AUBURN UNIVERSITY
Samuel Ginn College of Engineering

Research Report

BEST PRACTICES FOR CONSTRUCTION SITE STORMWATER TREATMENT USING FLOCCULANTS

Submitted to

The Alabama Department of Transportation

Prepared by

Billur Kazaz, Ph.D., EI, CPESC
Jannell Clampitt, EI, CPESC-IT
Michael A. Perez, Ph.D., P.E., CPESC
Wesley N. Donald, Ph.D., CPESC
Xing Fang, Ph.D., P.E.
Joey N. Shaw, Ph.D.

SEPTEMBER 2023

Highway Research Center
Harbert Engineering Center
Auburn, Alabama 36849

1. Report No.
931-017

2. Government Accession No.

3. Recipient Catalog No.

4. Title and Subtitle
Best Practices for Construction Site Stormwater Treatment Using Flocculants

5. Report Date
September 2023

6. Performing Organization Code

7. Author(s)
Kazaz, B., Clampitt, J., Perez, M.A., Donald, W.N, Fang, X., and Shaw, J.N.

8. Performing Organization Report No.

9. Performing Organization Name and Address
Highway Research Center
Department of Civil Engineering
238 Harbert Engineering Center, Auburn, AL 36849

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
931-017

12. Sponsoring Agency Name and Address
Alabama Department of Transportation
1409 Coliseum Blvd, Montgomery, AL 36110

13. Type of Report and Period Covered
Technical Report

14. Sponsoring Agency Code

15. Supplementary Notes
None

16. Abstract

Unmanaged construction stormwater runoff can pose a risk for the quality of downstream water bodies. Temporary sediment control practices are designed to capture sediment particles and reduce the turbidity of discharge; however, commonly used practices have limited performance in capturing fine-sized sediment particles. Flocculants can be introduced to construction stormwater runoff to enhance the performance of sediment control practices by increasing the settling velocity of suspended materials. This research study explored practical methods to enhance guidance for proper selection, use, and application of flocculants in construction stormwater management through (1) a state of the practice survey, (2) soil assessments, (3) bench-scale experiments, (4) flume experiments, and (5) intermediate-scale flume and large-scale evaluations. In total, 14 different products were used for bench-scale experiments. Best performing products for unique soils were identified with a match test study, which ranked products based on their performance. Results indicated that polyacrylamide (PAM) and chitosan-based products work most effectively across tested soil samples compared to other tested products. Testing results also showed the potential of flocculants to perform well in underdose conditions. Results revealed that pH, temperature, and flocculant concentration all significantly affect soil settling velocity which greatly influenced the accuracy of residual flocculant concentration predictions. Optimum dosage delivery mechanisms were evaluated through flume experiments by using block, sock, granular, and stock solution flocculant forms. A 40 ft (12 m) long flume was designed and constructed at the Auburn University - Stormwater Research Facility. Testing results indicated that the use of ditch checks for flocculant applications in channelized flow significantly improves the agitation and mixing by providing up to 96% turbidity reduction. Large-scale evaluations were accomplished using an in-channel sediment basin application using semi hydrated PAM-based flocculants in block form. Testing results indicated that flocculant usage provided a 90% turbidity reduction and showed residual concentration values from 5 to 8 mg/L exist in the discharge point. Flocculant application was evaluated on wattle ditch checks using granular PAM-based flocculant and silt fence ditch checks using block form PAM-based flocculant. Application and reapplication quantities and intervals were developed based on findings.

17. Key Words
stormwater, sediment control, flocculants

18. Distribution Statement

19. Security Classification (of this report)
Unclassified

20. Security Classification (of this page)
Unclassified

21. No. of Pages
339

22. Price
None

Research Report

BEST PRACTICES FOR CONSTRUCTION SITE STORMWATER TREATMENT USING FLOCCULANTS

Submitted to

The Alabama Department of Transportation

Prepared by

Billur Kazaz, Ph.D., EI, CPESC
Jannell Clampitt, EI, CPESC-IT
Michael A. Perez, Ph.D., P.E., CPESC
Wesley N. Donald, Ph.D., CPESC
Xing Fang, Ph.D., P.E.
Joey N. Shaw, Ph.D.

SEPTEMBER 2023

DISCLAIMERS

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of Alabama DOT, Auburn University, or the Highway Research Center. This report does not constitute a standard, specification, or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

Billur Kazaz, Ph.D., EI, CPESC
Jannell Clampitt, EI, CPESC-IT
Michael A. Perez, Ph.D., P.E., CPESC
Wesley N. Donald, Ph.D., CPESC
Xing Fang, Ph.D., P.E.
Joey N. Shaw, Ph.D.

ACKNOWLEDGEMENTS

This research is based on a study sponsored by ALDOT (Project 931-017). The authors gratefully acknowledge this financial support. The findings, opinions, and conclusions expressed in this report are those of the author and do not necessarily reflect the view of the sponsor.

EXTENDED ABSTRACT

Construction stormwater runoff constitutes an increased risk for downstream water bodies if excessive sediment-laden discharge exits a construction site. Federal and state regulations emphasize the significance of erosion and sediment controls on job sites and require the implementation of effective stormwater pollution prevention plans. Regulations aim to prevent impairment of receiving waterbodies by requiring the management of construction stormwater with proper design, implementation, and maintenance of erosion and sediment control practices.

Temporary sediment control practices are designed to capture sediment particles and reduce the turbidity of discharge; however, commonly used sediment control practices have limited performance in capturing fine-sized sediment particles. Flocculants are chemicals that can be introduced to construction stormwater runoff to enhance the performance of the sediment control practices by improving the capture of suspended sediment. These chemicals create a bridging mechanism between particles to form larger flakes and enhance settlement velocity. Although flocculants can be highly effective in reducing turbidity, improper dosing may risk polluting downstream water bodies and may create risks for aquatic life. The effectiveness of flocculants for stormwater management has been investigated; however, a large knowledge gap exists on guidance for effective usage, limiting factors, application rates and dosage for construction site applications.

This research study explores practical methods to enhance guidance for proper selection, use, and application of flocculants in construction stormwater management by developing design guidance on dosage rates and application techniques. This research evaluates construction stormwater treatment with flocculants through (1) state of the practice survey, (2) soil assessments, (3) bench-scale experiments, (4) flume experiments, and (5) intermediate-scale flume and large-scale evaluations.

The use of flocculants has been adapted by several State Departments of Transportation within the past decade on active construction sites to capture fine-sized sediment particles and minimize construction stormwater-related pollution in downstream waterbodies. However, the perception of agencies on flocculants varies due to the existing knowledge gap on flocculant usage and potential environmental consequences of overdoses. A state-of-the-practice survey was conducted to understand the current perspective of state agencies on flocculant usage and identify specific concerns and guidance needs. Survey results indicated that only 39% of state departments of transportation allow flocculant usage on construction sites. The majority of these agencies (55%) follow manufacturer guidance on dosage and the most common concern for flocculant dosage is the potential risk of polluting downstream waterbodies and damaging aquatic life.

The study details the methodology for identifying the performance of different flocculant types across various soil samples collected from named map units through bench-scale experiments for providing guidance on dosage and product selection. In total, 14 different products were used for bench-scale experiments, which included PAM, bentonite, sodium montmorillonite, alum, agricultural gypsum, and chitosan-based flocculants. Best performing products for 15 unique soils were identified with a match test study, which ranked products based on their performance. Following match test experiments, dosage experiments were conducted by ranging manufacturer recommended concentration values from 0% to 200% for observing the behavior of flocculants in underdose and increased dosing conditions. Results indicated that PAM and chitosan-based products work most effectively across the 15 tested soil samples compared to other tested products. Testing results also showed the potential of flocculants to perform well in underdose conditions and increase turbidity in increased dosage conditions.

Monitoring flocculant concentrations in discharge provide a supportive control mechanism to prevent possible overdoses and maintain proper dosage throughout flocculant applications on sites. However, only 23% of state agencies surveyed require monitoring residual flocculant in downstream water bodies. A field applicable residual concentration detection method was developed by using a turbid water sample with a specific testing soil. Settling velocities of each product were correlated with known concentration injections ranging from 0% to 30% of manufacturer dosage recommendation and standardized residual concentration plots were formed.

Optimum dosage delivery mechanisms were evaluated through flume experiments by using block, sock, granular, and stock solution flocculant forms. A 40 ft (12.2. m) long flume was designed and constructed at the Auburn University - Stormwater Research Facility (AU-SRF). Agitation and mixing requirements were identified with clear water and sediment introduction tests on 5% and 1% slopes by using 0.1 ft^3/s (0.003 m^3/s) controlled flow rate throughout the flume testing. Mimicked rock check dams were used within the flume for determining proper agitation. Testing results indicated that the use of ditch checks for flocculant applications in channelized flow significantly improves the agitation and mixing by providing up to 96% turbidity reduction.

Large-scale evaluations were accomplished with a collaborative effort of AU-SRF researchers on in-channel sediment basin application. Flocculant application on a sediment basin testing apparatus was evaluated by using semi hydrated PAM-based flocculants in block form. Three flocculant blocks were installed within the forebay of the inflow channel upstream of the basin to maintain contact with the introduced flow. The performance of flocculants within the sediment basin application was evaluated through turbidity reduction and residual concentration measurements. Testing results indicated that flocculant usage provided a 90% turbidity reduction, which was 8% more than the MFE-I treatment, and showed low residual concentration values from 5 to 8 mg/L exist in the discharge point. Large-scale in-channel

application evaluations were also subjected to turbidity reduction and residual concentration measurements. Anionic granular polyacrylamide flocculant was spread across three wattles spaced over 43 ft (13 m) at a rate of 6.36 oz. (180 g) per wattle. Results found that during a 0.75 ft^3/s (0.07 m^3/s) flow event, the channel is initially dosed with 14 mg/L above the manufacturer's recommendations and exponentially decreased over the first 25 minutes or 1,060 ft^3 (30 m^3) of flow to reach the recommended dosage of 5 mg/L. From this, it is recommended that reapplication of granular flocculant should be performed after 3,600 ft^3 (101.9 m^3) of flow or 1.0 in. (2.54 cm) of runoff per acre (0.4 ha). Anionic block form polyacrylamide tests were conducted, and results indicated that six flocculant blocks provided optimum dosing for a flowrate of 1.80 ft^3/s (0.05 m^3/s) of channel flow in a 4.0 ft (1.2 m) wide bottom channel; however, further analysis is necessary for accurate concentration predictions using block form flocculants. All flocculant applications evaluated indicated the need for at least one flocculant-free ditch check at the end of a channel to provide necessary mixing. Flocculants vary by manufacturer and are highly soil-dependent. Therefore, results may vary based on the product manufacturer and soil type.

Effective implementation of flocculants on construction sites is possible through proper dosage, dosage delivery mechanisms, and application. This research provides a framework for practitioners to establish effective flocculant implementation that would successfully treat construction stormwater. Findings of this study allow improvements on flocculant usage in construction stormwater treatment through new and improved guidelines as well as increasing the knowledge on the use of flocculant in the erosion and sediment control industry.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

The U.S. economy spends $1.67 trillion annually in construction activities. Among this, $163 billion is invested in linear highway and transportation projects (*1*). Construction activities pose a stormwater pollution risk by introducing contaminants to the environment such as sediment, chemicals, trash, fertilizers, and pesticides. Construction sites are highly dynamic with phasing, changing topography, non-uniform soil distributions, varying cover conditions, and seasonal precipitations. Stormwater runoff from construction sites has the potential to pollute downstream water bodies due to sediment release caused by ground-disturbing activities typical of land-grading operations. The U.S. Environmental Protection Agency (USEPA) considers sediment as one of the most persistent pollutants that threaten the waters of the nation (*2*, *3*). The dynamic nature of construction activities makes sediment the most concerning pollutant from construction activities for downstream waterbodies. Earthmoving operations during construction leave land exposed to wind and rainfall, increasing the risk of on-site erosion and off-site sediment deposition. Active construction sites are susceptible to an increased risk of rainfall-induced soil erosion and can create an annual soil loss of up to 100 tons/ac (224 tonnes/ha) (*4*).

Pollutants are often transferred into downstream waterbodies through stormwater discharge, which can carry a substantial amount of sediment in cases of discharge originating from poorly managed construction-related activities. The release of sediment into waterbodies creates a hazardous environment for aquatic life, deteriorates water quality, and decreases the capacity of streams and rivers, leading to potential flooding concerns (*5*). Suspension of fine-sized sediment particles results in light attenuation related to increased turbidity, which could interrupt photosynthesis in wetlands and reduce oxygen available for aquatic species (*6*). Moreover, the settlement of suspended solids can form a layer on aquatic nesting areas and damage the reproductive productivity of the aquatic ecosystem. These negative environmental impacts may potentially form economic consequences by increasing the need for remediation and interrupting the supply chain for the aquatic industry.

The Dust Bowl of the 1930s brought severe drought conditions to the Great Plains, which prolonged until the 1940s (*7*). This catastrophic event was a pivotal contributor to the development of soil conservation efforts in the U.S. The U.S. Soil Conservation Service (SCS) was established as a permanent agency by the Public Law 74-46. Initially, the National Industrial Recovery Act in 1933 provided funds for soil erosion prevention, which led to the establishment of the Soil Erosion Service (SES). SES initiated nationwide demonstrations for landowners in areas experiencing major erosion to emphasize the significance of conservation.

With the increasing concerns on the impacts of the Dust Bowl, the scope of the soil conservation-related issues expanded, and SES was changed into a permanent soil conservation agency as SCS in 1935 within the U.S. Department of Agriculture (USDA). In 1944, SCS was authorized to work on watershed investigations by the Flood Control Act. SCS's responsibilities expanded in the 1960s and the agency started to include rural development and recreation into the conservation objectives (*8*). Under the Clean Water Act of 1972, National Pollutant Discharge Elimination System (NPDES) was developed, which requires construction operators to obtain a Construction General Permit (CGP) (*9*). The CGP emphasizes the importance of a well-developed Stormwater Pollution Prevention Plan (SWPPP) to limit environmental hazards implicated by stormwater runoff from construction activities (*5*). SWPPP documents include project information, erosion and sediment control (E&SC) plans, and a description of stormwater management practices planned for the site (*10*). Failure to comply with CGP requirements may result in regulatory actions such as fines or stop-work orders. When properly designed and installed, E&SC practices protect downstream waterbodies by reducing soil loss and capturing eroded sediment prior to off-site discharge. Erosion control practices minimize the risk of dislodging soil by covering exposed land or slowing the overland flow of runoff. The success of an E&SC plan, and in turn a site's SWPPP, is dependent on the appropriate design, installation, and maintenance of practices used on site. Federal regulations and permits aim to enforce the use of proper E&SC practices throughout all project phases and minimize the risk of further impairments to waterbodies.

Construction stormwater-related pollution problems constitute global and nationwide recognition through governing regulations and public awareness. Among the regions of contiguous U.S., southeastern states have the highest soil loss risk due to the high erodibility of soils and severe storm events in the area. In the State of Alabama, rainfall erosivity factor ranges between 30,000 and 70,000 ft tons/ac/yr/in/hr (70,000 and 15,6200 tonnes/ha/yr/mm/hr) with high soil erodibility factors, which makes construction sites susceptible to erosion and sedimentation (*11*). The Alabama Department of Transportation (ALDOT) is responsible for a large amount of construction activity in the state with the responsibility of managing and maintaining approximately 11,000 mi (17,702 km) of state, U.S., and interstate highways (*12*). Together with this major construction and maintenance responsibility, ALDOT is under the responsibility and regulatory obligation to implement proper construction stormwater management. NPDES general permits issued by the Alabama Department of Environmental Management (ADEM), regulate construction discharge on ALDOT construction sites. Additional stormwater management regulations are dictated through Municipal Separate Storm Sewer System (MS4) permits. To meet regulatory requirements, ALDOT follows standardized design, implementation, maintenance, and inspection procedures for proper E&SC on construction sites (*13*). However, standard specifications should be evaluated under the light of emerging technologies in construction stormwater management and improvements should be implemented to increase the efficiency of E&SC practices on sites. ALDOT can highly benefit from an in-depth investigation on enhancing the performance of E&SC practices to meet the expectations of stormwater effluent regulations with a well-developed stormwater management program.

1.2 EROSION AND SEDIMENT CONTROLS IN CONSTRUCTION

Minimizing construction stormwater pollution is possible with the proper implementation of construction methods, strategies, and use of effective E&SC practices. Erosion control practices are used on construction sites to manage surface runoff and reduce the amount of soil loss due to rainfall impact, runoff, and wind. Proper placement of erosion control practices such as surface roughening, seeding, mulching, erosion control blankets, and slope drains can significantly minimize soil loss on construction sites (*14*). Conversely, sediment control practices capture dislodged sediment and reduce off-site transport of soil. Sediment control practices include flocculants, surface water skimmers, sediment barriers, inlet protection, and sedimentation basins, amongst others (*14–16*). However, traditional E&SC practices are not sufficient in removing fine-sized particles, which are difficult to remove from suspension and contribute to turbidity plumes (*16–19).* Typically, detention-based practices such as sediment basins and traps are used to capture these fine-graded particles. Sediment basins can be effective for reducing turbidity in runoff, but they require laminar flow conditions and adequate residence time for sediment to fall out of suspension (*14*).

Implementing proper methods and techniques for construction stormwater management brings numerous benefits for protecting the environment, maintaining social justice, and enhancing sustainability in the construction industry. Effective construction stormwater management contributes to preventing the impairment of receiving waters and improving the quality of aquatic life and downstream waterbodies.

1.3 CONSTRUCTION STORMWATER REGULATIONS

In the U.S., water pollution was first addressed in the Rivers and Harbors Act of 1899 by regulating the construction of structures over or in navigable waterways, which aimed to minimize negative impacts of water pollution on the nation’s waters. Later in 1943, the Federal Water Pollution Control Act was enacted as an attempt to prevent and control nationwide water pollution issues. These acts primarily focused on water pollution originating from wastewater and pollutant discharge from factories. Stormwater became a pollution concern later with the increased public awareness and concerns, which paved the way for the amendments in the law that formed the Clean Water Act in 1972. Point and nonpoint pollution sources are regulated by the Clean Water Act’s National Pollutant Discharge Elimination System (NPDES) Construction

General Permit (CGP) (*9*). Land disturbing activities on construction sites require the need for erosion and sediment control (E&SC) practices due to the amount of exposed land susceptible to erosion. Phase II of the NPDES program targets nonpoint source pollution and requires construction activities generating land disturbance greater than 1.0 ac (0.4 ha) to receive coverage through the CGP (*20*). The CGP permit requires the development and implementation of a site-specific Stormwater Pollution Prevention Plan (SWPPP); a comprehensive stormwater management implementation and maintenance plan for temporary E&SCs (*5*, *10*).

The permit enforces permittees to follow the non-numeric limits of the USEPA for construction activities, which originated from NPDES Phase II turbidity limits for large construction sites. These limits require proper implementation of dust control, inlet protection, perimeter controls, slope stabilization, and vegetative cover on active construction sites. In addition to these non-numeric enforcements, several states have numeric effluent limitation requirements. For instance, water quality regulations in Alabama and North Carolina require turbidity levels to not exceed more than 50 Nephelometric Turbidity Units (NTU) above background levels (*20*–*22*).

NPDES permits are issued by 48 states in the U.S. under the full or partial authorization of USEPA. Among these states, ten are partially authorized, nine are fully authorized including an approved biosolids program and 29 of them are fully authorized for NPDES permitting (*3*). The state of Alabama received its permitting authorization in 1979 and has been managing NPDES permitting procedures through ADEM. ADEM enforces numeric effluent limits, the development of effective SWPPPs, and compliance with regulations (*21*). Noncompliance with stormwater effluent regulations may result in environmental fines and potential litigation. Therefore, understanding the effectiveness of E&SC practices, and ensuring their efficiency with correct installation and maintenance methods is critical for designers and contractors.

1.4 FLOCCULANT’S ROLE

Flocculants are a water-soluble chemical additive that bonds particles together through polarity differences, creating larger clumps - known as flocs - that settle out of suspension faster (*23*–*26*). They are used in a variety of water treatment practices as they are used to speed up the settling process of fine particles in water. Unlike coagulants which use a chemical process that neutralizes colloid charge that causes particles to repel each other, flocculants take coagulation a step further by using a physical process that adheres neutral particles together to form larger flocs that can settle out of suspension (*27*–*29*). The most popular polymer products among these flocculant types are synthetic flocculants (*30*), apart from the other three categories of inorganic, bio/natural, and stimuli-responsive flocculants (*26*). Synthetic flocculants are sought after for their water-soluble properties that come as polymeric flocculants that are categorized according to their net electrical charge: anionic, cationic, non-ionic, and amphoteric (*30*–*32*).

Polyacrylamide (PAM) is a common form of commercial flocculant with the largest product volume as it's an extension of acrylamide (AM) which is a cost-effective product for being one of the most reactive monomers and high-water solubility (*30*). PAM is used in a variety of applications. Water and wastewater treatment commonly use PAM as a flocculating agent (*33*–*38*), agriculture soil conditioning and diapers use it for water absorption and retention (*32*, *39*–*41*), cosmetics for a thickening agent (*42*, *43*), and petroleum corporations for enhanced oil recovery to name a few (*44*–*46*). PAM flocculant is the most popular flocculant used in E&SC practices as it is highly water-absorbent and, when it comes in contact with water, forms a soft gel which is used to help capture and remove suspended sediment particles (*47*). Although flocculants have been found to be highly effective in assisting in removing fine particles suspended in water, their efficacy can be highly influenced by environmental conditions. Thus, even though there is a plethora of research on flocculants, there is still an abundance of questions that remain concerning BMPs on construction sites where environmental factors are difficult to control or predict.

1.5 RESEARCH OBJECTIVE

This research consists of three predominant components associated with design, improvement, and application requirements of construction stormwater treatment, with specific emphasis on flocculants.

The specific objectives of this research are as follows:

(1) Identify the improvement needs for flocculant usage and guidance on construction sites,
(2) Provide optimum dosage and product selection guidance across various flocculant products and develop a field applicable method for residual concentration monitoring, and,
(3) Develop optimum dosage delivery methodology, protocols, testing apparatus, and perform intermediate-scale and large-scale testing for identifying agitation and mixing requirements of proper flocculant implementation.

To achieve outlined research goals, the following tasks were performed:

(1) Identify and critically assess most recent advancements in the state-of-the-practice through a comprehensive literature review,
(2) Conduct a survey to evaluate the state-of-the-practice and perspectives of the state DOTs on flocculant usage and identify needs for improvement,
(3) Collect various soil samples across Alabama and perform soil assessment through Web Soil Survey desktop study and laboratory testing,
(4) Develop an applicable methodology and perform bench-scale testing for product selection, dosage delivery, and residual concentration detection,

(5) Design, construct and perform intermediate-scale and large scale testing for optimum dosage delivery and application evaluations, and,

(6) Analyze collected data from bench-scale, intermediate-scale, and large-scale testing for evaluating the effectiveness of flocculant treatment and providing guidance for proper implementation.

1.6 ORGANIZATION OF FINAL REPORT

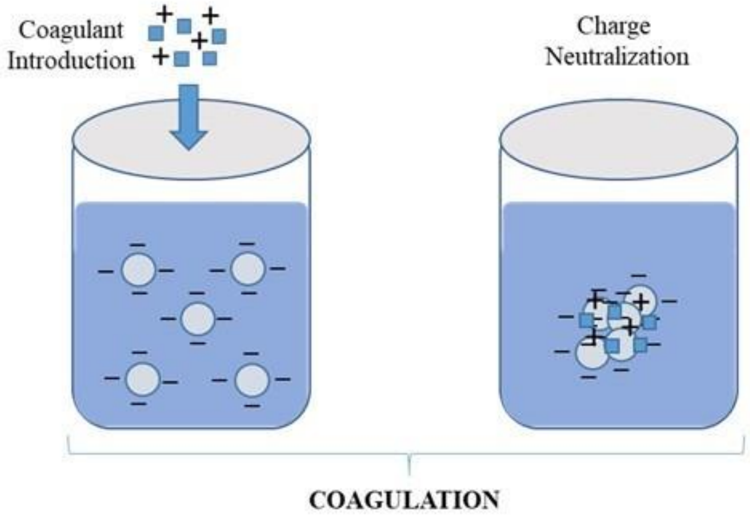
This report is divided into six sections that methodize, illustrate, and outline steps taken to meet defined research objectives. Following this chapter, Chapter Two: *Literature Review,* provides an overview of the current application and research performed on flocculants. Chapter Three: *State-of-the-Practice Survey: Flocculant Usage in Construction Stormwater Management*, details the perspective of state DOTs on flocculant usage for construction stormwater treatment and identifies knowledge gaps in flocculant application. Chapter Four: *Evaluation of Residual Detection Methods for Field Conditions and Bench-Scale Evaluation of Optimum Dosage and Residual Concentrations*, outlines the various explored residual flocculant detection methods for field application, along with methods and procedures developed for evaluating dosage requirements for different flocculant products and detecting residual concentrations. Chapter Five: *Intermediate-Scale Flume Application Evaluations* describes the design, apparatus, methods, and procedures developed for preparing and performing optimum dosage delivery evaluations through flume experiments on different flocculant forms. Chapter Six: *Large-Scale Application Evaluations* details the field-testing environments, methods, and procedures developed through full-scale field experiments using granular and block form flocculants. This chapter details the use of flocculants through a collaborative study on evaluating the performance of flocculant implementation for sediment basin application in addition to channel-based applications. Chapter Seven: *Conclusions,* presents a summary of the accomplished research tasks and provides insight into future research agendas to further advance this research effort. Additionally, a condensed implementation recommendation summary is included at the end of the conclusion section.

CHAPTER 2
LITERATURE REVIEW

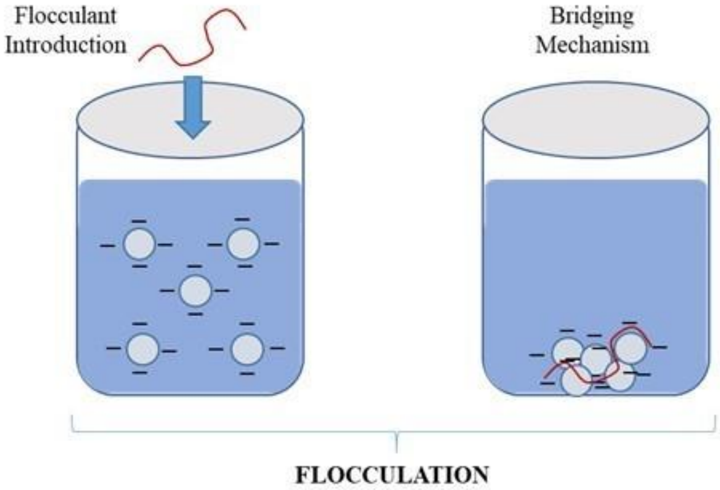
2.1 DEFINITION & PURPOSE OF FLOCCULANTS

Flocculants are chemical agents that function to aggregate solid particles together and increase their settling velocity (*25*). Some flocculants are soil-specific and perform based on specific soil characteristics. Flocculation and coagulation are two different procedures; however, they are often perceived as the same concept due to their similar nature. For example, Chibowski et al. (*48*) submits the term "flocculation" as a synonym of "coagulation". However, many other studies support the opposite. Vajihinejad et al. (*26*) define flocculation as the aggregation of particles due to high molecular weight polymers that occur as a result of bridging between particles. They define coagulation as a separate process, the aggregation of particles by the manipulation of solid surface charges. Stechemesser and Dobias (*28*) describe flocculation as an agitation stage that changes particle size from micro-floc to larger floc particles and coagulation as a neutralization stage of particle charges with the addition of oppositely charged chemicals.

Figure 2-1 compares coagulation and flocculation by illustrating their working mechanisms. Figure 2-1(a) displays coagulation, a physical process of the attraction between particles due to the charge neutralization after the coagulant introduction. Figure 2-1(b) presents flocculation, large particle formation, and settlement process due to the occurrence of a chemical bridging mechanism between particles after flocculant introduction.



(a) coagulation mechanism



(b) flocculation mechanism

Figure 2-1: Comparison of Coagulation and Flocculation Mechanisms.

2.2 FLOCCULANT TYPES & FORMS

Flocculants are manufactured in different physical forms such as powder, granular, blocks, socks, emulsion, dispersants, beads, and liquid(*27*). Figure 2-2 shows the most common commercially available flocculant forms; granular/powder, blocks, liquid, and socks.

(a) granular (*49*) (b) block (*50*)

(c) emulsion (*51*) (d) socks (*52*)

Figure 2-2: Typical Flocculant Forms.

Flocculant types are classified into four main groups: (a) synthetic flocculants, (b) inorganic flocculants, (c) bio/natural flocculants, and (d) stimuli-responsive flocculants. Synthetic flocculants are considered as the most commercially available flocculant type and are classified by their net charge: cationic (positively charged), anionic (negatively charged), nonionic (neutral), and amphoteric (changeable, depending on the pH of water) (*53*, *54*). These flocculants are produced with the use of polymerization of water-soluble monomers technique and their average molecular weight has a significant role in classifying their characteristics (*26*). Cationic flocculants can be highly toxic to aquatic life as the polymers have the potential of binding with the negatively charged hemoglobin in fish gills, causing suffocation (*3*, *31*, *55*, *56*). Anionic flocculants are commonly used in industrial wastewater treatment systems (*30*, *33*, *55*, *57*). Typically, anionic flocculants show very low residual concentration in treated water and their toxicity level is also very low compared to cationic flocculants (*55*, *58*). Nonionic flocculants are defined as polymers that do not carry any charge or carry less than 1% charge. Due to high molecular weight, nonionic flocculants tend to create flocculation by constructing bridging mechanisms with solid particles in the water (*25*, *30*). Amphoteric flocculants include both anionic and cationic charges due to the copolymerization of both groups. The charge of these flocculants is changeable depending on the pH of the water and they are effective in the rapid removal of oppositely charged pollutants (*54*, *59*). PAM is one of the most commonly used synthetic flocculants and can be manufactured in various chain lengths and charges (*60–64*). PAM rapidly aggregates soil particles, decreases soil bulk density, and absorbs water (*65*, *66*). Anionic PAM is commonly preferred for environmental applications since it has not been proven to be toxic to aquatic life (*3*, *66–68*)

Inorganic flocculants are also commonly used in the stormwater industry as they are generally less expensive than other flocculant types and can be more effective for flocculation. Inorganic flocculants have low molecular weight and a small size for aggregation between particles compared to organic flocculants (*69*). Examples of inorganic flocculants include alum, poly aluminum chloride (PAC), aluminum chloride, aluminum sulfate, ferric chloride, and ferrous sulfates (*69–72*).

Bio/Natural flocculants are plant or animal product-based polymers that consist of polysaccharides, tannins, and chitins. Even though synthetic flocculants have replaced the use of natural flocculants in many water treatment sectors, they are still commonly used by the mining and food industries (*71*, *73*, *74*). The most commonly used natural flocculants include chitosan, cellulose, starch, alginate, and amylopectin, which are polysaccharide-based chemical agents (*26*, *75*). Among these natural flocculants, chitosan requires special dosage precaution as it can be activated with the use of petroleum-based cationic monomers, which may be harmful to aquatic life when overdosed (*26*). With proper usage, chitosan can offer effective flocculation results. For instance, Zeng et al.(*76*) prepared a novel composite chitosan that can potentially replace PAC in the water treatment industry, a common inorganic flocculant. Kangama et al. (*77*) created a composite chitosan flocculant for tap water treatment that provided a 96% reduction in turbidity. Moreover, Yang et al. (*78*) reviewed various flocculation mechanisms and highlighted the effectiveness of chitosan-based flocculants with proper application techniques.

Stimuli-responsive polymers experience changes in their physical and chemical characteristics based on changing environmental conditions (*79*). Stimuli-responsive flocculants have three subcategories; thermo-responsive, pH-responsive, and electromagnetic responsive, showing different physical and chemical characteristics related to the changes in temperature, pH, and magnetic nature, respectively (*26*).

Flocculants have the potential to significantly improve methods for treating stormwater on construction sites since they provide rapid and effective results for decreasing turbidity.

Table 2-1 presents commonly used flocculants for turbidity treatment and explains their characteristics together with their drawbacks. Several types of chemical treatments have been used in stormwater treatment. Aluminum sulfate (*80*), calcium sulfate (*81*, *82*), and PAM (*83*) are commonly accepted flocculants in stormwater treatment among the others presented in Table 2-1.

Table 2-1: Typical Flocculants for Turbidity Treatment (*84*, *85*)

Flocculant	Type	Charge	Drawbacks
Chitosan	Natural Polymer	Cationic	Costly; toxic in case of an overdose
Polyacrylamide (PAM)	Synthetic Polymer	Anionic; Cationic; Nonionic	Cationic form is toxic to aquatic life; single compound acrylamide may be carcinogenic in high concentrations
Polyaluminum Chloride (PAC)	Inorganic Polymer	-	Dependent on pH
Diallyldimethyl ammonium chloride (DADMAC)	Monomer	Cationic	Highly toxic in case of an overdose
Calcium sulfate (Gypsum)	Inorganic Polymer	-	-
Aluminum sulfate (Alum)	Inorganic Polymer	-	May acidify water in case of an overdose
Aluminum chlorhydroxide	Inorganic Polymer	Cationic	Toxic in case of an overdose
Natural starch	Natural Flocculant	-	-
Mimosa bark	Natural Flocculant	-	Toxic in case of an overdose

2.3 CONSTRUCTION STORMWATER MANAGEMENT WITH FLOCCULANTS

Several research studies have been conducted to evaluate the use of flocculants in stormwater management applications. Harper investigated the effects of aluminum sulfate (alum) treatment in lake systems in Florida and concluded its use provided an effective and economical approach to reduce the toxicity of sediment particles in lake systems by reducing total nitrogen, total phosphorus, and heavy metals (*80*). Przepiora et al. (*82*) conducted laboratory testing on the efficiency of calcium sulfate compounds as a flocculant by treating sediment basin water from two different urban construction sites in the Piedmont region of the southeastern U.S. The study tested three types of calcium sulfate compounds; hemihydrate, agricultural gypsum, and phosphogypsum, which consist of different calcium sources. Test results showed that hemihydrate was the most effective calcium sulfate compound for treating stormwater runoff with rapid flocculation compared to agricultural gypsum, and less toxic compared to phosphogypsum.

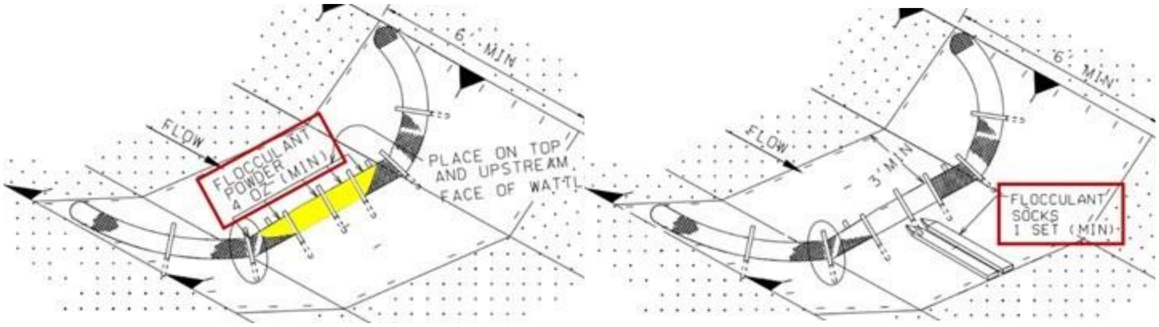
In another study, Przepiora et al. (*81*) implemented field testing at two urban construction sites to evaluate the efficiency of calcium sulfate compounds as a flocculant with large-scale testing methods. Hemihydrate was introduced to several sediment basins at the two construction sites and compared their turbidity with untreated basins throughout 14 rainfall events. This field evaluation showed that hemihydrate was highly successful in reducing the turbidity levels in sediment basins. The results indicated that hemihydrate decreased untreated turbidity levels (100-1,600 NTU) to less than 50 NTU in 20 hours. Bhardwaj and McLaughlin (*83*) used large-scale laboratory testing methods to evaluate active and passive PAM dosing systems in sediment basins. The passive treatment was conducted through the use of a PAM block, while the active treatment was implemented by injecting an aqueous PAM solution into the water pump. The study indicated that active PAM treatment provides the most effective treatment system compared to untreated or passively treated systems since it reduced Total Suspended Solids (TSS) by up to 80% at the outlet. The passive system provided a 65% turbidity reduction in an untreated discharge with a turbidity of 260 NTU. The active treatment introduces flocculants to captured stormwater through mechanical pumping and passive treatment introduces flocculants through rainfall and runoff (*86*).

Unique flocculant dosage and delivery techniques have been implemented around the world. For example, an innovative method was developed in New Zealand to dose sediment basins with the use of a rainfall-activated floc shed. This method includes three tanks: a header tank, a displacement tank, and a flocculant reservoir. Rainfall is collected on the roof of the floc shed and captured in the header tank which has three attached hoses at increasing depths. The header tank transfers this rainfall into the displacement tank through these hoses. The system introduces flocculant to a sediment basin according to the fill rate of the displacement tank and provides a controlled dosage based on rainfall intensity (*87*).

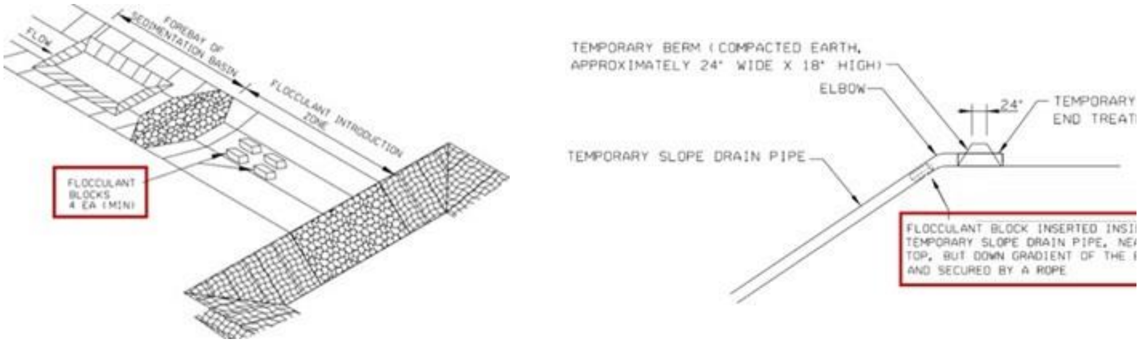
Flocculants have also been proven to work in other E&SC applications. Kang and McLaughlin (*88*) investigated the use of flocculants with geotextile dewatering bags. Dewatering bags are commonly used on construction sites to treat pumped sediment-laden water prior to off-site discharge. Their study implemented two different flocculant treatment systems: passive treatment with Chitosan and active treatment with PAM. The introduction of flocculants upstream of the dewatering bag provided a 97% turbidity reduction in the discharged water. Moreover, Lentz and Sojka (*89*) conducted field studies, which introduced PAM to irrigation water and showed positive results for reducing furrow erosion and increasing infiltration. The results showed that PAM provided a 57% sediment reduction in treated water.

The USEPA recommends the application of flocculants with proper dosage, guidance, and additional precautions to minimize pollution (*5*). State agencies are trying to integrate flocculants into their specifications and approved products in the U.S.; however, they are being very cautious while mentioning flocculants in their guidelines due to environmental concerns.

New York State Department of Environmental Conservation briefly mentions the use of PAM, aluminum sulfate (alum), and polyaluminum chloride for erosion control in E&SC specifications; however, the agency also states that flocculants cannot be used as standard E&SC applications (*90*). Although the use of flocculants has not been commonly adopted by the state agencies in the U.S., an interest in understanding and applying the principles of flocculation has emerged. The Minnesota Department of Transportation (MnDOT) funded a research project that investigated the safe dosage rates and application techniques for flocculants (*39*). ALDOT provides special drawings for the use of flocculants, which primarily rely on passive treatment through the use of powder, block, and sock forms of flocculants. These special drawings include flocculants upstream of sediment basins, within a channel, and inside of a slope drain as shown in Figure 2-3 (*91*, *92*). Based on the drawing presented in Figure 2-3(a), ALDOT requires a minimum application of 4 oz (113 g) granular flocculants on the top and upstream face of wattle ditch checks. Flocculant socks are being applied closer to the midsection downstream of wattle ditch checks in pairs as shown in Figure 2-3(b). ALDOT also utilizes flocculants in sediment basins by using a flocculant introduction zone between forebay and basin. Treatment with block form is being applied with a minimum of four blocks in the introduction zone as presented in Figure 2-3(c). Moreover, flocculant blocks are being inserted near the top in the temporary slope drains as described in Figure 2-3(d).



(a) ditch check powder application (b) ditch check sock application



(c) sediment basin block application (d) slope drain block application

Figure 2-3: ALDOT flocculant implementation (*93*)**.**

North Carolina Department of Transportation (NCDOT) maintains turbidity control by using anionic flocculants on wattle barriers, sediment basins, and rock ditch checks. The powder form is used on wattle barriers and re-application is required after every rainfall event that exceeds 0.5 inches (12.7 mm). The agency has developed its dosage guidance for PAM, which ranges between 1-5 mg/L within the approved products (*94*). Florida is one of the states that use flocculants for both erosion control and sediment control applications. The Florida Department of Transportation (FDOT) E&SC manual presents a case study about the use of PAM in a powder form on a severely damaged highway due to Hurricane Dennis (*95*). The treatment showed positive results and mitigated coastal erosion on U.S. Highway 98. Texas Department of Transportation (TxDOT) funded research that investigated the use of flocculants on construction sites for turbidity reduction by focusing on the performance testing of chemical agents (*96*, *97*). PAM and chitosan were specifically tested for turbidity reduction in construction runoff and nonionic PAM and chitosan showed promising results by decreasing turbidity levels of the synthetic runoff below 200 NTU according to the performed research (*97*). The California Department of Transportation (CalTrans) has preferred the use of chitosan, ferric chloride, and alum in past construction projects. Their stormwater manual suggests active treatment with flocculants on sediment basins for turbidity reduction. Moreover, PAM is used as a tackifier and soil stabilizer on Caltrans construction sites (*98*, *99*). Oregon DOT (ODOT) applies passive treatment with chitosan socks on treatment swales for sediment control. ODOT also implements active treatment using pumps, tanks, and filters; however, electricity outages and maintenance requirements may lead to issues with active treatment (*100*). Washington State DOT (WSDOT) allows the use of chitosan and anionic PAM within the limits of the DOT's dosage guidance; however, this agency suggests a pre-treatment facility prior to chitosan dosing (*101*).

2.3.1 COMMON FLOCCULANT IMPLEMENTATION CONCERNS

Although some state DOTs include flocculants in their standard specifications and manuals, it is common to see implementation, maintenance, and reapplication issues on construction sites. Figure 2-4 depicts examples of poorly implemented and maintained flocculant applications on construction sites. These photographs indicate a reduction in flocculant performance due to improper implementation and lack of maintenance. Figure 2-4(a) shows unmaintained flocculant blocks used in storm drain inlet application. The flocculant application in the figure is not effective due to the sediment layer along the sides of the blocks. Flocculants get activated through contact with the flow; however, the sediment layer interrupts the activation and reduces the flocculant dosage. Removing the sediment layer or replacing the flocculant blocks would improve the performance of flocculant implementation. Figure 2-4(b) illustrates another maintenance issue resulting in a poorly maintained flocculant application. Flocculants need to be protected from drying out in the sun and being covered in sediment for proper implementation. The dried sediment layer on the flocculant block solidifies the blocks and reduces the capacity to dose stormwater. Figure 2-4(c) shows the incorrect placement of a flocculant block downstream of a silt fence ditch check. The flocculant is placed on the right side of the weir, which is outside the range of the flow contact area. Placement of the block close to the mid-section of the weir would improve the effectiveness of the flocculant and provide sufficient flow contact. Figure 2-4(d) depicts the agitation and mixing failure of a flocculant application prior to discharge from a culvert. Flocculants require proper agitation and mixing through optimum dosage delivery mechanisms; however, in this picture, the blocks do not have enough distance or energy dissipaters between the flow contact point and discharge area to enhance agitation. Based on these presented examples, it can be observed that flocculant implementation on construction sites commonly experiences issues on maintenance, agitation, and placement.

(a) improper maintenance in storm drain inlet [A]

(b) lack of protection from sun and sediment [A]

(c) incorrect placement of flocculant

(d) lack of agitation and mixing [A]

Figure 2-4: Poorly Implemented Flocculant Applications.

Note: [A] photo credit Barry Fagan

2.4 TOXICOLOGY LIMITS

Flocculants enhance turbidity reduction in construction stormwater runoff, enhancing the performance of the temporary E&SC practices. Australia and New Zealand use flocculants throughout their stormwater BMPs. However, due to these chemicals having potential to be highly toxic if improperly used, the Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand heavily regulate and monitor flocculant treatment to minimize the possibility of contaminating downstream waterbodies, resulting in the loss of aquatic organisms (*102*). For example, the hemoglobin in fish gills has a negative charge, therefore cationic flocculants bind to fish hemoglobin, causing them to suffocate (*56*, *103–105*). Safety data sheets (SDS) require manufacturers to include toxicology limits for available products

(*106*). These toxicology limits are identified by acute toxicity tests that represent dose-response information in terms of lethal concentrations (LC_{50}) or lethal dose (LD_{50}) that kill 50% of experimental subjects (*107*). LC_{50} is used to refer to concentrations in air or water and is often reported in concentrations over volume. Alternatively, LD_{50} refers to an amount of a material that is given to the test subject all at once, often expressed in concentrations over body weight (*108*). The most common administration methods are by any route of entry, oral (given by mouth) or dermal (applied to the skin).

Acute toxicology limits are summarized in Table 2-2 for aquatic organism test subjects and Table 2-3 for mammal test subjects. Buczek et al. (*109*) evaluated five different anionic and one nonionic PAM products on early-life-stage freshwater muscles. LC_{50} values were determined after 24, 48, and 96-hours using concentrations two to three times greater than the recommended concentration for turbidity removal (<5 mg/L). The longer the time exposure, the lower the LC_{50}; therefore, values in Table 2-2 represent the 96-hour exposure time. Fort & Stover (*110*) focused on effects on freshwater fleas from cationic polymers, aluminum sulfate ($Al_2(SO_4)_3$), and ferric chloride ($FeCL_3$) and found acute toxicity at very low concentrations after 48-hours of exposure (*110*). Another study looking at freshwater fleas dealt with anionic PAM, cationic and nonionic polymers and found that after 96-hours, flocculants were a new class of micropollutants since they were found to be highly toxic to water organisms (*111*). Beim & Beim (*111*) goes on to emphasize the necessity for controlling for residual flocculants from discharging effluents and the need for identifying a Maximum Permissible Concentration (MPC) for flocculant types. Duggan et al. (*56*) evaluated zebrafish embryos over the course of 7-days with cationic PAM and cationic starch. They found no statistical difference from the number of deaths for embryos exposed to cationic starch compared to the embryo medium (control), thus encouraging switching cationic PAM with cationic starch.

Table 2-2. Summary of Aquatic Acute Toxicology Studies with Various Flocculants

Research Study	Flocculant Type	Aquatic Organism	Results (Lc_{50})
(*109*)	Anionic and Nonionic PAM	Freshwater Mussel (Lampsilis Cariosa)	≥ 127 mg/l
		Freshwater Mussel (Alasmidonta Raveneliana)	≥ 330 mg/l
		Freshwater Mussel (Mehalonaias Nervosa)	≥ 706 mg/l
(*110*)	Cationic Polymers	Freshwater Fleas (Ceriodaphnia Dubia)	< 0.025 mg/l
	$Al_2(SO_4)_3$	Freshwater Fleas (Ceriodaphnia Dubia)	< 0.025 mg/l
	$FeCl_3$	Freshwater Fleas (Ceriodaphnia Dubia)	< 0.025 mg/l
(*111*)	Anionic PAM	Freshwater Fleas (Daphnia Magna)	14.1 mg/l
		Planaria (Baicalobia Guttata)	> 100 mg/l
		Grmmaridae (Eulimnogammarus Verrucosus)	2,100 mg/l
		Minnows (Phoxinus Phoxinus L.)	> 1,000 mg/l
	Nonionic Polymer	Freshwater Fleas (Daphnia Magna)	≥ 13.2 mg/l
		Planaria (Baicalobia Guttata)	≥ 65 mg/l
		Grmmaridae (Eulimnogammarus Verrucosus)	≥ 2,050 mg/l
		Minnows (Phoxinus Phoxinus L.)	≥ 407 mg/l
	Cationic Polymers	Freshwater Fleas (Daphnia Magna)	≤ 2.1 mg/l
		Planaria (Baicalobia Guttata)	≥ 1.6 mg/l
		Grmmaridae (Eulimnogammarus Verrucosus)	≥ 70 mg/l
		Minnows (Phoxinus Phoxinus L.)	≥ 2.2 mg/l
(*56*)	Cationic PAM	Zebrafish Embryos (Danio Rerio)	17.4 mg/l
	Cationic Starch	Zebrafish Embryos (Danio Rerio)	3.8 mg/l

Rats and dogs were orally subjected to nonionic and anionic PAM to determine acute toxicity (Table 2-3). The maximum single dose that was accepted by the animals was 464 mg/kg (1023 mg/lb.) of body weight over the course of 90-days to which both animals showed no signs of toxicity but altered liver weights for female rats and depressed weight gain, increased organ weight, and abnormal stomach contents for dogs when fed concentrations above 10,000 mg/L (*112*). This 2-year study found no significant observed adverse effects for both rats and dogs that were fed diets containing 2,000 mg/L PAM. As PAM has larger molecules, it is not able to penetrate skin, thus making itself not significantly toxic (*42*). Acrylamide, however, is capable of penetrating skin and is far more lethal as it is classified as a neurotoxin (*113*). Erkekoglu & Baydar (*113*) emphasizes that low and high doses of acrylamide yield the same neurotoxic effects. Toxicity studies have evaluated effects of acrylamide on mice, rats, guinea pigs, rabbits, and cats via oral, dermal and/or injection. Results showed that there was no significant difference between exposed mammalian species (*42*, *113*, *114*). These results indicate that PAM is less of a concern than its acrylamide monomer (*42*, *47*, *111*, *115–118*). Although studies have indicated that PAM products contain residual acrylamide that ends up being released in the environment as the polymers untangle, the degradation of PAM leading to additional acrylamide release remains unclear from literature (*115*, *119–123*).

Table 2-3. Summary of Mammal Acute Toxicology Studies

Research Study	Toxicity Study	Flocculant Type	Test Organism	Results (LD_{50})
(*112*)	Oral	Nonionic PAM	Rats	was not reached with maximum dose of 464 mg/kg body weight
			Beagle Dogs	> 2,000 mg/L
		Anionic PAM	Rats	was not reached with maximum dose of 464 mg/kg body weight
			Beagle Dogs	> 2,000 mg/L
(*114*)	Oral	Acrylamide	Rats	≥ 107 mg/kg body weight
			Mice	≥ 107 mg/ kg body weight
			Guinea Pigs	≥ 150 mg/ kg body weight
	Dermal	Acrylamide	Rats	400 mg/ kg body weight
			Rabbits	1148 mg/ kg body weight
	Intravenous Injection	Acrylamide	Cats	85 mg/kg body weight
	Intraperitoneal Injection	Acrylamide	Rats	≥ 90 mg/kg body weight

Note: 1.0 mg/kg = 2.2 mg/lb.

The concern of polluting downstream waterbodies is a result from improper implementation of flocculants by overdosing. Manufacturers provide toxicology information as it differs between flocculant types. However, limited studies have been done on monitoring and detecting residual concentrations. Depending on the flocculant type, adding too much can have serious negative repercussions on the aquatic ecosystems (*38*) which would require a substantial amount of funding and effort to remedy. Kazaz et al. (*103*) breaks down the various flocculant types by their charge and drawbacks for individuals to easily see the difference between each type. Only natural starch, calcium sulfate (gypsum), and polyaluminum chloride (PAC) have not been reported as toxic in high concentrations (*84*, *122*). PAM has also been suspected to have carcinogenic properties because the single compound acrylamide, when present in high enough concentrations, is known to cause cancer (*38*, *124*, *125*). The U.S. Food and Drug Administration (FDA), USEPA, and the National Resources Conservation Service (NRCS) all regulate acrylamide concentrations in commercial PAM products (*126–129*). As polymer chains disentangle during flocculation, trapped acrylamide molecules in the chain can be released, which is the leading reason why U.S. drinking water treatment methods maintain

PAM concentrations below 1 mg/L (*32*, *123*, *128*, *130*). However, wastewater treatments are not held to the same stringent regulations.

Too much PAM can have negative impacts on not only the treatment efficiency, but also the environment (*38*, *131*, *132*). Wastewater treatments typically use high molecular weight PAM as it can serve several purposes other than flocculating particulates, however, an accidental spill can result in significant environmental challenges for surface and groundwater as associated acrylamide monomers become present through degradation process like chemical, mechanical, thermal, photolytic, and biological processes (*32*, *133*). Although many studies have evaluated the impacts of flocculant spills or overdosing, mitigation methods lack research. Research on naturally occurring microbes in sediment have been found to convert acrylamide into ammonia and acrylic acrid by-products that are nontoxic (*32*, *120*, *134–137*). These microbes were found to degrade acrylamide at a rate of 90 mg/L/day (*136*). Although microbes can be one method of mitigation, their ability to use up PAM has not been explored, nor is their mitigation rate fast enough to prevent a spill or overdose from expanding into other waterbodies. One discussed solution to mitigate a PAM spill or overdose quickly would be to add sediment to the contaminated area until the PAM is used up by forming flocs that can be later dredged out. However, literature was not found to support the idea of capturing PAM with sediment.

2.5 RESIDUAL CONCENTRATIONS OF FLOCCULANTS

The toxic impact of flocculants poses concerns in the construction stormwater management sector for potentially failing to meet environmental regulations in instances of improper implementation. For example, 35% of DOTs in the U.S. perceive flocculants as a potential risk to receiving waters and do not allow the use of flocculants (*103*). However, with effective application and dosage guidance, preventative measures can be taken to avoid environmental damage related to toxicity. Therefore, the measurement of residual concentrations in the discharge becomes a significant task that provides sufficient information for preventing overdoses and incidental environmental release into receiving waterbodies. Toxicology limits have been investigated in the literature and are usually provided by manufacturers for many types of flocculants; however, few studies exist for the detection of residual concentrations.

The studies for residual monitoring mainly focus on PAM and provide several methods for identifying residual concentrations. Sojka & Lentz (*127*) estimated PAM concentration in irrigation water by mixing kaolinite mineral standard with PAM-injected water sample and used a spectrophotometer to relate settling-related transmittance changes to PAM concentrations. Al Momani and Örmeci (*38*)also used a spectrophotometer for identifying PAM concentrations; however, by observing absorbance values and identifying a relationship between absorbance readings and known PAM concentrations. Kang et. al (*138*) developed a turbidimetric determination method for measuring PAM in soil extracts at low carbon content. Viscosity measurement was presented as an alternative method for PAM concentration detection in Jung, Jang, et al's (*139*) study. In addition to these studies on residual PAM concentrations, there are few studies conducted on detecting residual concentrations for other types of flocculants such as chitosan. Li et al. (*140*) and Miao et al. (*141*) focused on chitosan quantification by using acid hydrolysis and the high-performance liquid chromatography method. Moreover, spectrophotometry was also used as a method for chitosan determination (*142*).

2.6 FLOC CHARACTERISTICS AND POSSIBLE DETECTION METHODS

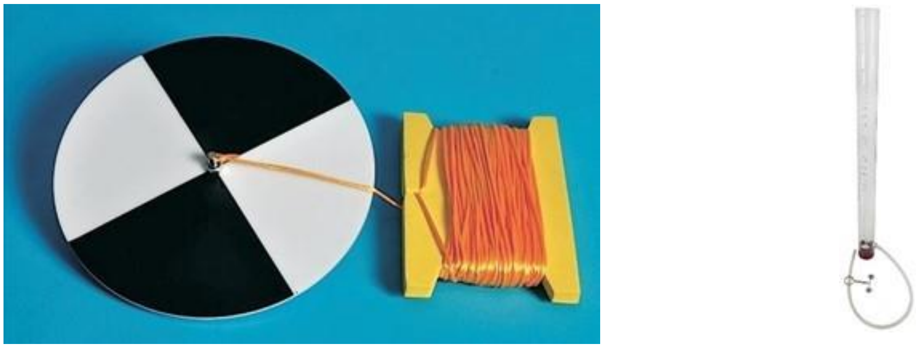
The performance of chemical treatments is commonly evaluated through ASTM standard jar testing procedures, which emphasizes the significance of observing floc characteristics. The standard ranges dosage in a six-place multiple stirrer machine and compare turbidity of the samples before and after flocculant introduction to evaluate the effectiveness of a treatment system. In addition to water quality observations, the standard also recommends observations on temperature, pH, floc formation, size floc, and settling velocity to evaluate floc characteristics after flocculation occurs (*143*).

There are several ways to detect polymers; however, reproducing consistent results in complex environments has been found challenging (*144*). Spectrophotometry has been used by Lentz et. al. (*89*) and Al Momani and Örmeci (*38*) to estimate residual concentrations of PAM. The method performed by Lentz et. al. (*89*) looked at combining kaolinite mineral standard with PAM and correlated transmittance variations of PAM concentrations with the settling. Light absorbance was measured and correlated with known PAM concentrations by Al Momani and Örmeci (*38*). PAM has also been evaluated using turbidimetry (*138*) and viscometry (*139*).

2.6.1 TURBIDITY

Turbidity is an optical characteristic of water that measures relative clarity based on the light attenuation of the water sample. Turbidity measurements are taken with the use of an instrument called a turbidimeter and are typically reported in NTU. Large NTU values occur in the presence of greater light attenuation, which indicates lower water clarity (*145*, *146*). Measuring visual clarity was initially used for the aesthetical aspect of the drinking water treatment. Turbidity measurements indicate a measure of the amount of sediment, microorganisms, organic and inorganic matter in water. However, these measurements do not detect the nature of the particles within the sample, which makes it a crude approach for water quality evaluations (*147*).

Turbidity can be measured with the use of Secchi disks, benchtop, portable turbidimeters, or turbidity tubes as illustrated in Figure 2-5Figure 2-5. Secchi disk is a black and white disk, shown in Figure 2-5(a), which measures visual water clarity by being lowered along a graduated line until the disk becomes non-visible. The Secchi depth presents a proportional relationship with the sum of light attenuation coefficients, which considers factors in the reflectance of the white face of the disk, water, and contrast threshold of the human eye (*148*).



(a) Secchi disk (*149*)

(b) turbidity tube (*150*)

(c) benchtop turbidimeter (*151*)

(d) portable turbidimeter (*152*)

Figure 2-5: Instruments for Turbidity Measurements.

Turbidity tubes, shown in Figure 2-5(b), often referred to as transparency tubes, also provide an economical approach for identifying the visual clarity of the water by lowering a clear tube in the water until the painted viewing disk disappears. The depth measurements are converted to NTU to quantify the clarity of the sample (*146*). However, human factors reduce the precision of results in Secchi disk and turbidity tube methods. On the other hand, turbidimeters offer more precise turbidity measurement results by measuring suspended particles with a light beam and a light detector installed perpendicular to the original beam. Turbidimeters are commercially available in benchtop and portable forms as presented in Figure 2-5(c) and (d). Benchtop turbidimeters can provide a wider range of turbidity measurements compared to portable turbidimeters (*151*, *152*). Both apparatuses were used in this research for evaluating turbidity reduction performance of flocculants.

Several other water quality parameters are broadly utilized for identifying suspended and dissolved solids in water such as Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and Suspended Sediment Concentration (SSC). TSS represents the total weight of non-filterable solids in a specific volume of water. On the other hand, TDS represents the total weight of solids that can pass a $7.9\text{x}10^{-5}$ in. (2 μm) filter and dissolve in a specific volume of water (*153*). SSC provides the total sediment mass in a water sample with the use of evaporation, filtration, or wet-sieving-filtration methods (*145*). However, in this research only turbidity was observed for evaluating the performance of flocculants per standardized jar testing requirements (*143*).

2.6.2 pH

The measure of acidity or basicity of water can be quantified through pH measurements, which compare the presence of hydrogen and hydroxyl ions in an aqueous solution. pH ranges between the values of 0 and 14 in a negative logarithmic function of the molar concentration of hydrogen ions, which classifies values smaller than seven as acidic and values larger than seven as basic aqueous media. In pH measurements, seven indicates the neutral condition. The pH of the water provides information on water solubility, nutrients, and biological availability (*154*). The distribution of species in aquatic habitats is impacted by the pH of the waterbodies. Sudden changes in pH outside of its range can cause a decrease in reproduction and growth. The optimal pH for most aquatic organisms to survive is ranging from 6.5 to 8; however, USEPA's water quality criteria ranges pH from 6.5 to 9 for freshwater (*155*).

The pH of an aqueous solution can be measured with the use of colorimetric or electrochemical methods. Colorimetric methods provide an economical and rapid measurement of pH with the use of indicator solutions and test strips as shown in Figure 2-6(a). However, electrochemical methods provide more accurate pH readings with the use of electrodes and a millivoltmeter, known as a pH meter. Benchtop and pocket versions of pH meters are commercially available. In this research, a pH meter in pocket form was used for pH and temperature measurements. pH meters, illustrated in Figure 2-6(b) and (c), require calibration with buffer solutions to maintain the accuracy of the pH reading as shown in Figure 2-6(d).

(a) pH test strips (*156*)		(b) benchtop pH meter (*157*)

(c) pocket pH meter (*158*)		(d) buffer solutions (*159*)

Figure 2-6: Methods for pH Measurements.

2.6.3 VISCOSITY

Since PAM is highly water-absorbent and will form a soft gel when hydrated, it influences the viscosity when diluted in water (*47*). Several researchers have explored these influencing characters to predict PAM viscosity for various applications better. Shin and Cho (*160*) developed an equation for viscosity of PAM solutions that accounts for shear-thinning of non-Newtonian characteristics and temperatures. This study used 1,000 mg/L of granular PAM diluted with distilled water to create a 0.1% solution PAM solution. A falling needle viscometer and Brookfield viscometer were used to quantify the viscosity of the samples. Results indicated that 1,000 mg/L PAM solution viscosity at shear rates below 0.001 s-1 was found to be most sensitive to temperatures between 20 to 60℃ (68 to 140℉), whereas shear rates between 10.0 to 200 s-1 were nearly uninfluenced by temperature.

Other studies reported that PAM degradation impacts viscosity as it is influenced by application techniques. Viscosity changes were measured using a granular PAM application method for agricultural use. Superfloc A836, that is commonly used irrigation furrow, and

Pristine, an inverse oil emulsion PAM, were selected for this study conducted by Bjorneberg (*161*). The study reported that for every 10 mg/L increase for both PAM solutions, it resulted in an approximate 5% increase in viscosity, relative to water. These viscosity measurements were performed using a no. 50 and a no. 150 Cannon-Fenske kinematic viscometer. This study continued to report that temperature, concentration, and flow conditions all significantly varied PAM viscosities and had been backed by Jung et al. (*139*). Even though Bjorneberg (*161*) evaluated flow conditions that have high shear stresses, the report details the significant 15 to 20% reduction in viscosity from one pass through a centrifugal pump was likely a result of broken PAM chains. Indicating the fragility of PAM molecules would need to be considered in any PAM viscosity analysis.

Time is another factor that can influence the viscosity of PAM solutions. Narkis and Rebhun (*162*) evaluated PAM viscosity over time with an aqueous emulsion and granular form PAM. The two respective flocculant types, Cyanamer P-26 and Cyanamer P-250, have different molecular weights, ranging from 2.24x105 and 1.95x106, respectively. Narkis and Rebhun (*162*) found that over 57 days, PAM undergoes an osculating process of disentanglement and re-entanglement of the polymer chains. This osculation eventually reaches equilibrium over time, but higher concentrations and molecular weights lead to more time required to reach equilibrium. Narkis and Rebhun (*162*) found that viscosity is based on the entanglement of PAM molecules. Therefore, viscosity readings will continue to change for a solution until equilibrium is achieved.

2.6.4 FLOC FORMATION AND SIZE

Visual monitoring of flocculants during mixing procedures provides information on floc formation, break-up, and regrowth. Flocs form when required mixing for activation is achieved. Flocs have a limited capacity re-grow under the reduced mixing rate. Floc breakage is a partially reversible mechanism that impacts floc formation. Each flocculant type has a different floc formation behavior due to its different chemical content and soil-dependent characteristics. For instance, Polyaluminum Chloride (PAC) forms larger flocs compared to alum (*163*). Figure 2-7 illustrates an example for floc formation after sufficient shear rate is achieved through mixing.

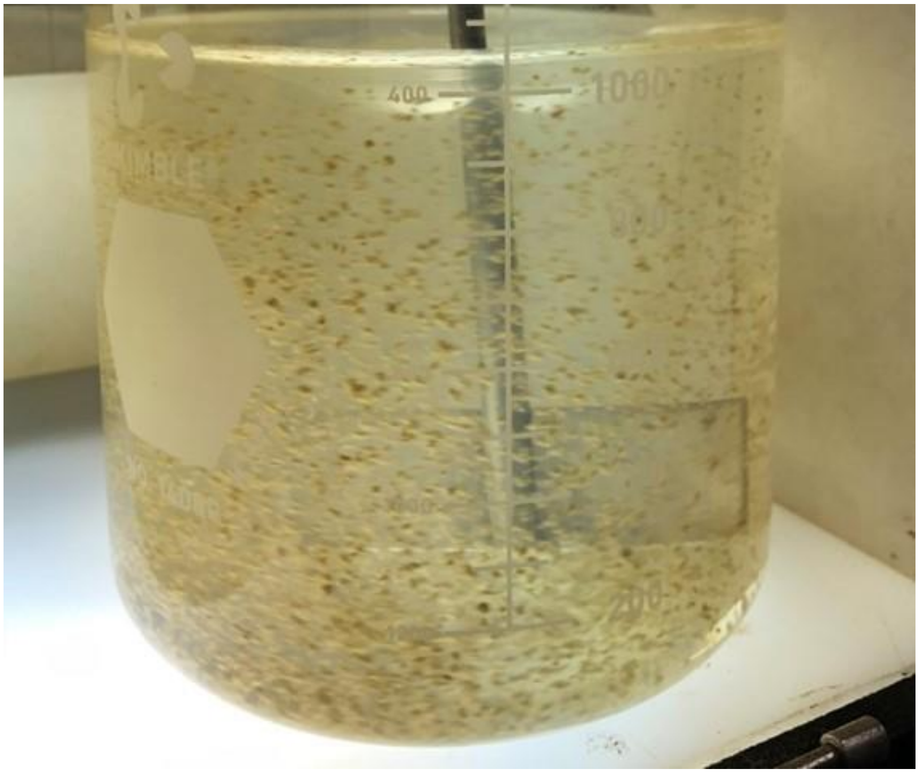


Figure 2-7: Floc Formation.

Floc formation can be simulated through computer-based applications by calculating the volume density of particles in formed flocs (*164*). In this research, floc formation was visually observed by evaluating the time that it takes for floc formation and the size of flocs per the requirements of standard jar testing (*143*). Floc size can be easily determined at a fixed measuring time based on a standardized reference chart presented in Figure 2-8. The chart classifies the size of the flocs in seven categories from the smallest (A) to the largest (G) floc size (*165*).

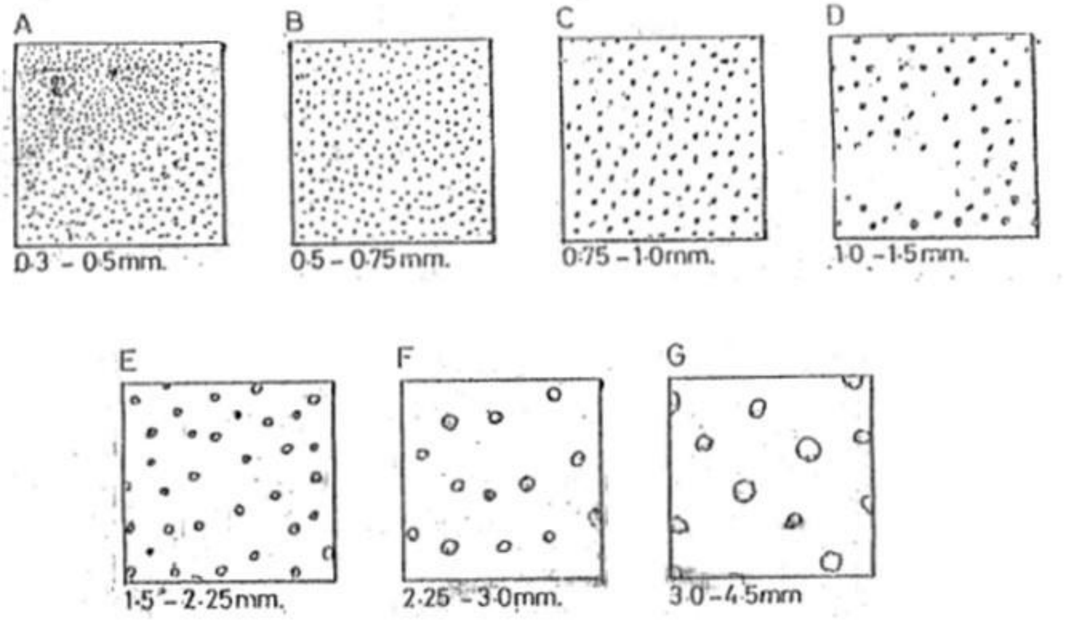


Figure 2-8: Floc Size Standard Reference Chart (*165*).

2.6.5 SETTLING VELOCITY

Settling velocity testing is typically applied in metallurgical studies on sludge settling for estimating the thickening capacity of flocculated suspensions (*166*). This method has also been used in oceanography for estimating the porosity of large suspended particles (*167*). The principle behind settling velocity observations comes from Stoke's Law that emphasizes the resisting impact of the drag force towards gravitational forces during the settling of a fine-sized spherical particle through a fluid media (*168*, *169*). The settling rate of a small spherical particle in a Newtonian fluid can be calculated by the use of this law (*168*), as expressed in Eq. 2-1.

$$U_{stokes} = -\frac{2gr^2(\rho_2 - \rho_1)}{9\mu_1} \quad \textbf{Eq. 2-1}$$

Where,

U = terminal settling velocity (m/s [ft/s])

ρ_2 = density of the small-sized spherical particle (kg/m^3 [slugs/ft^3])

ρ_1 = density of the fluid (kg/m^3 [lb/ft^3])

μ_1 = fluid viscosity (N s m^{-2} [lbf s ft^{-2}])

r = particle radius (m [ft])

g = gravitational acceleration (m s^{-2} [ft s^{-2}])

CHAPTER 3
STATE-OF-THE-PRACTICE

3.1 INTRODUCTION

Following the literature review, gaps of knowledge with how flocculants are implemented across the U.S. were investigated by developing a state-of-the-practice survey. State-of-the-practice surveys provide valuable input for research by outlining commonly used means and methods by practitioners. This chapter of the report focuses on the state-of-the-practice survey conducted for [1] understanding the perspective of U.S. Departments of Transportation (DOTs) on using flocculants for construction stormwater treatment and [2] identifying the needs of DOTs for implementing flocculants on construction sites. Survey development procedures, distribution methods, and discussion of results are presented in the subsections of this chapter.

The survey study provided a comprehensive review of flocculants and their use across DOTs for construction stormwater treatment. The survey questions prepared for DOTs were developed based on the literature review presented in Chapter Two, which provided information on the flocculation fundamentals, commonly used flocculant types, toxicology limits, residual concentration monitoring, and recent stormwater research studies. Survey findings guided further steps of this research for improving flocculant usage for construction stormwater treatment with proper dosage and application methods.

3.2 SURVEY DEVELOPMENT AND DISTRIBUTION

The state-of-the-practice review primarily focused on the literature review to build sufficient background for preparing a questionnaire survey. Qualtrics XM ™ survey software was used to create an online survey. Skip logic was incorporated into follow-up questions depending on the answers of the participants. The survey consisted of three multiple-choice questions for state agencies, which indicated they do not use flocculants, and up to ten multiple-choice questions for state agencies, which allow the use of flocculants. Open-ended questions were not included in the questionnaire to prepare a time-efficient survey for the target audience. The questionnaire focused on identifying which DOTs allow the use of flocculants for construction stormwater management. Understanding the background of the hesitation for using flocculants was an important factor that may potentially motivate further research studies. Therefore, respondents that indicated flocculant use was not permitted by their DOT were asked a follow-up question to devolve reasons for not using flocculants.

DOTs that allow the use of flocculants received detailed questions about their purpose to use these chemical agents. The literature review provided information on various types and forms of flocculants. Thus, the questionnaire also investigated the most common types and forms of flocculants that are preferred by the state agencies. Dosage is a significant factor for flocculant applications. Flocculants may be hazardous for the environment when overdosed. The survey also addressed a question to identify if state agencies are providing standard guidance on dosage and application rates or not. The perspective of agencies on residual monitoring in downstream receiving waters and including flocculant products in their approved product list was also questioned by the survey.

The target audience of this survey was DOTs in the U.S.; hence, the lead construction stormwater / environmental professionals of each state agency were identified. The questionnaire was published online and distributed through an e-mail invitation that included an anonymous link created by the Qualtrics XM^{TM} software. The survey was distributed in June 2020 to 51 DOTs in the U.S., and it was kept open through the end of July 2020. Three distribution cycles were needed as reminders and contact information corrections. However, altogether, 14 state agencies did not participate in the survey. E&SC manuals and specifications for these state agencies were manually analyzed and compiled with the survey data to gather appropriate data and complete the study. Several phone interviews were held with DOTs, which agreed to complete the survey over the phone. ArcMap^{TM} 10.5.1 geospatial processing software was used to compile, organize, and display results.

3.3 SURVEY RESULTS AND DISCUSSION

The survey was distributed to 51 DOTs in the U.S. Among these agencies, 37 of them responded to the survey invitation and participated in the questionnaire. The 14 potential respondents that did not respond to the survey invitation included Alaska, Colorado, Connecticut, District of Columbia, Hawaii, Illinois, Kentucky, Massachusetts, Michigan, Montana, New Jersey, New York, Pennsylvania, Rhode Island, and West Virginia. Data for these non-participating DOTs were only included in the results shown in Figure 3-1 based on information gathered from their E&SC manuals and specifications. Among the non-participating potential respondents, only Alaska, Connecticut, District of Columbia, Illinois, New York, Rhode Island, and West Virginia state agencies mentioned the use of flocculants in their E&SC manuals (*90*, *170–175*). However, the survey results which will be discussed further in this section did not include data for these. Results of the survey data showed that 13 state agencies are using flocculants and 24 state agencies are not.

Figure 3-1: Map of Flocculant Usage of the State Agencies in the U.S.

The addition of the non-participating states increased these numbers to 20 and 31, respectively. Figure 3-1 illustrates the flocculant usage of state agencies in the U.S. Light blue colored states represent the ones that avoid using flocculants and dark blue colored states represent the ones that prefer using flocculants in construction stormwater treatment. According to the pie chart in Figure 3-1, it can be observed that only 39% of the states are using flocculants on active construction sites to treat stormwater runoff. The data shows that flocculants are commonly used on the southeast and west coasts. Only a few DOTs outside of these regions use flocculants on construction sites.

Currently, 31 state agencies do not allow the use of flocculants for construction stormwater management. The reasons behind not using flocculants were investigated by the questionnaire. Figure 3-2 presents these reasons for 24 DOTs, which participated in the survey and confirmed that flocculants are not adopted by their agency. The results emphasized that the majority of DOTs (50%) perceive current E&SC practices as sufficient in treating stormwater. Another major reason for not allowing flocculant usage is toxicity concerns (35%). Regulatory restrictions and lack of guidance for dosage are also other factors that have a negative impact on flocculant usage. Maintenance requirements are not a concern for agencies according to the survey results displayed in Figure 3-2.

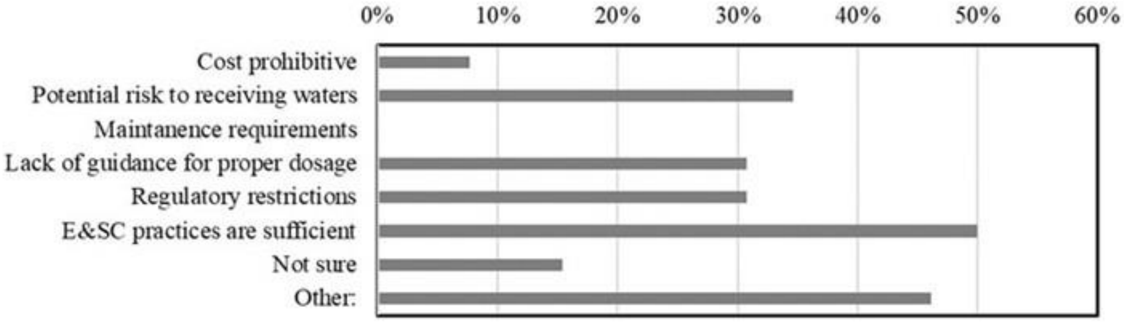


Figure 3-2: Reasons of State Agencies for Not Using Flocculants.

State agencies provided additional reasons for not using flocculants as a side note. According to some responses, implementing new products and methods has a slow procedure unless there is regulatory enforcement that requires their use. Moreover, another participating DOT stated that typically the state agencies evaluate new products of practices for erosion and sediment control through their research division; however, there are not enough research study results that provide sufficient information to move forward in utilizing flocculants.

The survey results highlighted sediment control as the main application for using flocculants. Among the agencies, which adopt flocculants into their construction stormwater management procedures, eight of them are utilizing flocculants just for promoting settling out of sediment in collected stormwater runoff and four of them are using them for both erosion and sediment control applications. One of the participants mentioned that they are using flocculants for very large sediment settle out needs or underground storm pipe drill boring in their agency. The most commonly used flocculant types among the DOTs are anionic PAM (62%), chitosan (38%), and polyaluminum chloride (PAC) (23%), respectively as shown in Figure 3-3.

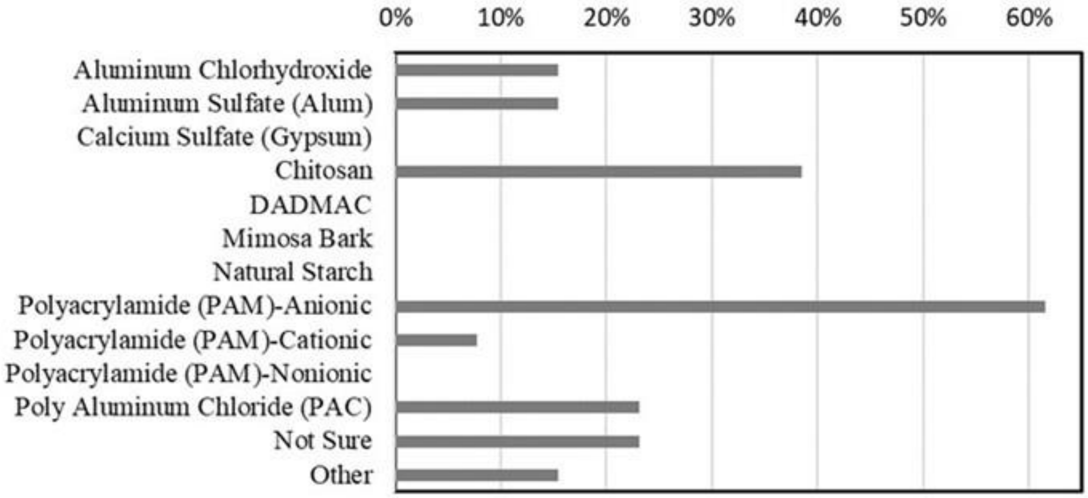


Figure 3-3: Flocculant Types That Are Preferred by the State Agencies.

Regulatory restrictions, non-toxic properties, and availability of the products are the reasons for DOTs to prefer these specific types of chemical agents. These products are commonly used in powder/granular and block forms by the DOTs. Survey data showed that 77% of DOTs are using powder/granular form and 68% of them are using block form. State agencies also use socks (46%) and emulsions (23%).

The questionnaire results identified the demand for developing regulations for dosage and application rates. Responses showed 54% of the state agencies rely on manufacturer guidance and only 15% of the agencies have regulations for dosage. Dosage and application rates are highly critical for preventing overdoses and taking precautions to not pollute receiving waters. Manufacturer guidance might be a temporary solution to implement the dosage requirements of the product. However, the DOTs would highly benefit from developing their own dosage and application regulations since manufacturer guidance might not be sufficient depending on differences in soil characteristics and climate for each state. In addition, residual testing is another substantial factor in protecting receiving waters from the toxic effect of flocculants. Residual concentrations can be used as a control mechanism by the agencies to ensure that they are not polluting the downstream receiving waters with high concentrations of chemical agents. However, the survey results showed that only 23% of the DOTs require monitoring residual flocculant in downstream receiving waters. Caltrans, FDOT, and SD DOT require the monitoring of residual flocculants prior to off-site discharge; however, these agencies do not specify a certain residual monitoring methodology in their E&SC manuals and specifications.

DOT-approved products or qualified product lists are detailed catalogs that provide preapproved manufacturers and products. The survey results presented that 54% of agencies do not include flocculant products and manufacturers on their approved product lists even if they actively use flocculants on construction sites. Based on this result, it can be interpreted that the majority of DOTs should start incorporating flocculants into their approved product list to have standardized product preferences based on their specific needs. This would potentially support the adoption of standard dosage and application rate guidelines based upon allowable products for each DOT.

3.4 SUMMARY

Traditional E&SC practices are often insufficient for capturing sediment-laden runoff on construction sites. Construction stormwater management applications have been benefiting from flocculants, which significantly improve the performance of E&SC practices with the flocculation mechanism that forms an environment for particles to bind together and settle out of suspension. This study conducted a comprehensive assessment of the use of flocculants across DOTs in the U.S.

The main goal of the study was to understand the perspective of state agencies on flocculant usage for construction stormwater management. Thus, an online survey, which consisted of detailed questions based on the literature review, was distributed to DOTs in the U.S. The survey had participants from 37 DOTs. Non-participating state agencies created a limitation for providing a complete national understanding of the state of the practice. However, to capture this data as much as possible, these state agencies were compiled together with the survey data for displaying flocculant usage in the U.S. by reviewing the E&SC manuals of these agencies. The results indicated that the majority of the DOTs, 61%, are not using flocculants. The reasons for not using flocculants are sufficient E&SC practices and the potential risk of polluting downstream waterbodies. Most of the DOTs, 54%, which allow flocculant usage, rely on manufacturer guidance. Some flocculants require soil sampling for site-specific formulation and manufacturer guidance might be insufficient due to changing soil characteristics. Thus, designers or permittees might potentially hesitate to use flocculants on construction sites. Furthermore, 31% of DOTs do not use flocculants due to regulatory restrictions on flocculant usage. States that must achieve a numeric turbidity limit are more inclined to use flocculant, to ensure the appropriate level of treatment. Conversely, some state agencies are deterred from applying flocculants due to regulative restrictions, such as monitoring effluent for flocculant concentrations. Such requirements add cost and effort to the erosion and sediment control plans.

CHAPTER 4
RESIDUAL DETECTION METHODS

4.1 INTRODUCTION

Optimum dosage requirements of flocculants can be identified through bench-scale evaluation of products in a controlled laboratory environment. The bench-scale evaluation phase of this research provided optimum dosage guidance by characterizing the behavior of various flocculant products across different Alabama soils and developed a residual concentration testing method that is suitable for estimating residual concentration values on various flocculant types. This chapter of the report emphasizes bench-scale evaluations of flocculants by discussing methods applied for soil assessment, match tests, dosage experiments, and detection of residual concentrations.

Bench-scale experiments were conducted in the Stormwater Laboratory at Auburn University Department of Civil and Environmental Engineering. In total, 14 different flocculant products were evaluated for performance, optimum dosage, and residual concentration detection. Based on the results of the bench-scale evaluations, a product selection tool: Floc Spread was developed for guiding practitioners on proper dosage, product selection, and cost estimation. The objective of this spreadsheet-based tool was to assist in the flocculant selection process by providing designers the ability to select an appropriate product based on soil-dependent performance change and apply proper dosage.

The findings of this research are expected to fill the knowledge gap in optimum dosage requirements of flocculants and residual concentration monitoring in construction stormwater management. Moreover. the results of this study aim to guide practitioners on product selection and proper dosage of flocculants.

4.2 METHODOLOGY

This section describes the methods and experimental procedures of the various detection methods and bench-scale evaluation phase of this research. Due to the low concentration range of PAM that was targeted for large-scale detection, multiple detection methods were explored as possible alternative methods. All flocculant detection methods were used to estimate concentrations above and below 5.0 mg/L of anionic granular H30 PAM flocculant from Manufacturer A (Product A-G) and anionic block H30 PAM flocculant from Manufacturer A (Product A-B). This target concentration was selected as it was the manufacturer's recommended dosage for this product. The following sections describes how the viscosity and particle charge of water was explored as a possible alternative to the settling velocity method that was used for large-scale testing using two different viscosity detection methods and one particle charge analyzer.

The bench-scale testing phase consisted of four main testing methodologies; soil assessment, match test, dosage experiments, and detection of residual concentrations, which are discussed in detail in the following sections. Bench-scale experiments primarily focused on providing guidance on the use of flocculants through soil assessment, match tests, and dosage experiments by testing the performance of 14 different flocculant products on 15 different soil samples collected from named map units across Alabama. Finally, researchers investigated the detection of residual concentrations by observing the relationship between settling velocity and concentration values in the bench-scale testing phase of this research.

4.3 DETECTION METHODS

There are several ways to detect polymers; however, reproducing consistent results in complex environments has been found challenging (*144*). Spectrophotometry has been used by Lentz et. al. (*89*) and Al Momani and Örmeci (*38*) to estimate residual concentrations of PAM. The method performed by Lentz et. al. (*89*) looked at combining kaolinite mineral standard with PAM and correlated transmittance variations of PAM concentrations with the settling. Light absorbance was measured and correlated with known PAM concentrations by Al Momani and Örmeci (*38*). PAM has also been evaluated using turbidimetry (*138*) and viscometry (*139*).

4.4 VISCOSITY

Finding detection methods that are portable, fast, and easy to perform while likely containing sediment to some degree within the sample poses as a challenge. As mentioned in the literature review previously, the viscosity of PAM is highly influenced based on the temperature, concentration, flow, and system conditions, and how long the PAM agent has been diluted. However, as many studies that evaluate viscosity look at solutions without sediment, this study focused on the ability to measure viscosity from field samples to determine if concentrations below 20 mg/L were capable of being quantified. If the desired range was capable of being quantified, further evaluations would investigate accounting for the known factors that can influence sample variability. A Cannon-Fenske Routine Viscometer and Brookfield Digital Viscometer two detection methods that were evaluated and are detailed in the following sections.

4.4.1 CANNON-FENSKE ROUTINE VISCOMETER

A Cannon-Fenske Routine Viscometer, or Cannon-Fenske tube, shown in Figure 4-1, is a glass “U” liked shaped tube used to measure the kinematic viscosity of a transparent Newtonian fluid

(*176*) by measuring the time it takes for a fluid to travel from point A to point B, known as the efflux time. This method was tested due to its low cost and simplicity of use, making it an ideal possibility for companies and state DOTs to invest and adopt the method. Cannon-Fenske tubes are hand-made glass tubes which differ by size depending on the volume and expected viscosity range that is being measured.

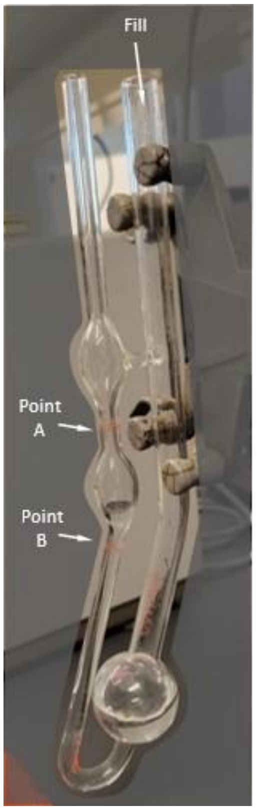


Figure 4-1*. Cannon-Fenske Tube*

4.4.1.1 Cannon-Fenske Routine Viscometer Testing Methodology

For this evaluation, two size 50 Cannon-Fenske tubes (notated as Tube 1 and Tube 2), with a viscosity range of 0.8 to 4.0 mm^2/s, were used to measure the viscosity of samples with Product A-G concentrations ranging from 1.0 mg/L to 20 mg/L, with the control being 0 mg/L of flocculant.

Cannon-Fenske tubes were held up with a burette clamp and placed so the upper half of the tubes were level and vertical. City of Auburn, AL tap water was used for these experiments. The test was conducted by creating a stock solution of each desired Product A-G concentration. For each test, the pH and temperature of the sample was recorded, then 0.33 fl oz (10 mL) of the evaluated solution was transferred into the Cannon-Fenske tube. Solutions are poured into the larger, back tube, labeled "Fill" in Figure 4-1, and siphoned up the front, smaller tube, until the solution head is above "Point A." Efflux time started when the solution passed “Point A,” and stops when it passed “Point B.” This process was repeated three times per sample concentration. Between samples, the Cannon-Fenske tube was flushed with deionized water.

When all data collection was completed, each tube was flushed with deionized water again and placed in a base bath for a minimum of 24 hours to ensure the vial was completely free of any possible contaminants. The tubes were rinsed well with deionized water once more to remove the base bath solution. Tubes were then flushed with a 90% Ethanol solution and blown dry with compressed air to ensure no residual fluids were left in the tube before storage.

4.4.1.2 Cannon-Fenske Routine Viscometer Results and Discussion

Both Cannon-Fenske tubes were tested using the same stock solution. The average measured values for this test are shown in Table 4-1.

Table 4-1. Cannon-Fenske Tube Measured Values

			Avg. Efflux Time, sec.	
Concentration, mg/L	**pH**	**Temperature, ℉ (℃)**	**Tube 1**	**Tube 2**
0.0	7.2	72.6 (22.6)	243.3	264.8
1.0	7.2	75.7 (24.3)	245.8	264.8
2.0	7.2	75.7 (24.3)	245.7	269.0
5.0	7.2	75.0 (23.9)	244.3	268.0
10.0	7.2	75.0 (23.9)	245.3	271.3
20.0	7.2	75.4 (24.1)	266.3	412.7

All data points from Table 4-1 are plotted in Figure 4-2.

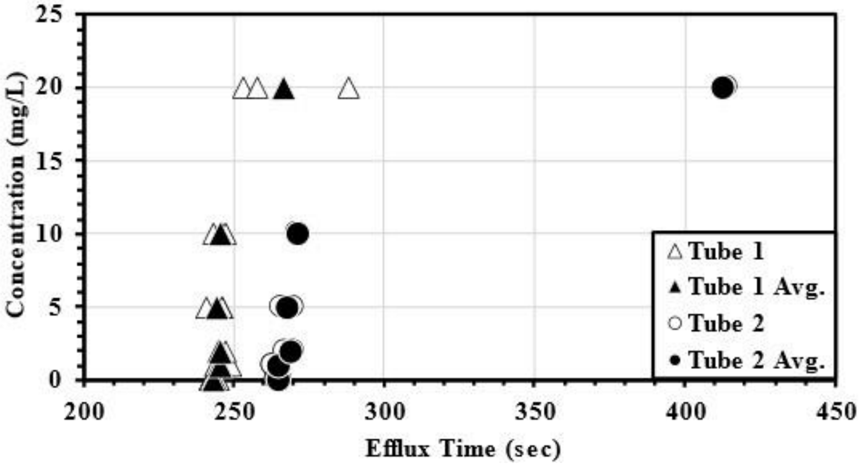


Figure 4-2. Cannon-Fenske Tube Test Results

Figure 4-3 displays the percent change plot where the average efflux time for each concentration is compared to the tap water average efflux time. This plot makes it easier to visualize how similar the low-concentration efflux times are to tap water with no PAM.

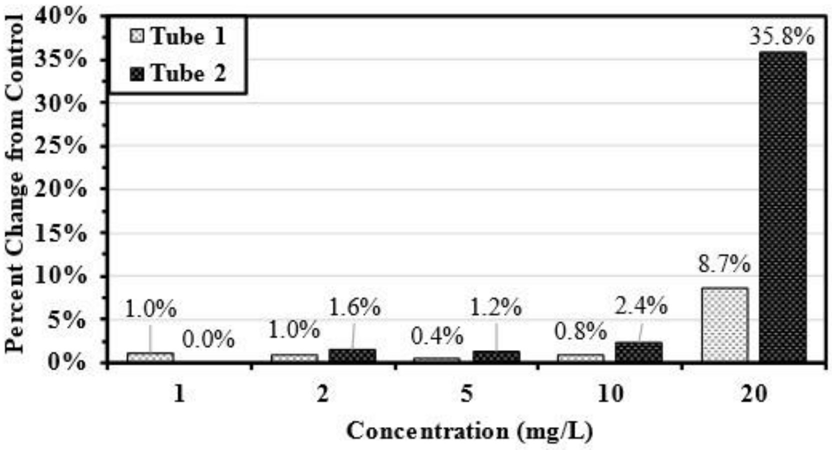


Figure 4-3. Cannon-Fenske Tube Percent Change Plot

A categorical MLR was also run to determine what concentrations significantly differed from the control (tap water with no PAM) between the two Cannon-Fenske tubes. Results for both tubes produced results that could measure change in concentrations above 5 mg/L by the sample's viscosity. Tube 2 results reported a significant change in efflux time with concentrations of 10 mg/L and 20 mg/L, while Tube 1 only had a significant change in efflux time with 20 mg/L. Indicating that this method is not sensitive enough to measure the manufacturer's recommended dosage concentrations and would only provide insight if increased dosing is already occurring. Additionally, the difference in readings between Tube 1 and Tube 2 suggests that sensitivity results may vary with different Cannon-Fenske tubes. Note that this test used the second smallest tube size of 50 with a viscosity range of 0.8 to 4.0 mm^2/s. The smallest Cannon-Fenske tube size is 25 with a viscosity range of 0.5 to 2.0 mm^2/s. So, there is a possibility that the size 25 tube would be capable of measuring changes in viscosity at lower concentrations. However, it is important to note that Cannon-Fenske tubes require samples to be purified of all any possible solids that may clog the tubing. Since this method was evaluated for the possibility of large-scale applications, field samples would likely contain small amounts of sediment that would need to be completely removed before placing in the Cannon-Fenske tube. Thus, adding an additional source of possible error in readings and an additional challenge to mitigate in the field.

Table 4-2. Cannon-Fenske Tube Multiple Linear Regression Analysis

	Tube 1		Tube 2	
Variables	**Coefficient**	**p-value**[a]	**Coefficient**	**p-value**[a]
Intercept	243.250	<0.001	264.750	<0.001
1.0 mg/L	2.750	0.647	-0.750	0.756
2.0 mg/L	2.417	0.687	4.250	0.095
5.0 mg/L	1.083	0.856	3.250	0.192
10.0 mg/L	2.083	0.728	6.583	0.015
20.0 mg/L	23.083	0.002	147.917	<0.001
R^2	0.608		0.998	

[a]Comparison to effects of base at 95% confidence interval and p-value <0.05

Cannon-Fenske Routine viscometers measure a solution's efflux time between two points, which needs converted to into units that describe viscosity. For this experiment, values were not converted into viscosity units as the results did not produce significant results within the desired range of 5 mg/L and the calibration certificates for the Cannon-Fenske Routine viscometers used were not located, which contain necessary information to conduct constant calculations. The process to convert efflux time results into viscosity is done with a viscometer constant. This constantly changes with each temperature. Cannon-Fenske Routine viscometer's calibration must be done using 0.33 fl oz (10 mL) of a standard at 77℉ (25℃) (*177*). Using the ASTM standard for kinematic viscometers (*178*), Eq. 4-1 can be used to determine the viscometer constant at other temperatures.

$$C = C_0\left(1 - \left[\frac{4V(\rho_f - \rho_t)}{\pi d^2 h \rho_t (T_t - T_f)}\right][T_t - T_f]\right) \quad \text{Eq. 4-1}$$

Where C is the constant of the viscometer being calibrated; C_0 is the constant of the calibrated viscometer; V is the volume of charge, cm^3, given value on the Cannon calibration certificate for that particular Cannon-Fenske Routine viscometer; ρ_f is the fill density, g/cm^3; ρ_t is the test density, g/cm^3; d is the average diameter of the meniscus in the upper reservoir, cm, given value on the Cannon calibration certificate for that particular Cannon-Fenske Routine viscometer; h is the average driving head, cm, given value on the Cannon calibration certificate for that particular Cannon-Fenske Routine viscometer; T_t is the test temperature, ℃; and T_f is the fill temperature, ℃. Since flocculants differ in density by type and manufacturer, it is recommended to use a pycnometer to determine the density of the solution at each concentration for accurate calculations (*179*).

Eq. 4-2 would be used to convert the measured efflux time to kinematic viscosity (*178*).

$$v = tC \quad \text{Eq. 4-2}$$

Where v is the kinematic viscosity is in mm^2/s; t is the efflux time, sec; C is the viscometer constant.

Eq. 4-3 would be the last step used to convert the kinematic viscosity to viscosity (*177*).

$$\mu = vd \qquad \text{Eq. 4-3}$$

Where μ is the viscosity, cP; $nu{:}\,v$ is the kinematic viscosity is in mm^2/s; and d is the density, g/mL.

4.4.2 BROOKFIELD DIGITAL VISCOMETER

The second instrument that was tested for measuring viscosity was the Brookfield Digital Viscometer (Figure 4-4). It is a type of rotational viscometer where it measures the viscosity of a fluid by measuring the torque required to rotate a spindle at a constant speed inside a fluid (*180*). Users can select the desired spindle size, depending on the expected viscosity range of the fluid. The selected spindle is attached to a rotating shaft and lowered into a fluid. When the spindle reaches a constant speed, the percent torque value is displayed. Newer machines have the capability to calculate and display the viscosity units, however, the machine used for this testing only displayed the percent torque, which was then converted into viscosity units. This method was tested due to its low cost and simplicity of use, making it an ideal possibility for companies and state DOTs to invest and adopt the method.

Figure 4-4. Brookfield Digital Viscometer Testing Apparatus

4.4.2.1 Brookfield Digital Viscometer Testing Methodology

For this study, a #2 spindle was used on the Brookfield Digital Viscometer, model RVTD. Samples with Product A-G concentrations ranging from 1.0 mg/L to 20 mg/L, with the control being 0 mg/L of flocculant were evaluated. One liter stock solutions of each sample were created using tap water from the City of Auburn, Alabama. Each stock solution was then poured into three 6.76 fl oz (200 mL) beakers for three replicates of each measured concentration. The #2 spindle was then placed at a constant depth for each sample. Next, the machine was switched on, and the percent torque reading was set to zero. The motor was then switched on to allow the spindle to begin spinning. The rotational speed and spindle used for each sample was recorded. After about 30 seconds, the percent torque reading would stabilize, and the value was recorded. Once the data for the sample was collected, the spindle was removed and rinsed with deionized water and wiped clean with a one percent Alconox® Liquinox cleaning solution. Operating manuals contain pertinent information regarding how to convert the percent torque reading to viscosity, depending on the viscometer model, spindle shape and size used, and rotational speed chosen. All tests in this study were conducted using a RV series viscometer, #2 spindle, at 50 rpm, which gives a constant factor of 8 used in the calculations (*181*).

Eq. 4-4 is the formula needed to convert the percent torque output value to viscosity,

$$\mu = \%torque * Factor \qquad \text{Eq. 4-4}$$

where μ is the viscosity, cP; $\%torque$ is the output value given by the viscometer; and $Factor$ is the factor constant found in the operating manual that is dependent on the spindle size and rotational speed used.

4.4.2.2 Brookfield Digital Viscometer Results and Discussion

The viscometer readings fluctuated between 0.9 and 1.0% torque, which translated to 7.2 to 8.0 cP. When the results were averaged, samples that fluctuated between those two values can be found with values of 7.7 cP. Table 4-3 displays the average of three readings for each concentration.

Table 4-3. Brookfield Digital Viscometer Measured Values

Concentration, mg/L	pH	Temperature, ℉ (℃)	% Torque	Viscosity, cP
0.0	7.2	72.6 (22.6)	0.9	7.2
1.0	7.2	75.7 (24.3)	1.0	8.0
2.0	7.2	75.7 (24.3)	1.0	7.7
5.0	7.2	75.0 (23.9)	1.0	7.7
10.0	7.2	75.0 (23.9)	1.0	8.0
20.0	7.2	75.4 (24.1)	1.0	7.7

Figure 4-5 plots all data points with the averaged data from Table 4-3. Making it easier to see which concentrations produced consistent readings.

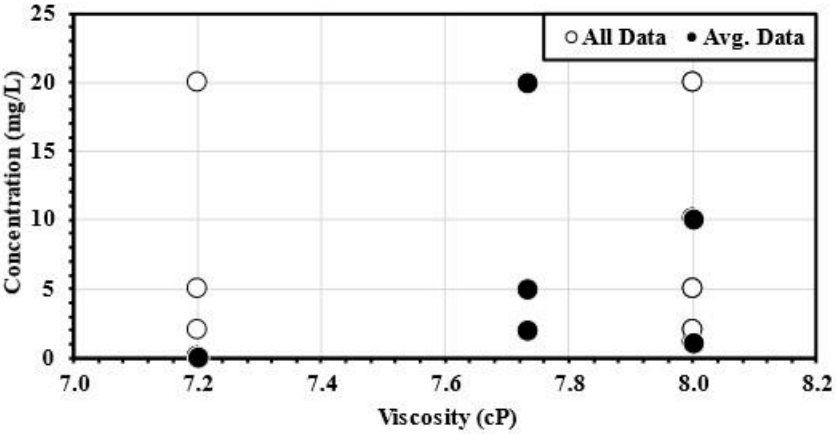


Figure 4-5. Brookfield Digital Viscometer Test Results

Figure 4-6 displays a percent change plot where each concentration of PAM tested is compared to the control (tap water with no PAM).

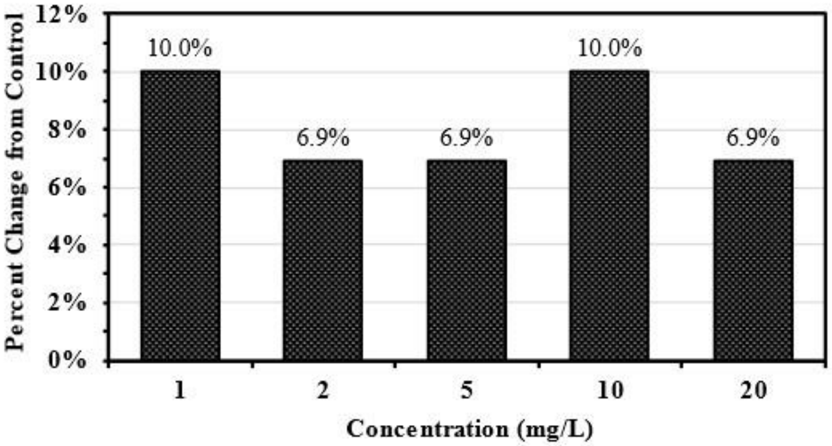


Figure 4-6. Brookfield Digital Viscometer Percent Change Plot

The concentrations with a 10% change significantly differed from the control when the results were run through a categorical MLR (Table 4-4). Indicating that only the samples which produced consistent readings through all three replicates were found to be significant. However, these concentrations were 1.0 mg/L and 10 mg/L. Since the viscometer used was not capable of producing readings between 0.9 and 1.0% torque, and the values between those concentrations were found to produce inconsistent results between the three replications, it suggests the significant results were produced more by chance, rather than by the characteristics of the fluids tested. With addition to that, the manual states that values under 10% torque are considered inaccurate as the machine has a ± 1% error. Since all readings were well below the 10% torque threshold, it confirms that the viscosity of PAM flocculant solutions at concentrations below 20 mg/L are not capable of being measured using the Brookfield Digital Viscometer.

Table 4-4. Brookfield Digital Viscometer Multiple Linear Regression Analysis

Variables	Coefficient	p-value[a]
Intercept	7.200	<0.001
1.0 mg/L	0.800	0.011
2.0 mg/L	0.533	0.069
5.0 mg/L	0.533	0.069
10.0 mg/L	0.800	0.011
20.0 mg/L	0.533	0.069
R^2	0.500	

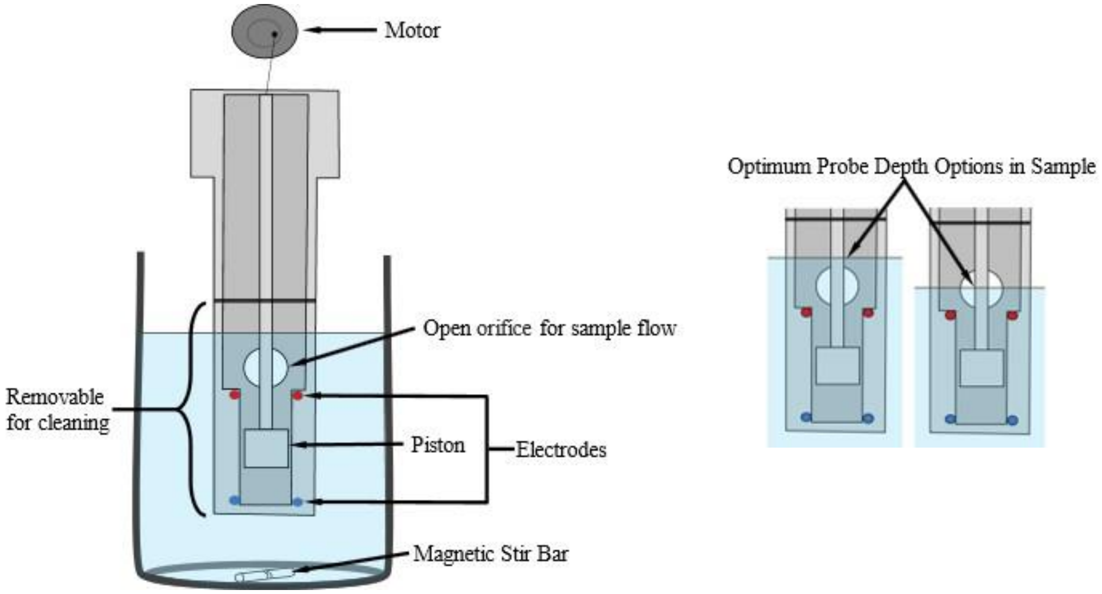
[a] Comparison to effects of base at 95% confidence interval and p-value <0.05

4.4.3 PARTICLE CHARGE ANALYZER

A Laboratory Charge Analyzer (LCA) (Figure 4-7), also referred to as Streaming Current Detector or Particle Charge Analyzer, is a type of streaming current device which is used to determine the net charge in a sample via the streaming current detection method (*182–184*). This technology is commonly used in research and development, as well as industrial applications for a variety of applications, including flocculant use.

Figure 4-7. Laboratory Charge Analyzer Testing Apparatus

The product used for this study was an LCA-02 from Chemtrac Systems, Inc. A streaming current device (SCD) identified by its reciprocating plastic piston inside a cylindrical measuring cell, equipped with two electrodes on opposite ends of the cell. An aqueous sample flows freely through the circular orifice above the piston and electrodes. See Figure 4-8(a) for location of each described feature. The reciprocating piston sits between the two electrodes and displaces the liquid inside, forcing it to move rapidly inside the cylindrical measuring cell with each up- and down-stroke. Creating an alternating current, which uses Van Der Waals attraction forces to causes select counter-ions to move to the cylinder walls, generating a tiny current which is detected via the electrodes positioned in the measuring cell (*182*, *185*). The SCD measures the existing charge on suspended particles (*186*), which is different from pH that is measured by determining the electrical potential (*187*). There is currently no ASTM standard for a SCD method (Bhatia et al., 2014). For optimal readings, the probe depth is based on the sample level relative to the open orifice. Figure 4-8(b) shows the two acceptable iterations to achieve consistent results. Users should consult the product manual for the specific make and model. A magnetic stir bar is used to keep the sample continuously moving. Failure to use the stir bar will result in inaccurate readings. The LCA machine has the capability to be equipped with a temperature and pH probe if desired.



(a) sensor schematic (b) optimum probe depth

Figure 4-8. Streaming Current Device

The LCA has been found to be a quick and effective way of measuring a variety of cationic residual flocculant concentrations (*184*, *185*). However, the exploration of evaluating its performance with anionic flocculants is minimal. This is lack of research is because the machine is not designed for measuring negative concentrations (*182*). Nevertheless, this study investigated evaluating the use of anionic PAM flocculants using the LCA. The decision was justified as the LCA machine was capable of detecting a small range of negative values. Since this study focused on detecting concentrations above and below 5 mg/L, this study aimed to see if the charge streaming current value (SCV), or also referred to as the particle charge or ionic charge, was within the accurately measurable range.

4.4.3.1 Laboratory Charge Analyzer Testing Methodology

The LCA was used to evaluate three different flocculant forms at various concentrations. Both Product A-G and Product A-B forms were evaluated at concentrations ranging from 0.125 to 7.00 mg/L and 0.250 to 7.00 mg/L, respectively. One cationic flocculant, chitosan, was also evaluated to compare negative and positive residual flocculant detection trends. Chitosan was evaluated in concentrations ranging from 20.0 to 200 mg/L. Both anionic flocculants used have a 5.0 mg/L manufacturer dosage recommendation, and chitosan's manufacturer dosage recommendation was set to 100 mg/L. Values below and above the manufacturer dosage recommendations were evaluated.

A stock of tap water from the City of Auburn, Alabama was used to ensure that all samples were at the same initial pH and similar water temperatures. Beakers with a maximum volume of 50.72 fl oz (1,500 mL) were used to hold each 30.81 fl oz (1,000 mL) sample. The LCA machine was equipped with a probe to measure the temperature of the sample and the pH was recorded with a hand-held pH meter separately. Concentrations of 1, 3, 5, and 7 mg/L of Product A-G was used for this calibration test. The same concentrations were evaluated for Product A-B. Chitosan was evaluated in concentrations of 20, 40, 80, 100, and 200 mg/L of Product J from Manufacturer IV was added to each of the respective beakers when the next sample was ready and was flash mixed at 120 rpm for 1 minute with the paddle mixer. Sample was then transferred to the LCA machine, and a magnetic stirrer was placed in the sample and set on high. The SCD requires constant monitoring to ensure the sample continues to stir continuously. Stagnant samples will result in inaccurate readings. After the SCD was lowered into the sample to depths previously mentioned in Figure 4-8(b), the pH meter was propped to sit in the sample and obtain an accurate pH reading while the machine obtained a stable reading. Once the pH meter and SCD had stabilized, results were recorded. The machine was flushed with deionized water between each sample and wiped down with a clean shop towel to remove any extra debris. Once a sample set was completed, the SCD was disassembled and scrubbed clean with a pipe cleaner brush and Alconox® Liquinox cleaning solution and rinsed thoroughly with deionized water to ensure all soil and flocculant were removed as best as possible. The next sample was placed on the magnetic stirrer and this process was repeated. Each sample was replicated three times to identify inconsistencies. Once all samples clean tap water samples (notated as No Sediment) were run through the LCA, 20g of sandy clay loam AU-SRF soil, located in East Alabama, was sieved through #200 sieve was added to each beaker and flash mixed at 120 rpm for 1 min. The sample was then given 15 min to settle, and the supernatant was separated and ran through the SCD again (notated as Sediment) to see how the pH and increased turbidity impacted the same readings. Supernatant samples had turbidity values between 5.00 to 100 NTU. Samples that did not contain any flocculant for both the No Sediment and Supernatant samples were used as the control.

Some important thing to note is that the flocculant in each sample must be completely dissolved to obtain accurate readings. During testing, the includes the average time taken to ensure each sample was fully aqueous and time to obtain a stable reading were recorded and included in Table 4-5.

Table 4-5. Brookfield Digital Viscometer Multiple Linear Regression Analysis

Flocculant Type	Time to Fully Dissolve, hr	Time for LCA to Obtain a Stable Reading, min
Product A-G	~0.5	10-20*
Product A-B	2-3	10-20*
Liquid Chitosan	N/A	3-10

N/A = sample is already in liquid form and thus only needs to be adequately mixed
*Samples <1.0 mg/L took between 30-45 min

The term "fish eyes" is used to describe a water/polymer gelatinous mass present in water which originated from a dry flocculant application that was insufficiently hydrated after application and before water introduction (*39*, *84*, *188*, *189*). Figure 4-9 displays an example of when 'fish eyes' are present in a sample. Product A-G and Product A-B form flocculants were considered fully aqueous when 'fish eyes' were no longer visible in the sample. Lastly, the supernatant sample, after sediment introduction into each sample, still contained small amounts of sediment. This sediment could build up in the piston area of the SCD and cause readings to take longer. If the signal health on the LCA display remained above 95%, the machine is in acceptable condition to continue processing the sample. If the signal health reading dropped below 95%, the user would need to remove the sample, disassemble, and clean the SCD before completing the sample reading or continuing with further sample processing.

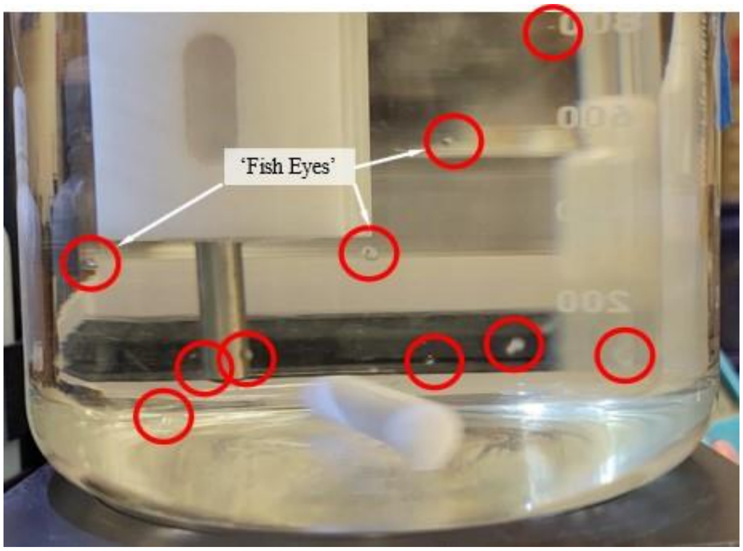


Figure 4-9. Flocculant 'Fish Eyes'

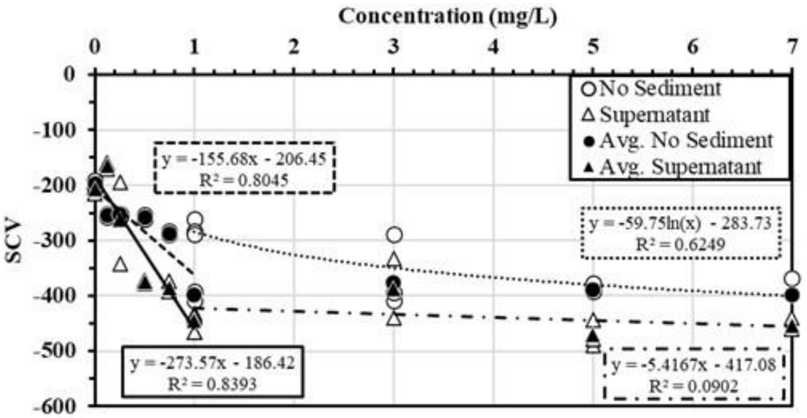
4.4.3.2 Laboratory Charge Analyzer Testing Results and Discussion

This analysis broke the data up by flocculant type and compared the SCV readings produced from the LCA to the measured concentration and pH value. Figure 4-10 displays the SCV readings against the flocculant concentration. Note that Figure 4-10(a) and (b) have the same x- and y-axis units and Figure 4-10(c) is drastically different. This is because the manufacturer's recommended dosage of the Product A-G and Product A-B forms was the same, while the chitosan was much higher. Additionally, Product A-G and Product A-B form flocculants are both anionic, while chitosan is cationic.

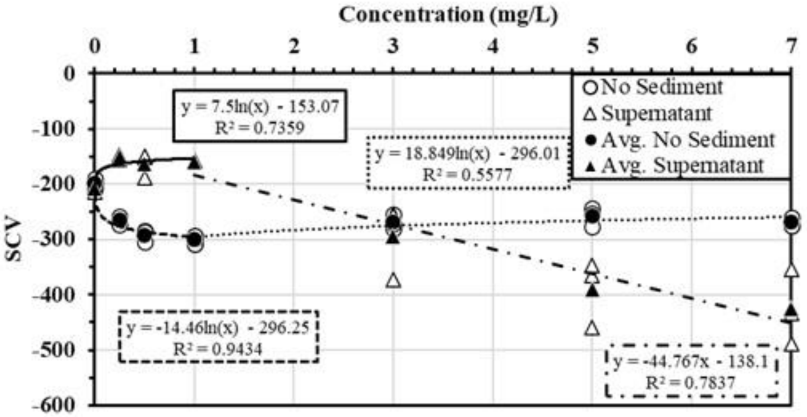
Figure 4-10(a), Product A-G, presents a separation of two linear plots, No Sediment and Supernatant samples, for concentrations below 1 mg/L where the trend is rapidly decreasing in SCV, concentrations above 1 mg/L, the trend flattens out. Meaning that anionic Product A-G can be detected using a SCD; however, it would not serve as an accurate approximation for concentration of flocculant present at concentrations above 1 mg/L. Making it difficult to know if increased dosing is occurring.

Figure 4-10(b), Product A-B, yielded less consistent results. For Supernatant samples, concentrations below 1 mg/L increased in SCV with a logarithmic trend and the trend for greater than 1 mg/L rapidly decreased in SCV linearly when soil is present. Making it difficult to predict low concentrations. However, it could be used for predicting higher concentrations to know if increased dosing is occurring. Interestingly, the inverse relationship with the increase and decrease of SCV values occurred with No Sediment samples. Meaning that this relationship may change with different soil types and would need to be evaluated further.

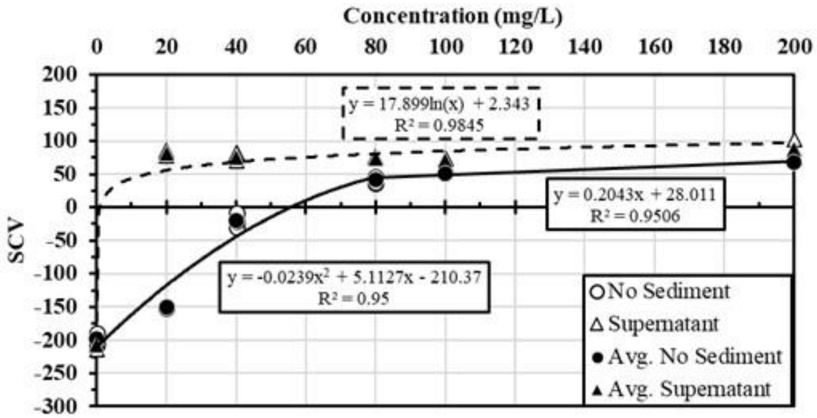
No Sediment sample presented in Figure 4-10(c), anionic chitosan, displayed a power function trend between 0 mg/L to 80 mg/L, where values above 80 mg/L form a linear trend with a slightly increasing slope. The Supernatant samples presented a logarithmic relationship where the lowest concentration evaluated (20 mg/L) was presented as the point where the logarithmic trend flattens out. Meaning that the use of an LCA to estimate Chitosan concentrations in the field could be used to estimate the presence of flocculant but not accurately estimate the concentration present or if increased dosing is occurring.



(a) Product A-G



(b) Product A-B



(c) chitosan

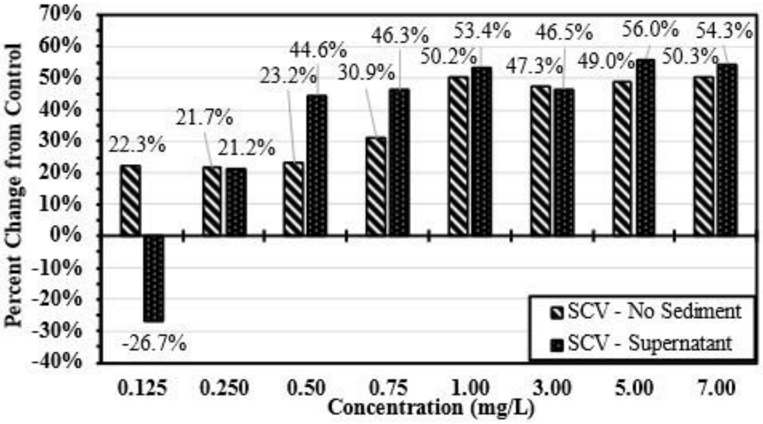
Figure 4-10. Flocculant Concentration Trends Against Their Streaming Current Value

Figure 4-11 displays the percent change from the control (no flocculant for both No Sediment and Supernatant samples) for each flocculant evaluated. For both anionic flocculant forms, Figure 4-11(a) and Figure 4-11(b), all No Sediment samples had a negative percent change compared to the control. Meaning that anionic flocculant indeed decreased the water's SCV, whereas the cationic flocculant had reverse results.

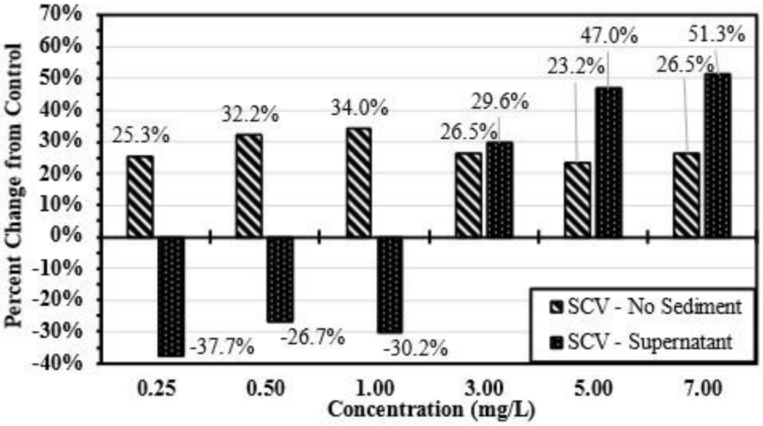
In Figure 4-11(a), Product A-G had a relatively similar percent change values for No Sediment and Supernatant samples. Meaning that the addition of sediment leads to similar results at concentrations above 1.00 mg/L.

In Figure 4-11(b), Product A-B indicates that sediment introduction from the Supernatant samples has a drastic impact on the SCV value. Showing the same trend is displayed in Figure 4-11(b) where concentrations below 1.00 mg/L increased the SCV and above 1.00 mg/L decreased it.

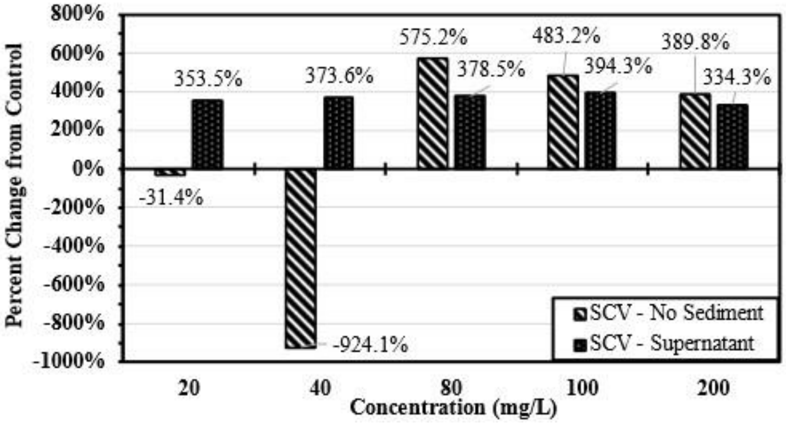
Chitosan flocculant, Figure 4-11(c), increased the SCV across all concentrations for No Sediment and Supernatant samples. While the No Sediment samples increased in SCV with concentration, the Supernatant samples at all concentrations had roughly the same percent change.



(a) Product A-G



(b) Product A-B

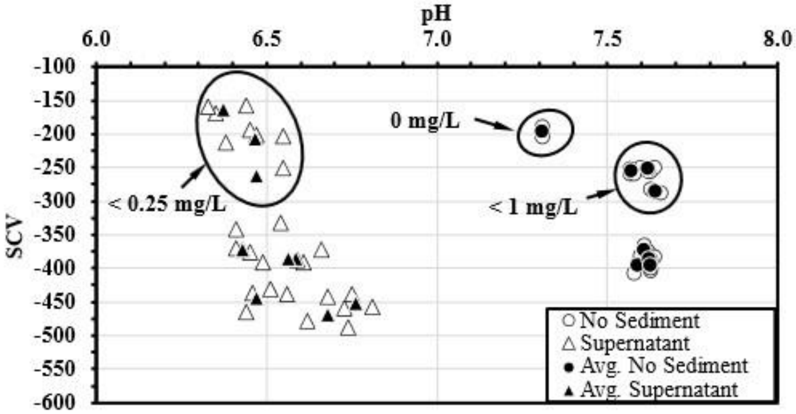


(c) chitosan

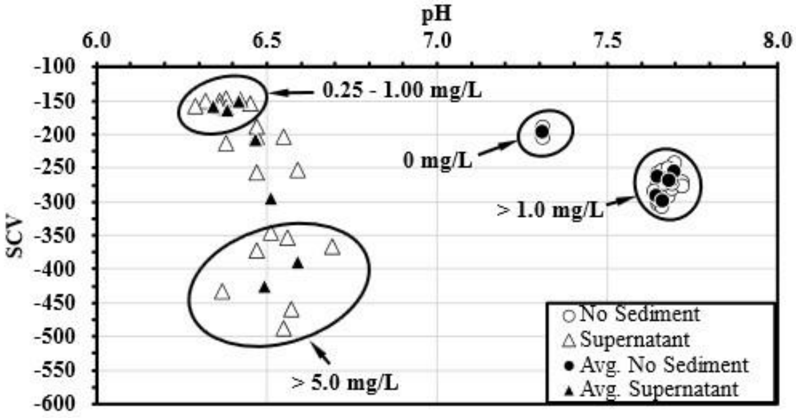
Figure 4-11. Streaming Current Value Percent Change from Control (no flocculant) Across Concentrations

Figure 4-12 displays how the SCV and pH compared to each other show data groupings at low and high flocculant concentrations. Presenting as another method for estimating flocculant presence for each evaluated flocculant type. Note that Figure 4-12(a) and (b) have the same y-axis, while Figure 4-12(c) changes, due to the anionic and cationic properties of the evaluated flocculants. This evaluation shows the relationship between the SCV value from a variety of flocculant concentrations and water pH. Showing that the use of any flocculant type can influence the overall pH of water. When sediment is introduced to flocculated water, depending on the soil type, it can help counteract the pH changes made. Note that conclusions made is from data collected from sample temperatures between of 70.2 to 72.0 ℉ (21.2 to 22.2℃) and a pH of 7.3. Further testing should be done to explore the relationships across various temperatures and pH ranges to see if data patterns persist.

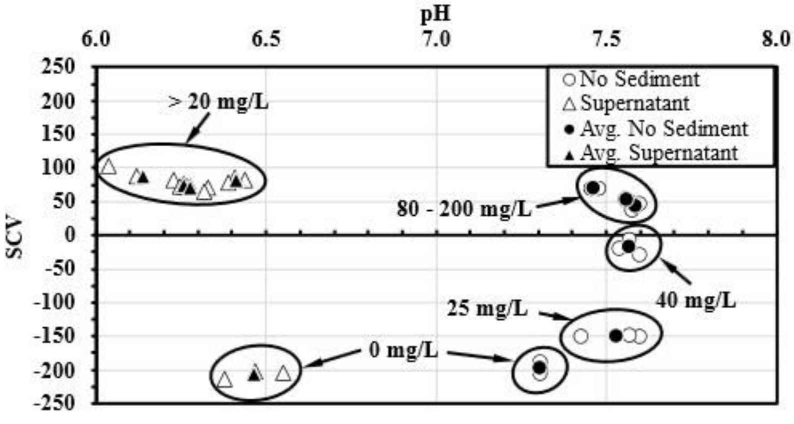
Figure 4-12(a), Product A-G, Supernatant results show that concentrations above and below 0.25 mg/L can be easily distinguished through data. The same claim can be made with above and below 1 mg/L of Product A-G in No Sediment samples. Figure 4-12(b), Product A-B groupings can be seen for concentrations between 0.25 to 1.00 mg/L and above 5.0 mg/L in Supernatant samples. No Sediment samples yielded two distinct tight groupings with and without flocculant. Figure 4-12(c), shows that in Supernatant samples, samples without flocculant started with a negative SCV value. When chitosan flocculant was added, all SCV readings were positively charged and formed a data cluster where concentrations above 20 mg/L can be easily identified. Whereas No Sediment samples show groupings at 0, 25, 40, and above 80 mg/L.



(a) Product A-G



(b) Product A-B



(c) chitosan

Figure 4-12. pH Trends Against Their Streaming Current Value

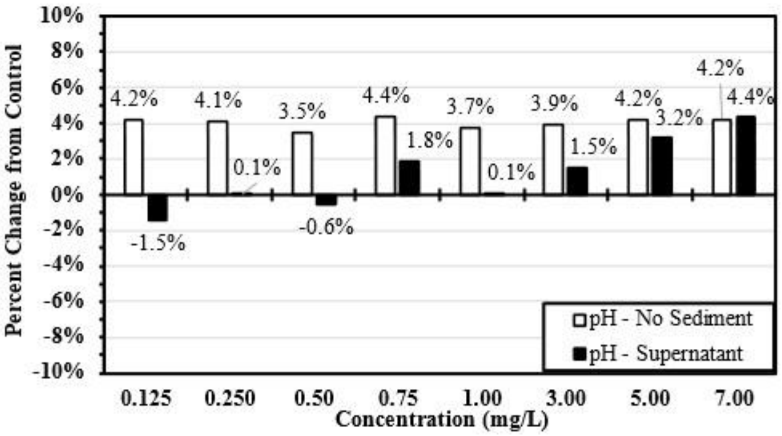
A categorical MLR, Table 4-6, was ran to identify the concentrations of each flocculant type significantly influenced the SCV. Both Product A-G and Product A-B form flocculants significantly lowered the SCV while chitosan significantly increased for No Sediment samples at every concentration. Although, after sediment was introduced, the Supernatant samples showed that Product A-G and Product A-B forms only significantly decrease the SCV after 0.5 mg/L and 3.0 mg/L, respectively. While chitosan continued to display a significant increase in SCV readings at all concentrations for Supernatant samples. Meaning that concentrations with significant differences in SCV are, at minimum, distinguishable from the control and can indicate the presence of flocculant. In other words, concentrations above 20 mg/L of cationic flocculant have significant changes in SCV compared to the control of no flocculant, so this testing method is capable of distinguishing chitosan concentrations between 20 to 200 mg/L. Between 0.5 to 7.0 mg/L of Product A-G and 3.0 to 7.0 mg/L of Product A-B are predictable concentration ranges for this testing method.

Table 4-6. Streaming Current Value Multiple Linear Regression Analysis

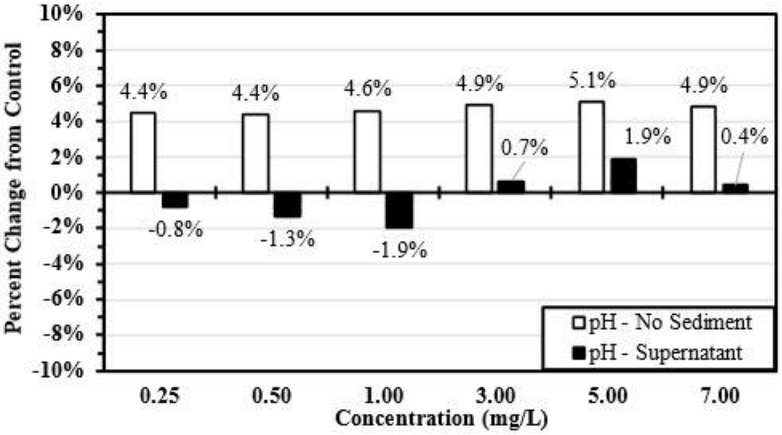
	No Sediment		Supernatant	
	Coefficients	**p-value[a]**	**Coefficients**	**p-value[a]**
Constant	-198.000	<0.001	-207.000	<0.001
Product A-G (Base: 0 mg/L)				
0.125 mg/L	-56.667	<0.001	43.667	0.120
0.25 mg/L	-55.000	<0.001	-55.667	0.052
0.50 mg/L	-59.667	<0.001	-166.667	<0.001
0.75 mg/L	-88.667	<0.001	-178.333	<0.001
1.00 mg/L	-199.333	<0.001	-237.667	<0.001
3.00 mg/L	-177.667	<0.001	-180.000	<0.001
5.00 mg/L	-190.333	<0.001	-263.333	<0.001
7.00 mg/L	-200.333	<0.001	-246.000	<0.001
Product A-B (Base: 0 mg/L)				
0.25 mg/L	-67.000	<0.001	56.667	0.134
0.50 mg/L	-94.000	<0.001	43.667	0.241
0.75 mg/L	-102.000	<0.001	48.000	0.200
3.00 mg/L	-71.333	<0.001	-87.000	0.029
5.00 mg/L	-59.667	<0.001	-183.333	<0.001
7.00 mg/L	-71.333	<0.001	-218.333	<0.001
Chitosan (Base: 0 mg/L)				
20 mg/L	47.333	<0.001	288.667	<0.001
40 mg/L	178.667	<0.001	282.667	<0.001
80 mg/L	239.667	<0.001	281.333	<0.001
100 mg/L	249.667	<0.001	277.333	<0.001
200 mg/L	266.333	<0.001	295.333	<0.001
R^2 Values				
Product A-G	0.994		0.940	
Product A-B	0.921		0.900	
Chitosan	0.998		0.997	

[a] Comparison to effects of base at 95% confidence interval and p-value <0.05

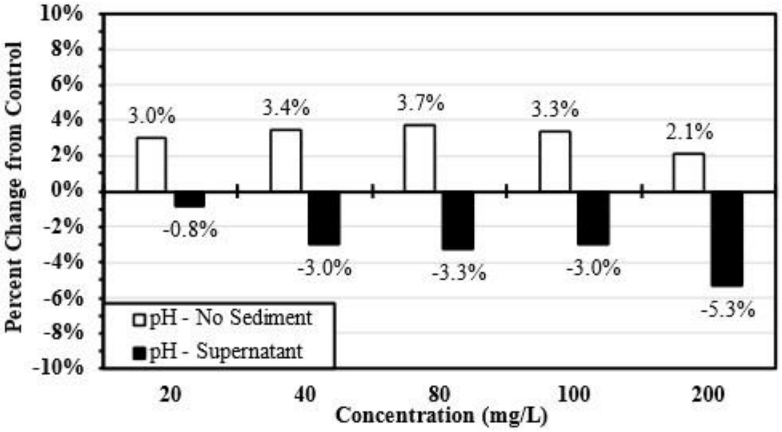
Data was also evaluated to see how the pH changes across increasing concentrations of flocculant. Figure 4-13 shows how the pH varies with flocculant concentrations compared to the control (no flocculant present). Data patterns show that when flocculant is added to tap water, the pH increases, regardless of if the flocculant added is cationic or anionic. This trend is also visible in the MLR shown in Table 4-7, where once the flocculant is added, it causes a significant change in pH at all concentrations, compared to the control. The anionic flocculants produced similar coefficients, indicating that the expected pH change when either Product A-G or Product A-B flocculants are added to water at any concentration will yield comparable results. This pattern persists with a lower coefficient for cationic flocculants.



(a) Product A-G



(b) Product A-B



(c) chitosan

Figure 4-13. pH Percent Change from Control (no flocculant) Across Concentrations

Though, if AU-SRF sandy clay loam sieved sediment is added and mixed into flocculated water, it lowers the pH back down near the initial tap water pH at lower concentrations. For Product A-G, Figure 4-13(a), as the concentration increases, the sediment added becomes less effective at combatting the pH change. For Product A-B, Figure 4-13(b), the results are less consistent with increasing concentrations. After sediment introduction for chitosan flocculant, Figure 4-13(c), pH continued to decrease as the flocculant concentration increased.

Table 4-7. pH Value Multiple Linear Regression Analysis

	No Sediment		Supernatant	
	Coefficients	**p-value**[a]	**Coefficients**	**p-value**[a]
Constant	7.310	<0.001	6.467	<0.001
Product A-G (Base: 0 mg/L)				
0.125 mg/L	0.317	<0.001	-0.093	0.068
0.25 mg/L	0.310	<0.001	0.003	0.945
0.50 mg/L	0.263	<0.001	-0.037	0.455
0.75 mg/L	0.333	<0.001	0.120	0.022
1.00 mg/L	0.283	<0.001	0.003	0.945
3.00 mg/L	0.300	<0.001	0.097	0.059
5.00 mg/L	0.317	<0.001	0.213	<0.001
7.00 mg/L	0.320	<0.001	0.297	<0.001
Product A-B (Base: 0 mg/L)				
0.25 mg/L	0.340	<0.001	-0.050	0.439
0.50 mg/L	0.337	<0.001	-0.083	0.206
0.75 mg/L	0.353	<0.001	-0.123	0.070
3.00 mg/L	0.380	<0.001	0.043	0.501
5.00 mg/L	0.390	<0.001	0.123	0.070
7.00 mg/L	0.373	<0.001	0.027	0.677
Chitosan (Base: 0 mg/L)				
20 mg/L	0.223	<0.001	-0.053	0.323
40 mg/L	0.260	<0.001	-0.187	0.004
80 mg/L	0.280	<0.001	-0.207	0.002
100 mg/L	0.253	<0.001	-0.187	0.004
200 mg/L	0.157	<0.001	-0.327	<0.001
R^2 Values				
Product A-G	0.991		0.859	
Product A-B	0.990		0.921	
Chitosan	0.898		0.810	

[a]Comparison to effects of base at 95% confidence interval and p-value <0.05

Table 4-7 shows the significant change in pH with Supernatant samples compared to 0 mg/L Supernatant samples. Showing the few concentrations that significantly change the pH with Product A-G and chitosan.

However, a separate MLR was ran to determine if pH changed between No Sediment samples and Supernatant samples, Table 4-8, and results found that both Product A-G and chitosan flocculants significantly lowered the pH value.

Table 4-8. Supernatant pH Value Multiple Linear Regression Analysis (Base: No Sediment)

	Coefficients	p-value[a]
Constant	7.412	<0.001
Product A-G	-1.048	<0.001
R^2	0.981	
Constant	7.470	<0.001
Product A-B	-1.163	<0.001
R^2	0.979	
Constant	7.488	<0.001
Chitosan	-1.199	<0.001
R^2	0.975	

[a] Comparison to effects of base at 95% confidence interval and p-value <0.05

4.5 SOIL ASSESSMENT

Most flocculant products are soil-dependent, and their performance changes based on the soil mineralogy and other physical and chemical characteristics of the soil. Therefore, the soil assessment phase of the bench-scale evaluation had a significant role in this research to provide effective guidance in the selection of flocculant type and dosage based on soil type. There are a total of 460 different soil series in Alabama within seven primary soil areas: limestone valleys and uplands, Appalachian plateau, piedmont plateau, coastal plain, Blackland prairie, major flood plains, and terraces, and coastal marshes and beaches as illustrated in Figure 4-14. Northern parts of the state are defined as limestone valleys and uplands derived from weathered limestone. The Appalachian Plateau is located in regions with high elevation in Alabama, which originated from sandstone or shale deposits. Following the Appalachian plateau, the piedmont plateau is present in the eastern region of the state and descends from granite, mica, and hornblende. The coastal plain derives from remnants of fluvial or marine deposits, and it is predominant in the majority of the state, especially in southern Alabama. The Blackland Prairie, known as the Black Belt, extends through central Alabama and consists of alkaline soils that have a darker topsoil appearance. In addition to these soil areas, major flood plains and terraces can be observed along Alabama's rivers, while the coastal marshes and beaches appear in the south along the coast (*190*).

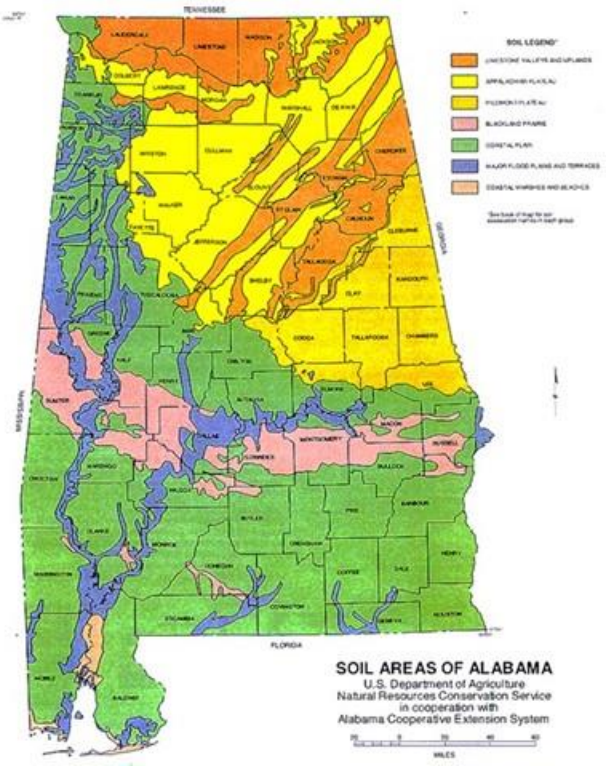


Figure 4-14: Soil Areas of Alabama (*190*)***.***

Soil variability does not only occur within the state but also exists within an active construction site. Many different named soil series can be observed within site boundaries throughout each construction phase. Moreover, excavation and embankment activities may also increase soil variability on sites and replace the naturally existing topsoil. The soil variability on construction sites requires soil assessments prior to the selection of flocculant products for construction stormwater treatment due to the soil-dependent nature of most flocculants.

Soil assessment in this study primarily focused on evaluating soil variability on active ALDOT construction sites across Alabama. ALDOT has five regions within the state of Alabama: East Central, North, Southeast, Southwest, and West Central regions. As a starting point for soil assessment in this research, a desktop study was conducted for identifying soil sampling locations on five active construction sites, one per ALDOT region. Within this desktop study, the U.S. Dept. of Agriculture Web Soil Survey (WSS) and Geographic Information Systems (GIS) tools were used to determine the target soil samples that needed to be collected during soil sampling site visits. The information on each construction project is presented in Table 4-9. Soil sampling sites were in Shelby (East Central), Etowah (North), Montgomery (Southeast), Mobile (Southwest), and Bibb (West Central) counties as shown in Figure 4-15.

Table 4-9: Sampling Sites

Project ID	Project Name	Location	Region
RAEDAA-0025 (556)	SR-25 Roadway relocation	Etowah, AL	North
BR-0006 (573)	SR-6 Bridge replacement	Bibb, AL	West Central
NHF-IMF-I065 (354)	I-65 Roadway improvement and bride replacement	Shelby, AL	East Central
NHF-0158 (502) & (508)	U.S. 98 / SR-158 Roadway extension	Mobile, AL	Southwest
BR-0006 (563)	SR-6 Bridge replacement at Jenkins creek	Montgomery, AL	Southeast

Figure 4-15: Soil Sampling Sites per ALDOT Region.

The information on the soil series existing on areas of intent was listed based on map unit name, acres in the area of intent, parent material name, surface texture, pH, soil chemistry information, soil erodibility factor, Unified Soil Classification, and American Association of State Highway and Transportation Officials (AASHTO) soil classification. The results of the desktop study were used to identify correlations with the field soil assessments later in this study.

Five active construction sites, one per ALDOT region, were visited to collect 12 target soil samples that were selected through the desktop study. Sampling locations were identified on-site based on the pre-determined sampling location coordinates through the WSS study. Topsoil was removed for soil sampling in each location with the support of ALDOT staff and five buckets per targeted soil sample were collected from the subsoil within the soil profile. Soil samples were air-dried on kraft paper in the sun and stored at the AU-SRF prior to soil classification experiments. Figure 4-16 illustrates soil sampling and storage procedures from the site visits.

(a) soil sample collection (b) air drying at AU-SRF

Figure 4-16: Soil Sampling and Storage Procedures.

Soil assessment initially focused on classifying soil samples in the laboratory by using the pipetting method for particle size analysis (*191*). The method required 0.35 oz (10 g) of soil samples to be dispersed overnight with the use of a shaker, distilled water, and dispersing agent formed by using Na_2CO_3 and $NaPO_3$. Dispersed soil samples were rinsed through a 270-mesh (53 μ) sieve and retained sand particles on the sieve were oven-dried at 212 °F (100 °C) for 48 hours. The dry weight of these samples was recorded after the completion of the 48 hours. The rinsed suspension was transferred into graduated cylinders and completed to 33.8 fl oz (1,000 mL) volume with distilled water. The suspension was mixed by inserting the glass tube connected to an air outlet and the air was introduced through the sample for at least five minutes. After the air introduction, samples were manually stirred for 30 seconds and kept undisturbed for 5 hours. By using the pipet setup, 0.85 fl oz (25 mL) of the clay suspensions were pipetted into empty 1.69 fl oz (50 mL) pre-weighed beakers. Figure 4-17 shows the pipette testing method setup used with clay suspension samples. Samples were back washed with water and 0.85 fl oz (25 mL) of water was pipetted into the beakers. All samples of the clay suspension were placed in the oven at 221 °F (105 °C) for 72 hours. Oven-dried samples were placed in a desiccator for an hour and dry weights were recorded.


(a) clay suspension samples (b) pipet setup

Figure 4-17: Particle Size Analysis with Pipet Method.

Particle size analysis with pipet method provides information on soil texture by identifying percent clay, silt, and sand in the soil samples. This method is widely used in soil sciences for classifying soils based on soil texture. However, soil assessment in this research also required the classification of soils based on AASHTO and USCS classification systems, which follow ASTM testing standards. These soil classification systems are commonly used on construction projects and the objective of the study was to provide flocculant usage guidance on construction sites. Therefore, the pipet method analysis was not applied for further soil analysis within this research.

Soil assessment studies continued with soil tests following ASTM standard testing procedures, which included wet sieve, dry sieve (*192*), hydrometer (*193*), and Atterberg limits (*194*) tests to characterize collected soil samples. The first step in the laboratory analysis for soil assessment was dry sieving 10.6 oz. (300 g) of crushed soil samples through No. 4, 10, 20, 40, 60, 100, and 200 sieves with the use of Humboldt© H-4325 Motorized Sieve Shaker by following standard procedures. Figure 4-18 illustrates the sieve machine setup used in the laboratory for dry sieve analysis. The weights of the sieves were recorded before and after soil introduction and passing rates were calculated for particle size distribution. Based on the sample characteristics and results of the dry sieve analysis, soil samples were wet sieved for capturing fine-sized particles sticking on the coarse particles during the dry sieve analysis. Wet sieve procedures required rinsing 3.5 oz (100 g) of soil samples through a stacked sieve set that consisted of No. 20 and No. 200 sieves until the water passes through visually becomes clear. Soil retained on the No. 20 and No. 200 sieves, was also rinsed into separate bowls and wet sieved samples were oven-dried. After the drying process of the samples, secondary dry sieving was applied to the retained soil for correcting the coarse fraction particle size distribution of the soil samples.

Figure 4-18: Sieve Machine Setup.

Soil testing procedures continued with hydrometer analysis on soils containing a substantial percentage of fines for identifying percent clay within the sample passing through the No. 200 sieve, which represents the fine fraction of the samples by following ASTM standards (*193*). Figure 4-19 shows the hydrometer setup used in the laboratory, which consisted of a control jar and graduated cylinders with soil samples. After the completion of sieve analysis, soil passing through the No.200 sieve was saved for hydrometer analysis and dispersed with the use of sodium hexametaphosphate and a mixing procedure. The dispersed soil was transferred into graduated cylinders and the volume of the samples was increased to 33.81 fl oz (1,000 mL) with the addition of deionized water. The graduated cylinder was capped with a rubber stopper and the solution was agitated by turning the cylinder upside down and back 30 times in a minute. The sedimentation jar was placed on a counter and remained undisturbed for 48 hours. Hydrometer readings were taken on specified durations identified by the ASTM standard (*193*). According to the hydrometer readings and calculations, % fine values that showed particle diameter smaller than 7.9 x10^{-5} in. (0.002 mm) were identified as the clay portion of the fines. The fine fraction of the particle size distribution curve was completed with the hydrometer analysis results.

Figure 4-19: Hydrometer Testing Setup.

Following hydrometer analysis, the liquid and plastic limits of the soil samples were identified by using standardized methods (*194*). The liquid limit is the water content of the soil that shows the change from the plastic state to the liquid state. Soil passing No. 40 was used in the Casagrande liquid limit machine and groove closing behavior of the soil was observed in 15-20, 20-25, 25-30, and 30-35 counts by adding water into the sample. Figure 4-20 shows the manual Casagrande liquid limit tool used in the experiments.

Figure 4-20: Manual Casagrande Liquid Limit Tool.

The soil sample, which reached the liquid limit in 20-25 counts, was used for the plastic limit test. The plastic limit is the water content of the soil that shows crumbling behavior when the soil is rolled into a 0.125 in. (3.2 mm) diameter thread. Results of these tests were used to identify plasticity index and group index values for soil classification.

Each soil analysis step was repeated three times for ensuring the accuracy of the results obtained in laboratory soil testing procedures. Results were evaluated for identifying particle size distribution and classifying collected soil samples based on USCS, ASHTO, and United States Department of Agriculture (USDA) soil classification systems. Soil reports were produced for each tested soil (see Appendix A **SOIL ASSEMENT REPORTS**) and results were compared to the WSS study for determining the correlation between the desktop study and the existing soils on the job sites.

Cationic Exchange Capacity (CEC) of soils was another factor considered for correlating the performance of flocculants on different soils. CEC is a measure of cations that can be held on soil particle surfaces in milliequivalent per hundred grams (meq/100 g). Soil samples were tested for CEC at the Auburn University Soil Testing Center and the results were evaluated for correlating the performance of the flocculants on soils with CEC. Typically, high organic matter and clay content in soils result in higher CEC values. Thus, the CEC of the soil shows variability within the soil profile shown in Figure 4-21. For instance, the A horizon has the highest CEC within the soil profile and the E horizon shows low CEC due to low organic matter and clay content. B horizon with high clay content can also have high CEC values. Soil samples in this research were collected from 12 in. (30.48 cm) below the surface in the B horizon, which represents the subsoil layer that accumulates clay transported from O and A horizons.

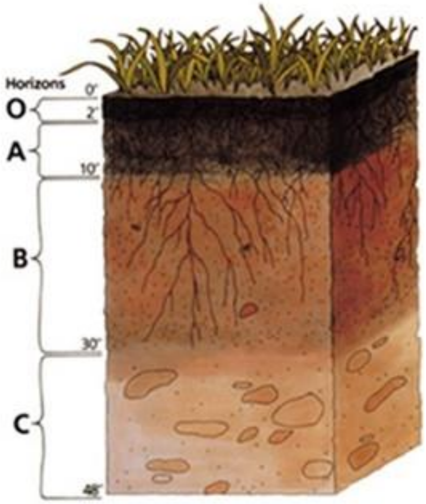


Figure 4-21: Soil Profile (*195*)**.**

In addition to the soil assessment of targeted soil samples, three additional soil samples from collected known sources were included in the study for extending evaluated soils within the texture triangle. The first additional soil sample was sampled from the Cecil map unit and classified to also be used in residual concentration experiments, intermediate-scale, and large-scale testing phases of this research. The second sample was collected from a construction site in the Montgomery, AL area, which is located within the boundaries of Blackland Prairie. Finally, a soil sample from the Gwinnett soil sample was collected from an area located south of Auburn, AL, which consisted of mixed crystalline materials of Piedmont.

4.6 MATCH TEST

Due to the soil-dependent nature of most flocculants, identifying the best performing product(s) for each soil provides benefits to the dosage study by eliminating the least effective products for each soil type. Match test experiments enabled the performance observation and comparison of each product on testing soils. The testing methodology followed ASTM standard jar testing procedures and tested the performance of 14 different flocculant products on 15 testing soil samples (*143*).

The product selection was made by considering approved products by ALDOT which included PAM, bentonite, and sodium montmorillonite-based flocculant products; however, additional flocculant types such as alum, agricultural gypsum, chitosan, and a coagulant agent were included in this research for providing comprehensive guidance on the use of flocculants. Table 4-10 displays information on the selected products for the bench-scale evaluation phase of this research. Stock solutions were prepared for most of the granular products by using manufacturer dosage recommendations. However, some products did not form a homogenous stock solution with the recommended concentration value; thus, these products were used in granular form for the bench-scale experiments. These products were A, N, F, G, and H as shown in Table 4-10.

Table 4-10: Summary of Evaluated Flocculant Products

Product	Manufacturer	Flocculant	Type	Form	Dosage (mg/L)
A	I	PAM	Synthetic	Granular	5
B	II	PAM	Synthetic	Stock solution	50
C	II	PAM	Synthetic	Stock solution	50
D	II	PAM	Synthetic	Stock solution	50
E	II	PAM	Synthetic	Stock solution	50
F	II	PAM	Synthetic	Granular	50
G	II	PAM	Synthetic	Granular	50
H	II	PAM	Synthetic	Granular	50
I	III	Bentonite-based	Inorganic	Stock solution	180
J	IV	Chitosan	Natural	Emulsion	100
K	IV	Chitosan + coagulant	Natural	Emulsion	100
L	V	Calcium sulfate	Inorganic	Stock solution	300
M	VI	Aluminum sulfate	Inorganic	Stock solution	10
N	VII	Sodium Montmorillonite	Inorganic	Granular	2,000

Match test experiments were performed by using A&F Machine Products Co. 88-2152 Jar Mixer© with six stirring stations. Sample turbid water was prepared by mixing an amount of the fine soil passing through No. 200 sieve with 33.8 oz (1,000 mL) tap water to reach 1,500 ± 300 NTU per jar. An injection rack was designed and built by following the ASTM jar testing standard procedures for instantaneous injection of flocculant products into the beakers during the use of the mixing machine. The injection rack was built by using a 2 in. (5.08 cm) diameter PVC pipe, PVC pipe fittings, caps, and 2x8 lumber pieces. Figure 4-22 shows the injection rack design of the researchers that was used in this research.

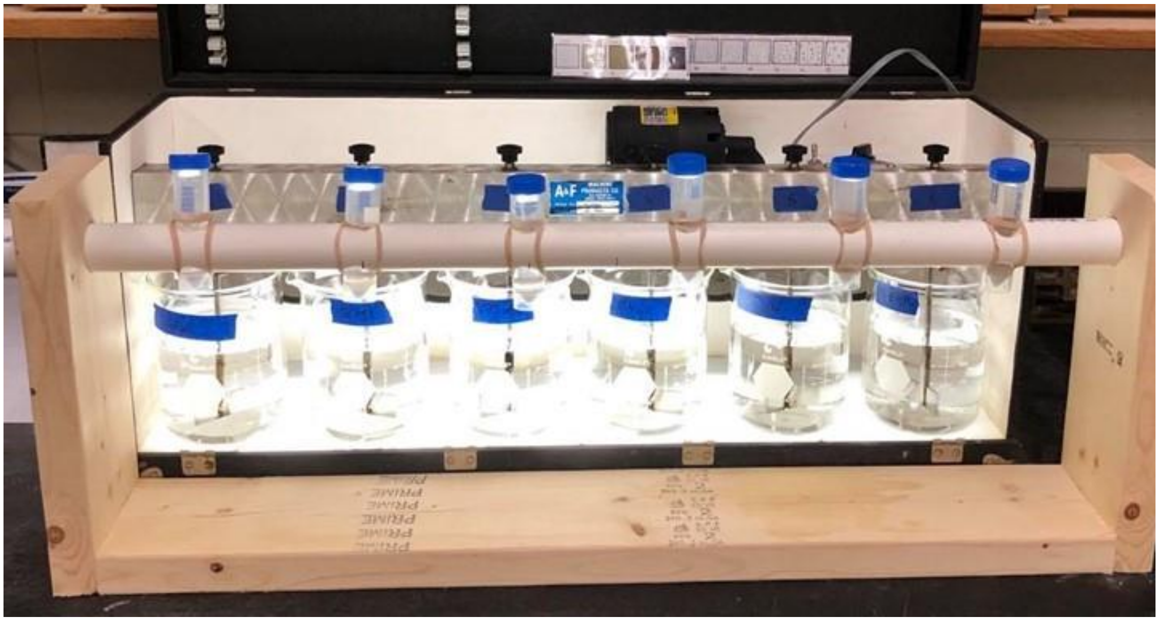
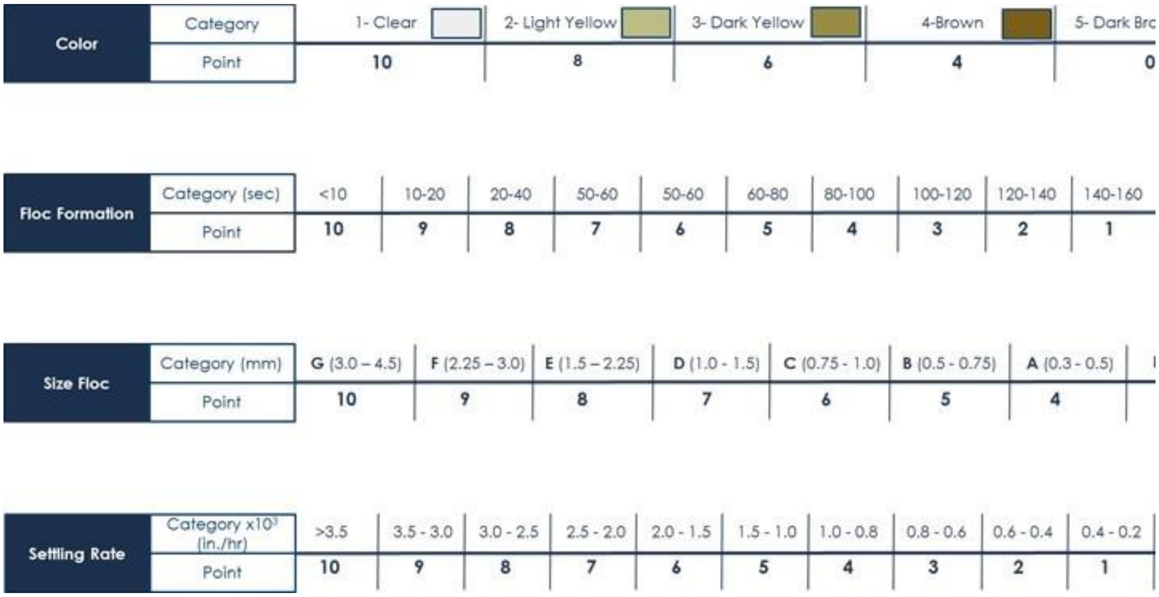


Figure 4-22: Flocculant Injection Rack

Each flocculant product was introduced into the sample turbid water with the use of an injection rack and testing samples were flash mixed for a minute at 120 rpm by using the mixing machine. The flash mix step activated each introduced chemical agent through rapid hydration. Following the flash mix step, slow mixing procedures were applied by reducing the mixing speed of the machine to approximately 60 rpm for 20 minutes. This step enabled floc formation by creating a bridging mechanism between suspended soil particles. Finally, the machine was stopped, mixing paddles were taken out of the beakers, and settling was observed for 15 minutes. These procedures were also used in the dosage test experiments, which will be discussed in the next subsection of the methodology.

Match test experiments evaluated each product on each testing soil for identifying the best performing chemical agents. In total 168 samples were evaluated together with the no flocculant control condition, and observations included color, floc formation, floc size, and settling velocity. The performance of the products was compared to each other and to the control condition, which did not contain any flocculant. A point system was developed for analyzing the match test results by assigning points to each observation category. Products were ranked based on the point system shown in Figure 4-23 and the top three best-performing products for each soil were selected based on the highest scores. The selected products were further investigated for optimum dosage guidance in the dosage test experiments.



Color	Category	1- Clear □	2- Light Yellow ■	3- Dark Yellow ■	4-Brown ■	5- Dark Br
	Point	10	8	6	4	0

Floc Formation	Category (sec)	<10	10-20	20-40	50-60	50-60	60-80	80-100	100-120	120-140	140-160
	Point	10	9	8	7	6	5	4	3	2	1

Size Floc	Category (mm)	G (3.0 – 4.5)	F (2.25 – 3.0)	E (1.5 – 2.25)	D (1.0 - 1.5)	C (0.75 - 1.0)	B (0.5 - 0.75)	A (0.3 - 0.5)
	Point	10	9	8	7	6	5	4

Settling Rate	Category x10^3 (in./hr)	>3.5	3.5 - 3.0	3.0 - 2.5	2.5 - 2.0	2.0 - 1.5	1.5 - 1.0	1.0 - 0.8	0.8 - 0.6	0.6 - 0.4	0.4 - 0.2
	Point	10	9	8	7	6	5	4	3	2	1

Figure 4-23: Match Test Point System

4.7 DOSAGE EXPERIMENTS

Match test experiment results were used to identify optimum dosage rates on the best performing products through dosage experiments. Dosage experiments also followed ASTM jar testing standard procedures as explained in the match test methodology (*143*). The experiments evaluated 15 soils for optimum dosage with the top three best-performing products per soil. Each experiment was repeated three times, which resulted in 130 tests in total, and observations included turbidity, pH, color, and temperature measurements.

Sample turbid water for dosage experiments was prepared with the same methodology used in match test procedures, which aimed to have samples with 1,500 ± 300 NTU. Initial turbidity and pH readings were taken from turbid water samples before each experiment. The dosage of each product in testing beakers ranged between 0% to 200% of the manufacturer recommendation. Figure 4-24 illustrates the dosage ranges used in the dosage test procedures.

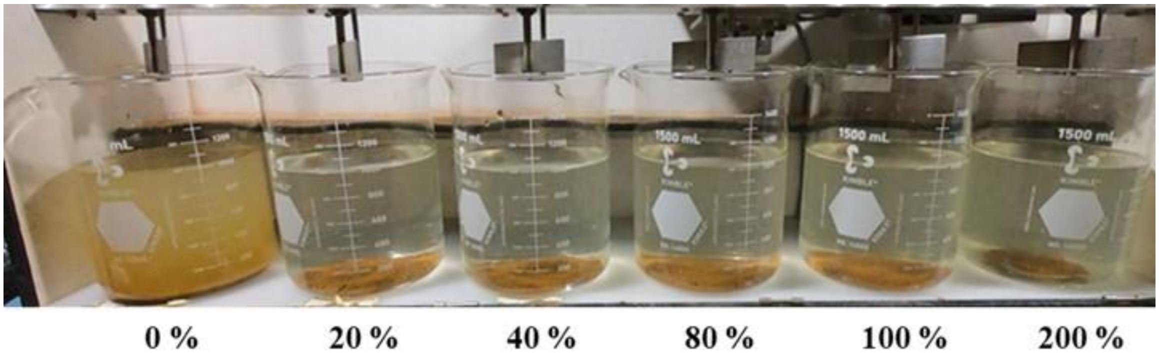


Figure 4-24: Dosage Range.

The control beaker (0%) did not contain any flocculant product for representing conditions with no flocculant addition. Manufacturer dosage recommendation was represented as 100% and was increased to 200% in each experiment to observe over-dosing conditions. After the completion of the settling procedure, supernatant samples were collected from each beaker and tested for final turbidity and pH values. The data analysis included calculating turbidity reduction, change in pH, quantifying color change, and floc size.

4.8 DETECTION OF RESIDUAL CONCENTRATIONS

The development of a method for identifying residual concentrations across various types of flocculants provided a practical solution for detecting residual concentrations in the runoff and evaluating the longevity of different flocculant products. As an initial attempt, correlating absorbance readings with known flocculant concentration was used as a method for detecting residual concentrations. This method was previously applied to PAM and chitosan-based flocculants in previous studies (*38*, *142*). The validation of this method across products different than PAM and chitosan was evaluated in this study with the use of a spectrophotometer machine.

Figure 4-25: Eppendorf© 5810 Centrifuge Unit

Known concentration samples with flocculants were prepared in beakers filled with 33.8 fl oz (1,000 mL) tap water. Samples consisted of flocculant types including PAM, chitosan, sodium montmorillonite, aluminum sulfate, calcium sulfate, and bentonite-based flocculant products. Known concentration samples were flash mixed for a minute and 1.7 fl oz (50 mL) of the supernatant was captured in centrifuge tubes. The samples captured in centrifuge tubes were centrifuged for 5 minutes at 4,000 rpm and transferred into the spectrophotometer cuvette with a pipette for absorbance readings in a spectrophotometer. Figure 4-25 shows samples being centrifuged in the Eppendorf© 5810 centrifuge unit. The observed absorbance readings were plotted with known concentration values and the statistical relationship between these factors was evaluated. However, later in the study, this method was abandoned since it was not valid for many different flocculant types, which will be discussed in the results and discussion section of this chapter.

After identifying the limitations in the spectrophotometer method, researchers focused on detecting flocculant concentrations by observing settling velocities of samples treated with different types of flocculants and correlating velocity observations with known concentration values. For consistency, a single soil sample was used in the development of the residual testing methodology. Sample turbid water was prepared by mixing 0.7 oz (20 g) of the fine soil passing through the No. 200 sieve with 33.8 fl oz (1,000 mL) of tap water. The fine soil was sieved from a high clay-content soil from AU-SRF in East Alabama. High fine and clay content was the major decision-making factor for identifying the testing soil due to its capability of maintaining suspension. In addition, the soil showed a well-characterizable color palette during settling trials, which was beneficial for tracking settling velocity. The soil itself had a relatively short settling period of approximately 14.5 minutes, without flocculant injection, which shortened experiment durations. The study evaluated residual detection testing on 14 different products and six flocculant types. PAM, chitosan, sodium montmorillonite, aluminum sulfate, calcium sulfate, and bentonite-based flocculant products were identified as testing chemicals.

Testing soil was oven-dried to a constant mass at a temperature of 110±5˚C (230±10˚F) and crushed in a pan for reducing the size of clumpy particles. The soil was dry sieved through No. 4, 10, 20, 40, 60, 100, 200 sieves. Sample turbid water prepared by mixing 0.7 oz (20 g) of the fine soil passing through No. 200 sieve with 33.81 fl oz (1,000 mL) of tap water was mixed using a multiple stirrer machine following methods described in ASTM jar testing standard flash mixing speed suggestion (120 rpm) (*196*). Known concentrations of flocculant products, ranging from 0% (no flocculants, control sample) to 30% of the manufacturer's guidance, were injected into the turbid water samples and flash-mixed for 1 minute in the mixing machine. Following the flash mix of flocculant products with turbid water, the machine was stopped, and samples were immediately poured into graduated cylinders with 33.8 fl oz (1,000 mL) capacity. This step ensured instantaneous suspension of the flocculated particles for a brief period and provided enough settling distance to track settling depth with time. In addition to flocculated samples, control samples were prepared with turbid water samples containing no flocculant. Settling rate testing of control samples enabled observing typical settling characteristics of the fine soil.

The settling procedure of each flocculant type with different known concentrations was tested in graduated cylinders by visually observing settling depths with the use of a ruler and a timer. Figure 4-26 shows the experimental setup for settling depth tracking across different concentration values of product B ranging from 0% to 30 % of the manufacturer guidance in the laboratory testing environment. Experiments were replicated three times with average settling velocity values for each concentration rate calculated by using observed depth and time data. Residual measurement plots were prepared by using calculated average settling values with corresponding known concentrations. Linear regression analysis was performed on the residual plots to statistically identify the strength of the relationship between settling velocity and concentration.

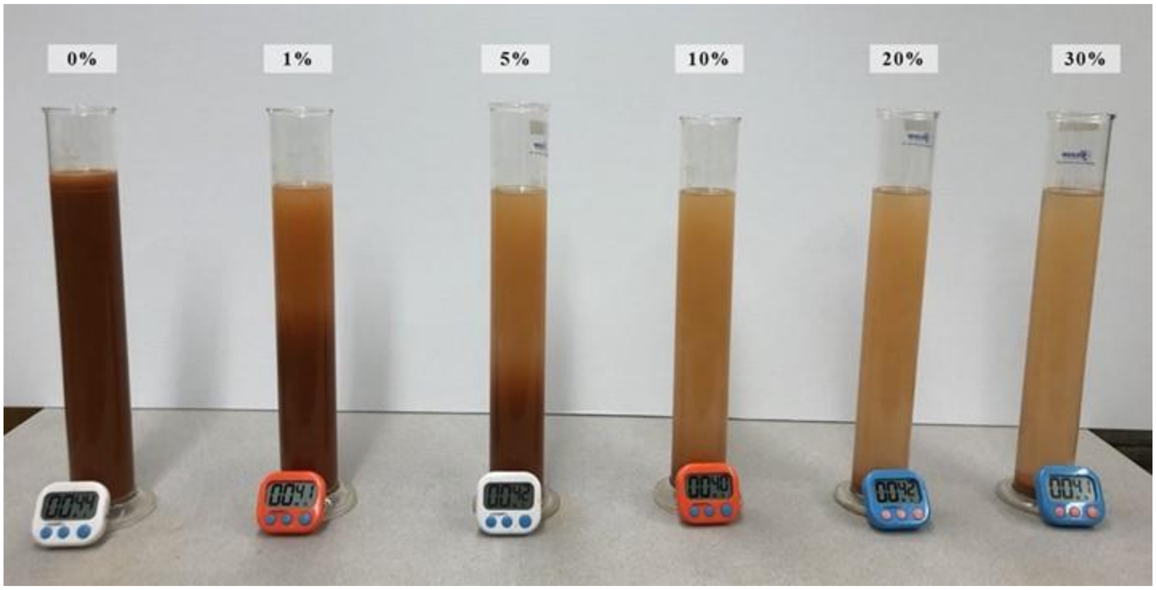


Figure 4-26: Settling Depth Tracking for Product B

4.8.1 EXPANDED RESIDUAL SETTLING CURVES WITH INFLUENCING FACTORS

A 27-gal (102 L) plastic tote was used to set the pH of the water to the desired range. Smaller volumes are more difficult to set and control the pH range. The tub was filled with tap water from the City of Auburn, Alabama where the water temperature was close to the desired temperature. Low temperatures (50℉ [10℃] and below) will require water to be chilled overnight prior to testing). Depending on the desired pH range, add acid or base buffering solution to tap water to raise or lower the pH, respectively. General Hydroponics pH Control acid and base buffering solutions were used to change the pH of tap water. A paint mixer was used to sufficiently mix solution before taking a pH reading. The water pH was set to values between 5.35 to 5.45, 6.35 to 6.45, 7.35 to 7.45, or 8.35 to 8.45 to ensure consistency between samples. Once the pH was within the desired range, the temperature was set by using heat lamps to raise the temperature. If samples needed cooled, 33.81 fl oz (1,000 mL) of pH set water was transferred to 50.72 fl oz (1,500 mL) glass beakers. All samples at each pH, temperature, and concentration were ran in triplicate to identify data inconsistencies. If the temperature needed to cool a couple degrees, samples would be placed in a refrigerator for 10-15 minutes. Samples that needed cooled to temperatures below 50℉ (10℃) were placed in a salted ice bath, being careful to not contaminate the pH water with any salt. While the pH water was being set to the desired temperature, a Jar Test Multiple Stirrer machine cleaned prior to any use in case to remove any possible contaminates. This was done by rinsing the stirring rods, paddles, and paddle rest with deionized water, spraying with Alconox® Liquinox cleaning solution, and wiping clean with a paper towel.

Glass graduate cylinders were prepped with ruler tape on the cylinder side, with zero starting at the cylinder base. The cylinders were placed in front of a white poster board to aid in seeing gradients when samples were poured. A GoPro camera was set up in front of the graduated cylinder and positioned so the top and bottom of the cylinder were visible in the GoPro screen. Ruler tape was positioned to the side of the cylinder in the GoPro screen to ensure it was not obstructing the view of the sample that would be poured. A digital clock - with hours, minutes, and seconds on display - was placed beside the cylinder and in the GoPro frame and used to record the sample settling time. See Figure 4-27. Placement of Cylinder and Clock Within GoPro Screen for placement of cylinder and clock in GoPro screen. Sourced sandy clay loam soil was sieved through #200 sieve and weighed out into jars, each containing 20g of sieved soil. A precision scale was used to weigh out flocculant. The scale was calibrated every day before use to ensure accurate weights. Flocculant was weighed with ±0.1 mg accuracy. The Product A-B was weighed out by using a cheese grater to create smaller pieces. Fresh material was grated daily and stored in an airtight jar to prevent it from drying out. Weighed Product A-B was used within 1 hour of weighing to ensure flocculant does not dry out and harden, which could impact results. If Product A-B hardened before use, sample was reweighed out with freshly grated flocculant block.

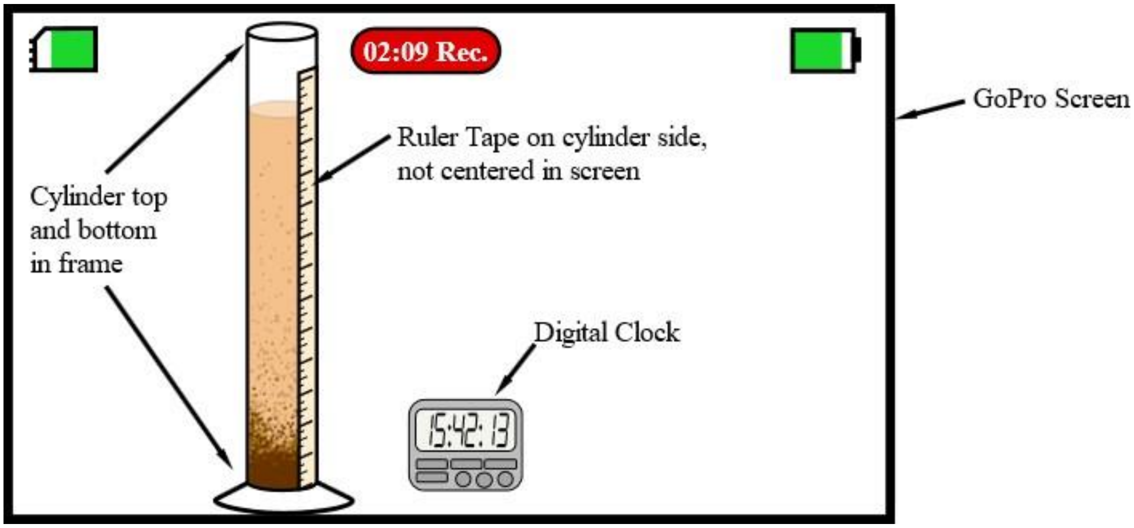
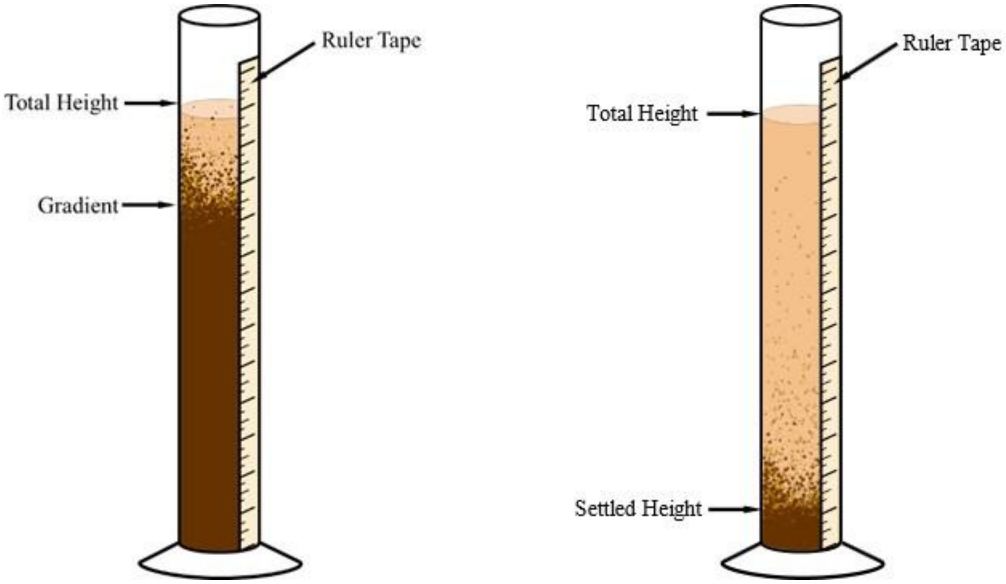


Figure 4-27. Placement of Cylinder and Clock Within GoPro Screen

Once the pH water reached the desired temperature, samples were moved to a jar test multiple stirrer machine and 20 g of sieved testing soil was added to the pH and temperature set sample. The sample was then flash mixed (120 rpm) for one minute. Sample beakers were then removed from the machine and the weighed flocculant was added to the center of the beaker. Flocculant was never added to the sample was on the stirring machine and stirring rods in sample to prevent the possibility of flocculant sticking to the beaker sidewalls or stirring rod, which would prevent it from being mixed into the sample. GoPro video camera recording was started, and sample beakers were placed back on the stirrer machine and flash mixed (120 rpm) again for one minute. Samples were quickly removed from the machine and poured into the prepped glass cylinder, being sure to pour fast enough so that all sediment in sample remains suspended while pouring. Samples were recorded until sediment was fully settled, or for one hour if gradient was not easily visible. See Figure 4-28. Visible Gradient and Settled Sample Example for an example of a visible gradient and settled sample.



(a) visible gradient (b) settled sample

Figure 4-28. Visible Gradient and Settled Sample Example

After samples were settled, the glassware was cleaned with hot water and scrubbed clean with Alconox® Liquinox cleaning solution. The Jar Test Multiple Stirrer machine was cleaned by rinsing with deionized water, spraying with Alconox® Liquinox cleaning solution, and wipe clean with a paper towel. If sample flocculated under 30 sec, it is recommended to repeat the cleaning process two or three time to ensure all flocculant is removed. GoPro video recordings of the sample were reviewed to capture the time the sample was poured, total height of the sample in the cylinder using the ruled tape in the cylinder side, settled time, and settled height. This information was then used to calculate the settling velocity by taking the difference in time and height for the soil to settle. Settle time and height varies depending on the floc size. Sample was considered as settled when the lowest gradient point touched the fully settled sediment. The settled height is taken at the same time the settled time is recorded as sediment will continue to compress after suspended sediment settles. See Figure 4-29. Determining Settled Sample Time and Height to visually understand how to determine when sample is settled. Note that some samples were difficult to determine a gradient. GoPro videos record in 10-minute video clips. If gradients could not distinguish between these video clips, a video editing software was used to stitch multiple video clips together. When moving the scrub bar rapidly back and forth across the entire settling time, a gradient was able to be distinguished. See Appendix E for a step-by-step testing procedure.

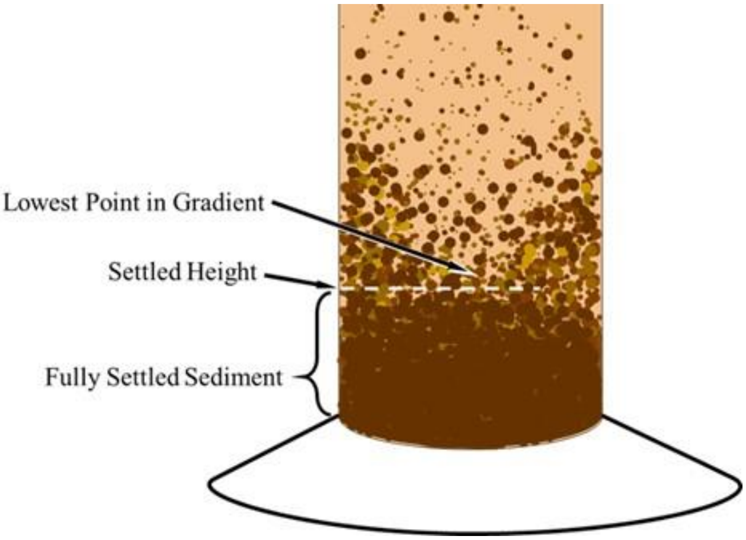


Figure 4-29. Determining Settled Sample Time and Height

This testing methodology has many possibilities for error and contamination. By being as efficient as possible with sample preparations, implementing a GoPro to record setting rates, use of glassware rather than plastic, and strict cleaning procedures, several possible sources of error and contamination can be accounted for. The GoPro allows samples to be evaluated from the same distance and perspective and more precise sampling start and end times to be captured. Glassware is used rather than plastic to prevent PAM adhesion and cross-contamination. However, weighing out low-weight samples in milligrams, reusing glassware multiple times in one day, and reusing jar testing multiple stirrer machine, there are still possibilities for error and sample contamination. Cleaning glassware with hot water can help dilute and rid PAM from glassware and rinsing with deionized water and wiping the stirring machine multiple times with a cleaning agent can also assist in minimizing cross-contamination.

4.9 RESULTS AND DISCUSSIONS

Bench-scale evaluations were completed with the finalization of the dosage test and residual concentration experiments. The data was analyzed prior to dosage delivery experiments in intermediate-scale flume and large-scale application evaluation. Research findings provided substantial input for further investigations in both intermediate- and large-scale testing regarding optimum dosage guidance and residual detection. Results of bench-scale evaluations for optimum dosage are discussed in four subsections including results of 1) soil assessment, 2) match test, 3) dosage experiments and 4) detection of residual concentrations.

4.10 SOIL ASSESSMENT

Results of the soil assessment provided insight into the bench-scale evaluation of this research for product selection and optimum dosage guidance based on soil characteristics. The assessment presented a WSS-based desktop study and compared laboratory soil testing results to investigate the need for soil testing procedures to classify soils for flocculant product selection.

According to the WSS study results, 12 soil series were identified as target soils on sampling sites. For the southwest region sampling site in Mobile County, three soil series were selected for soil sampling: Wadley loamy fine sand (WaB), Malbis fine sandy loam (MaD), and Benndale fine sandy loam (BeB). Wadley series are originated from sandy and loamy marine deposits, Malbis series are fine-loamy marine deposits and Benndale series are coarse-loamy fluviomarine deposits derived from sedimentary rock. For the north region sampling site in Etowah, three soil series were targeted: Chewacla Silt Loam (9), Dewey Silt Loam (18), and Minvale cherty loam (43). Chewacla series are loamy alluvium derived from sedimentary rock, Dewey series are originated from clayey residuum weathered from limestone and Minvale series are loamy colluvium derived from cherty limestone. In the east-central region, two soil series were selected for soil sampling in Shelby county: Townley-Sunlight complex (TsE) and Townley-Urban land complex (TtE), which are clayey residuum weathered from shale. For the west-central region soil sampling site in Bibb county, two soil series were identified as target sampling soils: Mantachie, Kinston, Iuka soils (MIA), and Columbus loam (CmA), which are loamy alluvium and loamy fluviomarine deposits, respectively. Finally, for the southeast region sampling site in Montgomery County, two soil series were targeted for soil sampling: Izagora fine sandy loam (IdB) and Kipling clay loam (KcA). These soil series are originated from loamy and clayey fluviomarine deposits and clayey marine deposits derived from chalk, respectively. Target soil samples were selected based on acres in the area of intent and accessibility of the locations on job sites. Each sample was tested in the laboratory for soil classification by following ASTM standard testing procedures as mentioned in the methodology section. The testing results were compared soil classification results with the WSS study findings. Table 4-11 shows the comparison of WSS soil classification results with the laboratory soil testing findings.

Table 4-11: Soil Assessment Comparison Results

	USDA WSS			LABORATORY TESTS		
Soil Sample	**AASHTO**	**USCS**	**USDA**	**AASHTO**	**USCS**	**USDA**
Mobile WaB	A-2-4	SM	Fine Sandy Loam	A-2-6	SP-SC	Sand
Mobile MaD	A-4	SC	Fine Sandy Loam	A-2-6	SC	Loamy Sand
Mobile BeB	A-4	SC-SM	Fine Sandy Loam	A-2-4	SC	Sandy Loam
Etowah 9	A-4	ML	Silt Loam	A-2-6	SC-SM	Sandy Loam
Etowah 18	A-6	CL	Silt Loam	A-2-6	SC	Clayey Sand
Etowah 43	A-4	GM	Cherty Loam	A-2-6	SC	Sandy Loam
Shelby TsE	A-4	ML	Silt Loam	A-2-6	SM	Sandy Loam
Shelby TtE	A-4	CL	Silt Loam	A-2-6	SC	Loamy Sand
Bibb CmA	A-4	CL	Loam	A-2-4	SW-SC	Sand
Bibb MIA	A-4	CL	Sandy Clay Loam	A-2-7	SC	Sandy Clay Loam
Montgomery IdB	A-4	SM	Fine Sandy Loam	A-2-4	SW-SC	Sandy Loam
Montgomery KcA	A-7-6	CL	Clay Loam	A-2-6	SC-SM	Sandy Loam

The comparison of laboratory testing results with the WSS output shows that soil classification of most of the soil samples is showing substantial differences. There are some soil samples showing similarities in USCS and USDA classification systems such as Mobile MaD and Bibb MiA. However, an exact match between the WSS study and lab testing does not exist on any soil samples. This result indicates that even though WSS is a useful tool to identify existing soils on construction sites, additional laboratory soil testing is necessary due to the impacts of the dynamic nature of the construction activities. Flocculant selection based on soil type can be accomplished with the combination of desktop study and soil testing. However, completely relying on WSS desktop study results may falsify product selection procedures.

Soil reports for tested soil samples were prepared and included soil texture, particle size distribution, soil mineralogy, and CEC information. Results indicated that most of the classified soil samples were falling into the bottom right corner of the USDA texture triangle, which represents sand, loamy sand, and sandy loam as shown in Figure 4-30.

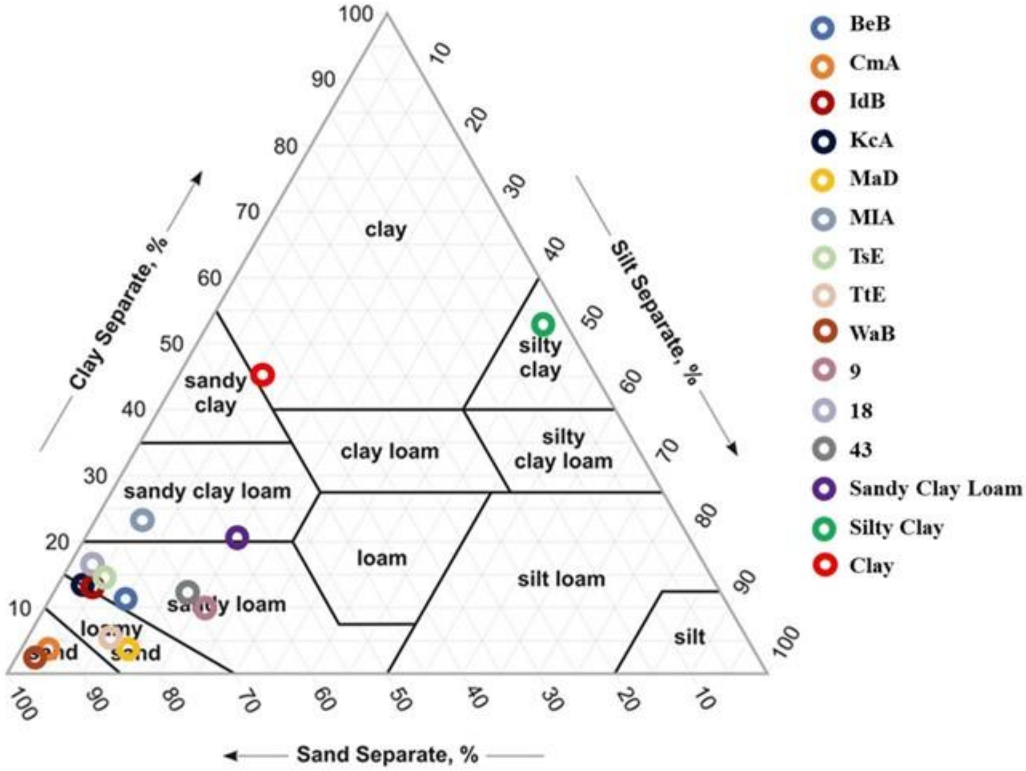


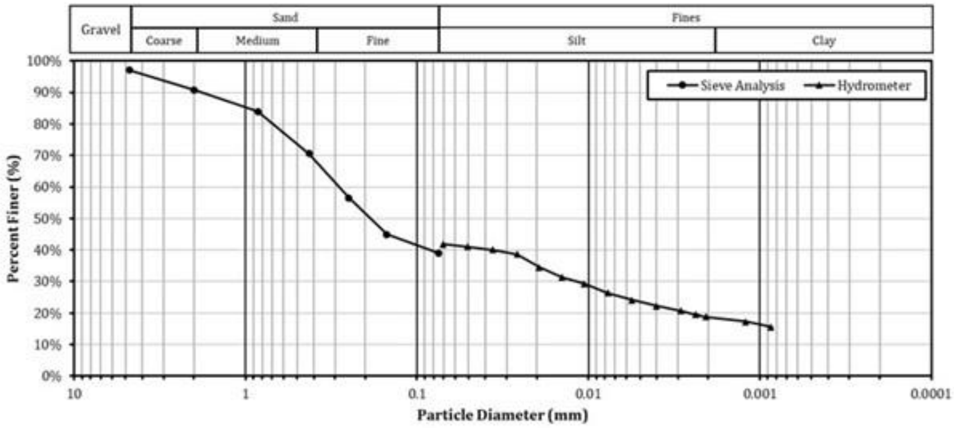
Figure 4-30: USDA Soil Classification Results.

The main goal of the soil assessment was to collect a range of soil types for bench-scale evaluation. Therefore, three more additional soils were included in the study, and samples were gathered from known sources within the state. These known sourced soils were classified as sandy clay loam, silty clay, and clay on the USDA texture triangle as symbolized with purple, dark green, and red in Figure 4-30. The addition of known sourced soil samples into the bench-scale experiments provided an opportunity to evaluate a wider range of soil samples on the texture triangle.

One of the additional soil samples was collected in East Alabama from AU-SRF and included in the product selection and dosage experiments. This soil was also used in residual, intermediate-scale flume, and large-scale testing studies. The reference soil was sampled from a Cecil map unit (fine, kaolinitic, thermic Typic Kanhapludults). Cecil is a benchmark soil found on over 5 million acres (2 million ha) of the southeastern U.S. Piedmont. Subsurface and subsoil horizons, such as what was used in this study, have low activity mineralogy (CEC < 16 cmol kg^{-1} clay) with clay fractions dominated by kaolinite and hydroxy-interlayered vermiculite with lesser amounts of iron and aluminum oxides. The low activity reference soil is representative of several million acres of southeastern Piedmont and Coastal Plain landscapes (*197*). The raw testing soil was classified as an A6 (fair to poor clayey soil) by the AASHTO method and as an SC (clayey sand soil) by the USCS method. Figure 4-31(a) shows the texture of the testing soil and

Figure 4-31(b) presents the particle size distribution curve. The testing soil has about 40% fines (silt and clay sizes) and about 18% of clay sizes; therefore, about 39% of the soil will pass through the No. 200 sieve (0.074 mm), Figure 4-31(b).

(a) soil texture



(b) particle size distribution

Figure 4-31: Soil Characteristics of Clayey Sand Testing Soil

The other additional soil sample, which was classified as sandy clay loam, was collected from construction sites located in Montgomery, AL as mentioned in the soil assessment methodology. This silty clay soil was specifically used in this study due to its typical grey-white characteristic that has a fine-grained texture and high plasticity, commonly observed in prairie regions. The soil showed high carbonate content and consisted of 95% fines including approximately 51% clay size and 44% silt size particles.

The final additional soil sample, which was collected from south of Auburn, AL, was used in dosage experiments to include clay in the evaluated soil samples. This clay soil was sampled from the Gwinnett map unit, (fine, kaolinitic, thermic Rhodic Kanhapludults). Gwinnett soil series typically exist in Piedmont Plateau with deep, well-drained, moderately permeable soils. The reference clay soil consisted of approximately 44% clay, 10% silt, and 46% sand-size particles.

Identifying the Cationic Exchange Capacity (CEC) of tested soils provides additional information for evaluating the behavior of flocculants on each soil sample. Table 4-12 presents CEC results based on the experiments conducted at Auburn University Soil Testing Laboratory.

Table 4-12: CEC Analysis Results

Soil Sample ID	CEC (meq / 100 g)	Clay Content (%)	CEC / Clay Content (meq / 100 g)
Shelby TtE	26.07	6.1	427
Bibb CmA	6.28	3.7	170
Mobile WaB	3.32	3.0	111
Shelby TsE	9.31	13.7	68
Montgomery Silty Clay	31.25	51.0	61
Mobile MaD	2.45	4.2	58
Montgomery KcA	7.05	13.9	51
Bibb MIA	10.00	21.3	47
Etowah 9	4.43	10.4	43
Etowah18	6.60	15.9	42
Etowah43	5.55	13.1	42
Montgomery IdB	4.82	12.7	38
Mobile BeB	4.12	12.1	34
AU-SRF Sandy Clay Loam	3.40	18.0	19
South Auburn Clay	5.55	43.8	13

The table presents raw CEC data tested in the soil testing lab and the percent clay content for each testing soil. To provide accurate data analysis, raw CEC values were normalized by dividing the values by the clay content of the soil properties. Based on the results Shelby TsE, Bibb CmA, and Mobile WaB have the highest CEC value reported as 427.4, 169.73, and 110.7 meq/100g, respectively. This indicates that cationic flocculants may get activated easily and provide effective flocculation on this soil. CEC results were correlated with the match test results in this research to validate flocculant selection based on changing soil characteristics.

4.11 MATCH TEST

Match test experiments provided a comprehensive data set regarding flocculant performance on various soil samples. Based on the point system developed for this test method, the products were ranked based on the highest score. The top three flocculant products with the highest score were selected for each tested soil and these products were further investigated in the dosage study. Match test procedures reduced time and resources in dosage test procedures by eliminating the products with mediocre performance.

Tabel 4-5 shows the top three ranking products for each soil together with product scores. The results indicate that the most effective flocculant type in the range of tested soil samples is PAM. Following PAM products, chitosan showed promising results on multiple soil samples when introduced into turbid water samples with a coagulant agent. It was also effective without the coagulant agent on two tested soil samples: Mobile WaB and Shelby TtE. These soil samples showed high CEC values based on the soil assessment results discussed in the previous subsection. As a cationic charge-activated natural flocculant, chitosan effectively facilitated flocculation on these soil samples due to their high capacity to retain cations.

Among the evaluated products, A performed well on 87% of the tested soils, while product F showed promising results on 80% of the soils. Product N was also effective on most of the soils; however, this sodium montmorillonite-based product was eliminated from the testing procedure due to pH concerns, which will be discussed in the dosage experiment results. For validating pH concerns, the product was included in the match test results for Shelby TtE as the fourth selected product for additional pH evaluations in the dosage experiments.

Table 4-13: Match Test Results

Soil ID	Product	Flocculant Type	Score
Etowah 9	D	PAM	32
	E	PAM	30
	K	Chitosan + Coagulant agent	31
Etowah 18	E	PAM	31
	F	PAM	28
	A	PAM	28
Etowah 43	F	PAM	33
	K	Chitosan + Coagulant agent	24
	A	PAM	34
Mobile WaB	F	PAM	26
	J	Chitosan	21
	K	Chitosan + Coagulant agent	21
Mobile BeB	E	PAM	26
	F	PAM	28
	A	PAM	25
Mobile MaD	B	PAM	25
	F	PAM	27
	A	PAM	29
Montgomery IdB	F	PAM	31
	K	Chitosan + Coagulant agent	25
	A	PAM	31
Montgomery KcA	E	PAM	27
	F	PAM	32
	A	PAM	36
Bibb MIA	G	PAM	30
	H	PAM	31
	A	PAM	31
Bibb CmA	D	PAM	27
	A	PAM	31
	H	PAM	26
Montgomery Silty Clay	A	PAM	32
	E	PAM	29
	F	PAM	29
AU-SRF Sandy Clay Loam	A	PAM	34
	D	PAM	32
	F	PAM	33
South Auburn Clay	A	PAM	34
	F	PAM	32
	G	PAM	29
Shelby TsE	E	PAM	27
	F	PAM	28
	A	PAM	27
Shelby TtE	F	PAM	28
	J	Chitosan	19
	A	PAM	26

	N	Sodium Montmorillonite	31

4.12 DOSAGE EXPERIMENTS

The use of flocculants in construction stormwater management provides substantial turbidity reduction in the stormwater runoff; however, there is a need for proper dosage guidance for ensuring pollution prevention and the safety of aquatic organisms. Dosage experiments in this research evaluated optimum dosage rates for the products selected as a result of match test experiments. The manufacturer's dosage recommendation was ranged from 0% to 200% through six beakers in the mixing machine for evaluating the impacts of underdose and increased dosage conditions. Results were analyzed based on turbidity reduction, pH, temperature, and color change.

Turbidity reduction was the major identifier for optimum dosage determination in dosage experiments. The % turbidity reduction was calculated by using initial and final turbidity readings as shown in Eq. 4-5.

$$\%\,Turbidity\ Reduction = 100 - 100\ x\,\frac{T_f}{T_i} \qquad \textbf{Eq. 4-5}$$

Where,

T_i = initial turbidity reading (NTU)

T_f = final turbidity reading (NTU)

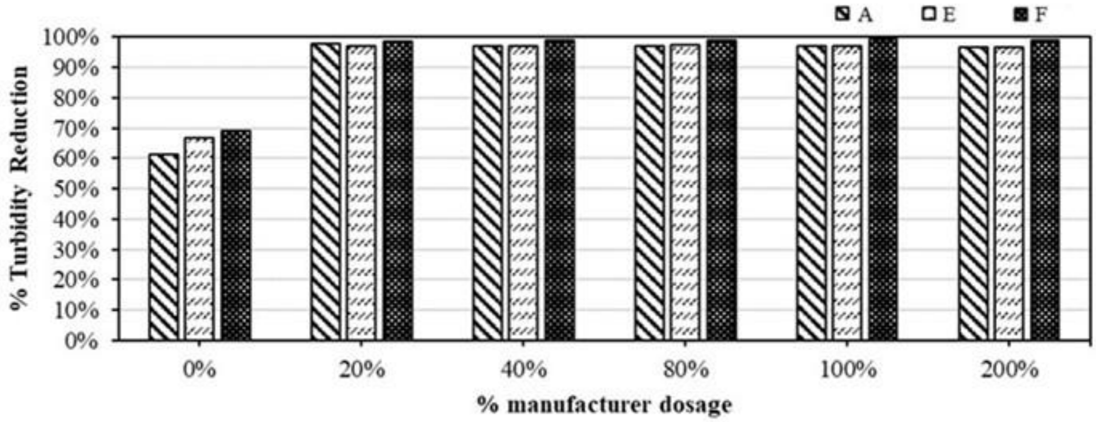
Table 4-14 illustrates an example data analysis result for the dosage experiment conducted on Bibb CmA soil sample with product D flocculant introduction. The dosage recommendation of the manufacturer was 50 mg/L, and it was ranged in the experiment between 0% to 200 % of this value. According to the turbidity reduction results, it was observed that the normal settling behavior of the soil showed 72.6% turbidity reduction, while the manufacturer dosage guidance showed a 97% reduction. The highest reduction in turbidity was reached in underdosing conditions on the sample that had a flocculant dosage of 10% of the recommendation. The sample showed a 98.8% reduction in turbidity which is not a substantial difference compared to the recommended dosage. In this case, it can be observed that reducing the dosage would provide potential benefits for cost and resource management. However, following the manufacturer's guidance would meet the maintenance requirements of the product on-site conditions since storm events will gradually contribute to product wash-off. For the change in pH, there was no substantial difference noted in the data analysis for this specific product when applied to Bibb CmA soil. Color evaluations on the supernatant showed that underdose conditions provided substantial clarity in the water compared to the control sample. However, the increased dosage condition showed less clear color on the supernatant sample compared to underdose samples. Floc size showed an increase of 80% of the recommended dosage value and maintained the 1.0-1.5 mm range in the 100% and 200% samples.

Table 4-14: Dosage Experiment Results for Bibb CmA with Product D Application

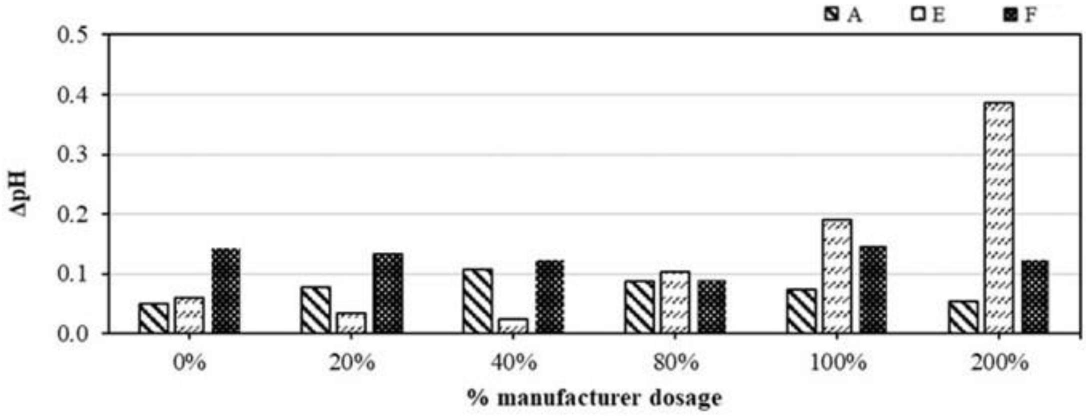
Dosage (mg/L)	0	10	20	40	50*	100
ΔNTU (%)	72.6	98.8	97.6	97.3	97	96.4
ΔpH	0.05	0.04	0.10	0.10	0.07	0.09
Color	Light yellow	Clear	Clear	Clear	Clear	Less clear
Floc Size (mm)	N/A	0.75-1.0	0.75-1.0	1.0-1.5	1.0-1.5	1.0-1.5

** manufacturer dosage recommendation*

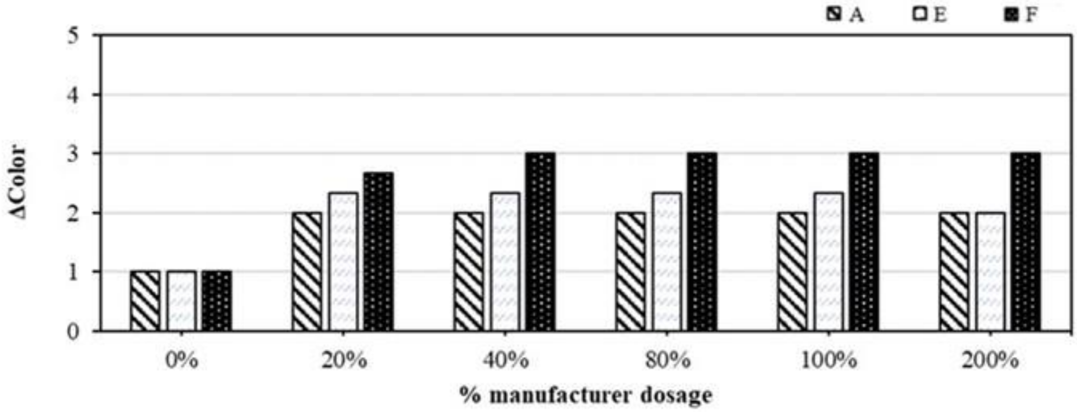
The data analysis shown in Table 4-14 was conducted for each dosage experiment and optimum dosage reports were prepared by producing turbidity reduction, ΔpH, and color plots. These data analysis plots presented dosage experiment results for behavior evaluation of the top three selected products on sampled soils as shown in the example presented in Figure 4-32.



(a) % turbidity reduction



(b) change in pH



(c) change in color

Figure 4-32: Dosage Test Data Analysis Plots for Shelby TsE

Figure 4-32 illustrates an example for the dosage test data analysis plot by displaying percent turbidity reduction, pH, and color change results for Shelby TsE soil with the introduction of products A, E, and F PAM-based flocculants. In Figure 4-32(a), percent turbidity reduction data were plotted versus dosage range based on percent manufacturer dosage recommendation. Results indicated that all of the three selected products show high turbidity reduction rates that stay above 97% in underdose dosage rates, recommended dosage rate, and overdosage conditions. The normal settling condition of the control sample showed an average value of 66% turbidity reduction. It can be observed that the use of these products provides approximately a 30% additional decrease in turbidity.

Figure 4-32(b) displays results for change in pH after the completion of dosage experiments. There was no substantial difference observed for pH change on any tested product for Shelby TsE. However, it should be noted that product E showed approximately 0.4 change in pH in case of the increased dosage condition. This behavior was also observed on other tested soils such as Montgomery KcA, Mobile BeB, Etowah 9, and Etowah 18.

Figure 4-32(c) shows the change in color in the turbid water samples after the settling period in the dosage experiment procedures. The turbid water samples that were prepared with the use of Shelby TsE soil showed the highest change in color with the introduction of product F. This product changed the sample color from brown to clear. Products A and E also showed promising performance for providing clear color; however, the clarity of the supernatants was not as clear as product F samples.

Temperature was another factor that was included in the data analysis. Researchers did not record any substantial change in the temperature during dosage experiments after the flocculant introduction.

Dosage study results provided the opportunity to identify the significance of the pH measurements for flocculant dosage evaluation. For instance, sodium montmorillonite-based testing product (Product N) showed concerning changes in pH on multiple different soil samples during match test and dosage test procedures. This product was also tested for pH on a clear water sample. The pH of tap water that was used in the experiment ranged between 6.7 and 7.6. The pH measurement results after the introduction of product N showed a substantial drop in pH by almost 4.0 as shown in Figure 4-33.

Reducing pH might be a secondary benefit of flocculant products for attracting fine soil particles; however, USEPA highlights the optimal pH range for aquatic organisms as 6.5 to 8.5. Hence, the use of this product in the experiments was perceived as concerning and the product was removed from further investigations in the study.

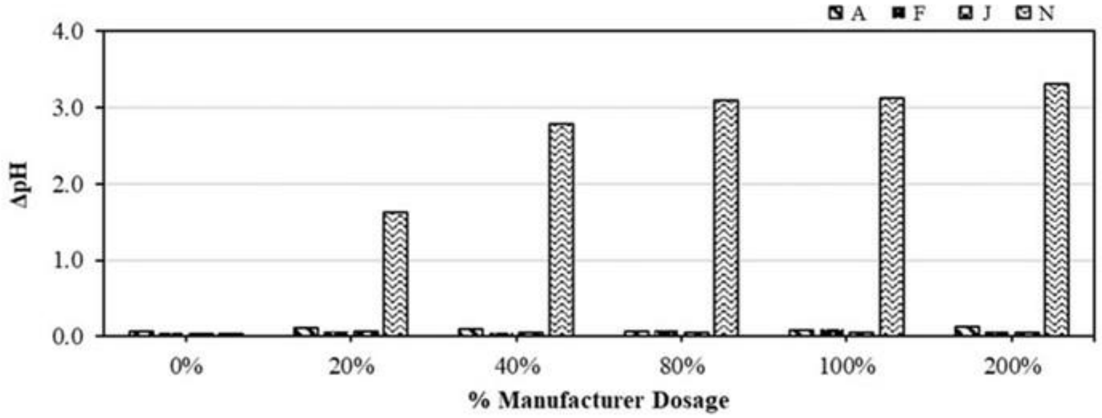


Figure 4-33: Change in pH on Shelby TtE

Results of the dosage experiments indicated that lower flocculant concentrations show similar performance compared to the recommended dosage rates obtained from manufacturers. This observed similarity was statistically analyzed with ANOVA by comparing turbidity reduction of flocculant doses used in the experiments. The control condition was left out of the ANOVA analysis since it did not contain any flocculant concentration. In total, 42 ANOVA analyses were conducted on average turbidity reduction values obtained from dosage experiments. Results indicated statistically significant similarities between dosage rates at the 95% confidence level, except for the dosage experiment conducted on product D and Bibb CmA soil. ANOVA analysis on this specific dosage experiment showed a statistically significant difference between dosage rates, which required rejecting the null hypothesis with a p-value less than 0.05. To identify which pairs of dosage rates show a significant difference in turbidity reduction, ten series of paired t-tests were completed at a 95% confidence level. Results indicated that using 20% of the manufacturer's dosage rate showed a significant difference compared to 40% of the recommended dosage with a p-value of 0.0249. Table 4-15 shows statistical significance comparisons between dosage rate pairs.

Table 4-15: Statistical Significance Comparisons

Dosage Experiment ID	Comparison	p-value
Bibb CmA- Product D	20% and 40%	0.0250*
	20% and 80%	0.2070
	20% and 100%	0.3340
	20% and 200%	0.1242
	40% and 80%	0.3877
	40% and 100%	0.4306
	40% and 200%	0.1821
	80% and 100%	0.4653
	80% and 200%	0.0605
	100% and 200%	0.8422

*Indicates statistical significance (p<0.05)

Statistical analysis provided supportive data for observations made on the similarity of lower concentrations to the manufacturer's dosage recommendation. After the completion of the dosage experiments and during a presentation of results at a conference, it was determined that product manufacturer II had miscommunicated dosage recommendations for several PAM products (products B, C, D, E, F, G, H). A dosage recommendation of 50 mg/L was used where it should have actually been 5 mg/L. This miscommunication did not invalidate the testing results since dosage experiments were designed to range the recommended dosage concentrations between lower and higher dosage rates. However, it is important to note that completely relying on manufacturer guidance, which is a commonly used approach by state agencies, might potentially cause application issues on construction sites. This further validates the need for further research on flocculant guidance for construction applications.

Dosage experiments showed promising results for the determination of optimum flocculant dosage rates in a laboratory setting. Testing different flocculant products across various soil samples provided significant information for filling the gap in knowledge for optimum dosage guidance. These results provided a basis for identifying the methodology of the next phases of this research, which integrates intermediate-scale flume testing and large-scale testing procedures for mimicking construction site conditions.

4.13 DETECTION OF RESIDUAL CONCENTRATIONS

Residual monitoring of flocculants plays a supportive role in protecting downstream water bodies from high concentration discharge of polymers and following toxicology limits. As mentioned in the methodology section, initially the spectrometer method was utilized for detecting residual concentrations in this study. The absorbance values obtained from spectrophotometer readings were attempted to be correlated with known flocculant concentrations to measure existing flocculants in samples. Results indicated that although this method worked on PAM and chitosan-based products, it was not valid for other flocculant types. Figure 4-34 presents the absorbance and known concentration relationship of the product I, which was one of the products that the method was not effective. Known concentration samples had the flocculant concentration of 0, 36, 72, 144, 180, and 360 mg/L. It was expected to observe a linear relationship between absorbance readings and known concentration values to develop standard residual concentration curves. However, results showed a low R^2, which indicated a poor linear relationship for this specific product.

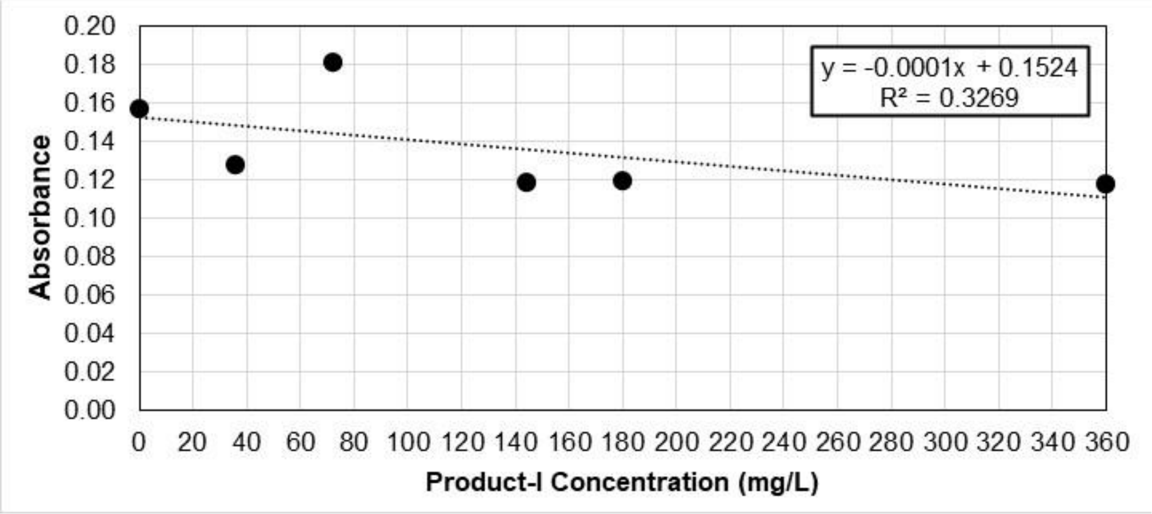


Figure 4-34: Absorbance Readings for Known Concentration Samples of the Product I

Due to the limitations observed in the spectrophotometer method, the residual detection methodology was shifted to correlation settling velocity of flocculated samples with known concentrations. The results of the study showed that flocculant concentrations can be measured under field conditions by using a turbid water sample with a specific soil type. Each flocculant product exhibits a unique settling behavior on the fine soil. Therefore, observing the settling velocities of known concentration injections provided significant data for the development of standardized residual concentration plots.

Experimental data showed a linear relationship between settling depth and settling time. Furthermore, data plots exhibited a decrease in settling time with an increase in flocculant concentration. Figure 4-35 shows depth and time observation data for product I. The soil passing through the No. 200 sieve was weighed as 0.71 oz (20 g) and mixed in with the known concentration samples for settling velocity observations. The presented graph includes settling depth and time data for control and known concentration samples ranging in 1%, 5%, 10%, 20%, and 30% of the manufacturer concentration recommendations. The manufacturer concentration recommendation for the product tested in Figure 4-35 was 180 mg/L (100%). Therefore, known concentration samples consisted of 0 mg/L (0%), 1.8 mg/L (1%), 9 mg/L (5%), 18 mg/L (10%), 36 mg/L (20%), and 54 mg/L (30%) for product I as illustrated in Figure 4-35. The corresponding average settling velocities are 51, 74, 80, 97,125, and 236 in./hr (130, 188, 203, 246, 318, and 599 cm/hr), respectively. Similar plots were developed for each evaluated product.

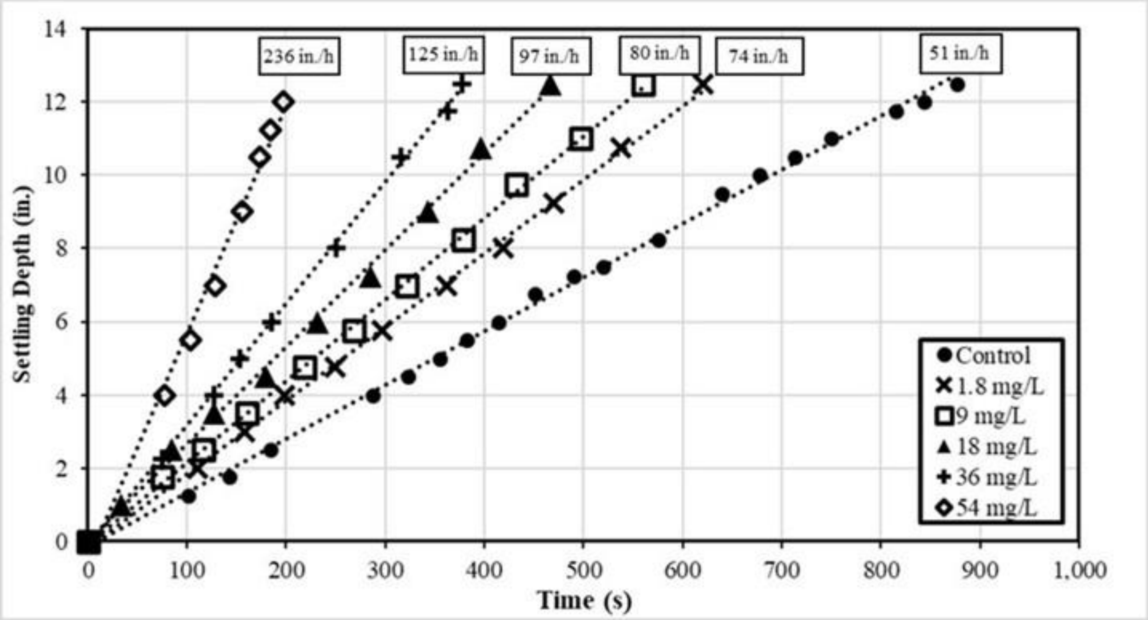
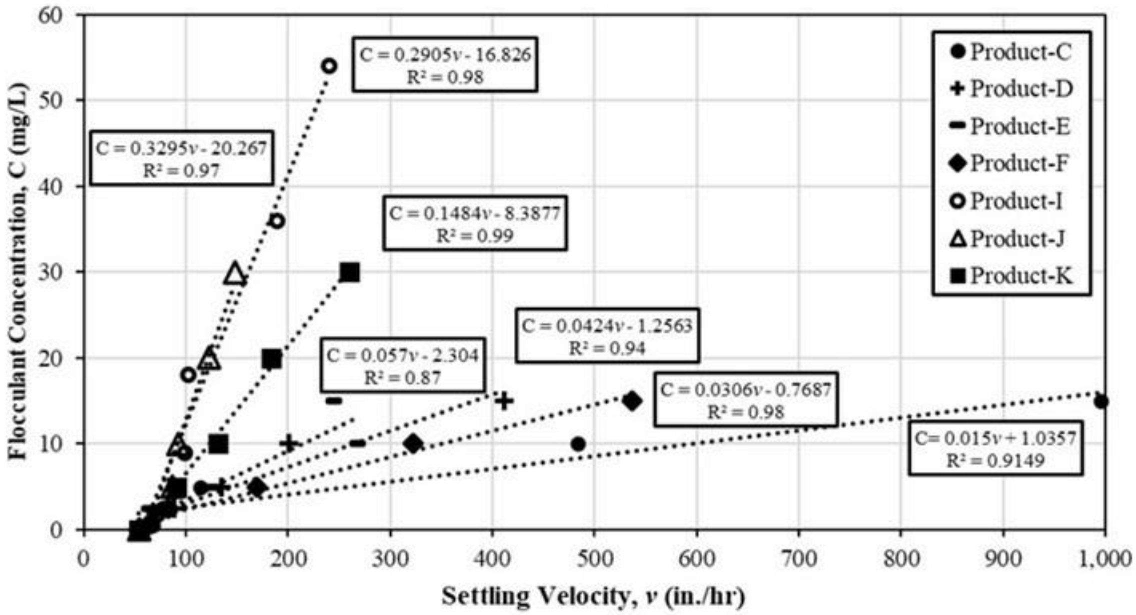


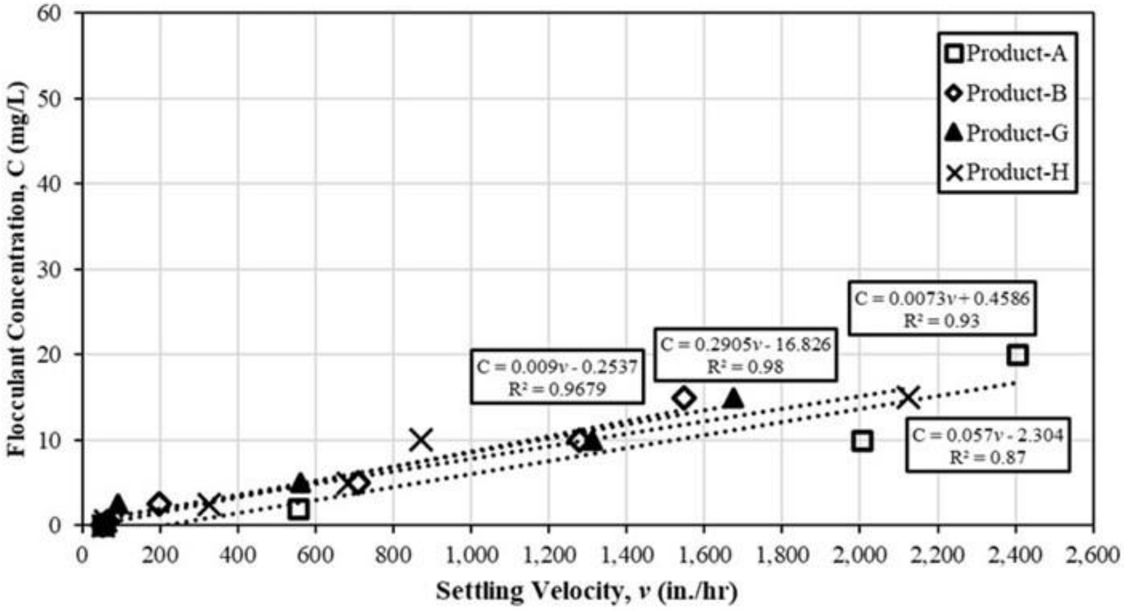
Figure 4-35: Settling Depth vs. Time Plot of Product I for Six Residual Concentrations

As observed in Figure 4-35, the control sample had a longer settling period than samples with flocculant residuals. The data for each sample showed a linear trend with 0.99 coefficient of determination (R^2) values and the slope of the trendlines increased with increasing concentrations. The slope of the trendline gives the settling velocity. These plots validated the initial assumption of the study; an increase in residual concentration decreases the settling time. The plot depicts that the settling of the turbid sample takes approximately 875 seconds when it does not have any flocculant residuals (ideal/best scenario), while the water sample with the highest evaluated concentration (54 mg/L) of flocculant residuals settles in approximately 200 seconds. The preparation of these plots for each product and experiment repetitions showed promising results for relating settling velocities with known concentrations of flocculant residuals.

Of the 14 evaluated products, two products, agricultural gypsum (Product L), and alum (Product N) were excluded from the study results since residual settling plots did not show a meaningful trend. The results indicated that the settling velocity of these products does not present a significant relationship with known concentration values of the flocculant residuals. Standardized residual settling plots were created for the remaining products by using average settling velocity (in./hr) data from three repeated tests with known residual concentration (mg/L) values, as shown in Figure 4-36. Standardized residual settling results were presented in two plots in Figure 4-36 for facilitating data visualization due to the wide settling-velocity ranges of products. Figure 4-36(a) presents residual settling data for products C, D, E, F, I, J, and K, while Figure 4-36(b) presents residual settling plots for products A, B, G, and H. Subscripts of C and v stands for product index in these figures. In this study, the residual concentrations of different flocculants are known, and the corresponding settling velocities were determined experimentally, but the settling velocity versus the residual concentration was not plotted in Figure 4-36(a) and (b). When plotted, the flocculant residual concentration versus the settling velocity in Figure 4-36(a) and (b), these plots can be directly used for future monitoring applications: when the settling velocity is first determined from the effluent, one can then find the flocculant residual concentration from the plots.



(a) residual settling plots (part 1)



(b) residual settling plots (part 2)

Figure 4-36: Standardized Residual Settling Plots

Residual settling data were used for regression analysis to identify the correlation between settling velocities and known residual concentration values. A strong relationship between these two parameters exists in almost all tested products except agricultural gypsum and alum. R^2 values for products A, B, C, D, F, G, H, I, J, and K were above 0.91. The lowest R^2 value was 0.87 for product E, which still indicated a valid relationship between settling velocity and residual concentration values. Regression results showed that approximately 90% of known concentration values of each product were fully characterized by settling velocities.

The resulting regression equations in Figure 4-36(a) and (b) proved relationships between the settling velocity and residual concentrations and provided a sufficient and accurate solution for determining an unknown residual flocculant concentration in discharge (effluent) samples. Figure 4-37 illustrates an example application: estimating/determining the residual concentration for a sample with an unknown residual concentration for product N. The average settling velocity of the sample was determined to be 1,270 cm/hr (500 in./hr) after three repetitions of the measurement and using Figure 4-37, the residual concentration of the product was determined to approximate 415 mg/L.

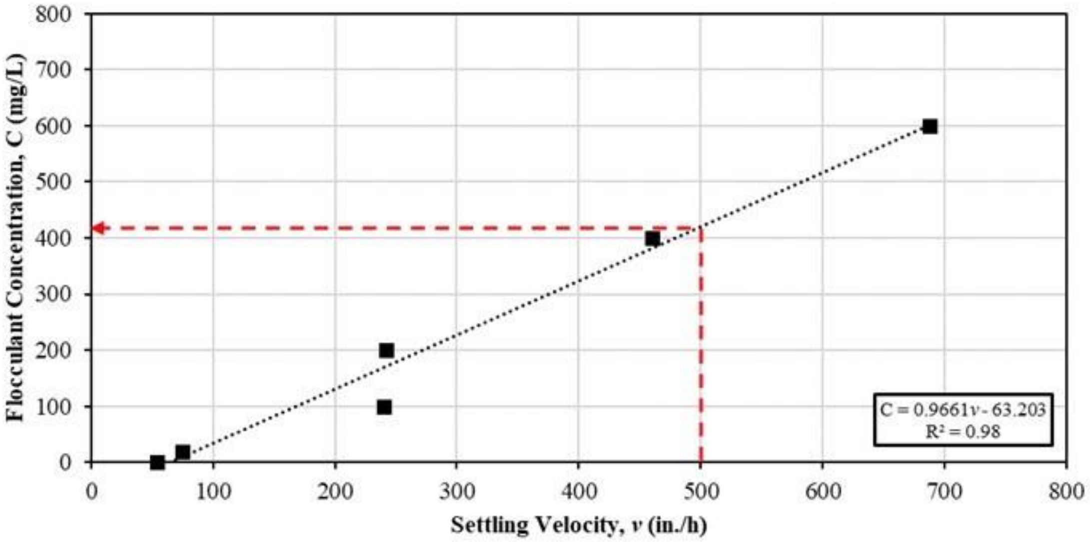


Figure 4-37: Concentration Determination Example with Product N

For effective measurement in field conditions, approximately 33.8 fl oz (1,000 mL) of water samples should be collected closer to the downstream discharge point after flocculant application. These samples should be mixed with a pre-determined amount of testing soil that forms the residual settling plots. The mixed sample with unknown flocculant residual concentration should be poured into a graduated cylinder and settling depth should be observed over time with the use of a stopwatch and a ruler. Recorded settling depth and time data should be used as an input to calculate the average settling velocity. This procedure should be repeated three times to estimate the average settling velocity. Once the average settling velocity value of the sample is determined, it can be used as an input for estimating the residual concentration of flocculant present in the sample based on the developed regression equations.

The results of this study have provided an effective approach for monitoring residual concentrations to be applied on construction sites during flocculant usage. The presented data have the potential to be adapted to the field conditions by requiring limited equipment (three graduated cylinders with a ruler and a stopwatch) and technical knowledge. This study can be easily adapted for different testing soils and site-specific residual monitoring can be rapidly accomplished by practitioners on construction sites.

4.13.1 EXPANDED RESIDUAL SETTLING CURVES WITH INFLUENCING FACTORS

Granular PAM

A total of 80 samples were replicated three times at four pH concentrations between 5.4 to 8.4, four temperatures between 1.0 to 30℃, and five concentrations between 0.0 and 7.0 mg/L, resulting in 240 total samples evaluated to generate the Product A-G settling velocity calibration. A cumulative distribution function of the data (Figure 4-38) was used to determine the acceptable level of variability with the data once each of the initial samples were ran with the three replicates each. The CDF was created by calculating the standard deviation between the three replicates for each sample that was tested at the different pH values, temperatures, and concentrations measured, resulting in 80 total standard deviation values. The standard deviation values were then ranked in ascending order. The probably for the lowest standard deviation sample value was calculated by dividing one by the number of standard deviation values, yielding 1.25%. All subsequent probability calculations were calculated by adding 1.25% to the previous probability value. The largest standard deviation value should have a probability equal to 100%, if properly calculated. The standard deviation and probability values were then plotted on the CDF plot, Figure 4-38. Here, the variability can be seen that of 90% of the data Is within 500 in./hr for the first 240 samples collected (initial samples). Meaning, the top 10% of the initial samples collected are considered as outliers. This was justified because the top 10% of the data was notably more dispersed. Therefore, any sample replicates that were more than 500 in./hr from the mean of the other two, all three replicates of that sample would be repeated. This process was repeated until all three sample replicates were within the specified range for each of the 80 samples. The final 240 samples that were within the specified range, were then plotted in the CDF plot.

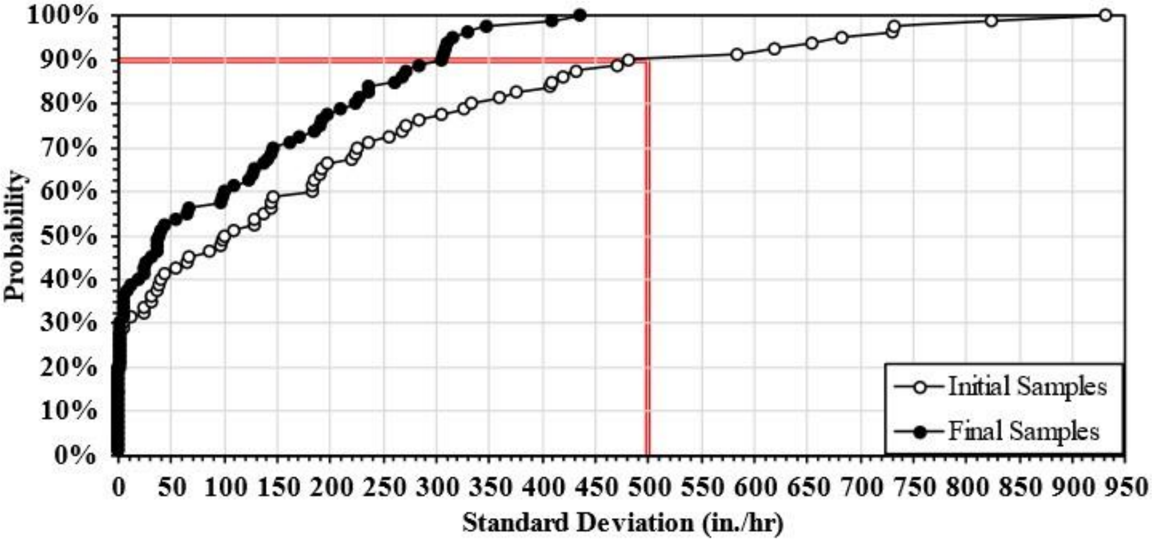


Figure 4-38. Product A-G CDF Plot

Figure 4-39 shows how each temperature, pH, and Product A-G concentration influences the settling rate. As the temperature increases, flocculant settling velocities increase across all pH concentrations, but these settling velocities are fastest at lower pH concentrations. This is because anionic PAM is a negatively charged functional group that is considered as a Lewis base due to its ability to donate electron pairs to a Lewis acid, enabling the formation of flocs through covalent bonds (*198*). A Lewis acid is defined as an atom, ion, or molecule that can accept an electron pair from another atom, while a Lewis base can donate the electron pair (*199*).

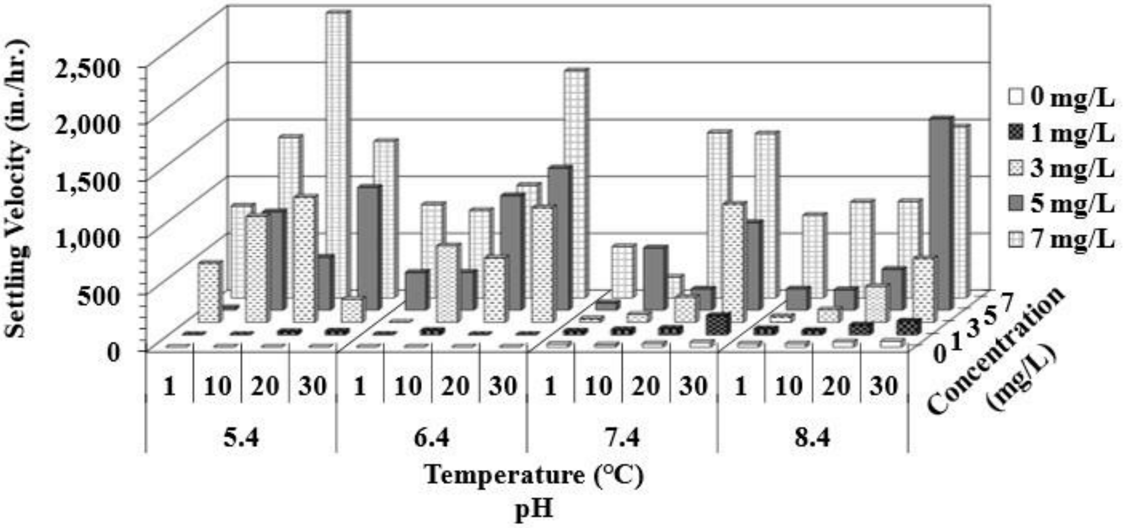


Figure 4-39. Soil Settling Velocity Against Different pH Concentrations, Temperatures, and Increasing Product A-G Concentrations

Table 4-16 shows MLR results that indicate pH, temperature, and Product A-G concentration all significantly influence the settling velocity.

Table 4-16. Product A-G Settling Velocity Multiple Linear Regression Analysis

	Coefficients	***p*-value**[a]
Constant	153.134	0.305
pH	-68.605	<0.001
Temperature (℃)	17.536	<0.001
Product A-G Concentration (mg/L)	156.184	<0.001
R^2	0.620	

[a]Comparison to effects of base at 95% confidence interval and *p*-value <0.05

The MLR regression equation was rewritten to solve for Product A-G concentration, shown in Eq. 4-6.

$$C_{Product\ A-G} = \frac{v_{settle} - 153.13 + 68.61pH - 17.54T}{156.18} \qquad \text{Eq. 4-6}$$

Where $C_{Product\ A-G}$ is the Product A-G concentration (mg/L); v_{settle} is the soil settling velocity (in./hr); pH is the pH value of sample before performing residual test; and T is the temperature of sample before performing residual test (℃). Allowing users to enter known pH, temperature, and measured settling velocity data from large-scale test samples to predict Product A-G dosing concentrations in the field during different seasons and geographical locations. Eq. 4-6 can be rewritten to solve for the soil settling velocity, which can be used for detention pond designing to ensure the treated water has sufficient time to settle out of suspension before being discharged off-site. This equation was based on a concentration calibration range between 1 mg/L to 7 mg/L of Product A-G. High concentrations may not be accurate predictions. Even though data did include flocculant free settling velocities, the lowest flocculant concentration that could be accurately measured was 1 mg/L, thus, this equation is not able to accurately predict concentrations under 1 mg/L. Temperature and pH ranges used for this calibration equation accounted for 1.0 ℃ (34℉) to 30℃ (86℉), and 5.4 to 8.4 pH, respectively.

It is important to note that this equation is flocculant and soil specific. The flocculant used was Product A-G from Manufacturer I. Since flocculants are also soil specific and flocculants differ by manufacturer, a calibration curve for each flocculant type for each manufacturer matched with each soil type.

Block PAM

A total of 144 samples were replicated three times at four pH concentrations between 5.4 to 8.4, four temperatures between 1 ℃ (34℉) to 30℃ (86℉), and five concentrations between 0 and 200 mg/L, resulting in 432 total samples evaluated to generate the Product A-B settling velocity calibration. A cumulative distribution function of the data (Figure 4-40) was used to determine the acceptable level of variability with the data once each of the initial samples were ran with the three replicates each. The CDF was created by calculating the standard deviation between the three replicates for each sample that was tested at the different pH values, temperatures, and concentrations measured, resulting in 144 total standard deviation values. The standard deviation values were then ranked in ascending order. The probably for the lowest standard deviation sample value was calculated by dividing one by the number of standard deviation values, yielding 0.78%. All subsequent probability calculations were calculated by adding 0.78% to the previous probability value. The largest standard deviation value should have a probability equal to 100%, if properly calculated. The standard deviation and probability values were then plotted on the CDF plot, Figure 4-40. Here, the variability can be seen that of 95% of the data is within 60 in./hr for the first 432 samples collected (initial samples). Meaning, the top 5% of the initial samples collected are considered as outliers. This was justified because the top 5% of the data was notably more dispersed. Therefore, any sample replicates that were more than 60 in./hr from the mean of the other two, all three replicates of that sample would be repeated. This process was repeated until all three sample replicates were within the specified range for each of the 144 samples. The final 432 samples that were within the specified range, were then plotted in the CDF plot.

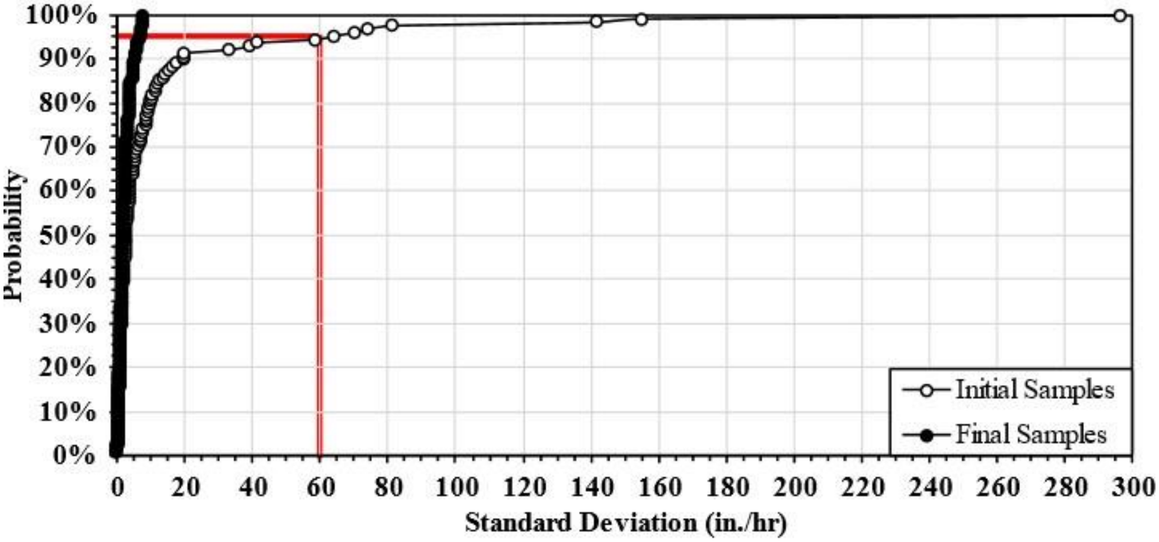


Figure 4-40. Product A-B CDF Plot

Figure 4-41 shows how each temperature, pH, and Product A-B concentration influences the settling rate. As the temperature, pH, and concentration increases, soil settling velocities also increase. This is slightly different from Product A-G where a low pH resulted in increased settling velocities. This data was based on a concentration calibration range between 3 to 200 mg/L of Product A-B, and 0 mg/L was also evaluated and used as the control. A range of 3 to 200 mg/L of Product A-B was evaluated to see if there would be a correlation with Product A-G concentrations at various pH and temperatures. Since Product A-B and Product A-G contain the same flocculating agent, the concentration range of Product A-B was expanded well beyond the manufacturer’s recommendations of 5 mg/L to assess if the quantity of flocculating agent could be correlated with the two PAM forms. However, due to the nature of a flocculant block being a gelatinous consistency before being subjected to water, it is challenging to quantify how much flocculant dissolved into the sample. Meaning while this data was collected by weighing out grated pieces of Product A-B and adding the known weights to one liter of water with sediment, it can be said that the turbid water came in contact with the known amount of Product A-B. However, it is unknown how much of the known amount dissolved and became accessible to create flocs. During testing, Product A-B clumps were occasionally observed when graduated cylinders were cleaned. However, due to the scale of Product A-B pieces used for obtaining various weights, recovering Product A-B after the test was not a viable option. Therefore, there is a possibility that even though all samples were ran at different pH values, temperatures, and Product A-B concentrations, only a small amount of the flocculant may have made it in the sample. Which, if the concentration is low enough, would result in settling velocities to be similar across the board.

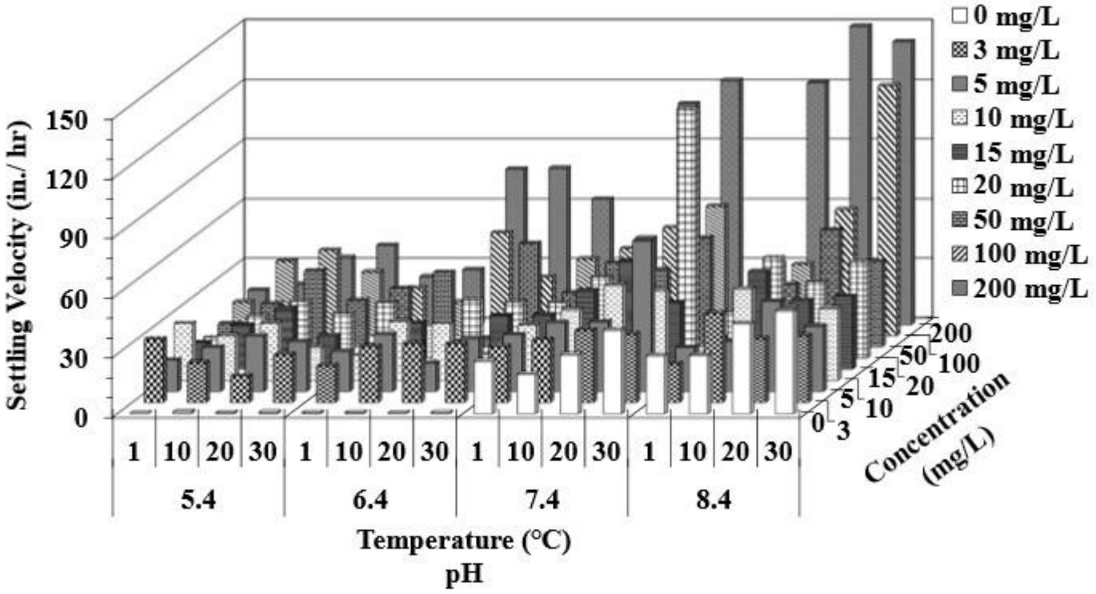


Figure 4-41. Soil Settling Velocity Against Different pH Concentrations, Temperatures, and Increasing Product A-B Concentrations

Samples evaluated at pH 7.4, temperatures above 20℃ (68℉), and concentrations above 50 mg/L had the highest variability outside of the acceptable range of 60 in./hr from the mean of the other two sample replications, resulting in these samples being repeated multiple times. The same occurred with pH 8.4, temperatures above 20℃ (68℉), and concentrations above 10 mg/L where these samples had the highest variability and required reevaluations. Samples at the highest pH, temperature, and top two concentrations were ran 11 times before obtaining consistent results. Indicating that the higher the pH, temperature, and concentration, the less consistent the results were and required multiple runs. Suggesting the possibility that the wide range of variability was due to more of the flocculating agent dissolved into the sample. Since the flocculant block was grated and small pieces were used to weigh out the samples, there was no consistency with each gelatinous piece. Thus, the high variability could have been a result of smaller pieces of Product A-B dissolving and forming flocs where the larger pieces only partially dissolved. Therefore, the ASTM jar testing methodology (*143*) may be ideal for Product A-G but not Product A-B. It is recommended for future evaluations to change the testing methodology for block form flocculants to allow for additional time for the block to dissolve where it can create flocs and correlate those results to settling velocities collected in large-scale testing.

Table 4-17 shows MLR results that indicate pH, temperature, and Product A-B concentration all significantly influence the settling velocity.

Table 4-17. Product A-B Settling Velocity Multiple Linear Regression Analysis

	Coefficients	***p*-value**[a]
Constant	-54.422	<0.001
pH	9.841	<0.001
Temperature (℃)	0.784	<0.001
Product A-B Concentration (mg/L)	0.215	<0.001
R^2	0.524	

[a]Comparison to effects of base at 95% confidence interval and *p*-value <0.05

The MLR regression equation was rewritten to solve for Product A-B concentration, shown in Equation Eq. 4-7.

$$C_{Product\ A-B} = \frac{v_{settle} + 54.42 - 9.84pH - 0.78T}{0.22} \qquad \text{Eq. 4-7}$$

Where $C_{Product\ A-B}$ = Product A-B concentration (mg/L); v_{settle} = soil settling velocity (in./hr); pH = pH value of sample before performing residual test; and T = temperature of sample before performing residual test (℃). Same as the prediction equation for Product A-G, this equation allows users to enter known pH, temperature, and measured settling velocity data from large-scale test samples to predict Product A-B dosing concentrations in the field during different seasons and geographical locations. Again, Eq. 4-7 can be rewritten to solve for the soil settling velocity, which can be used for detention pond designing to ensure the treated water has sufficient time to settle out of suspension before being discharged off-site.

It is important to note that this equation is flocculant and soil specific. The flocculant used was Product A-B from Manufacturer I. Since flocculants are also soil specific and flocculants differ by manufacturer, a calibration curve for each flocculant type for each manufacturer matched with each soil type.

4.14 SUMMARY

This study has shown the need for determining a field-applicable residual testing method and applying bench-scale experiments for identifying proper dosage and product selection requirements due to the soil-dependent nature of most flocculant products. The demonstrated study developed optimum flocculant dosage guidance and a method for estimating residual flocculant concentrations in laboratory settings by conducting bench-scale experiments. The study included an assessment of viscosity, particle charge analyzer, and settling velocity-based detection methods, soil samples, development of match test procedures for performance evaluation, and dosage experiments for identifying optimum dosage rates.

There are several methods for quantifying flocculants, but the challenge was to find a detection method that is simple and easy to perform without extensive lab training, low cost, works with sediment-ladened samples, produces reliable results in a short time, and can quantify concentrations above and below the PAM manufacturer's recommendation of 5.0 mg/L. A Cannon-Fenske Routine Viscometer and Brookfield Digital Viscometer were not sensitive enough to discern concentration changes below 20 mg/L. Cannon-Fenske tubes also required samples to be silt-free before evaluation since debris could block the tubes and affect results.

LCA was performed using two anionic forms of flocculant, G and Product A-B, and one cationic form, chitosan. Product A-G and chitosan were not viable options for determining increased dosing by measuring the sample's SCV in the presence of sediment, whereas Product A-B was able to quantify concentrations between 3 and 7 mg/L. When soil is present at 0.125 to 7.00 mg/L, 3.00 to 7.00 mg/L, and 20 to 200 mg/L, Product A-G, Product A-B, and chitosan flocculants dramatically lower pH values. Using sample pH change versus SCV may be able to approximate concentration ranges that would be difficult to distinguish from concentration versus SCV plots alone. Future evaluations should include additional flocculants and soil types because trends and connections may vary.

Findings obtained in the soil assessment phase of the study revealed the need for identifying soil properties in the pre-product selection stage and emphasized the significance of understanding the role of soil chemistry on flocculant performance. The study evaluated 15 different soil samples collected across Alabama for particle size distribution and CEC to identify soil characteristics that have a role in the flocculation mechanism. Soil classification results were also compared with the WSS desktop study, which was conducted before planned soil sampling visits to active construction sites. Even though WSS provides significant information on soil samples, the results showed the necessity to sample soils on sites for soil assessment procedure. Results indicated that identifying texture characteristics of soils is not sufficient alone for product selection since just the fine portion of the soils is being treated with flocculant. Therefore, evaluation of soil chemistry together with clay mineralogy would enhance the product selection procedure. Soil assessment results also marked the importance of CEC on flocculant selection. Soils with high CEC/ % clay content tended to perform well with flocculants activated by cationic charges, which were products J and K.

The development of match test procedures in this research provided a step-by-step product performance evaluation guidance based on the soil-dependent characteristics of the flocculants. The performance evaluation experiments provided rapid results for selecting the top three best-performing products for each evaluated soil sample before investigating the dosage requirements of these products. Among evaluated flocculant types in this study, all tested soils showed effective reaction with PAM. Chitosan and the combination of it with a coagulant agent performed well on five of the tested soils. However, other tested flocculant types did not perform well enough to be ranked as best performing products.

Following match test experiments, the study evaluated best performing products on each soil for dosage requirements. Dosage recommendations obtained from manufacturers were ranged from 0% to 200% of the suggested concentration values to observe underdose and increased dosage conditions. Dosage experiment results and statistical analysis on the turbidity reduction indicated that the underdose conditions show similar performance compared to the recommended concentration value at a 95% confidence level. Results of the dosage study showed that increased dosage condition leads to increased turbidity by increasing the viscosity of the sample, which interrupts the settling of formed flocs. The study also highlighted the significance of observing pH while identifying the dosage requirements of products.

In addition to dosage experiments, the study focused on providing a field applicable residual concentration detection method that is effective on different flocculant types. Settling velocity of flocculated turbid samples, which were prepared with testing soil and known concentration flocculants, was used as a variable that identifies residual concentrations. The data showed a linear trend between settling depth and time with 0.99 coefficient of determination (R^2) values. This result provided validation for the correlation of settling velocities with known concentrations. Standardized residual concentration plots were prepared for each tested product and the resulting plots established an effective solution for detecting residual concentrations in construction stormwater runoff.

Initial residual settling plots created had shown promise in preliminary large-scale testing for initial large-scale application of residual flocculant detection. Nonetheless, it was evident that environmental conditions present in the field that affect flocculant efficacy must be accounted for in this method. Residual settling plots were produced by monitoring the settling velocity for different flocculant concentrations at varied pH values and temperatures to assess flocculant efficacy across many parameters that can vary by geographical region and season. The settling velocities of Product A-G and Product A-B were found to be substantially affected by pH, temperature, and concentrations. According to Product A-G trends, temperature, concentration, and pH increase soil settling velocity, while Product A-B soil settling velocity trends increase as temperature, concentration, and pH increase. As it is uncertain whether the measured amount of Product A-B was completely dissolved in the sample before it was poured into graduated cylinders and the settling velocity was measured, additional analysis should be conducted with Product A-B. Therefore, Product A-B settling velocity equation may not be an accurate representation of field conditions due to the ASTM jar testing methodology used.

The results of this research effort provided a strong basis for optimum dosage guidance and integration of field-applicable dosage control mechanisms through residual testing. The study should allow practitioners to improve dosage controls on active ALDOT job sites utilizing flocculants for construction stormwater treatment. The knowledge gained in this study contributed to other phases of this research that focused on improving dosage delivery mechanisms and evaluating effective agitation techniques through intermediate-scale flume testing and large-scale testing, which will be discussed in the next two chapters, respectively. Future research efforts should emanate from this research by allowing opportunities to evaluate more soils with different types of flocculant products and expand knowledge on soil-dependent dosage requirements.

CHAPTER 5
INTERMEDIATE-SCALE FLUME EVALUATIONS

5.1 INTRODUCTION

Although bench-scale testing provides substantial data for investigating the use of flocculants in construction stormwater treatment, intermediate-scale flume testing was conducted to simulate ideal conditions for in-channel flocculant dosing. The objective of intermediate-scale flume testing in this research included utilizing knowledge obtained in bench-scale experiments phase in intermediate-scale flume conditions for identifying dosage, agitation, and mixing requirements. In this chapter of the report, an evaluation of practical dosage delivery mechanisms will be discussed based on the findings from flume experiments that mimicked channelized flow conditions on construction sites.

Using proper dosage delivery mechanism enhances a flocculant's performance in construction stormwater treatment. Dosage delivery methods were tested in a 40 ft (12 m) long flume by using existing intermediate-scale testing resources of AU-SRF. Intermediate-scale flume testing was performed on flocculants in granular, block, sock, and aqueous solution forms for evaluation of dosage delivery and agitation requirements. The flume testing phase of this research allowed a comprehensive investigation of practical methods to use for proper flocculant introduction into construction stormwater runoff in supercritical and subcritical flow conditions.

The findings of this research were used for guiding large-scale testing evaluations and are expected to improve flocculant application techniques on construction sites and guide practitioners on optimum dosage delivery, agitation, and mixing requirements of flocculants. Furthermore, the result of the study aims to promote residual concentration monitoring in construction stormwater treatment with flocculants by validating the developed bench-scale method through intermediate-scale applications.

5.2 AU-SRF OVERVIEW

The intermediate-scale phase of this research was conducted at the AU-SRF, which is an outdoor research facility that has sources and capabilities for mimicking storm events on construction site conditions for improving various construction and post-construction stormwater technologies. The facility is located at the National Center for Asphalt Technology (NCAT) Test Track in Opelika, AL. Initially, it was constructed as a 2.5-acre (1 ha) research facility in 2009 as part of a research collaboration between Auburn University and ALDOT. An expansion project led by the research team in Summer 2020 increased the research capacity of the facility by including an additional 7.5 acres (3.0 ha) to the existing area. Figure 5-1 presents an aerial image that displays the current boundaries of the facility after the completion of the expansion project.

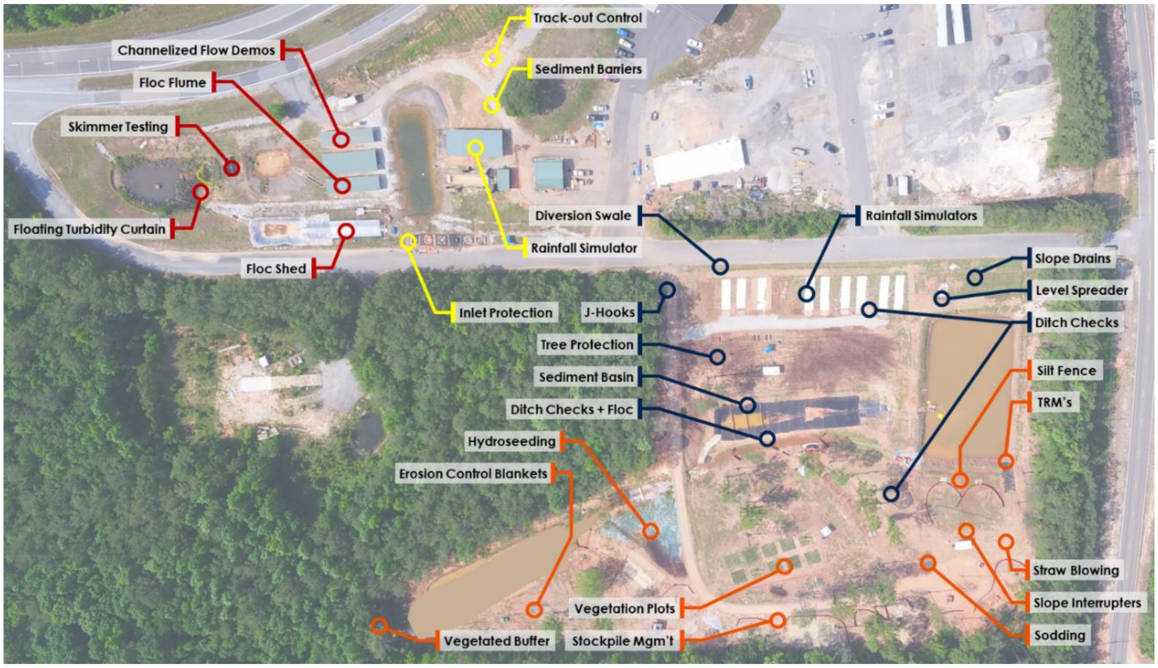


Figure 5-1: Auburn University – Stormwater Research Facility (AU-SRF)

The initial AU-SRF area consisted of two supply ponds, four channelized flow research stations, a rainfall simulator, and areas for sediment basin, inlet protection, surface skimmer, slope drains, stockpile management, ditch check testing, and training opportunities. The expansion activities advanced the capabilities of the research center by including new two storage ponds that provided additional 181,000 ft^3 (5,125 m^3) water storage volume (*11*).

The flume testing phase of this research was conducted in the initial AU-SRF area within the designated channelized flow research sheds that are located downstream of the supply pond. The drainage of the existing sediment basin downstream of flume testing channel was blocked to prevent contamination in the lower supply pond.

5.3 OPTIMUM DOSAGE DELIVERY FLUME EXPERIMENTS

This study carried the knowledge developed in the bench-scale phase of this research into a intermediate-scale phase by evaluating optimum dosage delivery mechanisms through intermediate-scale flume experiments. The objectives of this study were to [1] design and construct a flume at AU-SRF to mimic channelized flow, [2] develop a testing methodology for dosage delivery experiments in the flume, and [3] perform intermediate-scale flume testing to evaluate dosage delivery methods and agitation requirements. The findings of this research are expected to promote a proper and controlled treatment cycle on construction sites that adapt flocculants for construction stormwater treatment and guide practitioners on agitation and mixing requirements.

5.4 FLUME DESIGN

The optimum dosage delivery flume apparatus was designed by considering testing needs in different slope conditions that would represent supercritical and subcritical flow conditions. The design of the flume was completed by using AutoCad™ 3D modeling tools considering that the flume will be constructed on an existing channel that was built on a 3.5% slope. The flume apparatus was designed as 40 ft (12.2 m) long for evaluating the agitation and mixing of flocculant in a wide-span testing platform. The render of the flume design, illustrated in Figure 5-2, shows the dimensions of supporting frames and provides the diameter information of the semicircular flume body.

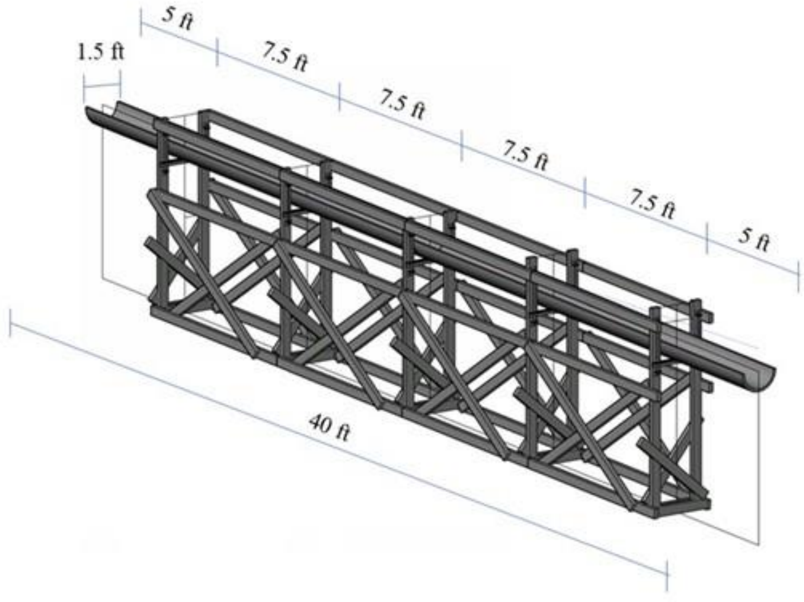


Figure 5-2: Flume Design

The flume design shown in the figure consisted of five supporting frames, which were placed 7.5 ft (2.29 m) apart from each other. The supporting frames were reinforced with vertical and horizontal lumber bracings for increasing structural stability during the flow introduction in the experiments. A semicircular flume shape with a 1.5 ft (0.46 m) diameter was preferred in the design for the practical use of mimicked check dams throughout the flume. The upstream and downstream ends of the flume were left unsupported in the initial design phase, however; additional supports were constructed in these sections to avoid changes in slope due to bending.

The supporting frames of the flume were designed with a capability of slope adjustability for experimenting with different flow conditions. To enable changes in the slope throughout different phases of the flume experiments, each side of the supporting frames included threaded rods connected to the bracket system. Figure 5-3 presents the design for the adjustable support system.

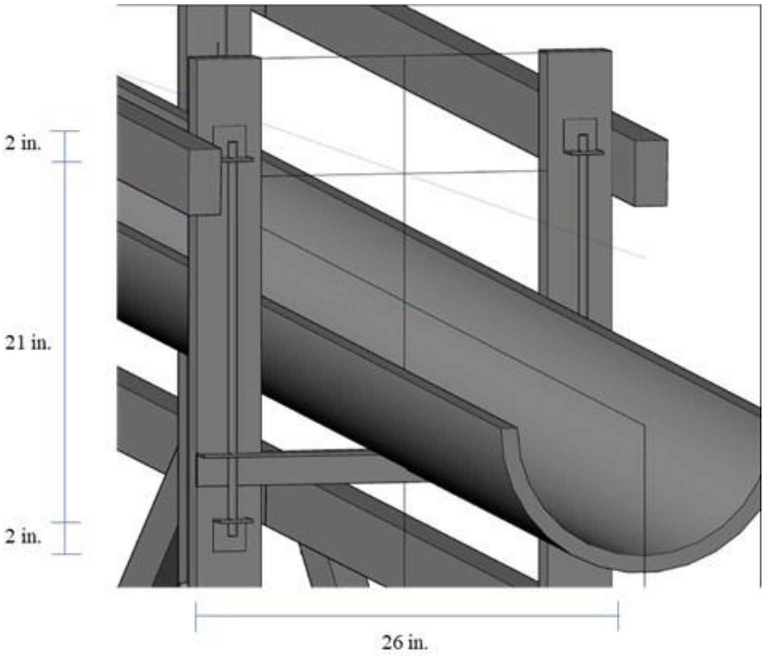


Figure 5-3: Adjustable Supporting Frame Design

The threaded rods with 0.5 in. (1.3 cm) diameter were assembled through 2 in. (5.1 cm) width metal brackets. This system served as adjustable support for the 26 in. (66 cm) metal angle brackets, which carry the semicircular flume body. The presented design approach allowed slope adjustments during the calibration and testing phase of the flume and minimized the improper installation risk in the construction phase, which will be discussed in the next section.

5.5 FLUME CONSTRUCTION

The structural frame of the flume was constructed by using 2x4 lumber pieces, and plywood pieces with 0.5 in. (1.3 cm) thickness for cost-effectiveness and portability. An 18 in. (46 cm) diameter double wall corrugated smooth interior HDPE pipe was cut in half by using a circular saw. The cut pieces were used to obtain a 40 ft (12.2 m) length as shown in Figure 5-4(a) and (b).

(a) double wall corrugated smooth interior pipe (b) half cut pipe

Figure 5-4: Construction of the HDPE Pipe Flume Body

After the completion of the flume frame construction, the flume body was assembled on the frame by adding the female end of the HDPE pipe to the male end of the other half. The connection area was smoothed and leveled by using a waterproof silicone sealer to avoid hydraulic jumps during flow introduction. The smoothness of the area was tested prior to conducting experiments by introducing flow into the flume and observing the existence of hydraulic jump conditions in this specific section, as depicted in Figure 5-5.

Figure 5-5: Flume Mid-section Hydraulic Jump Test

The flume frame consisted of adjustable legs made of metal threaded rod pieces and brackets as mentioned in the design section. The flume sits on metal angles installed on the threaded metal rods located in each leg of the supporting frames. These angles were stabilized on the threaded rods with the use of 0.5 in. (1.27) cm diameter nuts and washers. Figure 5-6(a) shows the adjustable support system assembly on one of the structural supports built for the flume frame. During the construction of supporting frames, the channel was prepared for the flume assembly by covering the metal plates in the testing area with a non-slip plastic liner as illustrated in Figure 5-6(b). This step was necessary to maintain safety around the flume during flocculant experiments considering the slippery surface conditions that might occur due to the existence of flocculants in the testing area. The channel slope was stabilized in the channel bottom by compacting the bare soil area and leveling the slope from lined metal plates to the discharge point by using two 4 ft x 8 ft (123 cm x 244 cm) plywood sheets with 0.5 in. (1.27 cm) thickness.

(a) supporting leg assembly (b) channel preparation

Figure 5-6: Flume Construction Phase

After the completion of channel preparation and supporting leg assembly, the frames were connected within the testing area in the channel by using horizontal bracings made of 2x4 lumber. Moreover, the flume legs were supported by using crossed bracings and plywood sheets. The flume body was assembled on the supporting frames. The slope of the flume was set to approximately 5% for the initial phase of the experiments by using an electronic level and adjusting the angle support with threaded rods. The height of each supporting frame was adjusted by measuring the slope on the prior support with the electronic level.

Figure 5-7 presents the completed flume set up in the testing channel at AU-SRF. The interior wall of the flume was lined with clear plastic, which was replaced in between each experiment, for avoiding contamination due to flocculant introduction.

The upstream and downstream ends of the flume required additional support to maintain the adjusted slope during intermediate-scale testing. Hence, a supporting table was built for the downstream of the flume to have extra space to store sampling bottles around the downstream sampling area. Furthermore, an additional platform was built upstream of the flume, which supported the flume upstream and served as a sediment introduction area. A mixing through between the upstream of the flume and the flow introduction weir was constructed and installed on the sediment introduction platform.

Figure 5-7: Post-construction Flume Setup

5.6 METHODOLOGY

This section details the methods, materials and experimental testing regimen used to evaluate optimum dosage delivery mechanisms through intermediate-scale flume testing. The testing methodology of flume experiments focused on evaluating four different flocculant forms: granular, emulsion, block, and sock for dosage delivery mechanisms by mimicking channelized flow conditions within the flume. Data collection in the experiments consisted of turbidity and settling velocity observations on the samples collected along the flume.

5.6.1 FLOW AND SEDIMENT INTRODUCTION

Channelized flow conditions were created by introducing flow into the flume with a steady flow rate by using an equalizing tank. The equalizing tank, which had a 300-gal (1,136 L) volume capacity, was placed upstream of the flume to maintain accurate flow introduction throughout the experiments. The water was pumped from the supply pond into the equalizing tank with the use of two DuroMax 3 in. (7.6 cm) gasoline engine portable water pumps (Model No. XP650WP). Even if one of the pumps was sufficient for supplying water for the experiments, an additional pump was used to avoid any interruption related to the performance of the pumps during the test.

Figure 5-8 shows the equalizing tank system used for the flume experiments. For flume experiments, two 3 in. (7.6 cm) inlets on the backside of the equalizing tank were connected to pumps with flexible hoses as illustrated in Figure 5-8(a). Two 3 in. (7.6 cm) gate valves were used to adjust the inflow flow rate and prevent overflow within the tank. Turbulence within the tank was minimized by installing a wooden baffle perpendicular to the inflow. The equalizing tank system included a rectangular weir on the flume side, which introduced the flow into the wooden mixing weir with a controlled flow rate during experiments.

(a) the backside of the equalizing flow tank (b) flow control guide

Figure 5-8: Equalizing Tank System for Flow Introduction

The flow rate was controlled by using a scaled flow control plate that quantifies flow rates starting from where the flow passes the weir. The flow control plate was placed on the side of the tank based on flow calibration results together with a 0.5 in. (1.3 cm) clear plastic tube that shows the corresponding water level passing the weir as shown in Figure 5-8(b). The flow calibration procedure included maintaining the water level at the bottom of the weir, where it corresponds to 0 ft^3/s (0 m^3/s) on the scaled flow control plate. Then, the water level was increased to a target flow rate on the plate and an empty container was filled with a known target volume by tracking time. The flow control system passed the calibration since the flow rate on the scaled flow control plate matched the flow rate calculation made based on the volume and time information obtained to fill the empty container.

Sediment introduction rate in flume experiments was identified based on 1,500 ± 500 NTU target turbidity level to effectively relate the dosage knowledge obtained in the bench-scale testing phase to the flume testing. A wooden mixing through with diversion vanes was built to maintain adequate mixing during sediment introduction into the flume. The mixing through was assembled between the rectangular weir and upstream of the flume as shown in Figure 5-9.

Figure 5-9: Wooden Mixing Trough

The sediment introduction system was calibrated by tracking the time and amount of sediment introduction that would meet the targeted turbidity level. During calibration tests for sediment introduction, it was observed that introducing approximately 10.4 oz (294 g) soil per minute was sufficient for reaching the targeted turbidity level in the flume. The testing soil was selected as the Cecil soil, which was collected from AU-SRF and previously classified as sandy clay loam during the soil assessment phase of this research. The reason for selecting this specific soil was having readily available residual concentration plots prepared with it. Before each test, the testing soil was air-dried and sieved through a 0.5 in. (1.27 cm) sieve. The sieved soil was weighed and stored in plastic bottles, which contained 3.42 oz (97 g) of the testing soil.

Sediment introduction was initially maintained by using a 50 in. x 7.8. in. (127 cm x 19.8 cm) Happy Buy Belt Conveyor table (Model No. PMSSJ-10000000001V1) with 70 rpm conveying speed. However, the conveyor system was not efficient enough to maintain sediment introduction without any interruption throughout the testing duration. Thus, pre-weighed sediment containers were continuously hand-shaken upstream of the mixing trough every 20 seconds throughout the experiment. The sediment introduction setup is illustrated in Figure 5-10.

Figure 5-10: Sediment Introduction Setup

5.6.2 SUPERCRITICAL AND SUBCRITICAL FLOW DOSAGE DELIVERY EXPERIMENTS

Optimum dosage delivery mechanisms were evaluated for granular, block, sock, and aqueous solution forms of flocculants through dosage delivery experiments in the flume by mimicking the channelized flow. Initially, supercritical flow conditions were evaluated by placing the flume on a 5% slope. Facilitating effective agitation and mixing in the channelized flow area required the installment of scaled-down rock ditch checks covered with jute matting for preventing wash-offs of the product. The spacing of scaled-down ditch checks was identified by following Eq. 5-1.

$$L = \frac{H}{S} \qquad \textbf{Eq. 5-1}$$

Where,

L= Spacing length (ft [m])

H= Height of the ditch check

S = Longitudinal slope (%)

The height of the scaled-down ditch checks was identified as 4 in. (10.2 cm). For installing ditch checks in a 40 ft (12.2 m) long flume with a 5% longitudinal slope, the required ditch check spacing was calculated as 6.67 ft (2.03 m). Based on this calculation, five ditch checks were used within the flume for supercritical flow experiments. Later in the study, the flume was adjusted to a 1% slope to observe the impact of subcritical flow conditions. In this case, ditch check spacing was calculated as 33.3 ft (10.2 m), which required the use of one ditch check in the experiments.

The scaled-down rock ditch checks were built by using large and small size rocks, 2 ft x 4 ft (0.61 m x 1.22 m) jute matting, plastic tarp straps, and sod staples. Each ditch check location was marked on the side of the flume since ditch checks were rebuilt between each experiment to avoid contamination due to remaining flocculant residuals. For building ditch checks, jute mattings were laid in the flume, and sod staples connected to tarp straps were installed through the openings of the matting. Large size rocks were piled onto the matting to obtain 4 in. (10.2 cm) height and smaller rocks were used upstream of the ditch checks. The matting was wrapped over the ditch checks and tarp straps were attached to the walls of the flume to avoid wash-offs during the experiments. Figure 5-11 illustrates the installed ditch checks in the flume.

Figure 5-11: Scaled-down Rock Ditch Checks in the Flume

The scaled-down ditch checks were used to determine the flow capacity of the flume prior to conducting flocculant experiments. The flow was introduced into the flume by using the equalizing tank and the flow rate was increased to reach the maximum impoundment depth in each installed ditch check. Calibration tests indicated that the ditch checks would provide maximum structural stability and impoundment under 0.1 ft^3/s (0.003 m^3/s) flow rate. Hence, the flow rate for the flume experiments was identified as 0.1 ft^3/s (0.003 m^3/s). Before each experiment, flocculant products were sprayed with water and the flow was introduced for 2 minutes to the system for maintaining a steady flow throughout the flume and activating the flocculant product.

For each evaluated flocculant form, dosage delivery experiments were conducted in two separate phases: [1] clean water and [2] sediment introduction. The experiment duration for each phase was 9 minutes and samples were collected by using 33.4 fl oz (1,000 mL) plastic bottles every 3 minutes throughout the experiment. For the supercritical flow ditch check setup, which included five scaled-down ditch checks, sampling locations were identified as follows: [1] upstream of the flume, [2] upstream of the second ditch check (DC-2), [3] upstream of the fourth ditch check (DC-4), and [4] downstream of the flume. Upstream samples represented control conditions, which do not contain any flocculant. Therefore, these samples were collected before the first flocculant introduction in the flume. Mid-section samples represented low agitation conditions by allowing limited mixing distance for flocculation and downstream samples represented high agitation conditions. The ditch check setup for subcritical flow conditions required changes in sampling locations and focused on sampling from upstream and downstream of the flume and the installed ditch check. Figure 5-12 presents the framework for optimum dosage delivery experiments in the flume.

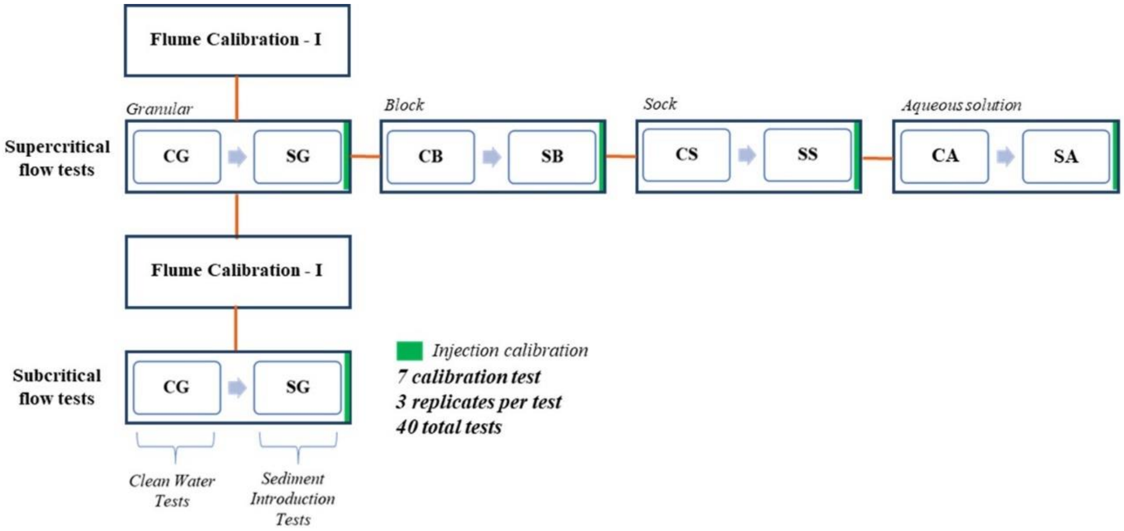


Figure 5-12: Optimum Dosage Delivery Testing

The green color in the presented framework in Figure 5-12 represents injection calibration tests that were conducted before each flocculant form evaluation set. Initially, the flume was calibrated for flow and sediment introduction in the "Flume Calibration-I" phase. Following the calibration phase, the granular form was tested with clean water (CG) and sediment introduction (SG) experiment. Following the granular set, block, sock, and aqueous solution products were tested in the subcritical flow conditions. The flow was re-calibrated for the subcritical flow condition experiments. Following the secondary calibration, the granular product was evaluated for optimum dosage delivery under subcritical flow conditions.

Clearwater experiments were conducted before evaluating each flocculant form with sediment introduction and aimed to evaluate control conditions for residual testing procedures. Net concentrations of released flocculants were effectively observed in clear water flume experiments since flocculants did not have an opportunity to bind with sediment and settle out of suspension. The testing regimen consisted of flow introduction for 9 minutes and samples were collected in 3 minutes intervals. Figure 5-13 exemplifies a clear water experiment for evaluating dosage delivery with a granular flocculant form in the flume.

Figure 5-13: Clearwater Flume Experiments with a Granular Form

After the completion of clear water tests, samples were mixed with 0.71 oz (20 g) residual testing soil and flash mixed in the mixing machine for a minute. Then, samples were transferred into a graduated cylinder for settling velocity observations. Flocculant concentrations for each sample were identified following the developed residual detection method in the bench-scale phase of this research. Results were compared with the observed residual concentrations in sediment introduction tests.

Following clear water tests, sediment introduction experiments were conducted for each tested flocculant form. Sieved and pre-weighed soils were continuously hand-shaken into the flume during the 9-minute testing period. Sampling intervals were kept the same with the clear water experiments; however, samples were collected in two 33.8 fl oz (1,000 mL) bottles from each sampling location. One of these paired bottles was set aside in each sampling location for 15 minutes and the supernatant was removed from the undisturbed samples for turbidity readings. On the other hand, the other sample bottle in the pair for each location was poured into a 33.8 fl oz (1,000 mL) beaker and flash mixed in the mixing machine for a minute. After the completion of the flash mix, samples were allowed to settle for 15 minutes similar to the bench-scale testing phase and turbidity measurements were taken from the supernatant. Turbidity results of disturbed and undisturbed samples were compared for evaluating the agitation and mixing efficiency. Figure 5-14 shows sediment introduction in flume experiments. After the completion of each test, ditch check materials covered in flocculant were removed from the flume, and the plastic liner was replaced before new ditch check installations.

Figure 5-14: Sediment introduction experiments

Following the completion of turbidity readings of disturbed samples, the supernatant was transferred into a clean beaker and residual concentrations in the samples were estimated by following the previously discussed residual concentration detection methodology. Results were compared to clear water conditions and findings were used for optimum dosage delivery evaluations.

Match test experiments were previously conducted on the testing soil in the bench-scale phase of this research for identifying best performing flocculant products. These results were used to identify testing flocculant products for flume testing. According to match test results, product A was selected for granular form evaluations. This product was also used to form a stock solution for aqueous solution evaluations in the study. A semi hydrated block, product A2, was obtained for block form evaluations, which consisted of product A and another PAM formulation. Even though, the Product I did not make the top three best performing products list, this product was still effective enough to be selected for sock form evaluations. Table 5-1 presents flocculant products that were used in flume experiments.

Table 5-1: Summary of Evaluated Flocculant Products in Flume Experiments

Product	Manufacturer	Flocculant	Type	Form	Dosage (mg/L)
A	I	PAM	Synthetic	Granular/ Stock solution	5
A2	I	PAM	Synthetic	Block	5
I	III	Bentonite-based	Inorganic	Sock	180

Figure 5-15 illustrates flocculant introduction in the flume experiments with the use of different flocculant forms. Granular form introduction, shown in Figure 5-15(a), was performed by using 0.21 oz (6 g) of Product A on each ditch check in the flume except the last-ditch check (DC-5) located downstream of the flume. The dosage was adjusted by applying optimum dosage requirements in the intermediate-scale flume phase and considering possible product wash-offs. Product A was spread on each flocculant introduction ditch check in a way that continuous contact with the flow can be maintained throughout the experiments.

Figure 5-15(b) presents block form flocculant introduction in the flume experiments. The original block product was scaled down to a smaller block by considering the mimicked ditch check dimensions in the flume. The original block was sliced into four equal rectangular pieces and each piece was covered with the same netting of the original product. The block form was only introduced on the first ditch check throughout the flume since product wash-off was not a concern with this specific form. The block piece was placed downstream of the first ditch check (DC-1) and secured on the jute matting with the use of zip ties. Between each sediment introduction experiment the block was cleaned, and the remaining sediment particles were scraped from the product.

(a) granular form introduction (b) block form introduction

(c) sock form introduction (d) aqueous solution form introduction

Figure 5-15: Introduction of Different Flocculant Forms in Flume Experiments

Figure 5-15(c) illustrates the sock form introduction system in the flume. The sock product consisted of Product I, which was originally in a 5 ft (1.2 m) sock material. The sock material was scaled down by considering the bench-scale dosage recommendation, which was 180 mg/L. In bench-scale experiments, 33.8 fl oz (1,000 mL) turbid water with 1,500 ± 300 NTU was treated with 0.06 oz (1.8 g) of the Product-I based on manufacturer recommendation. The treatment volume in flume experiments was calculated as 54 ft^3 (1.5 m^3) based on a 0.1 ft^3/s (0.003 m^3/s) flow rate and 9-minute experiment duration. The required amount of product-I was calculated as 9.7 oz (275 g) for treating 54 ft^3 (1.5 m^3) turbid water in the flume. Hence, the sock material was cut into a smaller piece and filled with 9.7 oz (275 g) of product-I. The scaled-down flocculant sock was installed downstream of the DC-1 and secured with zip ties connected to the jute matting. Between each experiment, the sock was washed with high-pressure water to remove the retained sediment particles from the sock fabric.

Figure 5-15(d) depicts an aqueous solution introduction system downstream of the first ditch check. Based on the manufacturer's recommendation, the aqueous solution was initially formed by introducing 0.33 oz (9.45 g) of granular product A into 5-gal (18.9 L) water and mixing the stock solution with a paint mixer drill bit attachment on a power drill until it visually shows homogeneous appearance. During mixing, it was determined that the solution had an excessively high concentration (0.49 g/L) of flocculant. This was due to misleading information obtained from the manufacturer. The mixture was too viscous for continuous flocculant injection. For the purpose of proper dosage introduction, this stock solution had to be diluted 10,000 times. The new stock solution had a 0.045 mg/L concentration, which matches the dosage recommendation obtained in the bench-scale phase of the project. In each experiment, five 5-gal (18.9 L) solution buckets were used for the solution injection into the flume. Prepared solutions were agitated by using the paint mixer before each test. To maintain continuous solution injection, two Seaflo^{TM}350 gal/h (1324.89 L/h) 12 V Bilge Pumps (Model No. SFBP1-G350-01) were used. The pumps were powered by two DieHard^{TM} Marine 24M, 550CCA batteries (Model No. 24DC-1), and the nylon hose barb on the bilge pumps were connected to 0.75 in. (1.91 cm) clear PVC tubing. The pumps were submerged in the solution and continuous injection was maintained by alternating buckets throughout the experiment. The ends of the PVS tubes were placed and secured downstream of the DC-1 and the solution was introduced by alternating injection tubes throughout the experiments. Figure 5-16 displays the aqueous solution injection setup.

(a) agitation of stock solution (b) bilge pump setup

(c) solution injection setup

Figure 5-16: Aqueous Solution Introduction

Following the completion of supercritical flow evaluation on four different flocculant forms, the slope of the flume was adjusted to 1% for observing subcritical flow conditions on granular flocculant introduction. Based on the previously mentioned ditch check spacing calculations, only one scaled rock ditch check was used for subcritical flow evaluations. The flow rate was kept the same with supercritical flow experiments but decreasing the flume slope created subcritical flow conditions, which had a slow and stable behavior due to having greater actual water depth compared to the critical depth. Granular product was introduced on the ditch check with the same methodology applied in supercritical flow experiments. Clear water and sediment introduction tests were conducted, and sampling locations were changed to the upstream and downstream of both flume and ditch checks. Figure 5-17 illustrates flume experiments in subcritical flow conditions.

Figure 5-17: Subcritical Flow Evaluations

5.6.3 LONGEVITY TEST

Prior to adjusting the slope of the flume for subcritical flow evaluations, the longevity of the granular product was evaluated through a longevity experiment in the flume. The product was applied on the first four scaled-down ditch checks and clear water was continuously introduced into the flume with a 0.1 ft^3/s (0.003 m^3/s) flow rate for 2 hours. Samples were initially collected in 3, 6, and 9 minutes within the first 10 minutes duration; then, the sampling interval was increased to every 10 minutes for the remaining 110 minutes experiment duration. The purpose of not using sediment introduction in the longevity experiment was to avoid the floc formation while identifying the actual concentration of the product dosed in the flume. Flocculant concentrations in each collected sample were estimated by using the settling velocity observation method and the results were evaluated for identifying the required reapplication interval for the granular form. Figure 5-18 shows clear water introduction on one of the scaled-ditch checks during the longevity test.

Figure 5-18: Longevity Test Clear Water Introduction

5.7 RESULTS AND DISCUSSION

This section presents and discusses the data analysis and results collected for the intermediate-scale flume experiments. The evaluated flocculant treatments included clear water and sediment introduction on granular, block, sock, and aqueous solution forms. The section analyzes the results in three subsections; [1] supercritical flow experiments, [2] subcritical flow experiments; and [3] longevity test results.

5.7.1 SUPERCRITICAL FLOW EXPERIMENTS

Supercritical flow experiments investigated the optimum dosage delivery mechanisms in a %5 slope to mimic channelized flow for flocculant introduction with [1] granular, [2] block, [3] sock, and [4] aqueous solution forms. Results for each flocculant form will be discussed in this subsection.

5.7.1.1 Granular Form Evaluations

The first series of tests that were conducted in the flume was the clear water introduction tests on the granular flocculant form. The clear water introduction experiments were performed under a series of three tests. Samples were collected from upstream, upstream of DC-2 and DC-4, and downstream of the flume. The settling velocity of each sample was correlated with the standard flocculant concentration plot prepared for product A. Residual flocculant concentrations were estimated for each sample based on the plot shown in Figure 5-19.

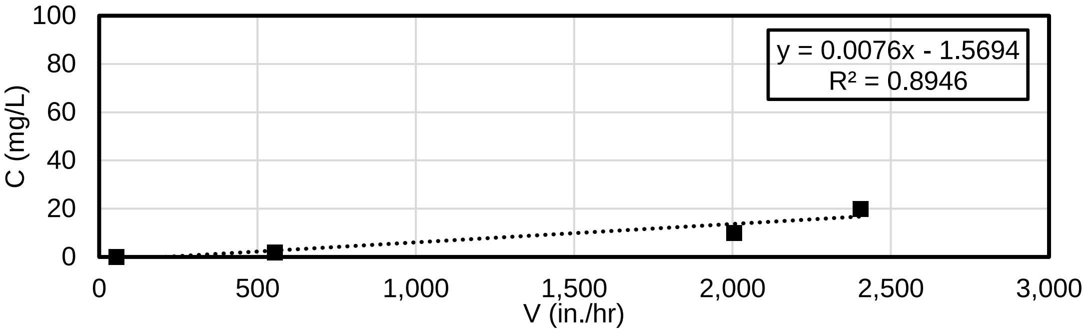
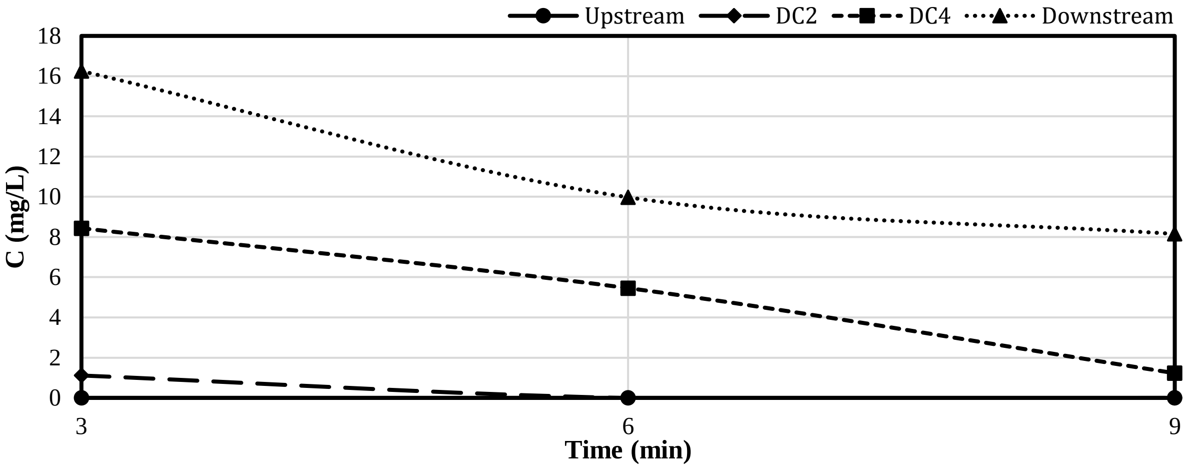


Figure 5-19: Product-A Standard Residual Concentration Plot

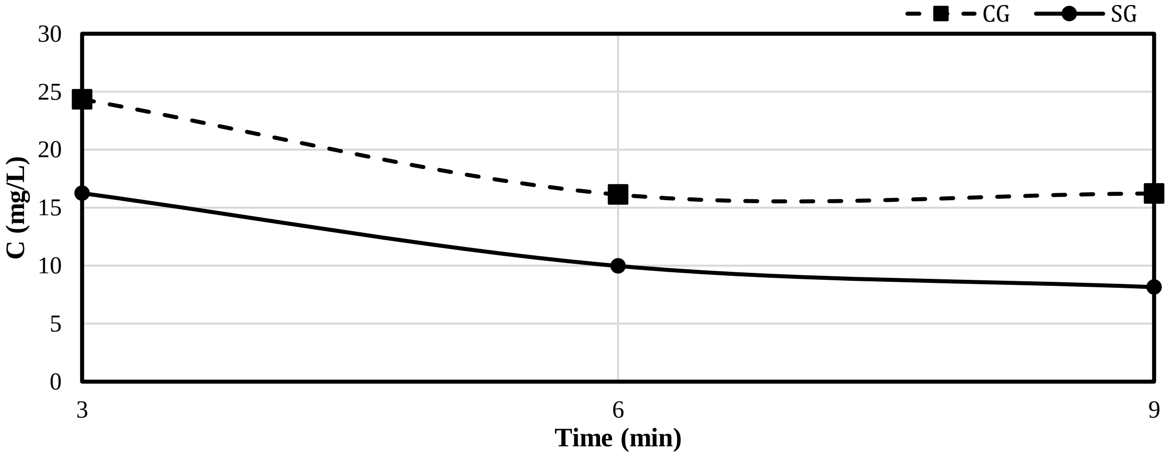
The estimated average flocculant concentration results of the three runs showed 0 mg/L flocculants upstream of the flume. This result was expected since flocculants were introduced into the flume after the upstream sampling location. Therefore, upstream samples represented the control condition during the experiments by not containing any flocculant concentration. The rest of the concentration results showed that upstream DC-2 experienced lower flocculant concentrations compared to DC-4 and downstream samples. The highest concentration, 24 mg/L, was reached within the 3 minutes of the experiments in the downstream samples. However, concentrations in each sampling location showed a decrease with time due to product wash-off.

Following CG set in supercritical flow condition, testing soil was introduced into the flume for evaluating dosage delivery on the granular form with the existence of sediment in the system. Figure 5-20 displays the residual concentration results in each sampling location throughout the SG testing duration and compares the downstream concentrations with the CG set results. Concentration detection results for each flume experiment with clear water and sediment introduction were analyzed and compared with the similar data analysis method presented in Figure 5-20 . SG set results indicated no flocculant condition in the upstream sampling area similar to the CG set. Flocculant concentrations also experienced a reduction with time due to product wash-off in each sampling location, as shown in Figure 5-20(a). For example, in DC-2 residual concentration was reduced to 0 mg/L in 6 minutes and concentrations dropped to 1.2 mg/L in DC-4. Downstream concentrations experienced an approximate decrease of 8 mg/L at the end of the 9-minute sampling period. The highest residual concentration values were observed in the downstream sampling location throughout the experiment duration.

Based on the presented residual concentration data, it can be interpreted that the system maintained sufficient dosage in the first three ditch checks from upstream of the flume. However, after DC-4 the system over-dosed itself due to the impoundment occurring upstream of the DC-5 before the downstream discharge point. This observation indicated that flocculant introduction on each ditch check is not necessary towards the downstream of the channelized flow in supercritical flow conditions. Eliminating flocculant introduction on DC-4 would provide a solution for this overdosing situation in downstream samples and regulate the dosage.



(a) residual concentration results for SG tests



(b) SG and CG sets downstream concentration comparison

Figure 5-20: Average Residual Concentration Results for the Granular Treatment

Flocculant concentrations showed a decreasing behavior during the SG set compared to the CG set flume experiments, as illustrated in Figure 5-20(b). All tested flocculant forms experienced a decrease in residual concentrations due to successful floc formation that facilitated settling throughout the flume during sediment introduction.

In addition to residual concentration observations, turbidity reduction data for disturbed and undisturbed samples was evaluated for each sampling location during sediment introduction experiments. The initial turbidity levels were measured upstream of the flume prior to flocculant introduction. Turbidity readings were taken from the supernatant of undisturbed samples after the 15-minute settling period in the post-experiment phase. Disturbed samples were flash mixed in the mixing machine and turbidity of the supernatant was measured after the completion of the settling period for each sample. The SG treatment turbidity reduction results for samples collected in 9-minute intervals are presented in Figure 5-21.

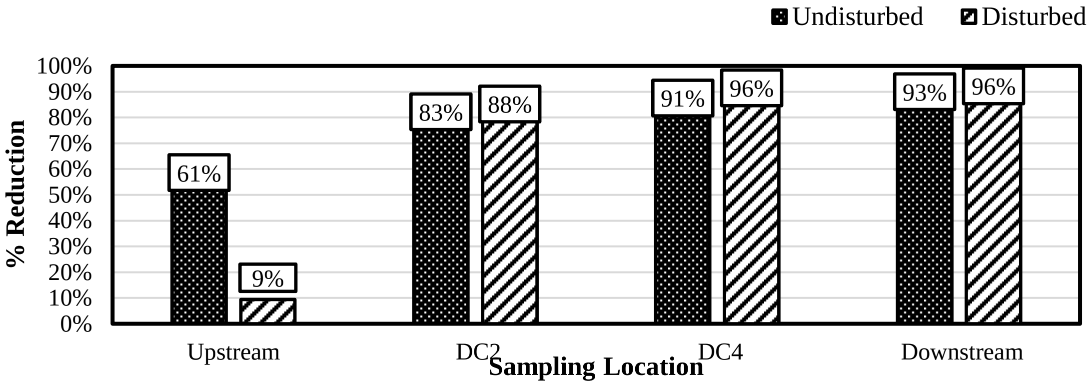


Figure 5-21: Turbidity Reduction Results for SG Treatment 9-minute Samples

The dotted pattern on the resulting plot represents undisturbed samples, while the hatched pattern symbolizes disturbed samples for turbidity reduction evaluations per sampling location. Disturbed samples demonstrated the best-case scenario for proper mixing and agitation of tested flocculant products by achieving ideal mixing conditions in the laboratory environment. Turbidity reductions of undisturbed samples were compared to this best-case scenario to determine if adequate mixing and agitation conditions were achieved in the intermediate-scale flume experiments. Turbidity reduction results indicated that upstream disturbed samples, which did not contain any flocculant, showed minimal reduction compared to undisturbed samples. This observation was made since the mixing machine created higher suspension in no flocculant upstream samples compared to the undisturbed state. Moreover, sediment clumps were captured in some of the upstream sample bottles, which increased the turbidity of samples when mixed in the machine. In DC-2, and DC-4 sampling locations, flocculant introduction provided 88%, and 96% turbidity reduction in the disturbed samples, respectively. DC-4 and downstream samples experienced the same percent turbidity reduction. At the end of the 9-minute sampling period, undisturbed samples achieved adequate mixing and agitation throughout the flume and showed similar turbidity reduction results to the best-case scenario observed in disturbed samples. For example, turbidity reduction of undisturbed downstream samples was only 3% less than the disturbed samples.

Flume evaluations on the granular form indicated that granular products typically require frequent reapplication and maintenance. In case of an intense storm event, the granular products would get detached from the flocculant introduction area on ditch checks before reaching the activation state and these inactivated granular particles would be washed off in the channel due to the strong impact of the flow. It is also important to highlight that granular flocculant application becomes more effective with the use of jute matting on ditch checks, which increases the attachment of granular particles in the flocculant injection area.

5.7.1.2 Block Form Evaluations

After the completion of granular form evaluations, semi-hydrated block form flocculant, product A2, was tested in the supercritical flow conditions by facilitating flocculant introduction downstream of the DC-1. Upstream samples showed 0 mg/L flocculant concentration, while upstream of the DC-2 had an average of 22 mg/L concentration in clear water experiments. DC-4 and downstream samples contained higher concentrations ranging between 27-39 mg/L. These concentrations were estimated by using the standard residual concentration plot developed for product A2, which is presented in Figure 4-35.

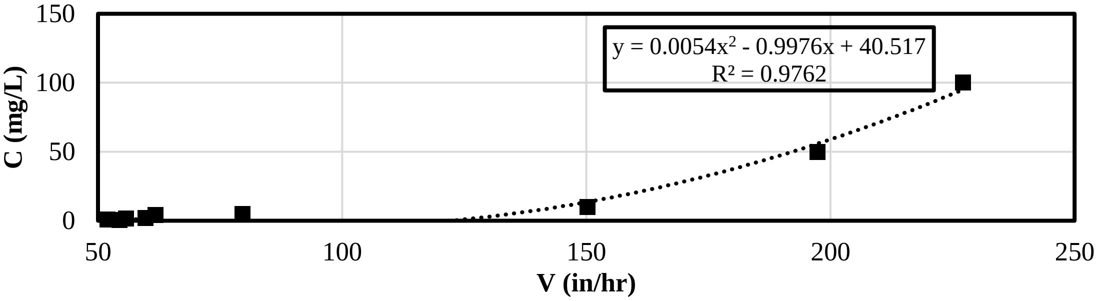


Figure 5-22: Product-A2 Standard Residual Concentration Plot

Sediment introduction experiments for block form evaluation indicated no flocculant concentration upstream. Figure 5-23 shows average flocculant concentrations observed in each sampling location during SB treatment. Flocculant concentrations were detected upstream of the DC-2 with an average value of 7.8 mg/L. This concentration value was increased to approximately 27.7 mg/L in DC-4; however, downstream concentrations remained within the same range as the DC-4 samples. Similar residual concentrations in DC-4 and downstream samples emphasized the steady dosage delivery feature of the block form. The block product facilitated continuous and controlled dosing in the mimicked channelized flow. However, high residual concentrations were observed in downstream samples due to floc built up in the impoundment of ditch checks installed towards the downstream. In addition, a decrease in flocculant concentration was also observed in block form experiments, when CB treatment results were compared to the estimated flocculant concentrations obtained in SB treatment.

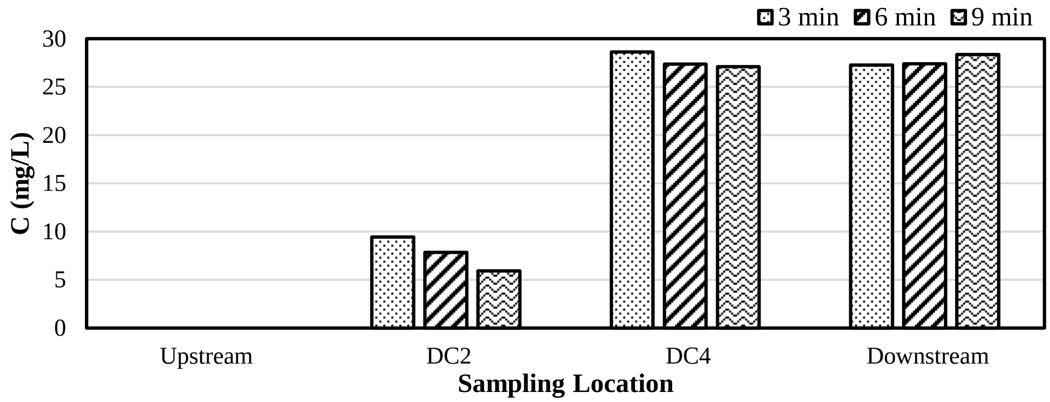
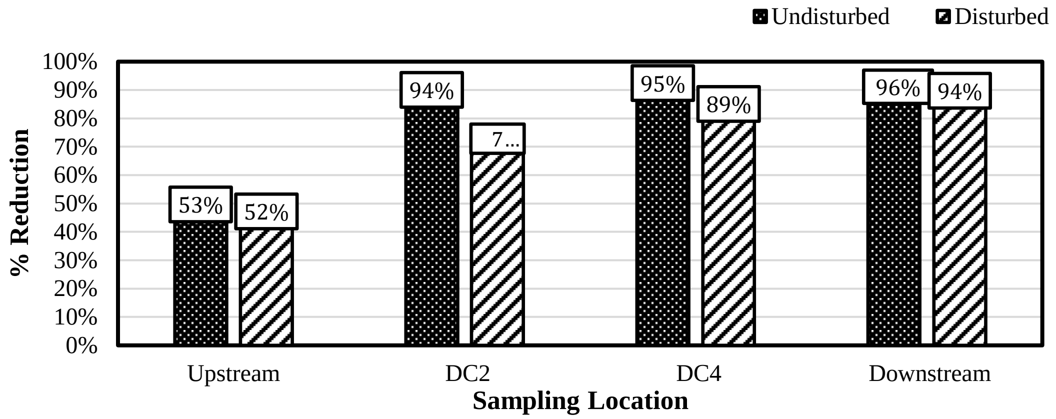
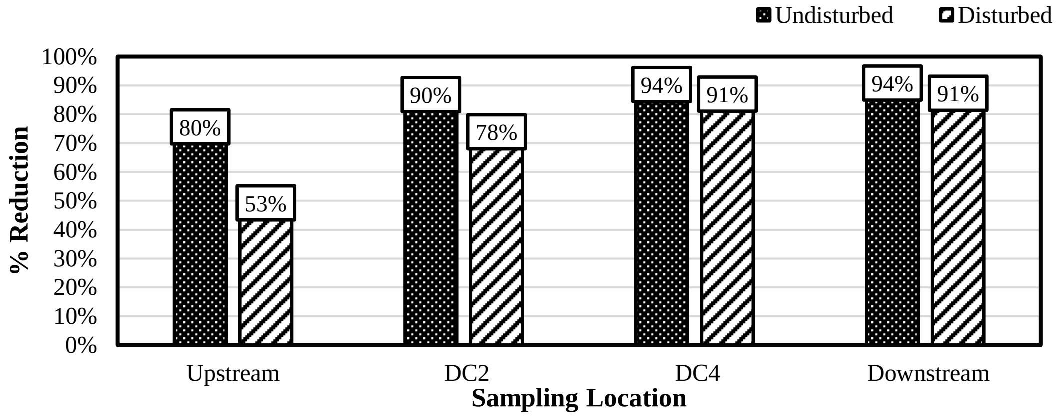


Figure 5-23: Residual Concentration Results for SB Treatment

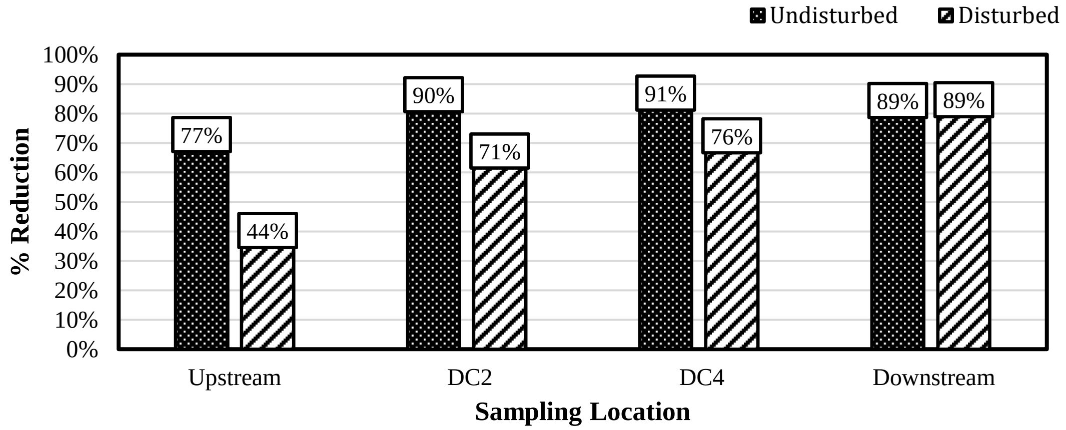
Turbidity reduction data implied highly effective agitation and mixing in block form introduction experiments by providing up to 96% turbidity reduction in undisturbed samples. Figure 5-24 displays %flocculant reduction results for the SB experiments. Again, the disturbed upstream samples showed lower turbidity reduction rates due to increased suspension in no flocculant samples. Interestingly, undisturbed samples showed higher turbidity reduction than the disturbed samples in DC-2 and DC-4 sampling locations as illustrated in Figure 5-24(a) and (b). However, it can be observed in Figure 5-24(c) that the system experienced increased dosage towards the downstream during the 9-minute sampling period, which showed a decrease in the turbidity reduction for both disturbed and undisturbed samples compared to samples collected in 3 and 6 minutes. The turbidity reduction in increased dosage conditions was also observed in the bench-scale phase of this research. These results also validated the bench-scale experiment findings on increased dosages through intermediate-scale flume observations.



(a) results for in 3-minute samples



(b) results for in 6-minute samples



(c) results for 9-minute samples

Figure 5-24: Turbidity Reduction Results for SB Treatment Samples

Flume experiments on the block form showed that flocculant blocks maintain a uniform dosage delivery mechanism compared to granular flocculant introduction in supercritical flow conditions. Moreover, it was observed that the required reapplication frequency of the block form is lower than the other evaluated flocculant forms in this study. However, block forms often require frequent maintenance in field conditions. For the accuracy of the experiment results, sediment particles on the tested blocks were cleaned between each experiment. It is important to note that the performance of the block form is highly dependent on proper maintenance on job sites, which typically includes sun protection and cleaning procedures.

5.7.1.3 Sock Form Evaluations

Sock form dosage delivery experiments in supercritical flow conditions investigated bentonite-based Product-I in a sock fabric. This product had a 180 mg/L manufacturer dosage recommendation in the bench-scale phase of this research. Residual concentration estimations for this particular product were based on a standard plot with a 0.97 R^2 value presented in Figure 5-25.

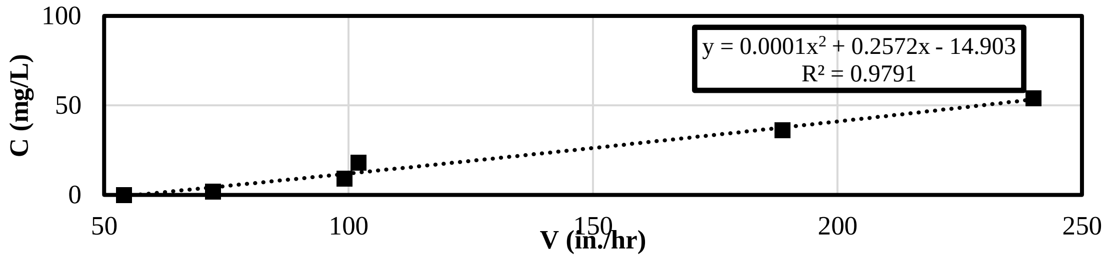


Figure 5-25: Product-I Standard Residual Concentration Plot

Estimated concentration values for CS and SS treatments are presented in Table 5-2. Clearwater experiment results showed that the product releases up to 33 mg/L flocculant concentration in the flume during supercritical flow conditions, which is below the recommended concentration value. Results revealed that downstream samples had higher flocculant concentrations compared to DC-2 and DC-4 samples in both CS and SS experiments. The product dosage rates increased until the 6-minute sampling period; however, dosage rates showed a decrease with time in the 9-minute sample collection.

Table 5-2: Comparison of Residual Concentration in CS and SS Treatments

	Sampling Time (min)	Residual Concentration (mg/L)			
		Upstream	DC-2	DC-4	Downstream
CS	3	0	20	21	33
	6	0	30	31	29
	9	0	15	14	21
	Sampling Time (min)	Residual Concentration (mg/L)			
		Upstream	DC-2	DC-4	Downstream
SS	3	0	31	21	28
	6	0	28	24	27
	9	0	16	22	25

According to the concentration detection results, it can be also observed that estimated flocculant concentrations for SS treatment showed a minimal decrease in concentration levels during the CS treatment phase. This implies that Product-I was less effective on the testing soil compared to other tested products and it did not facilitate sufficient floc formation. During the match test phase of this research, Product-I was not listed in the top three best-performing products for the testing soil. However, it was preferred in the flume testing phase due to limited options for commercially available sock form flocculants. Flume experiment results validated the match test findings on the product-I.

The underperformance of Product-I can be also seen in the turbidity reduction data obtained in SS treatment experiments. The product showed a 77% turbidity reduction in undisturbed samples during the 9-minute sampling period as shown in Figure 5-26. The turbidity reduction data presented a noticeable difference in the performance of disturbed and undisturbed samples. Disturbed samples had higher turbidity reduction rates in each sampling location compared to undisturbed samples, which showed the failure of the Product-I in meeting agitation and mixing requirements.

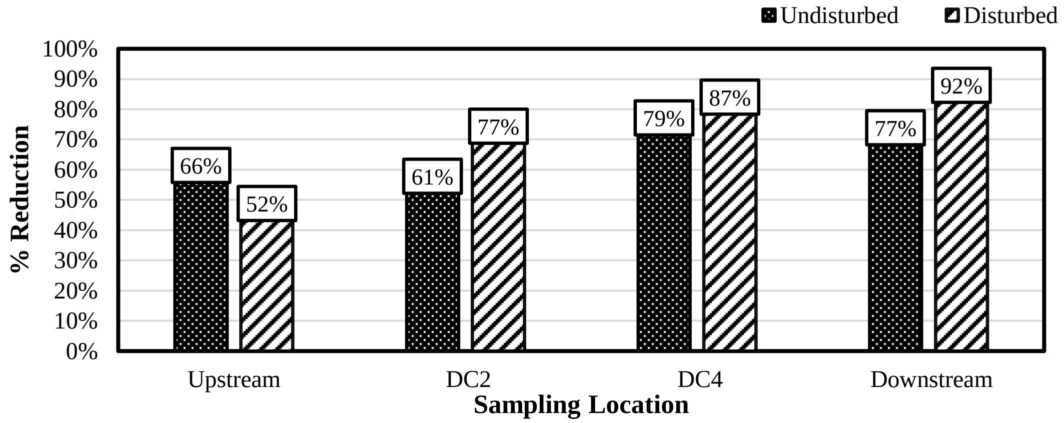


Figure 5-26: Turbidity Reduction Results for SS Treatment 9-minute Samples

5.7.1.4 Aqueous Solution Form Evaluations

Aqueous solution flocculant introduction in the flume evaluated dosage delivery in a semi-passive treatment system, which continuously injected the solution into the flume by using bilge pumps. Aqueous solution experiments in supercritical flow conditions were conducted by using a stock solution prepared with Product-A. Thus, the residual concentrations for the aqueous solution treatments were estimated based on the standard concentration plot developed for Product-A, which was previously presented in Figure 5-27.

Compared to evaluated flocculant forms in this research, aqueous solution treatment provided the most effective and controlled dosage delivery mechanism in the channelized flow. Residual concentrations showed an average value of 3 mg/L in CA treatments, and it decreased to 2.4 mg/L during the SA treatment set. Downstream and upstream DC-4 were exposed to similar flocculant concentrations throughout the testing. Flocculant concentrations reached their peak point in 6-minute samples and slightly decreased in 9-minute samples as illustrated in Figure 5-27. The observed residual concentrations proved the steady and effective dosage delivery performance of the aqueous solution treatment by displaying low standard deviation values for estimated concentrations in DC-2, DC-4 and downstream; 0.76, 0.58, and 0.34, respectively.

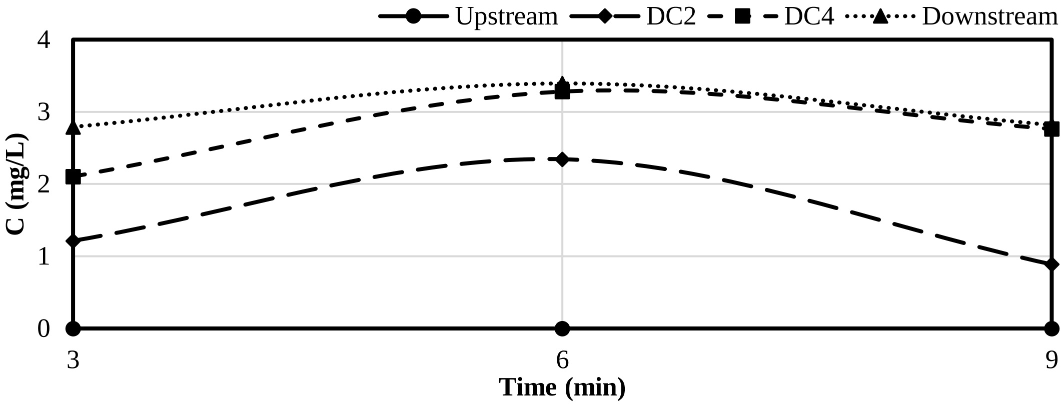


Figure 5-27: Residual Concentration Results for SA Treatment

Aqueous solution introduction in flume experiments also performed well for decreasing turbidity levels throughout the flume and providing sufficient agitation. Turbidity reduction data for the 9-minute sampling period demonstrated in Figure 5-28 provides evidence for proper agitation and mixing by displaying turbidity reduction rates higher than 90% in downstream disturbed and undisturbed samples.

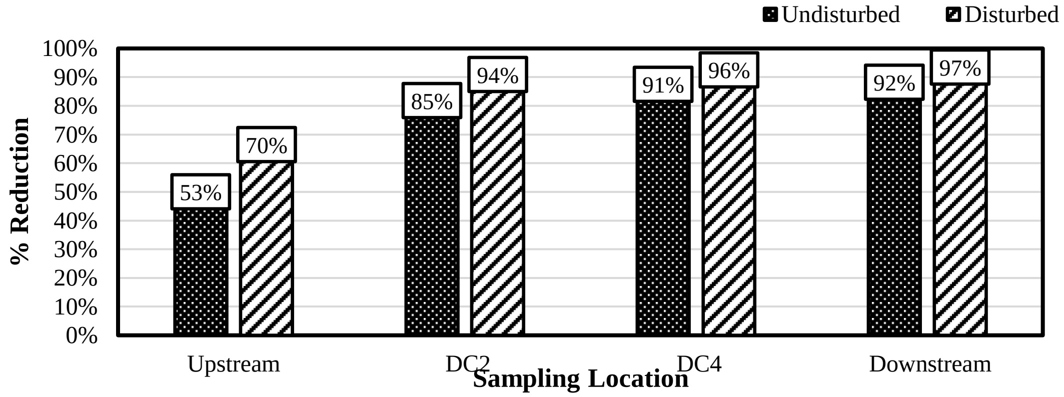


Figure 5-28: Turbidity Reduction Results for SA Treatment 9-minute Samples

Upstream samples showed higher turbidity reduction behavior in disturbed samples (70 %), which indicated an increased amount of sediment capture in the upstream undisturbed sample bottles. The turbidity reduction performance of the aqueous solution improved after the DC-2 sampling location.

Although aqueous solution introduction provided the most effective dosage delivery mechanism results, it is important to highlight that this type of flocculant application is not commonly adapted in construction applications. Construction stormwater treatment with an aqueous solution brings maintenance challenges for field applications since the semi-passive treatment requires periodic maintenance to keep continuous dosing in the system.

Supercritical flow condition flume evaluations on different flocculant forms provided a comprehensive understanding of dosage delivery and agitation requirements for proper flocculant introduction in channelized flow. Overall results obtained from granular, block, sock, and aqueous solution experiments were statistically analyzed to identify performance differences between each tested form. ANOVA analysis was conducted on the turbidity reduction data obtained from 9-minute data collection for each form by considering equal turbidity reduction behavior as the null hypothesis. Results required the rejection of the null hypothesis with a 95% confidence level and showed a significant difference in turbidity reduction performance between evaluated flocculant forms. To identify turbidity reduction differences in flocculant forms, six series of paired t-tests were applied at a 95% confidence level. Results of the paired t-test analyses are presented in Table 5-3.

Table 5-3: Statistical Significance Comparisons for Flocculant Forms

Comparison	p-value
Block - Sock	0.0691
Block - Granular	0.1614
Block - Aqueous Solution	0.0296*
Sock - Granular	0.0295*
Sock - Aqueous Solution	0.2900
Granular - Aqueous Solution	0.0001*

* indicates statistical significance ($p<0.05$)

T-test results revealed a significant difference between block-aqueous solution, sock-granular, and granular-aqueous solution pairs by computing p-values less than 0.05. However, the sock form did not show a significant difference with block and aqueous solution forms for turbidity reduction performance. Moreover, block and granular forms statistically displayed similar turbidity reduction performance.

The significant difference between granular and aqueous solution was one of the interesting findings of this research since these forms were both made of the same chemical agent. Among all evaluated flocculant forms, the aqueous solution provided the most effective dosage delivery and agitation. Following aqueous solution, block and granular forms performed well in treating turbid channelized flow by providing enough agitation and mixing throughout the testing. Sock product was the least effective flocculant form for providing effective agitation and proper dosage delivery.

5.7.2 SUBCRITICAL FLOW EXPERIMENTS

Subcritical flow conditions were evaluated with granular flocculant application (Product-A) by lowering the slope of the flume to 1%. The purpose of the subcritical flume experiments was to identify dosage delivery and agitation requirements in channelized flow with low critical depth. The channel characteristics required the use of one scaled-down check dam for 1% slope experiments. Granular flocculant was applied on this ditch check, which was located closer to upstream of the flume.

The impact of subcritical conditions was observed in clear water and sediment introduction experiments with a similar methodology applied in the supercritical flow testing. Estimated flocculant concentrations in clear water experiments showed no flocculant condition upstream of the flume and the scaled-down ditch check. Downstream of the ditch check and flume experienced steady dosage delivery with an average concentration value of 5 mg/L, which corresponds to the manufacturer's dosage recommendation in the bench-scale phase. Compared to supercritical conditions, delivered dosage concentrations were approximately 20 mg/L lower in the clear water subcritical flow experiments. In this specific flow condition, product wash-off was not observed in the granular form. Based on the concentration estimations, it can be interpreted that granular form dosage delivery performance in subcritical flow conditions is more efficient compared to supercritical flow. This comparison also indicates that granular form in subcritical flow requires less frequent reapplication.

In sediment introduction experiments, residual concentration results detected an insignificant amount of flocculant upstream of the ditch check with an average of 0.5 mg/L concentration. Downstream of the ditch check showed slightly lower residual concentrations compared to the downstream of the flume as shown in Table 5-4.

Table 5-4: Residual Flocculant Concentrations in Subcritical Flow SG Treatment

	Sampling Time (min)	Residual Concentration (mg/L)			
		Upstream	Upstream DC	Downstream DC	Downstream
SG	3	0	0.5	2.8	5.2
	6	0	0.6	2.6	3.3
	9	0	0.5	2.5	3.7

Additionally, granular form application in subcritical flow showed sufficient agitation and mixing throughout the flume by showing effective turbidity reduction in undisturbed samples. Figure 5-29 presents the 9-minute sampling period turbidity reduction results in subcritical flow conditions. Undisturbed samples provided up to 96% turbidity reduction, which was only 3% lower than the turbidity reduction of disturbed samples.

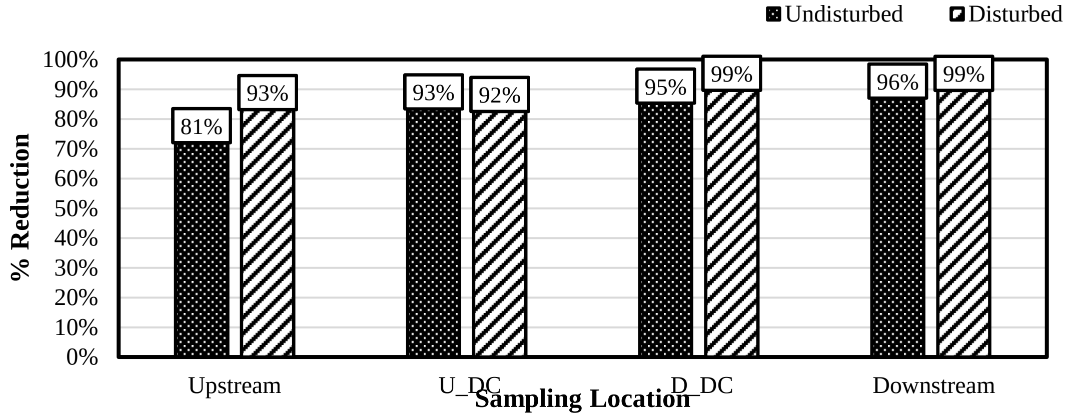


Figure 5-29: Turbidity Reduction Results for SG 9-minute Samples in Subcritical Flow

5.7.3 LONGEVITY TEST

Prior to subcritical flow slope adjustments on the flume, the granular form was tested for longevity in the supercritical flow experiment setup. Clearwater was introduced into the flume for two hours and flocculant concentrations were estimated for each sample collected throughout the experiment. Upstream samples were excluded from the longevity evaluations since these samples did not contain any flocculant. Estimated flocculant concentrations were plotted versus time as shown in Figure 5-30 and linear trendlines for DC-2, DC-4, and downstream samples were evaluated for identifying the longevity of the product. The trendlines had R^2 values of 0.71, 0.49, and 0.65, respectively. Each trendline showed a negative slope, which indicated product wash-off with time.

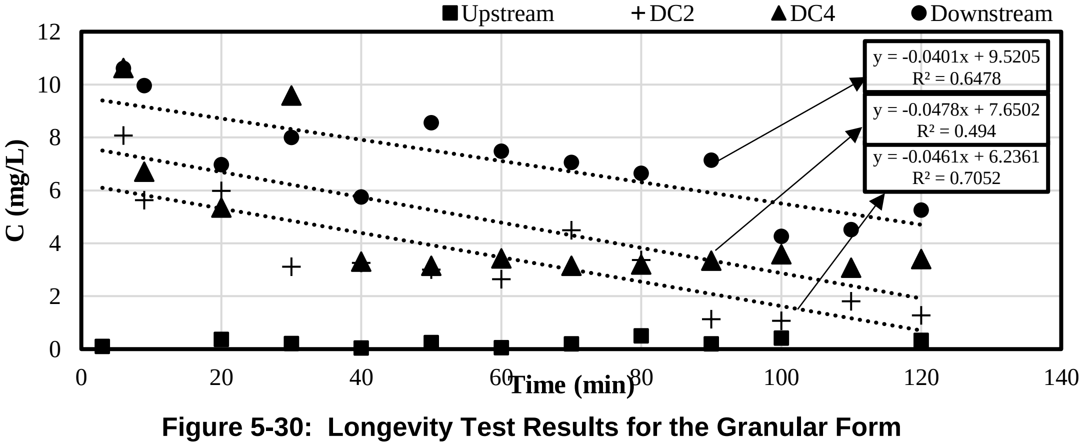


Figure 5-30: Longevity Test Results for the Granular Form

Based on the equation of the linear fit trendlines, the time for complete wash-off in each sampling location was calculated by using 0 mg/L as the concentration input in the trendline equations. Table 5-5 presents the longevity of the granular product in each sampling location.

Table 5-5: Granular Product Longevity Estimation Results

Sampling Location	Trendline Equation	Estimated Longevity (min)	Treated flow volume ft^3 (m^3)
DC-2	$y = -0.0401x + 9.5205$	237	1,422 (40.3)
DC-4	$y = -0.0478x + 7.6502$	160	960 (27.2)
Downstream	$y = -0.0461x + 6.2361$	135	810 (22.9)

Results indicated that the complete wash-off condition would be achieved in 3 hours 57 minutes in the entire channelized flow flume setup by treating 1,422 ft^3 (40.3 m^3) turbid water. This longevity result indicated that 27,346 ft^3 (1.67 m^3) of volume could be treated before reapplication of flocculant is required in the channel. DC-4 and DC-2 sampling locations reached 0 mg/L concentration in 2 hours 40 minutes and 2 hours 15 minutes, respectively. These observations showed that towards the upstream of the channelized flow, the granular product had less longevity compared to downstream.

5.8 SUMMARY

Current use of PAM in E&SC practices lacks information necessary to guide practitioners appropriately for effective results without wasting product or causing environmental harm. This work has identified requirements for proper dosage delivery mechanisms by validating bench-scale phase findings of this research through intermediate-scale flume application evaluations.

Flume experiments focused on identifying dosage delivery, agitation, and mixing requirements of flocculant introduction in channelized flow. The channelized flow was mimicked in a 40-ft (12 m) long flume with scaled-down ditch check installations under supercritical and subcritical flow conditions. Different flocculant forms were evaluated in supercritical flow conditions and results indicated that aqueous solution promoted the most effective dosage delivery mechanism among granular, block, and sock forms. However, due to implementation difficulties of aqueous form introduction in field conditions, block and granular forms were identified as the effective forms for passive dosing in channelized flow. The study identified increased residual concentrations downstream during block and granular form applications due to the self-overdosing behavior of the system. Granular and block applications require increased distance between the introduction and discharge area, which indicates that using flocculant on each ditch check might interrupt the proper dosage delivery mechanism downstream. Among all tested flocculant forms, the sock form was identified as the least effective product for enhancing turbidity reduction.

The flume study observations determined that granular form flocculants are highly susceptible to product wash-off under supercritical flow conditions. The granular form provided effective dosage delivery in subcritical flow by providing up to 96% turbidity reduction and relatively low residual concentrations. The study evaluated the longevity of the granular form by extending the flume testing duration to 2 hours. Results showed that the approximate time for complete product wash-off for the granular product under supercritical flow was 3 hours 57 minutes.

Intermediate-scale evaluations on flocculants were essential in this research to elevate the knowledge gained in the bench-scale phase by replicating construction conditions. The findings of this research aim to guide practitioners in implementing adequate dosage delivery techniques on active job sites. Findings showed the importance of residual concentration detection not just for overdosage monitoring, but also for identifying the agitation needs of the flocculant applications. It is important to note that these studies were conducted using PAM flocculants from Manufacturer I with AU-SRF sandy clay loam soil.

CHAPTER 6
LARGE-SCALE EVALUATIONS

6.1 INTRODUCTION

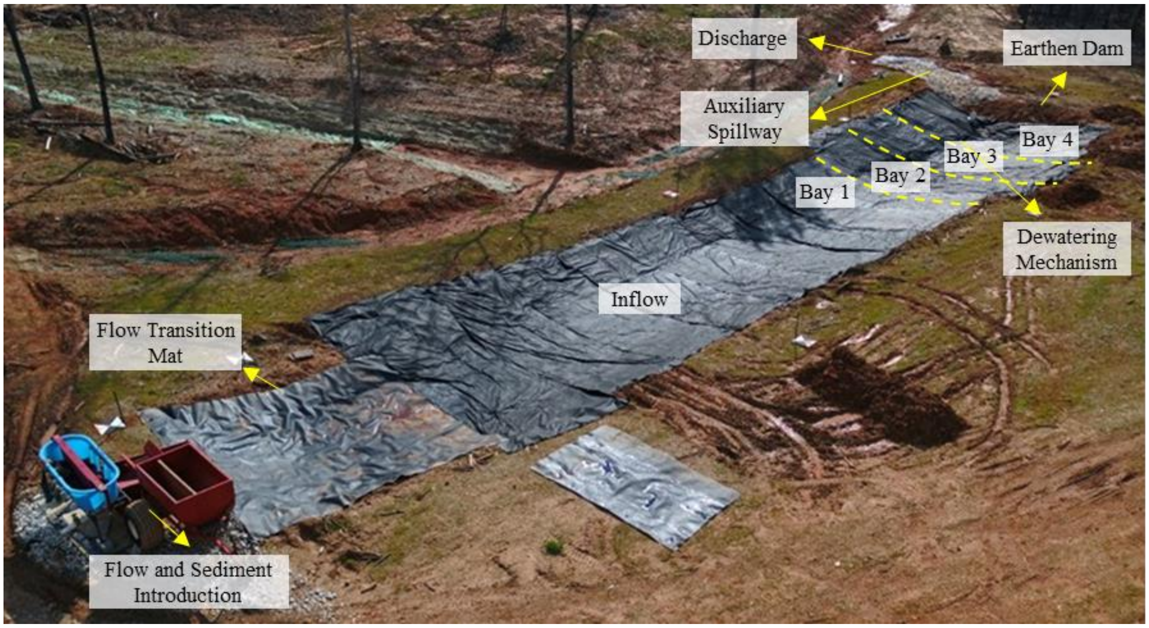
Large-scale testing is necessary to assess flocculant application methods in a testing environment with similar conditions to field applications, and while bench scale and intermediate flume testing provided substantial data for examining the use of flocculants in construction stormwater treatment, this information is not sufficient for making informed decisions. In this study, the goal of large-scale testing was to determine dose, agitation, and mixing needs by applying information gained from the bench-scale and intermediate-scale flume studies phase. Based on the results of in-channel field studies that replicated channelized flow conditions encountered on construction sites, this section of the report will offer an evaluation of feasible dosage delivery techniques.

The large-scale application evaluation phase was expanded into a collaborative research effort that implemented flocculants on a large-scale sediment basin apparatus with a 3,031 ft^3 (85.8 m^3) storage volume, which was constructed at AU-SRF for improving Iowa DOT in-channel sediment basin applications through the controlled testing environment. This study integrated flocculant application into the developed “Most Feasible and Effective Installation (MFE-I)” treatment phase, which included the combination of geotextile lining, forebay, and skimmer. The flocculant product, which was used in this collaborative study, was selected through the match test procedures developed in this research. Moreover, residual concentrations were monitored throughout the testing and dewatering phases in the sediment basin experiments by utilizing the developed residual detection method in this research. The large-scale testing phase of this research allowed a comprehensive investigation of practical methods to use for proper flocculant introduction into construction stormwater runoff. Additionally, large-scale channel-based testing was performed on granular and block form flocculants. Wattles and silt fence ditch check installations were used for the two respective flocculant forms for evaluating dosage delivery and agitation throughout the channel and flow event.

The results of this study are anticipated to enhance flocculant application techniques on construction sites and provide practitioners with guidance on the optimal dosage delivery, agitation, and mixing requirements of flocculants. In addition, the study's findings are intended to promote residual concentration monitoring in construction stormwater treatment with flocculants by validating the developed intermediate-scale method through large-scale applications.

6.2 SEDIMENT BASIN-BASED LARGE-SCALE TESTS

The sediment basin apparatus used in this study was built for a comprehensive sediment basin research sponsored by Iowa DOT, which evaluated the performance of the in-channel basin with various treatments. The basin apparatus was designed in a 200 ft (61 m) channel with 3,031 ft^3 (85 m^3) storage volume and constructed on a 3% slope channel at AU-SRF based on Iowa DOT design standards (*200*). Figure 6-1 shows the sediment basin apparatus located in the expansion area of the AU-SRF. The basin apparatus included a flow and sediment introduction area, flow introduction mat, earthen berm, dewatering mechanism, auxiliary spillway, and discharge area as illustrated in Figure 6-1(a). Controlled flow and sediment introduction provided mimicked construction conditions in the basin and different treatments were evaluated for the basin performance by Schussler (*200*).



(a) basin components

(b) MFE-I configuration

Figure 6-1. Sediment basin apparatus at AU-SRF

The evaluated treatments included Iowa DOT configuration, geotextile lining, surface skimmer, coir baffles, forebay, and the most feasible and effective installation (MFE-I) as shown in Figure 6-1(b). Research collaboration efforts in this study took place during flocculants implementation with the most feasible and effective installation treatment phase.

6.2.1 SEDIMENT BASIN-BASED TESTING METHODOLOGY

The first step of the flocculant application on a large-scale sediment basin study was selecting the best performing flocculant product for the Iowa native clayey testing soil, which was previously classified as USCS sandy clay loam and AASHTO clayey soil. Match test experiments were conducted on this soil and the testing results listed products A and A2 in the best performing product list based on the developed point system in the bench-scale phase of this research. Product A2 was selected for the sediment basin testing for evaluating block form application in large-scale evaluations.

Following product selection, flocculants were installed in the sediment basin testing apparatus. The testing setup included each component of the MFE-I treatment: a combination of geotextile lining, forebay, and skimmer. In total, three floc blocks were placed horizontally upstream of the rock check dam prior to the forebay for promoting full contact with the flow and ensuring sufficient agitation and mixing throughout the testing. The blocks were secured in the flocculant introduction area by using t-posts and sod staples as illustrated in Figure 6-2. Retained sediment on the blocks was scraped and blocks were covered with plastic between each test to prevent sediment layer and sun exposure on the testing products.

Figure 6-2. Flocculant introduction in testing channel *(Schussler 2022)*

The testing was conducted in two stages: filling and overfilling periods, which consisted of 30-minute flow and sediment introduction with 4.5 hours of dewatering in between. Following the overfilling period, the basin was dewatered for 48 hours to complete the testing and prepare the basin for clean-up (*200*). Flocculant application with the MFE-I treatment test was repeated three times for obtaining accurate data for the large-scale evaluations.

Water samples were collected in the (1) inflow channel, (2) second bay, (3) fourth bay, and (4) discharge by using automated samplers. In addition to automated sampling, hand samples were collected from the inflow location and downstream of the forebay for flocculant performance evaluation. Data collection for flocculant dosage delivery and performance evaluations included turbidity measurements and residual concentration. In addition, sediment retention was measured by Schussler for comparing MFE-I treatment to sediment retention performance of MFE-I with flocculant treatment in the basin (*200*). Samples collected from forebay, Bay 2, and discharge points were used for flocculant performance evaluation in this study.

Turbidity measurements were used to evaluate turbidity reduction and dosage delivery performance of the flocculant product. The settling velocity of each sample was also observed for estimating residual concentrations by using the developed detection method in the bench-scale phase of this research.

6.2.2 SEDIMENT BASIN-BASED LARGE-SCALE RESULTS AND DISCUSSION

Flocculant application on the sediment basin apparatus provided an opportunity to evaluate block form dosage delivery mechanism performance in large-scale testing conditions. This section elaborates on the data analysis and results collected in this collaborative research effort from the flocculant performance evaluation perspective.

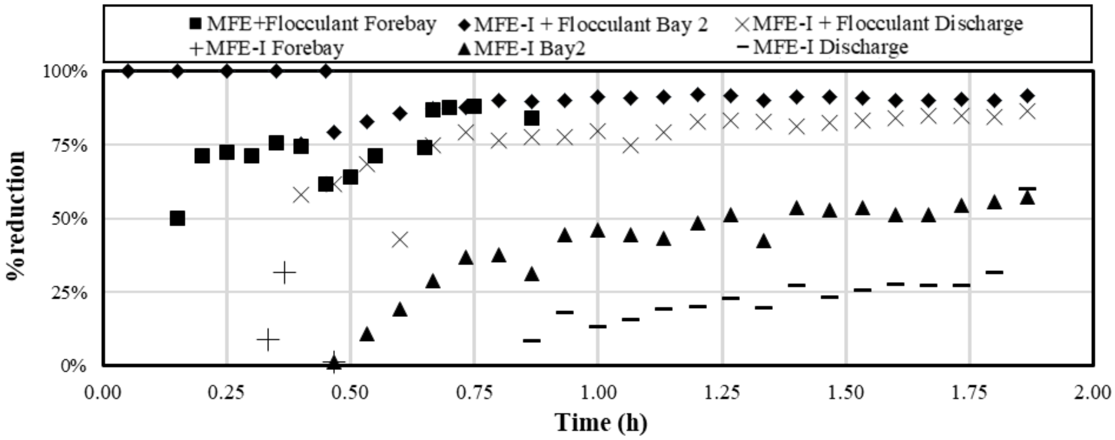
The match test experiments, which were conducted in this study prior to flocculant application on the basin apparatus, emphasized the important role of soil-dependent product selection. The selected PAM product was ranked in the top three best-performing products by gaining 31 points based on its supernatant color, floc formation, size floc, and settling rate performance. The product was highly capable of capturing fine-sized sediment particles in the tested Iowa native soil. Hence, obtaining significant turbidity reduction results was expected in case of proper dosage delivery during the large-scale sediment basin experiments. However, it is important to note that product selection is also dependent on cost, application, maintenance, and available resources in real-life flocculant implementation on active job sites.

Proper dosage delivery was achieved in this study by ensuring complete flow contact throughout the testing and introducing flocculants prior to forebay in the sediment basin. The location of the flocculant introduction area within the basin apparatus had a significant role in promoting proper agitation and mixing. The existence of a forebay downstream of the flocculants facilitated floc formation by providing slow mixing within the impoundment occurring upstream of the forebay. In addition, the distance between the flocculant introduction area and the downstream of the basin allowed sufficient activation and settling period for formed flocs.

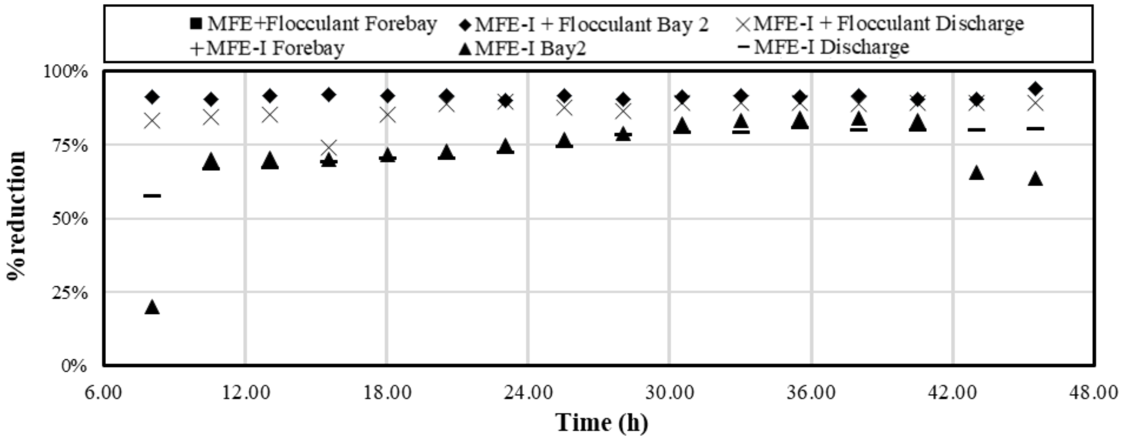
Flocculant application with MFE-I treatment tests showed an average inflow turbidity value of 753 NTU, this was reduced to 125 NTU in the discharge sampling location by the end of the filling period. Overflow testing duration had an average of 430 NTU inflow turbidity, which was reduced to 53 NTU at the discharge point after the 30-minutes sampling period. The MFE-

I treatment without flocculant had average inflow turbidity of 334 NTU in the filling phase and 440 NTU in overflow observations. These values were decreased to 254 and 113 NTU in the discharge area, respectively. Turbidity observation in MFE-I and MFE-I + flocculant treatments showed that the use of flocculant in the basin enhances the turbidity reduction of the MFE-I treatment.

Turbidity reductions in each sampling location were calculated based on average inflow values for evaluation turbidity reduction during the testing and post-testing periods. Figure 6-3 compares the turbidity reduction of MFE-I + Flocculant with MFE-I treatment by displaying data collected from forebay, Bay 2, and discharge in each treatment set.



(a) turbidity reduction between 0:00 – 2:00 h



(b) turbidity reduction in 6:00 – 48:00 h

Figure 6-3. Turbidity reduction comparison between MFE-I and MFE-I + Flocculant

Turbidity reduction of flocculant application during the first 2-hour testing period was compared to MFE-I treatment in discharge sampling location as illustrated in Figure 6-3(a). Square and plus markers show observed turbidity reduction behavior in the forebay sampling area for MFE-I and MFE-I + Flocculant treatments. As it can be observed from the presented turbidity reduction plot, the introduced flow did not overtop the rock check them in the first 8 minutes during the MFE-I + Flocculant treatment, and 50% turbidity reduction was observed after the filling was completed in the forebay area. The turbidity reduction in the forebay reached its peak point, 88% in 40 minutes, and stopped in 48 minutes due to dewatering. On the other hand, during the MFE-I installation, the forebay area initially showed higher turbidity levels than the average turbidity observed in the inflow. However, turbidity reduction increased to 32% in 22 minutes and showed a decrease in the initial filling period. After 30 minutes from the start of the testing, the turbidity reduction was not observed for the forebay area of MFE-I treatment due to dewatering occurring upstream of the check dam.

Diamond markers in the plot represent average turbidity reduction in Bay 2 for MFE-I + Flocculant treatment, while triangle markers display turbidity reduction results obtained in MFE-I treatment during testing. According to the observed results, the MFE-I + Flocculant treatment was more efficient than the MFE-I treatment in Bay 2 sampling location. Turbidity reduction was up to 100% within approximately 8 minutes in the filling phase. Throughout the testing, turbidity reduction of MFE-I + flocculant treatment was higher than the MFE-I treatment during the testing.

The discharge sampling point during flocculant introduction, which was symbolized with a cross marker, also showed higher turbidity reduction rates compared to the MFE-I treatment. Flocculant introduction increased the turbidity reduction in discharge up to 90% towards the end of the first two-hour sampling period, where MFE-I treatment showed a maximum turbidity reduction of 67%.

Figure 6-3(b) illustrates the turbidity reduction results for forebay, Bay 2, and discharge point samples during the 48-hour monitoring period. The results indicated that integrating flocculants into MFE-I treatment enhanced the decrease in turbidity and provided a steady turbidity reduction behavior in each sampling location. Forebay did not show any turbidity reduction data for the 48-hour monitoring period since it was completely dewatered. However, Bay-2 and discharge sampling points had a maximum of 87% and 90% turbidity reduction, respectively. These values were comparatively high considering the turbidity reduction of MFE-I treatment, which had a maximum 82% turbidity reduction in Bay 2 and the discharge sampling point. In addition to turbidity reduction observation, Schussler quantified the sediment retention of MFE-I+ Flocculant treatment and compared it to MFE-I testing results (2022). The comparison indicated that flocculant application increased the sediment capture by 2% in the basin.

Residual flocculant concentrations were observed throughout the MFE-I + Flocculant treatment testing on the sediment basin apparatus according to the standard flocculant concentration plot developed for Product A2. Samples were collected from downstream of the flocculant introduction area, in and downstream of the forebay and discharge point in the basin. The supernatant of the samples was used for identifying residual concentrations by observing the settling velocity behavior of each sample with the residual testing soil. The average residual concentration results shown in Figure 6-4 illustrated that the dosage delivery was successful within the basin by not exceeding 8 mg/L throughout 48 hours of monitoring. The manufacturer dosage concentration guidance on product A2 was 5 mg/L to treat 1,500 ± 300 NTU turbid water.

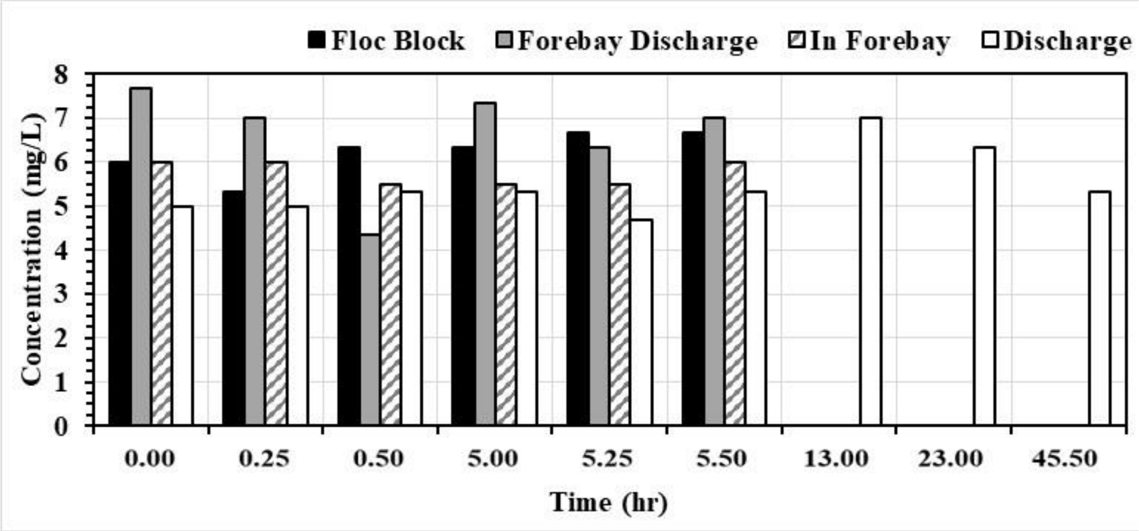


Figure 6-4. Residual concentration monitoring results

Samples collected downstream of the floc block, displayed in a striped pattern, had an average residual concentration of 6 mg/L during the 6 hours monitoring period. Similar behavior was observed within the forebay. However, downstream of the forebay, illustrated with a vertical dashed pattern, had slightly higher concentrations compared to upstream samples. Discharge point, shown in hatched pattern, had lower residual concentrations within the first 6 hours; however, concentration values reached to the maximum level, 7 mg/L, in a 13-hour sampling period and slowly decreased to 5 mg/L in 48 hours.

Based on manufacturer guidance, one block of product A could treat 800,000 gal (3,028 m^3) turbid water. Throughout the one-hour testing period, 137,028 gal (519 m^3) of water was introduced into the basin, which, per provided guidance, requires only 17% of one block. However, it is important to consider that not all introduced flow made adequate contact with the blocks. Therefore, it was important to increase the number of blocks and place them in a way that facilitates maximum contact area with the flow introduction. Therefore, three blocks were required to provide sufficient dosage throughout the basin even if each of them had a higher treatment capacity than needed.

As observed in the intermediate-scale flume experiments, block form flocculant provided a consistent dosage and promoted effective turbidity reduction with proper agitation and mixing techniques. This was also observed in the large-scale sediment basin application study due to low and uniform residual concentrations. Low residual concentration results and turbidity reduction data implied that flocculant introduction throughout the basin apparatus provided sufficient dosage delivery and agitation. The flocculant introduction system did not show any sign of increased dosage throughout the 48-hr monitoring period.

6.3 CHANNEL-BASED LARGE-SCALE EXPERIMENTS

Initial large-scale testing using Product A-G and Product A-B was conducted in the expanded area at AU-SRF. Testing started with Product A-B where three silt fence ditch checks were installed in the 222 ft (67.7 m) long channel shown in Figure 6-5. The average channel top width was 16 ft (5 m). The three silt fence ditch checks were spaced 130, 59, and 46 ft (40, 18, and 14 m) apart, respectively, moving downstream the channel, beginning from measuring the distance from the end of the sediment mixing trough. The silt fence ditch checks were spaced by placing the third ditch check towards the end of the channel. The third silt fence ditch check weir was cut to 16 in. (41 cm) to accommodate two additional ditch checks upstream. Then, using a string and bubble line level, one end of the string was placed held at the lowest point of the weir, while the other end of the string was walked up the channel until the string and ground intersection point yielded a straight, level line. This level line represented a standing pool impoundment length. The subsequent upstream silt fence ditch check was then installed at the end of the predicted standing pool impoundment length to ensure maximum impoundment was achieved during flow conditions. The second weir was then cut to 8 in. (20 cm) and the first weir was cut to 16 in. (41 cm). Samples were collected upstream (U in figures and tables) when water overtopped the ditch check (DC in figures and tables), before coming in contact with the flocculant blocks, between the first and second ditch check, and after ditch check two and three. Two flocculant blocks were installed directly after the first silt fence ditch check so that overtopping water would fall directly onto the blocks. The blocks were secured in place with rope to ensure consistent dosing throughout the duration of the test. Samples were collected as the silt fence ditch checks impounded water at 4, 8, 12, and 16 in. (10, 20, 30, and 41 cm) depths and every 10-minutes for 40-minuts after the channel reached steady state. All silt fence ditch check weirs were cut to be 16 in. (41 cm) from the ground, meaning the 16 in. (41 cm) impoundment depth sample was taken when the weir overtopped. All samples were collected in 33.4 fl oz (1,000 mL) multi-use plastic jars. Sediment was introduced into the channel at 23.3 lb./min (10.6 kg/min) with 1.75 ft^3/s (0.16 m^3/s). Flocculant blocks were hydrated using a watering can prior to channel flow to activate the flocculant and simulate rainfall before channel flow.

Note: 1.0 ft = 0.3 m

Figure 6-5. Initial Product A-B Testing Channel

All collected samples were processed for residual flocculant within four days after collection. Residual tests were performed by shaking each sample bottle to resuspend all sediment and transferring the samples to 51 fl oz (1,500 mL) glass beakers. The samples were then placed on a jar test multiple stirrer machine and flash-mixed (120 rpm) for 1-minute. Samples were removed from the machine and set aside to rest for 15 minutes, allowing the sediment to settle out of suspension. After 15-minutes, the settled sediment was separated by slowly pouring the supernatant into a new, clean 51 fl oz (1,500 mL) glass beaker. Next, prepared AU-SRF sediment was added to the supernatant sample. The AU-SRF sediment consisted of 0.71 oz (20 g) of soil sieved through a #200 sieve. Once soil was added, the sample was placed back on the jar test multiple stirrer machine and flash mixed again for 1-minute. The sample was immediately poured into a 34 fl oz (1,000 mL) graduated cylinder where the settling velocity was measured and recorded.

The soil settling velocity curve for Product A-B initially developed was modified to create a better-fit line and used to predict the Product A-B concentration from large-scale tests (Figure 6-6). Three replications were run with block form flocculant and the settling velocity of each sample was measured. Data was averaged across all three replications. Field soil settling velocities from samples were plugged into the respective equation in Figure 6-6, based on the settling velocity range being above or below 80 in./hr (203 cm/hr).

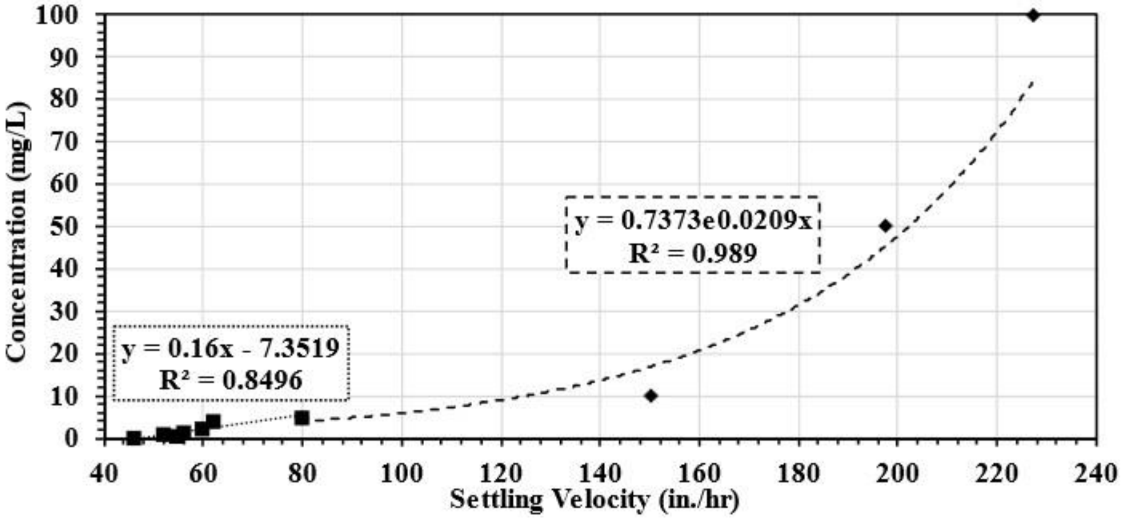


Figure 6-6. Initial Product A-B Soil Settling Velocity Curve

Table 6-1 shows Product A-B predicted concentrations that range between 9 and 352 mg/L. This range indicated brought about concern with accurately predicting concentrations in the field and prompted further investigation into the sampling methods and techniques used. The manufacturer's recommended dosing concentration with Product A-B is 5 mg/L, so 352 mg/L using two blocks indicated substantial overdosing, using the initial prediction equation. Additionally, upstream samples were predicted to contain high flocculant concentrations, indicating cross-contamination between tests in the sample containers.

Table 6-1. Initial Product A-B Predicted Concentrations

Sampling Time	**Predicted Settling Concentration (mg/L)**				
	U	**DC-1**	**DC-2**	**DC-3**	**D**
4 in. (10 cm) Impoundment Depth	9	14	19	27	N/A
8 in. (20 cm) Impoundment Depth	22	19	44	51	N/A
12 in. (30 cm) Impoundment Depth	14	30	26	352	N/A
16 in. (41 cm) Impoundment Depth	23	28	71	125	56
10 min	14	26	49	37	23
20 min	37	35	50	38	57
30 min	37	40	42	24	25
40 min	12	72	37	20	51

Observations during large-scale tests indicated that flocs were observed in all samples collected. Further investigations found that PAM adheres to plastic surfaces by forming weak intermolecular bonds via polymer chains (*201*, *202*). Regardless of how well the plastic containers were cleaned, flocs consistently formed in the sample containers with or without being subjected to flocculant during testing. Alternatively, PAM is much less likely to stick to a glass surface as glass is a relatively inert material with a smooth and nonporous surface, making it difficult for adhesion to occur (*203*, *204*). However, as field conditions are not a glass-friendly environment, single-use plastic bags were substituted instead (Figure 6-7. Sample Collection Containers).

(a) multi-use plastic containers (b) single-use plastic bags

Figure 6-7. Sample Collection Containers

Since the soil settling velocity curve was developed using tap water, a curve offset was used to assess if predictions improved. Pond water from large-scale tests was sampled and used to measure the soil settling rate, without flocculant. The settling velocity difference from the collected large-scale test samples and pond water was used to create an adjusted settling velocity prediction (Eq. 6-1).

$$Adjusted\ Settling\ Velocity = Field\ Test\ Sample - Pond\ Water \qquad \text{Eq. 6-1}$$

Table 6-2 contains the initial adjusted Product A-B predicted concentrations with a range of 0 to 12 mg/L. Although this concentration prediction range is more reasonable, predicting residual flocculant only at DC-3 during the second half of water impoundment was highly unlikely. There would be some degree of residual flocculant needed at the first half of impounding water at DC-3 and subsequent ditch checks prior. Thus, these results indicated this technique was not ideal for predicting residual concentrations of Product A-B.

Table 6-2. Initial Adjusted Product A-B Predicted Concentrations

Sampling Time	Predicted Settling Concentration (mg/L)				
	U	DC-1	DC-2	DC-3	D
4 in. (10 cm) Impoundment Depth	0	0	0	0	N/A
8 in. (20 cm) Impoundment Depth	0	0	0	0	N/A
12 in. (30 cm) Impoundment Depth	0	0	0	12	N/A
16 in. (41 cm) Impoundment Depth	0	0	0	4	0
10 min	0	0	0	0	0
20 min	0	0	0	0	0
30 min	0	0	0	0	0
40 min	0	0	0	0	0

As cross-contamination seemed to be the outstanding issue, single-use plastic bags were then used to replace all sampling containers and large-scale tests started back up with Product A-G testing. The large-scale testing channel configuration for initial Product A-G tests is shown in Figure 6-8. The 70.1 m (230 ft) long channel consisted of three 20 in. (51 cm) diameter straw wattle ditch checks (DC-1, DC-2, and DC-3) and one 20 in. (51 cm) excelsior wattle (DC-4) at the end of the channel. The first three ditch checks were spaced 39, 16, and 27 ft (12, 5, and 8 m) apart, respectively, moving downstream the channel, beginning from measuring the distance from the end of the sediment mixing trough. The wattles were spaced by placing the third ditch check in the channel to allow for sample collection before flow was directed to the underground pipe. Then, using a string and bubble line level, one end of the string was placed held at the lowest point of the wattle, while the other end of the string was walked up the channel until the string and ground intersection point yielded a straight, level line. This level line represented a standing pool impoundment length. The subsequent upstream wattle was then installed at the end of the predicted standing pool impoundment length to ensure maximum impoundment was achieved during flow conditions. The first two ditch checks, labeled DC-1(F) and DC-2(F), each contained 5.1 oz. (145 g) of Product A-G spread according to ALDOT standards – on the top and upstream face of the wattle (*93*), where the “F” indicates flocculant application. Sampling location “U” represents samples collected upstream of flocculated water, “P” is samples collected directly after the underground corrugated pipe, and “G” represents samples collected further downstream the grass channel. The maximum flow the channel could hold was 0.75 ft^3/s (0.07 m^3/s) where 17.8 lb/min (8.07 kg/min) of sediment was mixed with incoming channel flow. Granular flocculant was hydrated using a watering can prior to channel flow to activate the flocculant and simulate rainfall before channel flow. Samples were collected during the first flush and every 10-minutes for 120-minutes after steady state was reached in the channel.

Figure 6-8. Initial Product A-G Testing Configuration

All samples collected were processed the same day, immediately after sample collection with the idea that allowing samples to be processed within four days was one source for inconsistent data. Residual tests were performed same as before with Product A-B samples where samples were shaken, transferred into 51 fl oz (1,500 mL) glass beakers, flash mixed, settled for 15 minutes, supernatant separated, 0.71 oz (20 g) of #200 AU-SRF sieved sediment added, flash mixed again, and poured into a 34 fl oz (1,000 mL) graduated cylinder where the settling velocity was recorded.

The soil settling velocity curve for Product A-G initially developed was modified to create a better-fit line and used to predict the Product A-G concentration from large-scale tests (Figure 6-9). Three replications were run with granular flocculant and the settling velocity of each sample was measured. Data was averaged across all three replications. Field soil settling velocities from samples were plugged into the respective equation in Figure 6-9.

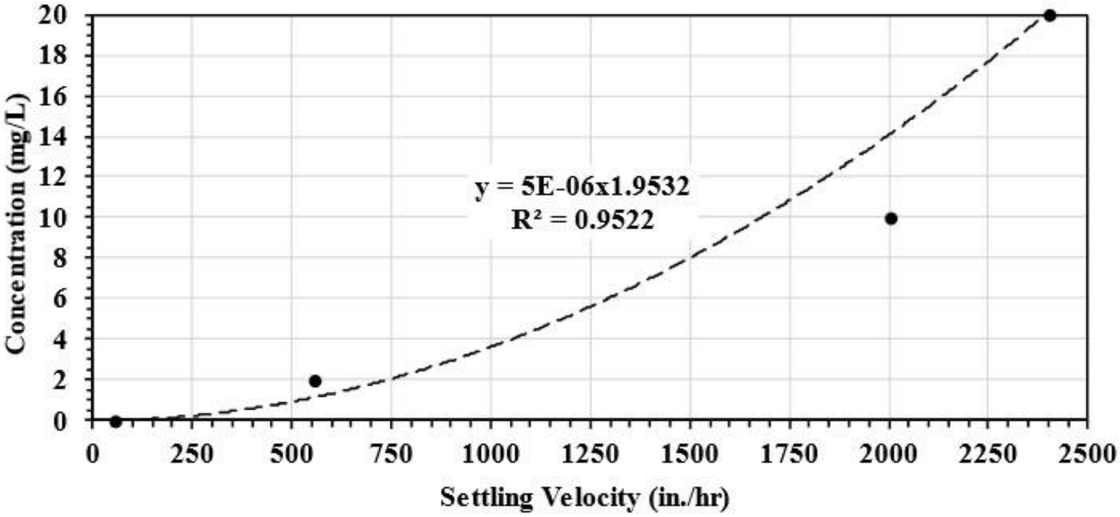


Figure 6-9. Initial Product A-G Soil Settling Velocity Curve

Table 6-3 shows Product A-G predicted concentrations that range between 0 and 56 mg/L. Although Product A-G predicted concentrations were more consistent than Product A-B predictions, they were not consistent enough to rule out the need to continue searching for improved detection methods. Manufacturer's recommended dosing concentration for Product A-G is also 5 mg/L. Meaning, replacing multi-use plastic containers with single-use plastic bags was only one part of the solution. First flush (FF in Tables) samples were expected to contain higher concentrations of flocculant as the flocculant wouldn't have much of an opportunity to mix or dilute. However, fluctuations from 5.0 to 56 and then an unexpected drop to 4.0 mg/L concentrations at DC-2(F), DC-3, and P sampling locations respectively, indicated the prediction equation needed expanded to account for a higher concentration range than 20 mg/L. Additionally, upstream samples still contained predicted concentrations which suggested a deeper analysis of environmental conditions was still needed.

Table 6-3. Initial Product A-G Predicted Concentrations

Sampling Time	Predicted Residual Concentration (mg/L)						
	U	DC-1(F)	DC-2(F)	DC-3	P	G	DC-4
FF	0	2	5	56	4	9	0
10 min	0	1	3	4	N/A	N/A	0
20 min	0	1	2	2	N/A	N/A	0
30 min	0	1	2	2	N/A	N/A	0
40 min	3	2	1	1	N/A	N/A	0
50 min	1	2	2	3	N/A	N/A	0
60 min	0	1	2	2	0	1	0
70 min	0	2	1	2	N/A	N/A	0
80 min	0	2	2	2	N/A	N/A	0
90 min	0	1	4	3	N/A	N/A	0
100 min	0	0	1	1	N/A	N/A	0
110 min	0	0	1	1	N/A	N/A	0
120 min	1	0	1	1	1	1	0

Adjusting the settling velocity was performed to see how data would change for Product A-G data when the settling velocity difference from the collected large-scale test samples and pond water were used to create an adjusted settling velocity prediction shown in Table 6-4. The adjusted concentration prediction range maximum was reduced by 2 mg/L, indicating this technique was not sufficient in better predicting residual Product A-B nor Product A-G.

Table 6-4. Initial Adjusted Product A-G Predicted Concentrations

Sampling Time	Predicted Residual Concentration (mg/L)						
	U	DC-1(F)	DC-2(F)	DC-3	P	G	DC-4
FF	0	1	3	54	3	7	0
10 min	0	0	1	3	N/A	N/A	0
20 min	0	0	0	1	N/A	N/A	0
30 min	0	0	0	0	N/A	N/A	0
40 min	1	1	0	0	N/A	N/A	0
50 min	0	0	0	2	N/A	N/A	0
60 min	0	0	0	0	0	0	0
70 min	0	0	0	0	N/A	N/A	0
80 min	0	0	0	0	N/A	N/A	0
90 min	0	0	2	1	N/A	N/A	0
100 min	0	0	0	0	N/A	N/A	0
110 min	0	0	0	0	N/A	N/A	0
120 min	0	0	0	0	0	0	0

Initial Product A-B and Product A-G large-scale tests were conducted prior to expanding on the soil settling velocity detection method. Although the standardized residual settling plots proved positive for large-scale application, this study was used to expand on this technique by applying the residual prediction methodology to large-scale applications to validate field condition applicability. This section detailed cross-contamination sources that can easily be resolved by avoiding multi-use plastic containers when sampling and that the plots previously developed with better fit lines still remains inaccurate but shows promise for a good foundation method. Since the initial residual settling plots were performed using tap water, field conditions include an assortment of environmental conditions that influence flocculant efficacy and settling rate, such as soil types, metal salts, water salinity, pH, and temperature (*24*, *166*, *205–211*). Meaning the residual settling plots initially developed require additional environmental conditions that need to be accounted for when developing standardized residual settling plots. By creating a calibration curve using the same soil at the testing facility, assumptions of minting similar soil types, metal salts, and salinity were assumed. Salinity would also be accounted for by checking the calibration curves with collected pond water during testing. Leaving pH and temperature as necessary components to be included calibration the soil setting velocity curve.

6.3.1 CHANNEL-BASED LARGE-SCALE TESTING METHODOLOGY

The testing methodology is divided into two portions where [1] describes the large-scale testing and sample collecting process and [2] describes large-scale sample processing for granular and block form flocculant tests.

6.3.1.1 Collecting Channel-Based Large-Scale Samples for Granular PAM

Flocculant dosing was based on previous intermediate-scale testing evaluations conducted in a 40.0 ft (12.2 m) long, 1.5 ft (0.5 m) wide adjustable flume to evaluate various flocculant applications. This comparison was done to see how intermediate-scale testing compared to large-scale applications. For Product A-G flume tests, the channel was subjected to 0.1 ft^3/s (0.003 m^3/s) and 0.85 oz. (24 g) of Product A-G was spread across four rock ditch checks with jute lining. These values for intermediate-scale testing were compared to the large-scale conditions by their flow rates to find the desired Product A-G application rate. Eq. 6-2 shows the formula used to scale up the intermediate-scale testing to large-scale applications.

$$\left(\frac{Q_{flume}}{W_{granular\ flume}}\right)=\left(\frac{Q_{channel}}{W_{granular\ channel}}\right) \qquad \text{Eq. 6-2}$$

Where Q_{flume} is the flow rate used in intermediate-scale flume testing (ft^3/s [m^3/s]); $W_{granular\ flume}$ is the total weight of Product A-G used in intermediate-scale flume testing (oz. [g]); $Q_{channel}$ is the design flow rate for large-scale application testing (ft^3/s [m^3/s]); and $W_{granular\ channel}$ is the total weight of Product A-G required for large-scale application testing (oz. [g]). This equation was written to solve for $W_{granular\ channel}$ to mimic the application rate used in intermediate-scale testing. Large-scale application testing used a flow rate of 0.75 ft^3/s (0.02 m^3/s). The total calculated weight needed for Product A-G was 6.35 oz. (180 g).

The testing location allowed for three 10 ft (3.1 m) long, 20 in. (51 cm) diameter straw wattles to be installed in the channel between the flow and sediment introduction system and the underground corrugated pipe. The three ditch checks were spaced 39, 16, and 27 ft (12, 5, and 8 m) apart, respectively, moving downstream the channel, beginning from measuring the distance from the end of the sediment mixing trough. The wattles were spaced by placing the third ditch check in the channel to allow for sample collection before flow was directed to the underground pipe. Then, using a string and bubble line level, one end of the string was held at the lowest point of the wattle, while the other end of the string was walked up the channel until the string and ground intersection point yielded a straight, level line. This level line represented a standing pool impoundment length. The subsequent upstream wattle was then installed at the end of the predicted standing pool impoundment length to ensure maximum impoundment was achieved during flow conditions. Figure 6-10 shows the large-scale application setup, along with each sampling location marked with an “O” and the location name. Samples were collected downstream of the wattles, before the next impoundment to allow the flocculant time to be mixed into the water. Each wattle ditch check sampling location was labeled as “DC” with the “(F)” indicating that 2.12 oz. (60.1 g) of flocculant was applied to the upstream wattle. Upstream sampling location is notated as “U,” after corrugated pipe is “P,” and at the end of the grassed channel is marked as “G.” Resulting in six sampling locations throughout the channel.

Figure 6-10. Wattle Product A-G Large-Scale-Testing Setup

Wattles were installed according to ALDOT standards (*93*), shown in Figure 6-11.

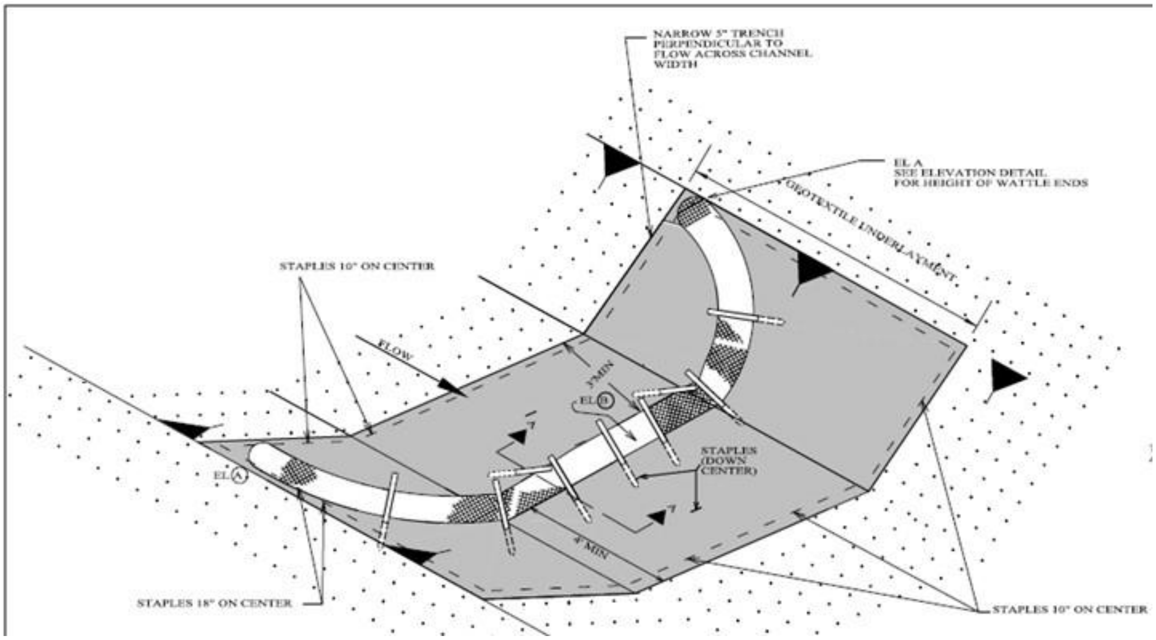
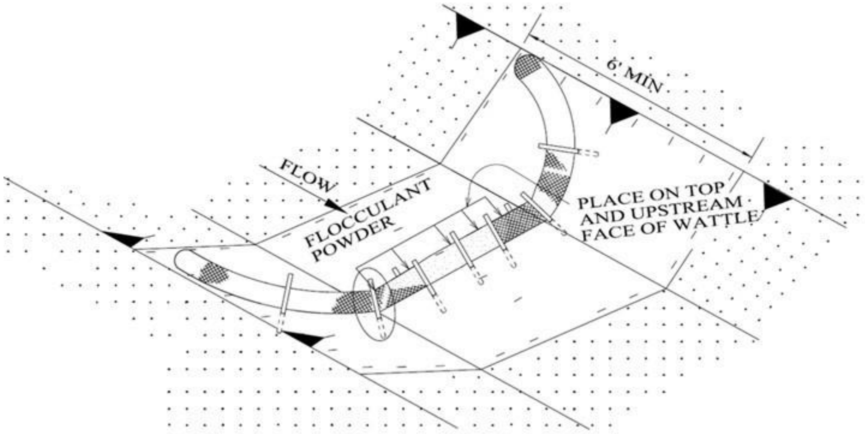
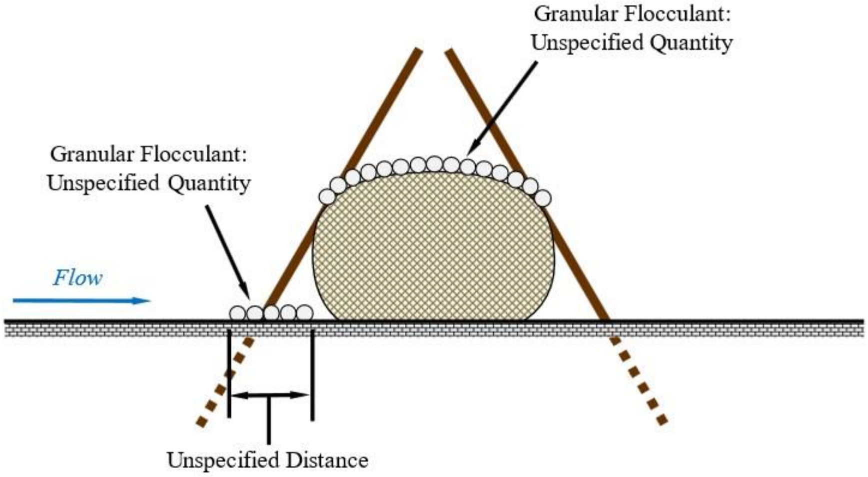


Figure 6-11. Wattle Installation Standards (*93*)

The Product A-G was applied considering NCDOT standards where one-quarter of the Product A-G is applied to the wattle face, half on the wattle top, and a quarter on the wattle back in the lower center portion of the wattle where water will flow to increase surface contact with applied flocculant (*212*). This application is different from ALDOT's method, which recommends flocculant application on the wattle top and face only (*93*). Figure 6-12(a) shows ALDOTs granular flocculant application standards. Figure 6-12(b) is a side profile creation of ALDOT standards to better show how flocculant is to be applied.



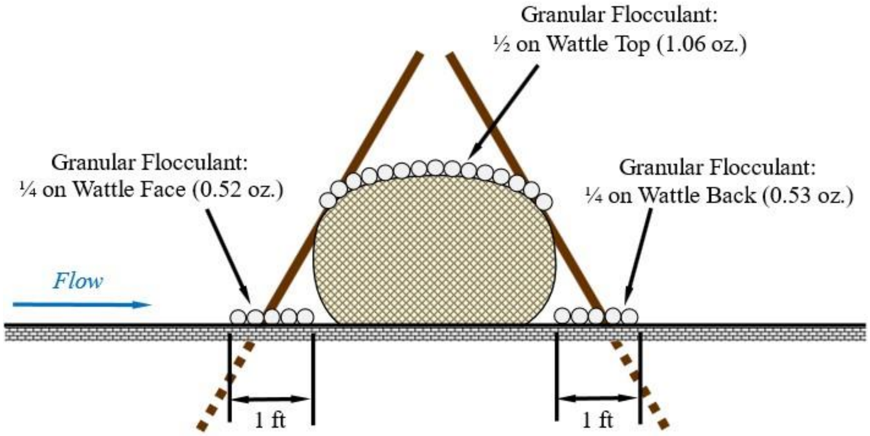
(a) application description (*93*)



(b) side profile of ALDOT application description

Figure 6-12. ALDOT Granular Flocculant Application

Even though NCDOT indicates granular flocculant should be applied 2.0 ft (0.6 m) minimum upstream and 6.0 ft (1.8 m) minimum downstream of the wattle, flocculant was applied within 1.0 ft (0.3 m) upstream and downstream of the wattle, Figure 6-13(a). This application modification was made to maximize flocculant surface contact without the need for additional installation materials. Additionally, this application technique is more likely to occur in the field as it is difficult to apply granular flocculant strictly to the wattle top and face. All three wattles had 2.12 oz (60.1 g) applied to each wattle according to Figure 6-13. After Product A-G was applied to the wattle, a watering can was used to saturate and activate the flocculant, simulating rainfall prior to channel flow. This was a crucial step for testing granular PAM flocculant applications to prevent flocculant 'fish eyes' in treated water, which would drastically impact residual flocculant predictions during testing (*39*, *84*). Activation occurs during rainfall as dry granular flocculant is saturated prior to runoff commencing.



(a) large-scale testing application schematic

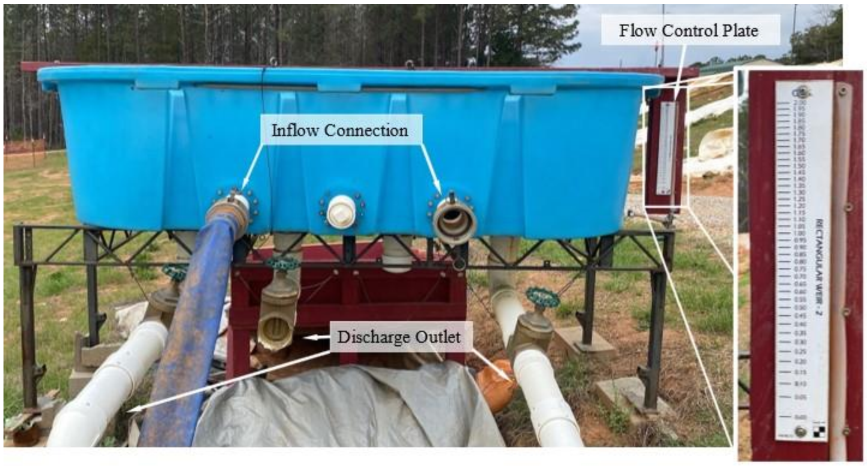
Note: 1.0 ft = 0.3 m, 1.0 oz = 28.3 g

(b) large-scale testing application images

Figure 6-13. Large-scale Testing Product A-G Application Method

An equalizing tank system was used to control water inflow rate, Figure 6-14. Figure 6-14(a) shows how pumps with flexible hoses were attached to the equalizing tank where a wood baffle, perpendicular to the inflow in the middle of the tank dissipated water inflow energy. Water exited the tank through a trapezoidal weir. Figure 6-14(b) displays a scaled flow control plate that uses a piezometer to quantify the flow rate of water overtopping the trapezoidal weir. Exit valves located at the tank bottom were used to adjust the flowrate if necessary to achieve the design flow rate. The equalizing tank system was used to introduce 0.75 ft^3/s (0.02 m^3/s) of flow during each test for 120 minutes. A two-hour test is referred to as a ‘longevity test’ as it is used to measure the flocculant dosing concentration over time. Allowing enough data to be collected to generate trends that are capable of being used for quantifying how long one flocculant dose will last after application and predict when reapplication would be necessary. Samples were collected at 0, 10, 20, 30, 60, 90, and 120 minutes at each of the six sampling locations and three test replications, resulting in 126 samples. The 0-minute sample represented first flush.

(a) front



(b) back

Figure 6-14. Water and Sediment Introduction System

Soil was mixed with water introduction in the channel (Figure 6-15) at a rate of 17.8 lb./min (8.09 kg/min). This sediment introduction rate was based on the design flow rate and a 1,500 ± 500 NTU target turbidity. This sediment introduction rate was based on laboratory trial and error testing with scaled flow rates to reach the target turbidity. Due to the length of the test, sediment was only introduced 10 minutes before every sample collected, with the exception to first flush samples. Ensuring that each sample would be taken when the intended turbidity was consistent throughout the entire channel, allowing for turbidity reduction evaluations to be assessed. Turbidity reduction assessments were used to determine if sufficient mixing was occurring in the channel, which would indicate if the installation configurations were sufficient to maximize flocculant dosing. If sufficient mixing and agitation was not achieved, then other ditch check configurations or installations could be substituted to ensure proper mixing and agitation. Turbidity reduction analysis was conducted by collecting turbidity samples of initial, undisturbed, and disturbed samples.

Figure 6-15. Sediment Introduction Method

Samples were collected in single-use plastic bags to prevent cross-contamination between tests. Since temperature can play a significant role in affecting the efficacy of flocculants, sample bags were placed in coolers with ice and a wooden insert to protect the sample bags from the possibility bags being punctured from the ice (Figure 6-16). This allowed samples to remain in the upright position for easy storage, transport, and most importantly, prevent samples from heating up during testing so that all sample temperatures remain consistent. Once samples were collected and placed in the cooler, they were left undisturbed for 15 minutes. Once the 15 minutes passed, turbidity subsamples were collected from the top portion of each sample. This undisturbed turbidity subsample represented the mixing that was occurring in the channel. Disturbed samples were collected the next day when samples were processed in the lab where the sample bags were shaken for 1 minute and allowed to settle for

15 minutes. After 15 minutes, a subsample was collected from the top portion of each sample again. The disturbed turbidity subsample represented the best-case scenario mixing to ensure the flocculant has an opportunity to be fully agitated and maximize the contact with any remaining soil. The undisturbed and disturbed samples were compared to initial turbidity samples that were collected at the very end of the large-scale test where each upstream sample, where flocculant was not subjected to, was shaken to resuspend all sediment in the sample. Initial subsamples were collected immediately after agitation and used to represent the initial turbidity of the channel at that time. Each turbidity sample was compared to the initial turbidity at the respective sampling time and used to calculate the percent change in undisturbed and disturbed samples so they could be directly compared to each other.

(a) wooden insert installation (b) wooden insert placement

Figure 6-16. Sample Collection Control Environment

Visual test samples were also collected to confirm the presence of flocculants by visually observing the floc size. Visual samples were collected in 17 fl oz (500 mL) clear plastic jars with 0.35 oz (10 g) of #200 sieved AU-SRF sediment. This amount of sieved sediment quantity was selected as it was the same ratio of sediment to water used for residual testing when measuring settling velocity, allowing for observed floc size testing methodology as in match testing to be maintained. Figure 6-17 shows how visual samples were collected during testing. Visual test samples were only collected at sampling location D as it was after the last dich check with flocculant. It was not collected further downstream at sites P or G, as further locations may have differing flocculant concentrations in the event residual flocculant built up in the underground coregulated pipe between test replications.

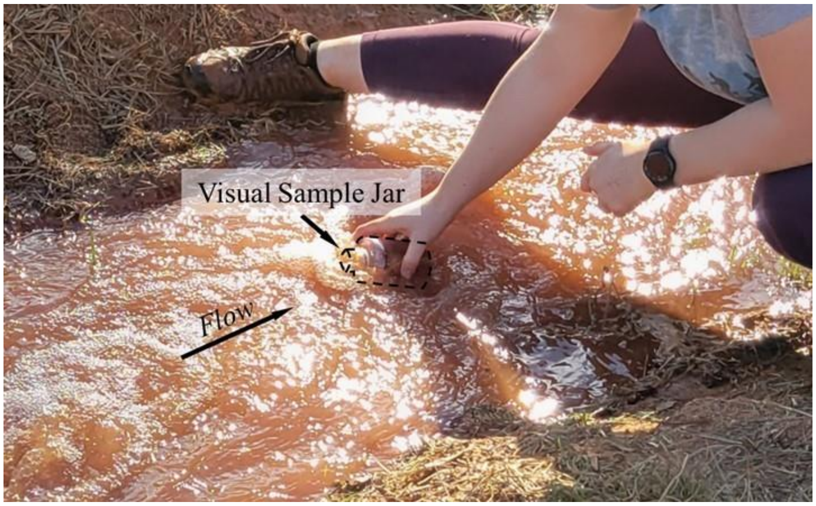


Figure 6-17. Product A-G Visual Sample Collection at Sampling Location D

6.3.1.2 Collecting Channel-Based Large-Scale Samples for Block PAM

The target flocculant dosing was based on previous intermediate-scale testing evaluations conducted via Flume testing. A 40 ft (12 m) long, 1.5 ft (0.5 m) wide semicircle-shaped, adjustable flume was used to evaluate various flocculant applications. This comparison was done to see how intermediate-scale testing compared to large-scale applications. For Product A-B flume tests, the channel was subjected to 0.1 ft^3/s (0.003 m^3/s) with a flocculant block that was sliced into four equal rectangular pieces. These pieces ended up being 4.5 x 8.0 x 2.5 in. (11.5 x 20.3 x 6.4 cm) length, width, and height respectively. One of the block pieces was used in flume testing and was placed downstream a ditch check where overtopping water would come in contact with the block. These values for intermediate-scale testing were compared to the large-scale conditions by their flow rates to find the desired number of flocculant blocks for large-scale testing. Eq. 6-3 shows the formula used to scale up the intermediate-scale testing to large-scale applications.

$$\frac{\left(\frac{Q_{flume}}{w_{flume\ block}}\right)}{SA_{flume\ block}} = \frac{\left(\frac{Q_{channel}}{w_{wier\ bottom}}\right)}{SA_{block\ total}} \qquad \text{Eq. 6-3}$$

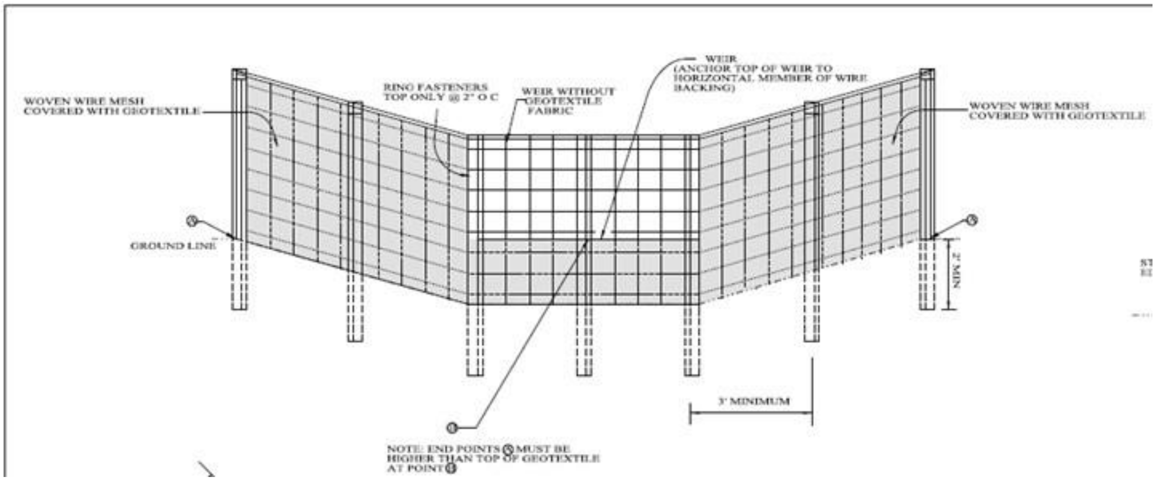
Where Q_{flume} is the flow rate used in intermediate-scale flume testing (ft^3/s [m^3/s]); $w_{flume\ block}$ is the total width of Product A-B used in intermediate-scale flume testing (in. [cm]); $SA_{flume\ block}$ is the surface area of the block used in intermediate-scale flume testing, excluding the bottom face of the block as it is assumed that water would not be flowing underneath the block (in.^{2} [cm^2]); $Q_{channel}$ is the design flow rate for large-scale application testing (ft^3/s [m^3/s]); and $w_{wier\ bottom}$ is the bottom width of the weir for flow introduction (in. [cm]). $SA_{block\ total}$ is the total surface area of all flocculant blocks for large-scale application testing (in.^{2} [cm^2]). This equation was written to solve for $SA_{block\ total}$ where a full block has length, width, and height dimensions of 9.0 x 16 x 2.5 in. (23 x 41 x 6.4 cm), respectively. The number of blocks needed could be deduced by again excluding the bottom face of the blocks as water would not be flowing underneath the blocks and dividing $SA_{block\ total}$ by the water contact surface area of a single block. This was done to mimic the application rate used in intermediate-scale flume testing. Large-scale application testing used a flow rate of 1.80 ft^3/s (0.05 m^3/s). The total calculated number of Product A-B needed was six full-sized blocks. Since flocculant block dosing is much slower due to the gelatinous consistency, the test was set up to evaluate how dosing changed as blocks were added to flow during testing. Therefore, flocculant blocks were added to the channel in sets of two to evaluate how dosing changed between 2, 4, 6, and 8 blocks.

The testing location allowed for one silt fence ditch check installation and multiple flocculant blocks to be installed downstream of the ditch check. Figure 6-18 shows the large-scale application setup, along with the two sampling locations marked with an “O” and the location name. Sampling location A was collected from overtopping water before it came in contact with Product A-B and sampling location B was collected 38 ft (11.6 m) downstream from sampling location A. Resulting in two sampling locations for this test setup. All samples were collected in the same single-use plastic bags as was used in Product A-G large-scale testing. All collected samples were also placed in a cooler with ice to maintain a constant temperature, just as was done in Product A-G large-scale testing.

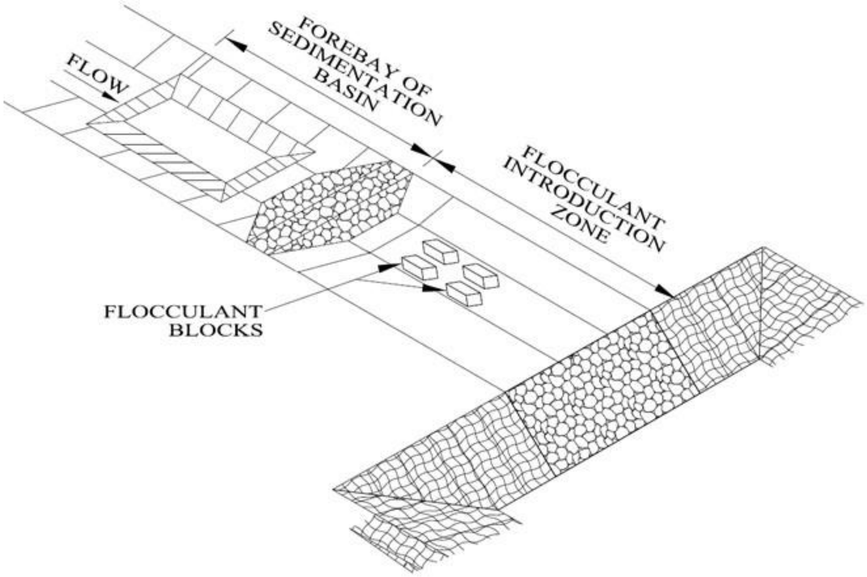
(a) upstream sample point (b) downstream sample point

Figure 6-18. Product A-B Sampling Locations

The silt fence ditch check was installed according to ALDOT standards (*93*) and is shown in Figure 6-19(a). ALDOT standards use flocculant blocks for sediment basin application where the blocks should be placed in the channel, somewhere between the forebay and sediment basin, Figure 6-19(b).



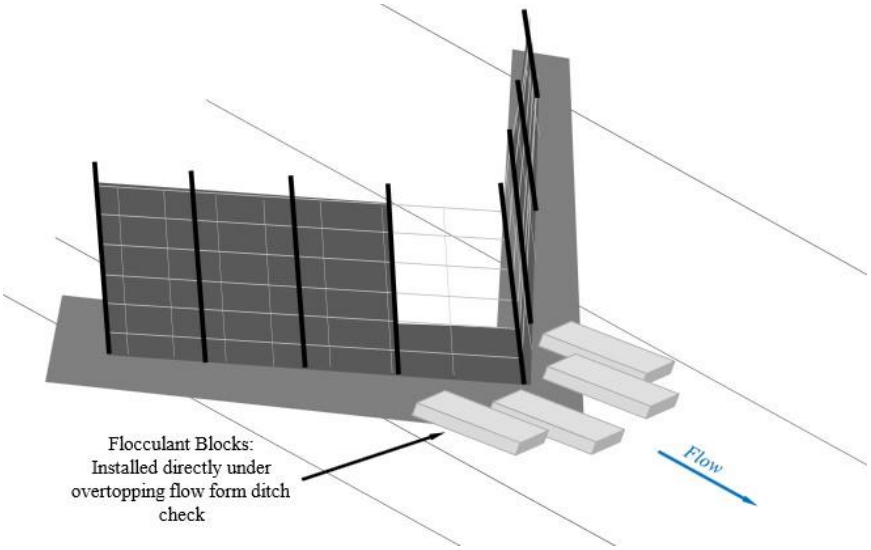
(a) silt fence installation



(b) flocculant block standards

Figure 6-19. Silt Fence Installation and Flocculant Block Standards (*93*)

Since this study looked to evaluate the use of flocculant blocks with a test apparatus that sought to improve ALDOT standards, a silt fence ditch check was selected to assist in localizing flow, increasing agitation for flocculant mixing, and minimizing sediment buildup on flocculant blocks. Figure 6-20(a) shows flocculant block placement with a silt fence ditch check. Placing blocks directly under the overtopping water from a silt fence ditch check ensures that a majority of the sediment is already captured by the silt fence and the impact of the overtopping water helps remove sediment that may accumulate on the blocks. This test aimed to evaluate how flocculant dosing changed with the number of blocks in a channel, if the number of blocks installed in the channel exceeded the space available directly underneath overtopping flow from the silt fence ditch check. In this case, only four blocks could fit within this area, subsequent blocks were placed downstream in areas of concentrated flow, Figure 6-20(b).

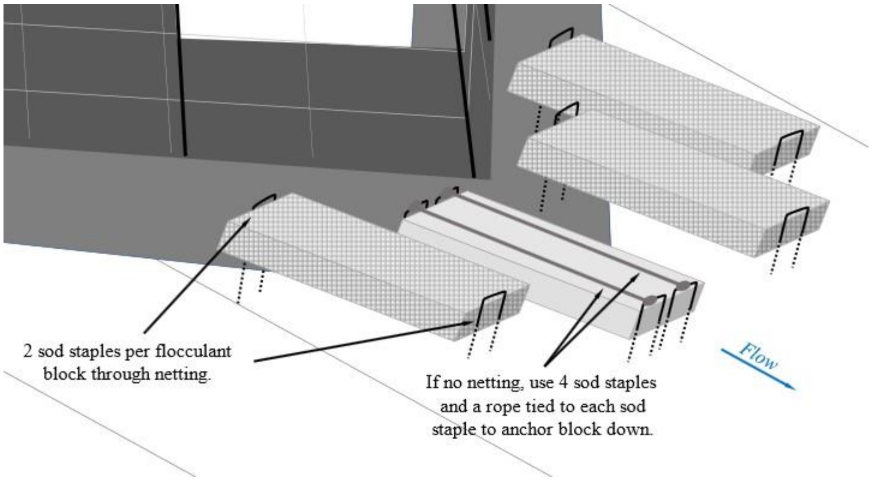


(a) installation schematic

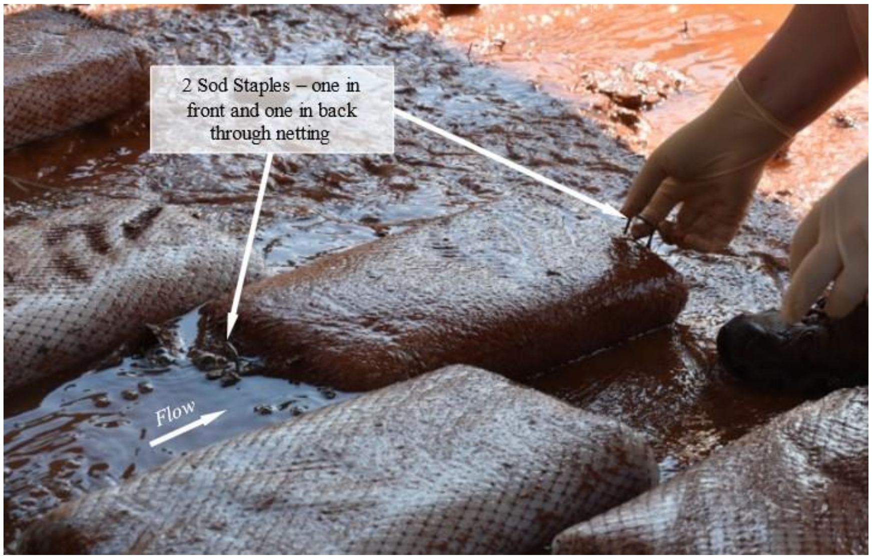
(b) installation zone

Figure 6-20. Product A-B Installation Placement

ALDOT standards do not specify how to secure flocculant blocks as manufacturers have their own recommendations. However, due to the recommended placement of flocculant blocks for silt fence ditch check, Figure 6-21(a) details how to install flocculant blocks with a silt fence ditch check, regardless of if comes with or without a mesh netting. Since Product A-B came with a mesh netting, Figure 6-21(b) shows how the two sod staples were used to secure blocks during testing.



(a) Product A-B securement method



(b) example of Product A-B anchoring

Figure 6-21. Product A-B Installation Securement

Each set of blocks placed in the channel soaked in a tub of water for 10-minutes, prior to installation. This mimicked rainfall activating the blocks prior to the commencement of runoff. The same water introduction system and sediment mixing trough was used to control and monitor flow and create sediment-laden water for Product A-G was used for Product A-B large-scale tests. Sediment was mixed with flow at a rate of 42.8 lb./min (19.4 kg/min). This sediment introduction rate was based on laboratory trial and error testing with scaled flow rates to reach the target turbidity of 1,500 ± 500 NTU recommended by Manufacturer I to match the target concentration of flocculant. Two blocks were installed in the channel prior to flow and time started once the channel reached steady state. Samples were collected at 3, 6, and 9 minutes.

After the last sample was collected, the next two flocculant blocks that were soaking in water were installed in the channel during flow. Samples were collected again at 3, 6, and 9 minutes after the next two blocks were installed and the process was repeated until eight blocks were installed in the channel.

Visual test samples were collected for Product A-B large-scale testing to confirm the presence of flocculants by visually observing the floc size. Clear plastic jars with a 16.9 fl oz (500 mL) volume were used to collect large-scale test samples at sample site B and contained 0.35 oz (10 g) of #200 sieved AU-SRF sediment in each jar. This amount of sieved sediment quantity was selected as it was the same ratio of sediment to water used for residual testing when measuring settling velocity, allowing for observed floc size testing methodology as in match testing to be maintained. Figure 6-22 shows how visual samples were collected during testing at sampling location B. Due to the velocity of the water at sampling location B, water was collected by redirecting water upward and capturing the water as it fell, ensuring that the sediment in the jar was not lost during collection.

Figure 6-22. Product A-B Visual Sample Collection at Sampling Location B

6.3.1.3 Processing Channel-Based Large-Scale Samples

Both Product A-G and Product A-B were subjected to the same sample processing procedure where large-scale tests samples were completed at 4:30 PM on large-scale test days; samples were then brought to the lab where the ice in the coolers was removed and the coolers were left open overnight to reach room temperature before processing all samples the following day, starting at 7:30 AM. This ensured all samples were subjected to the same conditions once collected, minimizing the possibility for data inconsistencies that could result from temperature changes after collection or flocculant degradation over time.

Sample processing began with shaking sample bags vigorously for one minute and poured into three clean 51 fl oz (1,500 mL) glass beakers, each containing more than 34 fl oz (1,000 mL) of the sample. Each collected sample was split into thirds and ran in triplicate to ensure settling velocity readings remained consistent between each replication to identify possible contamination during processing. Samples were given 15 minutes to allow sediment present in the sample to settle out of suspension. After 15 minutes, 1,000 mL of the supernatant was poured into a new clean 1,500 mL glass beaker and the pH, temperature, and turbidity of the sample was taken. Disturbed turbidity samples taken after sample bags were shaken and set for 15 minutes represented disturbed conditions. Turbidity samples were run through a turbidimeter by filling a small glass vial with the sample water and placing it in the machine. Undisturbed and initial turbidity samples taken during the large-scale test were run by shaking the sample bag until all sediment was suspended and transferring it into glass vial to be placed in the turbidimeter. The jar test multiple stirrer machine was cleaned before use by rinsing the stirring rods, paddles, and paddle rest with deionized water, spraying with Alconox® Liquinox cleaning solution, and wiping clean with a paper towel.

Following the same procedures that were done for the settling velocity tests, ruler tape was placed on glass graduation cylinders with zero at the base. To see gradients when pouring samples, cylinders were put in front of a white poster board. A GoPro camera was placed in front of the graded cylinder to show its top and bottom. To avoid blocking the sample pour, ruler tape was placed on the side of the cylinder in the GoPro screen. A digital clock with hour, minute, and second displays was put beside the cylinder and in the GoPro frame to record sample settling time. Sandy clay loam soil was sieved through #200 sieve and weighed into 0.71 oz (20 g) jars.

Samples were moved to a jar test multiple stirrer machine and 0.71 oz (20 g) of sieved testing soil was added to the sample. GoPro video camera recording was started, and the samples were flash mixed (120 rpm) for one minute. Samples were quickly removed from the machine and poured into the glass graduated cylinder, being sure to pour fast enough so that all sediment in sample remains suspended while pouring. Only two samples were mixed and poured simultaneously as it was important to pour the sample before the sediment settled in the beaker. Samples were recorded until sediment was fully settled, or for one hour if gradient was not easily visible.

Between processing samples for measuring the settling velocity, visual sample jars were shaken to resuspend all sediment and were placed in front of a camera to record the observed floc size. These recordings were done in a studio box where lighting could be maximized, and reflections could be minimized. The videos were recorded in high resolution and the jars were always placed the same set distance from the camera. This allowed for consistency and visual floc size to be later observed when videos were reviewed.

When samples settled, glassware was cleaned with hot water and Alconox® Liquinox. The Jar Test Multiple Stirrer machine was cleaned by rinsing all the paddles with deionized water, spraying with Alconox® Liquinox, and wiping off residual flocculant or sediment with a paper towel. To ensure all flocculant was removed from the paddles of the Jar Test Multiple Stirrer machine, the paddles were sprayed and wiped down two to three times, depending on the amount of residual flocculant observed on the paddles. The sample's poured time, total height in the cylinder using the ruled tape on the cylinder side, settled time, and settled height were recorded using GoPro video. The difference in soil settlement time and height was used to compute the settling velocity. The sample was considered settled when the lowest gradient point reached the bottom of the cylinder. As the settled sediment pile continues to compress after all sediment has reached the bottom of the cylinder, it was important to record the time when the base of the gradient reached the settled pile at the base of the cylinder. Video editing software was used to fuse multiple video recordings together if gradients were not distinguishable in shorter clips. After stitching multiple videos together, a gradient was then visible by rapidly rotating the scrub bar throughout the settling time. A step-by-step testing method can be found in Appendix F.

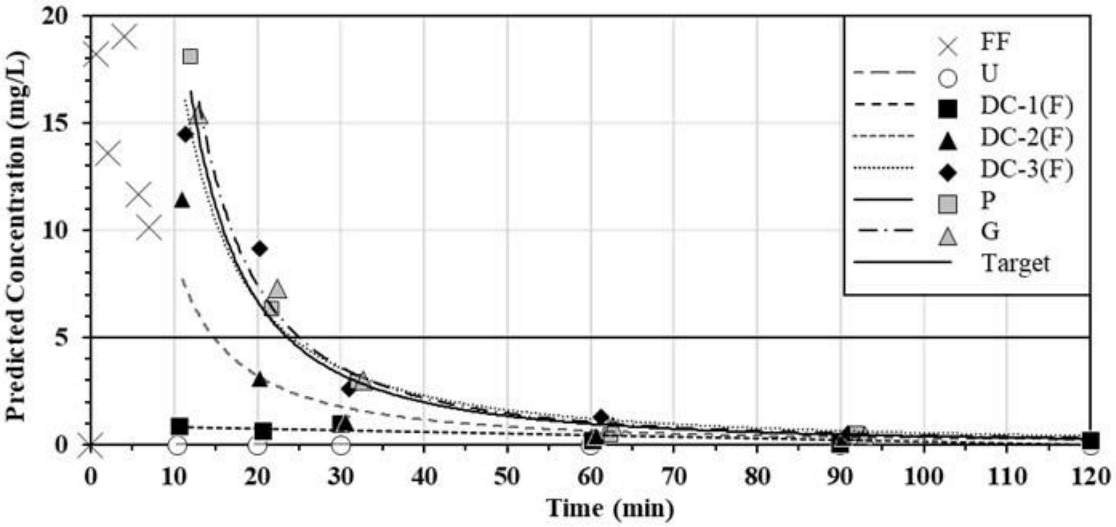
This testing approach is prone to error and contamination. Using glassware instead of plastic, a GoPro to monitor setting rates, and careful cleaning procedures can reduce error and contamination. The GoPro helps analyze samples from the same distance and obtain more precise sampling start and end times. PAM adherence was prevented by using glassware in the lab and single-use plastic bags for large-scale sample collection. However, reusing glassware and the jar testing multiple stirrer machine can lead to errors and sample contamination. Washing glassware with hot water and cleaning the stirring machine multiple times between uses can assist in preventing sample cross contamination.

6.3.2 CHANNEL-BASED RESULTS AND DISCUSSION

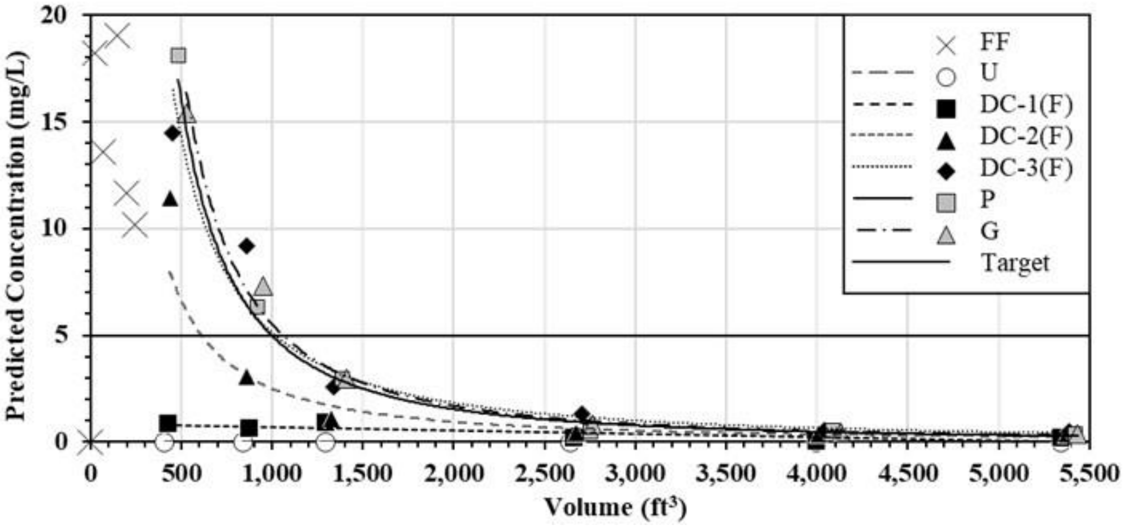
Three different evaluations were conducted during Product A-G large-scale tests. The first evaluation focused on dosage and longevity testing. These two tests were conducted by quantifying the residual concentration from collected samples, enabling dosing levels to be evaluated over time to better predict reapplication needs. The second evaluation, turbidity reduction, collected subsamples of each of each sample and compared undisturbed and disturbed sample turbidities differences to assess mixing occurring in the channel. The last evaluation was a visual test which used samples collected in a clear plastic jar at sample site D, downstream of the last flocculant application, where sieved sediment was mixed in the visual test jar and the floc size was visually observed and recorded. Allowing for the observed floc size to be correlated with residual concentrations to confirm flocculation efficacy. Product A-B large-scale tests were also subjected to three different evaluations. The first was dosage and longevity testing, which was done by collecting large sample volumes at each respective sampling location and evaluating the residual concentration from settling velocities to determine the dosing levels over time and determine when reapplication would be necessary. The second two tests were turbidity reduction and visual test. As the testing location was different from Product A-G large-scale tests, the sampling location for visual tests was at sample site B. The results for each of these three evaluations are described in detail in the following sections.

6.3.2.1 Granular PAM Dosage and Longevity

Once all settling velocity videos were reviewed, the Product A-G concentration equation was used to predict the concentration of Product A-G in each sample. Each sample collected was ran in triplicate to identify irregularities for cross contamination within glassware and mixing equipment. However, all three replicates of each collected sample were kept as no inconsistencies were identified. The 126 samples collected were split into thirds and individually evaluated for its soil settling velocity, resulting in 378 total evaluated samples. Each data point plotted in Figure 6-23(a) and (b) represents nine averaged samples. Since the prediction equation cannot accurately predict concentrations below 1.0 mg/L of Product A-G, the upstream predicted concentration, which was not subjected to any flocculant, had predicted concentrations below 0.9 mg/L. To better represent the predicted concentrations for all samples in Figure 6-23(a) and (b), the upstream sample predicted concentration was used to offset the predicted concentrations of all other flocculated subsequent samples by subtracting the upstream predicted concentration from each subsequent sampling location per sample time.



(a) over time



(b) over volume

Figure 6-23. Predicted Product A-G Concentration Trends

Results displaying the predicted concentrations over time are provided in Figure 6-23(a). Figure 6-23(b) shows flocculant concentration predictions based on volume and can provided indication on how concentrations may change based on contact time and rainfall events. In both Figure 6-23(a) and (b), it can be seen that the total 2.12 oz. (60 g) of Product A-G spread each of the three wattles begins dosing at high predicted concentrations of 19 mg/L during the first flush, then rapidly decreases to 3.0 mg/L predicted concentrations over the first 30 minutes or 1,500 ft^3 (42.5 m^3) of flow. Using the regression equations for the last sampling location, G, in Table 6-5, the manufacturer's recommended concentration is predicted to be reached after 25.1 minutes.

Table 6-5. Regression Equations for Product A-G Concentration Trends Over Time

Collection Site	Regression Equation	R^2
U	$y = 0$	N/A
DC-1(F)	$y = -0.0074x + 0.895$	0.704
DC-2(F)	$y = 256.61x^{-1.462}$	0.972
DC-3(F)	$y = 678.58x^{-1.542}$	0.944
P	$y = 1302.5x^{-1.759}$	0.999
G	$y = 1497.4x^{-1.77}$	0.991

When predicting based on flow, looking at predicted based on flow, using Table 6-6, the manufacturer’s recommended concentration is predicted to be reached after being subjected to 1,060 ft^3 (30 m^3) of flow.

Table 6-6. Regression Equations for Product A-G Concentration Trends Over Volume

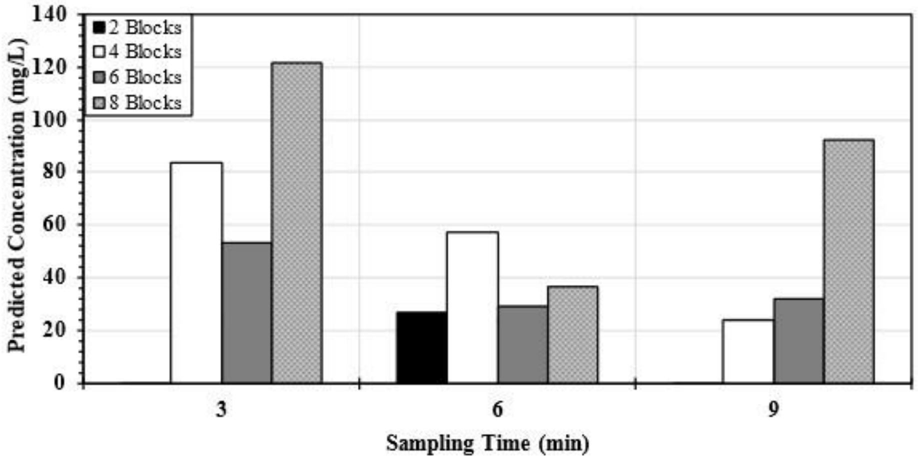
Collection Site	Regression Equation	R^2
U	$y = 0$	N/A
DC-1(F)	$y = -0.0002x + 0.8858$	0.704
DC-2(F)	$y = 41539x^{-1.407}$	0.978
DC-3(F)	$y = 140708x^{-1.479}$	0.937
P	$y = 594191x^{-1.692}$	0.999
G	$y = 724182x^{-1.706}$	0.988

Since increased dosing occurred for the first 25 minutes, it is recommended to balance this by underdosing for a period, especially since flocculant is still found effective at concentrations as low as 20% of the recommended dosage as reported in bench scale testing. Therefore, it is recommended to reapply Product A-G after 3,600 ft^3 (101.9 m^3) or 1.0 in. (2.5 cm) of runoff per acre.

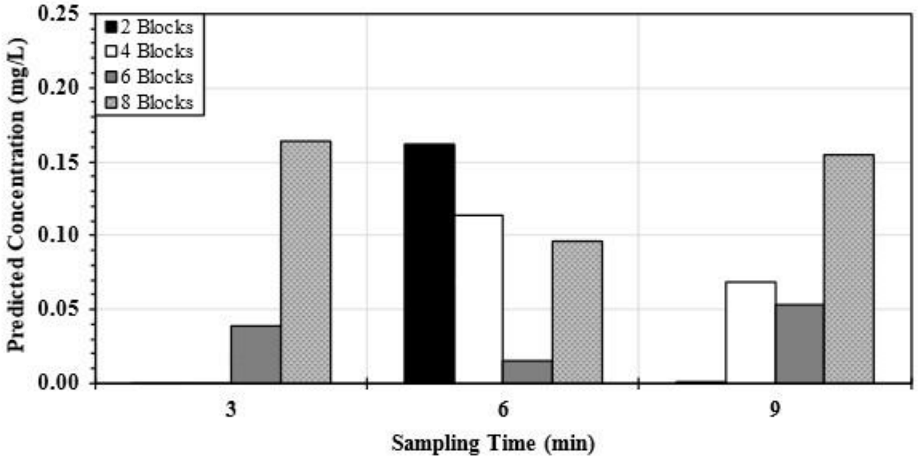
Manufacturer I SDS reports an oral rat toxicity LD_{50} > 5,000 mg/kg body weight with an ‘unlikely aquatic toxicity’ as Product A-G does not hydrolyze (*213*). The rat oral LD_{50} value matches the study performed by Christofano et al. (*112*) mentioned in the literature review where an orally administrated LD_{50} for rats was not reached. For aquatic organisms, the maximum predicted concentration of 19 mg/L from Product A-G large-scale tests well below the toxic range for many aquatic organisms mentioned in the literature review, except freshwater fleas with an LD_{50} = 14.1 mg/L (*214*). As the maximum concentration only occurred during the first flush and rapidly decreased below aquatic toxicity limits within the first 20-minutes, this application rate was justified by waiting to reapply flocculant until predicted concentrations fall below 1.0 mg/L. Ensuring high initial concentrations are diluted down below all aquatic organism toxicity limits when effluent leaves the construction site.

6.3.2.2 Block PAM Dosage and Block Quantity

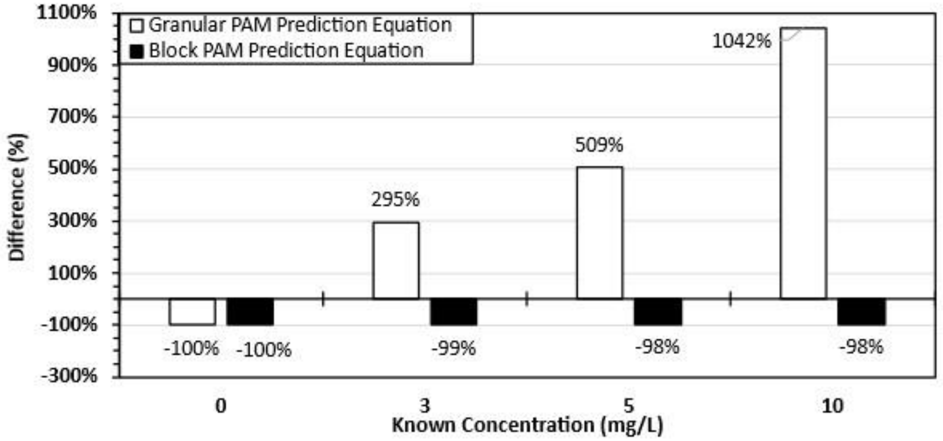
Once all settling velocity videos were reviewed, the Product A-B concentration prediction equation was used to predict the concentration of Product A-B in each sample. Each sample collected was ran in triplicate to identify irregularities for cross-contamination within glassware and mixing equipment; however, all three replicates of each collected sample were kept as no inconsistencies were identified. The 72 samples collected were split into thirds and individually evaluated for their soil settling velocity, resulting in 216 total evaluated samples. Each data point plotted in Figure 6-24(a) represents nine averaged samples. To better represent the collected samples, the difference between the upstream sample, before flocculant introduction, and the downstream sample, after flocculant introduction, was taken after prediction calculations were completed for all Product A-B plots.



(a) Product A-B prediction equation results



(b) Product A-G prediction equation results



(c) percent difference from known concentration

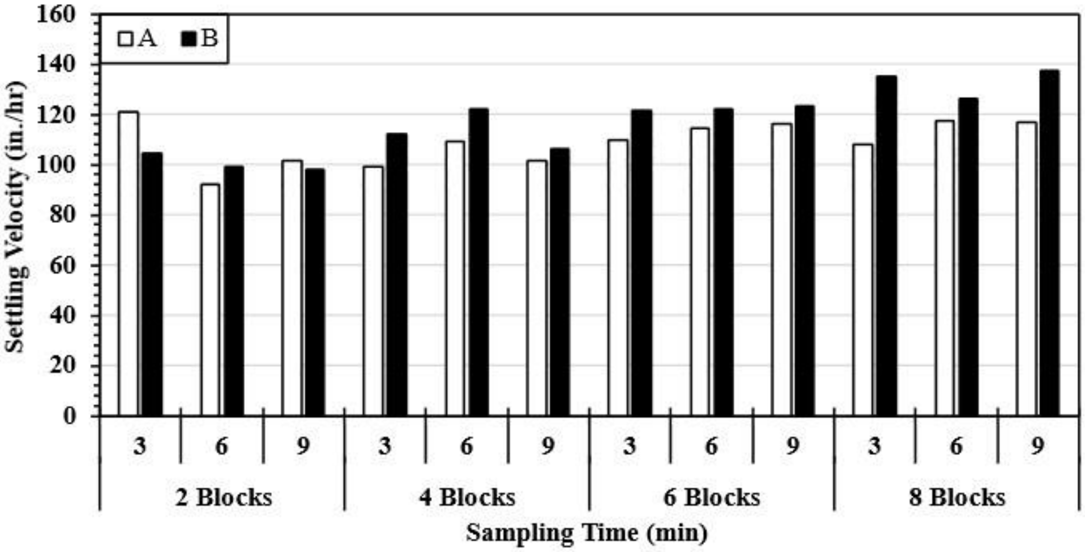
Figure 6-24. Prediction Equation Results

The flocculant concentration prediction equation for Product A-B shows values between 0 to 122 mg/L. This range of predictions is likely due to the difficulty quantifying flocculant in block forms. Since Product A-B does not dissolve in water easily, and the prediction curve was created by grating a flocculant block, weighing out small pieces, and flash mixing with sediment for one minute, it is impossible to know how much of the gelatinous flocculant pieces actually dissolve into the sample. It can only be said that 1.0 L of water came in contact with the specified amount of flocculant. Therefore, there is a possibility that the Product A-B concentration prediction data could actually contain the same flocculant concentration, regardless of the specified weights. This may result in the prediction equation to be inaccurate.

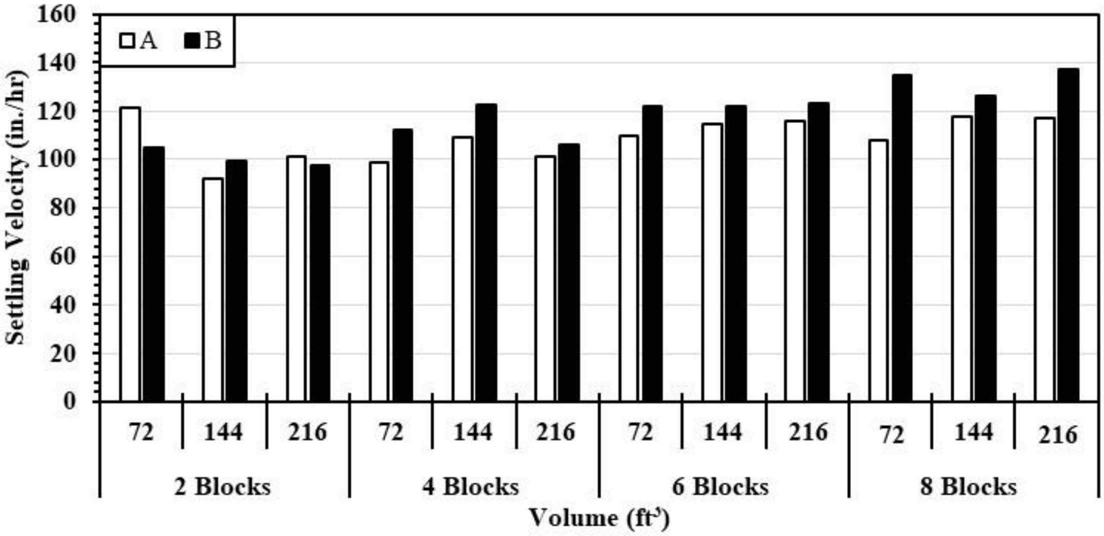
Since Product A-B and Product A-G forms are both based on the same flocculating agent, Product A-G concentration prediction equation was used to see how results may differ with respect to the PAM flocculating agent, regardless of other additives that may be present, Figure 6-24(b). Here, flocculant concentration predictions were below 1.0 mg/L, which falls outside of the measurable range for this equation; therefore using Product A-G concentration prediction equation was inconclusive.

During each large-scale test, water was collected directly after sediment was mixed with pond water at the time of the test. The purpose of this was to confirm that data created using tap water with measured flocculant concentrations for the prediction curve were representative of samples run with pond water with measured flocculant concentrations. Allowing the accuracy of the prediction curves to be assessed with conditions specific to the test conditions of temperature, pH, soil that was mixed into the water during testing, or any other environmental factors that may be specific to each test run. Figure 6-24(c) shows the percent difference from the measured concentration performed with the sediment-laden pond water collected during large-scale testing against the predicted Product A-B and Product A-G predicted concentrations. With all concentrations being above 98% different from the measured concentration, it was evident that neither prediction equation obtained reliable results.

With neither of the prediction equations being viable for predicting Product A-B flocculant concentrations, results were plotted by showing the soil settling velocities for the upstream (A in figures), no flocculant, and downstream (B in figures), with flocculant, sampling locations in Figure 6-26. Although the settling velocities do not differ greatly between the two sampling locations, a general trend can be noted that as the number of blocks in the channel increases, the settling velocities at sampling location B increases. Additionally, regardless of how long the blocks were in the channel or the volume of water that ran across them, the settling velocity remains relatively consistent.



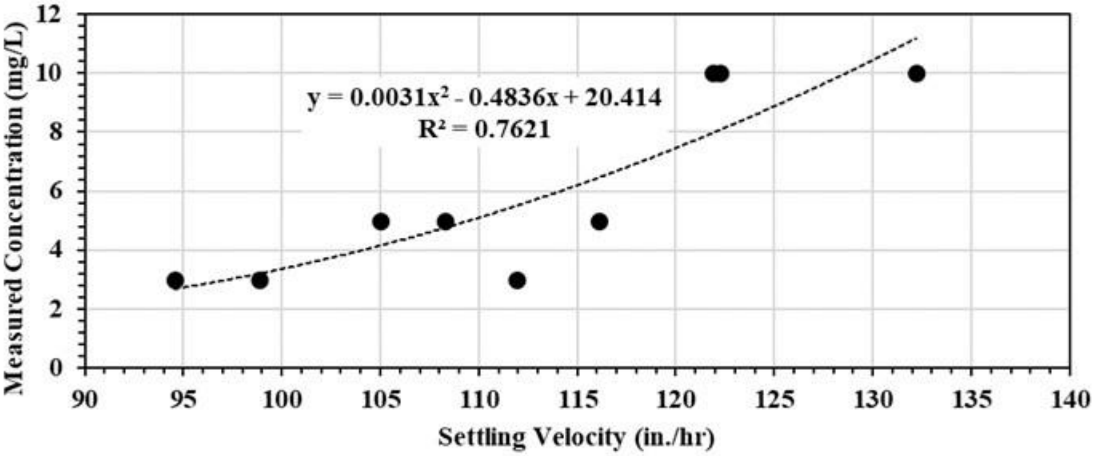
(a) settling velocity with respect to time



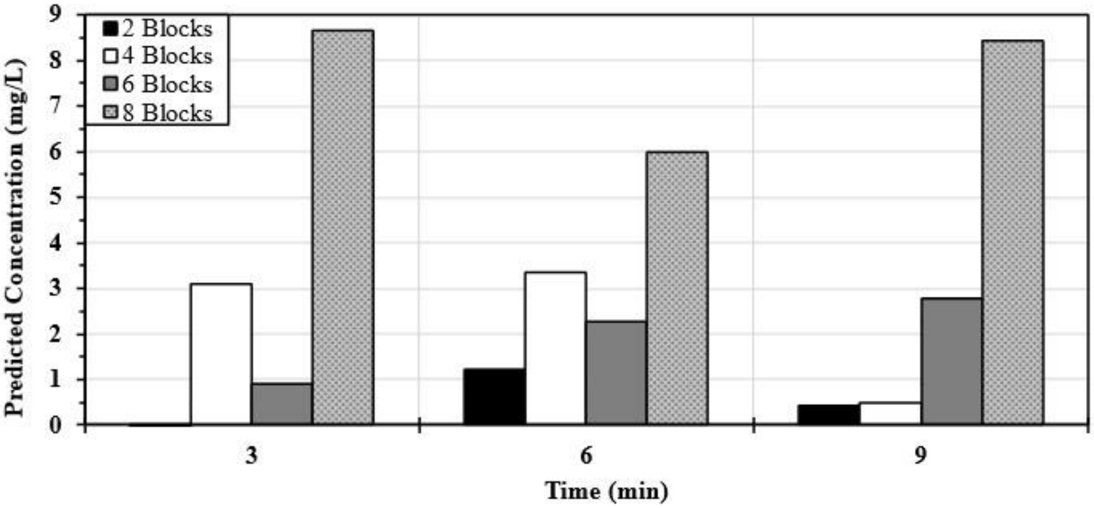
(b) settling velocity with respect to volume

Figure 6-25. Product A-B Large-Scale Test Settling Velocity Results

The sediment-laden pond water collected during large-scale testing that was used to confirm prediction values was also used for creating a prediction equation that was specific to the testing conditions. The measured amount of Product A-B and the soil settling velocity for each measured concentration is plotted in Figure 6-26(a). Samples with 0 mg/L were omitted as their oil settling velocities remained inconsistent across sample and test replications. The regression equation in Figure 6-26(a) was used as the pond concentration prediction equation where y is the measured quantity of Product A-B concentration and x is the measured soil settling velocity for flocculant blocks. This equation was used to generate the data in Figure 6-26(b) which obtained concentration predictions between 0.0 and 8.6 mg/L. A general trend is more prominent in Figure 6-26(b) where the offset predicted flocculant concertation increases as the number of flocculant blocks are added in the channel. Overall, when predicting Product A-B concentrations, it is clear that it is difficult to accurately measure known concentrations with current methods and it is recommended to adapt testing methodologies that best account different flocculant forms.



(a) Product A-B prediction trend and equation from pond water collected during testing



(b) Product A-B prediction results using pond concentration prediction equation

Figure 6-26. Product A-B Large-Scale Test from Pond Concentration Prediction

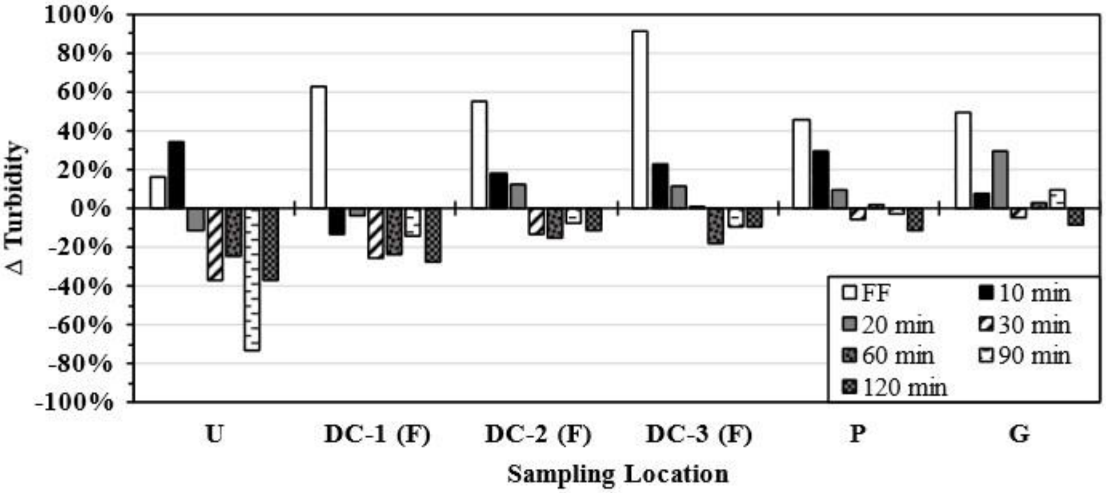
Since Product A-G and Product A-B consist of the same flocculating agent, the same SDS is used for both products. Once again, the oral rat toxicity LD_{50} > 5,000 mg/kg body weight with an ‘unlikely aquatic toxicity’ as Product A-B does not hydrolyze remains the same (*213*), which matches information from Christofano et al. (*112*) where an orally administrated LD_{50} for rats was not reached. Predicted Product A-B concentrations from Figure 6-26(b) indicate the maximum concentration reached was 8.6 mg/L with 8 blocks, which is well below the toxic ranges for all aquatic organisms mentioned in the literature review.

6.3.2.3 Turbidity Reduction

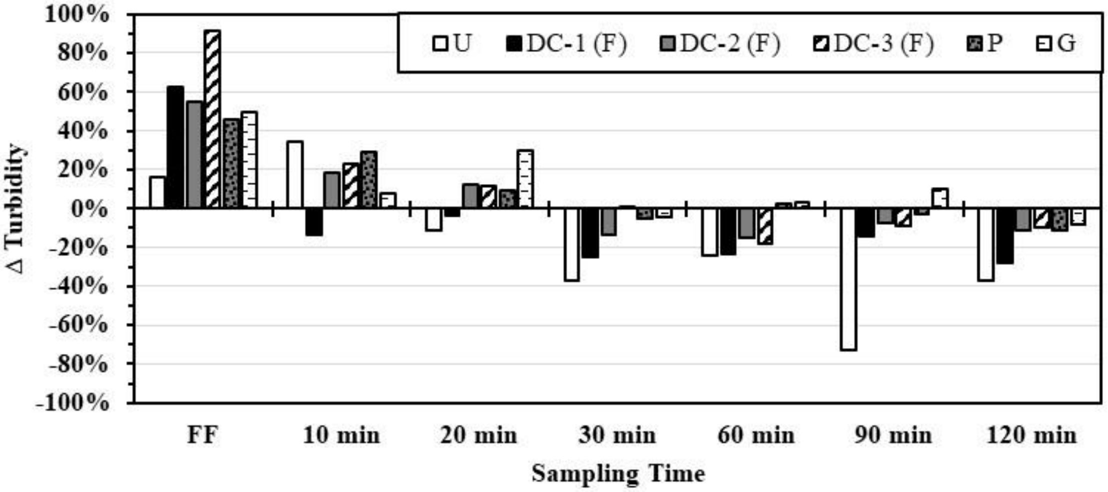
Turbidity reduction results were analyzed by calculating the percent change in turbidity between the initial turbidity against undisturbed turbidity and initial turbidity against disturbed turbidity. The percent change was then used to calculate the difference between the undisturbed percent change against disturbed percent change, referred to as Δ turbidity, making it easier to observe the difference between the two samples. The following sections discuss results for Product A-G and Product A-B large-scale tests.

6.3.2.3.1 Granular PAM

Figure 6-27(a) and (b) contain the Δ turbidity results for Product A-G large-scale tests and are plotted in against the sampling location and sampling time, respectively. Negative Δ turbidity results indicate disturbed samples had a lower turbidity than the undisturbed, meaning flocculant was not sufficiently mixed in the channel at that location or time.



(a) sampling location



(b) sampling time

Figure 6-27. Product A-G Turbidity Reduction

High flocculant concentrations beginning from first flush (FF in figures) through the first 30 minutes of flow, that was discussed in the dosage and longevity results previously, is also displayed in the turbidity reduction plot in Figure 6-27(b), where the positive Δ turbidity indicates additional agitation is not needed to achieve similar turbidity reduction results. The trend in Figure 6-27(b) shows as time passes during testing and flocculant concentration decreases, the location where sufficient agitation (positive Δ turbidity values) occurs continues to move further downstream in the channel. For example, at 20 minutes, U and DC-1(F) are not adequately mixed, whereas all other sampling locations are well mixed. Looking at samples from 90 minutes, U through P are all inadequately mixed as G is the last sampling location that indicates proper flocculant mixing. By the time the test reached 120 minutes, the flocculant concentration was predicted to be below 1 mg/L, where flocculation efficacy decreases compared to higher concentrations. Results indicate that one additional wattle without flocculant installed at the end of the channel would be beneficial to ensure sufficient mixing before discharging to a sediment basin.

Turbidity reduction results are also separated by sampling locations in Figure 6-27(b): upstream (U in figures), first ditch check (DC-1 in figures), second ditch check (DC-2 in figures), third ditch check (DC-3 in figures), after the underground pipe (P in figures), and at the end of the grass channel (G in figures). When upstream samples have a lower Δ turbidity value than any consecutive downstream samples, it indicates sediment is being captured in the channel with likely successful flocculation. When upstream samples have greater Δ turbidity values than downstream samples, it suggests minimal to no flocculation is occurring and additional sediment is being picked up throughout the channel.

6.3.2.3.2 Block PAM

Since Product A-B large-scale test setup included only one silt fence ditch check with the purpose of determining the ideal number of flocculant blocks to target recommended dosing, the setup was not constructed for appropriate mixing. A negative Δ turbidity results indicates that the flocculant is not sufficiently mixed in the channel. Therefore, the results in Figure 6-28 confirm that nearly all samples collected were not subjected to sufficient mixing in the channel. This indicates that flocculant blocks need to be installed where water would flow over at least one additional ditch check before discharging into a sediment basin to ensure sufficient mixing.

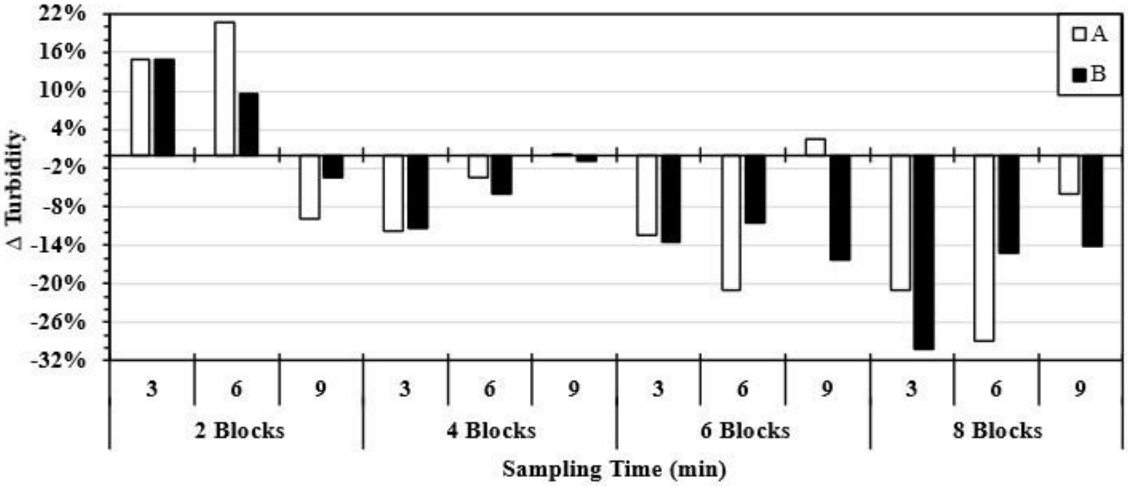


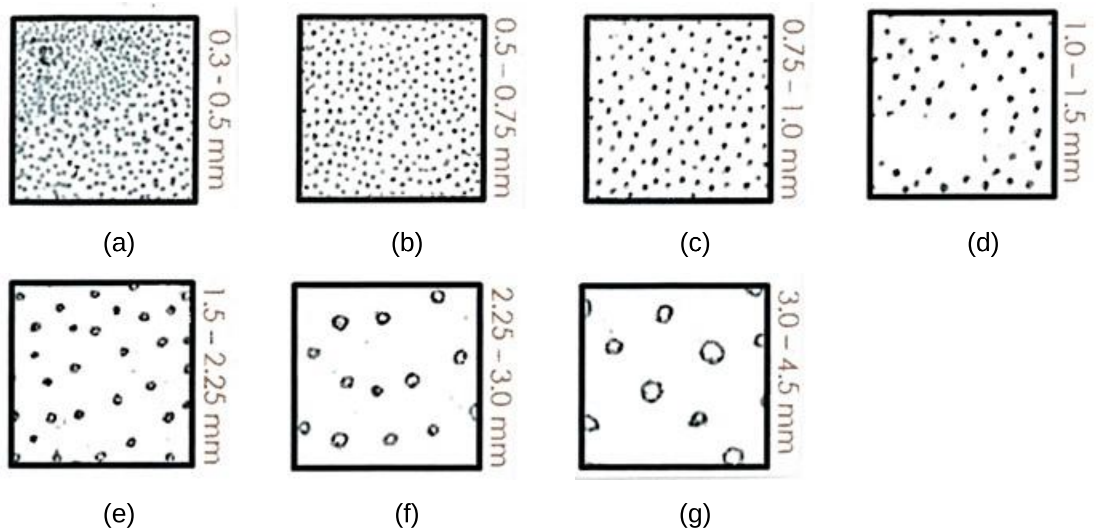
Figure 6-28. Product A-B Large-Scale Test Turbidity Reduction

Turbidity reduction results are also separated by upstream (A in figure), no flocculant, and downstream (B in figure), with flocculant, sampling locations in Figure 6-28. When upstream samples have a lower ∆ turbidity value than downstream samples, it indicates sediment is being captured in the channel. Due to the channel design and downstream sampling location, sediment reduction between the two sampling locations is most likely due to flocculation. When upstream samples have greater ∆ turbidity values than downstream samples, it suggests minimal to no flocculation is occurring and additional sediment is being picked up in the channel due to downstream scour. Figure 6-29 displays downstream scour that was observed after each test replication.

Figure 6-29. Observed Downstream Scour After Large-scale Block Test

6.3.2.4 Visual Tests

Visual test sample recordings for both Product A-G and Product A-B were reviewed with a floc sizing template that was used during match testing (Figure 6-30). The following sections discusses results for Product A-G and Product A-B large-scale test results, respectively.



(a) (b) (c) (d)

(e) (f) (g)

Figure 6-30. Visual Test Floc Sizing Observation Guide (*165*)

6.3.2.4.1 Granular PAM

One test replication of visual test samples are shown in Figure 6-31, where after 5 seconds of settling, the observed floc size can be easily seen for the first two samples (D0 and D10 – first flush and 10 minute sample time for sampling location D, respectively), but becomes progressively more difficult to distinguish flocs as the sampling time continues.

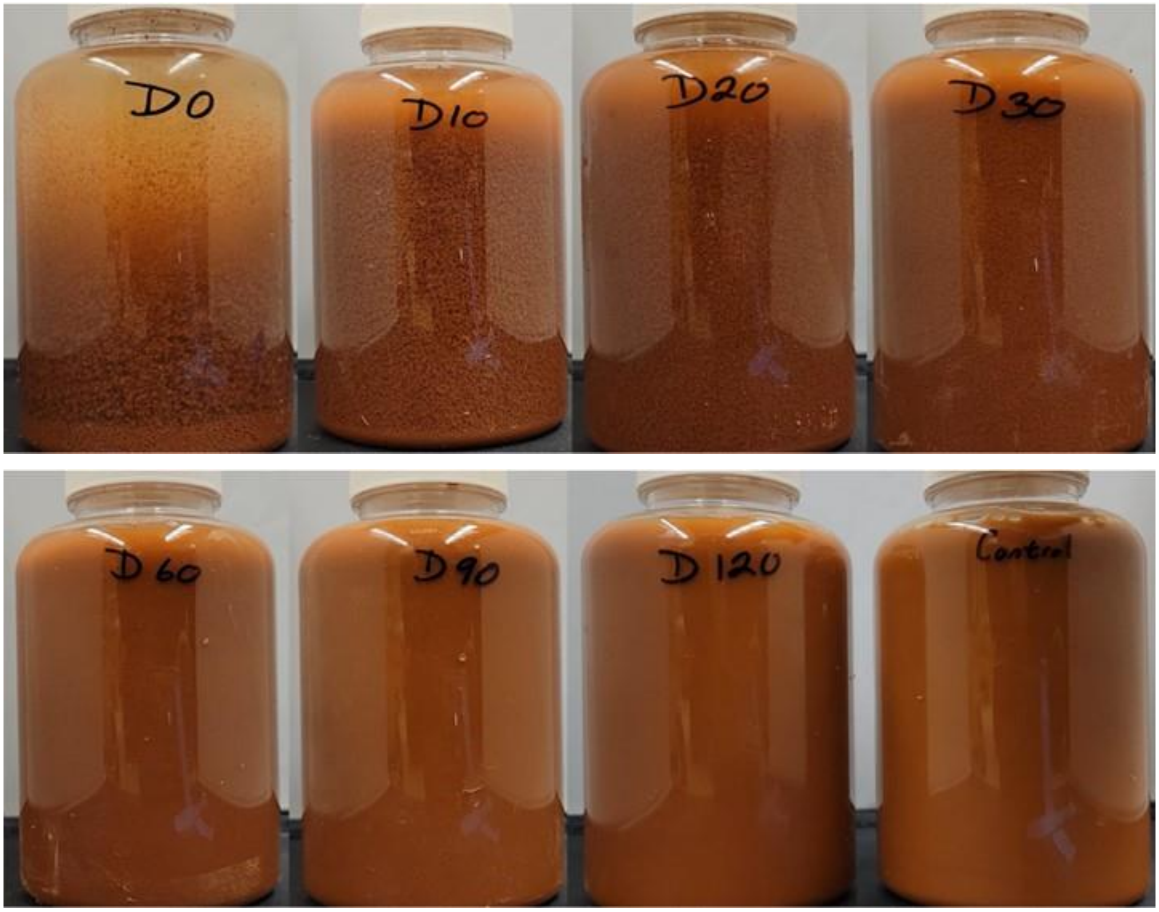


Figure 6-31. Product A-G Large-Scale Test Visual Jars after 5 Seconds of Settling Time

Once all the floc sizes were visually approximated using the template, the maximum range from the floc size template was used to quantify each sample. The results between all three test replications were averaged for each sampling time and results are shown in Figure 6-32. Here, trends are similar to the dosage and longevity results where after 60 min, flocs formed are very small, indicating that the dosing levels are below 1 mg/L but still marginally greater than 0 mg/L.

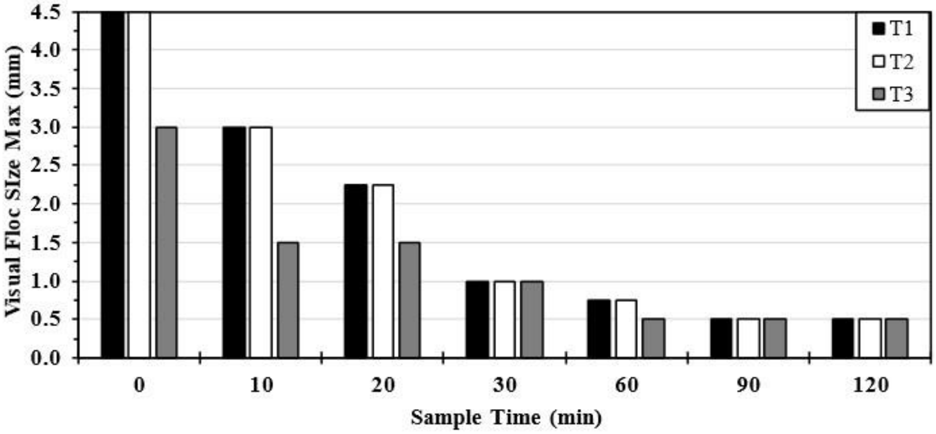


Figure 6-32. Product A-G Large-Scale Test Visual Results

6.3.2.4.2 Block PAM

One test replication of visual test samples are shown in Figure 6-33, where after 1.5 minutes of settling, the observed flocs are difficult to see across all samples when compared to the control, however, a slight gradient difference can be observed in Figure 6-33 from all samples compared to the control.

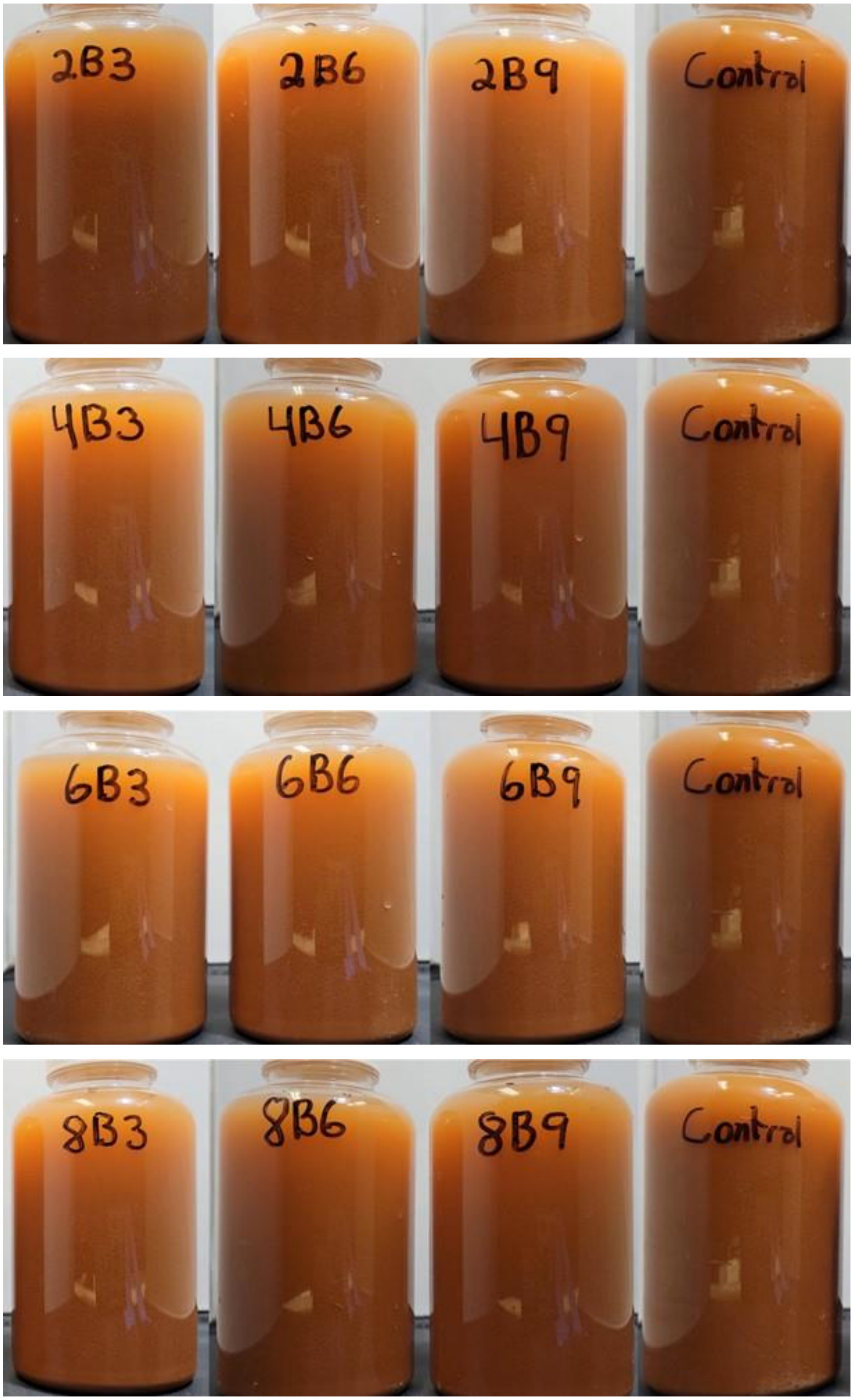


Figure 6-33. Product A-B Large-Scale Test Visual Jars after 1.5 Minutes of Settling Time

When quantifying and plotting the observed floc sizes in Figure 6-34, the trend shows that observed floc size increases over time with two flocculant blocks installed in the channel. Four, six, and eight flocculant blocks result in consistent observed floc sizes during testing. Six and eight flocculant blocks yielded the same observed floc size. Meaning six flocculant blocks are recommended to obtain maximum and consistent floc sizes under tested flow conditions.

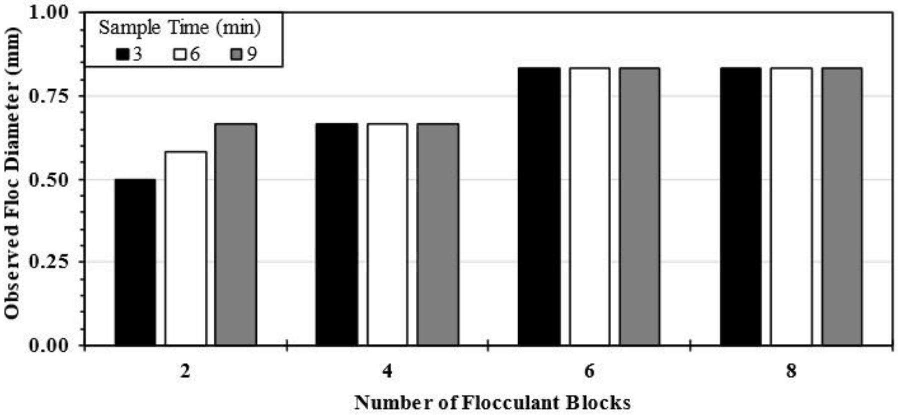


Figure 6-34. Product A-B Large-Scale Test Visual Results

6.4 SUMMARY

Research has investigated flocculant impacts in controlled or monitored settings ranging from uses in water, wastewater treatment, cosmetics, agriculture, mining industries, and more. However, the use of PAM in E&SC practices lacks guidance and consistency with application and maintenance that allows practitioners to maximize the use of the product without causing environmental harm. This work has identified requirements for proper dosage delivery mechanisms by validating bench- and intermediate-scale phase findings of this research through large-scale application sediment basin and channel-based evaluations. Performing large-scale test evaluations with granular and block form PAM using the expanded settling velocity residual detection method has enabled dosage rates over time to be quantified.

A collaborative research effort was pursued to implement flocculants on a large-scale sediment basin apparatus. This section of the report focused on evaluating dosage delivery and turbidity reduction of block form flocculants in the basin from the flocculant performance perspective. Blocks were installed upstream of the rock check dam before the forebay to provide enough distance for effective agitation and mixing. Turbidity reduction performance of flocculants in the basin was compared to MFE-I treatment in the study together with residual concentration monitoring. Testing results validated the knowledge obtained in the bench-scale and flume testing phases of this research by demonstrating the positive impacts of proper dosage delivery, agitation, and mixing in the large-scale sediment basin apparatus. Findings of the testing highlighted product selection, complete flow contact, and upstream flocculant introduction as key components of proper flocculant implementation in the sediment basin application.

Initial large-scale testing showed promise of using residual settling plots initially developed for large-scale application of residual flocculant detection. However, it was clear that environmental conditions present in the field that influence flocculant efficacy needed to be accounted for. Residual settling plots were recreated by measuring the settling velocity for different flocculant concentrations at different pH values and temperatures to quantify flocculant efficacy across multiple factors that can vary by geographical region and season. Both Product A-G and Product A-B settling velocities were found to be significantly influenced by pH, temperature, and concentrations. Product A-G trends show that the soil settling velocity increases as the temperature and concentration increase and pH decreases. Whereas Product A-B soil settling velocity increases as temperature, concentration, and pH increases. However, further analysis should be conducted with Product A-B as it is unknown if the measured quantity of Product A-B fully dissolved in the sample before it was poured in graduated cylinders and the settling velocity was determined. Therefore, Product A-B settling velocity equation may not be an accurate representation of field conditions due to the ASTM jar testing methodology used.

Granular large-scale testing with Product A-G found that 180 g (6.36 oz.) spread across three wattles that were spaced over a total distance of 43 ft (13 m) initially dosed the channel with 19 mg/L and exponentially decreases to reach the recommended dosing concentration of 5.0 mg/L after 25.1 minutes and 1059.6 ft^3 (30.0 m^3) of flow. These results were developed by using the expanded residual settling velocity curves that include pH and temperature changes with various concentrations. Visual tests confirm predicted concentrations as visible flocs are progressively smaller as sampling time continues. After 60-minutes, very small flocs were observed, indicating dosing levels were under 1 mg/L but marginally greater than 0 mg/L. Results indicate that Product A-G should be reapplied after 3,600 ft^3 (101.9 m^3) of flow or 1.0 in. (2.54 cm) of runoff per acre (0.4 ha). This allows for underdosing above 1.0 mg/L to occur for an extended period of time to dilute initial increased dosing that is captured in a downstream sediment basin. Literature review found freshwater fleas to have the lowest LD$_{50}$ of 14.1 mg/L which was exceeded during the first 20-minutes of flow. By reapplying flocculant after the recommended 3,600 ft^3 (101.9 m^3) of flow or 1.0 in. (2.5 cm) of runoff per 1.0 ac (0.4 ha), the reapplication rate can be justified by diluting residual concentrations to be below all aquatic organism toxicity limits before the effluent leaves the construction site. Turbidity results indicate Product A-G should be applied in a way where at least one ditch check at the end of the channel is left without flocculant application to mix flocculated water before discharging into a sediment basin.

Expanded residual settling velocity curves from Block form flocculant using Product A-B large-scale testing were inconclusive. However, using pond water collected during testing, a test-specific concentration prediction equation was established. Product A-B trends showed that settling velocities increased as the number of blocks in the channel grew, regardless of water volume or length of time. Large-scale testing showed that Product A-B quantification is problematic since current technologies cannot reliably detect known quantities. It is suggested that ASTM jar testing standards be modified to better account for the gelatinous flocculant form, or that improved methods for weighing out known concentrations while maintaining saturation consistency be determined. Turbidity data suggest applying Product A-B so that at least one ditch check at the end of a channel is flocculant-free to mix flocculated water before discharging into a sediment basin. Visual tests support residual predicted trends showing floc size rises with channel block count. Based on testing at AU-SRF using Product A-B that is developed by Manufacturer I with 1.80 ft^3/s (0.05 m^3/s) of flow and with sandy clay loam soil present at the AU-SRF, it was determined that six flocculant blocks were for channel flow applications. The number of blocks was determined from visual tests as current residual detection methods using the ASTM jar testing method does not allow the product to fully dissolve and accurately reflect initial known concentrations. As products can vary greatly between manufacturers, the recommended number of flocculant blocks require testing based on product, flow, soils, and site-specific conditions. Based on testing at AU-SRF using Product A-B, block-form flocculants are not recommended for passive dosing systems as they were not as effective at flocculating the granular form flocculant (Product A-G) used. Passive dosing with flocculant blocks poses additional challenges to protect the product from drying out or sediment build-up, which can reduce its ability to treat stormwater. Further testing should be conducted to evaluate how long it takes for blocks to rehydrate to begin dosing during flow conditions or if the flocculation efficacy is impacted when the product is rehydrated after drying out. Additionally, flocculant block use in active treatment systems should be evaluated and compared to passive treatment methods using flocculant blocks to compare possible performance differences.

Large-scale evaluations on flocculants were essential to confirm results from intermediate-scale flume testing that contained controlled variables that would otherwise be uncontrolled in field applications. The findings of this research aim to guide practitioners in implementing adequate dosage delivery techniques on active job sites. This research demonstrated alternative ways of using residual concentration detection results to ensure proper dosage delivery in flocculant applications. Findings showed the importance of residual concentration detection not just for increased dosage monitoring, but also for identifying the agitation needs of the flocculant applications. It is important to note that these studies were conducted using PAM flocculants from Manufacturer I with AU-SRF sandy clay loam soil. Further analysis should be cautious when collecting large-scale test samples to ensure the use of single-use plastic bags when glass is not an option. Proper cleaning is critical to minimize cross-contamination. Protecting samples from heating up and maintaining constant temperature and resting time between collection and processing is critical in maintaining consistency with residual flocculant predictions. This research provides insight on flocculant dosing during flow in field conditions to predict guidance on how and where to apply granular and block form flocculant to achieve effective flocculation without causing environmental harm and when reapplication should be performed. Therefore, these tests may not produce similar results for different flocculants or soil types. This research is meant to serve as a baseline for testing methodologies that can be used to evaluate other flocculant products to provide guidance on optimum flocculant implementation for construction sites. Future research should also focus on how to implement flocculants on different large-scale testing apparatuses different than sediment basins, determine better methods for quantifying residual flocculant block concentrations, and evaluate flocculant block uses in active treatment systems and compare the results to passive treatment systems. Moreover, the findings of this research would potentially pave the way for a future field monitoring study for flocculant applications on active construction sites.

CHAPTER 7
CONCLUSIONS

7.1 INTRODUCTION

This research project aimed to improve guidance available for the use of flocculants in constructions stormwater applications. A comprehensive literature review was conducted along with a state-of-the-practice survey to catalog the current state-of-practice with flocculant use on construction sites. This research conducted bench-scale experiments to develop methodologies for match testing and dosage selection for various products and soil types. In addition, a method to determine flocculant concentration was developed. Finally, intermediate-scale and large-scale evaluations were conducted to develop guidance on field application of flocculants. This section summarizes the conclusions of each of the investigated research areas in this project and general limitations of the research performed and explores avenues by which the knowledge base can be expanded by performing additional studies and investigations. The presented research identified common unknowns in flocculant application for construction stormwater treatment and developed methods to provide specialized guidance to ALDOT practitioners. Practical and implementable findings are provided in this chapter. The major findings of this research will ultimately promote proper flocculant implementation on ALDOT construction sites and enhance the sediment capture function of temporary E&SC controls for protecting Alabama's waterbodies.

7.2 STATE-OF-THE-PRACTICE SURVEY

To achieve the first objective of this research, a state-of-the-practice survey was conducted to determine enhancement needs for flocculant usage and guidance on construction sites. The target audience of the survey was state DOTs to understand the nationwide perspective on implementing flocculants for construction stormwater management. The survey questions were prepared based on the literature review conducted in this research and distributed to 51 DOTs in the U.S. The survey was distributed through an online survey platform. We achieved a 73% response rate.

Survey findings provided a detailed overview of flocculant usage in construction stormwater management and identified research needs. Results showed that only 39% of the state agencies allowed for the use of flocculants on their active construction projects. Most DOTs were hesitant to use flocculants due to the liability of potentially polluting receiving waters. Another major finding identified that most agencies depended on manufacturer guidance for product selection and dosage. In addition, only 23% of the agencies stated that they require residual monitoring during flocculant application on construction sites.

Results of the survey shaped the objectives of bench-scale experiments to evaluate dosage and residual monitoring on commonly used flocculant products. Survey findings also guided the intermediate-scale flume and large-scale application phases of this research on investigating flocculant usage for the most commonly implemented sediment control practices.

The survey was distributed to 51 state DOTs in the U.S.; however, only 31 states responded to the survey invitation and provided complete answers to the survey questions. E&SC manuals non-responding agencies were reviewed and included in survey data for identifying flocculant usage. Another limitation of the survey was discrepancies provided by the state DOT professionals on some of the survey questions that did not directly match with their agency's E&SC manuals.

7.3 RESIDUAL DETECTION METHODS

The second objective of this research was accomplished through the development of bench-scale testing methods for developing guidance on product selection, dosage, and residual concentration monitoring. The study evaluated 14 different flocculant products against 18 soil samples collected across ALDOT construction sites to identify product selection and optimum dosage requirements of flocculants. In addition, the study evaluated how viscosity, particle charge analyzer, and soil settling velocity could potentially be used as a field applicable method for identifying residual flocculant concentrations in construction stormwater runoff.

Findings of the bench-scale study outlined a comprehensive methodology for effective product selection through match test experiments that ranked products based on their performance on each soil tested. The developed match test procedures identified the top three best performing products based on a point system evaluating effluent color, floc formation, size floc, and settling velocity. Results of match testing indicated that PAM and chitosan products were the most effective flocculant types on the soil samples used in this study. Top performing products were then evaluated in dosage experiments to identify rates that provided effective treatment. Dosage experiments revealed that manufacturer guidance may not directly apply to all soil types and in certain cases, lower concentrations, sometimes as low as 20% of target concentrations, were found to be more effective.

The development of the residual concentration detection method enabled a field applicable mechanism for monitoring residual flocculant concentrations on construction sites. The challenge was to find a detection method that was: simple and easy to perform, low cost, worked with sediment-ladened samples, produced reliable results in a short time, and can quantify concentrations near target application rates. Findings showed that settling velocity observations can be related to flocculant concentrations for most flocculant types tested. Settling velocity of various flocculant products was observed for samples with known flocculant concentration to develop plots for each product evaluated. Higher concentrations of flocculants corresponded to increased settling velocities. Further analysis was conducted using a range of pH values and temperatures to further optimize the detection method. Results of the method provided a practical solution for identifying the flocculant concentration of flocculant on the samples collected from job sites. In addition, the findings provided an effective solution for monitoring overdosages and validating proper dosage delivery based on estimated residual concentrations.

Among all tested flocculant types, alum and agricultural gypsum were the only two that did not show a linear behavior between settling depth and time. Hence, these flocculant types created a limitation in the standard residual concentration plot preparation. Another limitation was identifying a standard testing soil for settling velocity observations. This study can be easily adapted for different testing soils; however, using a specific and standard testing soil would improve the standard residual concentration plot production on various products. Future research should focus on developing standard residual concentration plots for different products and identifying a commercially available synthetic soil that would have a rapid settling velocity and well-characterizable color palette.

Several other methods for quantifying flocculants were evaluated, but the challenge was to find a detection method that is simple and easy to perform without extensive lab training, low cost, works with sediment-ladened samples, produces reliable results in a short time, and can quantify concentrations above and below the PAM manufacturer's recommendation of 5 mg/L. A Cannon-Fenske Routine Viscometer and Brookfield Digital Viscometer were not sensitive enough to discern concentration changes below 20 mg/L. Cannon-Fenske tubes also required samples to be silt-free before evaluation since debris could block the tubes and affect results.

A particle charge analyzer was evaluated using two anionic forms of flocculant, G and Product A-B, and one cationic form, chitosan. Product A-G and chitosan were not viable options for determining increased dosing by measuring the sample's SCV in the presence of sediment, whereas Product A-B was able to quantify concentrations between 3 and 7 mg/L. When soil is present at 0.125 to 7.00 mg/L, 3.00 to 7.00 mg/L, and 20 to 200 mg/L, Product A-G, Product A-B, and chitosan flocculants dramatically lower pH values. Using sample pH change versus SCV may be able to approximate concentration ranges that would be difficult to distinguish from concentration versus SCV plots alone. Future evaluations should include additional flocculants and soil types because trends and connections may vary.

Initial residual settling plots had shown promise in preliminary large-scale testing for initial large-scale application of residual flocculant detection. Nonetheless, it was evident that environmental conditions present in the field that affect flocculant efficacy must be accounted for in this method. Residual settling plots were produced by monitoring the settling velocity for different flocculant concentrations at varied pH values and temperatures to assess flocculant efficacy across many parameters that can vary by geographical region and season. The settling velocities of Product A-G and Product A-B were found to be substantially affected by pH, temperature, and concentrations. According to Product A-G trends, temperature, concentration, and pH increase soil settling velocity, while Product A-B soil settling velocity trends increase as temperature, concentration, and pH increase. As it is uncertain whether the measured amount of Product A-B was completely dissolved in the sample before it was poured into graduated cylinders and the settling velocity was measured, additional analysis should be conducted with Product A-B. Therefore, Product A-B settling velocity equation may not be an accurate representation of field conditions due to the ASTM jar testing methodology used.

Results of the bench-scale phase provided a basis for subsequent intermediate-scale testing. Furthermore, the findings of this research will allow ALDOT practitioners to implement appropriate dosage on sites and minimize the lack of knowledge on flocculant usage, which was identified in the literature and state-of-the-practice survey.

7.4 INTERMEDIATE-SCALE FLUME EVALUATIONS

Intermediate-scale flume experiments were conducted to evaluate flocculant form, placement, agitation, mixing, and reapplication requirements using different application techniques. Intermediate-scale flume testing was conducted at AU-SRF by using testing capabilities and resources of the research center.

Flume experiments were conducted in a 40-ft (12 m) long flume that was constructed at the AU-SRF. Flume tests were subjected to 0.10 ft^3/s (3.5 m^3/s) of flow with a sediment introduction rate of 0.4 oz/min (294 g/min) to reach a target turbidity of 1,500 ± 500 NTU. The target turbidity was selected to replicate bench scale turbidity dosages. The slope of the flume was adjusted to 5% and 1%, allowing for supercritical and subcritical flow conditions, respectively. The performance of flocculants including granular, block, sock, and aqueous solution forms were evaluated under supercritical conditions.

Granular flocculant was also tested for subcritical flow conditions and longevity experiments. For supercritical flow tests, granular flocculant was spread on the first four ditch checks, leaving the fifth ditch check free of applied flocculants. The highest concentration, 16 mg/L, was reached within the 3 minutes of the experiments in the downstream samples. The concentration decreased over time and was found to reach approximately 14 mg/L after 9 minutes. This decrease in concentration was likely due to product wash-off. Indicating that granular form flocculant typically requires frequent reapplication and maintenance. Additionally, application effectiveness increases with the use of jute matting on ditch checks to increase the attachment area for granular particles. Subcritical flow conditions for granular flocculant found that dosage was estimated to be 5.2 mg/L after 3 minutes at the end of the channel. Estimated concentrations dropped to 3.7 mg/L by 9 minutes. Supercritical flow conditions were more ideal for producing efficient flocculant dosing for granular applications. Granular longevity tests indicated complete wash-off was predicted in flume conditions to be reached by 3 hours and 57 minutes. The channelized flow flume setup was capable of treating 1,422 ft^3 (40.3 m^3) turbid water. This longevity result indicated that 27,346 ft^3 (1.67 m^3) of volume could be treated before reapplication of flocculant is required in the channel.

Block form flocculants subjected to supercritical flow tests were performed using a reduced size floc block that was placed after the first ditch check for intermediate-scale flume testing. The block was one quarter of the original flocculant block size to accommodate the flume dimensions. During testing, a concentration of 7.8 mg/L of residual flocculant was detected upstream of DC-2. Further down the channel to DC-4, the concentration increased to 27.7 mg/L. This increase in concentration was due to floc buildup in the ditch check impoundments. Results indicated that blocks facilitate a uniform dosage delivery when compared to granular flocculant in supercritical flow conditions. Moreover, it was observed that the required reapplication frequency of the block form is lower than the other evaluated flocculant forms in this study. However, it is important to note that the performance of the block form is highly dependent on proper maintenance on job sites, which typically includes sun protection and cleaning procedures.

Sock form flocculants evaluated in supercritical flow tests were also scaled down to match flume conditions and was installed after the first ditch check. Results showed residual concentrations of 28 mg/L after 3 minutes with sediment introduction. The residual concentration dropped to 25 mg/L after 9 minutes of flow with sediment. These results did not differ much from clear water test results, implying Product-I was less effective on the testing soil compared to other tested products and it did not facilitate sufficient floc formation. During the match test phase of this research, Product-I was not listed in the top three best-performing products for the testing soil. However, it was preferred in the flume testing phase due to limited options for commercially available sock form flocculants. Flume experiment results validated the match test findings on the Product-I.

Aqueous flocculant evaluated in supercritical flow tests was injected into the channel directly downstream of the first ditch check. The measured residual flocculant concentration was found to peak to 3 mg/L at 6 minutes and decrease to 2.4 mg/L at 9 minutes. Although aqueous solution introduction provided the most effective dosage delivery mechanism results, it is important to highlight that this type of flocculant application is not commonly adapted in construction applications. Construction stormwater treatment with an aqueous solution brings maintenance challenges for field applications since the semi-passive treatment requires periodic maintenance to keep continuous dosing in the system.

Turbidity reduction evaluations were conducted to validate sufficient mixing and agitation was being achieved in the channel, while confirming effective flocculation. It was found that all flocculant products evaluated achieved over 89% turbidity reduction at the downstream sampling location. Overall, turbidity reductions typically increased when samples were later mixed to simulate sufficient agitation. Indicating flocculant placement should be done further upstream where the product can be agitated through at least one subsequent ditch check installation that is free of applied flocculant, prior to discharge.

7.5 LARGE-SCALE APPLICATION EVALUATIONS

Large-scale flume experiments were conducted to re-evaluate flocculant form, placement, agitation, mixing, and reapplication requirements for granular and block form flocculant in a field setting with less controlled variables. Large-scale testing was conducted at AU-SRF through sediment basin and channel applications.

7.5.1 SEDIMENT BASIN TESTING USING FLOCCULANT BLOCKS

Large-scale evaluations in this research continued with flocculant application on a sediment basin apparatus that was constructed as a part of a sediment basin research effort at AU-SRF. This collaborative study compared the performance of the MFE-I treatment in the basin with and without flocculant usage. Block form flocculants were introduced upstream of the rock check dam, prior to the forebay being installed in the in-channel basin. Turbidity reduction and residual concentration monitoring throughout the testing allowed the evaluation of optimum dosage delivery within the basin. Results showed that block forms provide effective and steady dosage delivery by decreasing the turbidity by 90% in discharge. Moreover, lower residual concentrations were monitored throughout the testing in the basin, which showed the signs of proper flocculant implementation on the basin apparatus.

7.5.2 CHANNEL-BASED TESTING OF GRANULAR FLOCCULANT

Channelized testing using straw wattles found that 6.4 oz. (180 g) spread across three wattles spaced 43 ft (13 m) initially dosed the channel with 19 mg/L and exponentially decreased to the target dosing concentration of 5.0 mg/L after 25.1 minutes and 1,060 ft^3 (30 m^3) of flow. Expanded residual settling velocity curves with pH and temperature variations at varied concentrations were used to obtain concentration results. Visual observations show decreasing floc formation over time, confirming projected concentrations. After 60 minutes, minimally discernible flocs showed dosage levels <1 mg/L but above 0 mg/L. Results suggest reapplying Product A-G granular flocculant after 3,600 ft^3 (102 m^3) of flow or 1.0 in. (2.5 cm) of runoff per acre (0.4 ha) into a channel. This allows prolonged underdosing above 1.0 mg/L to dilute downstream sediment basin increased dosing. Turbidity data suggest applying granular flocculant so that at least one ditch check at the channel's terminus should be flocculant-free to ensure sufficient mixing is achieved for flocculated water before discharging into a sediment basin.

7.5.3 CHANNEL-BASED TESTING OF FLOCCULANT BLOCKS

Unlike the granular form flocculant, block form flocculants evaluated using the expanded residual settling velocity curves were inconclusive for Product A-B used during large-scale tests. However, using pond water collected during testing, a test-specific concentration prediction equation was established. Block form flocculant trends showed that settling velocities increased as the number of blocks in the channel grew, regardless of water volume or length of time. Large-scale testing showed that flocculant blocks quantification is problematic since current technologies cannot reliably detect known quantities.

Visual tests support residual predicted trends showing floc size increases with block count. Testing was conducted in a 4 ft (1 m) wide trapezoidal channel with 3:1 side slopes at a 5% slope. A standard ALDOT silt fence ditch check was installed within the channel and flocculant blocks were placed immediately downstream of the ditch check. A sandy clay loam soil was introduced at a rate of 42.8 lb./min (19.4 kg/min) to create a turbidity of approximately 1,500 ± 500 NTU. At the flow rate of 1.80 ft^3/s (0.05 m^3/s), it was determined that six flocculant blocks were effective providing proper dosage concentration. The number of blocks was determined from visual tests as residual detection methods using the ASTM Jar Testing Method did not allow the product to fully dissolve and accurately reflect initial known concentrations. Further testing is recommended by evaluating block requirements for different products and flow rates. In addition, passive dosing with flocculant blocks poses challenges to protect the product from drying out or from accumulating sediment build-up, which may impact its ability to treat stormwater. Evaluation of hydration requirements and longevity of flocculant blocks is needed.

Large-scale evaluations on flocculants were essential in this research to elevate the knowledge gained in the bench-scale and intermediate-scale phases by replicating construction conditions. The findings of this research aim to guide practitioners in implementing adequate dosage delivery techniques on active construction sites. This research demonstrated alternative ways of using residual concentration detection results to ensure proper dosage delivery in flocculant applications. Findings showed the importance of residual concentration detection not just for increased dosage monitoring, but also for identifying the agitation needs of the flocculant applications.

7.6 RECOMMENDATIONS FOR IMPLEMENTATION

This section lists practical recommendations for implementing results derived from this research study. Recommendations are limited to the products tested and conditions (soil, flow rates, dosage, etc.) evaluated in this study.

Match Testing:

- Although toxicity evaluations were not performed in this study, it is highly encouraged to review toxicity limitations of the possible products before match or dosage testing. A product SDS may not contain sufficient information regarding aquatic toxicology information. Practitioners should request toxicology reports performed by third parties to confirm accurate and complete representation. Product application rates may vary based on aquatic lethal dosage limits to minimize downstream environmental harm.
- Soils responsiveness to flocculant types and products was found to be variable. Physical soil properties and chemistry influence performance with flocculants. A clear correlation between soil properties and flocculant selection was not found. Therefore, several soil samples should be collected throughout the site and match tested following methods developed in this report to ensure proper product selection.
- Anionic PAM based flocculants were found to match with the most soil types evaluated in this study. All 15 soils that were evaluated consisted of at least one anionic flocculant type that yielded effective flocculation. Not all soil types effectively flocculated with the evaluated cationic flocculants. Sodium montmorillonite was found to match with only one evaluated soil type, while bentonite-based, calcium sulfate, and aluminum sulfate did not match with any tested soil types.
- pH should be monitored when evaluating flocculant products. Changes in pH may pose negative impacts to aquatic organisms.
- MSDS and other safety data sheets provided by manufacturers may not sufficiently indicate potential toxicity of flocculants. Toxicology reports should be reviewed prior to selecting a flocculant.

Dosage Testing:

- Manufacturer dosage guidance varies and often advises a higher concentration than what was determined to be effective in this study. Once match testing has been conducted, dosage testing should be performed to determine appropriate concentrations for effective flocculation.

Flocculant Types:

- Emulsion provided the most consistent dosage application, however required a mechanized system.

- Granular flocculant was found to provide a somewhat consistent rate of dosage application, however frequent reapplication is needed to maintain target dosage concentrations.
- Block flocculant dissolved slowly, requiring multiple blocks to achieve target flocculant dosage rates. Dosage delivery rate is more uniform than granular flocculant. Requirements to maintain block hydration and remove sediment may increase maintenance burden.

Sediment Basin Application:

- Iowa DOT sediment basin design allowed for block form flocculants to be interdicted upstream of the rock check dam, prior to the forebay being installed in the in-channel basin. As Iowa DOT sediment basin designs are built into the channel, installing flocculant blocks prior to the forebay allowed for sufficient agitation and steady dosing to capture sediment in the forebay.
- Place blocks in a way that facilitates maximum contact area with the flow introduction. Not all introduced flow will make adequate contact with the blocks, so it may be necessary to increase the number of blocks in the channel to provide sufficient dosage throughout the basin.

Granular Ditch Check Application:

- Granular flocculant requires a fibrous surface area for adhesion. Straw and excelsior filled wattles used in this testing performed adequately with granular flocculant application. Rock and other similar based ditch checks may require jute or coir overlays when applying flocculant. Although not evaluated in this study, silt fence ditch checks may not be suitable for granular applications.
- Testing results indicated granular flocculant should be applied at 2.1 oz (60 g) per ditch check. Flocculant should be applied in a thin layer across the front (0.52 oz [15 g]), back (0.52 oz [15 g]), and top (1.1 oz [30 g]) of the wattle where runoff will contact the product. Installers should limit flocculant application to a maximum of three wattles within a 250 ft channel section.
- Reapply granular flocculant after 3,600 ft^3 (102 m^3) of flow or 1.0 in. (2.5 cm) of runoff per acre (0.4 ha) into a channel.
- Place a minimum of one ditch check at the end of the channel free of flocculant to facilitate mixing and agitation prior to discharge from the channel.
- Gelatinous flocculant residue will be observed where the flocculant was placed after the storm event, however, this residue does not correlate with unused

flocculant available for subsequent runoff events. Apply new granular flocculant on the residue for preparation of the next storm event for proper dosing.

Flocculant Block Ditch Check Application

- Testing showed that six blocks were required for a flow rate of 1.80 ft^3/s (0.051 m^3/s). Indicating an application rate of one block per 0.3 ft^3/s (0.008 m^3/s) of flow.
- Flocculant dosage was not as effective with block form than it was with granular form flocculant.
- To promote dissolvement and to prevent sediment build-up, blocks should be secured in areas of supercritical flow conditions, preferably directly underneath overtopping flow.
- Use sod staples to secure the block to the channel floor at the desired location.
- Minimize sun exposure to flocculant blocks as much as possible as they will dry would quickly if left in the sun, which could negatively impact flocculant dosing rates.
- Inspect blocks after each storm event to readjust securement method and remove sediment buildup, if necessary.

7.7 LESSONS LEARNED, LIMITATIONS, AND FUTURE RESEARCH RECOMMENDATIONS

It is important to note that these studies were conducted using PAM flocculants from Manufacturer I with AU-SRF sandy clay loam soil and findings may be limited. Further analysis should be cautious when collecting field samples to ensure the use of single-use plastic bags when glass is not an option. Proper cleaning is critical to minimize cross-contamination. Protecting samples from heating up and maintaining constant temperature and resting time between collection and processing is critical in maintaining consistency with residual flocculant predictions. This research provides insight on flocculant dosing during flow in field conditions to predict guidance on how and where to apply granular and block form PAM using Product A-G and Product A-B, respectively, to achieve effective flocculation without causing environmental harm and when reapplication should be performed. Therefore, these tests may not produce similar results for different flocculants, soil types, or flow rates. This research is meant to serve as a baseline for testing methodologies that can be used to evaluate other flocculant products to provide guidance on optimum flocculant implementation for construction sites.

As flocculants are highly soil-dependent, future research efforts should emanate from this research by allowing opportunities to evaluate more soils with different types of flocculant products and expand knowledge on soil-dependent dosage requirements. These evaluations should strive to build a bank of standard residual concentration plots for different products and soil types. These standard residual concentration plots should include a range of temperatures, pH values, concentrations, soil types, and flocculant products from different manufacturers to build a bank of data that can be used to predict residual flocculant concentrations regardless of the season, geographical location, or product used. Additionally, using the SCV to predict residual flocculant concentrations should be further explored using additionally flocculant products and soil types to track trend changes. Even though this detection method may not be as feasible for large-scale applications due to time and cost restrictions, further evaluations with this product may aid in flocculant monitoring in more controlled environments.

The ASTM jar testing methodology (*143*) is not ideal for block form flocculant due to its gelatinous consistency that is designed to slowly dissolve. Future studies should focus on identifying methods for reliably quantifying residual flocculant block concentrations to allow for additional time for the block to dissolve where it can create flocs and correlate those results to settling velocities collected in large-scale testing. Subsequent studies should focus on how to implement flocculants on different large-scale testing apparatuses that can treat stormwater prior to being captured in a sediment basin, determine better methods for quantifying residual flocculant block concentrations, and evaluate flocculant block uses in active treatment systems and compare the results to passive treatment systems. Future testing should be conducted to evaluate how long it takes for blocks to rehydrate to begin dosing during flow conditions or if the flocculation efficacy is impacted when the product is rehydrated after drying out. Additionally, flocculant block use in active treatment systems should be evaluated and compared to passive treatment methods using flocculant blocks to compare possible performance differences.

REFERENCES

1. United States Census Bureau. Monthly Construction Spending. *United States Census Bureau*, 2022.
2. United States Environmental Protection Agency. *Federal Register 75, 56928-56935*. Washington, DC, 1998.
3. United States Environmental Protection Agency. *National Management Measures to Control Nonpoint Source Pollution from Urban Areas*. Washington, DC, 2005.
4. United States Environmental Protection Agency. Environmental Protection Agency: National Pollutant Discharge Elimination System - Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges. *United States Environmental Protection Agency*, 1999.
5. United States Environmental Protection Agency. Construction General Permit (CGP). *United Stated Environmental Protection Agency*. https://www.epa.gov/npdes/2017-construction-general-permit-cgp.
6. Donohue, I., and J. Garcia Molinos. Impacts of Increased Sediment Loads on the Ecology of Lakes. *Biological Reviews*. 4. Volume 84, 517–531.
7. Hansen, Z. K., G. D. Libecap, A. Thomas, J. Long, S. Reynolds, D. Lueck, D. Yao, L. Alston, S. Salant, R. Johnson, J. Ferrie, G. Crawford, J. Nickerson, M. Law, S. Barbara, L. Berkeley, and Y. Angeles. *Small Farms, Externalities, and the Dust Bowl of the 1930s*. 2004.
8. Natural Resources Conservation Service. Honoring 86 Years of NRCS – A Brief History. *Natural Resources Conservation Service*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/about/history/?cid=nrcs143_021392. Accessed May 4, 2022.
9. United States Congress. Federal Water Pollution Control Act (33 U.S.C. 1251 et Seq.). *United States Congress*, 2002.
10. United States Environmental Protection Agency. *Developing Your Stormwater Pollution Prevention Plan: A Guide for Construction Sites*. Montgomery, AL, 2007.
11. Schussler, J. C., M. A. Perez, W. N. Donald, J. B. Whitman, W. C. Zech, X. Fang, and B. Fagan. Decade of Research in Review at the Auburn University Stormwater Research Facility. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2676, No. 5, 2022, pp. 590–604. https://doi.org/10.1177/03611981221076449.
12. Alabama Department of Transportation. *Module 1 - History of ALDOT*. Montgomery, AL, 2015.
13. Alabama Department of Transportation. *Construction Stormwater CBMPP*. Montgomery, AL, 2016.
14. Perez, M. A., W. C. Zech, W. N. Donald, and X. Fang. Design Methodology for the Selection of Temporary Erosion and Sediment Control Practices Based on Regional Hydrological Conditions. *Journal of Hydrologic Engineering*, Vol. 21, No. 4, 2016. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001328.

15. Schussler, J. C., B. Kazaz, M. A. Perez, J. B. Whitman, and B. Cetin. Field Evaluation of Wattle and Silt Fence Ditch Checks. In *Transportation Research Record*, SAGE Publications Ltd, pp. 281–293.

16. Whitman, J. B., W. C. Zech, W. N. Donald, and J. J. LaMondia. Full-Scale Performance Evaluations of Various Wire-Backed Nonwoven Silt Fence Installation Configurations. *Transportation Research Record*, Vol. 2672, No. 39, 2018, pp. 68–78. https://doi.org/10.1177/0361198118758029.

17. Donald, W. N., W. C. Zech, X. Fang, and M. A. Perez. Hydraulic Method to Evaluate the Performance of Ditch Check Practices and Products. *Journal of Hydrologic Engineering*, Vol. 21, No. 11, 2016. https://doi.org/10.1061/(asce)he.1943-5584.0001311.

18. Perez, M. A., W. C. Zech, W. N. Donald, and X. Fang. Installation Enhancements to Common Inlet Protection Practices Using Large-Scale Testing Techniques. *Transportation Research Record*, Vol. 2521, No. 1, 2015, pp. 151–161. https://doi.org/10.3141/2521-16.

19. Whitman, J. B., W. C. Zech, and W. N. Donald. Improvements in Small-Scale Standardized Testing of Geotextiles Used in Silt Fence Applications. *Geotextiles and Geomembranes*, Vol. 47, No. 5, 2019, pp. 598–609. https://doi.org/10.1016/j.geotexmem.2019.04.002.

20. United States Environmental Protection Agency. *Stormwater Phase II Final Rule: Post-Construction Runoff Control Minimum Control Measure*. Washington, DC, 2018.

21. Alabama Department of Environmental Management. *Water Division - Water Quality Program, Volume 1, Division 335-6*. Montgomery, AL, 2019.

22. North Carolina Department of Environmental Quality. *North Carolina Administrative Code Surface Water and Wetland Standards*. 2019.

23. Hancock, B. Flocculants: How Do They Work and Why? *Mainland Machinery Ltd*, , 2017.

24. Kazaz, B., M. A. Perez, W. N. Donald, X. Fang, and J. N. Shaw. Detection of Residual Flocculant Concentrations in Construction Stormwater Runoff. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2676, No. 7, 2022, p. 036119812210779. https://doi.org/10.1177/03611981221077985.

25. Pillai, J. Flocculants and Coagulants: The Keys to Water and Waste Management in Aggregate Production. *Nalco*, No. Stone Review, 1997, p. 1,3.

26. Vajihinejad, V., S. P. Gumfekar, B. Bazoubandi, Z. Rostami Najafabadi, and J. B. P. Soares. Water Soluble Polymer Flocculants: Synthesis, Characterization, and Performance Assessment. *Macromolecular Materials and Engineering*, Vol. 304, No. 2, 2019, pp. 1–43. https://doi.org/10.1002/mame.201800526.

27. SNF Floeger, and Z. de Milieux. Coagulation - Flocculation. *SNF Floerger*, Vol. 33, No. 0, 2003, p. 10.

28. Stechemesser, H., and B. Dobiáš. Coagulation and Flocculation. In *Coagulation and Flocculation, Second Edition*, pp. 1–862.

29. Greenwood, J. How Are Coagulants and Flocculants Used in Water and Wastewater Treatment? *WCS Group Safe Efficient Complience*. https://www.wcs-group.co.uk/wcs-

blog/coagulants-flocculants-wastewater-treatment#:~:text=Coagulation and flocculation are two,easily separated from the liquid.

30. Dao, V. H., N. R. Cameron, and K. Saito. Synthesis, Properties and Performance of Organic Polymers Employed in Flocculation Applications. *Polymer Chemistry*, Vol. 7, No. 1, 2016, pp. 11–25. https://doi.org/10.1039/c5py01572c.

31. Biesinger, K. E., and G. N. Stokes. Effects of Synthetic Polyelectrolytes on Selected Aquatic Organisms. *Journal of the Water Pollution Control Federation*, Vol. 58, No. 3, 1986, pp. 207–213.

32. Xiong, B., R. D. Loss, D. Shields, T. Pawlik, R. Hochreiter, A. L. Zydney, and M. Kumar. Polyacrylamide Degradation and Its Implications in Environmental Systems. *npj Clean Water*, Vol. 1, No. 1, 2018. https://doi.org/10.1038/s41545-018-0016-8.

33. Kurenkov, V. F., H.-G. Hartan, and F. I. Lobanov. Application of Polyacrylamide Flocculants for Water Treatment. *Ул. К. Маркса Казань. Татарстан. Россия*, Vol. 3, No. 31, 2002, pp. 31–40.

34. Long, Y., X. You, Y. Chen, H. Hong, B. Q. Liao, and H. Lin. Filtration Behaviors and Fouling Mechanisms of Ultrafiltration Process with Polyacrylamide Flocculation for Water Treatment. *Science of the Total Environment*, Vol. 703, 2020, p. 135540. https://doi.org/10.1016/j.scitotenv.2019.135540.

35. Ma, J., R. Wang, X. Wang, H. Zhang, B. Zhu, L. Lian, and D. Lou. Drinking Water Treatment by Stepwise Flocculation Using Polysilicate Aluminum Magnesium and Cationic Polyacrylamide. *Journal of Environmental Chemical Engineering*, Vol. 7, No. 3, 2019, p. 103049. https://doi.org/10.1016/j.jece.2019.103049.

36. Chang, Q., X. Hao, and L. Duan. Synthesis of Crosslinked Starch-Graft-Polyacrylamide-Co-Sodium Xanthate and Its Performances in Wastewater Treatment. *Journal of Hazardous Materials*, Vol. 159, No. 2–3, 2008, pp. 548–553. https://doi.org/10.1016/j.jhazmat.2008.02.053.

37. Wong, S. S., T. T. Teng, A. L. Ahmad, A. Zuhairi, and G. Najafpour. Treatment of Pulp and Paper Mill Wastewater by Polyacrylamide (PAM) in Polymer Induced Flocculation. *Journal of Hazardous Materials*, Vol. 135, No. 1–3, 2006, pp. 378–388. https://doi.org/10.1016/j.jhazmat.2005.11.076.

38. Al Momani, F. A., and B. Örmeci. Measurement of Polyacrylamide Polymers in Water and Wastewater Using an In-Line UV-Vis Spectrophotometer. *Journal of Environmental Chemical Engineering*, Vol. 2, No. 2, 2014, pp. 765–772. https://doi.org/10.1016/j.jece.2014.02.015.

39. Druschel, S. J. Flocculation Treatment BMPs for Construction Water Discharges. *Minnesota Department of Transportation Resaerch Services & Library*, No. August, 2014.

40. Yu, H., C. Wang, F. Meng, J. Xiao, J. Liang, H. Kim, S. Bae, D. Zou, E. S. Kim, N. Y. Kim, M. Zhao, and B. Li. Microwave Humidity Sensor Based on Carbon Dots-Decorated MOF-Derived Porous Co3O4 for Breath Monitoring and Finger Moisture Detection. *Carbon*, Vol. 183, 2021, pp. 578–589. https://doi.org/10.1016/j.carbon.2021.07.031.

41. Khoo, S. C., X. Y. Phang, C. M. Ng, K. L. Lim, S. S. Lam, and N. L. Ma. Recent Technologies for Treatment and Recycling of Used Disposable Baby Diapers. *Process*

Safety and Environmental Protection, Vol. 123, 2019, pp. 116–129. https://doi.org/10.1016/j.psep.2018.12.016.

42. Anderson, F. A. Amended Final Report on the Safety Assessment of Polyacrylamide and Acrylamide Residues in Cosmetics. *International Journal of Toxicology*, Vol. 24, No. SUPPL. 2, 2005, pp. 21–50. https://doi.org/10.1080/10915810590953842.

43. Young, M. H., J. J. Tappen, G. C. Miller, S. Carroll, and R. B. Susfalk. Using Linear Anionic Polyacrylamide (LA-PAM) as an Alternative to Reduce Seepage Losses in Water Delivery Canals. *U.S. Bureau of Reclamation*, 2007.

44. Li, X., Z. Xu, H. Yin, Y. Feng, and H. Quan. Comparative Studies on Enhanced Oil Recovery: Thermoviscosifying Polymer Versus Polyacrylamide. *Energy and Fuels*, Vol. 31, No. 3, 2017, pp. 2479–2487. https://doi.org/10.1021/acs.energyfuels.6b02653.

45. Zolfaghari, R., A. A. Katbab, J. Nabavizadeh, R. Y. Tabasi, and M. H. Nejad. Preparation and Characterization of Nanocomposite Hydrogels Based on Polyacrylamide for Enhanced Oil Recovery Applications. *Journal of Applied Polymer Science*, Vol. 100, No. 3, 2006, pp. 2096–2103. https://doi.org/10.1002/app.23193.

46. Maurya, N. K., and A. Mandal. Studies on Behavior of Suspension of Silica Nanoparticle in Aqueous Polyacrylamide Solution for Application in Enhanced Oil Recovery. *Petroleum Science and Technology*, Vol. 34, No. 5, 2016, pp. 429–436. https://doi.org/10.1080/10916466.2016.1145693.

47. Rawat, A., H. K. Mahavar, S. Chauhan, A. Tanwar, and P. J. Singh. *Optical Band Gap of Polyvinylpyrrolidone/Polyacrilamide Blend Thin Films*. 2012.

48. Chibowski, E. M., M. Curie-Sklodowsk, and L. Poland. Flocculation and Dispersion Phenomena in Soils. *Encyclopedia of Agrophysics*, 2011. https://doi.org/10.1007/978-90-481-3585-1.

49. Applied Polymer Systems, Inc. 700 Series Silt Stop. *Applied Polymer Systems, Inc.* . 4. 4–5. https://www.siltstop.com/p.php?go=pinfo&PID=4-aps_700_series_silt_stop. Accessed Jun. 22, 2023.

50. Applied Polymer Systems, Inc. 700 Series Floc Logs. *Applied Polymer Systems*. 4. 4–5. https://www.siltstop.com/p.php?go=pinfo&PID=10-aps_700_series_floc_logs%C2%AE_. Accessed Jun. 22, 2023.

51. Lords World Inc. Flocculante Liquido - Chiarificatore Acqua Piscine - Antitorbidità 5Lt. *Lords World Flocculant Liquid Clarifier*. ttps://lordsworld.eu/gb/swimming-3 pool/5lt-flocculant-liquid-clarifier-swimming-pool-water-anti-turbidity. Accessed Jun. 15, 2020.

52. Floc Systems Inc. Tigerfloc Flocculant Belts/Socks. *Floc Systems Inc.* https://www.flocsystems.com/product/tigerfloc-flocculant-belts-socks. Accessed Jun. 15, 2020.

53. Lee, C. S., J. Robinson, and M. F. Chong. A Review on Application of Flocculants in Wastewater Treatment. *Process Safety and Environmental Protection*. 6. Volume 92, 489–508.

54. Wakema, J. R., and S. Tarleton. Solid/Liquid Separation. *Elsevier Science*, 2007, pp. 126–151. https://doi.org/10.1016/B978-1-85617-421-3.X5000-7.

55. Auckland Regional Council. *The Use of Flocculants and Coagulants to Aid the Settlement of Suspended Sediment in Earthworks Runoff: Trials, Methodology and Design (Draft)*. 2004.

56. Duggan, K. L., M. Morris, S. K. Bhatia, M. M. Khachan, and K. E. Lewis. Effects of Cationic Polyacrylamide and Cationic Starch on Aquatic Life. *Journal of Hazardous, Toxic, and Radioactive Waste*, Vol. 23, No. 4, 2019, pp. 1–12. https://doi.org/10.1061/(asce)hz.2153-5515.0000467.

57. Rabiee, A. Acrylamide-Based Anionic Polyelectrolytes and Their Applications: A Survey. *Journal of Vinyl and Additive Technology*, Vol. 16, No. 2, 2010, pp. 111–119. https://doi.org/10.1002/vnl.20229.

58. United States Environmental Protection Agency. *Stormwater Best Management Practice Polymer Flocculation*. Washington, DC, 2013.

59. Dobrynin, A. V., R. H. Colby, and M. Rubinstein. Polyampholytes. *Journal of Polymer Science, Part B: Polymer Physics*, Vol. 42, No. 19, 2004, pp. 3513–3538. https://doi.org/10.1002/polb.20207.

60. Xiong, B., R. D. Loss, D. Shields, T. Pawlik, R. Hochreiter, A. L. Zydney, and M. Kumar. Polyacrylamide Degradation and Its Implications in Environmental Systems. *Nature Partner Journals Clean Water*, Vol. 1, No. 1, 2018. https://doi.org/10.1038/s41545-018-0016-8.

61. Vajihinejad, V., S. P. Gumfekar, B. Bazoubandi, Z. Rostami Najafabadi, and J. B. P. Soares. Water Soluble Polymer Flocculants: Synthesis, Characterization, and Performance Assessment. *Macromolecular Materials and Engineering*, Vol. 304, No. 2, 2019, pp. 1–43. https://doi.org/10.1002/mame.201800526.

62. Lentz, R. D., and R. E. Sojka. Field Results Using Polyacrylamide to Manage Furrow Erosion and Infiltration. *Soil Science*, Vol. 158, No. 4, 1994, pp. 274–282. https://doi.org/10.1097/00010694-199410000-00007.

63. Kurenkov, V. F., H.-G. Hartan, and F. I. Lobanov. Application of Polyacrylamide Flocculants for Water Treatment. *Chemistry and Computer Modeling*, Vol. 3, No. 31, 2002, pp. 31–40.

64. Dao, V. H., N. R. Cameron, and K. Saito. Synthesis, Properties and Performance of Organic Polymers Employed in Flocculation Applications. *Polymer Chemistry*, Vol. 7, No. 1, 2016, pp. 11–25. https://doi.org/10.1039/c5py01572c.

65. Kang, J., and R. A. McLaughlin. Simple Systems for Treating Pumped, Turbid Water with Flocculants and a Geotextile Dewatering Bag. *Journal of Environmental Management*, Vol. 182, 2016, pp. 208–213. https://doi.org/10.1016/j.jenvman.2016.07.071.

66. Sojka, R. E., D. L. Bjorneberg, J. A. Entry, R. D. Lentz, and W. J. Orts. Polyacrylamide in Agriculture and Environmental Land Management. *Advances in Agronomy*, Vol. 92, No. 04, 2007, pp. 75–162. https://doi.org/10.1016/S0065-2113(04)92002-0.

67. Peng, F., and D. Pingkuan. Effect of Multivalent Salts- Calcium and Aluminum on the Flocculation of Kaolin Suspension with Anionic Polyacylamide. *Journal of Colloid and Interface Science*, Vol. 164, 1994. https://doi.org/https://doi.org/10.1006/jcis.1994.1161.

68. Qian, J. W., X. J. Xiang, W. Y. Yang, M. Wang, and B. Q. Zheng. Flocculation Performance of Different Polyacrylamide and the Relation Between Optimal Dose and Critical Concentration. *European Polymer Journal*, Vol. 40, 2004. https://doi.org/10.1016/j.eurpolymj.2004.03.009.

69. Tang, H. X., Z. K. Luan, D. S. Wang, and B. Y. Gao. Composite Inorganic Polymer Flocculants. *Chemical Water and Wastewater Treatment V*, 1998, pp. 25–34. https://doi.org/https://doi.org/10.1007/978-3-642-72279-0_3.

70. Salehizadeh, H., N. Yan, and R. Farnood. Recent Advances in Polysaccharide Bio-Based Flocculants. *Biotechnology Advances*, Vol. 36, No. 1, 2018, pp. 92–119. https://doi.org/10.1016/j.biotechadv.2017.10.002.

71. Okaiyeto, K., U. U. Nwodo, S. A. Okoli, L. V. Mabinya, and A. I. Okoh. Implications for Public Health Demands Alternatives to Inorganic and Synthetic Flocculants: Bioflocculants as Important Candidates. *Microbiology Open*, 2016. https://doi.org/10.1002/mbo3.334.

72. Harper, H. H., J. L. Herr, and E. H. Livingston. ALUM TREATMENT OF STORMWATER: THE FIRST TEN YEARS. *Journal of Water Management Modeling*, 1999. https://doi.org/10.14796/JWMM.R204-09.

73. Chatsungnoen, T., and Y. Chisti. Flocculation and Electroflocculation for Algal Biomass Recovery. In *Biofuels from Algae*, Elsevier B.V., pp. 257–286.

74. Wakema, J. R., and S. Tarleton. Pretreatment of Suspensions. In *Solid/Liquid Seperation Equipment Selection and Process Design*, Elsevier Science, pp. 126–151.

75. Salehizadeh, H., N. Yan, and R. Farnood. Recent Advances in Polysaccharide Bio-Based Flocculants. *Biotechnology Advances*. 1. Volume 36, 92–119.

76. Zeng, D., J. Wu, and J. F. Kennedy. Application of a Chitosan Flocculant to Water Treatment. *Carbohydrate Polymers*, Vol. 71, No. 1, 2008, pp. 135–139. https://doi.org/10.1016/j.carbpol.2007.07.039.

77. Kangama, A., D. Zeng, X. Tian, and J. Fang. Application of Chitosan Composite Flocculant in Tap Water Treatment. *Journal of Chemistry*, Vol. 2018, 2018. https://doi.org/10.1155/2018/2768474.

78. Yang, R., H. Li, M. Huang, H. Yang, and A. Li. A Review on Chitosan-Based Flocculants and Their Applications in Water Treatment. *Water Research*. Volume 95, 59–89.

79. Tan, S., K. Saito, and M. T. Hearn. Stimuli-Responsive Polymeric Materials for Separation of Biomolecules. *Current Opinion in Biotechnology*. Volume 53, 209–223.

80. Harper, H. H., J. L. Herr, and E. H. Livingston. Alum Treatment of Stormwater: The First Ten Years. *New Applications in Modeling Urban Water Systems – Monograph 7*, 1999.

81. Przepiora, A., D. Hesterberg, J. E. Parsons, J. W. Gilliam, D. K. Cassel, and W. Faircloth. Field Evaluation of Calcium Sulfate as a Chemical Flocculant for Sedimentation Basins. *Journal of Environmental Quality*, Vol. 27, No. 3, 1998, pp. 669–678. https://doi.org/10.2134/jeq1998.00472425002700030026x.

82. Przepiora, A., D. Hesterberg, J. E. Parsons, J. W. Gilliam, D. K. Cassel, and W. Faircloth. Calcium Sulfate as a Flocculant to Reduce Sedimentation Basin Water

Turbidity. *Journal of Environmental Quality*, Vol. 26, No. 6, 1997, pp. 1605–1611. https://doi.org/10.2134/jeq1997.00472425002600060021x.

83. A. K. Bhardwaj, and R. A. McLaughlin. Simple Polyacrylamide Dosing Systems for Turbidity Reduction in Stilling Basins. *Transactions of the ASABE*, Vol. 51, No. 5, 2008, pp. 1653–1662. https://doi.org/10.13031/2013.25324.

84. Mclaughlin, R. A., and A. Zimmerman. Best Management Practices for Chemical Treatment Systems for Construction Stormwater and Dewatering. *Federal Highway Administration U.S. Department of Transportation*, No. October, 2008, p. 12.

85. ProTech General Contracting Services Inc. *Polymer Coagulants and Flocculants for Stormwater Applications*. 2004.

86. Alabama Department of Transportation. *Alabama Department of Transportation - Section 672 - Stormwater Turbidity Control*. Montgomery, AL, 2013.

87. Cirtex Industries LTD. Large Floc Shed: Assembly + Maintenance Guide. *Cirtex Industries LTD*.

88. Kang, J., and R. A. McLaughlin. Simple Systems for Treating Pumped, Turbid Water with Flocculants and a Geotextile Dewatering Bag. *Journal of Environmental Management*, Vol. 182, 2016, pp. 208–213. https://doi.org/10.1016/j.jenvman.2016.07.071.

89. Lentz, R. D., and R. E. Sojka. Field Results Using Polyacrylamide to Manage Furrow Erosion and Infiltration. *Soil Science*, Vol. 158, No. 4, 1994, pp. 274–282. https://doi.org/10.1097/00010694-199410000-00007.

90. New York State Department of Environmental Conservation. *New York State Standards and Specifications for Erosion and Sediment Control*. 2016.

91. Alabama Department of Transportation. *Temporary and Permanent Erosion and Sediment Control Products List II-24*. Montgomery, AL, 2004.

92. Alabama Department of Transportation. *Standard Best Management Practices*. Montgomery, AL, 2016.

93. Alabama Department of Transportation. *Best Management Practice*. Montgomery, AL, 2020.

94. North Carolina Department of Transportation. *Erosion and Sediment Control Design and Construction Manual*. 2013.

95. Florida Department of Transportation. *Erosion and Sediment Control Designer and Reviewer Manual*. 2017.

96. Mcfalls, J., Y.-J. Yi, B. Storey, M. Barrett, D. Lawler, B. Eck, D. Rounce, T. Cleveland, H. Murphy, D. Dalton, A. Morse, and G. Herrmann. *Performance Testing of Coagulants to Reduce Stormwater Runoff Turbidity*. 2014.

97. Rounce, D. R., D. F. Lawler, and M. E. Barrett. Reducing Turbidity of Construction Site Runoff Via Coagulation with Polyacrylamide and Chitosan. *The University of Texas at Austin*, Vol. 66, No. August, 2012, pp. 37–39.

98. California Department of Transportation. *California Department of Transportation Stormwater Quality Handbooks Project Planning and Design Guide*. 2017.

99. California Department of Transportation. *Erosion Control New Technology Report, CTSW-RT-03-049*. 2003.

100. Oregon Department of Transportation. *Erosion Control Manual: Guidelines for Developing and Implementing Erosion and Sediment Controls*. 2023.

101. Washington State Department of Transportation. *Temporary Erosion and Sediment Control Manual*. 2019.

102. Australian and New Zealand Environment and Conservation Council, and Agriculture and Resource Management Council of Australia and New Zealand. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. *National Water Quality Management Strategy*, Vol. 1, 2000, p. Chapters 1-7.

103. Kazaz, B., M. A. Perez, and W. N. Donald. State-of-the-Practice Review on the Use of Flocculants for Construction Stormwater Management in the United States. *Transportation Research Record*, Vol. 2675, No. 7, 2021, pp. 248–258. https://doi.org/10.1177/0361198121995192.

104. Colen, C. Van, F. Rossi, F. Montserrat, M. G. I. Andersson, B. Gribsholt, P. M. J. Herman, S. Degraer, M. Vincx, T. Ysebaert, and J. J. Middelburg. Organism-Sediment Interactions Govern Post-Hypoxia Recovery of Ecosystem Functioning. *PLoS ONE*, Vol. 7, No. 11, 2012. https://doi.org/10.1371/journal.pone.0049795.

105. United States Environmental Protection Agency. *National Pollutant Discharge Elimination System (NPDES) Construction General Permit (CGP) for Stormwater Discharges from Construction Activities*. Washington, DC, 2022.

106. Occupational Safety and Health Administration 1910.1200. *Occupational Safety and Health Standards - Toxic and Hazardous Substances - Safety Data Sheets (Mandatory)*. 2012.

107. Stephan, C. E. Methods for Calculating an LC. *Aquatic Toxicology and Hazard Evaluation*, 2009. https://doi.org/10.1520/stp32389s.

108. Canadian Centre for Occupational Health and Safety. Chemicals and Materials What Is a LD 50 and LC 50 ? *Canadian Centre for Occupational Health and Safety*, 2023.

109. Buczek, S. B., W. G. Cope, R. A. McLaughlin, and T. J. Kwak. Acute Toxicity of Polyacrylamide Flocculants to Early Life Stages of Freshwater Mussels. *Environmental Toxicology and Chemistry*, Vol. 36, No. 10, 2017, pp. 2715–2721. https://doi.org/10.1002/etc.3821.

110. Fort, D. J., and E. L. Stover. Impact of Toxicities and Potential Interactions of Flocculants and Coagulant Aids on Whole Effluent Toxicity Testing. *Water Environment Research*, Vol. 67, No. 6, 1995, pp. 921–925. https://doi.org/10.2175/106143095x133149.

111. Beim, A. A., and A. M. Beim. Comparative Ecological - Toxicological Data on Determination of Maximum Permissible Concentrations (Mpc) for Several Flocculants. *Environmental Technology (United Kingdom)*, Vol. 15, No. 2, 1994, pp. 195–198. https://doi.org/10.1080/09593339409385420.

112. Christofano, E. E., J. P. Frawley, O. E. Fancher, and M. L. Keplinger. The Toxicology of Modified Polyacrylamide Resin. *Toxicology and Appllied Pharmacology*, Vol. 14, 1969, p. 616.

113. Erkekoglu, P., and T. Baydar. Acrylamide Neurotoxicity. *Nutritional Neuroscience*, Vol. 17, No. 2, 2014, pp. 49–57. https://doi.org/10.1179/1476830513Y.0000000065.

114. International Programme on Chemical Safety. Environmental Health Criteria No. 49, Acrylamide. *International Programme on Chemical Safety*. http://www.inchem.org/documents/ehc/ehc/ehc49.htm.

115. King, D. J., and R. R. Noss. Toxicity of Polyacrylamide and Acrylamide Monomer. *Reviews on Environmental Health*, Vol. 8, No. 1–4, 1989, pp. 3–16. https://doi.org/10.1515/reveh-1989-1-403.

116. Liebert, M. A. Final Report on the Safety Assessment of Polyacrylamide. *Journal of the American College of Toxicology*, Vol. 10, No. 1, 1991, pp. 193–203.

117. Uthra, C., S. Shrivastava, A. Jaswal, N. Sinha, M. S. Reshi, and S. Shukla. Therapeutic Potential of Quercetin against Acrylamide Induced Toxicity in Rats. *Biomedicine and Pharmacotherapy*, Vol. 86, 2017, pp. 705–714. https://doi.org/10.1016/j.biopha.2016.12.065.

118. McCollister, D. D., C. L. Hake, S. E. Sadek, and V. K. Rowe. Toxicologic Investigations of Polyacrylamides. *Toxicology and applied pharmacology*, Vol. 7, No. 5, 1965, pp. 639–651. https://doi.org/10.1016/0041-008X(65)90119-5.

119. Seybold, C. D. Polyacrylamide Review: Soil Conditioning and Environmental Fate. *Communications in Soil Science and Plant Analysis*, Vol. 25, No. 11–12, 1994, pp. 2171–2185. https://doi.org/10.1080/00103629409369180.

120. Smith, E. A., S. L. Prues, and F. W. Oehme. Environmental Degradation of Polyacrylamides. II. Effects of Environmental (Outdoor) Exposure. *Ecotoxicology and Environmental Safety*, Vol. 37, No. 1, 1997, pp. 76–91. https://doi.org/10.1006/eesa.1997.1527.

121. Caulfield, M. J., X. Hao, G. G. Qiao, and D. H. Solomon. Degradation on Polyacrylamides. Part I. Linear Polyacrylamide. *Polymer*, Vol. 44, No. 5, 2003, pp. 1331–1337. https://doi.org/10.1016/S0032-3861(03)00003-X.

122. Kazaz, B. *Improvements in Construction Stormwater Treatment Using Flocculants*. 2022.

123. Guezennec, A. G., C. Michel, K. Bru, S. Touze, N. Desroche, I. Mnif, and M. Motelica-Heino. Transfer and Degradation of Polyacrylamide-Based Flocculants in Hydrosystems: A Review. *Environmental Science and Pollution Research*, Vol. 22, No. 9, 2015, pp. 6390–6406. https://doi.org/10.1007/s11356-014-3556-6.

124. Carere, A. Genotoxicity and Carcinogenicity of Acrylamide: A Critical Review. *Annali dell'Istituto Superiore di Sanita*, Vol. 42, No. 2, 2006, pp. 144–155.

125. Besaratinia, A., and G. P. Pfeifer. A Review of Mechanisms of Acrylamide Carcinogenicity. *Carcinogenesis*, Vol. 28, No. 3, 2007, pp. 519–528. https://doi.org/10.1093/carcin/bgm006.

126. United States Environmental Protection Agency. *National Primary Drinking Water Regulations*. Washington, DC, 2023.

127. Sojka, R. E., and R. D. Lentz. PAM in Furrow Irrigation, an Erosion Control Breakthrough. *First European Conference & Trade Exposition on Erosion Control*, Vol. 1, 1996, pp. 183–189.

128. Touzé, S., V. Guerin, A. G. Guezennec, S. Binet, and A. Togola. Dissemination of Acrylamide Monomer from Polyacrylamide-Based Flocculant Use—Sand and Gravel Quarry Case Study. *Environmental Science and Pollution Research*, Vol. 22, No. 9, 2015, pp. 6423–6430. https://doi.org/10.1007/s11356-014-3177-0.

129. Code of Federal Regulations. Electronic Code of Federal Regulations. *Code of Federal Regulations*. https://www.ecfr.gov/.

130. Aguilar, M. I., J. Sáez, M. Lloréns, A. Soler, J. F. Ortuño, V. Meseguer, and A. Fuentes. Improvement of Coagulation-Flocculation Process Using Anionic Polyacrylamide as Coagulant Aid. *Chemosphere*, Vol. 58, No. 1, 2005, pp. 47–56. https://doi.org/10.1016/j.chemosphere.2004.09.008.

131. Mikulec, J., G. Polakovičová, and J. Cvengroš. Flocculation Using Polyacrylamide Polymers for Fresh Microalgae. *Chemical Engineering and Technology*, Vol. 38, No. 4, 2015, pp. 595–601. https://doi.org/10.1002/ceat.201400639.

132. Glover, S. M., Y. de Yan, G. J. Jameson, and S. Biggs. Dewatering Properties of Dual-Polymer-Flocculated Systems. *International Journal of Mineral Processing*, Vol. 73, No. 2–4, 2004, pp. 145–160. https://doi.org/10.1016/S0301-7516(03)00070-X.

133. Howard, P. H., S. J. Bosch, and S. S. Lande. Degradation and Leaching of Acrylamide in Soil. *ACS Division of Environmental Chemistry, Preprints*, Vol. 18, No. 2, 1978. https://doi.org/10.2134/jeq1979.00472425000800010029x.

134. Kay-Shoemake, J. L., M. E. Watwood, R. D. Lentz, and R. E. Sojka. Polyacrylamide as an Organic Nitrogen Source for Soil Microorganisms with Potential Effects on Inorganic Soil Nitrogen in Agricultural Soil. *Soil Biology and Biochemistry*, Vol. 30, No. 8–9, 1998, pp. 1045–1052. https://doi.org/10.1016/S0038-0717(97)00250-2.

135. Shanker, R., C. Ramakrishna, and P. K. Seth. Microbial Degradation of Acrylamide Monomer. *Archives of Microbiology*, Vol. 154, No. 2, 1990, pp. 192–198. https://doi.org/10.1007/BF00423332.

136. Shukor, M. Y., N. Gusmanizar, N. A. Azmi, M. Hamid, J. Ramli, N. A. Shamaan, and M. A. Syed. Isolation and Characterization of an Acrylamide-Degrading Bacillus Cereus. *Journal of Environmental Biology*, Vol. 30, No. 1, 2009, pp. 57–64.

137. K.Labahn, S., J. C. Fisher, E. A. Robleto, M. H. Young, and D. P. Moser. Microbially Mediated Aerobic and Anaerobic Degradation of Acrylamide in a Western United States Irrigation Canal. *Journal of Environmental Quality*, Vol. 39, No. 5, 2010, pp. 1563–1569. https://doi.org/10.2134/jeq2009.0318.

138. Kang, J., T. D. Sowers, O. W. Duckworth, A. Amoozegar, J. L. Heitman, and R. A. McLaughlin. Turbidimetric Determination of Anionic Polyacrylamide in Low Carbon Soil Extracts. *Journal of Environmental Quality*, Vol. 42, No. 6, 2013, pp. 1902–1907. https://doi.org/10.2134/jeq2013.07.0279.

139. Jung, J., J. Jang, and J. Ahn. Characterization of a Polyacrylamide Solution Used for Remediation of Petroleum Contaminated Soils. *Materials*, Vol. 9, No. 1, 2016, pp. 1–13. https://doi.org/10.3390/ma9010016.

140. Li, B., J. Zhang, F. Bu, and W. Xia. Determination of Chitosan with a Modified Acid Hydrolysis and HPLC Method. *Carbohydrate Research*, Vol. 366, 2013, pp. 50–54. https://doi.org/10.1016/j.carres.2012.11.005.

141. Miao, Q., Y. Cui, J. Zhang, Y. Mi, W. Tan, Q. Li, G. Gu, F. Dong, and Z. Guo. Determination of Chitosan Content with Ratio Coefficient Method and HPLC. *International Journal of Biological Macromolecules*, Vol. 164, 2020, pp. 384–388. https://doi.org/10.1016/j.ijbiomac.2020.07.013.

142. Badawy, M. E. I. A New Rapid and Sensitive Spectrophotometric Method for Determination of a Biopolymer Chitosan. *International Journal of Carbohydrate Chemistry*, Vol. 2012, 2012, pp. 1–7. https://doi.org/10.1155/2012/139328.

143. ASTM International D2035-19. *Standard Practice for Coagulation-Flocculation Jar Test of Water*. 2008.

144. Dente, S. K., B. M. Gucciardi, N. Griskowitz, L. L. Chang, and D. L. Raudenbush. Chemistry . Function , and Fate of Acrylamide-Based. *Chemical Water and Wastewater Treatment VI*, 2000, pp. 1–2.

145. ASTM International D3977-97. Standard Test Methods for Determining Sediment Concentration in Water Samples. *American Society for Testing and Materials International*, 1997.

146. Davies-Colley, R. J., and D. G. Smith. Turbidity, Suspended Sediment, and Water Clarity: A Review. *Journal of the American Water Resources Association*, Vol. 37, No. 5, 2001, pp. 1085–1101. https://doi.org/10.1111/j.1752-1688.2001.tb03624.x.

147. Reinke, E. A. Water Quality and Treatment. *American Journal of Public Health*, 1951.

148. Tyler, J. E. The Secchi Disk. *Limnology and Oceanography*, Vol. 13, No. 1, 1968, pp. 1–6. https://doi.org/10.4319/lo.1968.13.1.0001.

149. Fisher Scientific Inc. *United Scientific Supplies Secchi Disktle*. 2022.

150. Fisher Scientific Inc. *GSC Turbidity Tube*. 2022.

151. Hach Inc. TL23 Series Laboratory Turbidimeter. *Hach Inc.* https://www.hach.com/turbidimeters/tl23-series-laboratory-turbidimeters/family?productCategoryId=50908490523. Accessed May 5, 2022.

152. Hach Inc. 2100Q Portable Turbidimeter. *Hach Inc.* https://www.hach.com/turbidimeters/2100q-portable-turbidimeter/family?productCategoryId=35547372710. Accessed Mar. 5, 2022.

153. ASTM International D5907-18. Standard Test Methods for Filterable Matter (Total Dissolved Solids) and Nonfilterable Matter (Total Suspended Solids) in Water. *American Society for Testing and Materials International*, 2018. https://doi.org/10.1520/D5907-18.

154. Covington, A. K., R. G. Bates, and R. A. Durst. Definition of PH Scales, Standard Reference Values, Measurement of PH and Related Terminology (Recommendations 1984). *Pure & Applied Chemistry*, Vol. 57, No. 3, 1985, pp. 531–542. https://doi.org/10.1351/pac198557030531.

155. United States Environmental Protection Agency. *National Water Quality Inventory: Report to Congress EPA 841-R-16-011*. Washington, DC, 2017.

156. Grainger Supply Inc. Ricca Chemical PH Test Strips: 2 to 9 PH. *Grainger Supply Inc.*, 2022.

157. Fisher Scientific Inc. *FisherbrandTM AccumetTM AE150 Benchtop PH Meter*. 2022.

158. Hach Inc. Pocket Pro PH Tester. *Hach Inc.* https://www.hach.com/pocket-pro-ph-tester/product?id=17990686202. Accessed Mar. 7, 2022.

159. Fisher Scientific Inc. *Thermo ScientificTM OrionTM Standard All-in-OneTM PH Buffer Kit*. 2022.

160. Shin, S., and Y. I. Cho. Temperature Effect on the Non-Newtonian Viscosity of an Aqueous Polyacrylamide Solution. *International Communications in Heat and Mass Transfer*, Vol. 20, No. 6, 1993, pp. 831–844.

161. Bjorneberg, D. L. Temperature, Concentration, and Pumping Effects on PAM Viscosity. *American Society of Agricultural Engineers*, Vol. 41, No. 208, 2013, pp. 1651–1655.

162. Narkis, N., and M. Rebhun. Ageing Effects in Measurements of Polyacrylamide Solution Viscosities. *Polymer*, Vol. 7, No. 10, 1966, pp. 507–512. https://doi.org/10.1016/0032-3861(66)90032-2.

163. Fitzpatrick, C. S. B., E. Fradin, and J. Gregory. Temperature Effects on Flocculation, Using Different Coagulants. *Water Science and Technology*, Vol. 50, No. 12, 2004, pp. 171–175. https://doi.org/10.2166/wst.2004.0710.

164. Vold, M. J. Computer Simulation of Floc Formation in a Colloidal Suspension. *Journal of Colloid Science*, Vol. 18, No. 7, 1963, pp. 684–695. https://doi.org/10.1016/0095-8522(63)90061-8.

165. Swift, T., L. Swanson, A. Bretherick, and S. Rimmer. Measuring Poly(Acrylamide) Flocculants in Fresh Water Using Inter-Polymer Complex Formation. *Environmental Science: Water Research and Technology*, Vol. 1, No. 3, 2015, pp. 332–340. https://doi.org/10.1039/c4ew00092g.

166. Parsapour, G. A., M. Hossininasab, M. Yahyaei, and S. Banisi. Effect of Settling Test Procedure on Sizing Thickeners. *Separation and Purification Technology*, Vol. 122, 2014, pp. 87–95. https://doi.org/10.1016/j.seppur.2013.11.001.

167. Kajihara, M. Settling Velocity and Porosity of Large Suspended Particle. *Journal of the Oceanographical Society of Japan*, Vol. 27, No. 4, 1971, pp. 158–162. https://doi.org/10.1007/BF02109135.

168. Hunter, R. J. *Foundations of Colloid Science*. Oxford, UK, 1986.

169. Singh, R., and R. Adhikari. Generalized Stokes Laws for Active Colloids and Their Applications. *Journal of Physics Communications*, Vol. 2, No. 2, 2018. https://doi.org/10.1088/2399-6528/aaab0d.

170. Connecticut Department of Environmental Protection. *Connecticut Stormwater Quality Manual*. Newington, CT, 2004.

171. Department of Energy and Environment. *District of Columbia Erosion and Sediment Control Manual*. Washington, DC, 2017.

172. Alaska Department of Transportation & Public Facilities. *Alaska Department of Transportation Construction General Permit*. Juneau, AK, 2022.

173. Illinois Department of Transportation. *Erosion and Sediment Control Field Guide for Construction Inspections*. 2010.

174. West Virginia Department of Transportation. *Erosion and Sediment Control Manual*. 2003.

175. Rhode Island SCC. Rhode Island Soil Erosion and Sediment Control Handbook. *Rhode Island State Conservation Committee*, 2016.

176. Cannon Instrument Company. CANNON-FENSKE ROUTINE VISCOMETER. *Cannon Instrument Company*. https://cannoninstrument.com/manual-glass-viscometers/cannon-fenske-routine-viscometer.html.

177. Cannon Instrument Company. Calculation of Viscometer Constants for Cannon-Fenske Routine and Cannon-Fenske Opaque Viscometers (Tech Brief 101). *Cannon Instrument Company*. https://cannoninstrument.com/pub/media/assets/product/documents/Whitepapers/GENERAL VISCOSITY/Calculation of Viscometer Constants for Cannon-Fenske Routine and Cannon-Fenske Opaque Viscometers (Tech Brief 101) .pdf.

178. ASTM International D446-12. *Standard Specifications and Operating Instructions for Glass Capillary Kinematic Viscometers*. 2009.

179. ASTM International D789-19. *Standard Test Method for Determination of Relative Viscosity of Concentrated Polyamide (PA) Solutions*. 2008.

180. Brookfield Engineering Laboratoried, Inc. Brookfield Dial Reading Viscometer Brookfield Digital Viscometer Model DV-I (Operating Instructions). *LabWrench*. https://photos.labwrench.com/equipmentManuals/4807-1512.pdf.

181. Brookfield. Brookfield Dial Viscometer (Operating Instructions). *Brookfield Engineering Laboratories, Inc.*, 2014.

182. Chmtrac Systems Inc. Laboratory Charge Analyzer (Operations Manual - Models: LCA-1, LCA-2, LCA-2). *Chmtrac Systems Inc.* 28. https://chemtrac.com/downloads-3/.

183. Bhatia, S. K., M. M. Khachan, A. M. Stallings, and J. L. Smith. Alternatives for the Detection of Residual Polyacrylamide in Geotextile Tube Dewatering-Streaming Current Detection and China Clay Settling Rate Methods. *Geotechnical Testing Journal*, Vol. 37, No. 4, 2014. https://doi.org/10.1520/GTJ20130162.

184. Bachand, P. A. M., S. M. Bachand, S. E. Lopus, A. Heyvaert, and I. Werner. *Treatment with Chemical Coagulants at Different Dosing Levels Changes Ecotoxicity of Stormwater from the Tahoe Basin, California, USA*. 2010.

185. Bhatia, S. K., M. M. Khachan, A. M. Stallings, and J. L. Smith. Alternatives for the Detection of Residual Polyacrylamide in Geotextile Tube Dewatering-Streaming Current Detection and China Clay Settling Rate Methods. *Geotechnical Testing Journal*, Vol. 37, No. 4, 2014. https://doi.org/10.1520/GTJ20130162.

186. Muzi Sibiya, S. Evaluation of the Streaming Current Detector (SCD) for Coagulation Control. *Procedia Engineering*, Vol. 70, 2014, pp. 1211–1220. https://doi.org/10.1016/j.proeng.2014.02.134.

187. Xylem. What Is the PH of Water and How Is PH Measured? What Does PH Measure? *YSI*. https://www.ysi.com/parameters/ph.

188. Mainland Macinery. Dry Flocculant Mixing and Feeding Design Considerations. *In Equipment, Informative, Manufacturing, Mining*. https://mainlandmachinery.com/dry-flocculant-mixing-feeding/.

189. WATERTECH of America Inc. Polymer Flocculants in Detail. *WATERTECH of America Inc*. https://www.watertechusa.com/Polymer-Flocculants-in-Detail.

190. Mitchell, C. C. Natural Resources Conservation Services Soil Areas in Alabama. *The United States Department of Agriculture*, 2008.

191. Olmstead, L. B., L. T. Alexander, and H. E. Middleton. A Pipette Method of Mechanical Analysis of Soils Base on Improved Dispersion Procedure. *United States Department of Agriculture*, 1930.

192. ASTM International D4318-17. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *American Society for Testing and Materials International*, 2018. https://doi.org/10.1520/D4318-17E01.

193. ASTM International D6913/D6913M-17. Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. *American Society for Testing and Materials International*, 2017. https://doi.org/10.1520/D6913_D6913M-17.

194. ASTM International D7928-21. Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. *American Society for Testing and Materials International*, 2021. https://doi.org/10.1520/D7928-21E01.

195. United States Environmental Protection Agency, and Natural Resources Conservation Service. Geospatial Data Gateway. https://gdg.sc.egov.usda.gov/.

196. *Standard Practice for Coagulation-Flocculation Jar Test of Water*. American Society for Testing and Materials, ASTM D2035-19, 2019.

197. Shaw, J. N., B. F. Hajek, and J. M. Beck. Highly Weathered Mineralogy of Select Soils from Southeastern U.S. Coastal Plain and Piedmont Landscapes. *Geoderma*, Vol. 154, No. 3–4, 2010, pp. 447–456. https://doi.org/10.1016/j.geoderma.2009.01.019.

198. Brown, P. M., D. A. Stanley, and B. J. Scheiner. An Explanation of Flocculation Using Lewis Acid-Base Theory. *Mining, Metallurgy & Exploration*, Vol. 6, 1989, pp. 196–200. https://doi.org/https://doi.org/10.1007/BF03403463.

199. Jensen, W. B. The Lewis Acid-Base Definitions: A Status Report. *American Chemical Society*, Vol. 78, No. 1, 1978.

200. Schussler, J. C. *Improvements in Stormwater Detention Technologies through Large-Scale Testing*. Doctoral Dissertation. Auburn University, 2022.

201. Menter, P. Electrophoretic Mobility Shift Assay (EMSA) Technical Bulletin. Acrylamide Polymerization - A Practical Approach (Tech Note 1156). *Bio-Rad Laboratories*, 2012.

202. Syed, S., A. Karadaghy, and S. Zustiak. Simple Polyacrylamide-Based Multiwell Stiffness Assay for the Study of Stiffness-Dependent Cell Responses. *Journal of Visualized Experiments*, Vol. 2015, No. 97, 2015. https://doi.org/10.3791/52643.

203. Al-Hashmi, A. R., and P. F. Luckham. Characterization of the Adsorption of High Molecular Weight Non-Ionic and Cationic Polyacrylamide on Glass from Aqueous Solutions Using Modified Atomic Force Microscopy. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 1–3. Volume 358, 142–148.

204. Hench, L. L., and J. Wilson. Surface-Active Biomaterials. *Science*, Vol. 226, No. 4675, 1984, pp. 630–636. https://doi.org/10.1126/science.6093253.

205. Butler, T. O., K. Acurio, J. Mukherjee, M. M. Dangasuk, O. Corona, and S. Vaidyanathan. The Transition Away from Chemical Flocculants: Commercially Viable Harvesting of Phaeodactylum Tricornutum. *Separation and Purification Technology*, Vol. 255, No. April 2020, 2021, p. 117733. https://doi.org/10.1016/j.seppur.2020.117733.

206. Labeeuw, L., A. S. Commault, U. Kuzhiumparambil, B. Emmerton, L. N. Nguyen, L. D. Nghiem, and P. J. Ralph. A Comprehensive Analysis of an Effective Flocculation Method for High Quality Microalgal Biomass Harvesting. *Science of the Total Environment*, Vol. 752, 2021, p. 141708. https://doi.org/10.1016/j.scitotenv.2020.141708.

207. Pérez, L., J. L. Salgueiro, R. Maceiras, Á. Cancela, and Á. Sánchez. Study of Influence of PH and Salinity on Combined Flocculation of Chaetoceros Gracilis Microalgae. *Chemical Engineering Journal*, Vol. 286, 2016, pp. 106–113. https://doi.org/10.1016/j.cej.2015.10.059.

208. Roselet, F., D. Vandamme, M. Roselet, K. Muylaert, and P. C. Abreu. Effects of PH, Salinity, Biomass Concentration, and Algal Organic Matter on Flocculant Efficiency of Synthetic Versus Natural Polymers for Harvesting Microalgae Biomass. *Bioenergy Research*, Vol. 10, No. 2, 2017, pp. 427–437. https://doi.org/10.1007/s12155-016-9806-3.

209. Roselet, F., D. Vandamme, M. Roselet, K. Muylaert, and P. C. Abreu. Screening of Commercial Natural and Synthetic Cationic Polymers for Flocculation of Freshwater and Marine Microalgae and Effects of Molecular Weight and Charge Density. *Algal Research*, Vol. 10, No. 1, 2015, pp. 183–188. https://doi.org/10.1016/j.algal.2015.05.008.

210. Forbes, E. Shear, Selective and Temperature Responsive Flocculation: A Comparison of Fine Particle Flotation Techniques. *International Journal of Mineral Processing*, Vol. 99, No. 1–4, 2011, pp. 1–10. https://doi.org/10.1016/j.minpro.2011.02.001.

211. O’Shea, J. P., G. G. Qiao, and G. V. Franks. Solid-Liquid Separations with a Temperature-Responsive Polymeric Flocculant: Effect of Temperature and Molecular Weight on Polymer Adsorption and Deposition. *Journal of Colloid and Interface Science*, Vol. 348, No. 1, 2010, pp. 9–23. https://doi.org/10.1016/j.jcis.2010.04.063.

212. North Carolina Department of Transportation. Erosion and Sediment Control Design and Construction Manual. *North Carolina Department of Transportation*. https://connect.ncdot.gov/resources/roadside/SoilWaterDocuments/Erosion and Sediment Control Design and Construction Manual_Rev20220519.pdf.

213. Carolina Hydrologic, L. *H30 PAM Safety Data Sheet*. 2019.

214. Beim, A. A., and A. M. Beim. Comparative Ecological - Toxicological Data on Determination of Maximum Permissible Concentrations (Mpc) for Several Flocculants. *Environmental Technology (United Kingdom)*, Vol. 15, No. 2, 1994, pp. 195–198. https://doi.org/10.1080/09593339409385420.

APPENDIX A
SOIL ASSEMENT REPORTS

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/16/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	NHF 0158 (502)
ALDOT District	Southeast District
Project Location	Mobile, AL
Sample Collection Date	November 13th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	WaB
Sampling Location	30.807088,-88.227599

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS

Map Unit Name	WaB - Wadley loamy fine sand, 0 to 5 percent slopes
Percent of AOI	13.1% (98.7 ac)
Parent material name	Sandy and loamy marine deposits derived from sedimentary rock
Surface texture	Loamy fine sand
K-factor	0.17
AASHTO Classification	A-2-4
USCS Classification	SM

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☐ - Hydrometer	**Date**	01/27/2020
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.12	**C_u**	3.17	**PL**	0
D_{30} (mm)	0.26	**C_c**	1.48	**I_p**	17
D_{60} (mm)	0.38	**LL**	17	**Group Index**	0

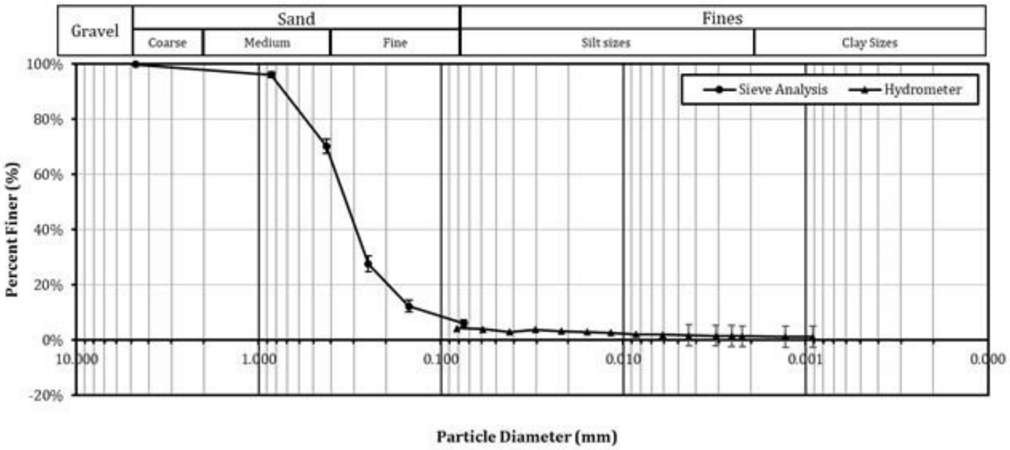


Figure 3- Particle Size Distribution Curve

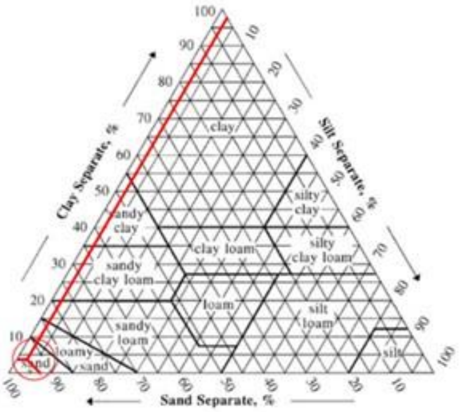
Soil Classification

% sand	93.90	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	3.10	**USCS**	**SP-SC** Poorly graded sand with clay
% clay	3.00		

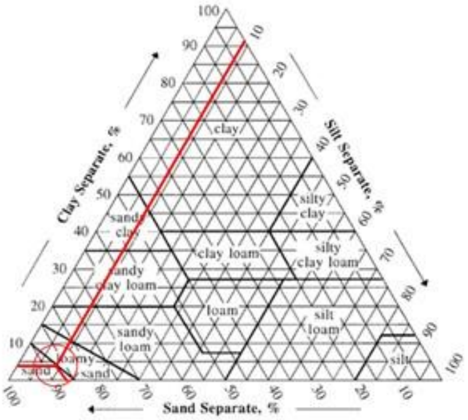
Pipette Testing (PSA) Results

% sand	86.61	**Texture Class**	Sand
%silt	8.76		
% clay	4.65		

USDA Texture Triangles



(a) PSD & Hydrometer Method



(b) Pipette (PSA)method

SOIL CHEMISTRY

Ca (ppm) Calcium	171	**K (ppm)** Potassium	37	**Mg (ppm)** Magnesium	33
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	259	**B (ppm)** Boron	0.2
Cu (ppm) Copper	1.3	**Fe (ppm)** Iron	30	**Mn (ppm)** Manganese	27
Na (ppm) Sodium	41	**Zn (ppm)** Zinc	1.8	**CEC (meq/100 g)** Cation Exchange Capacity	3.32

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/17/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	NHF 0158 (508)
ALDOT District	Southeast District
Project Location	Mobile, AL
Sample Collection Date	November 13th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	MaD
Sampling Location	30.801167,-88.273740

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	MaD – Malbis fine sandy loam, 2 to 5 percent slopes
Percent of AOI	0.3% (2.6 ac)
Parent material name	Fine-loamy marine deposits derived from sedimentary rock
Surface texture	Fine sandy loam
K-factor	0.2
AASHTO Classification	A-4
USCS Classification	SC

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☐ - Hydrometer	**Date**	02/20/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.07	**C_u**	3.69	**PL**	0
D_{30} (mm)	0.13	**C_c**	1.08	**I_p**	19
D_{60} (mm)	0.24	**LL**	19	**Group Index**	0

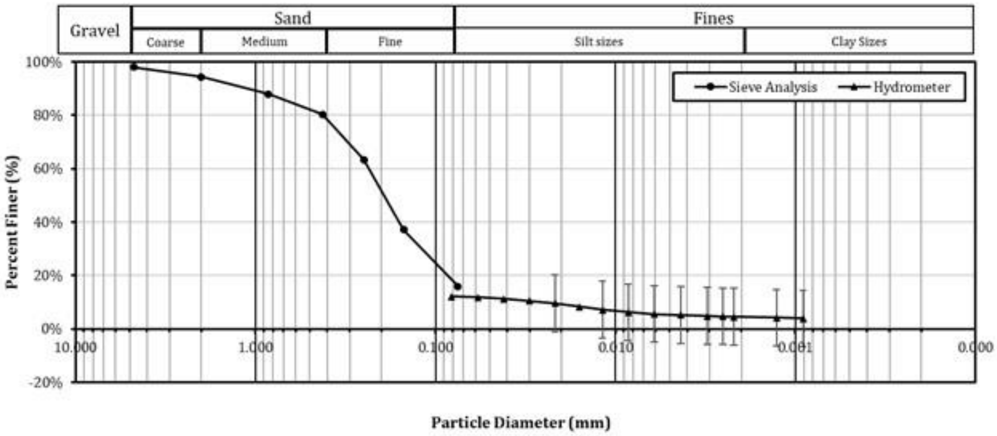


Figure 3- Particle Size Distribution Curve

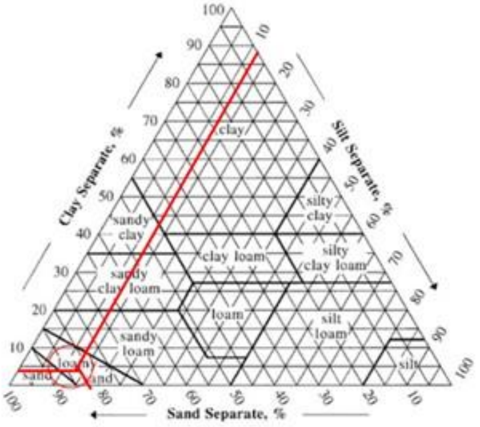
Soil Classification

% sand	82.10	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	11.70	**USCS**	**SC** Clayey sand
% clay	4.20		

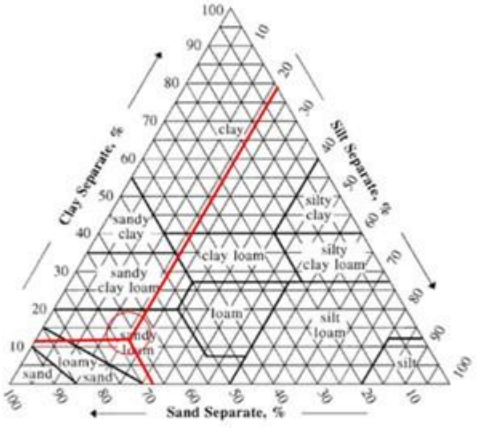
Pipette Testing (PSA) Results

% sand	67.11	**Texture Class**	Sandy Loam
%silt	21.91		
% clay	10.98		

USDA Texture Triangles



(a) PSD & Hydrometer Method



(b) Pipette (PSA)method

SOIL CHEMISTRY

Ca (ppm) Calcium	69	**K (ppm)** Potassium	23	**Mg (ppm)** Magnesium	22
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	412	**B (ppm)** Boron	0.2
Cu (ppm) Copper	1.6	**Fe (ppm)** Iron	30	**Mn (ppm)** Manganese	14
Na (ppm) Sodium	42	**Zn (ppm)** Zinc	0.5	**CEC (meq/100 g)** Cation Exchange Capacity	2.45

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/20/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	NHF 0158 (508)
ALDOT District	Southeast District
Project Location	Mobile, AL
Sample Collection Date	November 13th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	BeB
Sampling Location	30.804303, -88.253509

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	BeB- Benndale fine sandy loam, 2 to 5 percent slopes
Percent of AOI	4.6 % (35.1 ac)
Parent material name	Coarse-loamy fluviomarine deposits derived from sedimentary rock
Surface texture	Fine Sandy Loam
K-factor	0.28
AASHTO Classification	A-4
USCS Classification	SC-SM

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☐ - Hydrometer	**Date**	03/20/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.018	**C_u**	13.33	**PL**	0
D_{30} (mm)	0.095	**C_c**	2.09	**I_p**	15
D_{60} (mm)	0.24	**LL**	15	**Group Index**	0

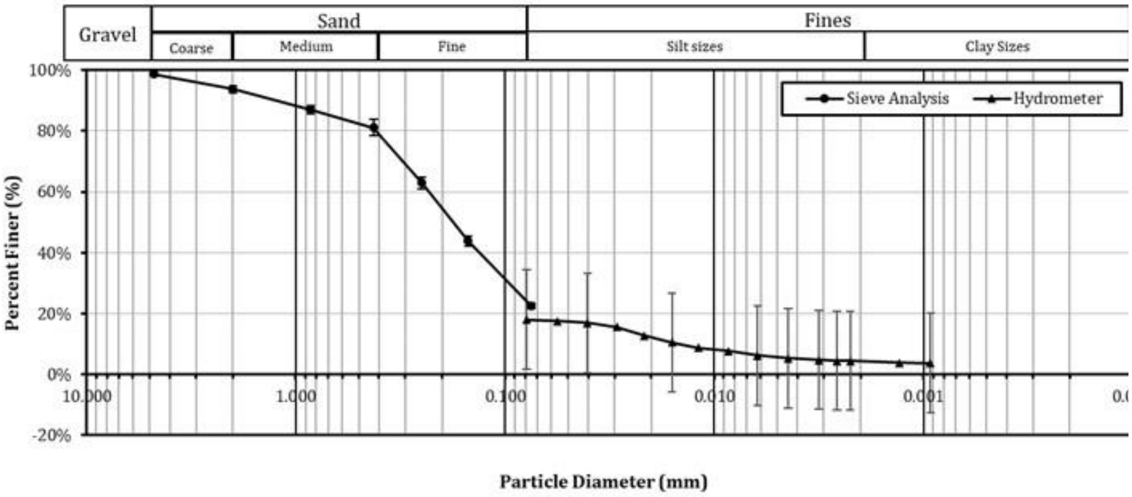


Figure 3- Particle Size Distribution Curve

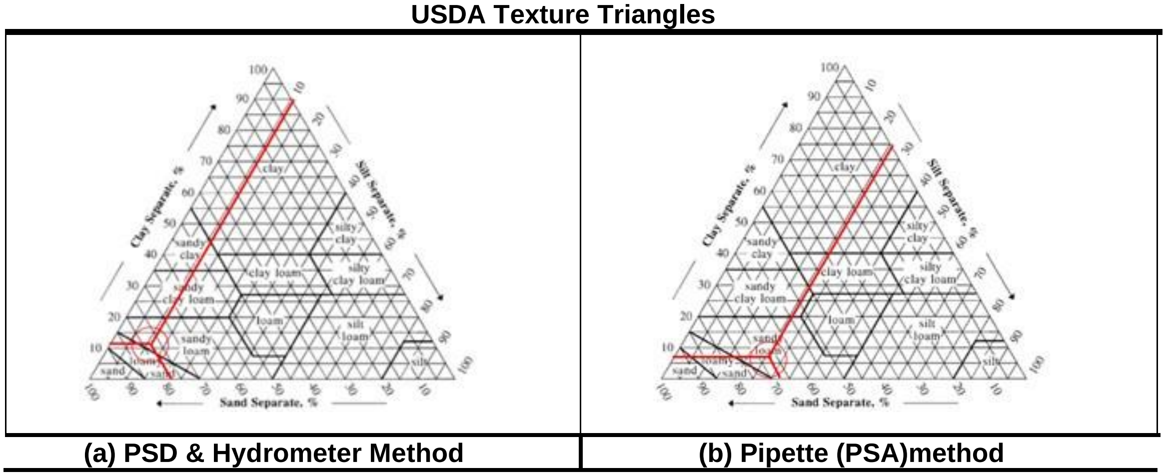
Soil Classification

% sand	77.60	**AASHTO**	**A-2-4** Silty or clayey gravel and sand
%silt	10.30	**USCS**	**SC** Clayey sand
% clay	12.10		

Pipette Testing (PSA) Results

% sand	65.30	**Texture Class**	Sandy Loam
%silt	26.73		
% clay	7.97		

USDA Texture Triangles



(a) PSD & Hydrometer Method

(b) Pipette (PSA)method

SOIL CHEMISTRY					
Ca (ppm) Calcium	324	**K (ppm)** Potassium	22	**Mg (ppm)** Magnesium	32
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	254	**B (ppm)** Boron	0.2
Cu (ppm) Copper	1.3	**Fe (ppm)** Iron	44	**Mn (ppm)** Manganese	9
Na (ppm) Sodium	42	**Zn (ppm)** Zinc	0.5	**CEC (meq/100 g)** Cation Exchange Capacity	4.12

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 04/27/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION

Project ID	RAEDAA-002(556)
ALDOT District	North District
Project Location	Etowah, AL
Sample Collection Date	March 12th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	9
Sampling Location	34.136294,-85.846311

Figure 1- Soil Sample

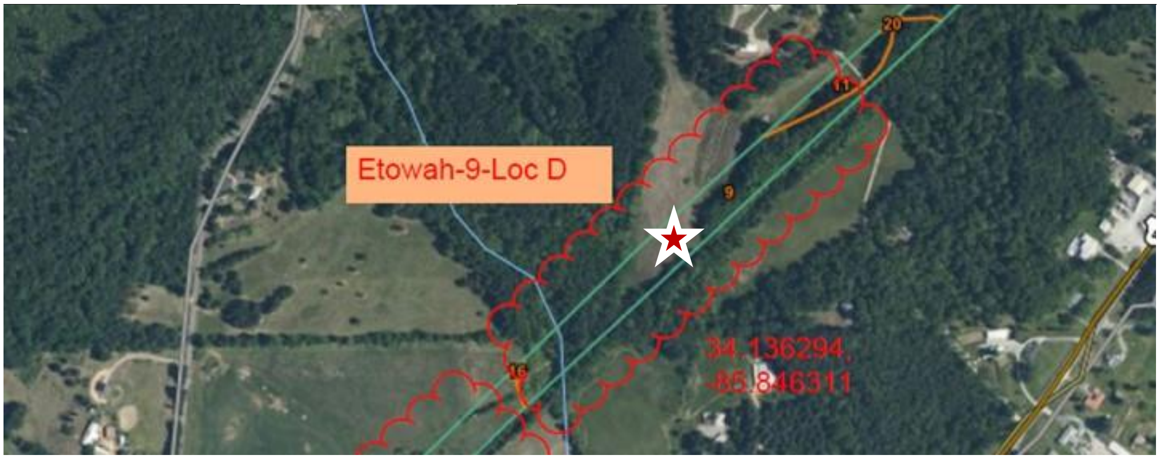


Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS

Map Unit Name	9 – Chewacla silt loam,
Percent of AOI	7.4% (7.4 ac)
Parent material name	Loamy alluvium derived from sedimentary rock
Surface texture	Fine-loamy, mixed, active, thermic, fluvaquentic dystrudepts
K-factor	0.28
AASHTO Classification	A-4
USCS Classification	ML

SOIL ANALYSIS

Testing method	• Dry and Wet sieve analysis • Atterberg limit test LL ☒ PL ✖ ☐ • Hydrometer	**Date**	4/10/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.001	**C_u**	222.22	**PL**	19
D_{30} (mm)	0.028	**C_c**	4.36	**I_p**	7
D_{60} (mm)	0.20	**LL**	26	**Group Index**	0

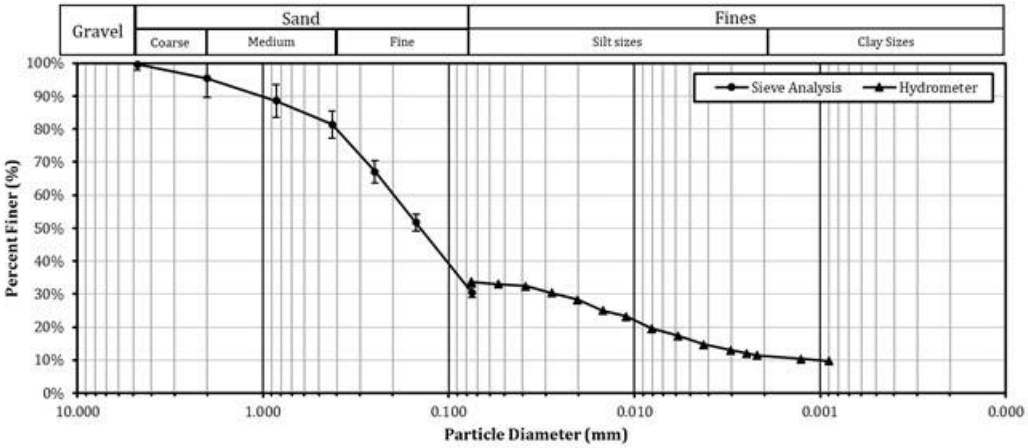
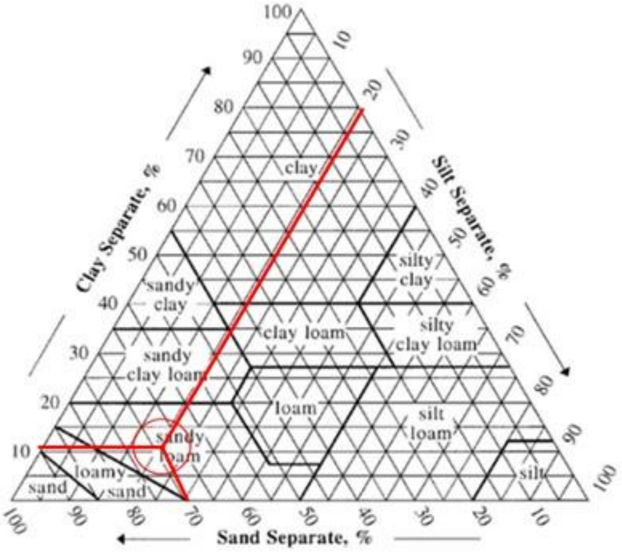


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	69.50	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
a-	20.10	**USCS**	**SC-SM** Silty clays; clayey silts and sands
% clay	10.40		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	294	**K (ppm)** Potassium	16	**Mg (ppm)** Magnesium	21
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	197	**B (ppm)** Boron	0.1
Cu (ppm) Copper	1.9	**Fe (ppm)** Iron	26	**Mn (ppm)** Manganese	89
Na (ppm) Sodium	45	**Zn (ppm)** Zinc	2.0	**CEC (meq/100 g)** Cation Exchange Capacity	4.43

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 05/10/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	RAEDAA-002(556)
ALDOT District	North District
Project Location	Etowah, AL
Sample Collection Date	March 12th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	18
Sampling Location	34.123568, -85.860645

Figure 1- Soil Sample

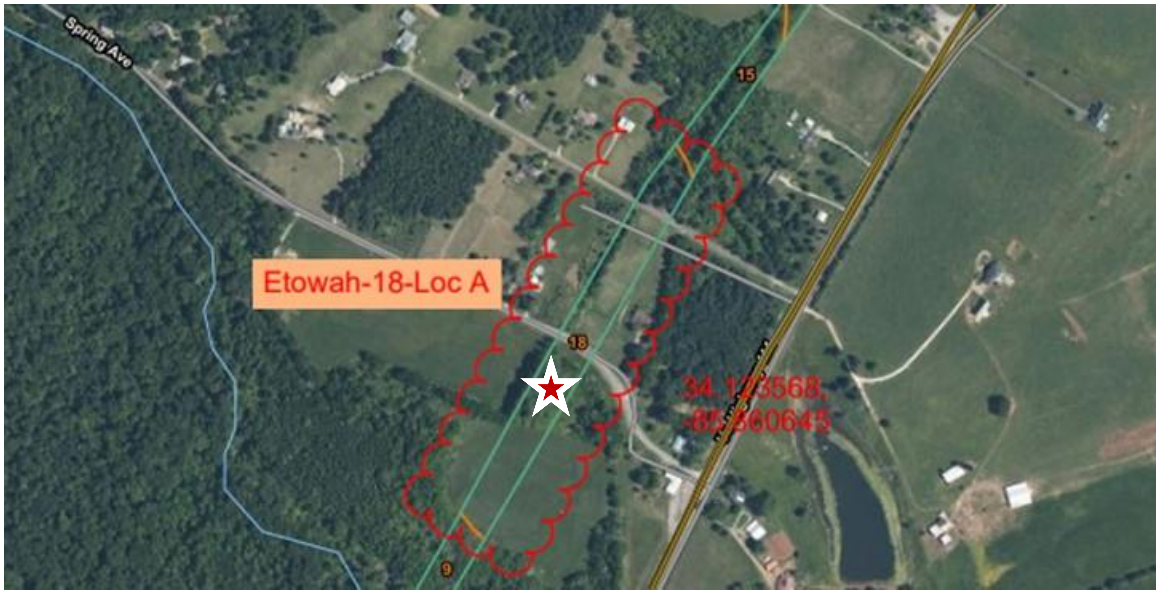


Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Dewey silty loam, 2 to 6 percent slopes
Percent of AOI	18.2% (18.3 ac)
Parent material name	Clayey residuum weathered from limestone
Surface texture	Fine, kaolinitic, thermic typic paleudults
K-factor	0.37
AASHTO Classification	A-6

USCS Classification CL

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ✖ ☐ - Hydrometer	**Date**	05/05/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.008	**C_u**	36.25	**PL**	17
D_{30} (mm)	0.02	**C_c**	0.10	**I_p**	14
D_{60} (mm)	0.29	**LL**	31	**Group Index**	0

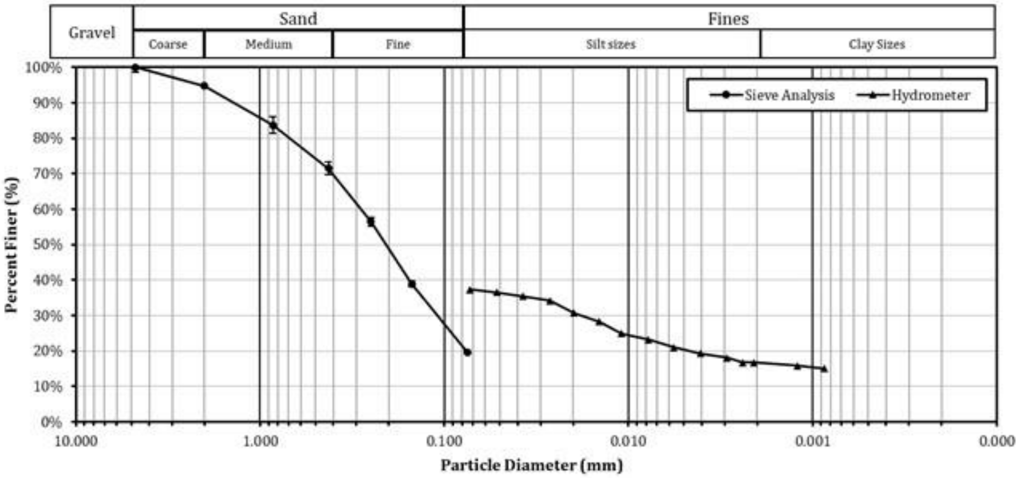
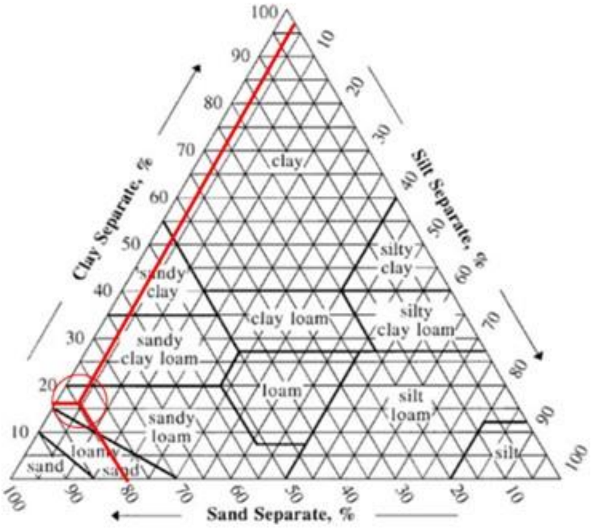


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	80.3	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	3.80	**USCS**	**SC** Clayey sand
% clay	15.9		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	698	**K (ppm)** Potassium	15	**Mg (ppm)** Magnesium	94
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	120	**B (ppm)** Boron	0.2
Cu (ppm) Copper	0.9	**Fe (ppm)** Iron	11	**Mn (ppm)** Manganese	9
Na (ppm) Sodium	48	**Zn (ppm)** Zinc	0.7	**CEC (meq/100 g)** Cation Exchange Capacity	6.60

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 05/19/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	RAEDAA-002(556)
ALDOT District	North District
Project Location	Etowah, AL
Sample Collection Date	March 12th, 2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	9
Sampling Location	34.132511, -85.851396

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	43
Percent of AOI	10.4% (10.4 ac)
Parent material name	Minvale cherty loam, 2 to 6 percent slopes
Surface texture	Fine-loamy, siliceous, subactive, thermic typic paleudults
K-factor	0.15
AASHTO Classification	A-4
USCS Classification	GM

SOIL ANALYSIS

Testing method	• Dry and Wet sieve analysis • Atterberg limit test LL ☒ PL ✖ ☐ • Hydrometer	**Date**	5/12/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.0009	**C_u**	211.11	**PL**	18
D_{30} (mm)	0.01	**C_c**	0.99	**I_p**	15
D_{60} (mm)	0.19	**LL**	33	**Group Index**	0

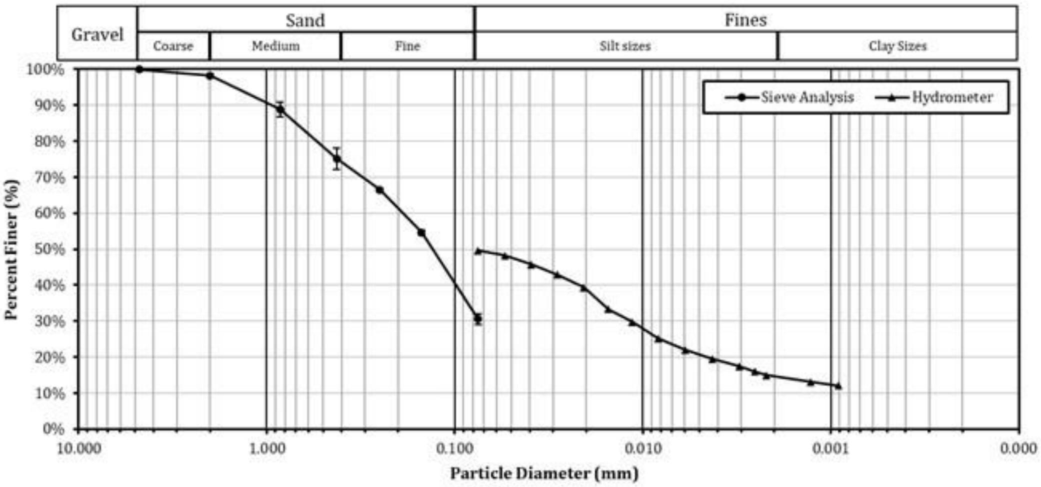
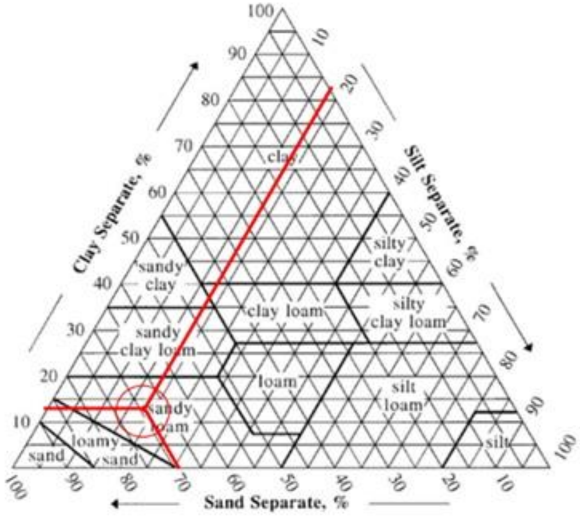


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	69.50	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	17.40	**USCS**	**SC** Clayey sand
% clay	13.10		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	399	**K (ppm)** Potassium	33	**Mg (ppm)** Magnesium	56
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	285	**B (ppm)** Boron	0.2
Cu (ppm) Copper	1.6	**Fe (ppm)** Iron	19	**Mn (ppm)** Manganese	129
Na (ppm) Sodium	46	**Zn (ppm)** Zinc	1	**CEC (meq/100 g)** Cation Exchange Capacity	5.55

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 06/05/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	NHF-IMF I065 (354)
ALDOT District	East Central District
Project Location	Shelby, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	TsE
Sampling Location	33.248293, -86.799105

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Townley-Sunlight complex, 12 to 35 percent slopes
Percent of AOI	51.7% (92.6 ac)
Parent material name	Clayey residuum weathered from shale
Surface texture	Fine, mixed, semiactive, thermic typic hapludults
K-factor	0.28
AASHTO Classification	A-4
USCS Classification	ML

SOIL ANALYSIS

Testing method	• Dry and Wet sieve analysis • Atterberg limit test LL ☒ PL ✖ ☐ • Hydrometer	**Date**	5/25/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.0013	**C_u**	615.38	**PL**	25
D_{30} (mm)	0.070	**C_c**	4.71	**I_p**	12
D_{60} (mm)	0.80	**LL**	37	**Group Index**	0

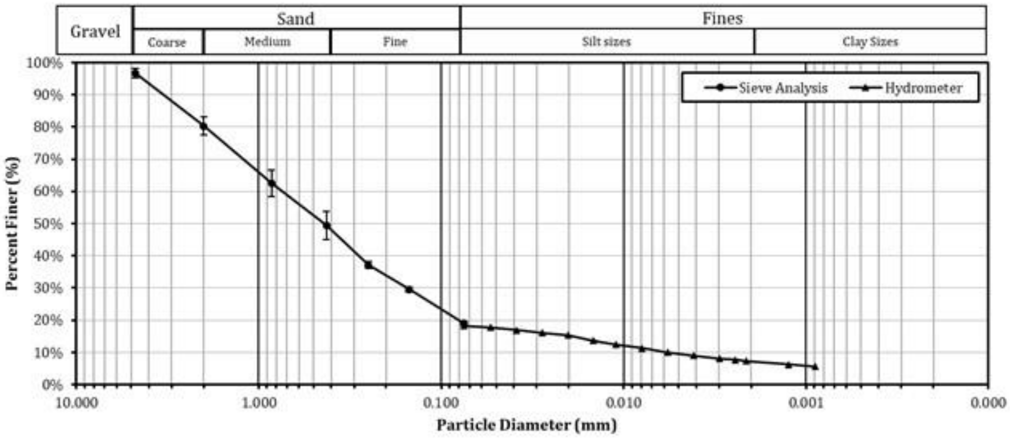
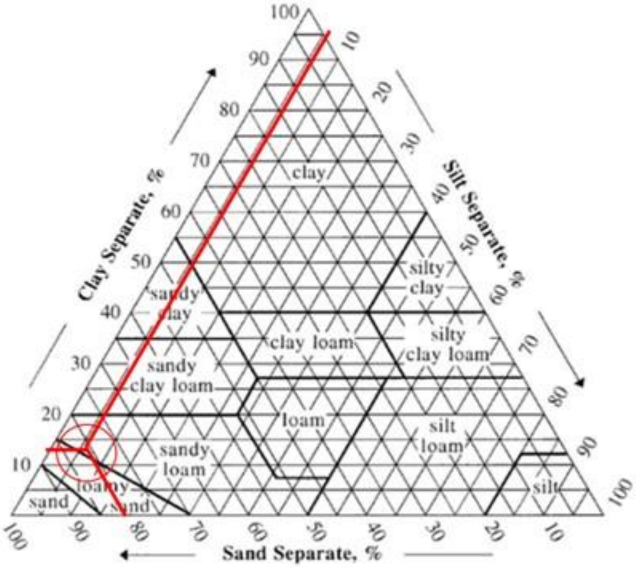


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	81.00	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	5.30	**USCS**	**SM** Silty sand
% clay	13.7		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	863	**K (ppm)** Potassium	60	**Mg (ppm)** Magnesium	295
P (ppm) Phosphorus	14	**Al (ppm)** Aluminum	122	**B (ppm)** Boron	0.2
Cu (ppm) Copper	2.7	**Fe (ppm)** Iron	19	**Mn (ppm)** Manganese	34
Na (ppm) Sodium	52	**Zn (ppm)** Zinc	1.5	**CEC (meq/100 g)** Cation Exchange Capacity	9.31

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 6/3/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	NHF-IMF I065 (354)
ALDOT District	East Central District
Project Location	Shelby, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	TtE
Sampling Location	33.257618,-86.798889

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Townley-Sunlight complex, 12 to 35 percent slopes
Percent of AOI	51.7% (92.6 ac)
Parent material name	Clayey residuum weathered from shale
Surface texture	Fine, mixed, semiactive, thermic typic hapludults
K-factor	0.28
AASHTO Classification	A-4

USCS Classification	CL

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☐ ✖ - Hydrometer	**Date**	5/12/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.006	**C_u**	141.67	**PL**	23
D_{30} (mm)	0.150	**C_c**	4.41	**I_p**	14
D_{60} (mm)	0.85	**LL**	37	**Group Index**	0

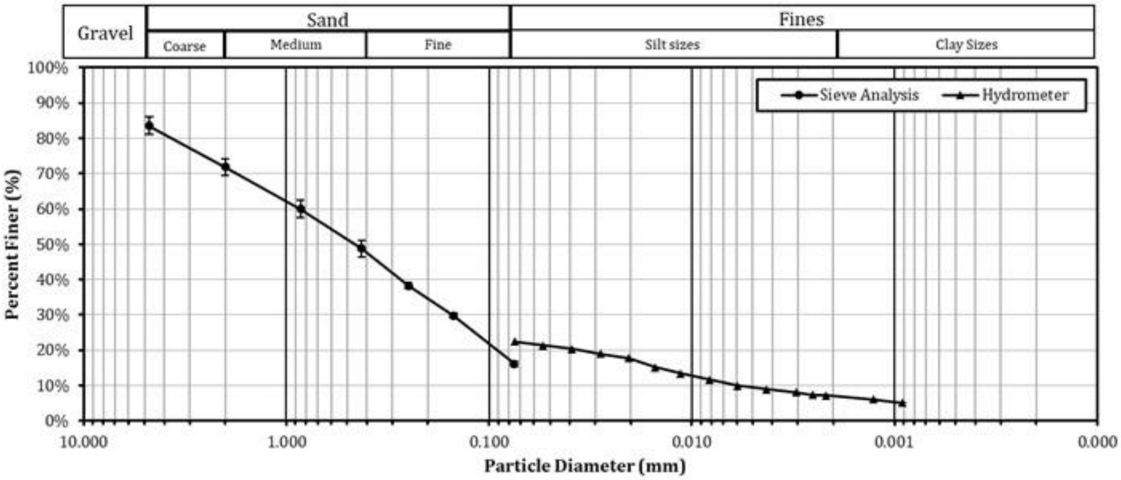
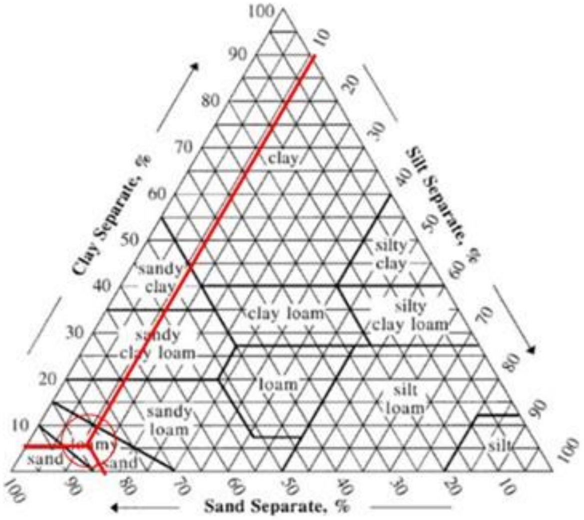


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	83.80	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	10.12	**USCS**	**SC** Clayey sand
% clay	6.1		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	4604	**K (ppm)** Potassium	26	**Mg (ppm)** Magnesium	329
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	110	**B (ppm)** Boron	0.3
Cu (ppm) Copper	0.6	**Fe (ppm)** Iron	2	**Mn (ppm)** Manganese	129
Na (ppm) Sodium	1.5	**Zn (ppm)** Zinc	1.7	**CEC (meq/100 g)** Cation Exchange Capacity	26.07

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 06/11/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	BR-006(563)
ALDOT District	West Central District
Project Location	Bibb, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	CmA
Sampling Location	32.933042, -87.059764

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Columbus loam, 0 to 2 percent slopes, occasionally flooded
Percent of AOI	18% (44 ac)
Parent material name	Loamy fluviomarine deposits
Surface texture	Fine-loamy, siliceous, semiactive, thermic aquic hapludults
K-factor	0.32
AASHTO Classification	A-4

USCS Classification	CL

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ✖ ☐ - Hydrometer	**Date**	06/08/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.004	**C_u**	52.50	**PL**	15
D_{30} (mm)	0.10	**C_c**	11.90	**I_p**	6
D_{60} (mm)	0.21	**LL**	21	**Group Index**	0

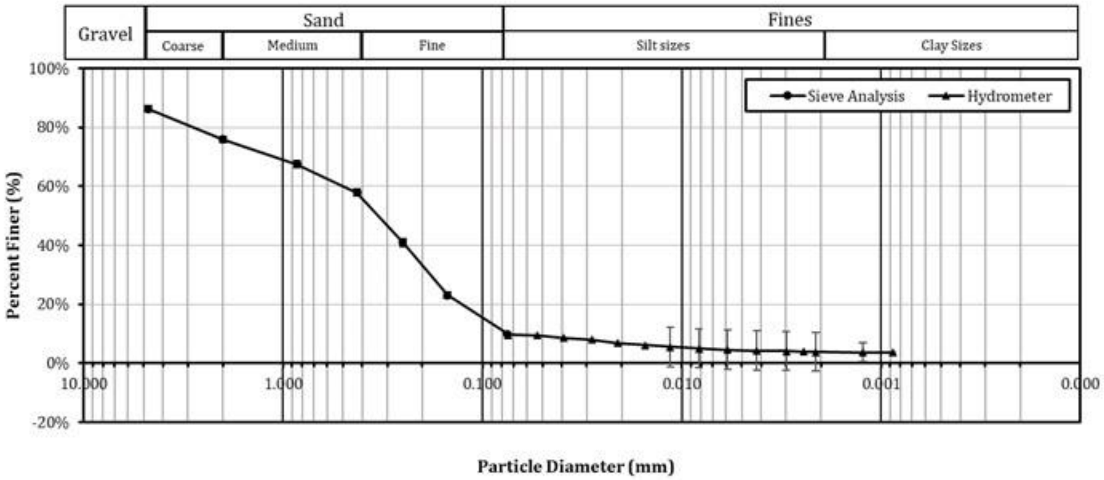
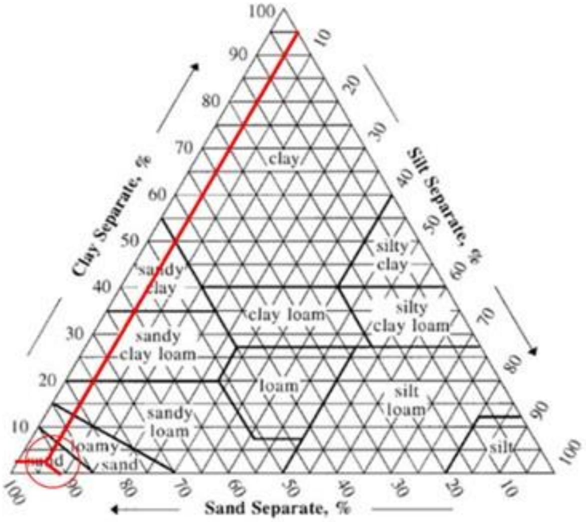


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	90.10	**AASHTO**	**A-2-4** Silty or clayey gravel and sand
%silt	6.20	**USCS**	**SW-SC** Well graded sand with clay
% clay	3.70		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	589	**K (ppm)** Potassium	15	**Mg (ppm)** Magnesium	104
P (ppm) Phosphorus	29	**Al (ppm)** Aluminum	172	**B (ppm)** Boron	0.1
Cu (ppm) Copper	1.5	**Fe (ppm)** Iron	37	**Mn (ppm)** Manganese	24
Na (ppm) Sodium	43	**Zn (ppm)** Zinc	0.9	**CEC (meq/100 g)** Cation Exchange Capacity	6.28

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 06/16/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	BR-006(563)
ALDOT District	West Central District
Project Location	Bibb, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	MiA
Sampling Location	32.934906, -87.062112

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Mantachie, Kinston, and Iuka soils, 0 to 1 % slopes, frequently flooded
Percent of AOI	9% (23.1 ac)
Parent material name	Loamy alluvium
Surface texture	Mantachie: fine-loamy, siliceous, active, acid, thermic fluventic endoaquepts Kinston: fine-silty, mixed, superactive, mesic aquic hapludolls Iuka:coarse-loamy, siliceous, active, acid, thermic aquic udifluvents
K-factor	0.17
AASHTO Classification	A-4

USCS Classification	CL

SOIL ANALYSIS			
Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ✖ ☐ - Hydrometer	**Date**	05/25/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.0008	**C_u**	500	**PL**	28
D_{30} (mm)	0.120	**C_c**	45	**I_p**	32
D_{60} (mm)	0.4	**LL**	60	**Group Index**	0

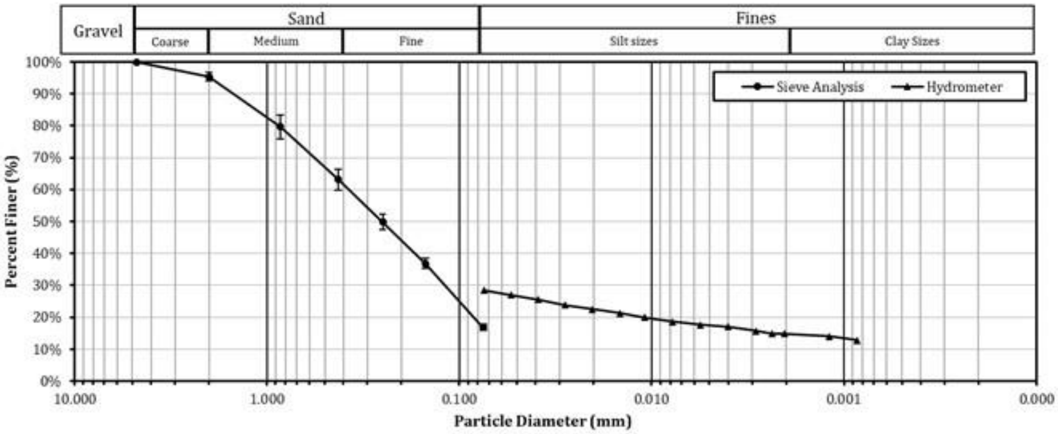
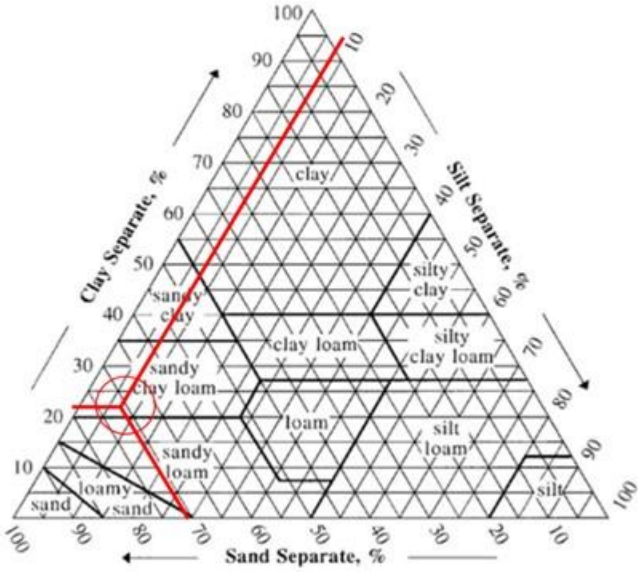


Figure 3- Particle Size Distribution Curve

Soil Classification			
% sand	71.00	**AASHTO**	**A-2-7** Silty or clayey gravel and sand
%silt	7.70	**USCS**	**SC** Clayey sand
% clay	21.30		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	389	**K (ppm)** Potassium	47	**Mg (ppm)** Magnesium	313
P (ppm) Phosphorus	<0.1	**Al (ppm)** Aluminum	249	**B (ppm)** Boron	0.0
Cu (ppm) Copper	2.0	**Fe (ppm)** Iron	29	**Mn (ppm)** Manganese	21
Na (ppm) Sodium	65	**Zn (ppm)** Zinc	1.8	**CEC (meq/100 g)** Cation Exchange Capacity	6.28

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 06/24/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION

Project ID	BR-006(563)
ALDOT District	Southeast District
Project Location	Montgomery, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	IdB
Sampling Location	32.295853, -86.194609

Figure 1- Soil Sample

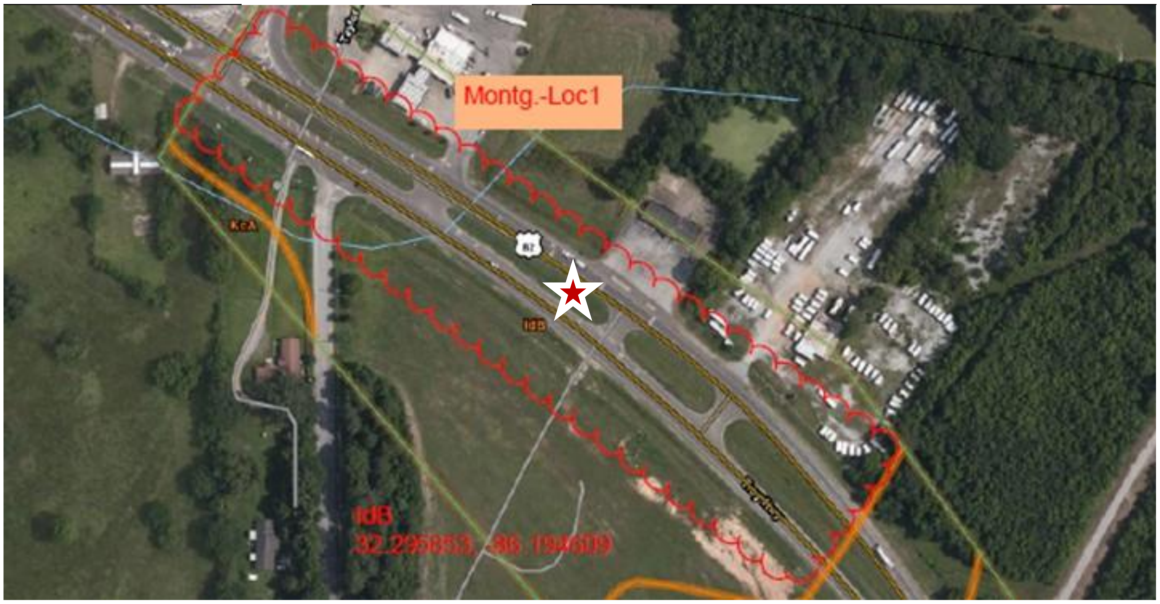


Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS

Map Unit Name	Izagora fine sandy loam, very gently sloping phase
Percent of AOI	28.1% (16.3 ac)
Parent material name	Loamy and clayey fluviomarine deposits
Surface texture	Fine-loamy, siliceous, semiactive, thermic aquic paleudults
K-factor	0.24
AASHTO Classification	A-4

USCS Classification SM

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ✖ ☐ - Hydrometer	**Date**	06/11/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.004	**C_u**	97.50	**PL**	14
D_{30} (mm)	0.170	**C_c**	18.53	**I_p**	5
D_{60} (mm)	0.39	**LL**	19	**Group Index**	0

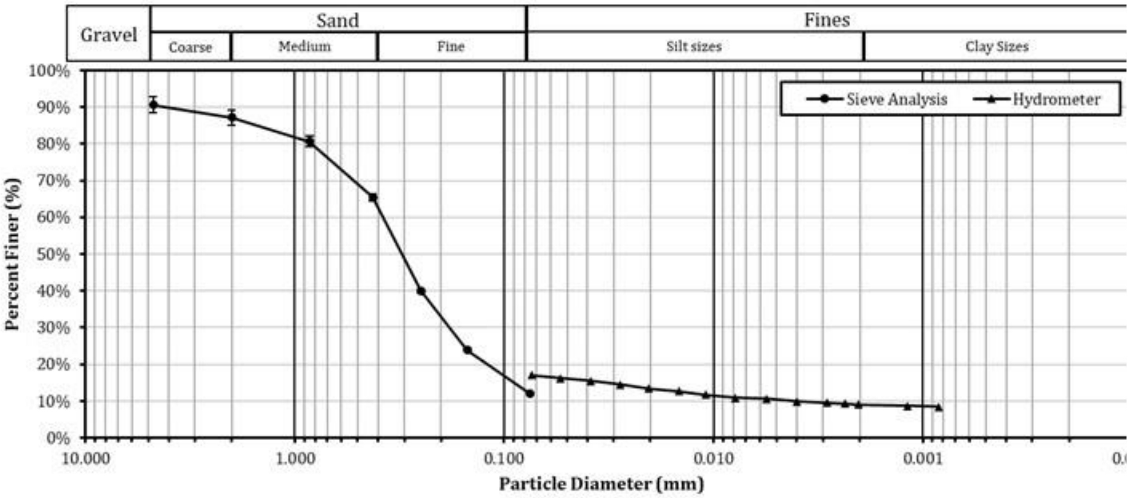
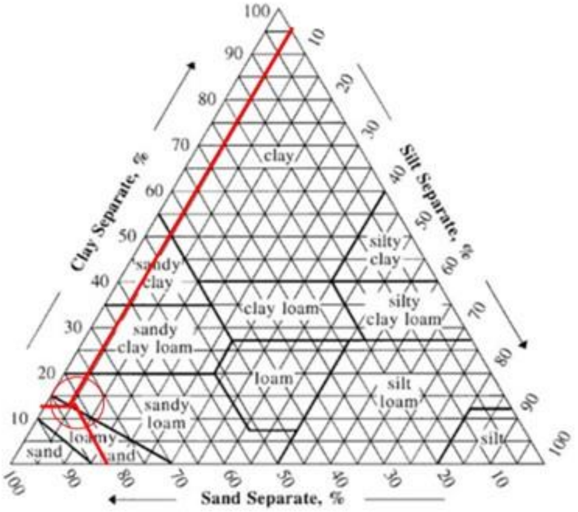


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	82.57	**AASHTO**	**A-2-4** Silty of clayey gravel and sand
%silt	4.73	**USCS**	**SW-SC** Well graded sand with clay
% clay	12.7		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	784	**K (ppm)** Potassium	23	**Mg (ppm)** Magnesium	74
P (ppm) Phosphorus	14	**Al (ppm)** Aluminum	95	**B (ppm)** Boron	0.2
Cu (ppm) Copper	2.6	**Fe (ppm)** Iron	65	**Mn (ppm)** Manganese	94
Na (ppm) Sodium	52	**Zn (ppm)** Zinc	3.7	**CEC (meq/100 g)** Cation Exchange Capacity	4.82

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 06/22/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	BR-006(563)
ALDOT District	Southeast District
Project Location	Montgomery, AL
Sample Collection Date	April 20th, 2021
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	KcA
Sampling Location	32.289275, -86.188428

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Kipling clay loam, 0 to 1 percent slopes
Percent of AOI	22.21% (12.8 ac)
Parent material name	Clayey marine deposits derived from chalk
Surface texture	Fine, smectitic, thermic vertic paleudalfs
K-factor	0.28
AASHTO Classification	A-7-6
USCS Classification	CL

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ✖ ☐ - Hydrometer	**Date**	05/25/2021
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)	0.002	**C_u**	150	**PL**	16
D_{30} (mm)	0.130	**C_c**	28.17	**I_p**	6
D_{60} (mm)	0.30	**LL**	22	**Group Index**	0

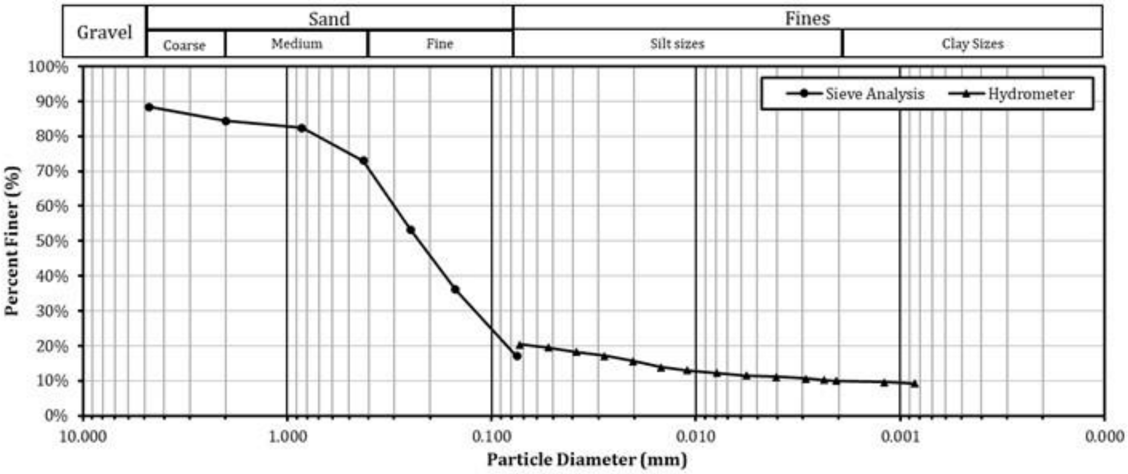
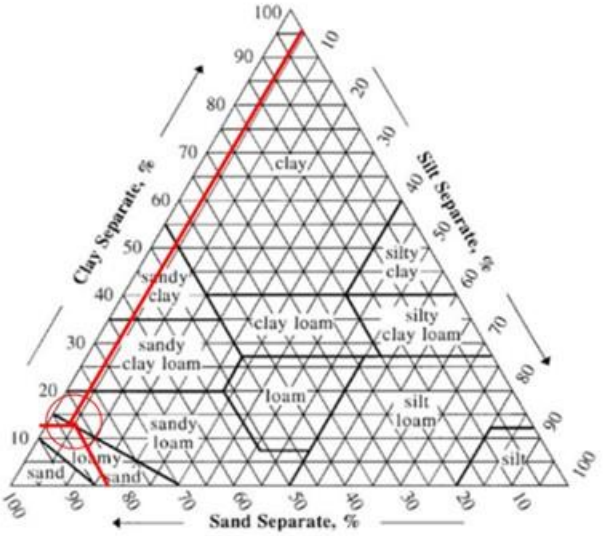


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	83.00	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	3.10	**USCS**	**SC-SM** Silty clays; clayey silts and sands
% clay	13.90		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY

Ca (ppm) Calcium	1141	**K (ppm)** Potassium	49	**Mg (ppm)** Magnesium	87
P (ppm) Phosphorus	12	**Al (ppm)** Aluminum	106	**B (ppm)** Boron	0.3
Cu (ppm) Copper	1.6	**Fe (ppm)** Iron	52	**Mn (ppm)** Manganese	50
Na (ppm) Sodium	113	**Zn (ppm)** Zinc	3.1	**CEC (meq/100 g)** Cation Exchange Capacity	7.05

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 05/03/2021
Prepared By: Billur Kazaz

PROJECT INFORMATION	
Project ID	AU-SRF
ALDOT District	N/A
Project Location	Opelika, AL
Sample Collection Date	07/15/2020
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	7
Sampling Location	32.593744,-85.294471

Figure 1- Soil Sample

Figure 2- Sampling Location Aerial Image

USDA WEB SOIL SURVEY RESULTS	
Map Unit Name	Cecil sandy loam, 2 to 6 percent slopes
Percent of AOI	100% (6.9 ac)
Parent material name	Residuum weathered from granite and gneiss and/or residuum weathered from schist
Surface texture	Fine, kaolinitic, thermic typic kanhapludults
K-factor	0.2
AASHTO Classification	A-2-4
USCS Classification	SC

SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☐ ✖ - Hydrometer	**Date**	01/27/2020
		Tested by	Billur Kazaz

Soil Information

D_{10} (mm)		**C_u**		**PL**	27
D_{30} (mm)		**C_c**		**I_p**	11
D_{60} (mm)		**LL**	38	**Group Index**	0

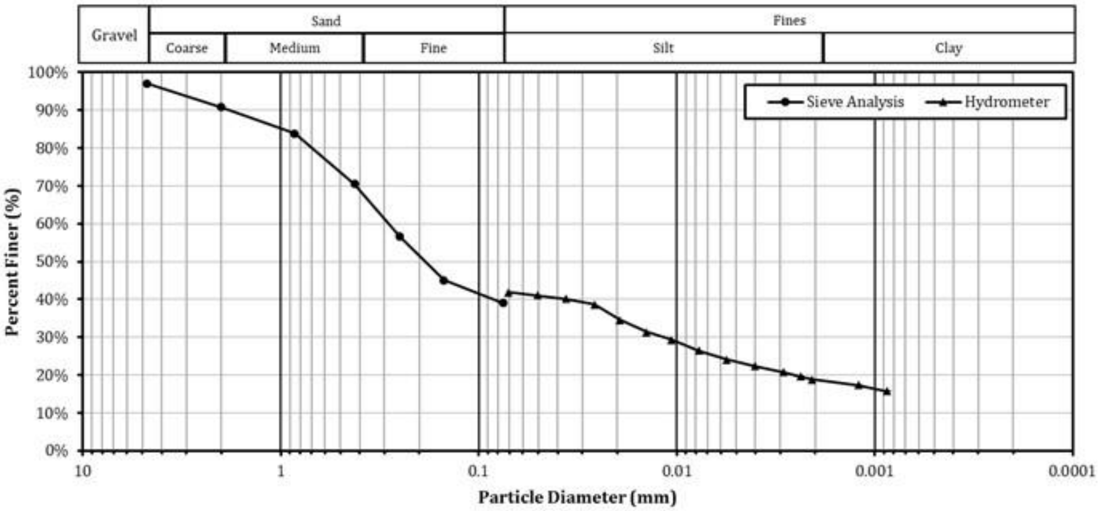
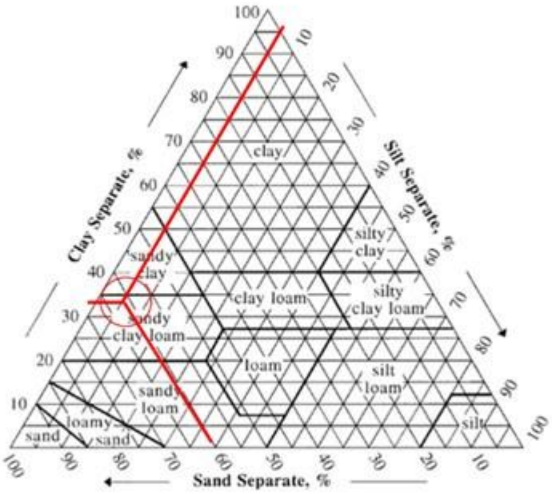


Figure 3- Particle Size Distribution Curve

Soil Classification

% sand	61.00	**AASHTO**	**A-6** Fair to poor clayey soils
%silt	4.45	**USCS**	**SC** Clayey sand
% clay	34.60		

USDA Texture Triangle



(a) PSD & Hydrometer Method

SOIL CHEMISTRY					
Ca (ppm) Calcium	93	**K (ppm)** Potassium	47	**Mg (ppm)** Magnesium	50
P (ppm) Phosphorus	3	**Al (ppm)** Aluminum	271	**B (ppm)** Boron	0.2
Cu (ppm) Copper	1	**Fe (ppm)** Iron	31	**Mn (ppm)** Manganese	11
Na (ppm) Sodium	55	**Zn (ppm)** Zinc	2	**CEC (meq/100 g)** Cation Exchange Capacity	3.4

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Prepared By: Billur Kazaz

PROJECT INFORMATION

Project ID	Silty Clay
ALDOT District	N/A
Project Location	Montgomery, AL
Sample Collection Date	N/A
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	N/A
Sampling Location	Montgomery, AL

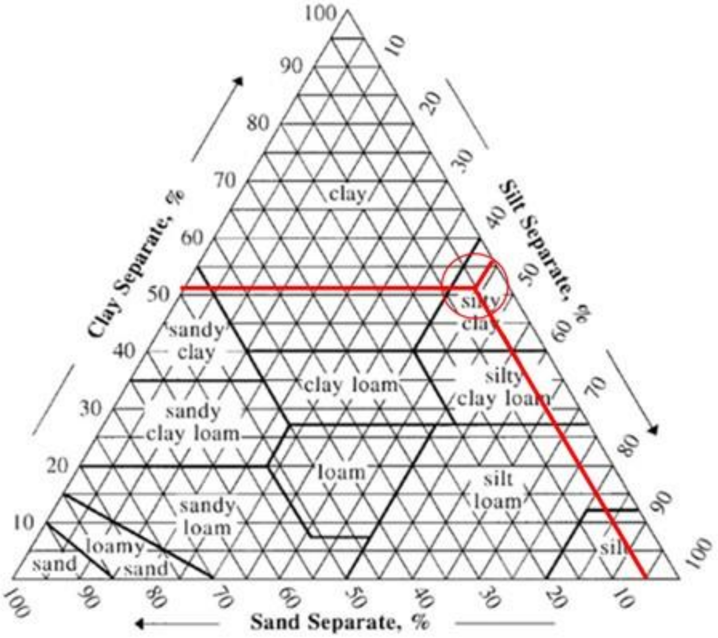
SOIL ANALYSIS

Testing method	• Dry and Wet sieve analysis • Atterberg limit test LL ☒ PL ☒ Hydrometer

Soil Classification

% sand	5	**CEC (meq/100g)**	5.55
%silt	44		
% clay	51		

USDA Texture Triangle



(a) PSD & Hydrometer Method

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Prepared By: Billur Kazaz

PROJECT INFORMATION

Project ID	Clay
ALDOT District	N/A
Project Location	Auburn, AL
Sample Collection Date	N/A
Tested by	Billur Kazaz
Map Unit Symbol (see WSS info)	N/A
Sampling Location	South Auburn

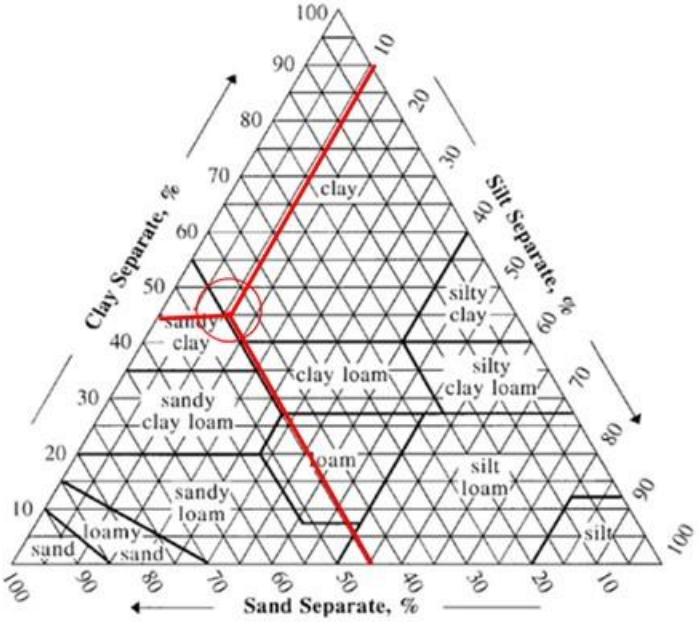
SOIL ANALYSIS

Testing method	- Dry and Wet sieve analysis - Atterberg limit test LL ☒ PL ☒ - Hydrometer

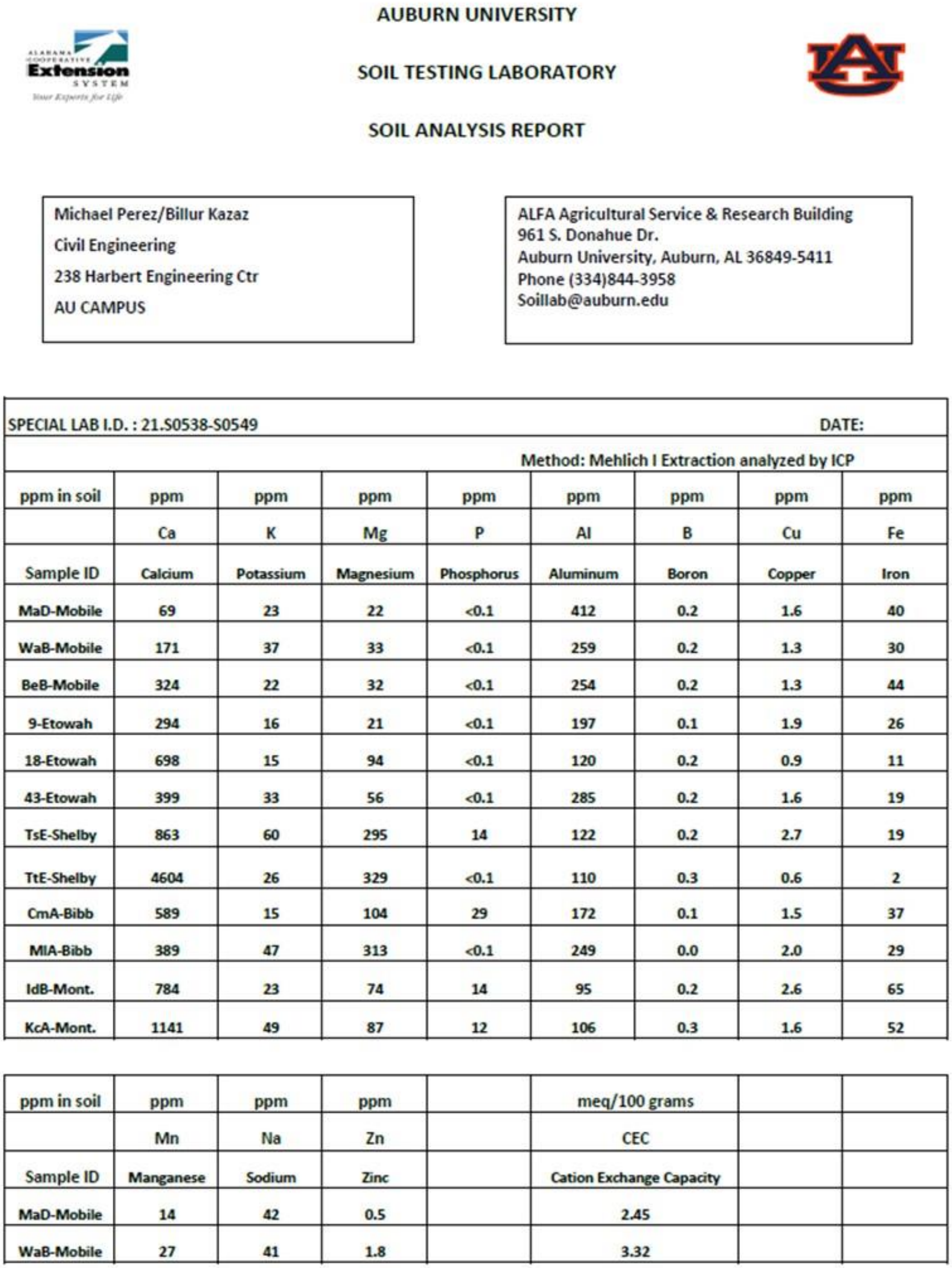
Soil Classification

% sand	46.60	**CEC (meq/100g)**	31.25
%silt	9.60		
% clay	43.8		

USDA Texture Triangle



(a) PSD & Hydrometer Method



AUBURN UNIVERSITY

SOIL TESTING LABORATORY

SOIL ANALYSIS REPORT

Michael Perez/Billur Kazaz
Civil Engineering
238 Harbert Engineering Ctr
AU CAMPUS

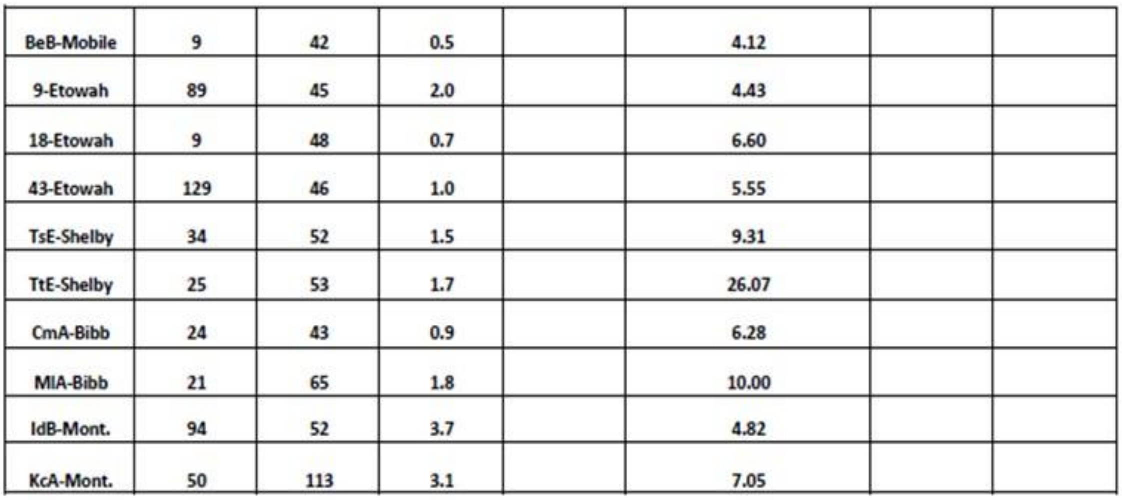
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

SPECIAL LAB I.D. : 21.S0538-S0549 DATE:

Method: Mehlich I Extraction analyzed by ICP

ppm in soil	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Ca	K	Mg	P	Al	B	Cu	Fe
Sample ID	Calcium	Potassium	Magnesium	Phosphorus	Aluminum	Boron	Copper	Iron
MaD-Mobile	69	23	22	<0.1	412	0.2	1.6	40
WaB-Mobile	171	37	33	<0.1	259	0.2	1.3	30
BeB-Mobile	324	22	32	<0.1	254	0.2	1.3	44
9-Etowah	294	16	21	<0.1	197	0.1	1.9	26
18-Etowah	698	15	94	<0.1	120	0.2	0.9	11
43-Etowah	399	33	56	<0.1	285	0.2	1.6	19
TsE-Shelby	863	60	295	14	122	0.2	2.7	19
TtE-Shelby	4604	26	329	<0.1	110	0.3	0.6	2
CmA-Bibb	589	15	104	29	172	0.1	1.5	37
MIA-Bibb	389	47	313	<0.1	249	0.0	2.0	29
IdB-Mont.	784	23	74	14	95	0.2	2.6	65
KcA-Mont.	1141	49	87	12	106	0.3	1.6	52

ppm in soil	ppm	ppm	ppm		meq/100 grams		
	Mn	Na	Zn		CEC		
Sample ID	Manganese	Sodium	Zinc		Cation Exchange Capacity		
MaD-Mobile	14	42	0.5		2.45		
WaB-Mobile	27	41	1.8		3.32		



BeB-Mobile	**9**	**42**	**0.5**		**4.12**		
9-Etowah	**89**	**45**	**2.0**		**4.43**		
18-Etowah	**9**	**48**	**0.7**		**6.60**		
43-Etowah	**129**	**46**	**1.0**		**5.55**		
TsE-Shelby	**34**	**52**	**1.5**		**9.31**		
TtE-Shelby	**25**	**53**	**1.7**		**26.07**		
CmA-Bibb	**24**	**43**	**0.9**		**6.28**		
MIA-Bibb	**21**	**65**	**1.8**		**10.00**		
IdB-Mont.	**94**	**52**	**3.7**		**4.82**		
KcA-Mont.	**50**	**113**	**3.1**		**7.05**		

AUBURN UNIVERSITY

SOIL TESTING LABORATORY

SOIL ANALYSIS REPORT

Billur Kazaz
Civil Engineering
238 Harbert Eng. Ctr.
AU Campus

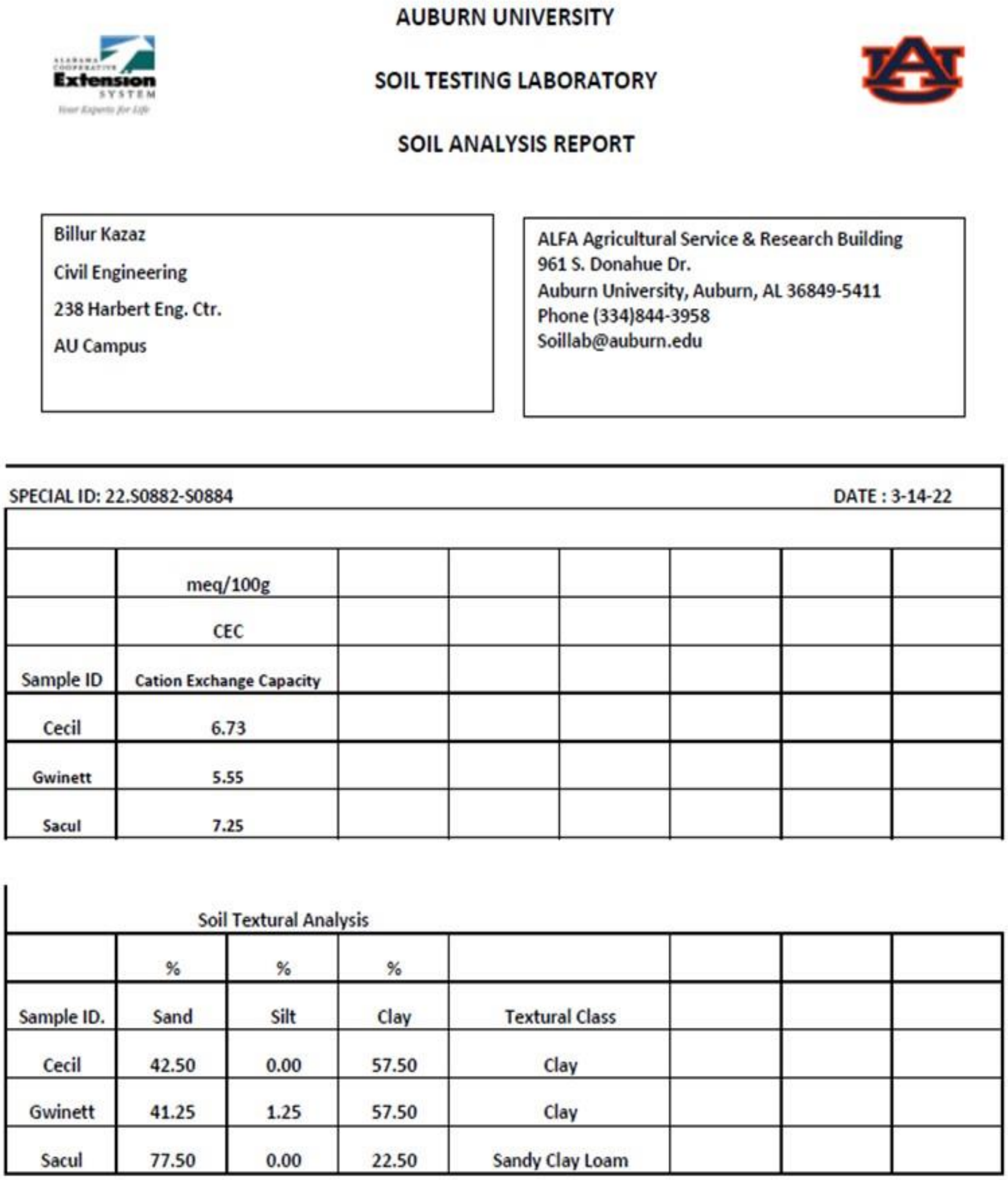
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

SPECIAL LAB I.D. : 22.S0032 **DATE: 10-8-21**

Method: Mehlich I Extraction analyzed by ICP

ppm in soil	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Ca	K	Mg	P	Al	B	Cu	Fe
Sample ID	Calcium	Potassium	Magnesium	Phosphorus	Aluminum	Boron	Copper	Iron
AUESCTF	93	47	50	3	271	0.2	1	31

ppm in soil	ppm	ppm	ppm			meq/100 grams	
	Mn	Na	Zn			CEC	
Sample ID	Manganese	Sodium	Zinc			cation exchange capacity	
AUESCTF	11	55	2			3.4	



AUBURN UNIVERSITY

SOIL TESTING LABORATORY

SOIL ANALYSIS REPORT

Billur Kazaz
Civil Engineering
238 Harbert Eng. Ctr.
AU Campus

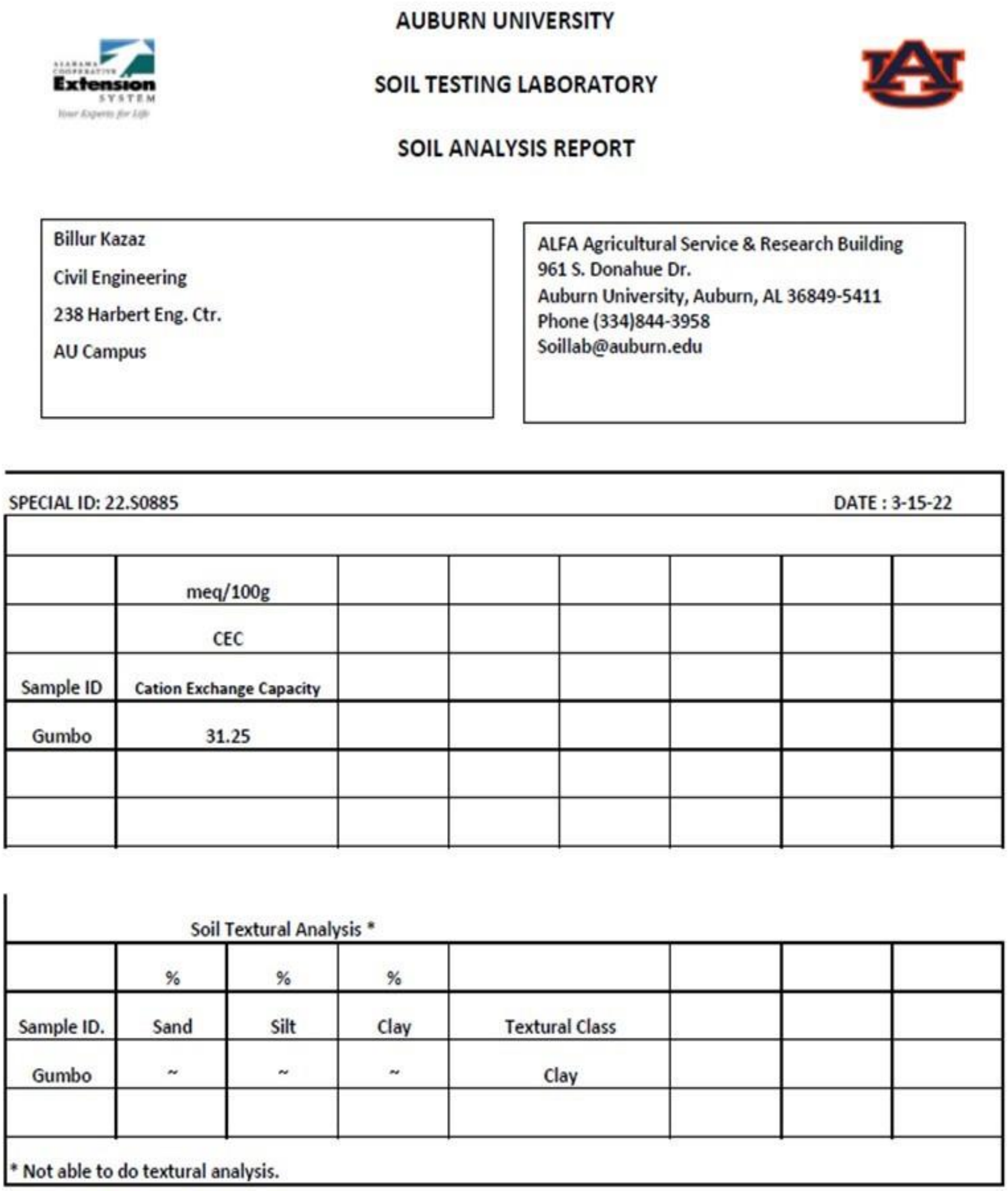
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

SPECIAL ID: 22.S0882-S0884 DATE : 3-14-22

	meq/100g						
	CEC						
Sample ID	Cation Exchange Capacity						
Cecil	6.73						
Gwinett	5.55						
Sacul	7.25						

Soil Textural Analysis

	%	%	%				
Sample ID.	Sand	Silt	Clay	Textural Class			
Cecil	42.50	0.00	57.50	Clay			
Gwinett	41.25	1.25	57.50	Clay			
Sacul	77.50	0.00	22.50	Sandy Clay Loam			



AUBURN UNIVERSITY

SOIL TESTING LABORATORY

SOIL ANALYSIS REPORT

Billur Kazaz
Civil Engineering
238 Harbert Eng. Ctr.
AU Campus

ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

SPECIAL ID: 22.S0885

DATE : 3-15-22

	meq/100g						
	CEC						
Sample ID	Cation Exchange Capacity						
Gumbo	31.25						

Soil Textural Analysis *

	%	%	%				
Sample ID.	Sand	Silt	Clay	Textural Class			
Gumbo	~	~	~	Clay			

* Not able to do textural analysis.

APPENDIX A
MATCH TEST PROCEDURES

Match Test Procedures

Equipment

1- Magnetic Stirrer (20 to 150 rpm) and magnets
2- Jar Test Multiple Stirrer
3- Beakers (Min. 1,000 mL, all same size and shape)
4- Reagent Rack
5- Pipets
6- Pipet Filler

Pre-Test

1- Fill the beakers with cold tap water (1,000 mL)
2- Weigh the soil into tins
3- Weigh the chemicals
    - Dry Chemicals → See dry manufacturer dosage guidance
    - Solutions → See solution concentration sheet
4- Prepare the datasheet by recording chemical names, experiment ID, etc.
5- Place the beakers in the multiple stirrers.
6- Stir the plates at the maximum speed
7- Pour the soil into the beakers and let it stir for 1 minute
8- Check for contaminated samples
9- If samples are flocculating, clean the beaker and the paddles on the machine.

Testing

1- Stir turbid water samples for 1 minute
2- Inject flocculants
3- Flash mix (120 rpm) for 1 minute
4- Slow mix (60 rpm) for 20 minutes
5- Check for floc formation
6- Last 5 min of the slow mix→ Classify the floc size for each jar
7- Last 1 min of the slow mix → Start the video for settling velocity observations
8- Take the paddles out and wait for settling for 15 minutes

Post-test

1- Color classification
2- Wash the jars, small beakers, and pipette tips
3- Clean the machine: Wipe it with tap water, then surface cleaner and again with tap water
4- Put the datasheet into the folder

APPENDIX B
RESIDUAL TESTING PROCEDURES

DOSAGE TEST PROCEDURES

Equipment

1- Magnetic Stirrer (20 to 150 rpm) and magnets
2- Jar Test Multiple Stirrer
3- Beakers (Min. 1,000 mL, all same size and shape)
4- Reagent Rack
5- Pipets
6- Pipet Filler

Pre-Test

1- Fill the beakers with cold tap water (1,000 mL)
2- Weigh the soil into tins
3- Weigh the chemicals assuming manufacturer guidance as 100% dosage:

Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Control	20 %	40 %	80 %	100 %	200 %

Jar 5 → Manufacturer guidance, follow dosage test concentration table

4- Prepare the datasheet by recording chemical names, experiment ID, etc.
5- Place the beakers in the multiple stirrer machine.
6- Stir the plates with the max. speed
7- Pour the soil into the beakers and let it stir for 1 min.
8- Check for contaminated samples
9- Grab 40 ml of the turbid water samples into small beakers by using the pipette
10- Take initial pH, turbidity, temperature, and color readings and record results to the datasheet

Testing

1- Stir turbid water samples for 1 min
2- Inject flocculants
3- Flash mix (120 rpm) for 1 min
4- Slow mix (60 rpm) for 20 min
5- Check for floc formation
6- Last 5 min of the slow mix→ Classify the floc size for each jar
7- Take the paddles out and wait for settling for 15 min
8- Color classification
9- Grab 40 ml of the turbid water samples into small beakers by using the pipette. Use a clean pipette tip for each jar.
10- Take final pH, turbidity, temperature, and color readings and record results to the datasheet.

Post-test

1- Wash the jars, small beakers, and pipette tips
2- Clean the machine: Wipe it with tap water, then surface cleaner and again with tap water
3- Put the datasheet into the folder

APPENDIX C
DOSAGE TEST DATA

RESIDUAL TESTING PROCEDURES

Equipment

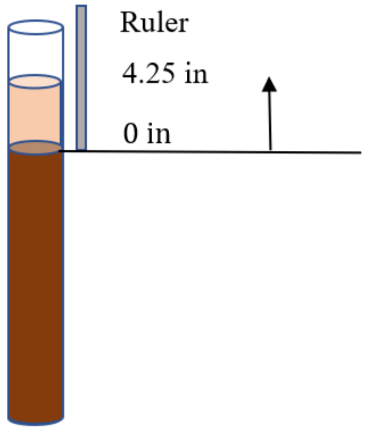
1- Jar Test Multiple Stirrer
2- Beakers (Min. 1,000 mL, all same size and shape)
3- Stopwatch
4- Ruler
5- Graduated cylinder

Pre-Test

1- Wait until the samples are fully settled.
2- Transfer the supernatant into empty beakers
3- Label the beakers

Testing

1- Stir the transferred water with 20 gr of testing soil at maximum speed for 1 min
2- Pour the sample into a graduated cylinder
3- Start the timer right after pouring the sample
4- Record settling depth with time on the datasheet



Measure from top of the dark line to the top of the water surface

Graduated Cylinder

Post-test

1- Wash the jars, and cylinders
2- Clean the machine: Wipe it with tap water, then surface cleaner and again with tap water
3- Put the datasheet into the folder

APPENDIX D
PRODUCT IDENTIFICATION

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**WaB**	**Sampling Location:**	**Mobile, AL**

Product: **APS 712**

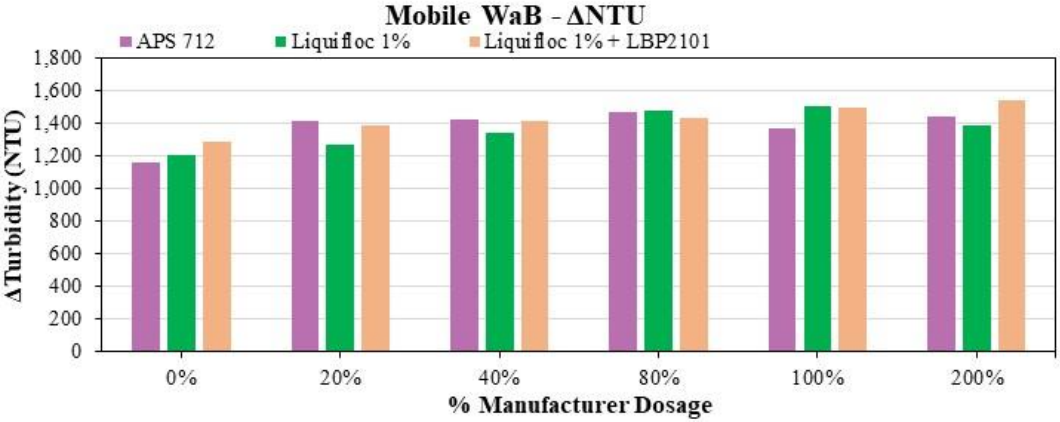
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,157.3	1,411.7	1,421.8	1,463.9	1,370.1	1,440.4
ΔpH	0.09	0.04	0.03	0.04	0.04	0.05
ΔTemperature	0.7	0.1	0.1	0.1	0.0	0.1
ΔColor	2	3	3	3	3	3

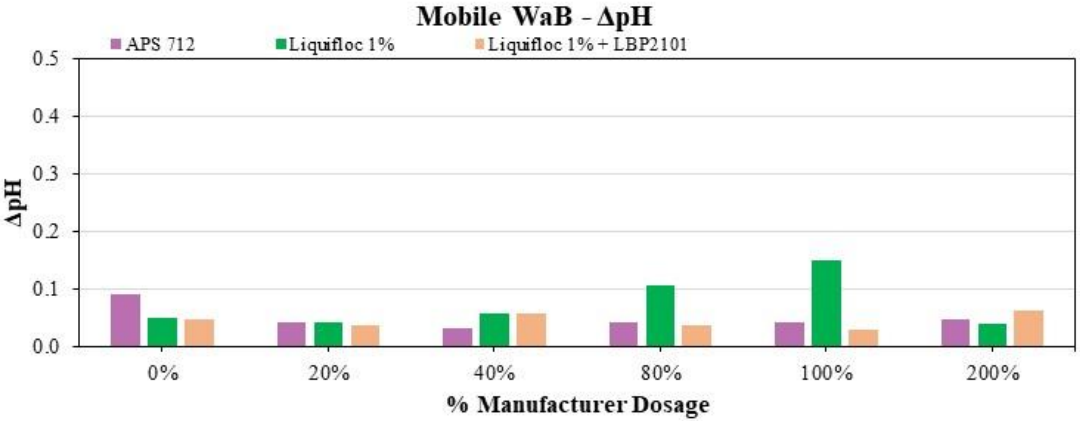
Product: **Liquifloc 1%**

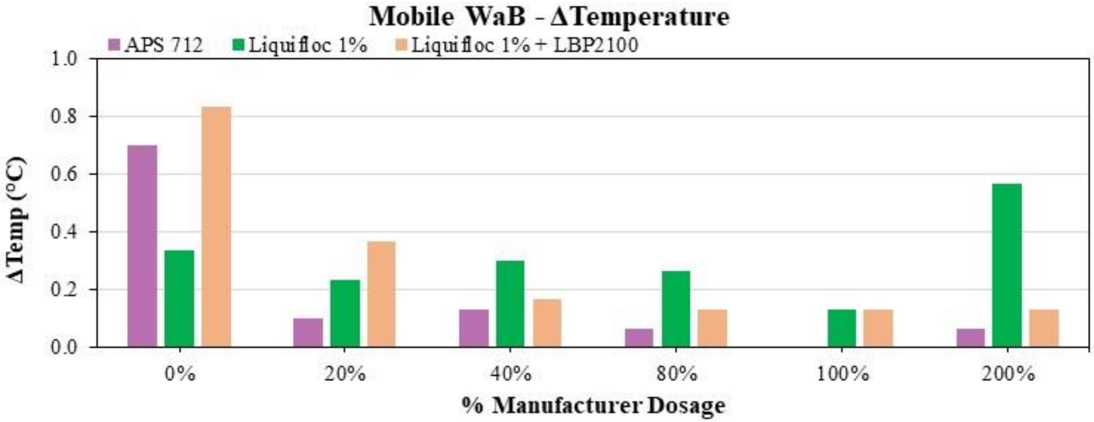
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,201.0	1,263.3	1,335.8	1,472.5	1,504.9	1,385.5
ΔpH	0.05	0.04	0.06	0.11	0.15	0.04
ΔTemperature	0.3	0.2	0.3	0.3	0.1	0.6
ΔColor	1	2	2	4	4	4

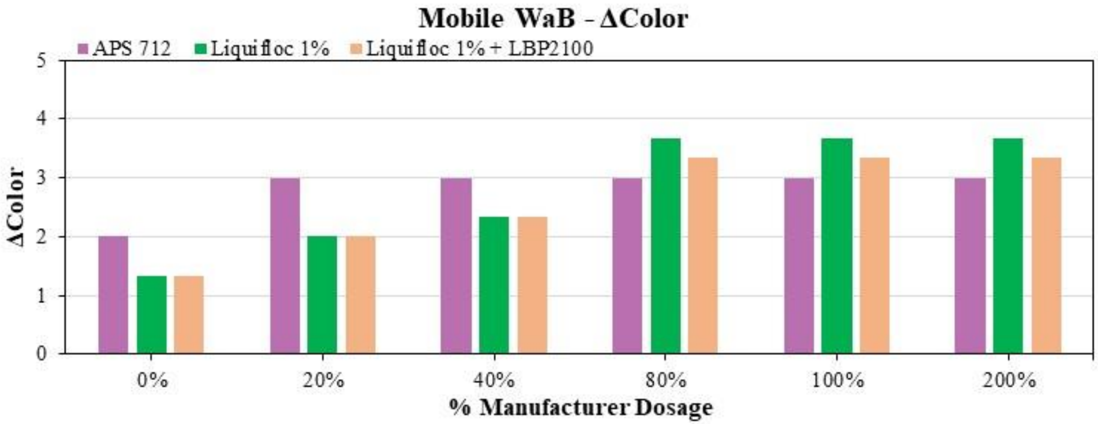
Product: **Liquifloc 1% + LBP 2101**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,282.3	1,389.2	1,411.9	1,434.1	1,496.8	1,535.6
ΔpH	0.05	0.04	0.06	0.04	0.03	0.06
ΔTemperature	0.8	0.4	0.2	0.1	0.1	0.1
ΔColor	1	2	2	3	3	3


Mobile WaB - ΔNTU
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2101
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile WaB - ΔpH
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2101
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile WaB - ΔTemperature
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2100
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile WaB - ΔColor
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2100
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**MaD**	**Sampling Location:**	**Mobile, AL**

Product: **H30**

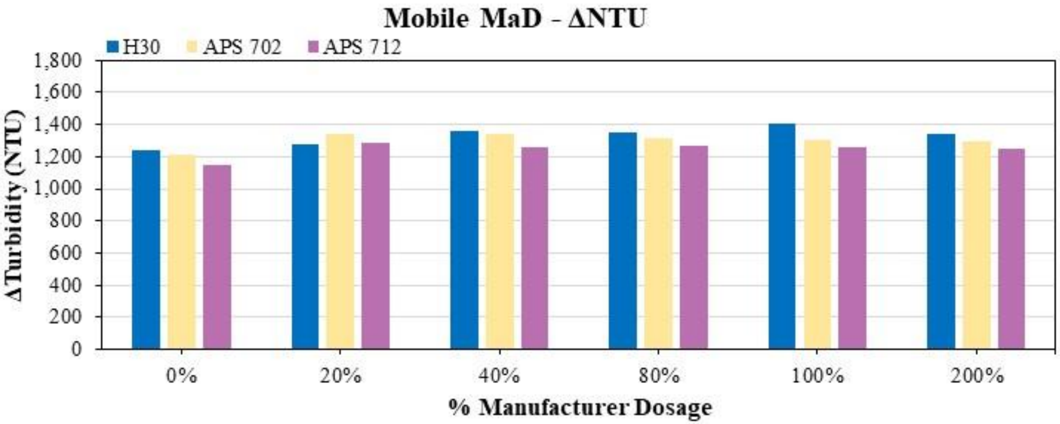
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,240.0	1,278.9	1,363.5	1,355.3	1,405.5	1,344.5
ΔpH	0.04	0.05	0.07	0.08	0.05	0.07
ΔTemperature	0.8	0.1	0.1	0.2	0.2	0.2
ΔColor	1	2	2	2	2	2

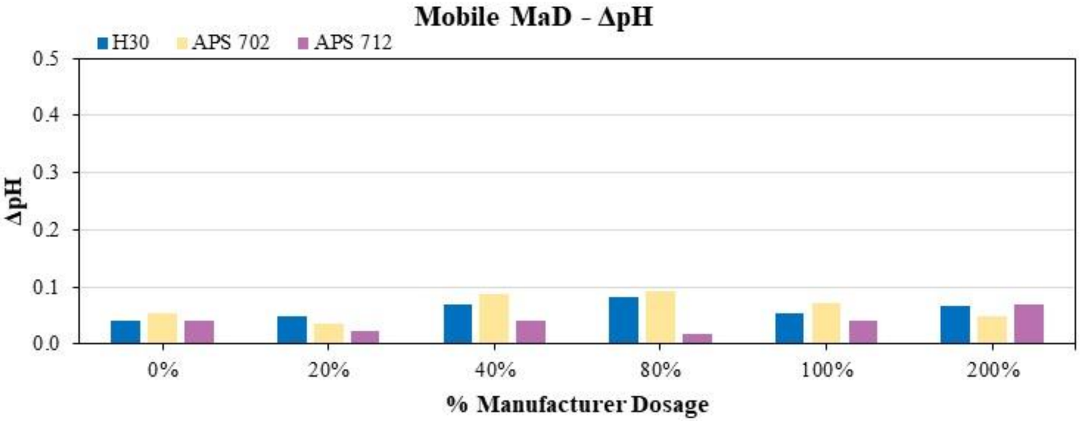
Product: **APS 702**

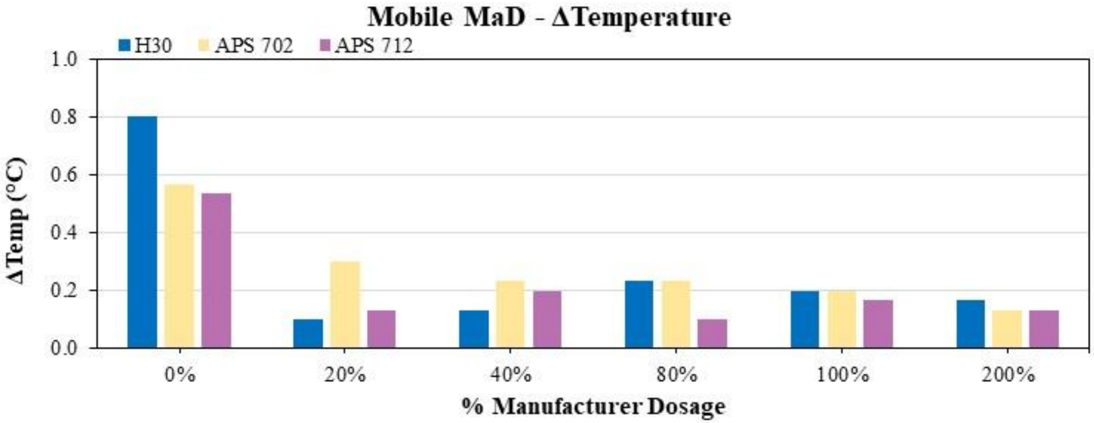
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,217.0	1,341.0	1,337.8	1,312.3	1,304.3	1,294.6
ΔpH	0.05	0.04	0.09	0.09	0.07	0.05
ΔTemperature	0.6	0.3	0.2	0.2	0.2	0.1
ΔColor	1	2	2	2	2	2

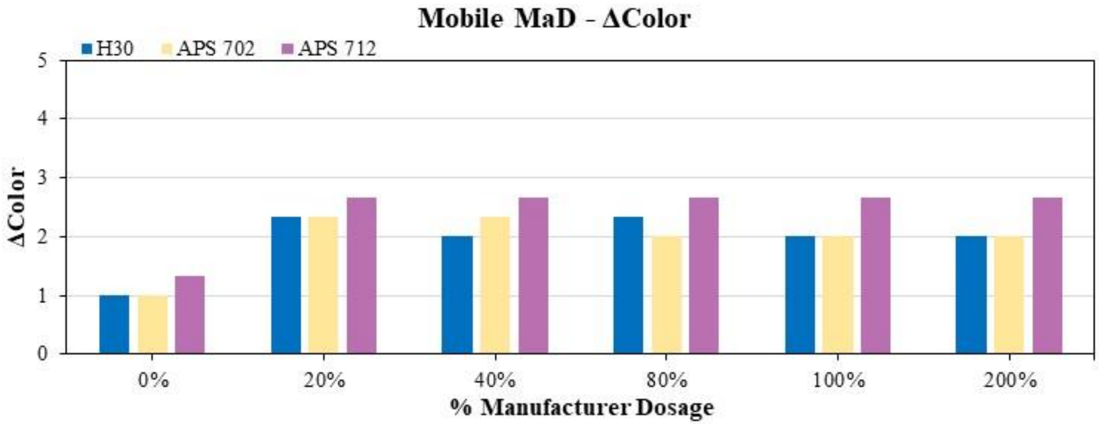
Product: **APS 712**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,150.5	1,281.9	1,259.5	1,272.4	1,255.3	1,246.9
ΔpH	0.04	0.02	0.04	0.02	0.04	0.07
ΔTemperature	0.5	0.1	0.2	0.1	0.2	0.1
ΔColor	1	3	3	3	3	3


Mobile MaD - ΔNTU
H30
APS 702
APS 712
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile MaD - ΔpH
H30
APS 702
APS 712
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile MaD - ΔTemperature
H30
APS 702
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile MaD - ΔColor
H30
APS 702
APS 712
ΔColor
5
4
3
2
1
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	BeB	Sampling Location:	Mobile, AL

Product: H30

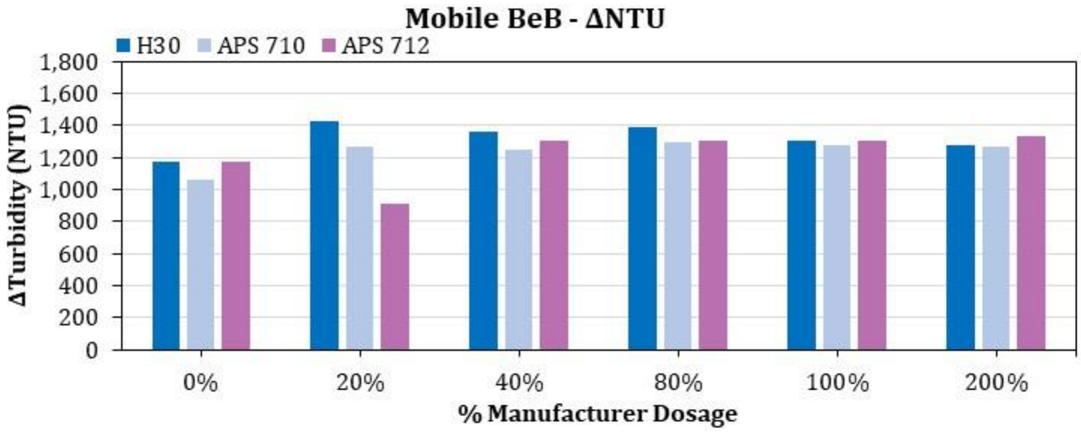
	JAR NUMBER					
	1	2	3	4	5	6
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,172.7	1,428.6	1,362.1	1,394.1	1,306.0	1,278.2
ΔpH	0.02	0.06	0.04	0.05	0.03	0.04
ΔTemperature	0.2	0.2	0.2	0.3	0.1	0.1
ΔColor	1	3	3	3	3	3

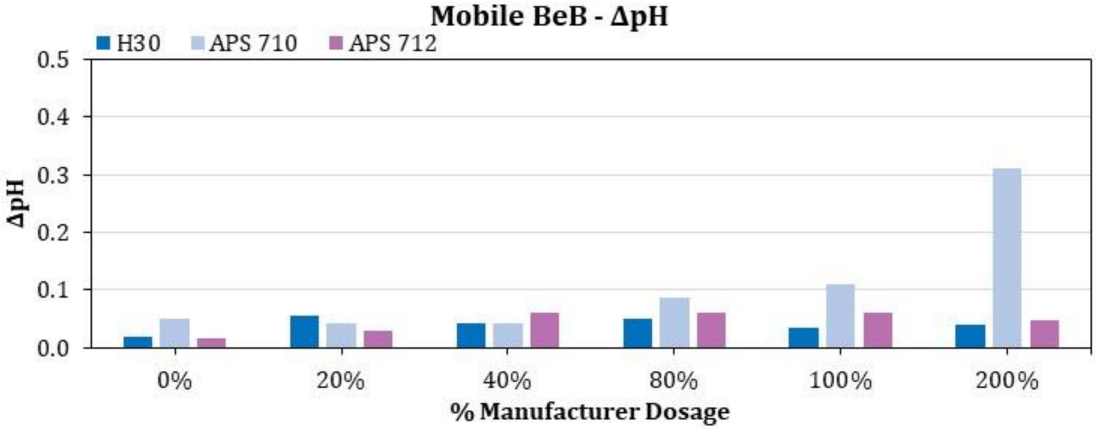
Product: APS 710

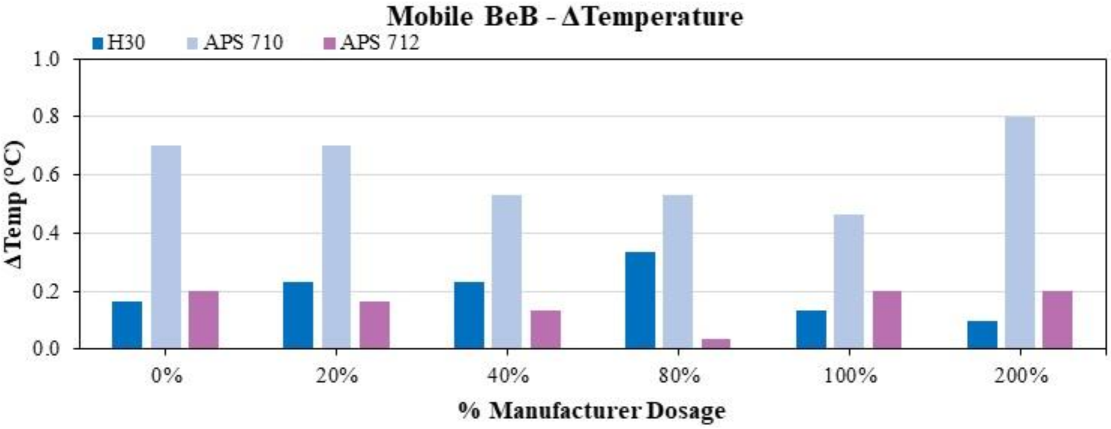
	JAR NUMBER					
	1	2	3	4	5	6
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,065.7	1,267.5	1,248.4	1,299.1	1,273.4	1,269.6
ΔpH	0.05	0.04	0.04	0.09	0.11	0.31
ΔTemperature	0.7	0.7	0.5	0.5	0.5	0.8
ΔColor	1	2	2	2	2	2

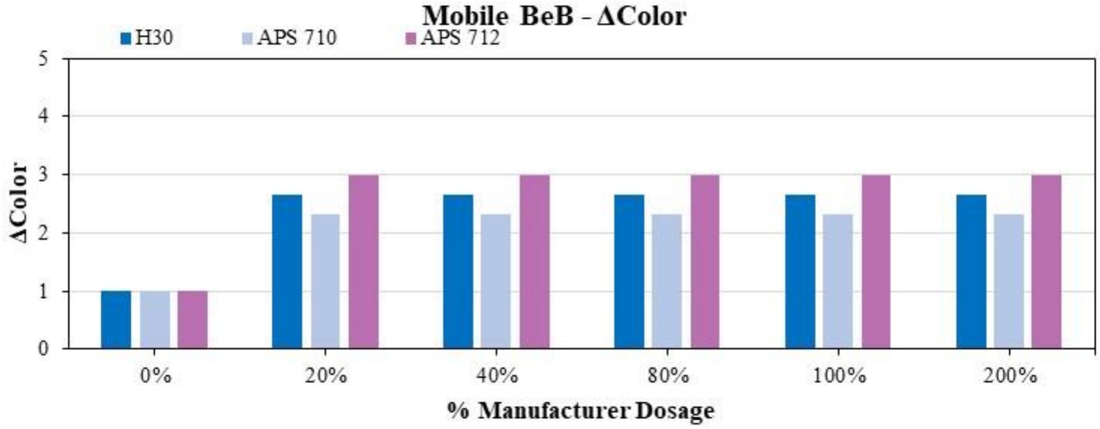
Product: APS 712

	JAR NUMBER					
	1	2	3	4	5	6
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,178.7	913.4	1,309.4	1,304.4	1,304.8	1,329.5
ΔpH	0.02	0.03	0.06	0.06	0.06	0.05
ΔTemperature	0.2	0.2	0.1	0.0	0.2	0.2
ΔColor	1	3	3	3	3	3


Mobile BeB - ΔNTU
H30
APS 710
APS 712
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile BeB - ΔpH
H30
APS 710
APS 712
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile BeB - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile BeB - ΔColor
H30
APS 710
APS 712
5
4
3
2
1
0
ΔColor
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**9**	**Sampling Location:**	**Etowah, AL**

Product: **APS 707**

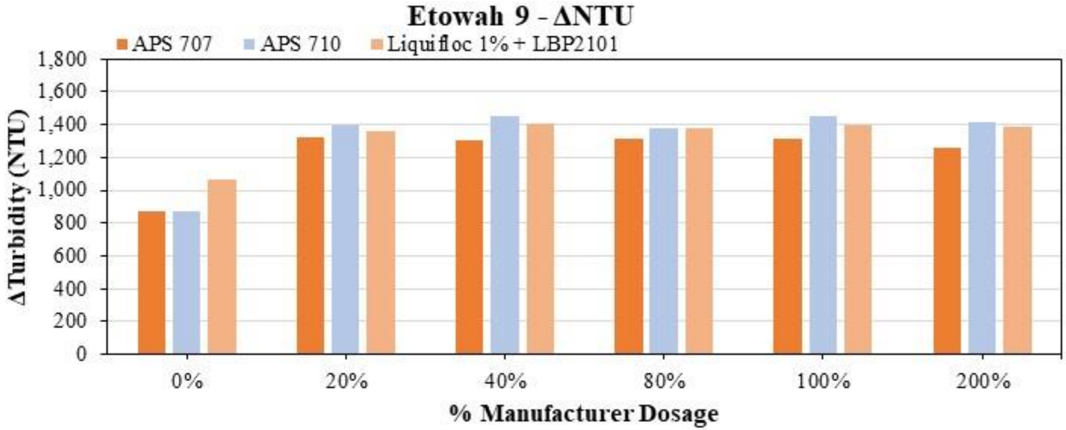
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	876.0	1,318.7	1,302.6	1,310.7	1,312.0	1,261.5
ΔpH	0.18	0.06	0.01	0.02	0.03	0.05
ΔTemperature	0.1	0.2	0.1	0.1	0.1	0.1
ΔColor	1	3	3	3	3	2

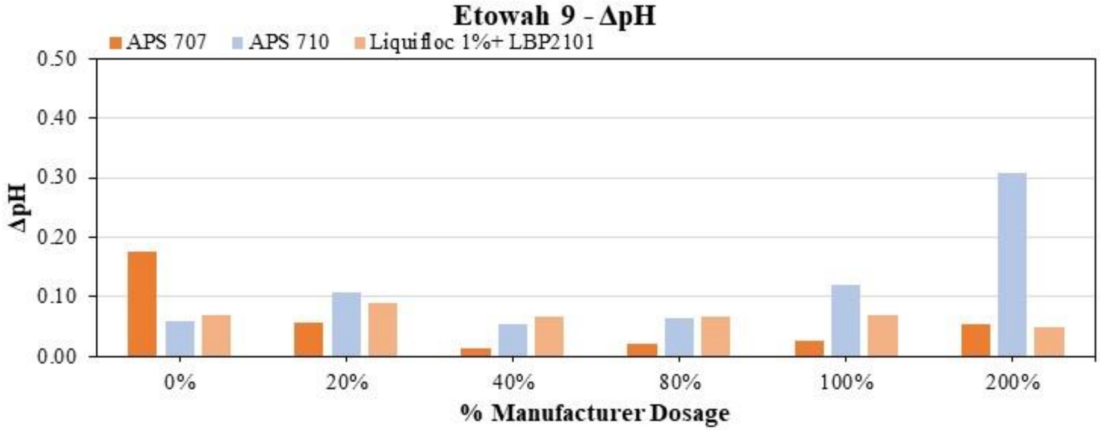
Product: **APS 710**

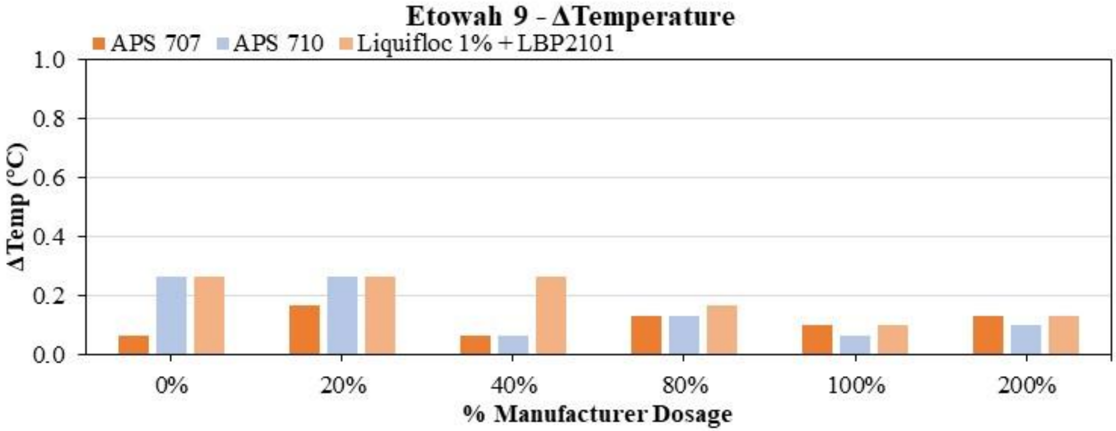
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	869.7	1,398.9	1,452.8	1,382.5	1,449.3	1,411.6
ΔpH	0.06	0.11	0.05	0.06	0.12	0.31
ΔTemperature	0.3	0.3	0.1	0.1	0.1	0.1
ΔColor	1	2	2	2	2	2

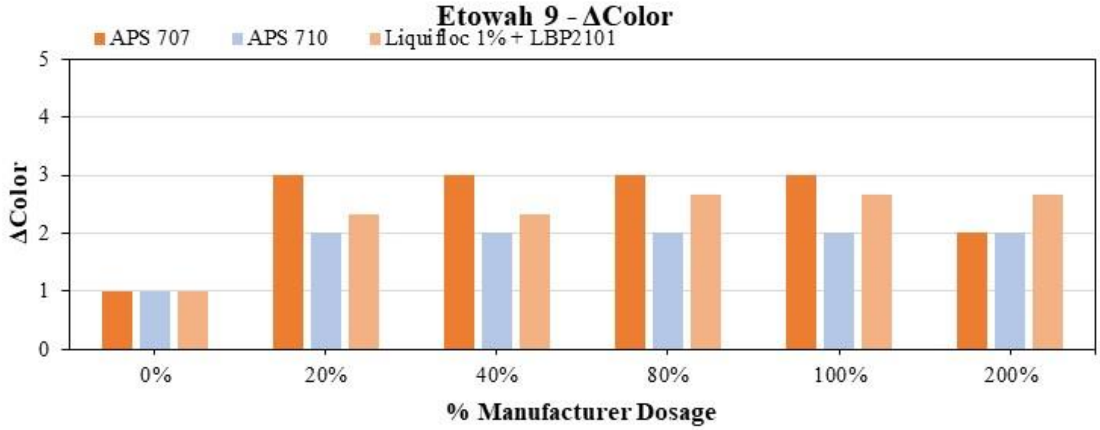
Product: **Liquifloc 1% + LBP2101**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,063.0	1,363.5	1,408.7	1,382.8	1,393.0	1,387.6
ΔpH	0.07	0.09	0.07	0.07	0.07	0.05
ΔTemperature	0.3	0.3	0.3	0.2	0.1	0.1
ΔColor	1	2	2	3	3	3


Etowah 9 - ΔNTU
APS 707
APS 710
Liquifloc 1% + LBP2101
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 9 - ΔpH
APS 707
APS 710
Liquifloc 1%+ LBP2101
ΔpH
0.50
0.40
0.30
0.20
0.10
0.00
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 9 - ΔTemperature
APS 707
APS 710
Liquifloc 1% + LBP2101
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 9 - ΔColor
APS 707
APS 710
Liquifloc 1% + LBP2101
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**18**	**Sampling Location:**	**Etowah, AL**

Product: **APS 710**

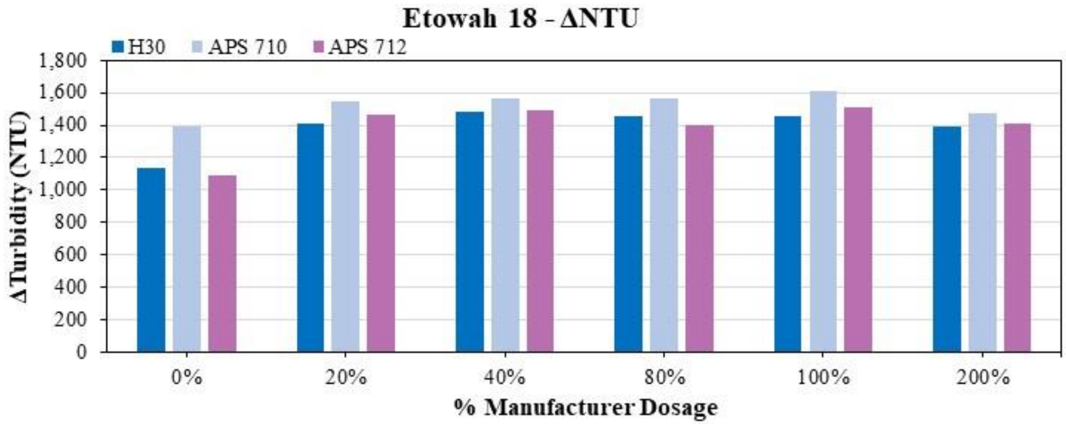
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,391.6	1,542.8	1,568.9	1,566.3	1,606.6	1,470.8
ΔpH	0.16	0.07	0.08	0.12	0.14	0.24
ΔTemperature	0.5	0.1	0.1	0.2	0.1	0.3
ΔColor	1	3	3	3	3	2

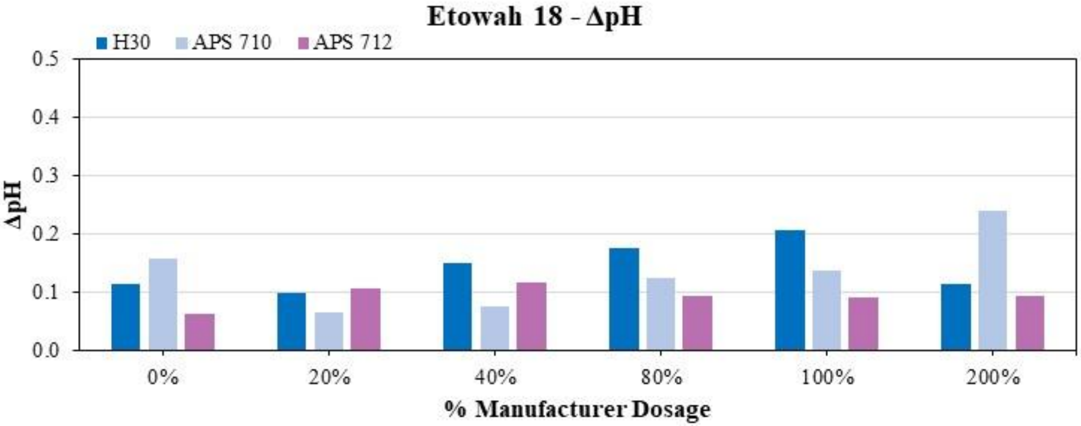
Product: **APS 712**

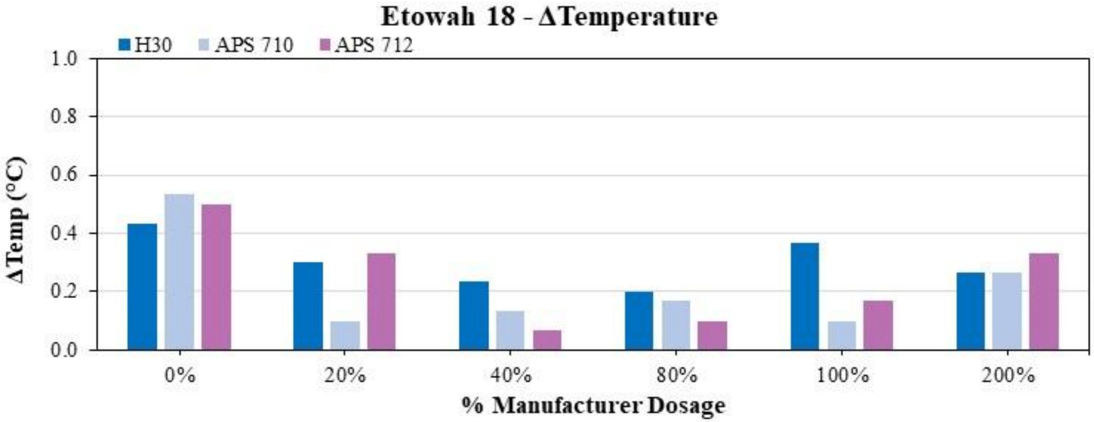
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,090.7	1,464.6	1,493.5	1,400.8	1,514.3	1,409.5
ΔpH	0.06	0.11	0.12	0.09	0.09	0.09
ΔTemperature	0.5	0.3	0.1	0.1	0.2	0.3
ΔColor	1	3	3	3	3	3

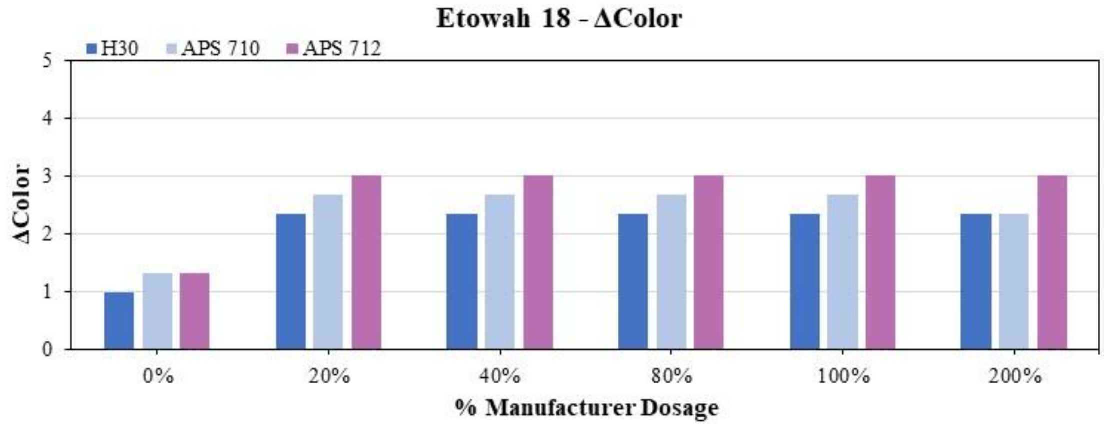
Product: **H30**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,134.0	1,409.7	1,478.4	1,459.3	1,453.2	1,387.6
ΔpH	0.11	0.10	0.15	0.18	0.21	0.11
ΔTemperature	0.4	0.3	0.2	0.2	0.4	0.3
ΔColor	1	2	2	2	2	2


Etowah 18 - ΔNTU
H30
APS 710
APS 712
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 18 - ΔpH
H30
APS 710
APS 712
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 18 - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 18 - ΔColor
H30
APS 710
APS 712
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**43**	**Sampling Location:**	**Etowah, AL**

Product: **H30**

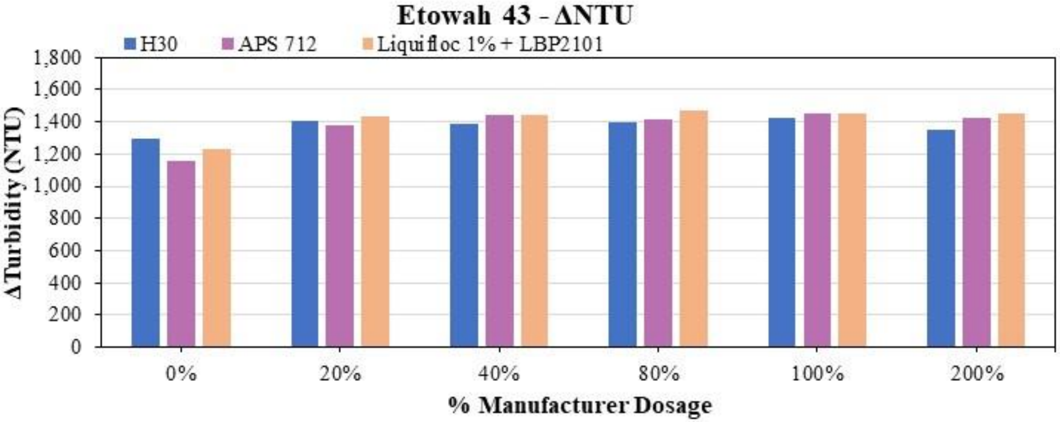
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,300.0	1,403.7	1,385.0	1,400.6	1,422.8	1,355.1
ΔpH	0.09	0.15	0.20	0.21	0.16	0.23
ΔTemperature	0.5	0.4	0.3	0.2	0.2	0.3
ΔColor	1	3	2	2	2	2

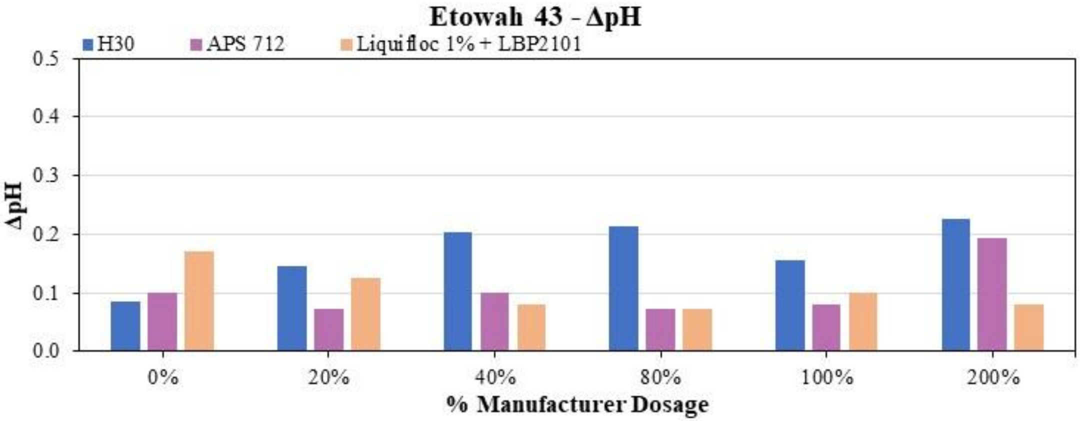
Product: **APS 712**

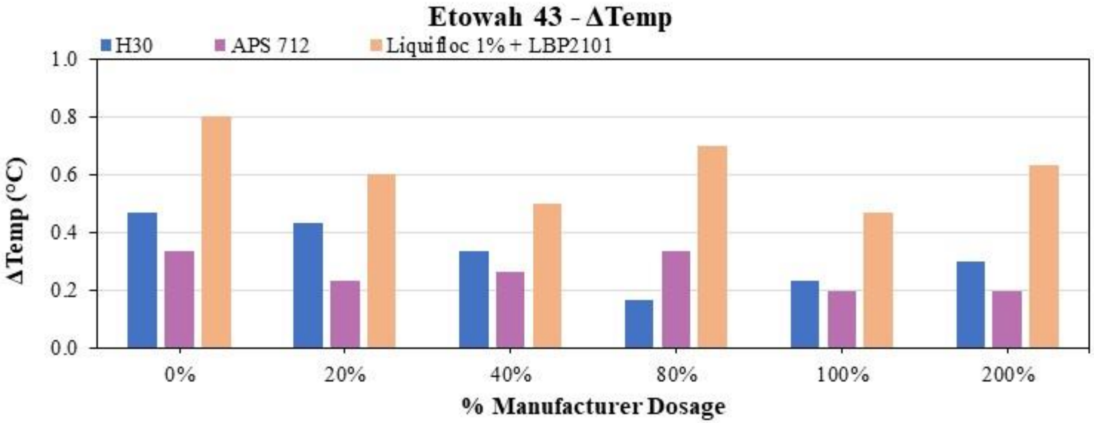
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,155.0	1,375.5	1,444.1	1,413.1	1,456.5	1,424.4
ΔpH	0.10	0.07	0.10	0.07	0.08	0.19
ΔTemperature	0.3	0.2	0.3	0.3	0.2	0.2
ΔColor	1	3	3	3	3	3

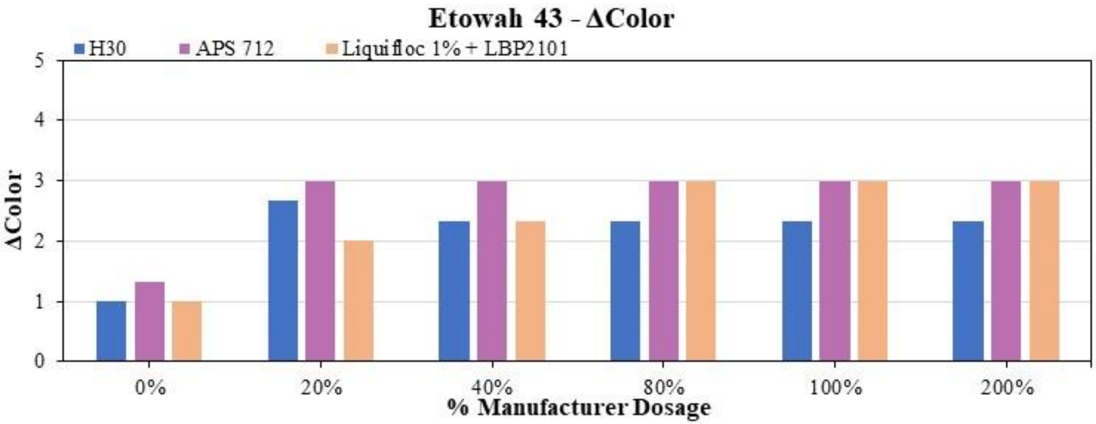
Product: **Liquifloc 1% + LBP 2101**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,234.7	1,436.6	1,445.6	1,468.2	1,449.8	1,451.0
ΔpH	0.17	0.13	0.08	0.07	0.10	0.08
ΔTemperature	0.8	0.6	0.5	0.7	0.5	0.6
ΔColor	1	2	2	3	3	3


Etowah 43 - ΔNTU
H30
APS 712
Liquifloc 1% + LBP2101
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 43 - ΔpH
H30
APS 712
Liquifloc 1% + LBP2101
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 43 - ΔTemp
H30
APS 712
Liquifloc 1% + LBP2101
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 43 - ΔColor
H30
APS 712
Liquifloc 1% + LBP2101
ΔColor
5
4
3
2
1
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**TsE**	**Sampling Location:**	**Shelby, AL**

Product: **H30**

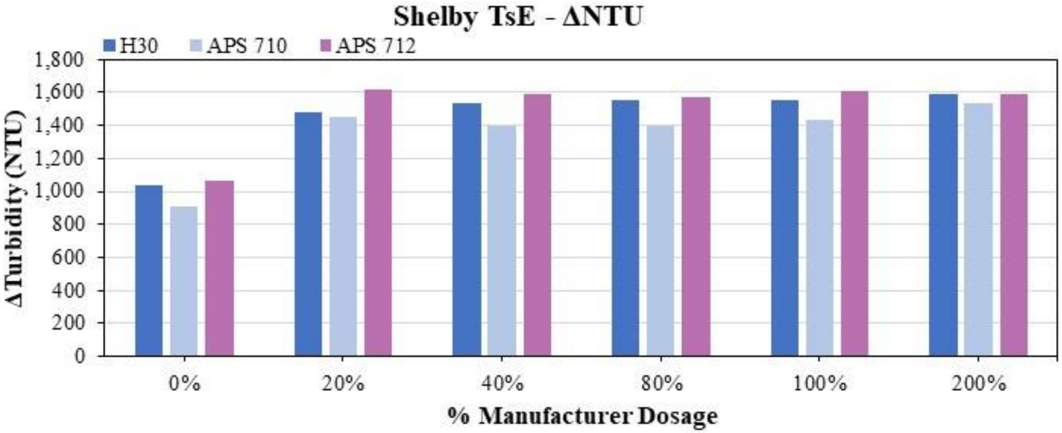
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,041.3	1,475.3	1,539.7	1,553.9	1,558.2	1,593.6
ΔpH	0.05	0.08	0.11	0.09	0.07	0.05
ΔTemperature	0.4	0.1	0.2	0.2	0.2	0.3
ΔColor	1	2	2	2	2	2

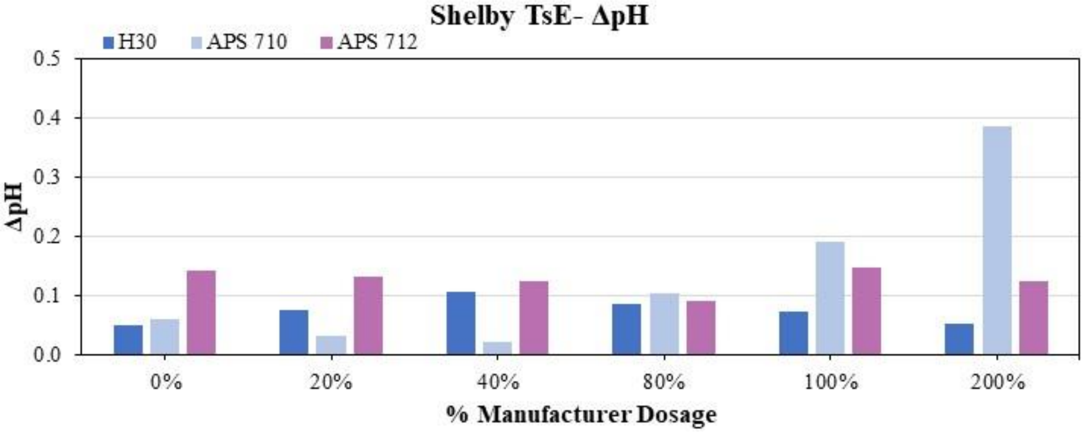
Product: **APS 710**

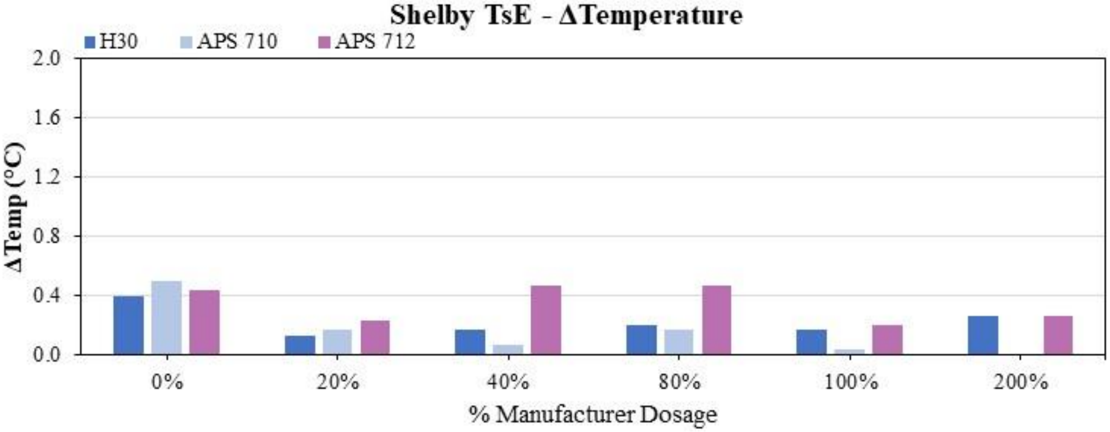
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	907.7	1,455.7	1,400.8	1,399.2	1,430.8	1,532.8
ΔpH	0.06	0.03	0.02	0.10	0.19	0.39
ΔTemperature	0.5	0.2	0.1	0.2	0.0	0.0
ΔColor	1	2	2	2	2	2

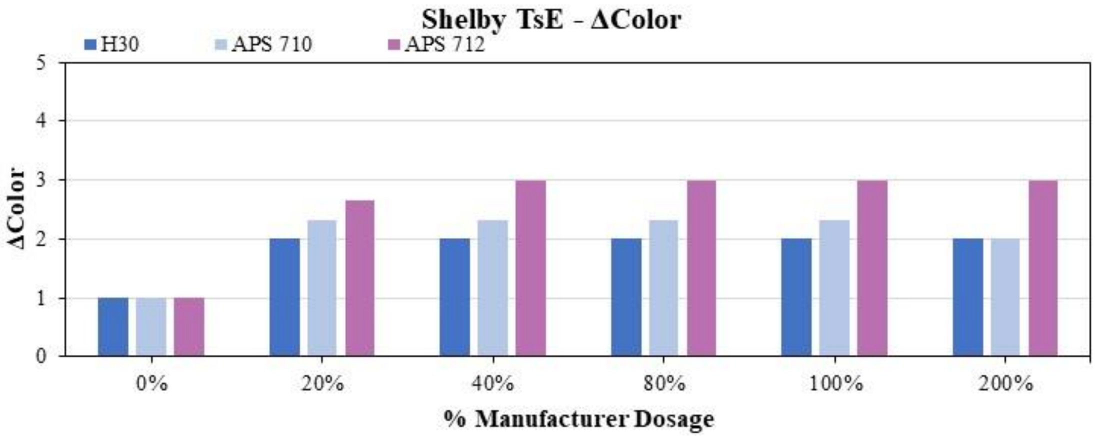
Product: **APS 712**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,068.0	1,618.6	1,594.2	1,570.9	1,610.3	1,587.4
ΔpH	0.14	0.13	0.12	0.09	0.15	0.12
ΔTemperature	0.4	0.2	0.5	0.5	0.2	0.3
ΔColor	1	3	3	3	3	3


Shelby TsE - ΔNTU
H30
APS 710
APS 712
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Shelby TsE- ΔpH
H30
APS 710
APS 712
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Shelby TsE - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
2.0
1.6
1.2
0.8
0.4
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Shelby TsE - ΔColor
H30
APS 710
APS 712
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**TtE**	**Sampling Location:**	**Shelby, AL**

Product: **H30**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	908.7	1,284.9	1,271.9	1,273.2	1,237.9	1,239.4
ΔpH	0.06	0.12	0.10	0.07	0.08	0.13
ΔTemperature	0.2	0.2	0.3	0.2	0.3	0.2
ΔColor	1	2	2	2	2	2

Product: **APS 712**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	981.3	1,284.2	1,303.4	1,273.8	1,239.4	1,282.4
ΔpH	0.06	0.07	0.06	0.08	0.10	0.07
ΔTemperature	0.2	0.2	0.1	0.2	0.1	0.0
ΔColor	1	3	3	3	3	3

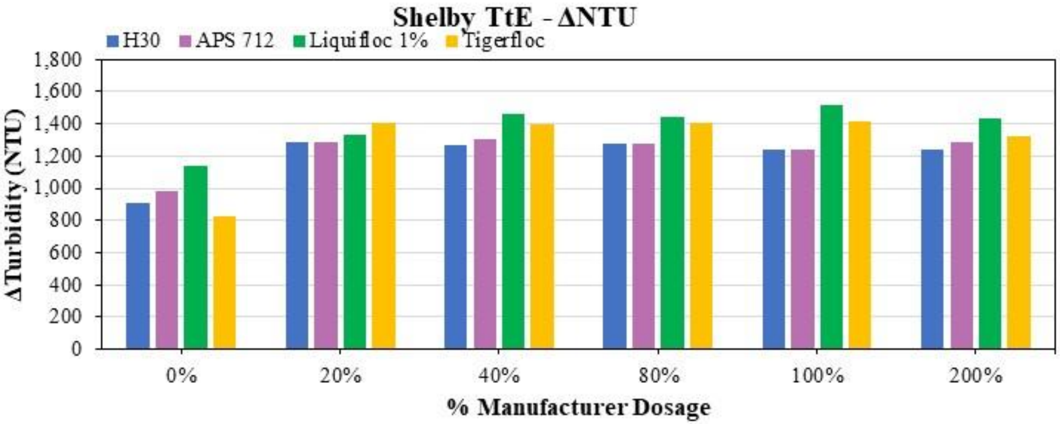
Product: **Liquifloc 1%**

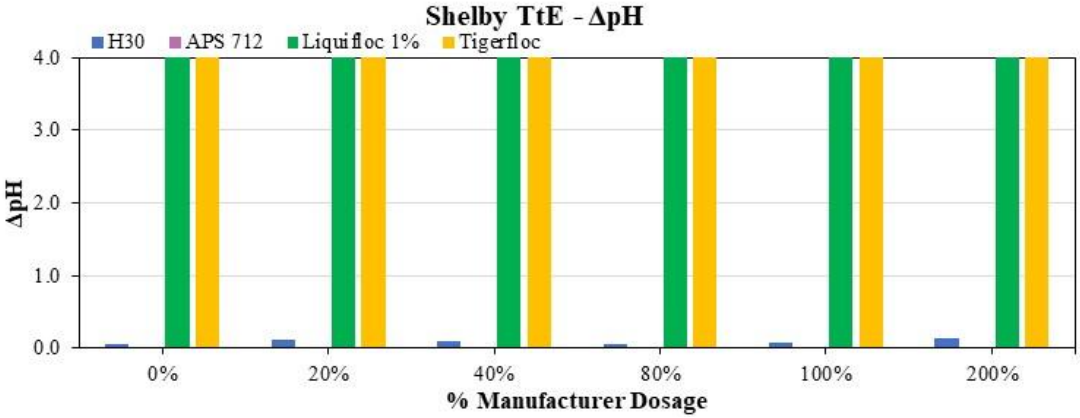
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,138.0	1,330.4	1,463.7	1,447.3	1,518.3	1,429.5
ΔpH	0.03	0.06	0.05	0.05	0.06	0.05
ΔTemperature	0.1	0.1	0.1	0.3	0.2	0.3
ΔColor	1	2	2	3	3	3

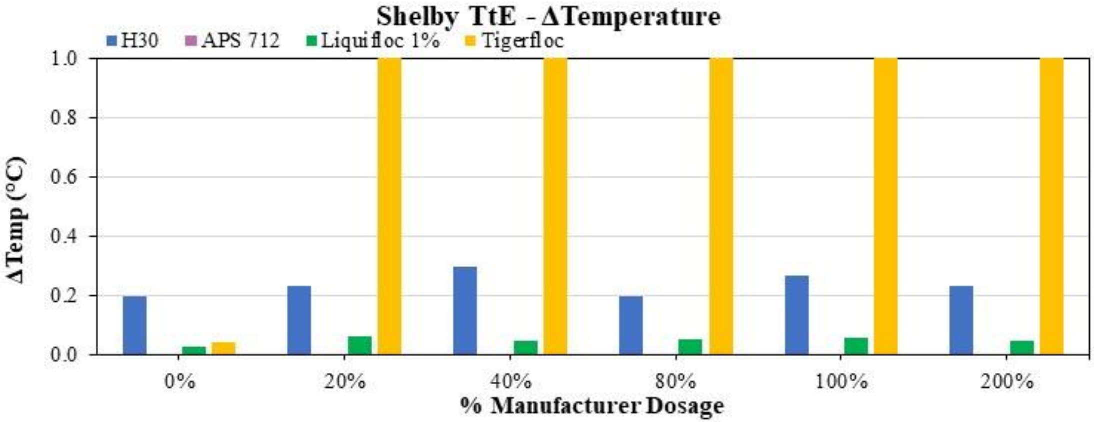
Product: **Tigerfloc**

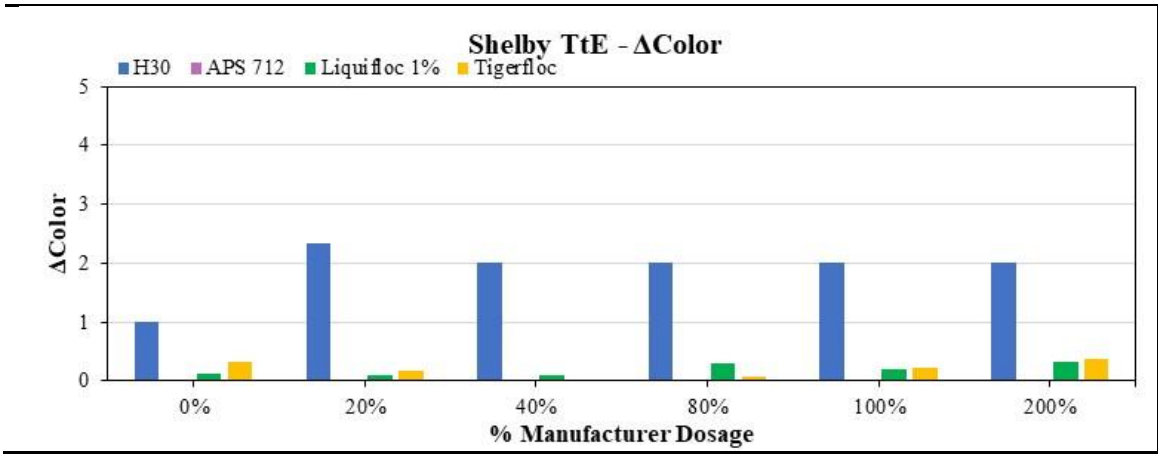
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	400	800	1,600	2,000	4,000
ΔNTU	830.3	1,403.0	1,397.5	1,408.0	1,411.6	1,320.7
ΔpH	0.04	1.62	2.78	3.08	3.12	3.31

ΔTemperature	0.3	0.2	0.0	0.1	0.2	0.4
ΔColor	1	3	3	3	3	3








Shelby TtE - ΔColor
H30
APS 712
Liquifloc 1%
Tigerfloc
ΔColor
5
4
3
2
1
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**CmA**	**Sampling Location:**	**Bibb, AL**

Product: **H30**

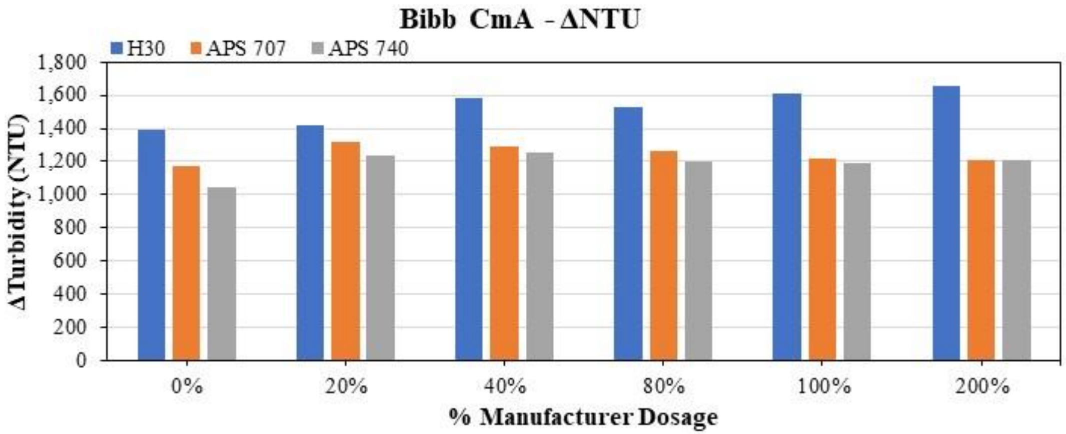
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,391.7	1,422.4	1,584.1	1,532.2	1,609.6	1,656.6
ΔpH	0.15	0.13	0.16	0.12	0.11	0.15
ΔTemperature	0.5	0.5	0.4	0.4	0.5	0.5
ΔColor	1	2	2	2	2	2

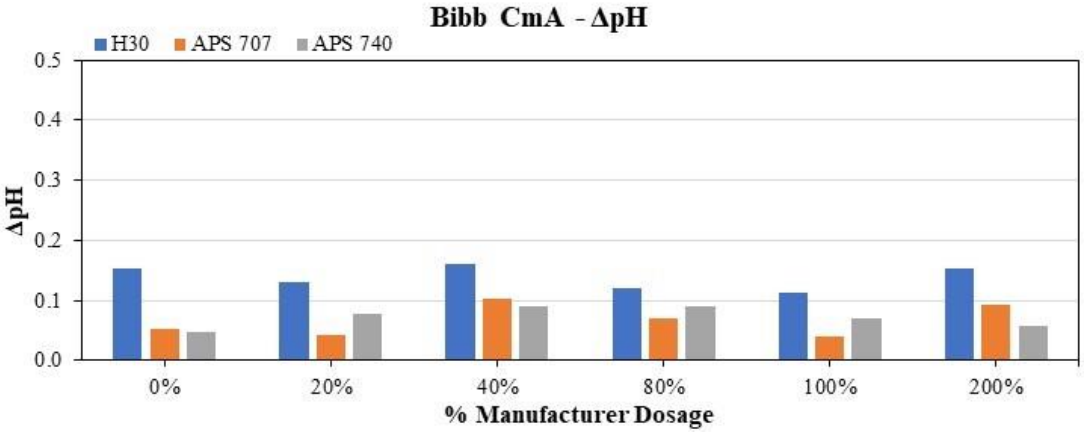
Product: **APS 707**

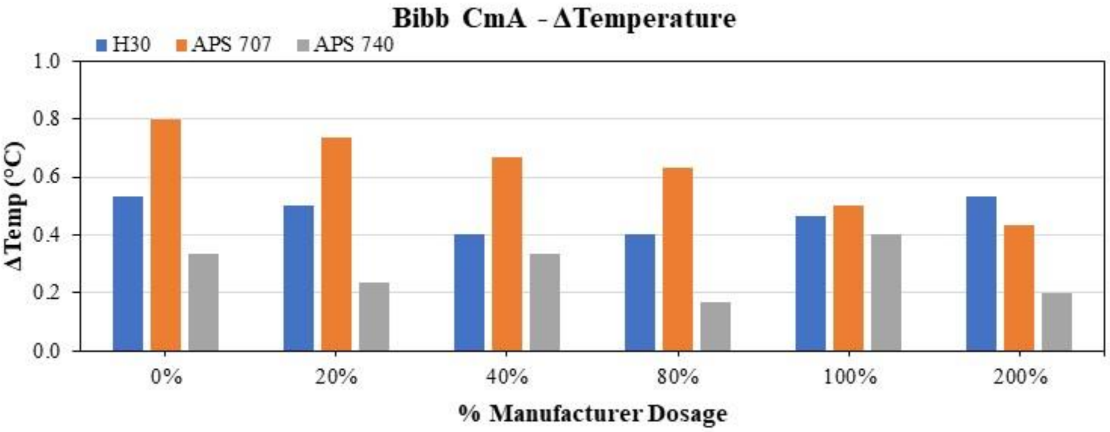
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,168.4	1,313.6	1,291.1	1,259.2	1,217.1	1,208.4
ΔpH	0.05	0.04	0.10	0.07	0.04	0.09
ΔTemperature	0.8	0.7	0.7	0.6	0.5	0.4
ΔColor	1	3	3	2	2	2

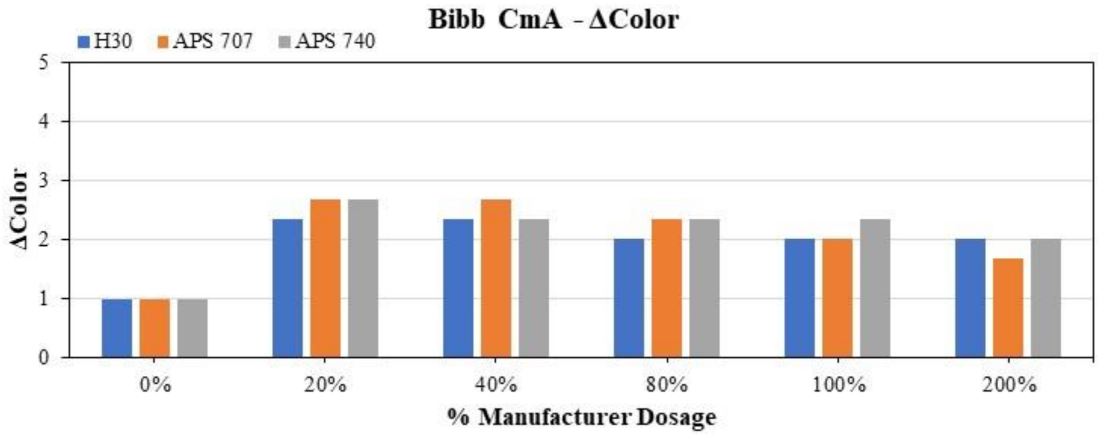
Product: **APS 740**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,046.3	1,240.2	1,254.0	1,202.2	1,187.9	1,205.4
ΔpH	0.05	0.08	0.09	0.09	0.07	0.06
ΔTemperature	0.3	0.2	0.3	0.2	0.4	0.2
ΔColor	1	3	2	2	2	2


Bibb CmA - ΔNTU
H30
APS 707
APS 740
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb CmA - ΔpH
H30
APS 707
APS 740
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb CmA - ΔTemperature
H30
APS 707
APS 740
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb CmA - ΔColor
H30
APS 707
APS 740
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**MIA**	**Sampling Location:**	**Bibb, AL**

Product: **H30**

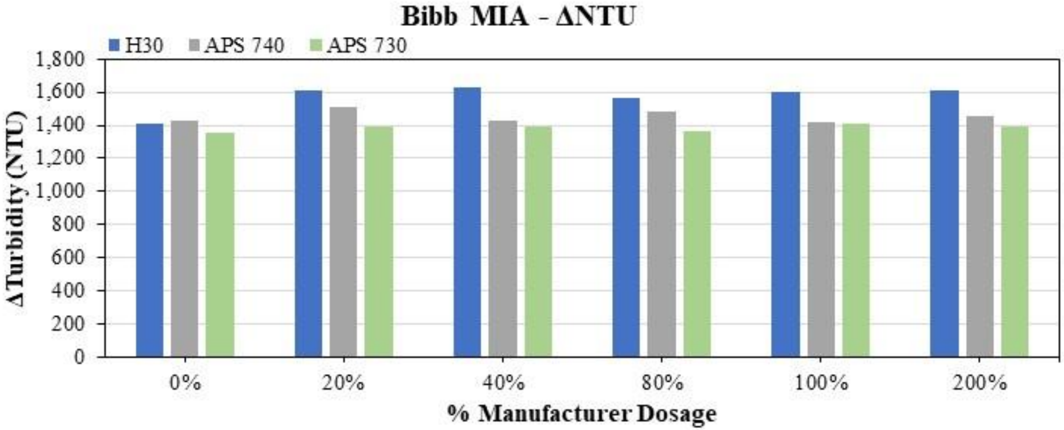
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,408.5	1,606.5	1,628.9	1,566.7	1,598.1	1,613.8
ΔpH	0.29	0.46	0.37	0.37	0.26	0.24
ΔTemperature	0.3	0.5	0.1	0.1	0.1	0.1
ΔColor	2	3	3	3	3	3

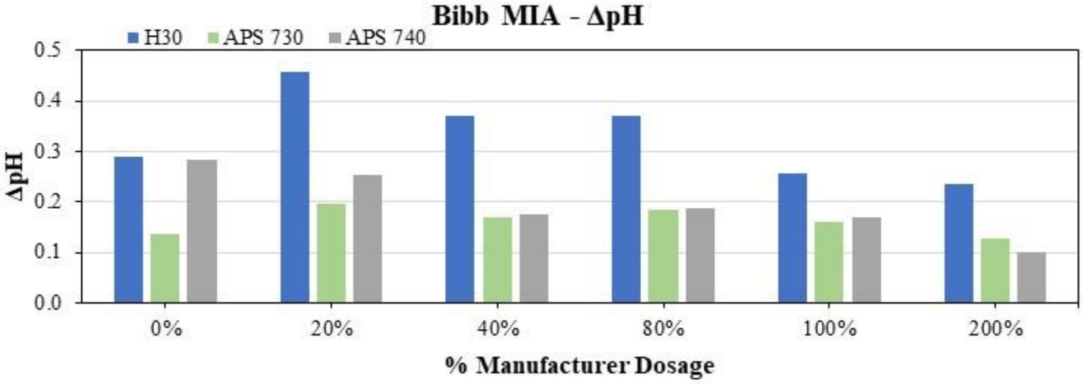
Product: **APS 730**

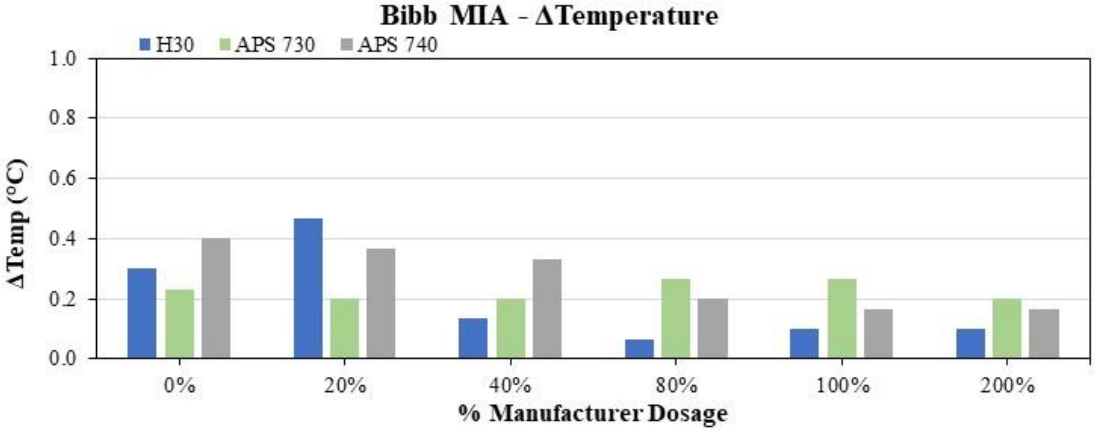
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,358.4	1,386.8	1,394.6	1,366.1	1,413.5	1,392.3
ΔpH	0.14	0.20	0.17	0.18	0.16	0.13
ΔTemperature	0.2	0.2	0.2	0.3	0.3	0.2
ΔColor	1	3	3	3	3	3

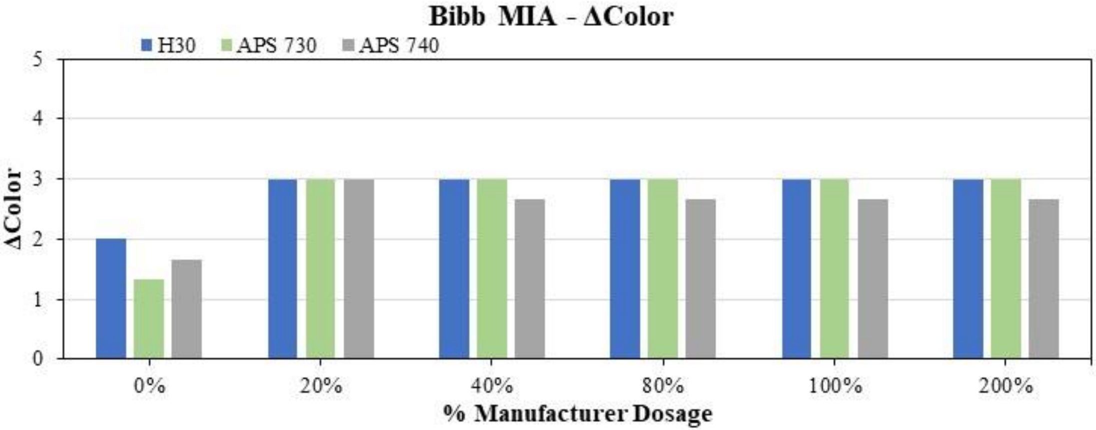
Product: **APS 740**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,424.1	1,510.6	1,426.0	1,480.3	1,415.4	1,455.5
ΔpH	0.28	0.25	0.18	0.19	0.17	0.10
ΔTemperature	0.4	0.4	0.3	0.2	0.2	0.2
ΔColor	2	3	3	3	3	3


Bibb MIA - ΔNTU
H30
APS 740
APS 730
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb MIA - ΔpH
H30
APS 730
APS 740
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb MIA - ΔTemperature
H30
APS 730
APS 740
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb MIA - ΔColor
H30
APS 730
APS 740
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

Soil ID:	**IdB**	**Sampling Location:**	**Montgomery, AL**

Product: **H30**

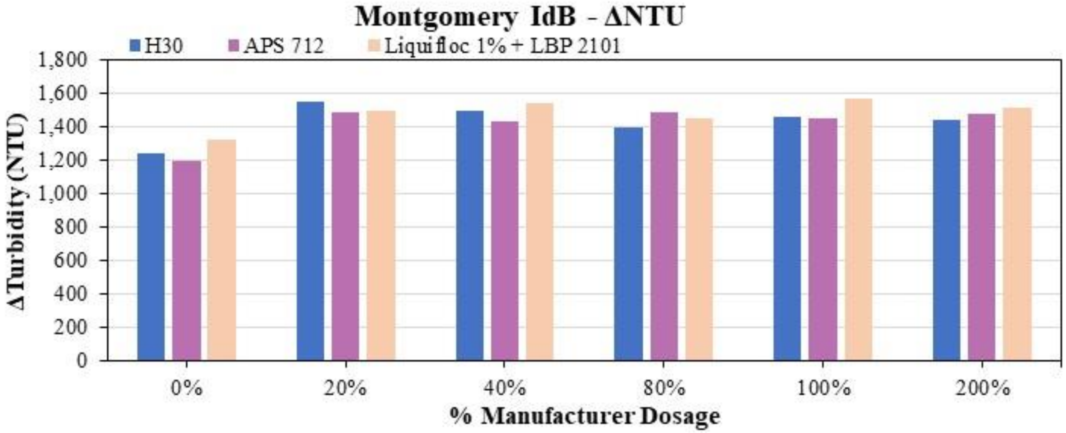
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,242.7	1,549.9	1,495.3	1,398.0	1,456.3	1,444.5
ΔpH	0.10	0.12	0.11	0.13	0.12	0.08
ΔTemperature	0.5	0.5	0.4	0.3	0.4	0.4
ΔColor	1	3	3	3	2	2

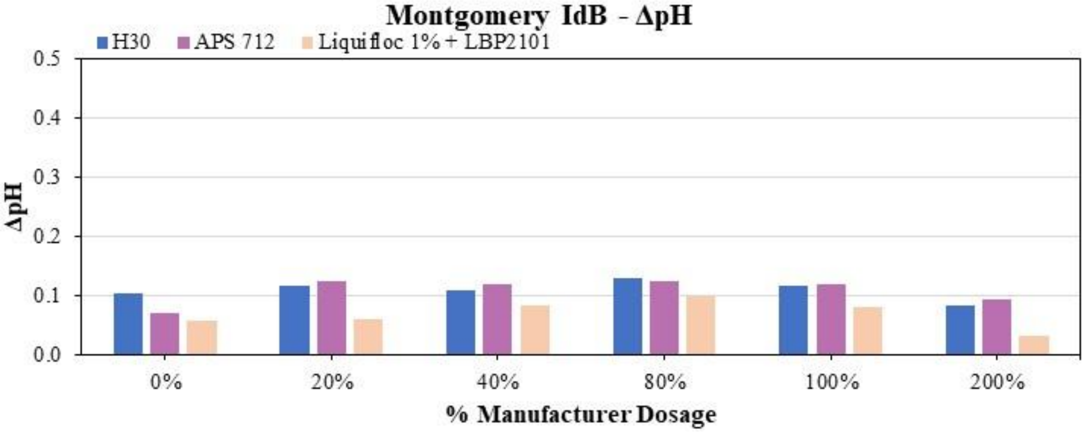
Product: **APS 712**

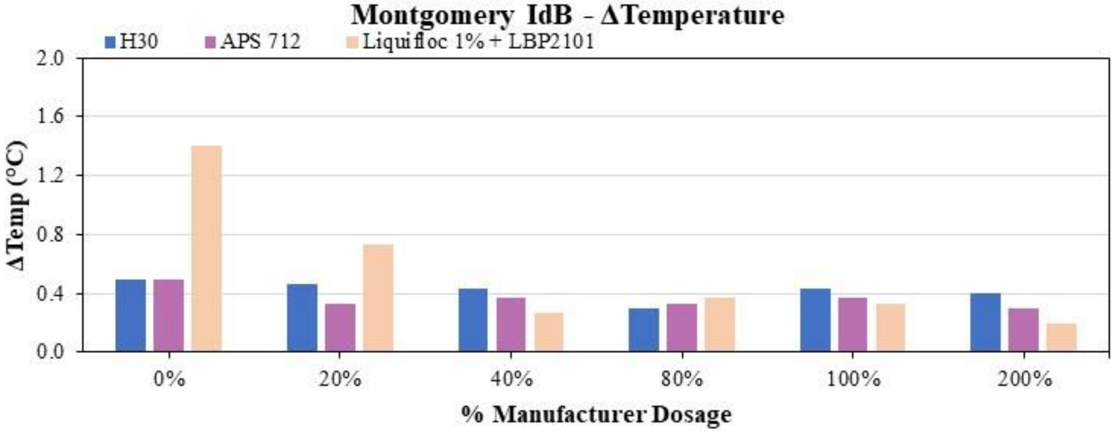
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,196.3	1,484.1	1,428.4	1,483.7	1,445.4	1,473.3
ΔpH	0.07	0.12	0.12	0.12	0.12	0.09
ΔTemperature	0.5	0.3	0.4	0.3	0.4	0.3
ΔColor	1	3	3	3	3	3

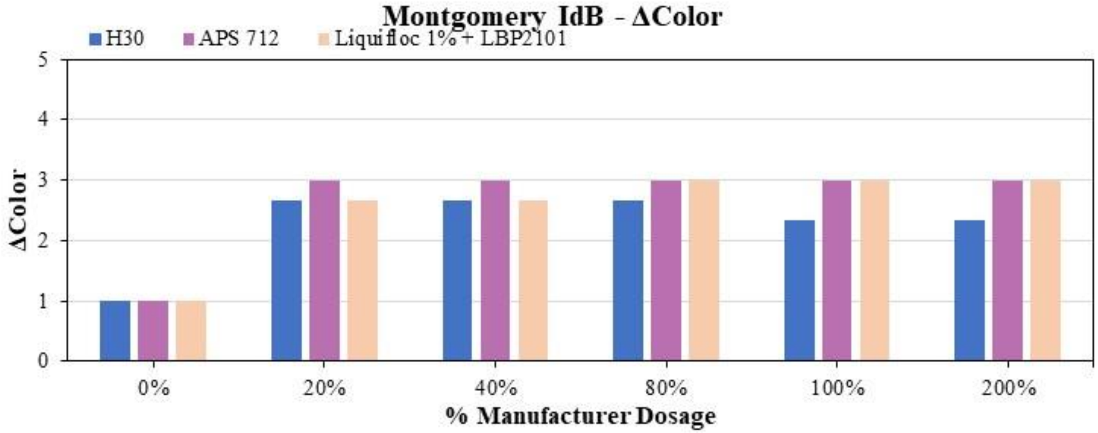
Product: **Liquifloc 1% + LBP 2101**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,324.7	1,495.2	1,539.8	1,451.6	1,566.2	1,511.1
ΔpH	0.06	0.06	0.08	0.10	0.08	0.03
ΔTemperature	1.4	0.7	0.3	0.4	0.3	0.2
ΔColor	1	3	3	3	3	3


Montgomery IdB - ΔNTU
H30
APS 712
Liquifloc 1% + LBP 2101
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery IdB - ΔpH
H30
APS 712
Liquifloc 1% + LBP2101
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery IdB - ΔTemperature
H30
APS 712
Liquifloc 1% + LBP2101
ΔTemp (°C)
2.0
1.6
1.2
0.8
0.4
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery IdB - ΔColor
H30
APS 712
Liquifloc 1% + LBP2101
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

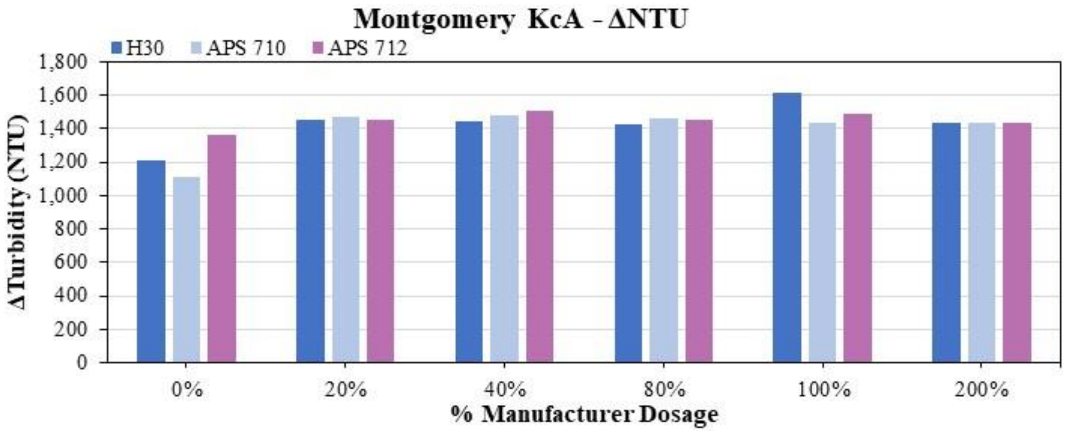
Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 10/08/2021
Prepared By: Billur Kazaz

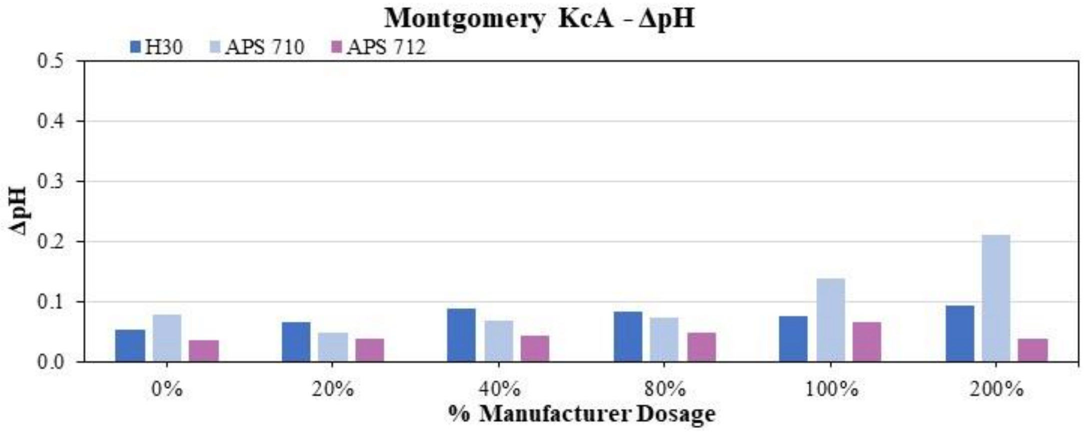
Soil ID:	**KcA**	**Sampling Location:**	**Montgomery, AL**

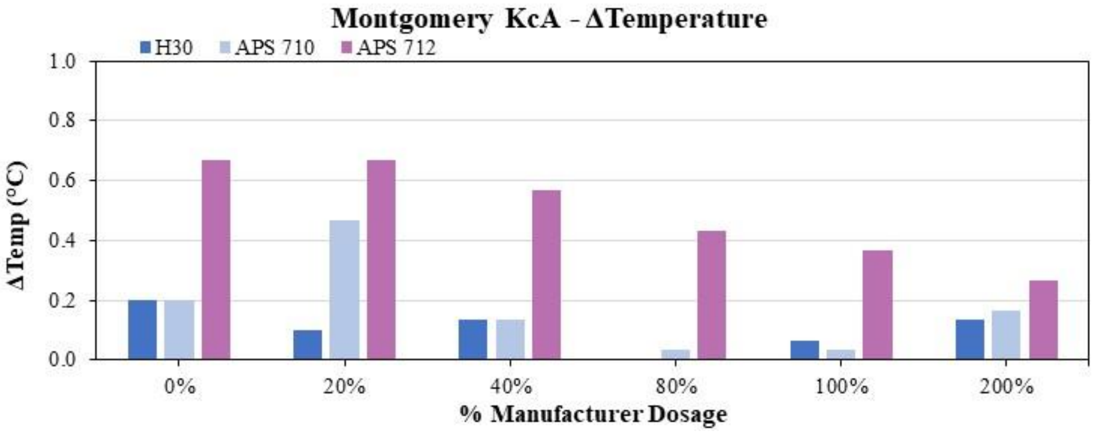
Product:	**H3O**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,210.7	1,449.7	1,445.9	1,421.4	1,617.6	1,430.5
ΔpH	0.05	0.07	0.09	0.08	0.08	0.09
ΔTemperature	0.2	0.1	0.1	0.0	0.1	0.1
ΔColor	1	3	3	3	3	3

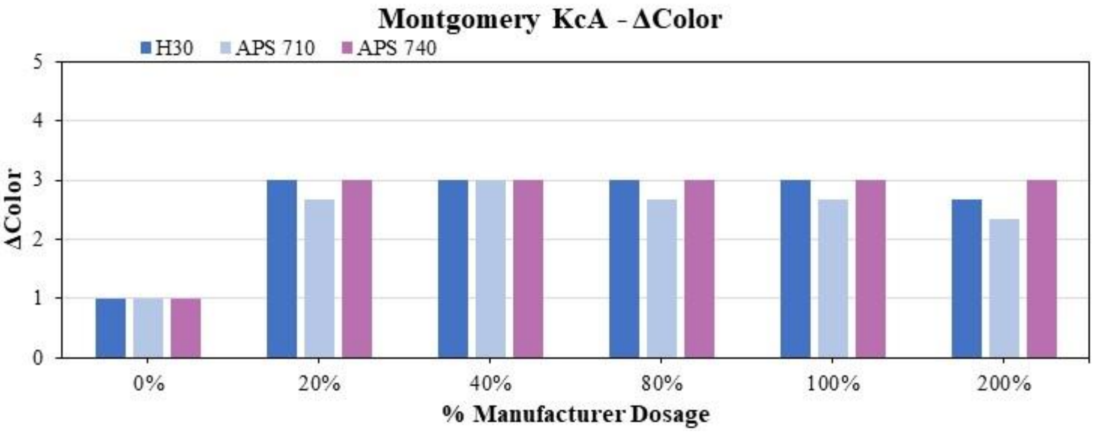
Product:	**APS 710**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,114.7	1,471.3	1,474.7	1,461.2	1,435.7	1,434.1
ΔpH	0.08	0.05	0.07	0.07	0.14	0.21
ΔTemperature	0.2	0.5	0.1	0.0	0.0	0.2
ΔColor	1	3	3	3	3	2

Product:	**APS 712**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,366.3	1,456.3	1,501.9	1,453.4	1,485.2	1,438.3
ΔpH	0.04	0.04	0.04	0.05	0.07	`0.04
ΔTemperature	0.7	0.7	0.6	0.4	0.4	0.3
ΔColor	1	3	3	3	3	3


Montgomery KcA - ΔNTU
H30
APS 710
APS 712
ΔTurbidity (NTU)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery KcA - ΔpH
H30
APS 710
APS 712
ΔpH
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery KcA - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery KcA - ΔColor
H30
APS 710
APS 740
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/18/2022
Prepared By: Billur Kazaz

Soil ID:	**AU-SRF**	**Sampling Location:**	**Opelika, AL**

Product: **H3O**

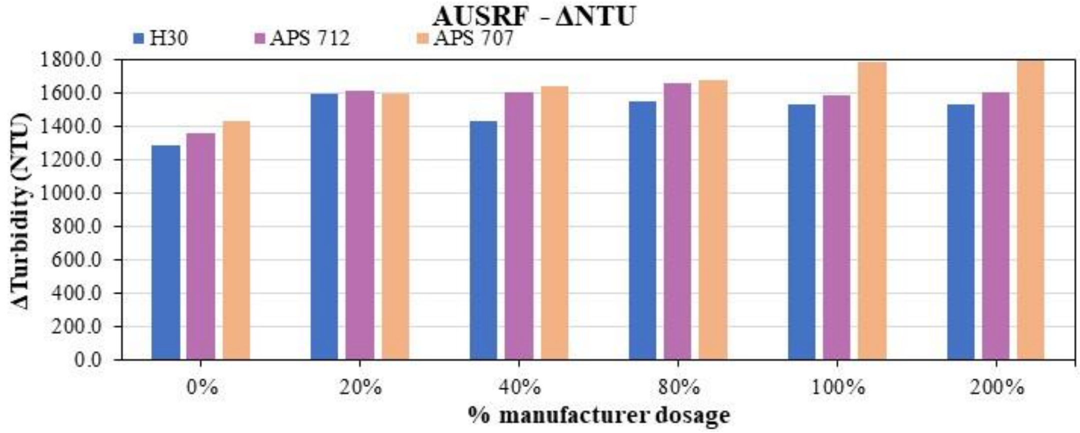
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1281.7	1589.8	1434.2	1546.0	1529.1	1528.8
ΔpH	0.49	0.09	0.07	0.10	0.15	0.54
ΔTemperature	0.8	0.8	0.8	0.8	1.3	1.8
ΔColor	1	3	3	3	3	3

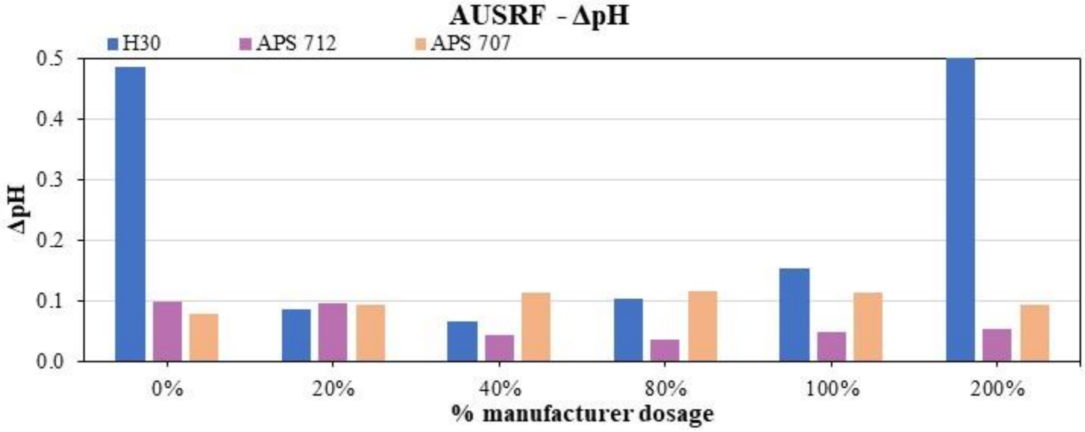
Product: **APS 712**

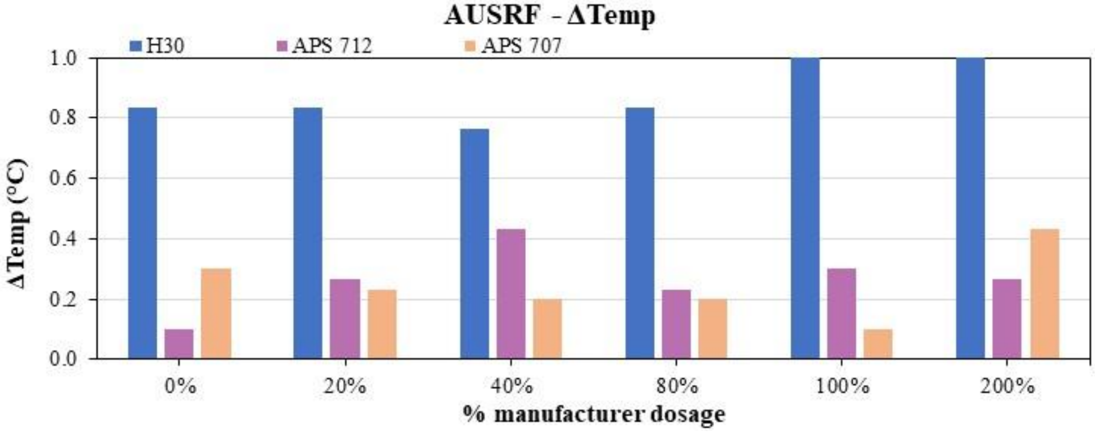
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1355.0	1614.3	1605.1	1661.5	1586.4	1600.6
ΔpH	0.10	0.10	0.04	0.04	0.05	0.05
ΔTemperature	0.1	0.3	0.4	0.2	0.3	0.3
ΔColor	1	3	3	3	3	3

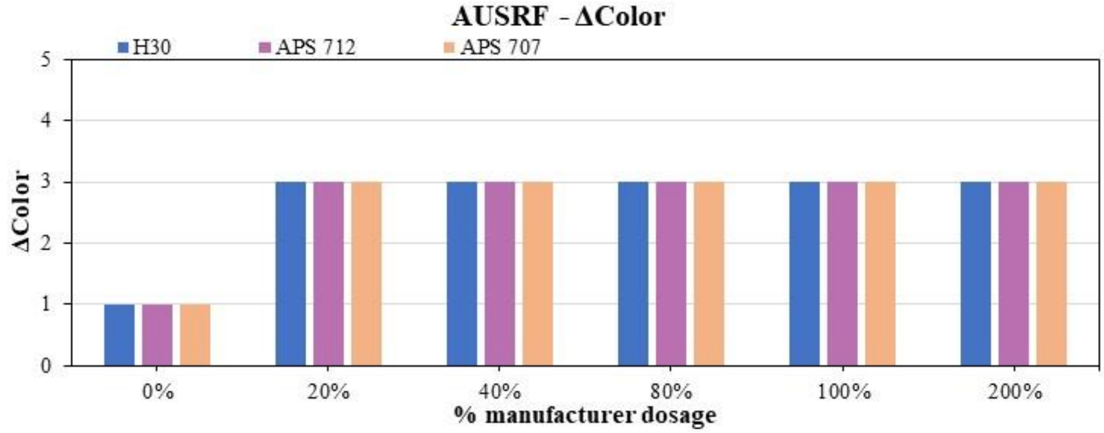
Product: **APS 712**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1428.3	1591.4	1635.6	1677.5	1780.3	1796.9
ΔpH	0.08	0.09	0.11	0.12	0.11	0.09
ΔTemperature	0.3	0.2	0.2	0.2	0.1	0.4
ΔColor	1	3	3	3	3	3


AUSRF - ΔNTU
H30
APS 712
APS 707
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
ΔTurbidity (NTU)
0%
20%
40%
80%
100%
200%
% manufacturer dosage


AUSRF - ΔpH
H30
APS 712
APS 707
0.5
0.4
0.3
0.2
0.1
0.0
ΔpH
0%
20%
40%
80%
100%
200%
% manufacturer dosage


AUSRF - ΔTemp
H30
APS 712
APS 707
1.0
0.8
0.6
0.4
0.2
0.0
ΔTemp (°C)
0%
20%
40%
80%
100%
200%
% manufacturer dosage


AUSRF - ΔColor
H30
APS 712
APS 707
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% manufacturer dosage

Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/18/2022
Prepared By: Billur Kazaz

Soil ID:	**Silty Clay**	**Sampling Location:**	**Montgomery, AL**

Product: **H3O**

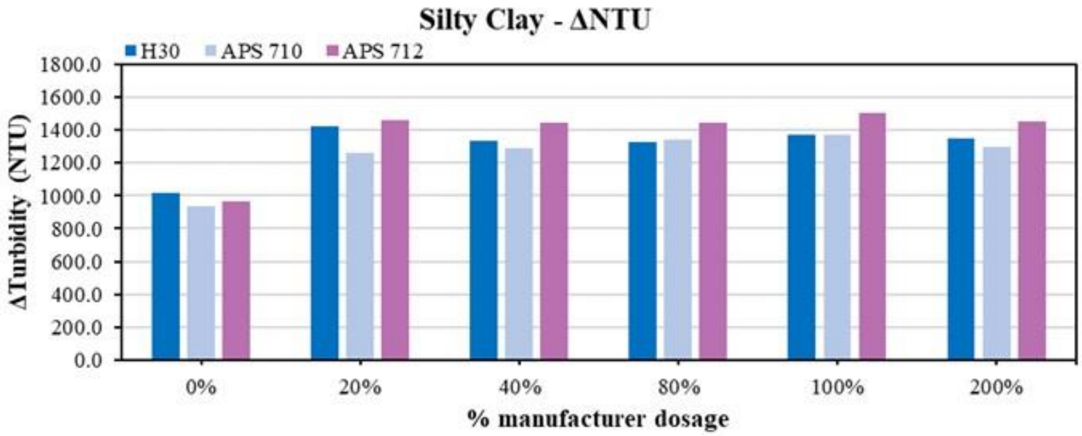
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1016.3	1423.8	1334.4	1329.8	1368.3	1351.5
ΔpH	0.42	0.38	0.35	0.34	0.26	0.30
ΔTemperature	0.7	0.7	0.6	0.3	0.1	0.2
ΔColor	1	2	2	2	2	2

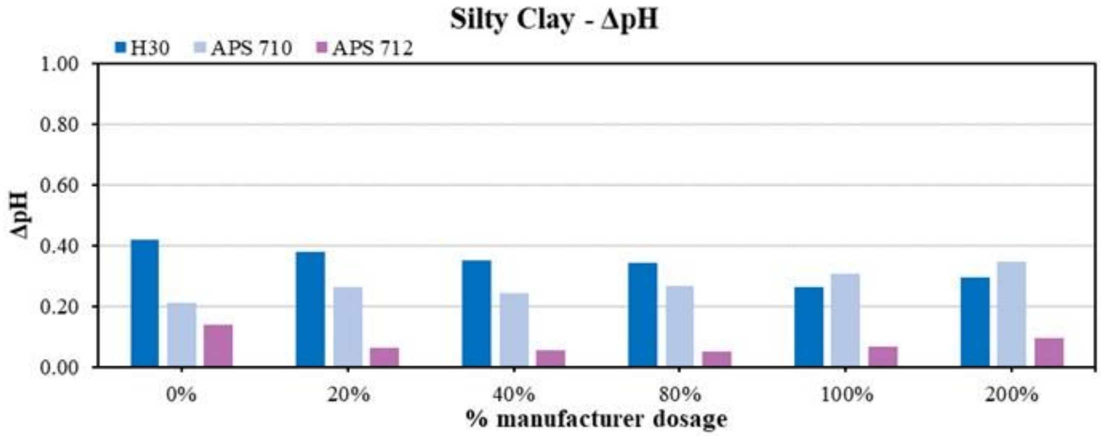
Product: **APS 710**

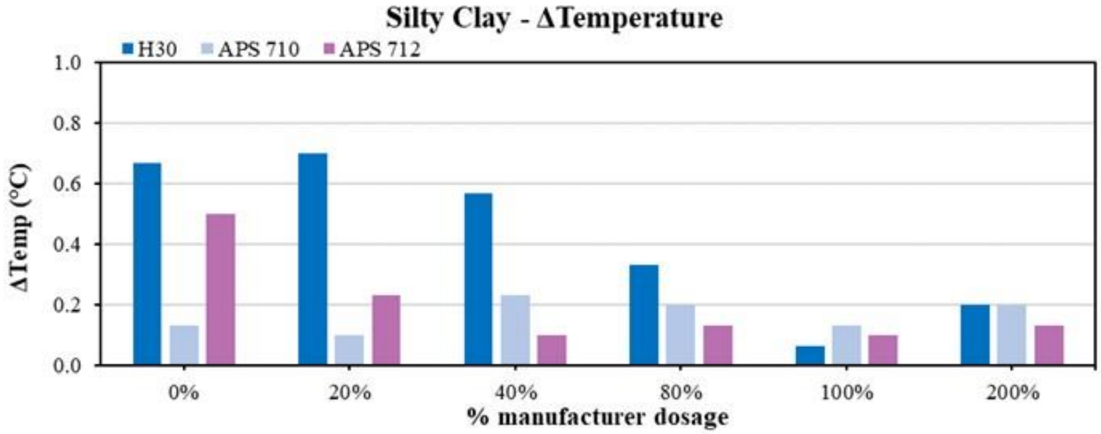
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	938.7	1259.1	1288.8	1341.3	1373.1	1300.8
ΔpH	0.21	0.26	0.24	0.27	0.31	0.35
ΔTemperature	0.1	0.1	0.2	0.2	0.1	0.2
ΔColor	1	2	2	2	2	2

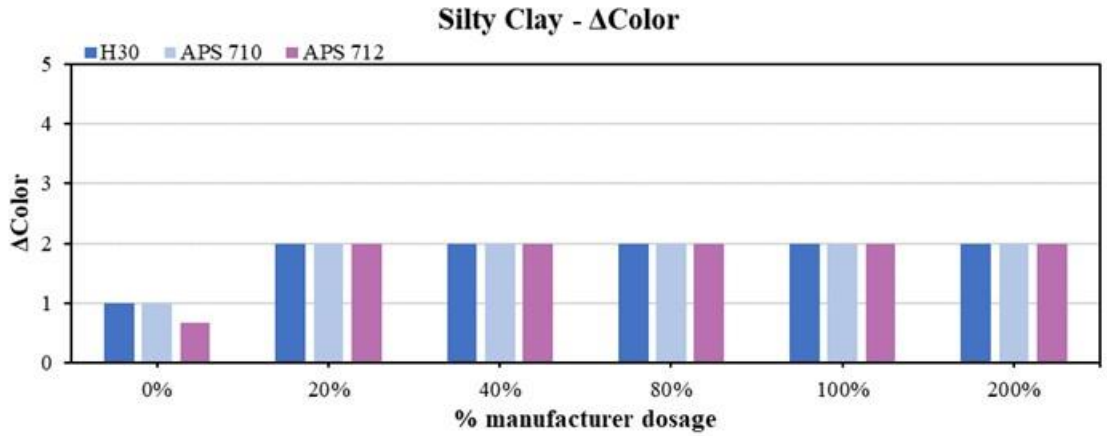
Product: **APS 712**

	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	969.3	1456.5	1443.9	1443.1	1506.9	1449.9
ΔpH	0.14	0.07	0.06	0.05	0.07	0.10
ΔTemperature	0.5	0.2	0.1	0.1	0.1	0.1
ΔColor	1	2	2	2	2	2


Silty Clay - ΔNTU
H30
APS 710
APS 712
ΔTurbidity (NTU)
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Silty Clay - ΔpH
H30
APS 710
APS 712
ΔpH
1.00
0.80
0.60
0.40
0.20
0.00
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Silty Clay - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Silty Clay - ΔColor
H30
APS 710
APS 712
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% manufacturer dosage

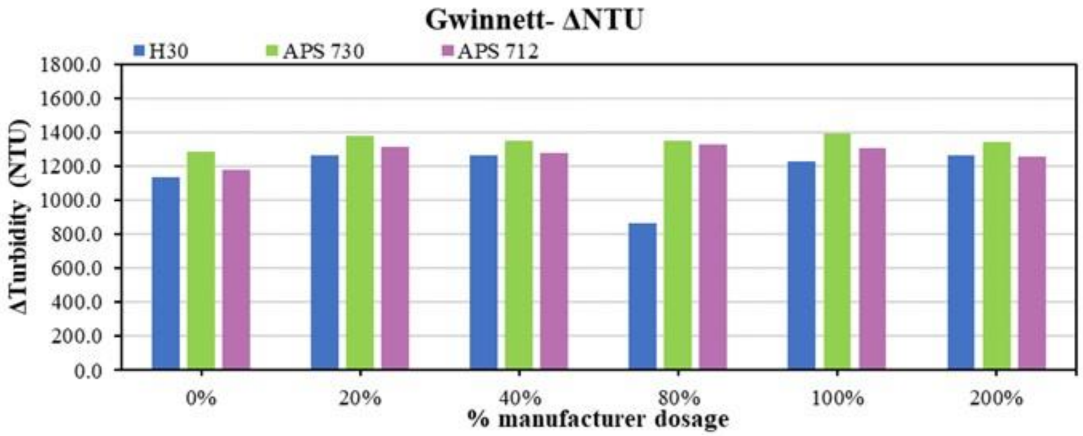
Project: Best Practices for Construction Stormwater Treatment Using Flocculants
Date: 03/25/2022
Prepared By: Billur Kazaz

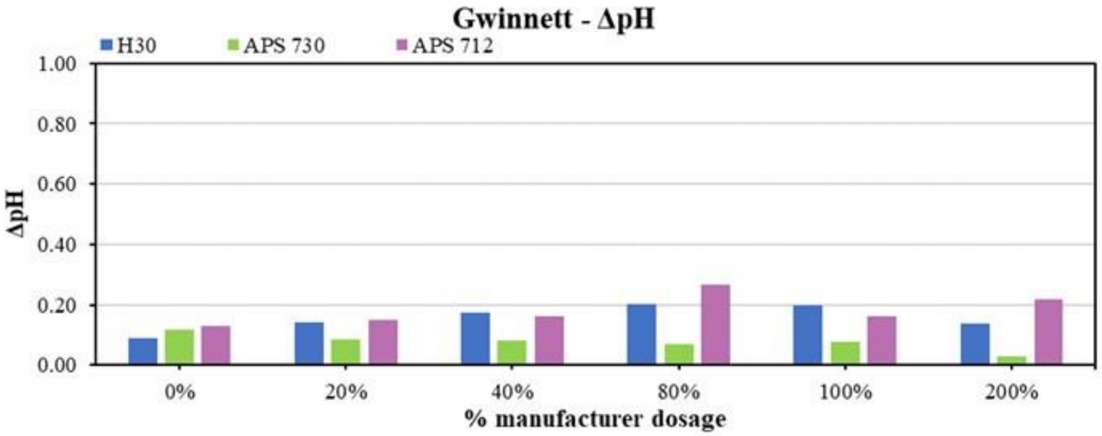
Soil ID:	**Gwinnett**	**Sampling Location:**	**Montgomery, AL**

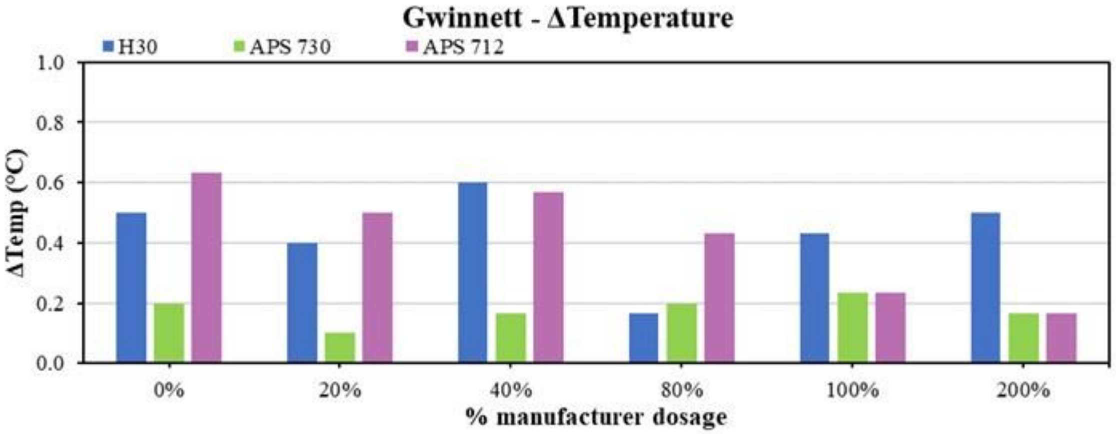
Product:	**H3O**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1132.7	1261.5	1263.7	864.3	1225.8	1264.1
ΔpH	0.09	0.14	0.17	0.20	0.20	0.14
ΔTemperature	0.5	0.4	0.6	0.2	0.4	0.5
ΔColor	1	3	3	3	3	3

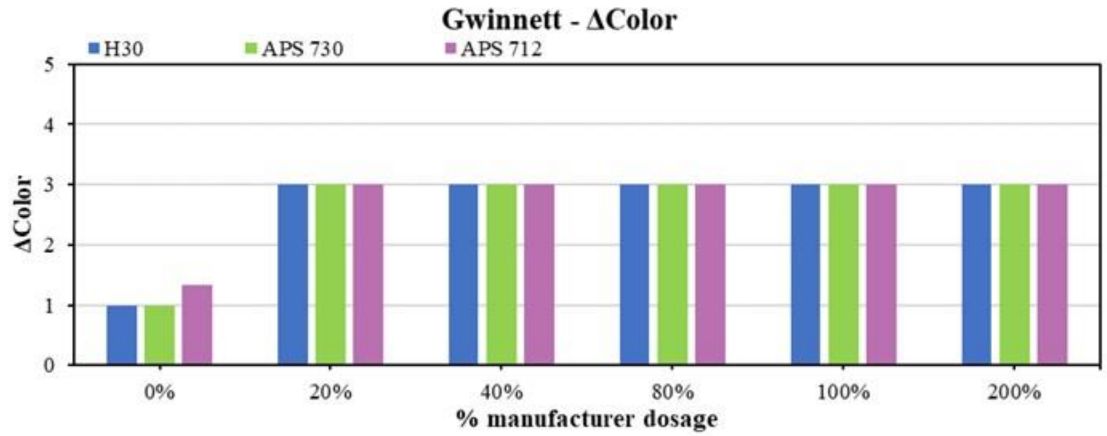
Product:	**APS 730**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1287.1	1375.1	1351.4	1349.4	1393.5	1345.9
ΔpH	0.12	0.09	0.08	0.07	0.08	0.03
ΔTemperature	0.2	0.1	0.2	0.2	0.2	0.2
ΔColor	1	3	3	3	3	3

Product:	**APS 712**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1177.9	1315.1	1278.3	1330.6	1303.4	1260.5
ΔpH	0.13	0.15	0.16	0.27	0.16	0.22
ΔTemperature	0.6	0.5	0.6	0.4	0.2	0.2
ΔColor	1	3	3	3	3	3


Gwinnett- ΔNTU
H30
APS 730
APS 712
ΔTurbidity (NTU)
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Gwinnett - ΔpH
H30
APS 730
APS 712
ΔpH
1.00
0.80
0.60
0.40
0.20
0.00
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Gwinnett - ΔTemperature
H30
APS 730
APS 712
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Gwinnett - ΔColor
H30
APS 730
APS 712
ΔColor
0
1
2
3
4
5
0%
20%
40%
80%
100%
200%
% manufacturer dosage

APPENDIX E
SETTLING VELOCITY CALIBRATION TESTING PROCEDURE

Settling Velocity Calibration Testing Procedure

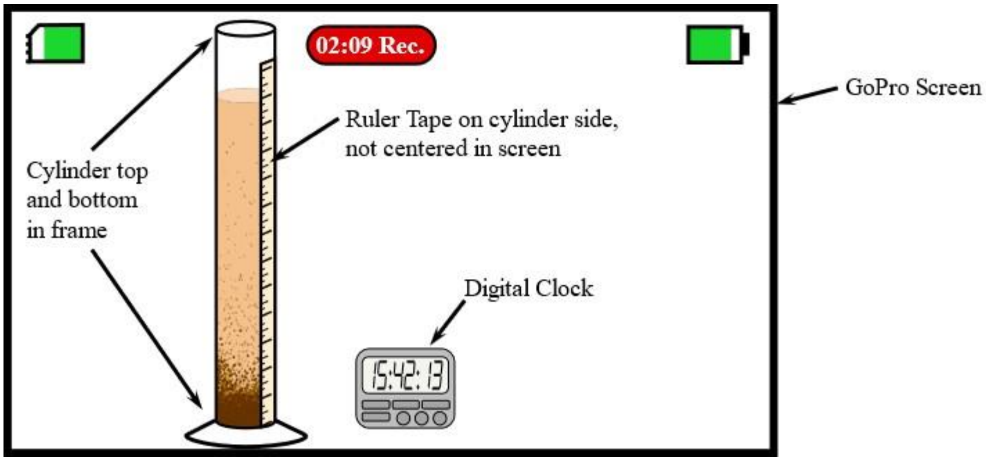
Equipment

1) Jar Test Multiple Stirrer
2) 1,500 mL Glass Beakers
3) Stopwatch
4) 1,000 mL Glass Graduated Cylinder
5) GoPro Camera
6) Digital Clock (with seconds!)
7) pH meter
8) Glass thermometer
9) Scale
10) Precision Scale
11) Acid and Base pH Buffering Solutions
12) Large Plastic Tub (27 gal. plastic tub recommended)
13) Cheese Grater
14) White Poster Board

Pre-Test

1) Fill a large plastic tub with tap water that is close to the desired testing temperature. Low temperatures (50℉ [10℃] and below) will require water to be chilled overnight prior to testing.
2) Depending on the desired pH range, add acid or base buffering solution to tap water to raise or lower the pH, respectively. Use a paint mixer to sufficiently mix solution before taking a pH reading. Note: adjusting the pH can take some time so temperature adjustments will be necessary later. Set pH range to a value between 5.35 to 5.45, 6.35 to 6.45, 7.35 to 7.45, or 8.35 to 8.45 to ensure consistency between samples.
3) Once the pH is within the desired range, set the temperature by using heat lamps to raise the temperature. To cool samples, proceed to the next step.
4) Fill glass beakers with 1,000 mL of pH set water. If samples need cooled a couple degrees, place in a refrigerator for 15-30 minutes. For lower temperatures, place beakers in a salted ice bath, being careful to not contaminate the pH water with any salt. Samples will need stirred periodically to ensure samples reach low temperature sets. While waiting for the temperature to reach the desired value, proceed to the next step.
5) Clean Jar Test Multiple Stirrer machine by rinsing the stirring rods, paddles, and paddle rest with deionized water, spraying with Alconox® Liquinox cleaning solution, and wipe clean with a paper towel.
6) Equip graduated cylinder with ruler tape on the side with zero starting at the cylinder base.

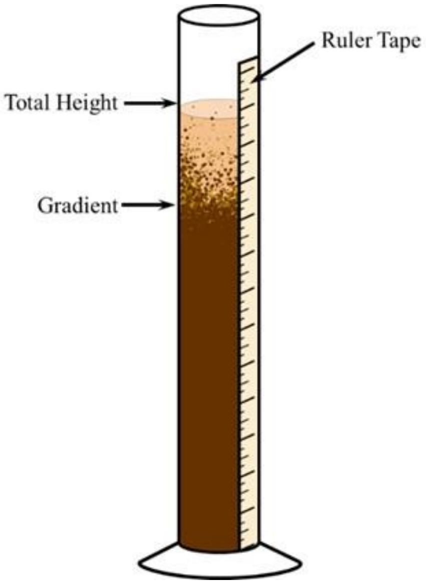
7) Insert microSD card in GoPro and ensure the video frame includes the top and bottom of the graduated cylinder, ruler tape on cylinder is visible on the side without obstructing the view of the sample in the cylinder, and digital clock visible and legible in frame. Place white poster board behind cylinder for a solid background to make it easier to see gradient when sample is poured.

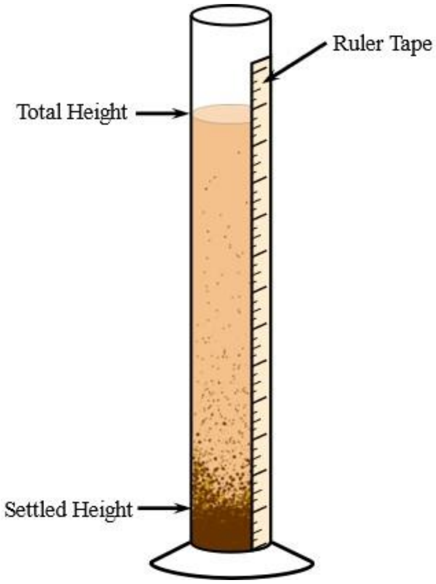


8) Weigh 20g of testing soil that was sieved through a #200 sieve and set aside.
9) Calibrate precision scale and use to weigh out desired flocculant in mg with ±0.1 mg acceptable error. If weighing out block form PAM, use the cheese grater to break up the block into smaller pieces. Fresh material will need grated daily and stored in an airtight jar as it will dry out and impact weights otherwise. Weighed block form PAM will need used within 1 hour of weighing to ensure flocculant does not dry out and harden, which could impact results.
10) Once the pH water reaches the desired temperature, proceed to the testing section.

Testing

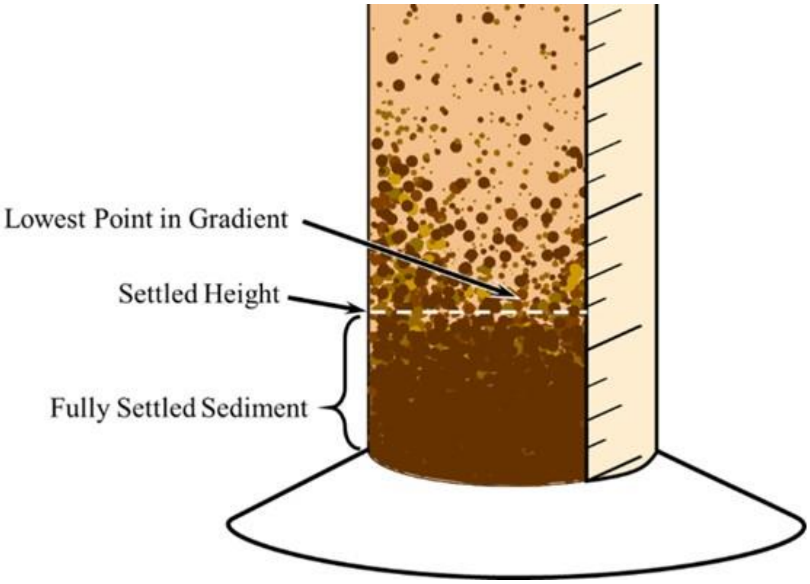
1) Start GoPro video recording of the graduated cylinder.
2) Add 20g of sieved testing soil to the sample and place on jar test multiple stirrer machine and flash mix (120 rpm) for 1 min.
3) Remove sample and add the desired flocculant in center of cylinder. Do not add flocculant while stirrers are still in sample as the flocculant may stick to the beaker walls or stirrer rod and not make it into the sample.
4) Place samples back on jar test multiple stirrer machine and flash mix (120 rpm) again for 1 min.
5) Quickly pour the sediment-supernatant sample into the graduated cylinder, being sure to pour fast enough so that all sediment in sample remains suspended while pouring.
6) Record the start hour and minute sample was poured and the sample total height.
7) Wait until sample is fully settled before stopping GoPro video. If sample gradient is not easily visible, allow for sample to settling for 1 hour before stopping video.





Post-Test

1) Wash glass beakers and cylinders with hot water and scrub clean with Alconox® Liquinox cleaning solution.
2) Clean Jar Test Multiple Stirrer machine by rinsing the stirring rods, paddles, and paddle rest with deionized water, spraying with Alconox® Liquinox cleaning solution, and wipe clean with a paper towel. If sample flocculated under 30 sec, it is recommended to repeat the cleaning process two or three time to ensure all flocculant is removed.
3) Review residual video to capture the seconds that the sample was poured and the settle time and height. Note that depending on the floc size, settle height will vary. Sample is considered as settled when the lowest gradient point touches the fully settled sediment. Samples that are difficult to distinguish a gradient and take longer to settle, multiple videos may need stitched together in a video editing software to be able to see gradient since GoPro videos record in 10-minute sections.


Lowest Point in Gradient
Settled Height
Fully Settled Sediment

APPENDIX F
RESIDUAL CONCENTRATION CALIBRATION TESTING PROCEDURE

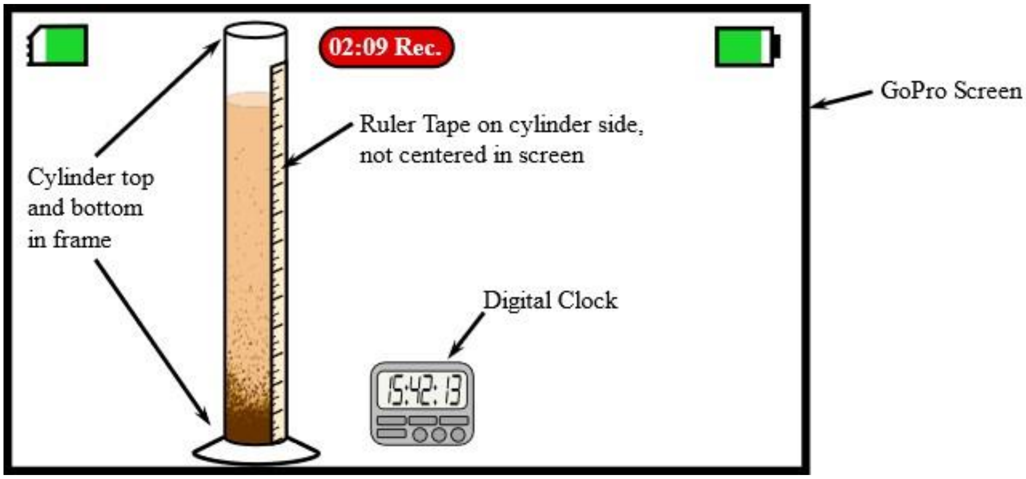
Residual Testing Procedure

Equipment

1) Jar Test Multiple Stirrer
2) 1,500 mL Glass Beakers
3) Stopwatch
4) 1,000 mL Glass Graduated Cylinder
5) GoPro Camera
6) Digital Clock (with seconds!)
7) pH meter
8) Glass thermometer
9) Scale

Pre-Test

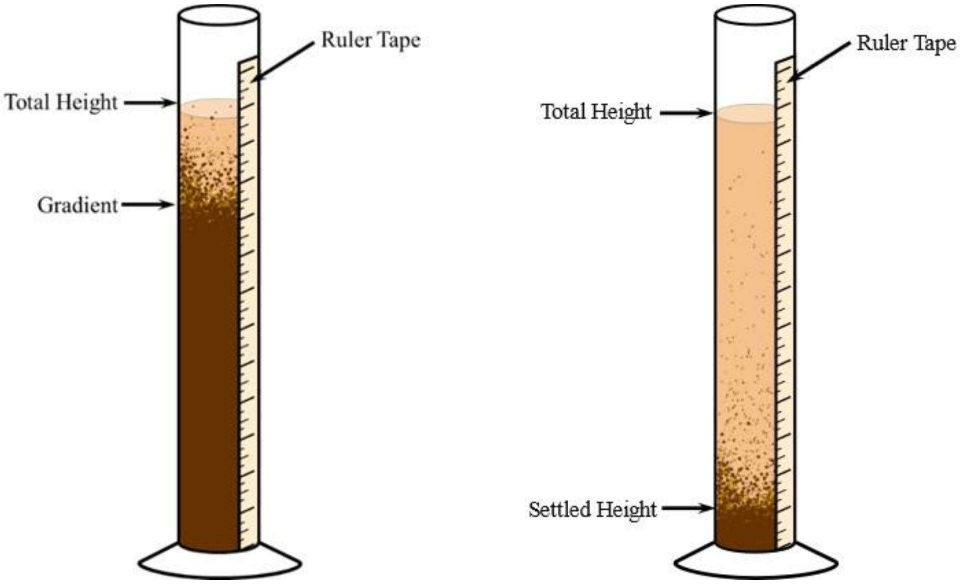
1) Shake field samples for 1 min, then pour >1,000 mL of sample into three clean 1,500 mL glass beakers and label.
2) Wait 15 min for sediment in sample to fully settle.
3) Clean Jar Test Multiple Stirrer machine by rinsing the stirring rods and paddles with deionized water, spraying with Alconox® Liquinox cleaning solution, and wipe clean with a paper towel.
4) Equip graduated cylinder with ruler tape on the side with zero starting at the cylinder base.
5) Insert microSD card in GoPro and ensure the video frame includes the top and bottom of the graduated cylinder, ruler tape on cylinder is visible on the side without obstructing the view of the sample in the cylinder, and digital clock visible and legible in frame.



6) Weigh 20g of testing soil that was sieved through a #200 sieve and set aside.
7) Transfer 1,000 mL of supernatant into a new clean 1,500 mL glass beaker and label beaker.
8) Take pH reading and temperature of sample

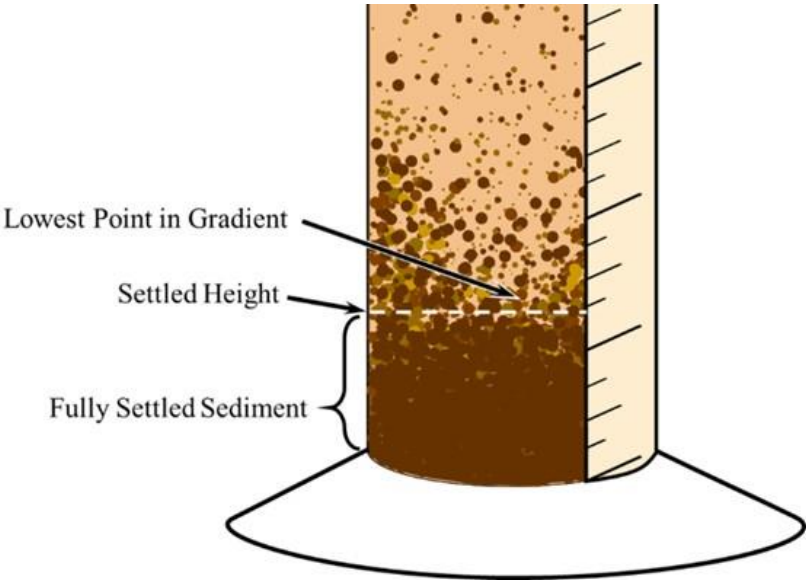
Testing

1) Start GoPro video recording of the graduated cylinder.
2) Add 20g of sieved testing soil to the supernatant sample and place on jar test multiple stirrer machine and flash mix (120 rpm) for 1 min.
3) Quickly pour the sediment-supernatant sample into the graduated cylinder, being sure to pour fast enough so that all sediment in sample remains suspended while pouring.
4) Record the start hour and minute sample was poured and the sample total height.
5) Wait until sample is fully settled before stopping GoPro video. If sample gradient is not easily visible, allow for sample to settling for 1 hour before stopping video.



Post-Test

1) Wash glass beakers and cylinders with hot water and scrub clean with Alconox® Liquinox cleaning solution.
2) Clean Jar Test Multiple Stirrer machine by rinsing the stirring rods, paddles, and paddle rest with deionized water, spraying with Alconox® Liquinox cleaning solution, and wipe clean with a paper towel. If sample flocculated under 30 sec, it is recommended to repeat the cleaning process two or three time to ensure all flocculant is removed.
3) Review residual video to capture the seconds that the sample was poured and the settle time and height. Note that depending on the floc size, settle height will vary. Sample is considered as settled when the lowest gradient point touches the fully settled sediment. Samples that are difficult to distinguish a gradient and take longer to settle, multiple videos may need stitched together in a video editing software to be able to see gradient since GoPro videos record in 10-minute sections.


Lowest Point in Gradient
Settled Height
Fully Settled Sediment

APPENDIX G
PRODUCT IDENTIFICATION

Product Identification

Product ID	Product	Manufacturer ID	Manufacturer	Flocculant	Charge	Dosage (mg/L)
A	H30	I	Carolina Hydrologic, LLC.	PAM	Anionic	5
A-G	H30	I	Carolina Hydrologic, LLC.	Granular PAM	Anionic	5
A-B	H30	I	Carolina Hydrologic, LLC.	Block PAM	Anionic	5
B	APS 702	II	Applied Polymer Systems	PAM	Anionic	50
C	APS 705	II	Applied Polymer Systems	PAM	Anionic	50
D	APS 707	II	Applied Polymer Systems	PAM	Anionic	50
E	APS 710	II	Applied Polymer Systems	PAM	Anionic	50
F	APS 712	II	Applied Polymer Systems	PAM	Anionic	50
G	APS 730	II	Applied Polymer Systems	PAM	Anionic	50
H	APS 740	II	Applied Polymer Systems	PAM	Anionic	50
I	FLOC	III	Innovative Turf Solutions	Bentonite-based	-	180
J	Liquifloc 1%	IV	Dober	Chitosan	Cationic	100
K	Liquifloc 1% + LBP 2101	IV	Dober	Chitosan + coagulant	Cationic	100
L	Agricultural Gypsum	V	USA Gypsum	Calcium sulfate	-	300
M	Alum	VI	Kroger Co.	Aluminum sulfate	-	10
N	Tigerfloc	VII	Floc Systems Inc.	Sodium Montmorillonite	-	2,000