) - 0.54 \times (Phosphorus). Five soil properties, Humic matter (HM), potassium (K), sulfur (S), pH, and phosphorus (P) were found to be significant (p < 0.05) when the soils were flocculated with the anionic PAM A20-H (Table 2.11). For this model, $R^2 = 0.90$, and the equation of the regression was: Reduction Efficiency (\%) = 67.6 - 9.31 \times (HM) + 0.28 \times (K) + 0.36 \times (S) - 0.31 \times (P) - 7.81 \times (pH). As for PAM A20, eight soil properties (Clay content, P, K, CEC, Ca, Mn, and Density) significantly ($R^2 = 0.91$) explained the variability in the flocculation results (Table 2.12). The regression model was: Reduction Efficiency (\%) = 99.4 + 0.83 \times (%Clay) - 0.41 \times (P) + 0.25 \times (K) + 0.02 \times (Ca) - 3.88 \times (CEC) -
0.13 * (Mn) – 52.1 * (Density). Similarly, the overall R squared were 0.81 and 0.83, respectively, for the PAMs A20-M and A13-H. Four soil properties, P, K, Ca, and S significantly explained the variability observed with A20-M, while P, K, S, and % Silt accounted for the variability observed with A13-H. The strength of the Goodness of fit of the various regression models associated with each PAM is presented in Figure 2.5. Out of all soil properties found to significantly explain the variability in the flocculation results, two remained constant, regardless of the polyacrylamide used: Potassium (K) and Phosphorus (P). No specific references have been made to these soil properties in the literature, and it is unclear at this point how they affect turbidity reduction with PAM.
Table 2.7. Average turbidity reduction for each combination of PAM (1 mg L\(^{-1}\)) and soil (10 g L\(^{-1}\)) tested using the hand-shake methods

<table>
<thead>
<tr>
<th>County of Origin</th>
<th>Soil Texture</th>
<th>Polyacrylamide</th>
<th>Turbidity Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Bladen</td>
<td>Sand</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Carteret</td>
<td>Sand</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>Brunswick</td>
<td>Loamy sand</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Cumberland</td>
<td>Loamy sand</td>
<td>66</td>
<td>41</td>
</tr>
<tr>
<td>Gates</td>
<td>Sandy Loam</td>
<td>57</td>
<td>70</td>
</tr>
<tr>
<td>Vance</td>
<td>Sandy Loam</td>
<td>79</td>
<td>80</td>
</tr>
<tr>
<td>Buncombe</td>
<td>Sandy Loam</td>
<td>67</td>
<td>74</td>
</tr>
<tr>
<td>Guilford</td>
<td>Sandy Loam</td>
<td>68</td>
<td>83</td>
</tr>
<tr>
<td>Wilkes</td>
<td>Sandy Loam</td>
<td>66</td>
<td>76</td>
</tr>
<tr>
<td>Yancey</td>
<td>Sandy Loam</td>
<td>81</td>
<td>91</td>
</tr>
<tr>
<td>Durham</td>
<td>Sandy Loam</td>
<td>88</td>
<td>92</td>
</tr>
<tr>
<td>Watauga</td>
<td>Sandy Loam</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td>Wake</td>
<td>Sandy Loam</td>
<td>96</td>
<td>90</td>
</tr>
<tr>
<td>Nash</td>
<td>Sandy Loam</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Davie</td>
<td>Loam</td>
<td>61</td>
<td>-54</td>
</tr>
<tr>
<td>Washington</td>
<td>Loam</td>
<td>69</td>
<td>81</td>
</tr>
<tr>
<td>Lee</td>
<td>Loam</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>Burke</td>
<td>Silt loam</td>
<td>83</td>
<td>95</td>
</tr>
<tr>
<td>Iredell</td>
<td>Silt Loam</td>
<td>90</td>
<td>91</td>
</tr>
<tr>
<td>Stokes</td>
<td>Silt loam</td>
<td>69</td>
<td>74</td>
</tr>
<tr>
<td>Chatham</td>
<td>Clay</td>
<td>74</td>
<td>85</td>
</tr>
<tr>
<td>Rowan</td>
<td>Clay</td>
<td>85</td>
<td>80</td>
</tr>
</tbody>
</table>
Table 2.8. Results of single regression analysis for the effect of pH on the effectiveness of the anionic PAMs

<table>
<thead>
<tr>
<th>PAM</th>
<th>R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A20</td>
<td>0.007</td>
<td>0.70</td>
</tr>
<tr>
<td>A20-M</td>
<td>0.006</td>
<td>0.72</td>
</tr>
<tr>
<td>A20-H</td>
<td>0.002</td>
<td>0.84</td>
</tr>
<tr>
<td>A13-H</td>
<td>&lt;0.001</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 2.9. Regression analysis results for the effect of soil properties on the effectiveness of PAM (N) for all soil samples tested (R² = 0.93). All other soil properties were not significant at p =0.05.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>92.76</td>
<td>N/A</td>
<td>0.002</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.32</td>
<td>0.72</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>CEC (meq/100cc)</td>
<td>-8.49</td>
<td>0.67</td>
<td>0.0002</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>0.06</td>
<td>0.64</td>
<td>0.0003</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.30</td>
<td>0.58</td>
<td>0.0009</td>
</tr>
<tr>
<td>pH</td>
<td>-11.55</td>
<td>0.45</td>
<td>0.0065</td>
</tr>
<tr>
<td>% Sand</td>
<td>-0.32</td>
<td>0.45</td>
<td>0.0064</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>43.34</td>
<td>0.36</td>
<td>0.0181</td>
</tr>
<tr>
<td>Mg (mg/L)</td>
<td>0.06</td>
<td>0.35</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Table 2. 10. Regression analysis results for the effect of soil properties on the effectiveness of PAM (P-mixed) for all soil samples tested ($R^2 = 0.44$). All other soil properties were not significant at $p = 0.05$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial $R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>50.67</td>
<td>N/A</td>
<td>0.0014</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.58</td>
<td>0.36</td>
<td>0.0049</td>
</tr>
<tr>
<td>Zn (mg/L)</td>
<td>-5.51</td>
<td>0.25</td>
<td>0.0238</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.54</td>
<td>0.20</td>
<td>0.0468</td>
</tr>
</tbody>
</table>

Table 2. 11. Regression analysis results for the effect of soil properties on the effectiveness of PAM (A20-H) for all soil samples tested ($R^2 = 0.90$). All other soil properties were not significant at $p = 0.05$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial $R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>67.58</td>
<td>N/A</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>HM (g/100cc)</td>
<td>-9.31</td>
<td>0.59</td>
<td>0.0002</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.28</td>
<td>0.57</td>
<td>0.0003</td>
</tr>
<tr>
<td>S (mg/L)</td>
<td>0.36</td>
<td>0.53</td>
<td>0.0006</td>
</tr>
<tr>
<td>pH</td>
<td>-7.81</td>
<td>0.47</td>
<td>0.0016</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.31</td>
<td>0.42</td>
<td>0.0038</td>
</tr>
</tbody>
</table>
Table 2.12. Regression analysis results for the effect of soil properties on the effectiveness of PAM (A20) for all soil samples tested ($R^2 = 0.91$). All other soil properties were not significant at $p = 0.05$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial $R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>99.36</td>
<td>N/A</td>
<td>0.0026</td>
</tr>
<tr>
<td>% Clay</td>
<td>0.83</td>
<td>0.53</td>
<td>0.0013</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.41</td>
<td>0.52</td>
<td>0.0015</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.24</td>
<td>0.40</td>
<td>0.0083</td>
</tr>
<tr>
<td>CEC (meq/100cc)</td>
<td>-3.88</td>
<td>0.34</td>
<td>0.0182</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>0.02</td>
<td>0.34</td>
<td>0.0179</td>
</tr>
<tr>
<td>Mn (mg/L)</td>
<td>-0.13</td>
<td>0.33</td>
<td>0.0209</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>-52.10</td>
<td>0.31</td>
<td>0.0255</td>
</tr>
</tbody>
</table>

Table 2.13. Regression analysis results for the effect of soil properties on the effectiveness of PAM (A20-M) for all soil samples tested ($R^2 = 0.81$). All other soil properties were not significant at $p = 0.05$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial $R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>25.19</td>
<td>N/A</td>
<td>0.0008</td>
</tr>
<tr>
<td>S (mg/L)</td>
<td>0.48</td>
<td>0.57</td>
<td>0.0002</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.22</td>
<td>0.40</td>
<td>0.0038</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>-0.01</td>
<td>0.36</td>
<td>0.0065</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.23</td>
<td>0.22</td>
<td>0.0447</td>
</tr>
</tbody>
</table>
Table 2. Regression analysis results for the effect of soil properties on the effectiveness of PAM (A13-H) for all soil samples tested (R² = 0.83). All other soil properties were not significant at p =0.05.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Partial R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>30.20</td>
<td>N/A</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% Silt</td>
<td>0.53</td>
<td>0.37</td>
<td>0.0055</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>0.15</td>
<td>0.25</td>
<td>0.0279</td>
</tr>
<tr>
<td>S (mg/L)</td>
<td>0.19</td>
<td>0.25</td>
<td>0.0302</td>
</tr>
<tr>
<td>P (mg/L)</td>
<td>-0.20</td>
<td>0.22</td>
<td>0.0452</td>
</tr>
</tbody>
</table>
Figure 2. 5. Regression analysis plots showing Predicted vs Actual Reduction Efficiencies for each PAM tested.
4.2. Influence of PAM Concentration and Characteristics on Turbidity Removal

4.2.1. PAM Concentration

The effect of PAM concentration on turbidity removal varied with soil and PAM type. For most soils tested, PAM concentrations of 1 and 5 mg L\(^{-1}\) led to the highest turbidity reduction efficiencies, which concurs with the published data (McLaughlin, 2004; McLaughlin & Bartholomew, 2007; Yan & Zhang, 2014). For example, when the sandy loam soil from Wake Co. was flocculated with the mixed polymer, P, 91% and 96% turbidity reductions were achieved at 1 mg/L and 5 mg/L, respectively (Figure 2.6). Increasing PAM concentration generally caused decreased turbidity reduction efficiencies, particularly in the case of the anionic PAMs (Figures 2.6 - 2.15). In some cases, PAM concentrations of 25 mg L\(^{-1}\) and higher led to final turbidities higher than the measured initial turbidities. For the most part, flocculation with the anionic PAMs resulted in higher settled turbidity than N and P.

Increased turbidity at high PAM concentrations has been attributed to steric stabilization or repulsion (Gregory & O'Melia, 1989). Steric stabilization in this case might be due to the adsorption of excess polymer to the soil particles. This creates a thick layer around suspended particles, making the distance between individual particles large enough that Van der Waals forces are too weak to cause adhesion and flocculation (Bartholomew, 2003; Gregory & O'Melia, 1989). Bjorneberg (1998) also demonstrated that increasing PAM concentration increases the viscosity of the solution, slowing the sedimentation rate of any flocculated particles. This ultimately causes an increase in turbidity.
Figure 2. 6. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the sandy loam soil from Wake County.

Figure 2. 7. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the sandy loam soil from Durham County.
Figure 2. 8 Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the sandy loam soil from Watauga County.

Figure 2. 9. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the sandy loam soil from Gates County.
Figure 2. 10. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the silt loam soil from Stokes County.

Figure 2. 11. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the silt loam soil from Iredell County.
Figure 2. 12. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the clay soil from Rowan County.

Figure 2. 13. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the sandy soil from Carteret County.
Figure 2. 14. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the loamy sand soil from Cumberland County.

Figure 2. 15. Turbidity reduction percentages as a function of PAM concentration for six PAM products tested with the loamy sand soil from Brunswick County.
4.2.2. PAM Charge density

The average residual turbidities for the six soils tested (Table 2.15) are plotted against PAM charge density (CD) as shown in Figure 2.16. Six high molecular weight PAMs with charge densities ranging from 0 to 30% were evaluated. Out of all PAM treatments, the polyacrylamide with charge density 3%, A3-H, led to the lowest turbidities in all soils (Figure 2.16). For instance, from an average initial turbidity of 3394 NTU, this PAM reduced the turbidity of the Burke soil to 63 NTU, while the Lee soil turbidity was reduced from 1024 NTU to 26.2 NTU (Table 2.15). CDs much higher than 3% were effective in applications such as infiltration and aggregate stability (18-20%) and mineral tailings (10%) when using anionic PAMs. Nonetheless, many published data indicate that as CD increases, the effectiveness of PAM decreases (Ben-Hur et al., 1992; Green et al., 2000; Nasser & James, 2006). A similar trend was observed in this study. As CD increased from 3% to 30%, flocculation of soil particles decreased, leading to higher final turbidity values. This trend was more pronounced for some soils (e.g. Durham Co.) than for others (e.g. Stokes Co.).

A possible explanation of this observation is that higher negative CD may have caused repulsion between negatively charged particles and PAM (Theng, 1979). Malik and Letey (1991) also attributed the poor performance of higher CD anionic PAMs to their molecular configuration in solution. Due to electrostatic repulsion between negative charges, the chain of anionic PAM is stretched out in solution, giving the molecule an undefined conformation. Excessive extension of the molecule – in the case of higher CD PAMs – may lead to its collapse onto the surface of soil particles or aggregates, which would defeat the purpose of bridging multiple suspended particles. In addition, it is possible that higher polymer extension may cause the polymer to coil around cations in solution (Bartholomew, 2003).

Laird (1997) stated that anionic PAM is generally more effective for flocculation than nonionic PAM. Theng (1982) demonstrated that only an average 60% of nonionic polymer chains extends into solution, with the rest coiled up. This decreases their ability to bind many particles, in comparison to their anionic counterparts (Laird, 1997; Malik & Letey, 1991; Theng, 1982). Our results mostly agree with these conclusions. All soil suspensions tested experienced far better turbidity removals with CDs of 3, 10, and 13% than 0%. However, the performance of PAMs with CDs of 20% and 30% exhibited an apparent dependence on soil properties. In the soils with finer
particles, Chatham (clay), Stokes (silt), and Burke (silt), PAMs with CDs of 20 and 30% also led to better flocculation than 0%, whereas in two soils with coarser particles, Gates (sandy loam) and Lee (loam), they performed equally well as the neutral PAM. Lastly, the sandy loam soil from Durham county experienced better turbidity reduction with 0% CD than 20 and 30% CD. Overall, anionic PAM with a CD of 3% was most effective at reducing turbidity.

Table 2. 15. Effect of charge density – final average turbidities of six different soils after PAM treatment

<table>
<thead>
<tr>
<th>Soil County</th>
<th>Soil texture</th>
<th>Average initial turbidity (NTU)</th>
<th>0%</th>
<th>3%</th>
<th>10%</th>
<th>13%</th>
<th>20%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chatham</td>
<td>Clay</td>
<td>388</td>
<td>197</td>
<td>24.3</td>
<td>37.3</td>
<td>49.7</td>
<td>95</td>
<td>73.3</td>
</tr>
<tr>
<td>Stokes</td>
<td>Silt loam</td>
<td>332</td>
<td>68.1</td>
<td>6.8</td>
<td>24.8</td>
<td>25.6</td>
<td>50.4</td>
<td>30.1</td>
</tr>
<tr>
<td>Burke</td>
<td>Silt loam</td>
<td>3394</td>
<td>307</td>
<td>63.2</td>
<td>73.2</td>
<td>112</td>
<td>164</td>
<td>91.6</td>
</tr>
<tr>
<td>Gates</td>
<td>Sandy loam</td>
<td>186</td>
<td>76.4</td>
<td>28.3</td>
<td>32.2</td>
<td>38.3</td>
<td>67.3</td>
<td>61.5</td>
</tr>
<tr>
<td>Durham</td>
<td>Sandy loam</td>
<td>832</td>
<td>189</td>
<td>48.1</td>
<td>61.2</td>
<td>86.4</td>
<td>437</td>
<td>611</td>
</tr>
<tr>
<td>Lee</td>
<td>Loam</td>
<td>1024</td>
<td>121</td>
<td>26.2</td>
<td>29</td>
<td>63.7</td>
<td>102</td>
<td>112</td>
</tr>
</tbody>
</table>
Figure 2. 16. Final average turbidity of six soil suspensions as a function of PAM charge density. Error bars represent one standard deviation.
4.2.3. PAM Molecular Weight

Three molecular weights of PAM with charge densities (CD) 0, 3, and 20% were tested. The PAMs with the highest MW did not always achieve the highest turbidity reductions in the soils tested. Each PAM CD demonstrated a specific trend, which was independent of the soil suspensions tested. In the group of PAMs having a CD of 3%, flocculation with the standard and high MW yielded the lowest turbidities in all three soils (Figure 2.17). No significant differences (p = 0.05) were found between these two MWs. As for the PAMs with 20% charge density, the medium and high MW polymers led to the lowest turbidity values in all soils, though pairwise t-tests revealed no significant differences (p = 0.05) between the effects of all three MW ranges (Figure 2.18). At 0% charge density, all three MWs produced similar turbidity reductions (Figure 2.19), with no significant differences (p = 0.05).

Levy and Agassi (1995) reported that MW was not a key factor in the efficacy of PAM on fine textured soils, but their study only focused on PAMs having charge density 20%. They explained that fine textured soils have a short distance between clay particles, which can be spanned by relatively short chain length polymers. Our results and those of Levy and Agassi (1995) deviate from those of other studies, in which PAMs needed to be of high MW to effectively flocculate soil suspensions (Bartholomew, 2003; Green et al., 2000; Gregory & O'Melia, 1989; Laird, 1997). Overall, it appears that both soil and PAM characteristics affect turbidity removal effectiveness such that generalizable conclusions are not possible.
Figure 2. 17. Average turbidity reduction as a function of molecular weight for the PAM A3. STD = Standard, SH = Medium, VHM = High. Error bars represent one standard deviation.
Figure 2. 18. Average turbidity reduction as a function of molecular weight for the PAM A20. STD = Standard, SH = Medium, VHM = High. Error bars represent one standard deviation.
Figure 2. 19. Average turbidity reduction as a function of molecular weight for the PAM N. STD = Standard, SH = Medium, VHM = High. Error bars represent one standard deviation.
4.3. Effect of mixing intensity on turbidity removal

Average residual turbidities of the Sandy Loam soil suspension from Wake County after flocculation with three PAMs are plotted against collision potential (G*t) values (Figure 2.20). Initial turbidities for this soil were in the range 1000–1300 NTU. For all three mixing intensities evaluated, 48, 130, and 640 s⁻¹, residual turbidities decreased with increasing G*t values, regardless of PAM type. With the neutral PAM, N, mixing at G = 640 s⁻¹ caused a drop from 114 NTU at G*t = 19200 to 17.3 NTU at G*t = 96000, whereas at G = 130 s⁻¹, average turbidity values diminished from 43.7 NTU at G*t = 19200 to 8.40 NTU at G*t = 96000. Applying a constant collision potential to the suspension, regardless of mixing intensity, did not yield similar results. For the three PAMs tested, G = 130 s⁻¹ resulted in the lowest residual turbidities at all G*t values. When flocculation was performed with A20-H at G*t = 19200, for example, the average residual turbidities were 23.8, 3.60, and 12.4 NTU for mixing intensities of 48, 130, and 640 s⁻¹, respectively.

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). Several studies have reported that increased shear rates resulted in polymer breakage and a loss of viscosity, which, in turn, negatively affected flocculation performance (Henderson & Wheatley, 1987; Nagashiro & Tsunoda, 1977; Nakano & Minoura, 1978; Scott et al., 1996).
Figure 2. Average turbidity as affected by mixing intensity for three distinct PAMs. Error bars represent one standard deviation.
4.4. Effect of mixing time on turbidity removal

4.4.1. Hand-shake Test

Increasing mixing time from 10 s to 60 s had variable impacts on turbidity depending on the soil (Figure 2.21). For three of the six soils, turbidity reduction decreased when dosed with N 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 percent turbidity reduction were also recorded, this effect was not as pronounced and no significant differences (p = 0.05) were found between 10 s and 60 s of mixing. In contrast, increasing mixing time did not affect the turbidity reduction by A20-H except for the Chatham soil (Figure 2.21f), 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 nonionic and anionic 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 N 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 2.11. Effect of mixing time on turbidity reduction for six soils flocculated with N and A20-H using the hand-shake method. For each PAM, data points with different letters are significantly different (p = 0.05).
4.4.2. Jar Test

Continuous mixing at 100 rpm for up to 300 s produced a steady decline in turbidity for both N and A20-H when tested with the Wake Co. soil (Figure 2.22). From an initial average value of 1083 NTU, turbidity dropped from 360 NTU after 10 s mixing to 10.8 NTU after 300 s mixing when flocculation was carried out with N. A comparable trend was also observed in the case of the anionic PAM, A20-H. Laird (1997) reported that anionic PAM was generally more effective at flocculating and stabilizing soil particles than nonionic polymers. However, lower turbidities were achieved with this A20-H, relative to N, at all time points.

![Figure 2.22. Effect of mixing time on turbidity of the sandy loam soil from Wake County flocculated with N and A20-H.](image-url)
4.5. Comparison of screening methods and their effect on the choice of PAM

The effect of mixing time on turbidity removal demonstrated a dependence on the screening method being used. After mixing PAM + soil suspensions for 10 s, the turbidity reductions achieved with the hand-shake test were much higher than the ones observed on the jar tester. For example, when flocculated with N, the turbidity of the sandy loam soil (from Wake County), decreased by 68% and 95% during the jar test and the hand-shake test, respectively (Figure 2.23b). Flocculation of the soil from Rowan County with A20-H on the jar tester led to roughly 40% turbidity reduction, while 84% removal was achieved with the manual shaking (Figure 2.23c). However, as mixing intensity was extended to 60 s, flocculation on the jar tester led to lower turbidity relative to the hand-shake analysis. With N, turbidity removal for the Wake Co. soil dropped from 95% to 84% when the manual shaking time increased, whereas it increased from 68% to 96% in the jar test over the same time increase. When the Wake Co. soil was flocculated with A20-H, turbidity reduction increased from 79% at 10 s to 99% at 60 s using the jar test. An underlying cause for the differences observed in these results could be the energy imparted to the suspensions during both tests. While suspensions were mixed at a constant 100 rpm (130 s⁻¹) in the jar tests, they were vigorously shaken during the hand-shake test, possibly creating a faster interaction between soil particles and PAM molecules. This may have led to high turbidity reduction after 10 s of mixing, but as the vigorous motion was sustained for 60 s, it is possible that the shear created may have induced breakage of the flocs formed, increasing turbidity. Though the mixing intensity was not quantified during the hand-shake test, it is also likely that this fluctuated over time from one operator to the other. However, no data was recorded to mark the differences between the various operators who participated in this analysis. The volume of suspension tested may also explain these differences. 100-mL samples of soil suspensions were prepared and tested with PAM during the manual screening method, whereas 1 L samples were prepared for the jar test. In a smaller sample volume, shorter inter-particle distances inevitably allow for increased interaction between soil particles. However, as shaking is extended over time, shorter inter-particle distances and increased interaction may end up causing floc break-up. As a result, an increase in turbidity is observed. In the larger volume, increasing mixing time enabled the interaction of a higher number of particles, thus decreasing the turbidity of the suspension.
Results of this analysis clearly indicate that depending on the screening test performed the type of PAM chosen for field applications may differ. After mixing for 10 seconds conclusions of the hand-shaking method show that flocculation with the neutral PAM, N, led to better turbidity removal in all soils, in comparison to the anionic PAM, A20-H. With the Burke County soil, for instance, 95.7% reduction was reached with N, while A20-H caused turbidity to drop by 78.8%. When flocculation tests were conducted on the jar tester for 10 seconds, the anionic PAM was more effective at reducing turbidity in all three soils. Turbidity of the same Burke Co. soil decreased by 83.3% with A20-H, as opposed to a 66.7% reduction with N. So, when trying to determine which PAM could effectively reduce turbidity on a construction site, one could be tempted to choose either a neutral PAM or a negatively charged PAM depending on the screening test performed. However, it appears that higher percent turbidity reductions were achieved with the hand-shaking test relative to the jar test. Overall, percent reduction values ranged from 78.8% to 96.4% with the hand-shaking test, whereas on the jar tester they varied from -19.3% to 83.3%. Consequently, the next logical step would be to determine which screening test better predicts performances realized during field testing and practical applications.
Figure 2.23. Average turbidity reduction efficiencies for three soil suspensions as a function of the screening method used. For each screening test, data points with different letters are significantly different (p = 0.05).
5. Conclusion

- The results presented show that increased turbidity reductions were generally observed in the clay and silt soils, as opposed to the sandy soils.
- However, the soil properties which significantly explained the flocculation results varied from one PAM to the other, with potassium and phosphorus content being the constant factors all throughout the analyses.
- Calcium content and pH of the soil suspensions used in this research did not play a key role in explaining the reductions observed for each soil individually.
- PAM concentrations of 1.0 and 5.0 mg/L generally resulted in the lowest turbidities in many of the soils tested throughout these experiments; increasing PAM concentration up to 250 mg/L caused floc break-up and increased turbidity, particularly with the anionic PAMs.
- For the sample of soils analyzed, the effect of PAM molecular weight on turbidity reduction showed a possible dependence on the charge density of the polymer tested.
- 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 was coincidental with increased turbidity reductions.
- The choice of the PAM to be used on a specific construction site may be dependent upon the screening method adopted.
6. References


Chapter 3: Ditch Simulator _ Effects of the Number of Check Dams on Turbidity Removal

1. Introduction

To reduce erosion and control turbidity on construction sites, best management practices (BMPs) such as check dams (CD) have become standard practice. CDs 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), CDs 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 CDs 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%. A field study conducted on two roadway projects in North Carolina found benefits of combining PAM and fiber check dams (FCD) to reduce turbidity runoff from construction sites (McLaughlin et al., 2009). Kang et al. (2013) also tested three distinct CDs – rock check dam, excelsior wattle or FCD, 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.

To date, there have not been any studies which examined the influence of the number of CDs on turbidity removal. As a rule of thumb, check dams are usually installed along the ditch with the bottom of each CD 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.

Therefore, the objectives of this study were to (1) evaluate the performance of a few PAM-soil combinations in a model ditch relative to jar tests in the laboratory and (2) assess how the number of CDs across the ditch may affect turbidity.
2. Materials and Methods

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 (Table 3.1). Four PAMs, FA 920, AN 905 VHM, AN 913 VHM, and AN 934 VHM, identified by their characteristic charge and charge density, were used in these experiments (Table 3.2). 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 (Figures 3.1 & 3.2) consisted of:

1) 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 12-inch PVC sewer pipes were halved longitudinally and used as the model channels.
2) a 170-Liter tank used to mix the soil suspensions;
3) An electric trolling motor used to keep the soil particles suspended in the tank;
4) 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;
5) two 22.7-Liter 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;
6) a 5.08-cm (2 inches) diameter discharge hose used as a connection between the tank and the buckets.
Figure 3.1. Experimental setup of the ditch simulator for field testing

Table 3.1. Particle size distribution and texture of soils used during field testing

<table>
<thead>
<tr>
<th>Soil County</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake</td>
<td>55</td>
<td>26.2</td>
<td>18.8</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>Lee</td>
<td>34.9</td>
<td>44.4</td>
<td>20.7</td>
<td>Loam</td>
</tr>
<tr>
<td>Burke</td>
<td>29.9</td>
<td>51.5</td>
<td>18.6</td>
<td>Silt Loam</td>
</tr>
<tr>
<td>Rowan</td>
<td>28.4</td>
<td>31.4</td>
<td>40.2</td>
<td>Clay</td>
</tr>
</tbody>
</table>
Table 3. 2. Nomenclature of PAMs used for ditch testing

<table>
<thead>
<tr>
<th>PAM</th>
<th>Charge</th>
<th>Charge Density (%)</th>
<th>Denomination</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA 920</td>
<td>Neutral (N)</td>
<td>0</td>
<td>N</td>
</tr>
<tr>
<td>AN 905 VHM</td>
<td>Anionic (A)</td>
<td>3</td>
<td>A3-H</td>
</tr>
<tr>
<td>AN 913 VHM</td>
<td>Anionic (A)</td>
<td>13</td>
<td>A13-H</td>
</tr>
<tr>
<td>AN 934 VHM</td>
<td>Anionic (A)</td>
<td>30</td>
<td>A30-H</td>
</tr>
</tbody>
</table>

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.

In the second series of simulations, the impact on turbidity of installing CDs across the ditches was evaluated. The CDs were 30-cm-long, 2.54 cm foam insulation for water pipes. These were glued with silicone in the channels perpendicular to the flow. The experiments were conducted with either one CD or three CDs in both channels. The CDs were placed (1) halfway in the ditches at 8.5 m for one CD and (2) evenly spaced (5.67 m between CDs) for three
CDs. Soils from Wake and Rowan counties and the anionic PAM A3-H were used. 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, twenty-four (24) 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 CD and three CDs, 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.

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. In addition, the results of the flocculation of the Wake County soil with the neutral PAM during the field tests are plotted against the findings of the collision potential (G*t) analysis (Chapter 2). Comparison of both sets of results was used to determine which G*t value most closely predicts the ones achieved on the field.

A series of t-tests were also conducted using the DATA package in Microsoft Excel 2016 to evaluate the differences between the effects of the distinct number of check dams tested.
Figure 3. 2. Experimental setup showing check dams in place across the ditches

Figure 3. 3. Schematic of Ditch Simulator showing sampling points for channels with one and three check dams.
3. Results and Discussion

3.1. PAM performance without check dam

In the absence of check dams, the effect of slope on turbidity reduction was extremely dependent upon both the soil flocculated and the PAM used to do so. Increasing the slope of the channel from 1% to 3% caused reduced turbidity reduction in the case of the clay and silt loam soils when flocculated with the anionic polymers A3-H, A13-H, and A30-H. When flocculated with A3-H, the turbidity reduction efficiency for the clay soil decreased from 54.8% in the 1% slope channel to 39.9% in the 3% slope channel (Figure 3.4). However, different observations were made for the sandy loam soil based on the PAM used. When treated with A3-H, turbidity reduction efficiency increased from 80.6% at 1% slope to 85.4% at 3% slope, while with A30-H, efficiencies decreased from 74.1% to 69.8% at 1% and 3% slopes, respectively (Figure 3.5). As for the nonionic PAM, N, increasing the slope resulted in lower turbidity, regardless of the soil in presence. For instance, percent turbidity reduction increased from 69.8% at 1% slope to 80.8% at 3% slope in the case of the silt loam soil from Burke County (Figure 3.6), whereas a rise from 52% to 56% was recorded in the sandy loam soil from Wake county. Though not very consequential, turbidity reduction jumped from 1% (1% slope channel) to 4% (3% slope channel) for the clay soil.

The lowest turbidities in all soils tested were achieved with A3-H, regardless of the slope of the channel. At 1% slope, for example, the highest reduction efficiencies were 54.8%, 80.6%, and 84.7% for the clay, sandy loam, and silt loam soils, respectively (Figures 3.4, 3.5, 3.6). This concurs with results obtained in section 4.2.2, where the effect of PAM charge density on turbidity reduction was evaluated in a laboratory setting.

In comparison to the jar tests conducted, reduction efficiencies for the sandy loam soil were similar, except for the N PAM, with which lower turbidity in the channel was observed. Turbidity reduction for the Burke soil was better in the jar tests, except for the N PAM 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 3.4). In the controlled environment provided in the laboratory, homogenous mixing allowed for increased interactions between many 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, percent removal
obtained in the laboratory were much 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.

Figure 3.4. Turbidity reduction as a function of PAM type in the ditch simulator for the Rowan County soil. For each PAM, data points with different lowercase letters are significantly different (p=0.05), and for each slope, data points with different uppercase letters are also significantly different (p=0.05).
Figure 3.5. Turbidity reduction as a function of PAM type in the ditch simulator for the Wake County soil. For each PAM, data points with different lowercase letters are significantly different (p=0.05), and for each slope, data points with different uppercase letters are also significantly different (p=0.05).
3.2. Impact of check dams on turbidity removal

For the evaluation of the influence of check dams on turbidity removal, the anionic PAM, A3-H, 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 3.7) 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 (Figure 3.8). Similar results were observed in the sandy loam soil from Wake County (increase from 81% to 88% reduction) (Figure 3.9). Comparable improvements in turbidity removal with the addition of check dams were also recorded 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 both soils tested (Table 3.4). 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 3.10 & 3.11). 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.

The important effect of the installation of check dams across the ditches came to light when comparing the ditch simulation tests and the laboratory analyses. The results obtained indicate that the performances of A3-H during the screening test in the lab can be achieved in the field using check dams, particularly in the case of the finer soil. During the laboratory analysis, flocculation of the Rowan County soil with this polymer reduced its turbidity by 87.5%, while field testing had a 40% decrease without check dam in the 3% ditch. However, installing one check dam helped increase turbidity reduction to 89%, slightly over lab results. Though less pronounced, the same effect was observed with the Wake county soil.
Figure 3. 7. Photo showing pool of soil suspension upstream of check dam and settled flocs during the simulation test

Table 3. Summary of t-tests comparing the effects of zero, one, and three check dams. Values in bold indicate significant differences (p = 0.05).

<table>
<thead>
<tr>
<th>Parameters compared</th>
<th>P-value</th>
<th>Parameters compared</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CD vs 3 CD</td>
<td>0.8500</td>
<td>1 CD vs 3 CD</td>
<td>0.1000</td>
</tr>
<tr>
<td>0 CD vs 1 CD</td>
<td>&lt; 0.001</td>
<td>0 CD vs 1 CD</td>
<td>0.0800</td>
</tr>
<tr>
<td>0 CD VS 3 CD</td>
<td>0.0300</td>
<td>0 CD VS 3 CD</td>
<td>0.0300</td>
</tr>
<tr>
<td>Wake</td>
<td></td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>1 CD vs 3 CD</td>
<td>0.9200</td>
<td>1 CD vs 3 CD</td>
<td>0.3300</td>
</tr>
<tr>
<td>0 CD vs 1 CD</td>
<td>&lt; 0.001</td>
<td>0 CD vs 1 CD</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>0 CD VS 3 CD</td>
<td>&lt; 0.001</td>
<td>0 CD VS 3 CD</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Rowan</td>
<td></td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3. 8. Turbidity reduction in the Rowan County soil suspension as a function of the number of check dams installed across the ditch simulator. For each slope, data points with different letters are significantly different (p=0.05).

Figure 3. 9. Turbidity reduction in the Wake County soil suspension as a function of the number of check dams installed across the ditch simulator. For each slope, data points with different letters are significantly different (p=0.05).
Figure 3. 10. Turbidity reduction at each sampling point along the ditches for the Clay soil. For each slope, data points with different letters are significantly different (p=0.05).

Figure 3. 11. Turbidity reduction at each sampling point along the ditches for the Sandy Loam soil. For each slope, data points with different letters are significantly different (p=0.05).
4. Conclusion

- The ditch simulations confirmed the results of the jar test presented in the previous chapter. The anionic PAM, A3, 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 A3 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.
5. References


