Improvements in Construction Stormwater Treatment using Flocculants

by

Billur Kazaz

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
May 7, 2022

Keywords: construction stormwater, flocculants, sediment control,
residual monitoring, bench-scale testing, large-scale testing

Approved by

Michael A. Perez, P.E., Chair, Assistant Professor of Civil Engineering
Wesley C. Donald, Research Fellow IV, Civil Engineering
Xing Fang, P.E., Professor of Civil Engineering
Joey N. Shaw, Professor of Crop, Soil, and Environmental Sciences

ABSTRACT

Construction stormwater runoff constitutes an increased risk for downstream water bodies if unmanaged 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 facilitate settlement. 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 application rates and dosage for construction site applications.

This dissertation 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) 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 dissertation 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 polyacrylamide, 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 overdose conditions. Results indicated that polyacrylamide 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 overdose 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 Auburn University Stormwater Research Facility (AU-SRF) researchers on in-channel sediment basin application. Flocculant application on a sediment basin testing apparatus was evaluated by using semi hydrated polyacrylamide-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.

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.

ACKNOWLEDGMENTS

The process of earning a doctoral degree is a long and challenging journey that certainly cannot be completed singlehandedly. It is a genuine pleasure to express my deep sense of thanks and gratitude to my advisor Dr. Michael A. Perez for his unconditional support, mentorship, and guidance throughout this journey. Studying in the U.S. was once just a childhood dream for me, I would like to thank Dr. Perez for believing in me and supporting me to make my dreams come true. He is an advisor who is worth moving states and countries for, and I am honored to be a part of his research team. Additionally, I would like to thank Dr. Wesley N. Donald, Dr. Xing Fang, Dr. Joey N. Shaw, and Dr. Eve Brantley, for their time and guidance throughout this research effort. I am deeply grateful for the mentorship and support provided by Dr. Blake Whitman and members of the ALDOT Technical Advisory Committee.

This work would not have been possible without the support from the Alabama Department of Transportation, Auburn University Highway Research Center, Auburn University Department of Civil and Environmental Engineering, and Samuel Ginn College of Engineering. I would also like to thank Mr. Kris Ansley and Mr. Guy Savage for testing support and coordination at the Auburn University Stormwater Research Facility. I would like to thank Blake Daiber for his laboratory assistance and share my gratitude for the numerous undergraduate assistants who helped me to successfully execute laboratory testing efforts by working in the heat on physical labor required tasks.

My time in graduate school brought me special friendships. I would certainly be remiss to not mention and sincerely thank my dear friend Jaime Schussler for being the most supportive sister-friend, colleague, and roommate throughout my graduate school experience. Without her support, the challenges of graduate school would be unbearable. I would like to also thank my

friends Emine Sahin, Omer Murat Durgun, Dilan Seref, Jessica Taylor, Dr. Jessica Talbot, Parker Dulin, Aaron Fewell, Veronica Ramirez, Loulou Dickey, Dr. Sylwia Stawska, and Dr. Catherine Whitman for making my time in graduate school a wonderful experience. I am thankful for being blessed with having a family away from home; Sue and Greg Schussler, Michelle and Jason Nellis, Christine and Brian Brueckner, who have included me in their family and shared numerous memories of laughter, support, and love. I would like to also thank Rosa "Mama Perez", and Luis Perez for considering our research group as their grandchildren.

I'm most of all grateful to my immediate family for their love and unending support. This work is a direct outcome of their encouragement, and unconditional love. Son olarak tüm hayatım boyunca benim yanımda olan, aldığım kararları ve hayallerimi her zaman destekleyen, beni hayata karşı cesaretlendiren ve moral veren babam Metin Kazaz'a, annem Hüzün Erberk'e, ablam Berrak Kazaz Çelikkaya'ya sonsuz şükranlarımı sunar ve teşekkür ederim.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADEM	Alabama Department of Environmental Management
ALDOT	Alabama Department of Transportation
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
AUSRF	Auburn University Stormwater Research Facility
CALTRANS	California Department of Transportation
CEC	Cationic Exchange Capacity
CGP	Construction General Permit
CONUS	Contiguous United States
DADMAC	Diallyl Dimethylammonium Chloride
DOT	Department of Transportation
E&SC	Erosion and Sediment Control
FDOT	Florida Department of Transportation
GIS	Geographic Information System
HDPE	High Density Polyethylene
LC_{50}	Lethal Concentration 50
MPC	Maximum Permissible Concentrations
MS4	Municipal Separate Storm Sewer System
NCAT	National Center for Asphalt Technology
NCDOT	North Carolina Department of Transportation
NPDES	National Pollutant Discharge Elimination Systems

NTU	Nephelometric Turbidity Unit
ODOT	Oregon Department of Transportation
PAC	Poly Aluminum Chloride
PAM	Polyacrylamide
PVC	Poly Vinyl Chloride
SCS	Soil Conservation Service
SES	Soil Erosion Service
SSC	Suspended Sediment Concentration
SWPPP	Stormwater Pollution Prevention Plan
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
TxDOT	Texas Department of Transportation
USCS	United Soil Classification System
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WSDOT	Washington State Department of Transportation
WSS	Web Soil Survey

CHAPTER ONE:
INTRODUCTION

1.1. BACKGROUND

The construction industry is one of the least sustainable industries due to the large number of non-renewable resources that are used by mankind for construction purposes. However, construction has a significant role in modern civilization due to the continuous demand for infrastructure. The U.S. economy spends \$1.67 trillion annually in construction activities. Among this expenditure, \$163 billion is invested in linear highway and transportation projects *(US Census Bureau 2022)*. 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. The dynamic nature of construction activities makes sediment the most concerning pollutant from construction activities for downstream waterbodies. 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 United States Environmental Protection Agency (USEPA) considers sediment as one of the most persistent pollutants that threaten the waters of the U.S. *(USEPA 1998, 2016)*. Erosion and the resulting sedimentation are a major concern in protecting the nation's water bodies. 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 (224.17 tonnes/ha) *(USEPA 1999)*. Earthmoving operations during construction leave land exposed to wind and rainfall, increasing the risk of on-site erosion and off-site sediment deposition.

Pollutants are often transferred into downstream waterbodies through stormwater discharge, which potentially carries a substantial amount of sediment in cases of discharge originating from 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 *(USEPA 2017b)*. 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 *(Donohue and Garcia Molinos 2009)*. 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 (Hansen and Libecap 2004). 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 United States Department of Agriculture. 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 *(NRCS 2021)*. 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) *(United States Congress 2002).* The CGP emphasizes the significance of a well-developed Stormwater Pollution Prevention Plan (SWPPP) to limit environmental hazards implicated by stormwater runoff from construction activities *(USEPA 2017b)*. SWPPP documents include project information, erosion and sediment control (E&SC) plans, and a description of stormwater management practices planned for the site *(USEPA 2007)*. 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. (CONUS), 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 *(Kazaz et al. 2022).* 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 *(ALDOT 2015)*. Together with this major construction and maintenance responsibility, ALDOT is under the responsibility and regulatory obligation to implement proper construction stormwater management. NPDES general permit issued by ADEM, regulates construction discharge on ALDOT construction sites and construction runoff in urban areas is controlled by 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 *(ALDOT 2016)*. 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 *(Perez et al. 2016a)*. 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 *(Perez et al. 2016a; Schussler et al. 2021; Whitman et al.*

2018). 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 *(Donald et al. 2016, Perez et al. 2015, Whitman et al. 2018, 2019)*. 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 *(Perez et al. 2016)*.

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.

1.2.1 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) *(U.S. Congress 2002)*. 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 *(USEPA 2000).* 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 *(USEPA 2007, 2017a).*

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 *(Alabama Department of Environmental Management 2019, North Carolina Department of Environmental Quality 2019).*

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 *(USEPA 2015)*. The state of Alabama received its permitting authorization in 1979 and has been managing NPDES permitting procedures through the Alabama Department of Environmental Management (ADEM). ADEM enforces numeric effluent limits, the development of effective SWPPPs, and compliance with regulations *(Alabama Department of Environmental Management 2019).* 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.

1.3. 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 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 large scale testing for optimum dosage delivery and application evaluations, and,

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

1.4. EXPECTED OUTCOMES

The outcomes of the study are to improve current flocculant application guidance and provide a better understanding of passive flocculant treatment by replicating field conditions in a controlled testing environment. The scientific results from this research will constitute an effective framework for flocculant application on construction sites and promote the use of flocculants with proper dosage rates and application techniques. The results of this study will provide designers and practitioners with the knowledge, resources, and educational outreach opportunities required to effectively use flocculants without risking harm to downstream water bodies. Future research efforts should emanate from this research allowing further opportunities for increasing knowledge in flocculant usage for construction stormwater treatment.

1.5. ORGANIZATION OF DISSERTATION

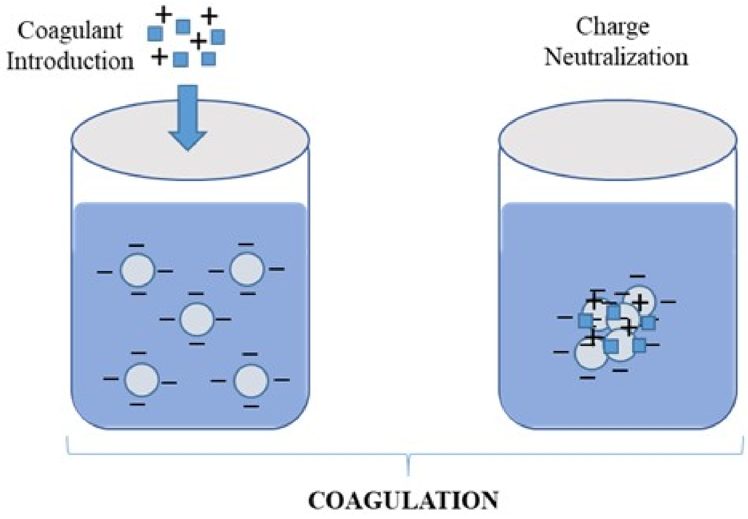
This dissertation is divided into seven chapters that methodize, illustrate, and outline steps taken to meet defined research objectives. Following this chapter, Chapter Two: *Flocculants Literature Review,* provides an overview of the current application and research performed on flocculants. Chapter 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: *Bench-Scale Evaluation of Optimum Dosage and Residual Concentrations*, outlines the methods and procedures developed for evaluating dosage requirements for different flocculant products and detecting residual concentrations. Chapter Five: *Large Scale 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. In addition, this chapter includes a collaborative study on evaluating the performance of flocculant implementation for sediment basin application. Chapter Six: *Conclusions and Recommendations,* presents a summary of the accomplished research tasks and provides insight into future research agendas to further advance this research effort.

CHAPTER TWO:
FLOCCULANTS LITERATURE REVIEW

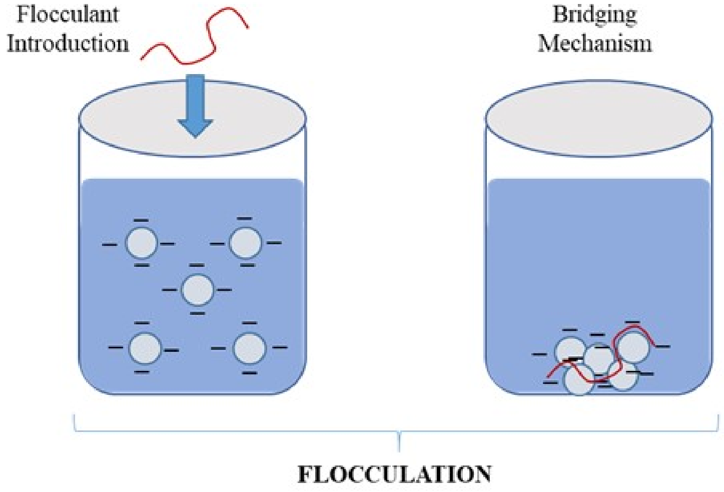
2.1 DEFINITION AND PURPOSE OF FLOCCULANTS

Flocculants are water-soluble molecules that consist of long chains with a combination of repetitive small molecules and they are capable of separating suspended fine particles from aqueous suspension *(USEPA 2013, Vajihinejad et al. 2019)*. Flocculants are chemical agents that function to aggregate solid particles together and increase their settling velocity *(Pillai 2013).* 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 *(2014)* submits the term "flocculation" as a synonym of "coagulation". However, many other studies support the opposite. Vajihinejad et al. *(2019)* 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 *(2005)* 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 1 compares coagulation and flocculation by illustrating their working mechanisms. Figure 1 (a) displays the coagulation mechanism, a physical process of the attraction between particles due to the charge neutralization after the coagulant introduction. Figure 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 1 Comparison of coagulation and flocculation mechanisms.

2.2 FLOCCULANT TYPES AND FORMS

Flocculants are manufactured in different physical forms such as powder, granular, blocks, socks, emulsion, dispersants, beads, and liquid *(De Milieux 2003)*. Figure 2 shows the most common commercially available flocculant forms; granular/powder, blocks, liquid, and socks.

(a) granular *(Applied Polymer Systems 2020)* (b) block *(Applied Polymer Systems 2020)*

(c) liquid *(Lords World Inc 2020)* (d) socks *(Floc Systems Inc. 2020)*

Figure 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) *(Lee et al. 2014, Wakema and Tarleton 2007)*. 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 *(Vajihinejad et al. 2019)*. 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 *(Auckland Regional Council 2004, Biesinger and Stokes 1986, Duggan et al. 2019, USEPA 2005)*. Anionic flocculants are commonly used in industrial wastewater treatment systems *(Auckland Regional Council 2004, Dao et al. 2016, Kurenkov et al. 2002, Rabiee 2010)*. Typically, anionic flocculants show very low residual concentration in treated water and their toxicity level is also very low compared to cationic flocculants *(USEPA 2013, Auckland Regional Council 2004)*. 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 *(Dao et al. 2016, Pillai 2013).* 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 *(Dobrynin et al. 2004, Wakema and Tarleton 2007)*. Polyacrylamide (PAM) is one of the most commonly used synthetic flocculants and can be manufactured in various chain lengths and charges *(Dao et al. 2016, Kurenkov et al. 2002, Lentz and Sojka 1994, Vajihinejad et al. 2019, Xiong et al. 2018)*. PAM rapidly aggregates soil particles, decreases soil bulk density, and absorbs water *(Kang and McLaughlin 2016, Sojka et al. 2007)*. Anionic PAM is commonly preferred for environmental applications since it has not been proven to be toxic to aquatic life *(Peng and Pingkuan 1994, Qian et al. 2004, Sojka et al. 2007, USEPA 2005)*

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 *(Tang et al. 1998).* Examples of inorganic flocculants include alum, poly aluminum chloride (PAC), aluminum chloride, aluminum sulfate, ferric chloride, and ferrous sulfates *(Okaiyeto et al. 2016, Salehizadeh et al. 2018, Tang et al. 1998).*

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 *(Chatsungnoen and Chisti 2019, Okaiyeto et al. 2016, Wakema and Tarleton 2007)*. The most commonly used natural flocculants include chitosan, cellulose, starch, alginate, and amylopectin, which are polysaccharide-based chemical agents *(Salehizadeh et al. 2018, Vajihinejad et al. 2019)*. 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 *(Vajihinejad et al. 2019).* With proper usage, chitosan can offer effective flocculation results. For instance, Zeng et al. *(2008)* prepared a novel composite chitosan that can potentially replace PAC in the water treatment industry, a common inorganic flocculant. Kangama et al. *(2018)* created a composite chitosan flocculant for tap water treatment that provided a 96.38% reduction in turbidity. Moreover, Yang et al. *(2016)* 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 condition*s (Tan et al. 2018)*. 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 *(Vajihinejad et al. 2019).*

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 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 *(Harper et al. 1999)*, calcium sulfate *(Przepiora et al. 1997, 1998),* and polyacrylamide *(Bhardwaj and McLaughlin 2008)* are commonly accepted flocculants in stormwater treatment among the others presented in Table 1.

Table 1 Typical flocculants for turbidity treatment *(Mclaughlin & Zimmerman 2008, ProTech General Contracting Services Inc 2004)*

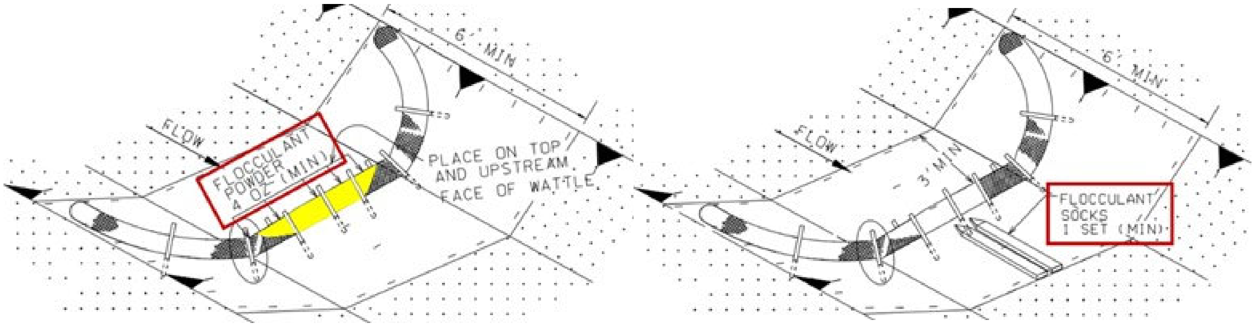
Flocculant	**Type**	**Charge**	**Drawbacks**
Chitosan	Natural Polymer	Cationic	Costly; toxic in case of an overdose
Polyacrylamide (PAM)	Synthetic Polymer	Anionic; Cationic; Nonionic	Cationic form is toxic to aquatic life; single compound acrylamide may be carcinogenic in high concentrations
Polyaluminum 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

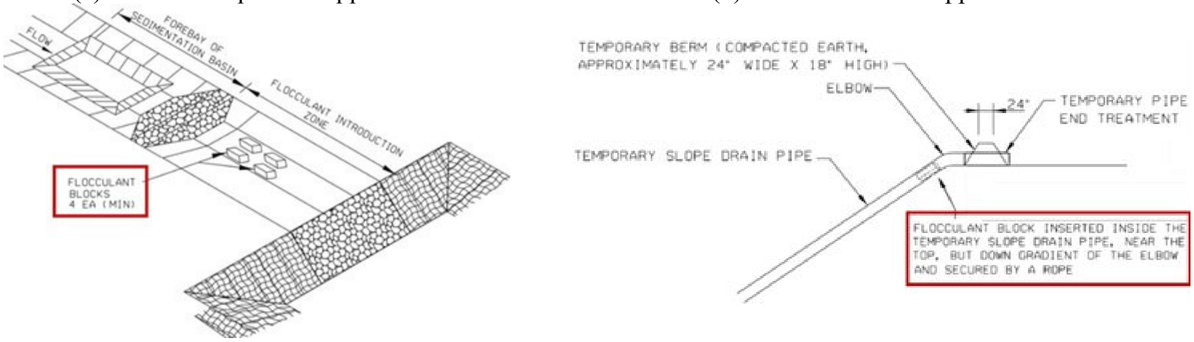
Several research studies have been conducted to evaluate the use of flocculants in stormwater management applications. Harper investigated the effects of aluminum sulfate (alum) treatment in lake systems in Florida and concluded its use provided an effective and economical approach to reduce the toxicity of sediment particles in lake systems by reducing total nitrogen, total phosphorus, and heavy metals *(Harper et al. 1999)*. Przepiora et al. *(1997)* 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. *(1998)* 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 *(2008)* 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 *(Alabama Department of Transportation 2013)*. 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 *(Cirtex Industries Ltd 2020)*.

Flocculants have also been proven to work in other E&SC applications. Kang and McLaughlin *(2016)* 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 *(1994)* 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 *(USEPA 2017b).* 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 *(New York State Department of Environmental Conservation 2016).* 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 *(Druschel 2014).* The Alabama Department of Transportation (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 3 *(ALDOT 2014; ALDOT 2015)*. Based on the drawing presented in Figure 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 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 3(c). Moreover, flocculant blocks are being inserted near the top in the temporary slope drains as described in Figure 3(d).



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



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

Figure 3 ALDOT flocculant implementation *(ALDOT 2014).*

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. *(NCDOT 2014)*. 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 *(Florida DOT 2013)*. 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 *(McFalls et al. 2014; Rounce et al. 2012)*. 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 *(Rounce et al. 2012)*. 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 *(CalTrans 2010; CalTrans 2003)*. Oregon Department of Transportation (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 create failure in active treatment (ODOT 2019). Washington State Department of Transportation (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 *(WSDOT 2019)*.

2.3.1 COMMON FLOCCULANT IMPLEMENTATION CONCERNS

Although some of the state DOTs include flocculants in their standard specifications and manuals, it is common to see implementation, maintenance, and reapplication issues on construction sites. Figure ***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 ***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 ***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.

(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 4 Poorly implemented flocculant applications.

Note: [A] photo credit Barry Fagan

Figure ***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 ***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.

2.4 TOXICOLOGY LIMITS

Flocculants enhance turbidity reduction in construction stormwater runoff, enhancing the performance of the temporary E&SC practices. However, these chemicals have the potential to be highly toxic for the environment by polluting downstream water bodies and causing fish kills in case of improper dosage and application techniques *(USEPA 2005)*. For instance, chitosan can easily bind with the hemoglobin in the gills of the fish and suffocate fish populations in the water bodies *(Duggan et al. 2019)*. Measuring the toxicity of flocculants is possible with acute toxicity measurements and most of the commercially available products include toxicity limits in their safety data sheets (SDS) that are usually provided by manufacturers. Moreover, the USEPA highlights approved methods for measuring the acute toxicity of effluent for use in the NPDES program *(USEPA 2002)*. The acute toxicity test identifies dose-response information in terms of the median lethal concentration (LC_{50}, μg/L, or mg/L), which represents the concentration lethal to 50% of the experimental subject *(Stephan 2009)*. Aquatic organisms typically used for LC_{50} testing can be grouped into two categories: (1) freshwater organisms and (2) estuarine and marine organisms. Freshwater organisms consist of water fleas (*ceriodaphnia dubia* and *daphnia pulex*), fathead minnows *(pimephales promelas),* and rainbow trout (*oncorhynchus mykiss*). Common estuarine and marine organism test subjects include e mysid *(mysidopsis bahia),* sheepshead minnow *(cyprinodon variegatus),* and inland silverside *(menidia beryllina) (USEPA 2002).*

Several research studies have investigated the acute toxicity of flocculants by dosing aquatic organisms with varying concentrations of chemical agents as shown in Table 2. Buczek et al. *(2017)* investigated the impact of PAM on freshwater mussels including *lampsilis cariosa, alasmidonta raveneliana,* and *mehalonaias nervosa* by identifying LC_{50} values for six different PAM products. Results indicated that LC_{50} values were significantly higher than typical dosage recommendations (1–5 mg/L); thus, PAM was considered as not acutely toxic for brief exposure periods of 48 hours or 96 hours. The study also highlighted the need for further investigation on PAM's toxicity. Another study evaluated organic flocculants and inorganic coagulants for acute testing by using water flea *(ceriodaphnia dubia)*, with results revealing that cationic flocculants, aluminum sulfate, and ferric chloride show acute toxicity at very low concentrations below 0.025 mg/L *(Douglas & Enos 1995)*. Beim & Beim *(1994)* conducted a study for identifying Maximum Permissible Concentrations (MPC) on several flocculant types and emphasized the necessity for the control of residual amounts in discharged effluents.

Table 2 Summary of Toxicology Studies

Research Study	Flocculant Type	Aquatic Organism	Results
Buczek et al. 2017	PAM	*Lampsilis cariosa*	$LC_{50} > 5$ mg/L
		Alasmidonta raveneliana	$LC_{50} > 5$ mg/L
		Mehalonaias nervosa	$LC_{50} > 5$ mg/L
Douglas & Enos 1995	Cationic polymers	*Ceriodaphnia dubia*	$LC_{50} < 0.025$ mg/L
	Aluminum Sulfate	*Ceriodaphnia dubia*	$LC_{50} < 0.025$ mg/L
	Ferric Chloride	*Ceriodaphnia dubia*	$LC_{50} < 0.025$ mg/L
Beim & Beim 1994	Anionic PAM	*Daphnia*	$LC_{50}^{96} = 14.1$ mg/L
	Nonionic polymer	*Daphnia*	$LC_{50}^{96} = 89.6$ mg/L
	Cationic polymers	*Daphnia*	$LC_{50}^{96} < 2.06$ mg/L

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 *(Kazaz et al. 2021)*. However, with effective application and dosage guidance, preventative measures can be taken to avoid environmental damages 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. Lentz et. al *(1996)* 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 Ormeci *(2014)* 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 *(2013)* 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 et. al's study *(2016)*. 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. *(2013)* and Miao et al. *(2020)* 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 *(Badawy 2012)*.

2.6 FLOC CHARACTERISTICS

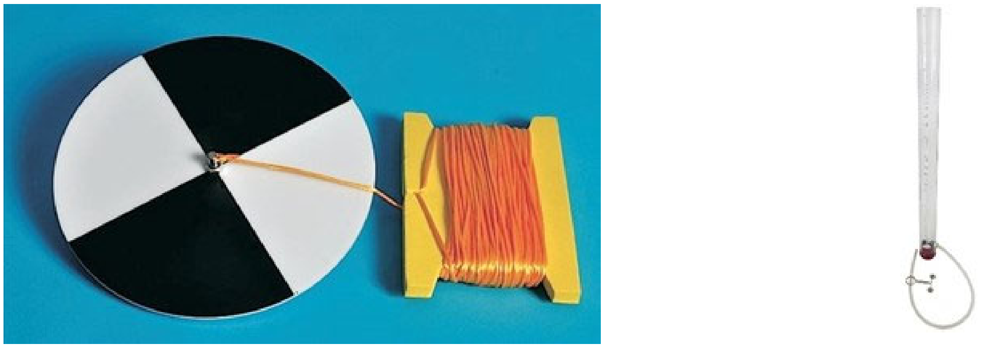
The performance of chemical treatments is commonly evaluated through ASTM standard jar testing procedures, which emphasizes the significance of observing floc characteristics. The standard ranges dosage in a six-place multiple stirrer machine and compare turbidity of the samples before and after flocculant 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 *(ASTM-D2035-19 2019)*.

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 (ASTM D3977-97(19) 2019; Davies-Colley and Smith 2001). 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 *(American Water Works Association 1951)*.

Turbidity can be measured with the use of Secchi disks, benchtop, portable turbidimeters, or turbidity tubes as illustrated in Figure 5. Secchi disk is a black and white disk, shown in Figure

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 (Tyler 1968).



(a) Secchi disk *(Fisher Scientific Inc. 2022)* (b) turbidity tube *(Fisher Scientific Inc. 2022)*

(c) benchtop turbidimeter *(Hach Inc. 2022a)* (d) portable turbidimeter *(Hach Inc. 2022b)*

Figure 5 Instruments for turbidity measurements.

Turbidity tubes, 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 *(Davies-Colley and Smith 2001)*. 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 5(c) and (d).

Benchtop turbidimeters can provide a wider range of turbidity measurements compared to portable turbidimeters *(Hach Inc. 2022a; b)*. 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. (2µm)filter and dissolve in a specific volume of water *(ASTM-D5907-18 2018)*. SSC provides the total sediment mass in a water sample with the use of evaporation, filtration, or wet-sieving-filtration methods *(ASTM-D3977-97(19) 2019)*. However, in this research only turbidity was observed for evaluating the performance of flocculants per standardized jar testing requirements (*ASTM-D2035-19* 2019).

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 *(Covington et al. 1985)*. 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 *(USEPA 2017)*.

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 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 6(b) and (c), require calibration with buffer solutions to maintain the accuracy of the pH reading as shown in Figure 6(d).

(a) pH test strips *(Grainger Supply Inc. 2022)* (b) benchtop pH meter *(Fisher Scientific Inc. 2022a)*

(c) pocket pH meter *(Hach Inc. 2022d)* (d) buffer solutions *(Fisher Scientific Inc. 2022b)*

Figure 6 Methods for pH measurements.

2.6.3 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 *(Gregory 2004)*. Figure 7 illustrates an example for floc formation after sufficient shear rate is achieved through mixing.

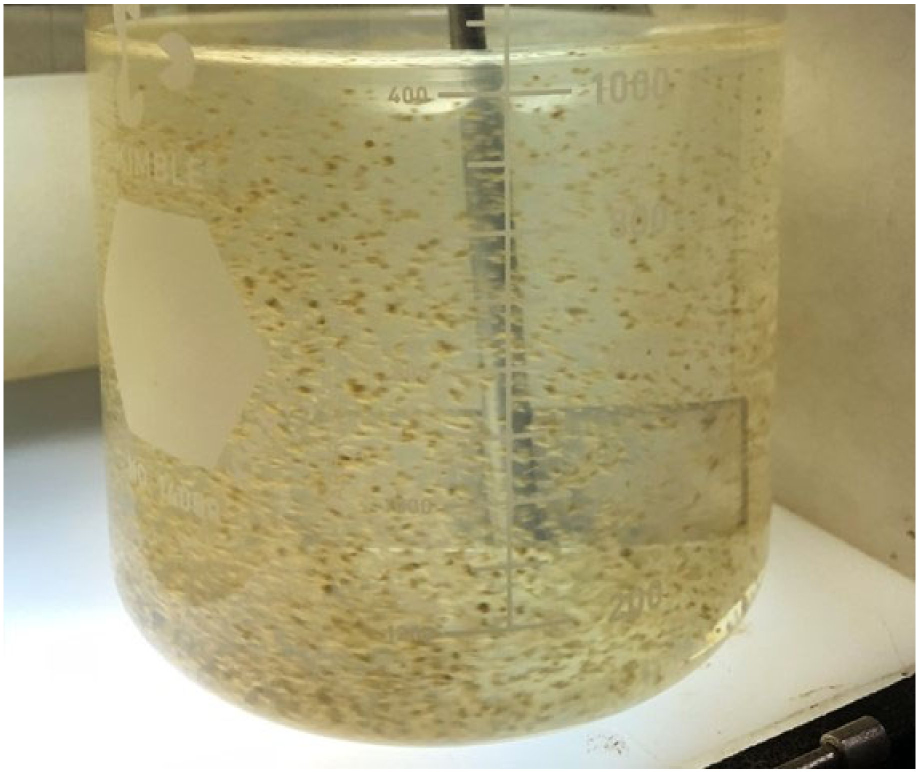


Figure 7 Floc formation.

Floc formation can be simulated through computer-based applications by calculating the volume density of particles in formed flocs *(Vold 1963)*. 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 *(ASTM-D2035-19 2019).* Floc size can be easily determined at a fixed measuring time based on a standardized reference chart presented in Figure 8. The chart classifies the size of the flocs in seven categories from the smallest (A) to the largest (G) floc size *(Swift et al. 2015)*.

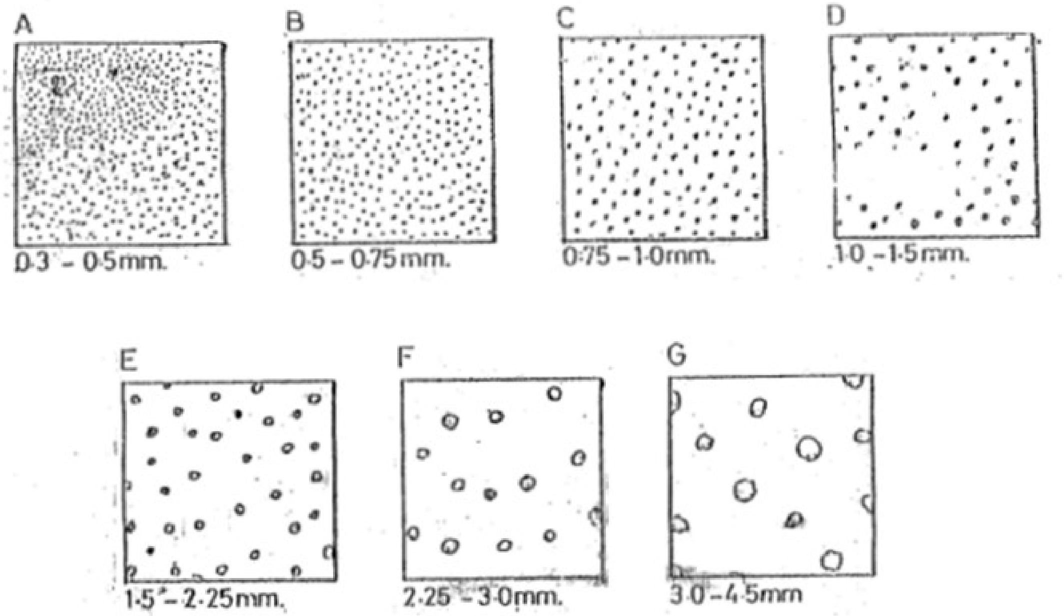


Figure 8 Floc size standard reference chart *(Swift et al. 2015).*

2.6.4 SETTLING VELOCITY

Settling velocity testing is typically applied in metallurgical studies on sludge settling for estimating the thickening capacity of flocculated suspensions *(Parsapour et al. 2014).* This method has also been used in oceanography for estimating the porosity of large suspended particles (*Kajihara* 1971). 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 *(Hunter 1986; Singh and Adhikari 2018).* The settling rate of a small spherical particle in a Newtonian fluid can be calculated by the use of this law *(Hunter 1986)*, as expressed in Eq. 1.

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

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}])

2.7 SUMMARY

Several research studies have been conducted on flocculants through laboratory experiments and field observations. This chapter provided a comprehensive review on flocculants and their use in construction stormwater management by summarizing relevant research on flocculation mechanism, flocculant types and forms, construction stormwater applications, toxicology limits, residual concentration monitoring, and floc characteristics.

CHAPTER THREE:
STATE-OF-THE-PRACTICE SURVEY: FLOCCULANT USAGE IN CONSTRUCTION STORMWATER MANAGEMENT

3.1 INTRODUCTION

State-of-the-practice surveys provide valuable input for research by outlining commonly used means and methods by practitioners. This chapter of the dissertation 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 $^{\text{TM}}$ 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 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 *(Alaska Department of Transportation 2016, Rhode Island State Conservation Committee 2014, Connecticut Department of Transportation 2004, Illinois Department of Transportation 2010, West Virginia Department of Transportation 2003, Department of Energy and Environment 2017, New York State Department of Environmental Conservation 2016).* 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.

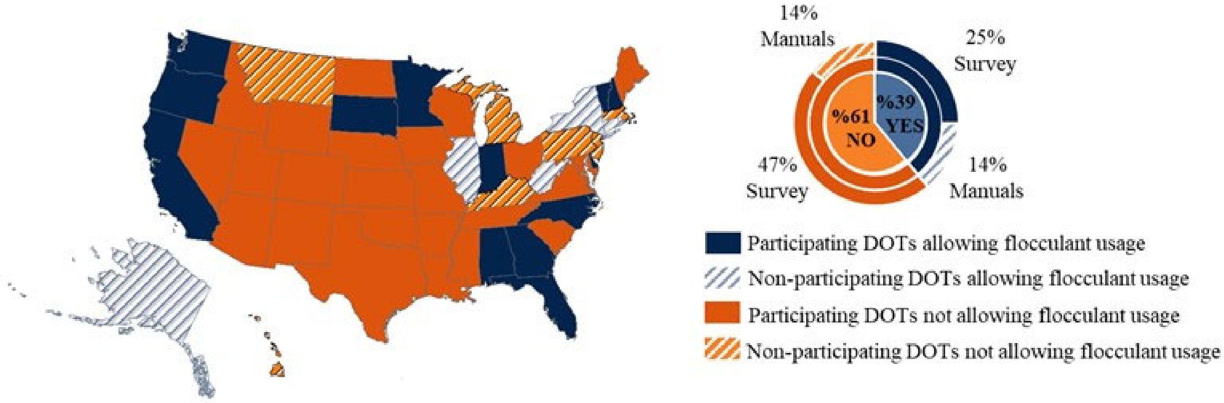


Figure 9 Map of flocculant usage of the state agencies in the U.S.

The addition of the non-participating states increased these numbers to 20 and 31, respectively. Figure 9 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 9, 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 10 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 10.

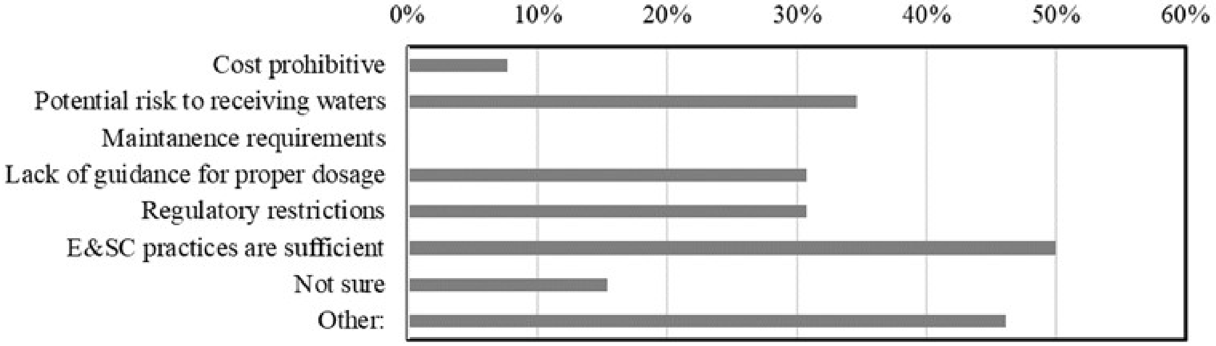


Figure 10 Reasons of state agencies for not using flocculants.

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 polyacrylamide (PAM) (62%), chitosan (38%), and polyaluminum chloride (PAC) (23%), respectively as shown in Figure 11.

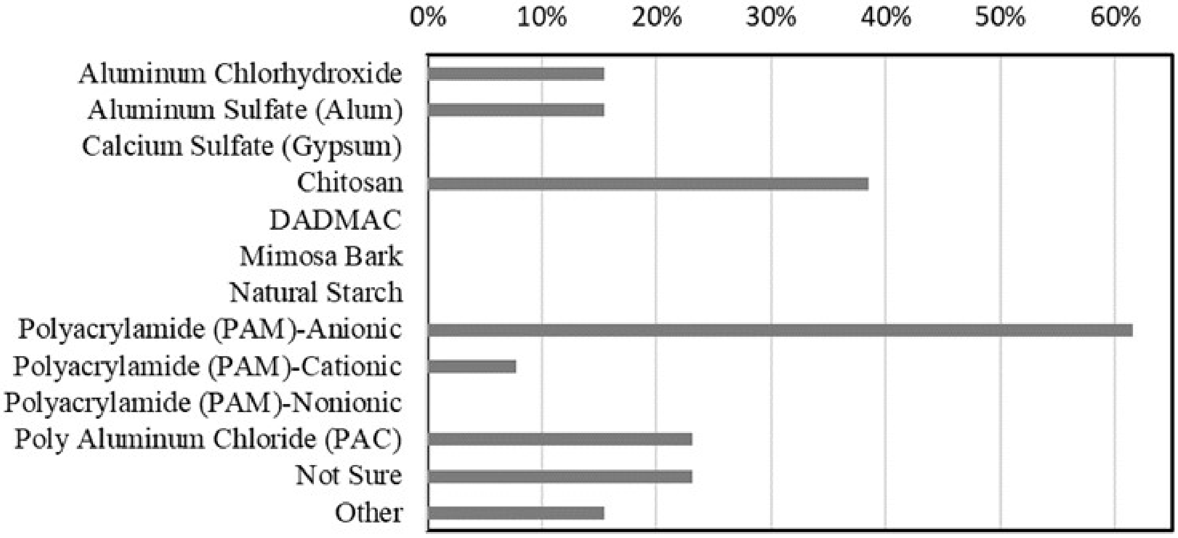


Figure 11 Flocculant types that are preferred by the state agencies.

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 CONCLUSION

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 FOUR:
BENCH-SCALE EVALUATION OF OPTIMUM DOSAGE AND RESIDUAL CONCENTRATIONS

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 dissertation 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 bench-scale evaluation phase of this research. 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.

4.2.1 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 12. 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 *(Mitchell 2008)*.

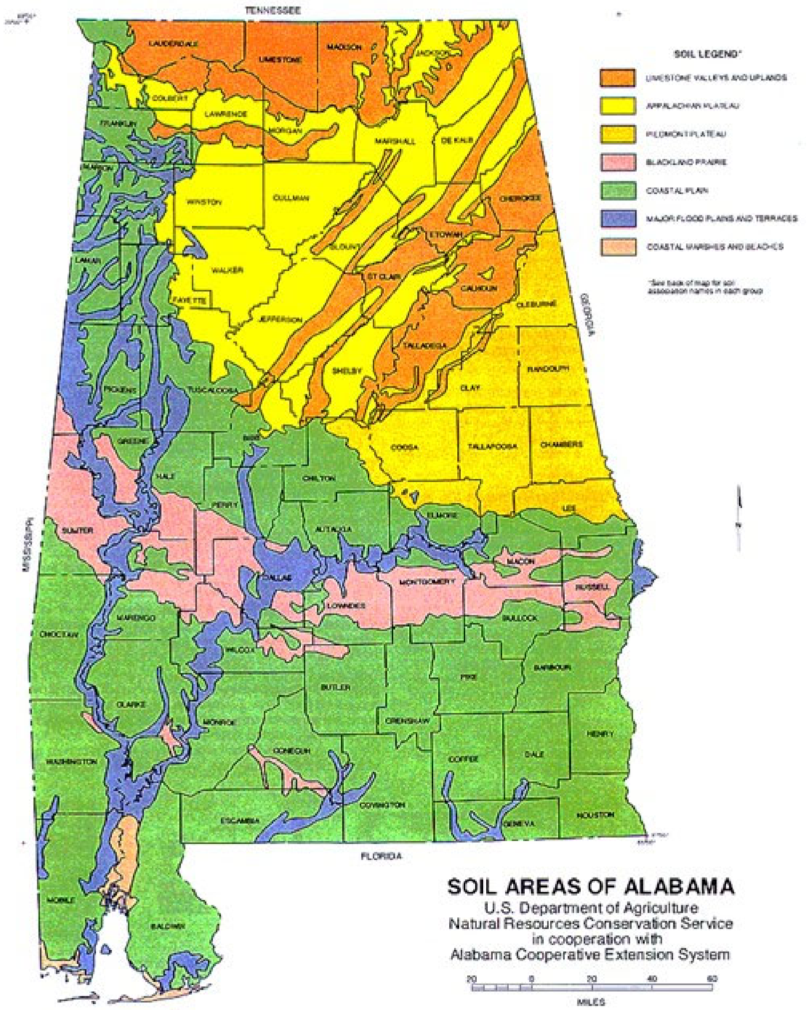


Figure 12 Soil areas of Alabama *(Mitchell 2008)*.

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 3. Soil sampling sites were in Shelby (East Central), Etowah (North), Montgomery (Southeast), Mobile (Southwest), and Bibb (West Central) counties as shown in Figure 13.

Table 3 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 13 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 14 illustrates soil sampling and storage procedures from the site visits.

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

Figure 14 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 *(USDA 1930)*. 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 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 oz (25 mL) of the clay suspensions were pipetted into empty 1.69 oz (50 mL) pre-weighed beakers. Figure 15 shows the pipette testing method setup used with clay suspension samples. Samples were back washed with water and 0.85 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 15 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 *(ASTM D4318 2005)*, hydrometer *(ASTM D6913-04R2009 2004)*, and Atterberg limits (*ASTM D7928 2017)* 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 16 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 16 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 *(ASTM D6913-04R2009 2004)*. Figure 17 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 oz (1000 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 *(ASTM D6913-04R2009 2004)*. 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 17 Hydrometer testing setup.

Following hydrometer analysis, the liquid and plastic limits of the soil samples were identified by using standardized methods (*ASTM D7928 2017).* 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 18 shows the manual Casagrande liquid limit tool used in the experiments.

Figure 18 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) 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 19. 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.

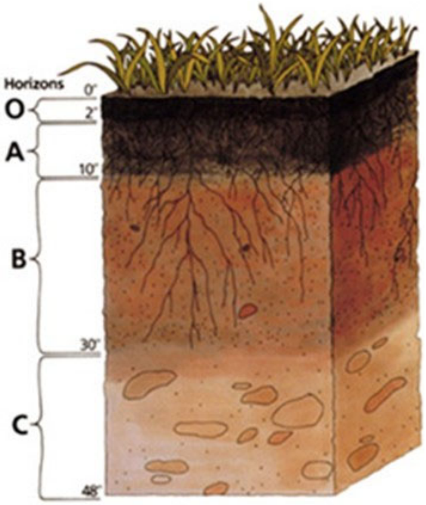


Figure 19 Soil profile *(USDA 2022).*

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 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.

4.2.2 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 *(ASTM D2035-19 2019)*.

The product selection was made by considering approved products by ALDOT which included polyacrylamide, 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 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 3.

Table 4 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 20 shows the injection rack design of the researchers that was used in this research.

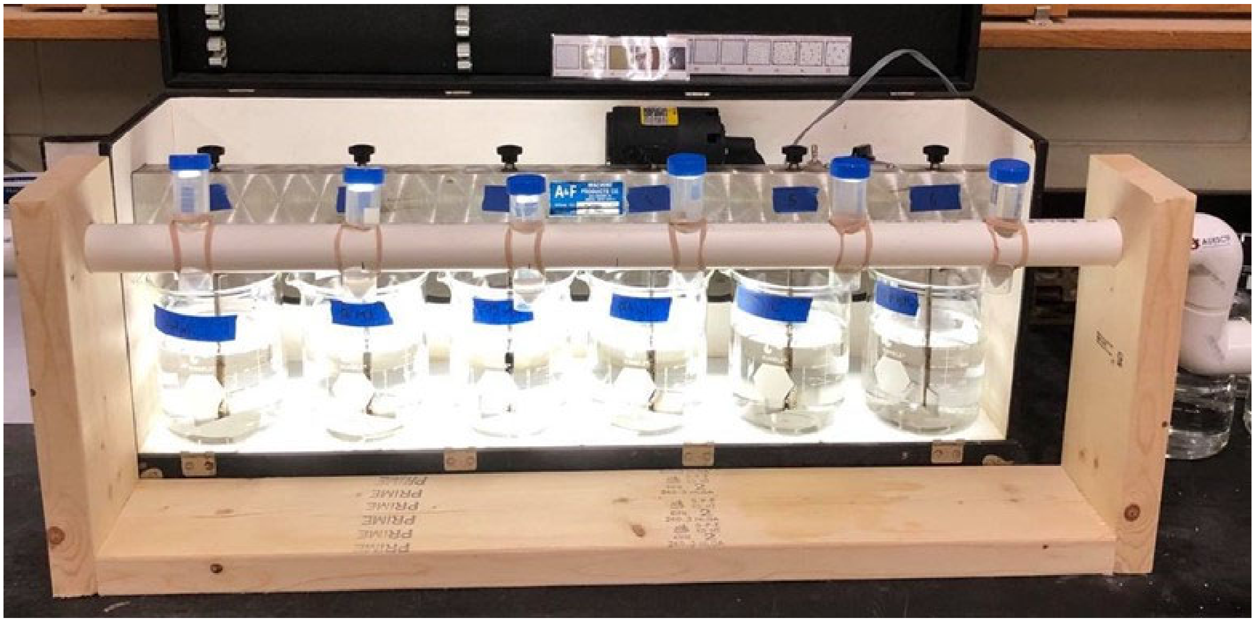
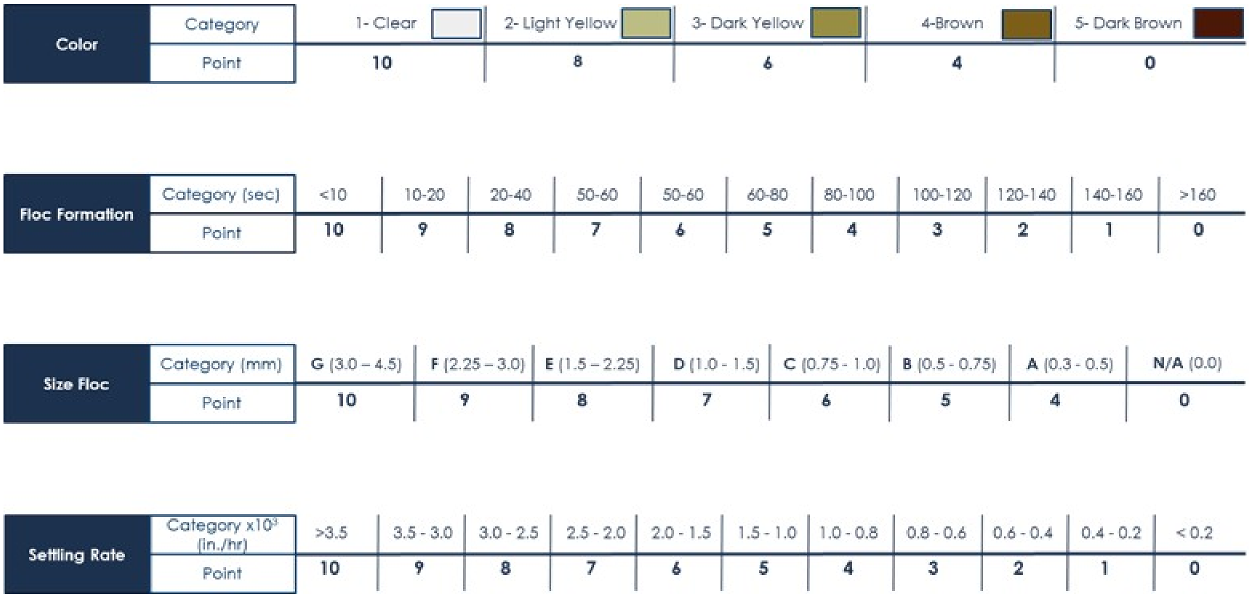


Figure 20 Flocculant injection rack.

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 21 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 Brown
	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	>160
	Point	10	9	8	7	6	5	4	3	2	1	0

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)	**N/A** (0.0)
	Point	10	9	8	7	6	5	4	0

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	< 0.2
	Point	10	9	8	7	6	5	4	3	2	1	0

Figure 21 Match test point system.

4.2.3 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 *(ASTM D2035-19 2019)*. 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 22 illustrates the dosage ranges used in the dosage test procedures.

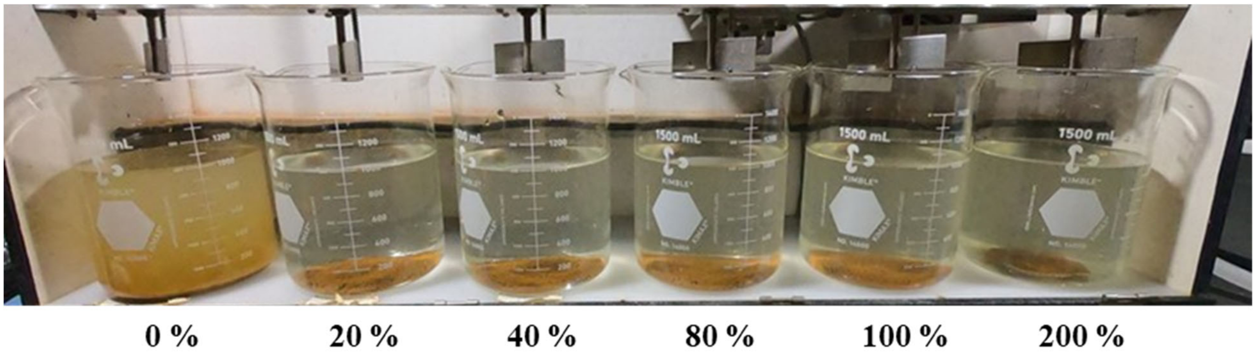


Figure 22 Dosage range.

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.

4.2.4 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 *(Badawy 2012; Al Momani and Örmeci 2014)*. 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 23 Eppendorf© 5810 centrifuge unit.

Known concentration samples with flocculants were prepared in beakers filled with 33.8 oz (1,000 mL) tap water. Samples consisted of flocculant types including polyacrylamide, chitosan, sodium montmorillonite, aluminum sulfate, calcium sulfate, and bentonite-based flocculant products. Known concentration samples were flash mixed for a minute and 1.7 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 23 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 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. Polyacrylamide, 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 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) *(ASTM D2035-19 2019)*. 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 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 24 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.

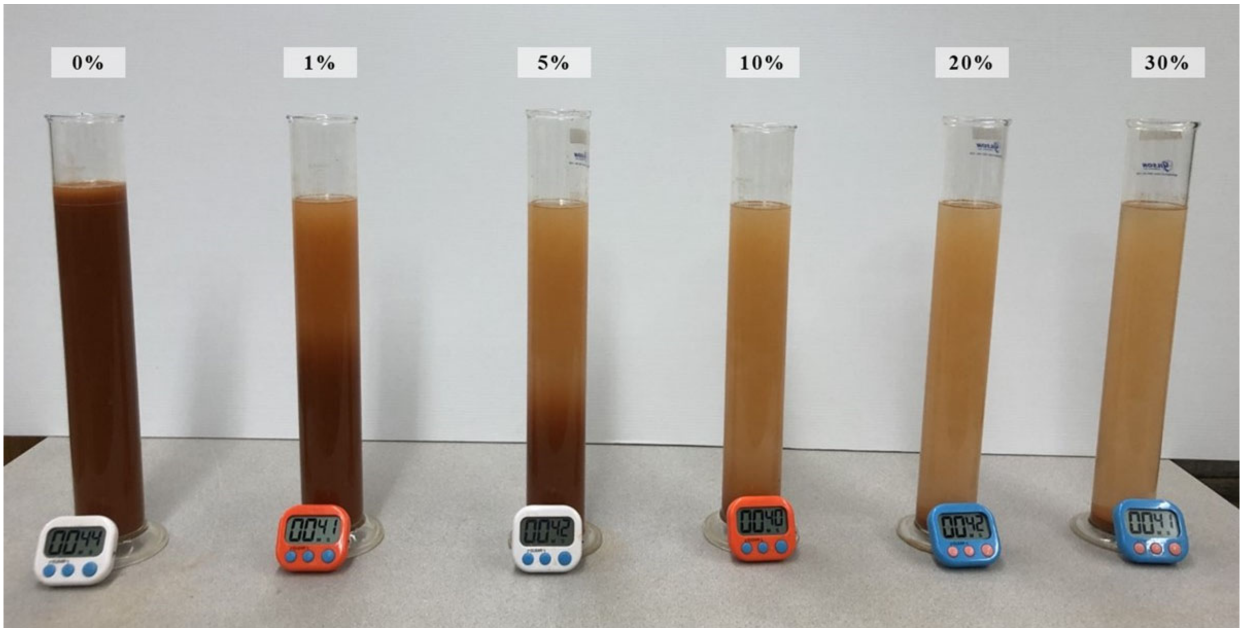


Figure 24 Settling depth tracking for product B.

4.3 Results and Discussions

Bench-scale evaluations were completed with the finalization of the dosage test and residual concentration experiments. The data were analyzed prior to dosage delivery experiments in large-scale application evaluation. Research findings provided substantial input for further investigations in 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.

4.3.1 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 5 shows the comparison of WSS soil classification results with the laboratory soil testing findings.

Table 5 Soil assessment comparison results

Soil Sample	USDA WSS			LABORATORY TESTS		
	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 25.

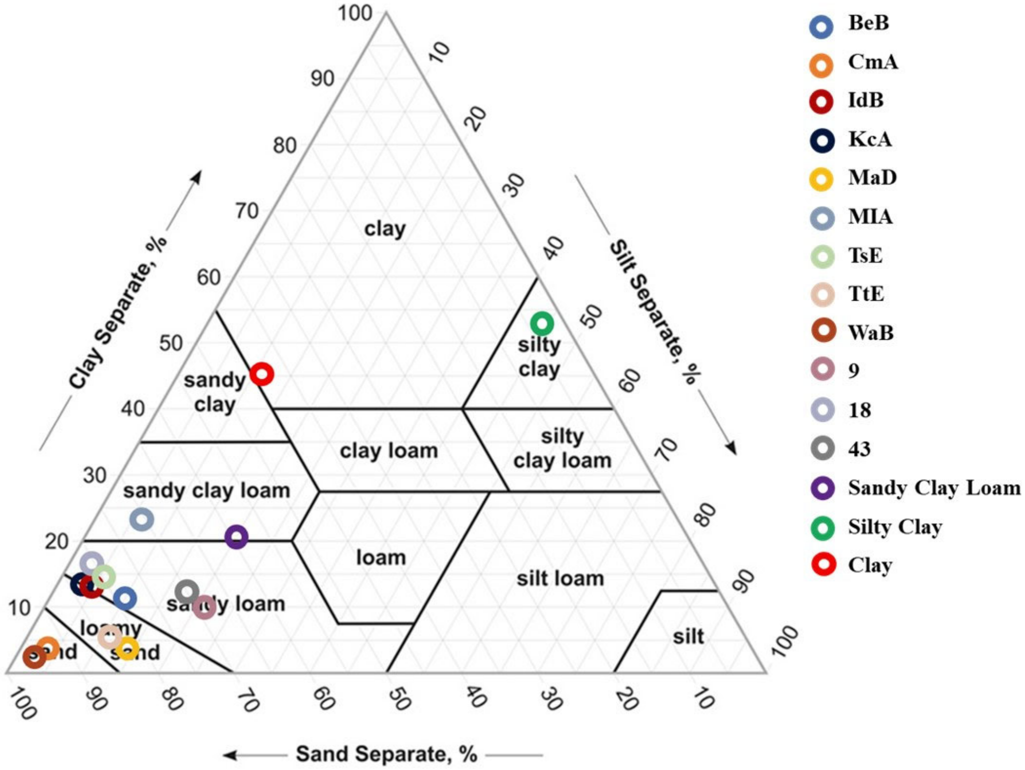
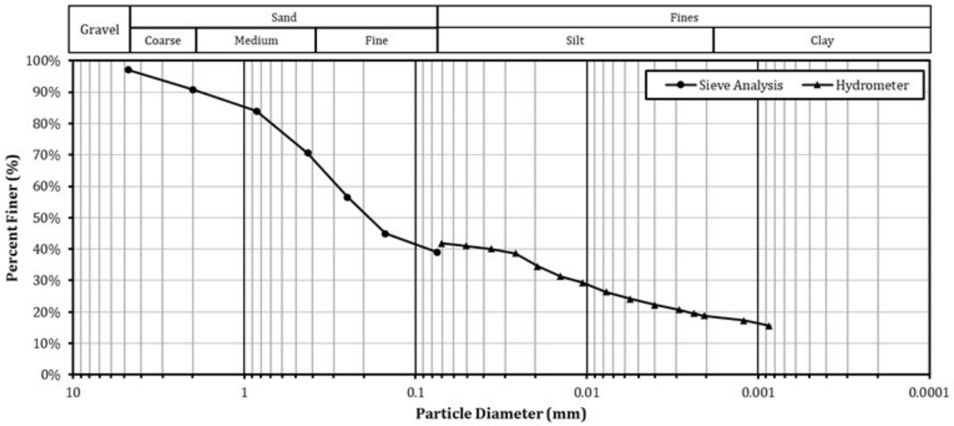


Figure 25 USDA soil classification results.

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 25. 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 testing 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 *(Shaw et al. 2010)*. 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 26(a) shows the texture of the testing soil and Figure 26(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 26(b)).

(a) soil texture



(b) particle size distribution

Figure 26 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 6 presents CEC results based on the experiments conducted at Auburn University Soil Testing Laboratory.

Table 6 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.

4.3.2 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.

Table 7 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 polyacrylamide (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 7 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

4.3.3 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 overdose 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. 2.

$$\%\, Turbidity\ Reduction = 100 - 100\ x \frac{T_f}{T_i} \qquad \text{Eq. 2}$$

Where,

T_i = initial turbidity reading (NTU)

T_f = final turbidity reading (NTU)

Table 8 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 overdose 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.

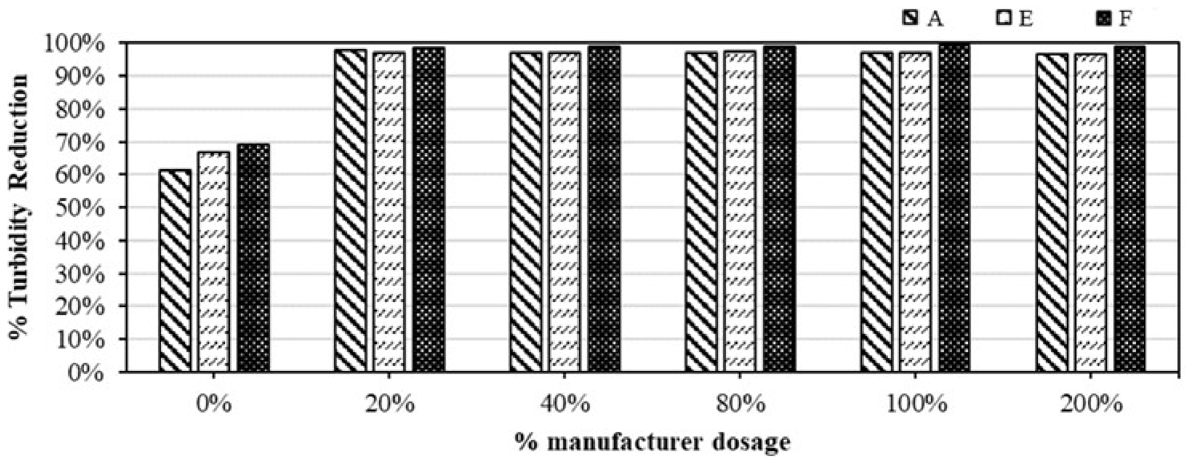
Table 8 Dosage experiment results for Bibb CmA with Product D application

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

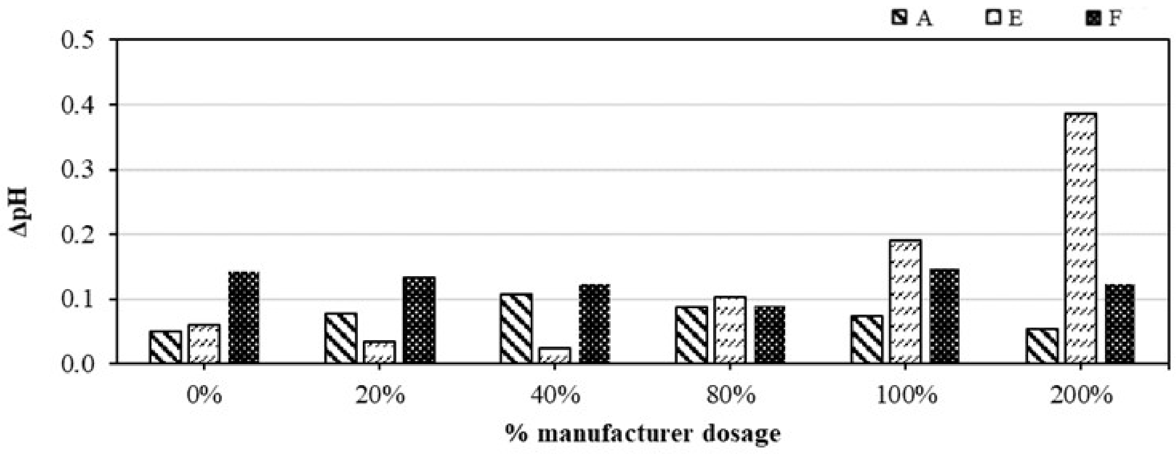
** manufacturer dosage recommendation*

The data analysis shown in Table 8 was conducted for each dosage experiment and optimum dosage reports were prepared by producing turbidity reduction, ΔpH, and color plots.

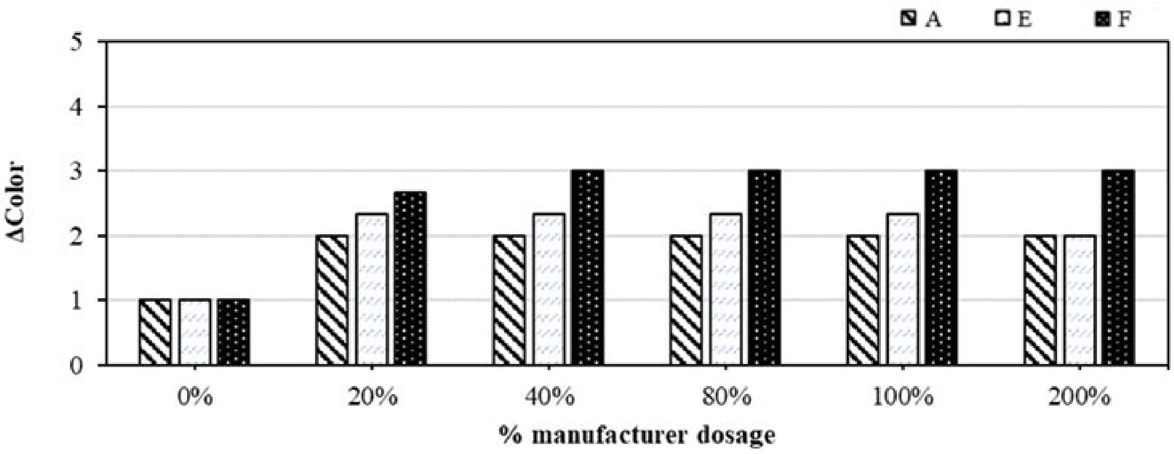
These data analysis plots presented dosage experiment results for behavior evaluation of the top three selected products on sampled soils as shown in the example presented in Figure 27.



(a) % turbidity reduction



(b) change in pH



(c) change in color

Figure 27 Dosage test data analysis plots for Shelby TsE.

Figure 27 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 polyacrylamide-based flocculants. In Figure 27(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 27(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 overdose condition. This behavior was also observed on other tested soils such as Montgomery KcA, Mobile BeB, Etowah 9, and Etowah 18.

Figure 27(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 28.

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.

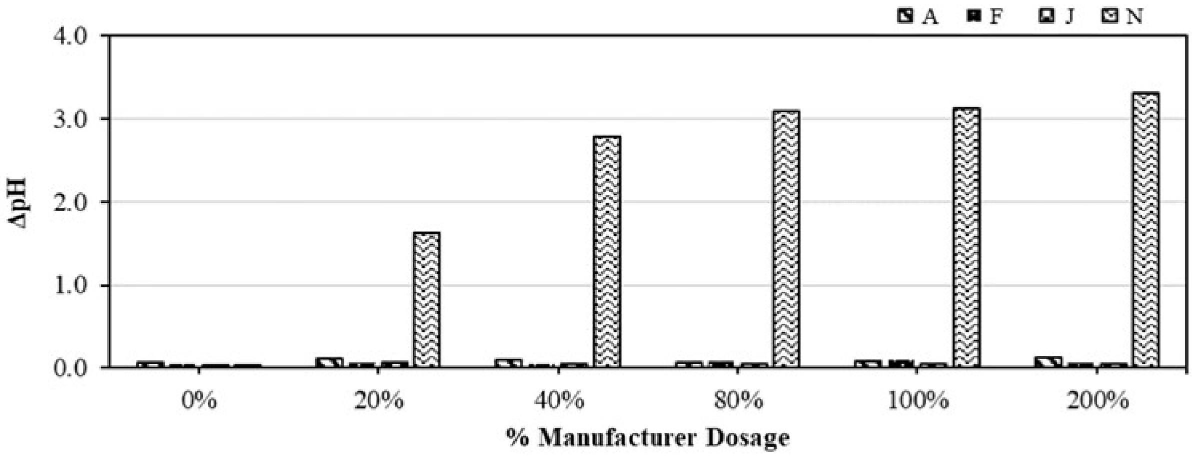


Figure 28 Change in pH on Shelby TtE.

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 9 shows statistical significance comparisons between dosage rate pairs.

Table 9 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 large-scale testing procedures for mimicking construction site conditions.

4.3.4 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 29 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.

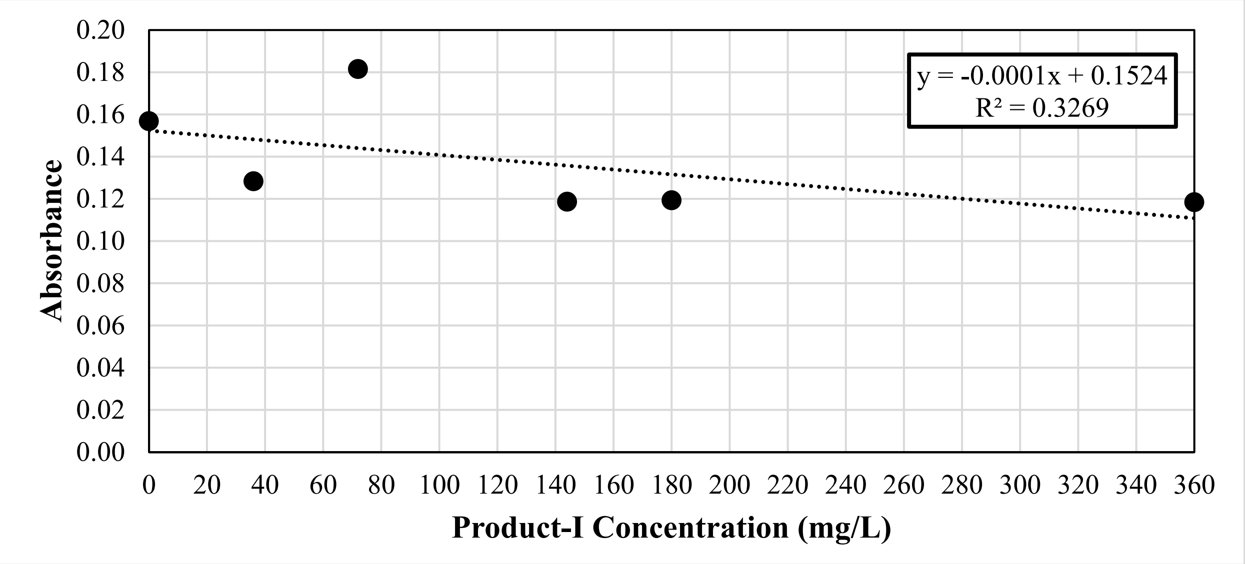


Figure 29 Absorbance readings for known concentration samples of the product I.

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 30 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 30 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 30. 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.

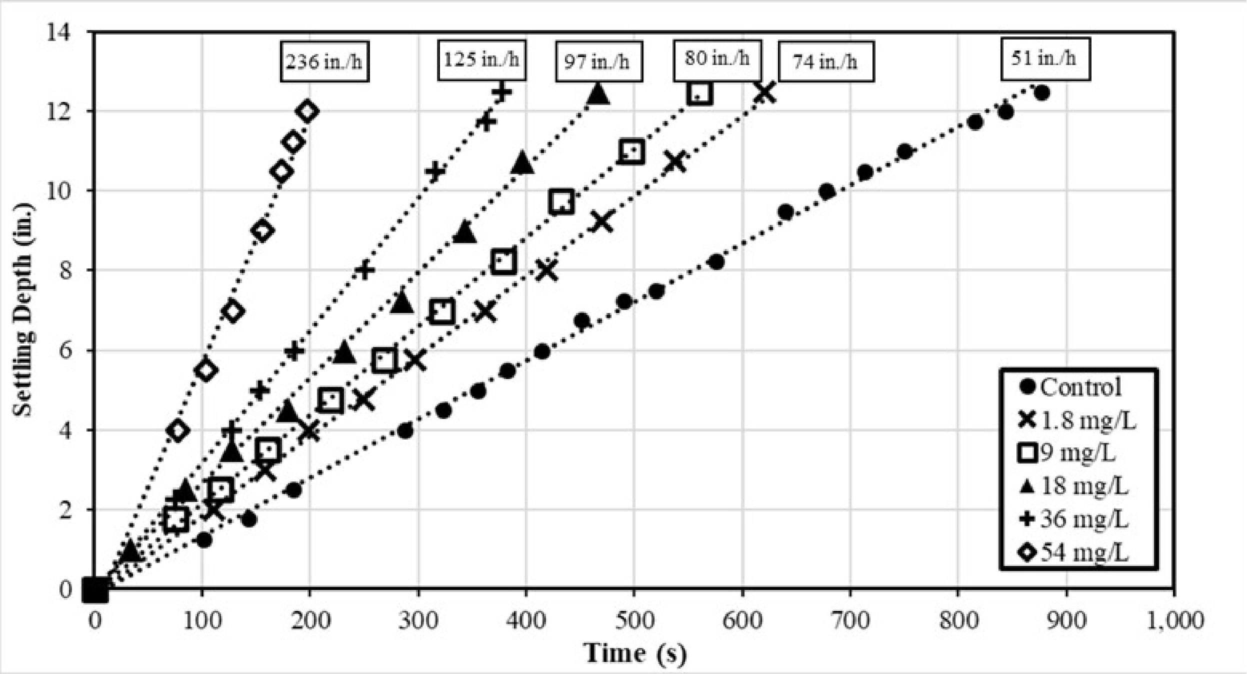
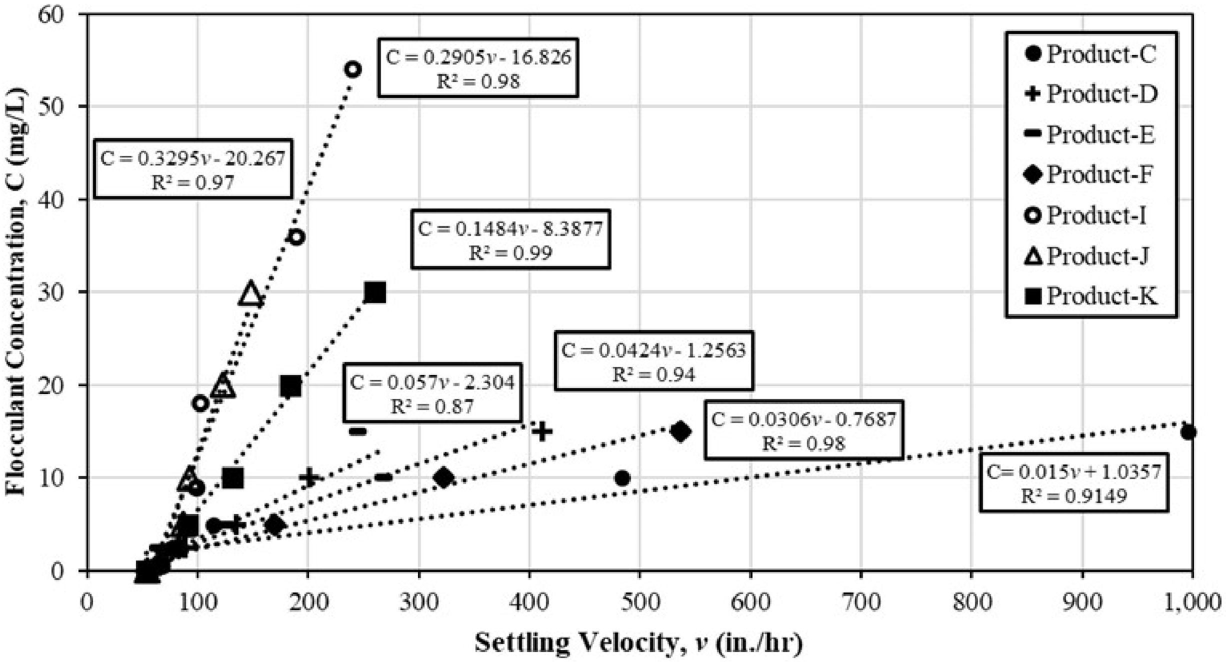


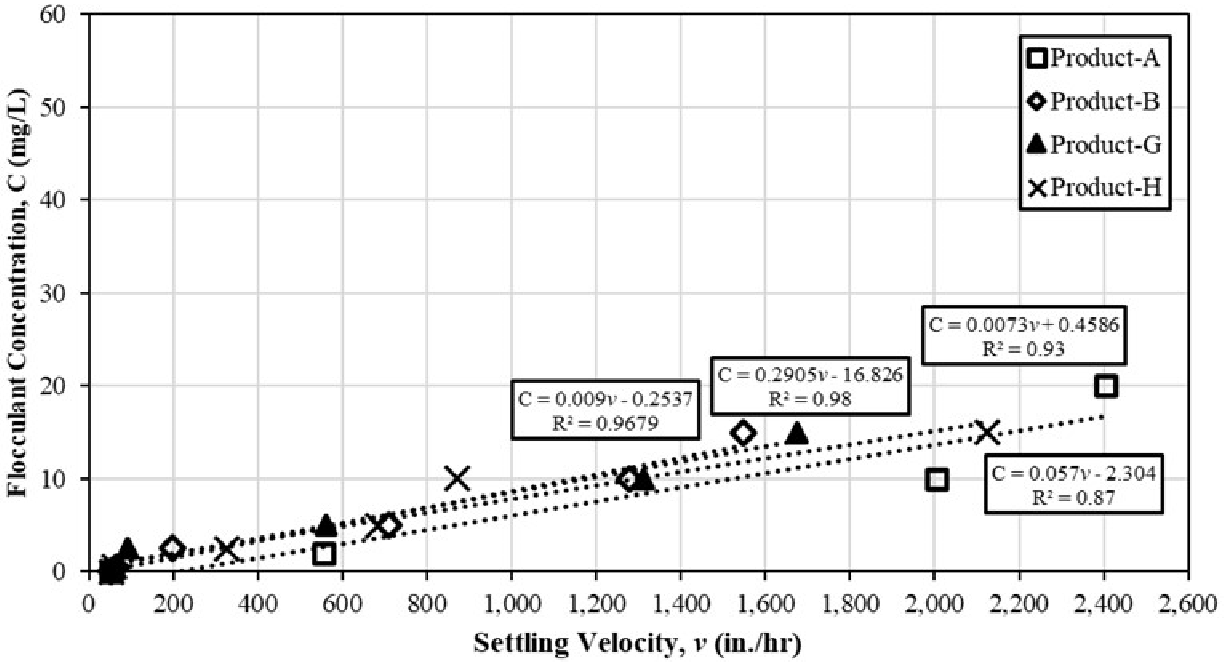
Figure 30 Settling depth vs. time plot of product I for six residual concentrations.

As observed in Figure 30, 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 31. Standardized residual settling results were presented in two plots in Figure 31 for facilitating data visualization due to the wide settling-velocity ranges of products. Figure 31(a) presents residual settling data for products C, D, E, F, I, J, and K, while Figure 31(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 31(a) and (b). When plotted, the flocculant residual concentration versus the settling velocity in Figure 31(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 31 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 31(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 32 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 32, the residual concentration of the product was determined to approximate 415 mg/L.

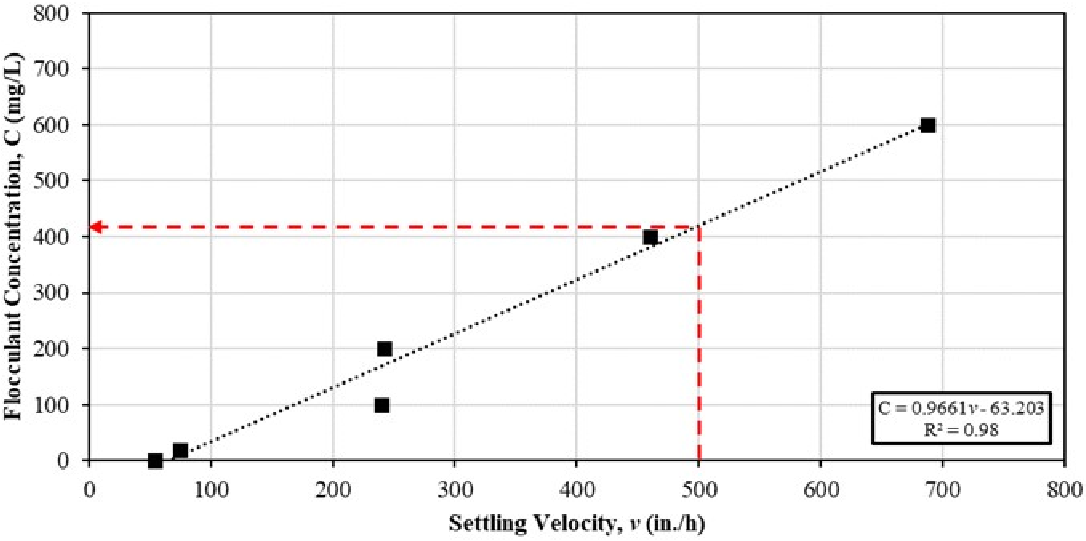


Figure 32 Concentration determination example with product N.

For effective measurement in field conditions, approximately 33.8 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.

4.4 DEVELOPMENT OF PRODUCT SELECTION TOOL: FLOCSPREAD

Based on the results obtained in the bench-scale phase of this research, a spreadsheet-based FlocSpread tool was developed for providing user-friendly product selection guidance. The goal of developing this tool was to guide practitioners on proper flocculant selection and dosage. This section will discuss the development procedure of the tool and provide details on the function of each worksheet within the tool. The FlocSpread tool was designed with the intent of applicability to any construction site in the U.S.; however, the database for soil classification-based product match was formed based on the tested soils across the state of Alabama.

4.4.1 TOOL DEVELOPMENT

A spreadsheet workbook was developed with five worksheets to allow users to classify soils based on three different soil classification systems, select proper products, and identify dosage and product costs.

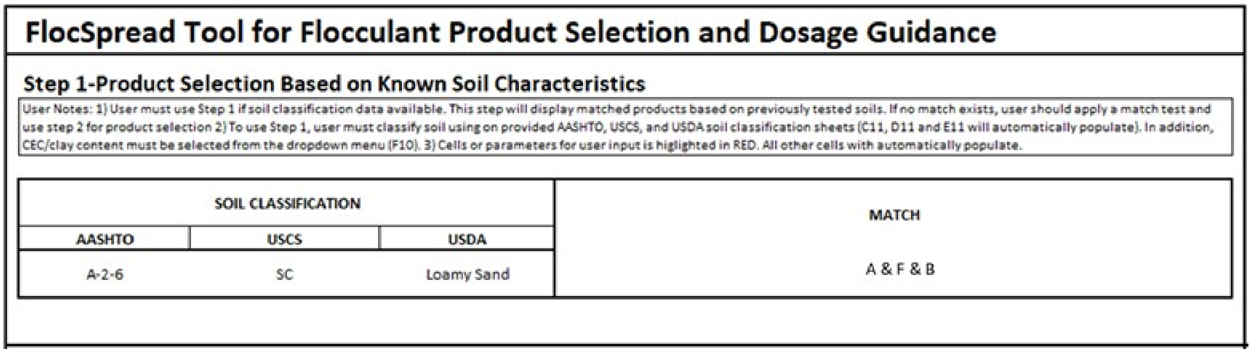
The individual worksheets listed in order are:

1) *FlocSpread*
2) *AASHTO*
3) *USCS*
4) *USDA*
5) *Unit Cost*

The workbook also contains three different database worksheets that store the data for the match test point system, previously completed match tests, and dosage recommendations. Sheet one is the primary output worksheet and sheets two through five supplements the calculations within the first sheet. Sheets two through four were integrated from pre-developed soil classification tools obtained from open-access sources *(Lee 2021; Miller 2014)*.

4.4.2 FLOCSPREAD OUTPUTS AND USER GUIDANCE

The first worksheet, *FlocSpread*, includes all user-defined inputs that are required to select proper flocculant products and appropriate dosage. The *FlocSpread* worksheet is divided into three primary sections: (1) product selection based on known soil characteristics, (2) product selection based on match test, and (3) dosage guidance. The first section provides users the ability to identify best-performing products based on previously tested soil with a match test. To utilize this section, the user should have laboratory soil testing results on the specific soil that needs to be evaluated for product selection. This section gathers the soil classification information from worksheets two to four and searches the soil classification combination within the previously tested soils for product selection. If the classified soil exists in the match test results obtained in this research, the worksheet auto-populates the top three best-performing products for the user as illustrated in Figure 33. In the illustrated example below, the tool retrieves the information for AASHTO, USCS, and USDA soil classification as A-2-6, SC, and Loamy Sand based on the user input in worksheets two, three, and four, respectively. By using this information, the tool finds this combination within the previously tested soils and suggests products A, F, and B for product selection. These products were previously ranked as the top three best performing products on a similar soil sample in this research during the match test experiments phase.



FlocSpread Tool for Flocculant Product Selection and Dosage Guidance

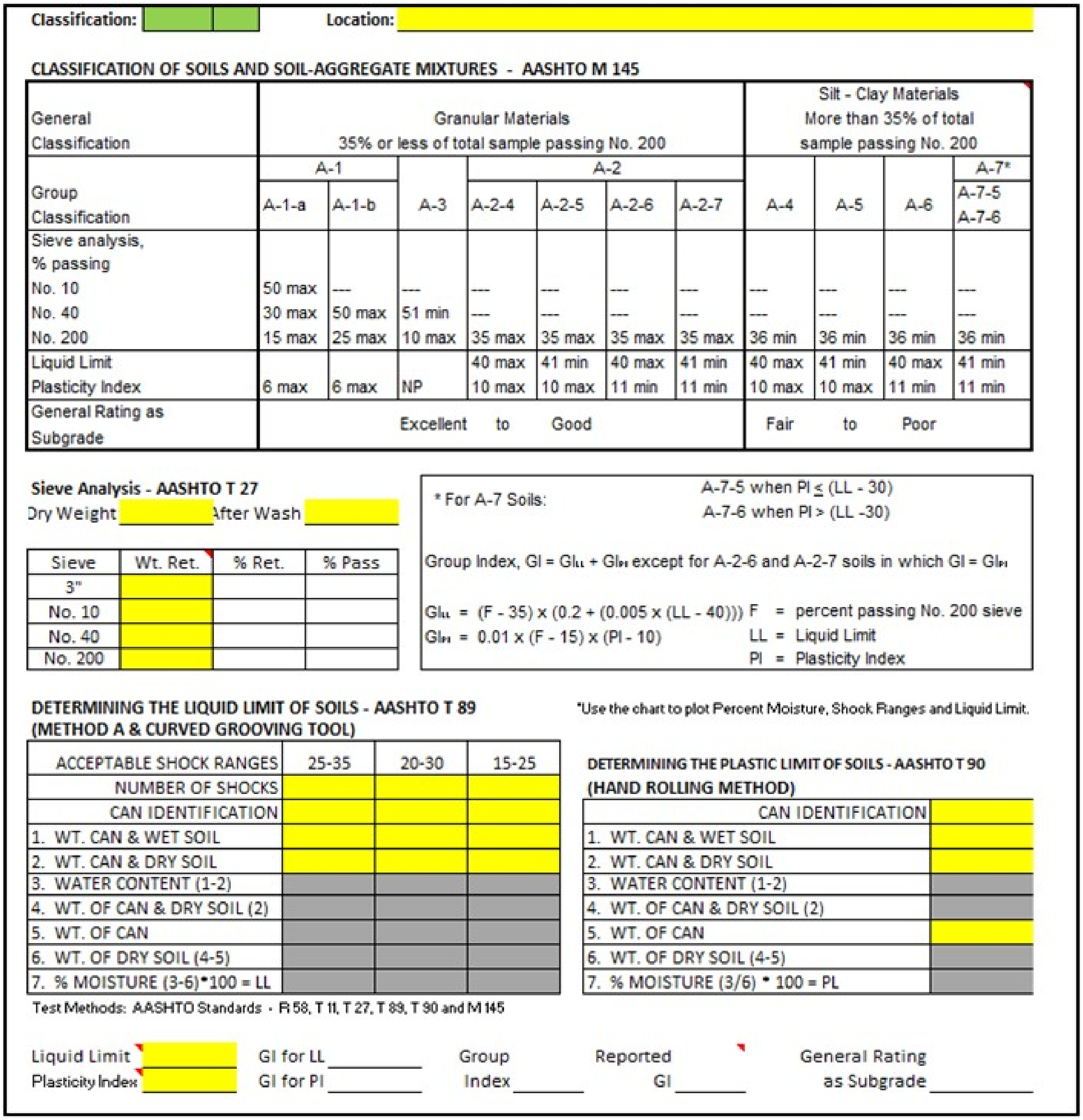
Step 1-Product Selection Based on Known Soil Characteristics

User Notes: 1) User must use Step 1 if soil classification data available. This step will display matched products based on previously tested soils. If no match exists, user should apply a match test and use step 2 for product selection 2) To use Step 1, user must classify soil using on provided AASHTO, USCS, and USDA soil classification sheets (C11, D11 and E11 will automatically populate). In addition, CEC/clay content must be selected from the dropdown menu (F10). 3) Cells or parameters for user input is higlighted in RED. All other cells with automatically populate.

SOIL CLASSIFICATION			MATCH
AASHTO	USCS	USDA	
A-2-6	SC	Loamy Sand	A & F & B

Figure 33 Output example for step 1 – FlocSpread.

Worksheet two offers an automated soil classification tool based on the AASHTO soil classification system and provides information for the first section of the FlocSpread tool. In order to use this worksheet, the user should complete the information in the cells highlighted with yellow. Figure 34 shows the required parameters to effectively use this worksheet. The required soil testing information for this sheet consists of the results obtained from standard sieve analysis and Atterberg limits tests. Based on the input, this worksheet auto-populates AASHTO soil classification, which is highlighted in green and provides information for the first section of the *FlocSpread* worksheet.



Classification: **Location:**

CLASSIFICATION OF SOILS AND SOIL-AGGREGATE MIXTURES - AASHTO M 145

General Classification	Granular Materials 35% or less of total sample passing No. 200							Silt - Clay Materials More than 35% of total sample passing No. 200			
	A-1			A-2							A-7*
Group Classification	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5 A-7-6
Sieve analysis, % passing											
No. 10	50 max	---	---	---	---	---	---	---	---	---	---
No. 40	30 max	50 max	51 min	---	---	---	---	---	---	---	---
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Liquid Limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max	6 max	NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
General Rating as Subgrade	Excellent to Good							Fair to Poor			

Sieve Analysis - AASHTO T 27

Dry Weight After Wash

Sieve	Wt. Ret.	% Ret.	% Pass
3"			
No. 10			
No. 40			
No. 200			

* For A-7 Soils: A-7-5 when PI ≤ (LL - 30)
A-7-6 when PI > (LL -30)

Group Index, GI = $GI_{LL} + GI_{PI}$ except for A-2-6 and A-2-7 soils in which GI = GI_{PI}

GI_{LL} = (F - 35) x (0.2 + (0.005 x (LL - 40)))
GI_{PI} = 0.01 x (F - 15) x (PI - 10)

F = percent passing No. 200 sieve
LL = Liquid Limit
PI = Plasticity Index

DETERMINING THE LIQUID LIMIT OF SOILS - AASHTO T 89 (METHOD A & CURVED GROOVING TOOL)

*Use the chart to plot Percent Moisture, Shock Ranges and Liquid Limit.

ACCEPTABLE SHOCK RANGES	25-35	20-30	15-25
NUMBER OF SHOCKS			
CAN IDENTIFICATION			
1. WT. CAN & WET SOIL			
2. WT. CAN & DRY SOIL			
3. WATER CONTENT (1-2)			
4. WT. OF CAN & DRY SOIL (2)			
5. WT. OF CAN			
6. WT. OF DRY SOIL (4-5)			
7. % MOISTURE (3-6)*100 = LL			

DETERMINING THE PLASTIC LIMIT OF SOILS - AASHTO T 90 (HAND ROLLING METHOD)

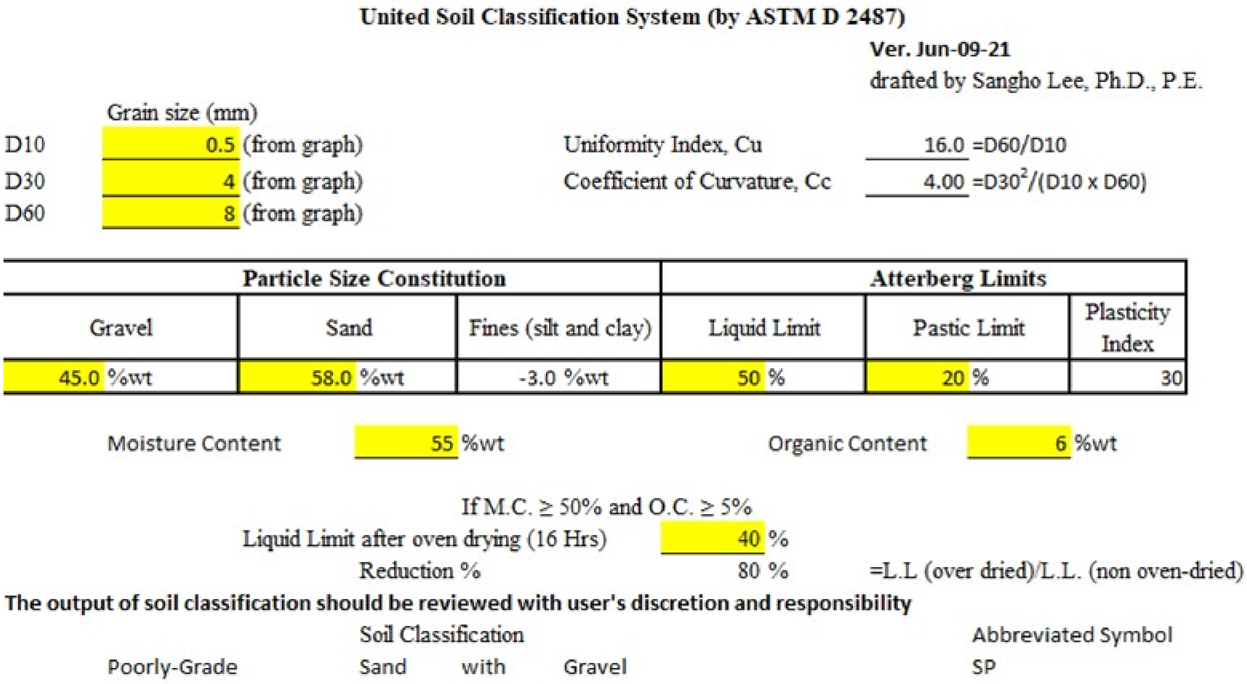
CAN IDENTIFICATION	
1. WT. CAN & WET SOIL	
2. WT. CAN & DRY SOIL	
3. WATER CONTENT (1-2)	
4. WT. OF CAN & DRY SOIL (2)	
5. WT. OF CAN	
6. WT. OF DRY SOIL (4-5)	
7. % MOISTURE (3/6) * 100 = PL	

Test Methods: AASHTO Standards - R 58, T 11, T 27, T 89, T 90 and M 145

Liquid Limit
Plasticity Index
GI for LL __________
GI for PI __________
Group Index ________
Reported GI ________
General Rating as Subgrade ___________

Figure 34 AASHTO worksheet.

Worksheet three classifies soils based on USCS and requires users to input information on grain size (D_{10}, D_{30}, and D_{60}), particle size (percent gravel, sand, and fines), liquid limit, plastic limit, moisture, and organic content. The input cells are highlighted in yellow as shown in Figure 35, and the tool auto-populates the soil classification result in an abbreviated symbol form in the right bottom corner. The *FlocSpread* worksheet gathers USCS soil classification information from this specific cell.



United Soil Classification System (by ASTM D 2487)

Ver. Jun-09-21

drafted by Sangho Lee, Ph.D., P.E.

	Grain size (mm)			
D10	0.5 (from graph)	Uniformity Index, Cu	16.0	=D60/D10
D30	4 (from graph)	Coefficient of Curvature, Cc	4.00	$=D30^2/(D10 \times D60)$
D60	8 (from graph)			

Particle Size Constitution			**Atterberg Limits**		
Gravel	Sand	Fines (silt and clay)	Liquid Limit	Pastic Limit	Plasticity Index
45.0 %wt	58.0 %wt	-3.0 %wt	50 %	20 %	30

Moisture Content 55 %wt

Organic Content 6 %wt

If M.C. ≥ 50% and O.C. ≥ 5%

Liquid Limit after oven drying (16 Hrs) 40 %

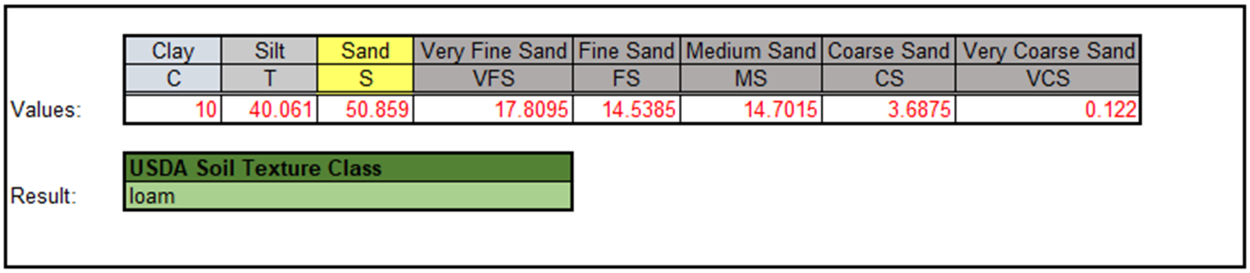
Reduction % 80 % =L.L (over dried)/L.L. (non oven-dried)

The output of soil classification should be reviewed with user's discretion and responsibility

Soil Classification				Abbreviated Symbol
Poorly-Grade	Sand	with	Gravel	SP

Figure 35 USCS Worksheet.

In addition to worksheets two and three, soil classification continues with worksheet 3 by using USDA soil classification. The worksheet requires information on %clay, silt, sand, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand. Once the user enters the values shown in red font in Figure 36, the worksheet auto-populates the USDA soil texture class based on the soil texture triangle. Again, the FlocSpread worksheet uses this classification for the first product selection section of the tool.



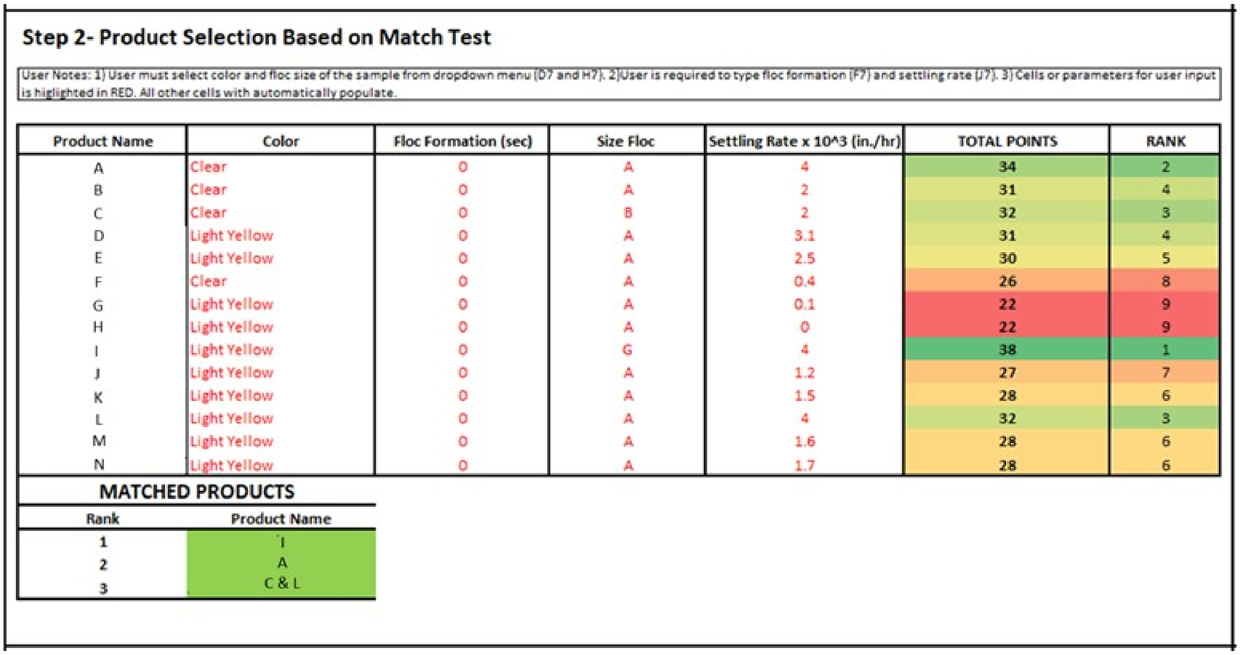
	Clay	Silt	Sand	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand
	C	T	S	VFS	FS	MS	CS	VCS
Values:	10	40.061	50.859	17.8095	14.5385	14.7015	3.6875	0.122

Result:

USDA Soil Texture Class
loam

Figure 36 USDA worksheet.

If the soil classification results for the specific soil that will be used for flocculant application do not exist in the match test database, the first section of the floc spread tool will not be able to display the top three best-performing products. In this case, the user should use the second section of the tool and a new match test should be conducted in the laboratory. The performance of products A through N on the specific soil sample should be evaluated based on developed match test procedures in this research and match test results for color, floc formation, size floc, and settling rate should be provided by the user as input for Step 2 of the tool. Figure 37 illustrates an output example for the use of Step 2. The user should provide information highlighted in red based on the obtained match test results. The tool automatically relates these input parameters with the developed reference point system discussed in the match test section of this chapter. The tool calculates total points with each product by using the point system and ranks them from the highest point to the lowest point. The developed worksheet also color codes total points and rankings; red tones indicate ineffective products and green tones represent well-performing products. The darker green tones show higher performance products, while darker red displays worse-performing products. The matched products section of Step 2 evaluates the color-coded rank column and lists the top-three best-performing products in the green highlighted rows.



Step 2- Product Selection Based on Match Test

User Notes: 1) User must select color and floc size of the sample from dropdown menu (D7 and H7). 2)User is required to type floc formation (F7) and settling rate (J7). 3) Cells or parameters for user input is higlighted in RED. All other cells with automatically populate.

Product Name	Color	Floc Formation (sec)	Size Floc	Settling Rate x 10^3 (in./hr)	TOTAL POINTS	RANK
A	Clear	0	A	4	34	2
B	Clear	0	A	2	31	4
C	Clear	0	B	2	32	3
D	Light Yellow	0	A	3.1	31	4
E	Light Yellow	0	A	2.5	30	5
F	Clear	0	A	0.4	26	8
G	Light Yellow	0	A	0.1	22	9
H	Light Yellow	0	A	0	22	9
I	Light Yellow	0	G	4	38	1
J	Light Yellow	0	A	1.2	27	7
K	Light Yellow	0	A	1.5	28	6
L	Light Yellow	0	A	4	32	3
M	Light Yellow	0	A	1.6	28	6
N	Light Yellow	0	A	1.7	28	6

MATCHED PRODUCTS

Rank	Product Name
1	I
2	A
3	C & L

Figure 37 Output example for step 2- product selection based on match test.

The example presented in Figure 37 shows that the user filled out the input parameters for color, floc formation, size floc, and settling rate based on the match test results. Color and size floc parameters can be selected from the provided dropdown menu within the tool. However, the user should manually enter the information for floc formation and settling rate parameters. After the completion of the input parameters in the example, the tool calculated the total points for each product and color-coded the results. Based on the color coding and total points, it can be easily observed that products G and H are the least effective ones, and product I is the best performing product among 14 different flocculant products. The tool also auto-populates the rank column and color-codes the rankings in this example, which provided supporting information for the evaluation of total points. In this specific scenario, products G and H were ranked as ninth and color-coded with dark red, while product I was ranked as first, and color-coded with dark green based on its performance on the tested soil.

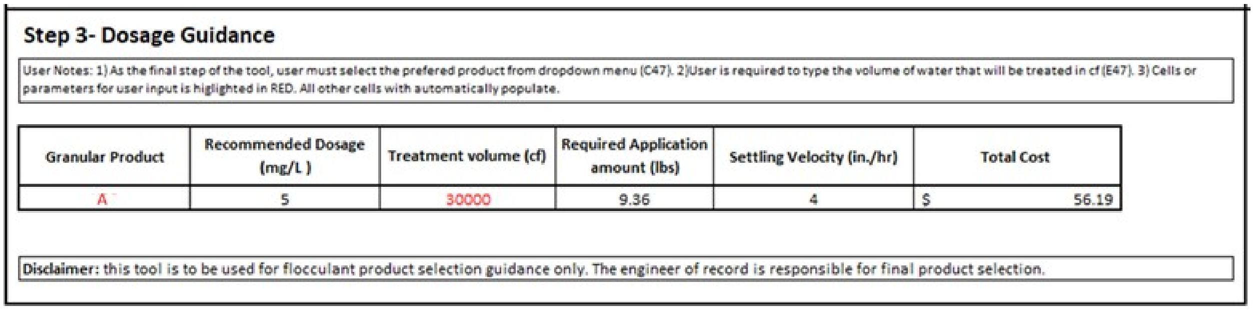
The tool selected the top three best-performing products and displayed them in the matched product section as products I, A, C, and L. In the presented scenario, two products were selected for the third-ranking: products C and L. This shows that the tool can assign the same ranking to the products that show an identical performance based on the point system. Thus, if the products gain the same total point in the match test, their ranking will be the same among all evaluated products in the experiments.

The discussed example showed the capability of the tool for suggesting flocculant products. However, it should be noted that the end-user of the tool is responsible for making the final decision on selecting the appropriate product. The decision-making on product selection is also dependent on available supplies, accessibility, and the cost of the products. These conditions may differ for each construction project and might require the user to prefer second or third-ranked flocculant products.

In addition to product selection guidance, the FlocSpread tool also offers dosage guidance on granular products through the Step 3 Dosage Guidance section within the *FlocSpread* worksheet. As the final step of the tool, the user should select the desired product from the dropdown menu provided in the granular product column. Once the product is selected the tool auto-populates a recommended dosage concentration rate in mg/L. The user is also required to provide the treatment volume as an input for the tool to calculate the required application amount for the selected product. The treatment volume can be easily calculated by the user based on storm-specific parameters such as peak flow and the duration of the expected storm event. The tool also retrieves the settling velocity information from Step 2 and displays it in section Step 3 for the selected product. This information can guide practitioners in evaluating the need for using skimmers in sediment basin applications. If the product shows substantially high settling velocity rates, the use of a skimmer in basin design might not be necessary.

As a final step, the tool auto-populates an estimated cost based on the unit cost of the product and the required application amount. The *FlocSpread* worksheet uses unit cost information provided in worksheet five and multiplies the unit cost for the calculated required application amount for providing a cost estimation. Since the unit cost of the products may be subjected to change based on the pricing policy of manufacturers, worksheet five was built in a way that cost information can be updated by the user.

Figure 38 provides an example scenario, where the user-selected product A among the FlocSpread product selection suggestions. For product A, the tool auto-populated the 5 mg/L dosage recommendation and retrieved settling velocity as 4 in./hr (10.2 cm/hr) from the Step 2 section within the *FlocSpread* worksheet. In this example, the user-provided 30,000 ft^3 (850 m^3) treatment volume as an input. The tool used this information and auto-populated the required application amount as 9.4 lbs (4.3 kg). Finally, the total cost was calculated as $56.10 by considering the cost/weight information provided in worksheet 5.



Step 3- Dosage Guidance

User Notes: 1) As the final step of the tool, user must select the prefered product from dropdown menu (C47). 2)User is required to type the volume of water that will be treated in cf (E47). 3) Cells or parameters for user input is higlighted in RED. All other cells with automatically populate.

Granular Product	Recommended Dosage (mg/L)	Treatment volume (cf)	Required Application amount (lbs)	Settling Velocity (in./hr)	Total Cost
A	5	30000	9.36	4	$ 56.19

Disclaimer: this tool is to be used for flocculant product selection guidance only. The engineer of record is responsible for final product selection.

Figure 38 Output example for step 3 – dosage guidance.

Example scenarios discussed in the previous section showcase the capabilities of the developed workbook and provide guidance on the use of the tool. The workbook summarizes results in the main *FlocSpread* sheet; however, supplemental sheets require user input for soil classification and cost analysis.

4.4.3 LIMITATIONS AND CONTRIBUTIONS

The FlocSpread tool provides an organized and user-friendly platform that utilized the bench-scale experiment findings of this research for product selection and dosage guidance. The developed workbook contains a two-step product selection procedure, allowing users to select products based on soil classification input or match test results. The tool offers a final step for dosage guidance based on product selection decisions made in the initial steps. This final step aims to provide an estimate of the required application amount and total cost for granular flocculant application.

The FlocSpread tool provides an automated product selection and dosage guidance within its limitations. One of the major limitations of the tool is the limited dosage guidance on different flocculant forms. The tool only focuses on providing dosage guidance on granular flocculant products, which limits the user in selecting other flocculant forms such as block, sock, or emulsion. Also, the tool suggests the required application amount in lbs (kg) and does not provide any guidance on the required number of block or sock forms. This limitation can be improved in future versions of the tool by modifying the second step of the tool with additional products in various forms.

Another limitation of the tool is the narrow data source for soil characteristic-based match in the first step. Currently, the tool retrieves the match information based on 15 soil samples evaluated within this research by applying a match test on 14 different flocculant products. The workbook displays the "no match" condition in Step 1 if the soil classification does not exist within these previously tested soils. The matched soil dataset should be improved with time by increasing the variety of tested soils. The use of this tool with a match test would allow the improvement of this limitation.

This tool aims to improve the decision-making process for flocculant product selection and dosage by providing an effective way of evaluating soil-dependent characteristics of flocculants and required dosage rates. The developed workbook should allow practitioners to efficiently and effectively apply flocculants on construction sites. Furthermore, the tool encourages bench-scale testing of products prior to field application and minimizes the impact of unguided flocculant implementation on sites by supplementing communication between stormwater professionals and construction personnel to use the correct product and dosage.

4.5 CONCLUSION

This study has shown the need for 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 soil samples, development of match test procedures for performance evaluation, and dosage experiments for identifying optimum dosage rates. The research also focused on developing a field-applicable residual testing method based on settling velocity observations.

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 overdose 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 overdose 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.

Bench-scale experiment results in this study led to the development of a spreadsheet-based tool, FlocSpread, which aims to guide product selection and dosage. The tool emphasizes the significance of soil testing and match test procedures for product selection. Moreover, it promotes the use of proper dosage rates for flocculant applications on construction sites by providing dosage recommendations, required application amount, and cost estimates to the user based on treatment volume and features of the selected product.

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 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 large-scale testing, which will be discussed in the next chapter. 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 FIVE: LARGE-SCALE APPLICATION EVALUATIONS

5.1 INTRODUCTION

Although bench-scale testing provides substantial data for investigating the use of flocculants in construction stormwater treatment, large-scale testing is a necessary step for evaluating the application methods of these chemical agents in a testing environment with similar conditions to real-life applications. The objective of large-scale testing in this research included utilizing knowledge obtained in bench-scale experiments phase in large-scale conditions for identifying dosage, agitation, and mixing requirements. In this chapter of the dissertation, 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. In addition, the application of flocculants on large-scale sediment basin testing apparatus will be evaluated through a collaborative study conducted at AU-SRF.

Using a proper dosage delivery mechanism enhances the flocculant performance for construction stormwater treatment. In this research, dosage delivery methods were tested in a 40 ft (0.3 m) long flume by using the large-scale testing resources of AU-SRF. Large-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.

Additionally, 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 large-scale experiments by utilizing the developed residual detection method in this research.

The findings of this research 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 large-scale applications.

5.1 AU-SRF OVERVIEW

The large-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 (0.03 km^2) to the existing area. Figure 39 presents an aerial image that displays the current boundaries of the facility after the completion of the expansion project.

Figure 39 Auburn University Stormwater Research Facility (AUSRF).

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 *(Schussler et al. 2022)*.

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 the downstream of flume testing channel was blocked to prevent contamination in the lower supply pond. The collaborative research on flocculant application with sediment basin apparatus took place in the expansion area. The in-channel sediment basin testing apparatus was built downstream of the upper supply pond and treated stormwater runoff was discharged to the lower supply pond after flocculant application with residual concentration monitoring in place.

5.2 OPTIMUM DOSAGE DELIVERY FLUME EXPERIMENTS

This study carried the knowledge developed in the bench-scale phase of this research into a large-scale phase by evaluating optimum dosage delivery mechanisms through large-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 large-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.

5.2.1 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^{TM} 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 40, shows the dimensions of supporting frames and provides the diameter information of the semicircular flume body.

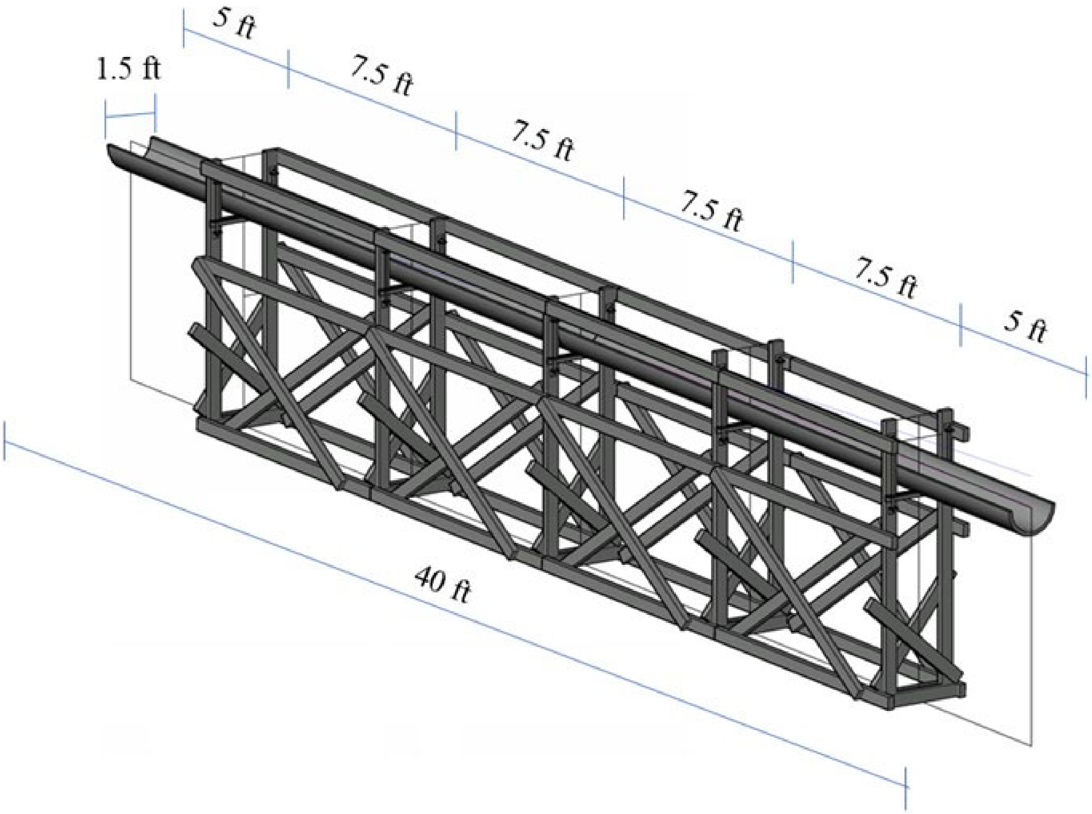


Figure 40 Flume design.

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 41 presents the design for the adjustable support system.

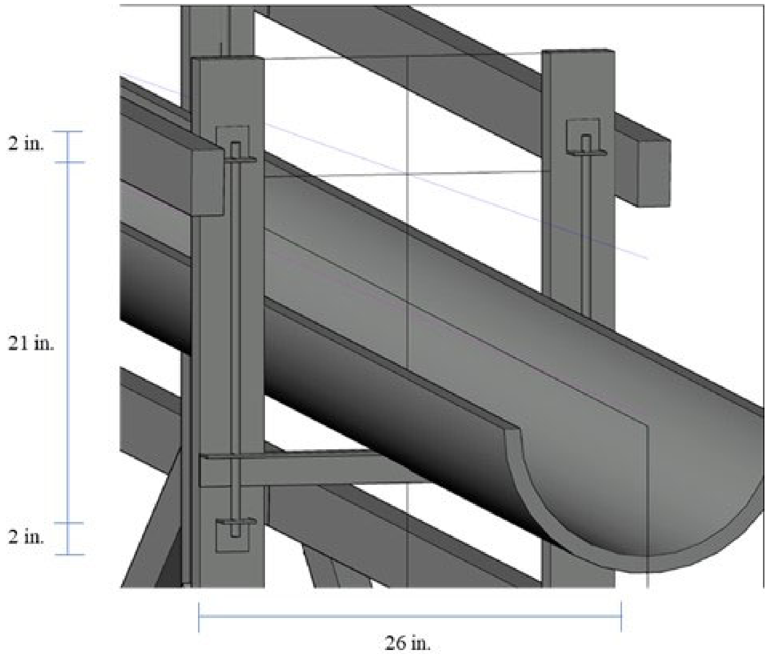


Figure 41 Adjustable supporting frame design.

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.

5.2.2 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. (45.7 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 42 (a) and (b).


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

Figure 42 Construction of the flume body.

After the completion of the flume frame, 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 43.

Figure 43 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 44 (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 44 (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 44 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 45 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 large-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.

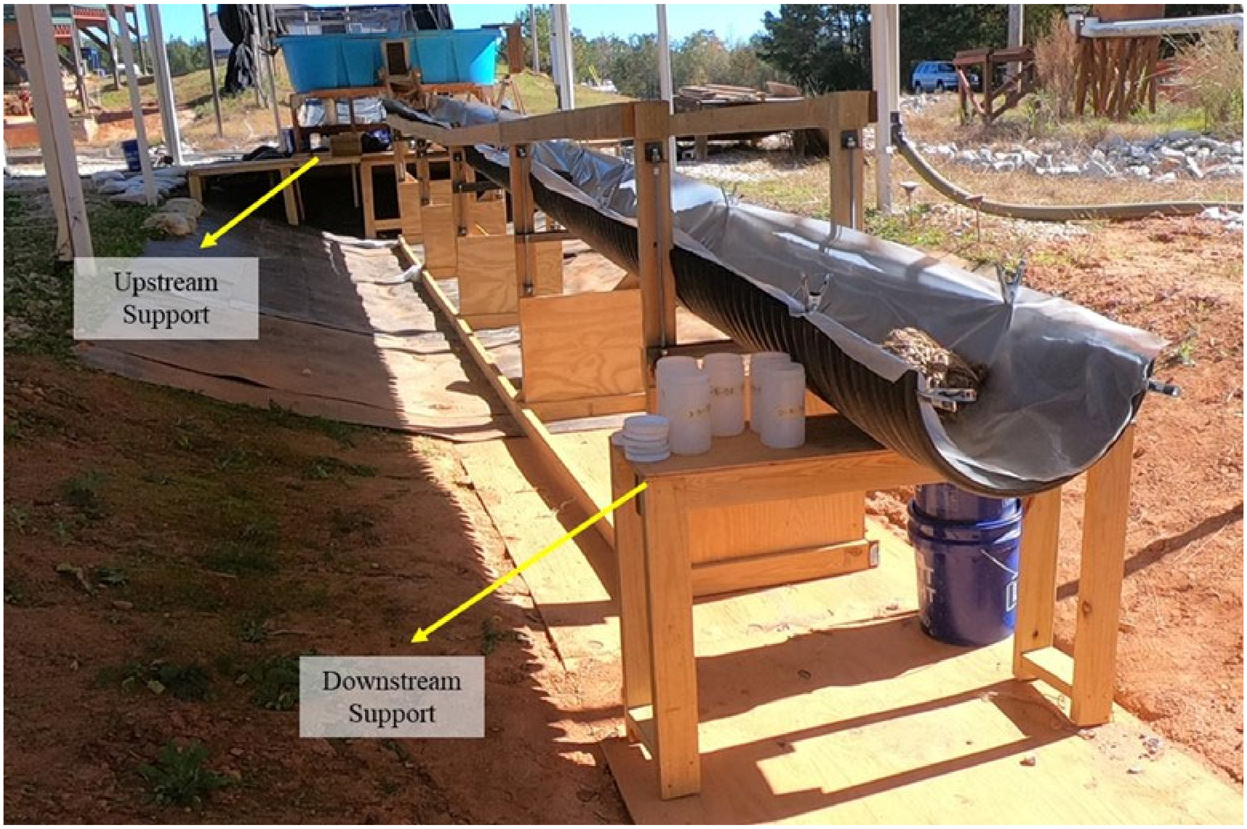


Figure 45 Post-construction flume setup.

5.2.3 METHODOLOGY

This section details the methods, materials and experimental testing regimen used to evaluate optimum dosage delivery mechanisms through large-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.

5.2.3.1 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 46 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 46(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 46 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 46(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 1500 +/- 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 47.

Figure 47 Wooden mixing through.

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 g) 97 g of the testing soil. Sediment introduction was initially maintained by using a 50 in. x 7.8. in. 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 48.

Figure 48 Sediment introduction setup.

5.2.3.2 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.3.

$$L = \frac{H}{S} \qquad \text{Eq. 3}$$

Where,

L= Spacing length (ft)

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 49 illustrates the installed ditch checks in the flume.

Figure 49 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 0.10 ft^3/s (3.5 m^3/s) flow rate. Hence, the flow rate for the flume experiments was identified as 0.10 ft^3/s (3.5 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 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 50 presents the framework for optimum dosage delivery experiments in the flume.

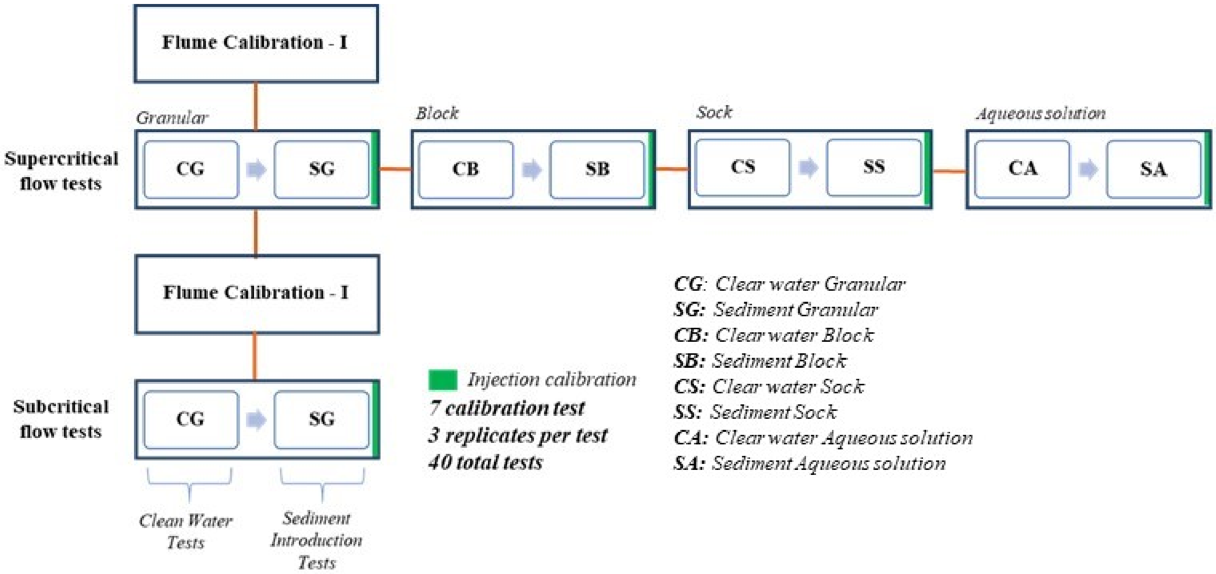


Figure 50 Optimum dosage delivery testing.

The green color in the presented framework in Figure 50 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 51 exemplifies a clear water experiment for evaluating dosage delivery with a granular flocculant form in the flume.

Figure 51 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 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 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 52 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 52 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 10 presents flocculant products that were used in flume experiments.

Table 10 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 53 illustrates flocculant introduction in the flume experiments with the use of different flocculant forms. Granular form introduction, shown in Figure 53(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 large-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 53(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 53 Introduction of different flocculant forms in flume experiments.

Figure 53(c) illustrated 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 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 53(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 54 displays the aqueous solution injection setup.

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

(c)solution injection setup

Figure 54 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. Clearwater and sediment introduction tests were conducted, and sampling locations were changed to the upstream and downstream of both flume and ditch checks. Figure 55 illustrates flume experiments in subcritical flow conditions.

Figure 55 Subcritical flow evaluations.

5.2.3.3 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 remaining110 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 56 shows clear water introduction on one of the scaled-ditch checks during the longevity test.

Figure 56 Longevity test clear water introduction.

5.2.4 RESULTS AND DISCUSSION

This section presents and discusses the data analysis and results collected for the large-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.

5.2.4.1 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.

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 57.

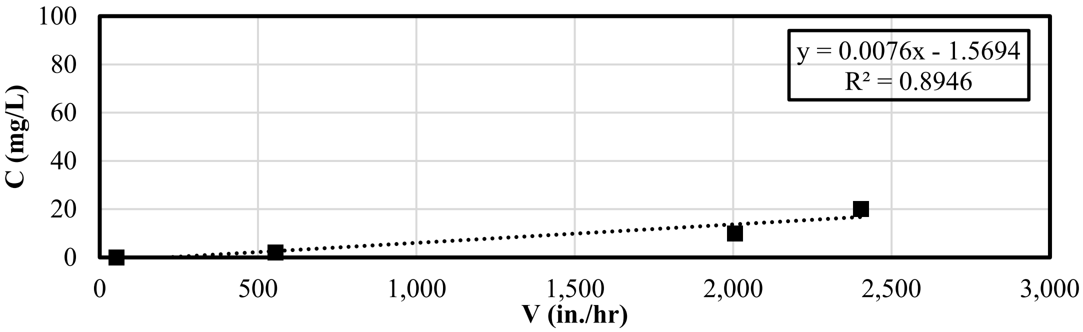
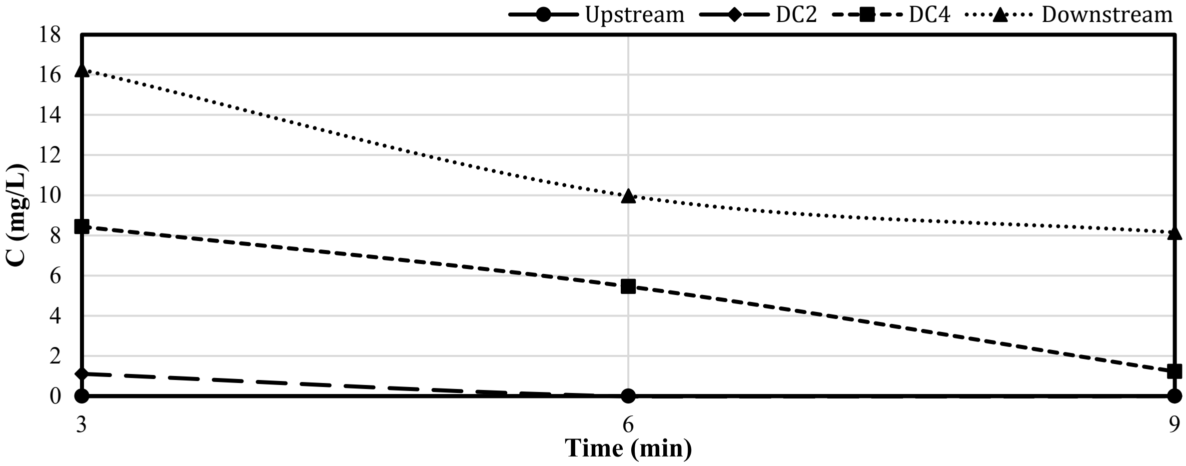


Figure 57 Product-A standard residual concentration plot.

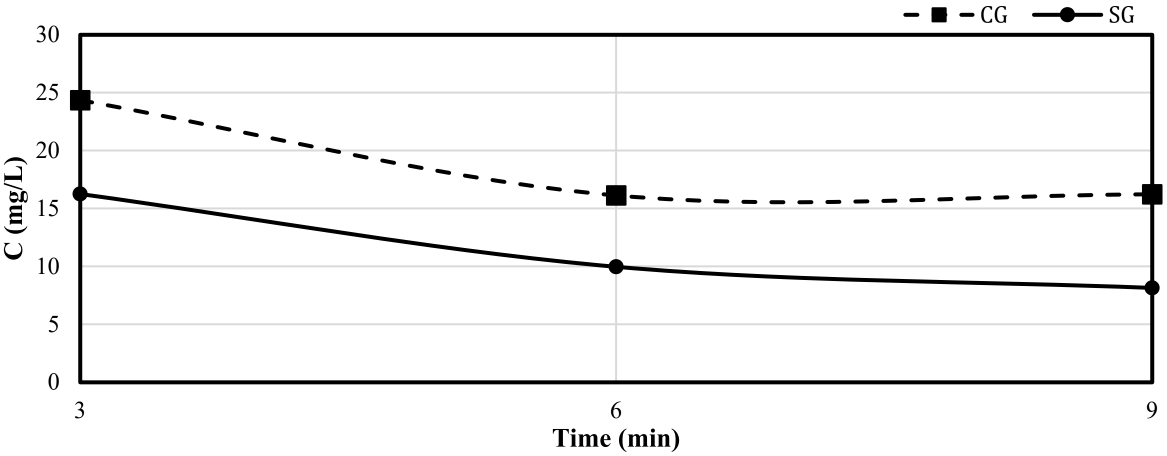
The estimated average flocculant concentration results of the three runs showed 0 mg/L flocculants upstream of the flume. This result was expected since flocculants were introduced into the flume after the upstream sampling location. Therefore, upstream samples represented the control condition during 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 58 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 58. 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 58(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 58 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 58(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 59.

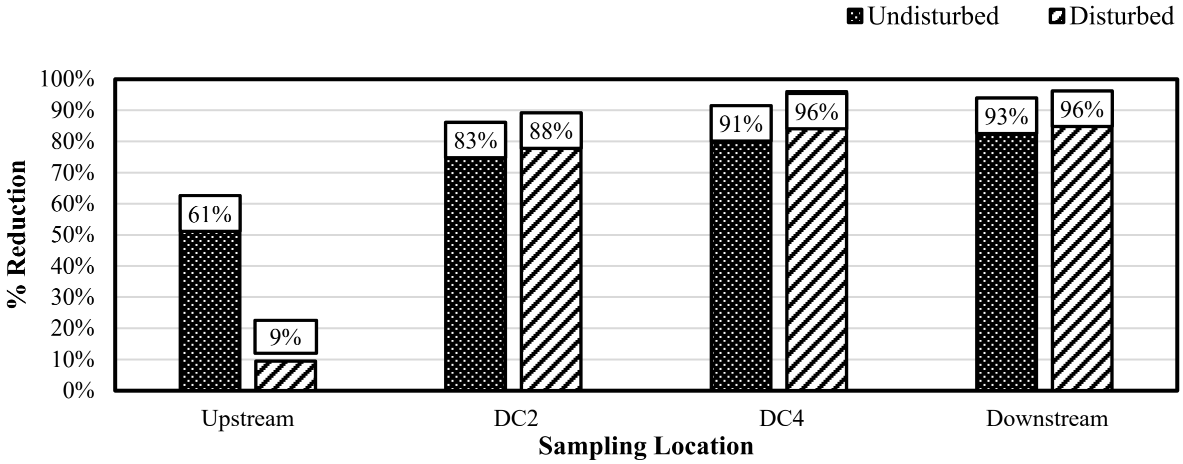


Figure 59 Turbidity reduction results for SG treatment 9-minute samples.

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 large-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 % 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.

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 60.

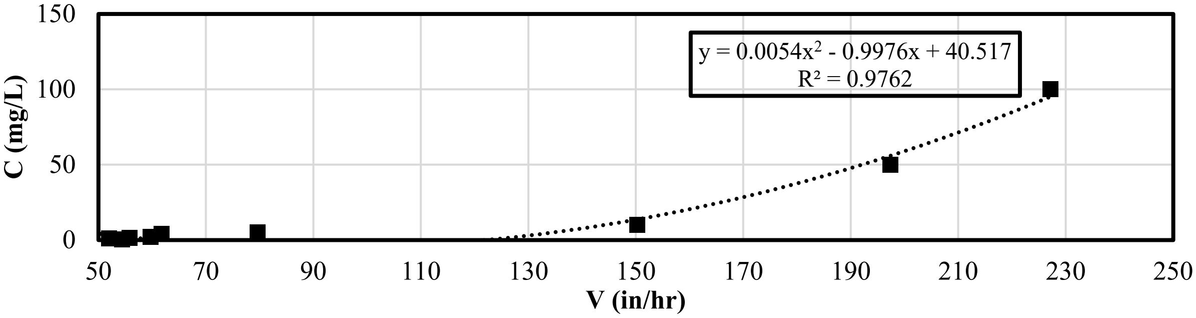


Figure 60 Product-A2 standard residual concentration plot.

Sediment introduction experiments for block form evaluation indicated no flocculant concentration upstream. Figure 61 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.

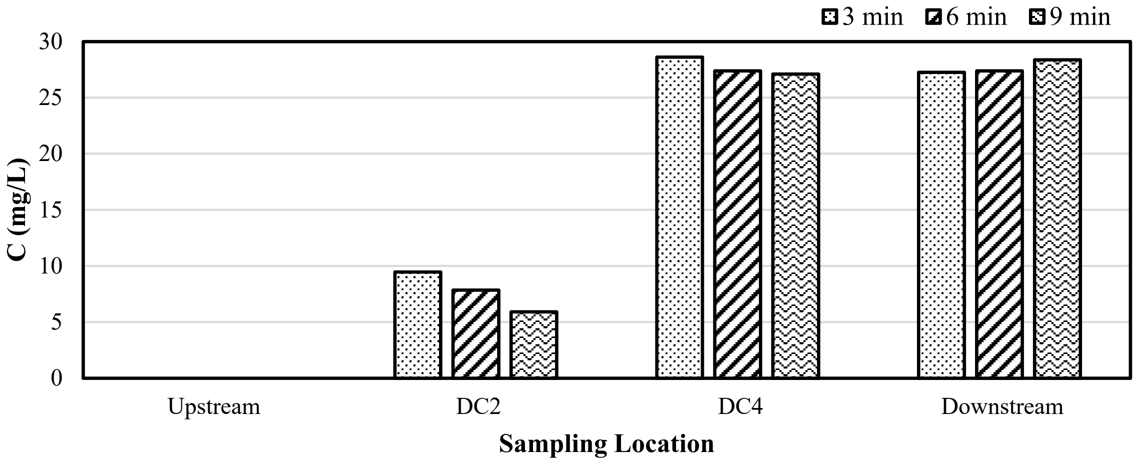
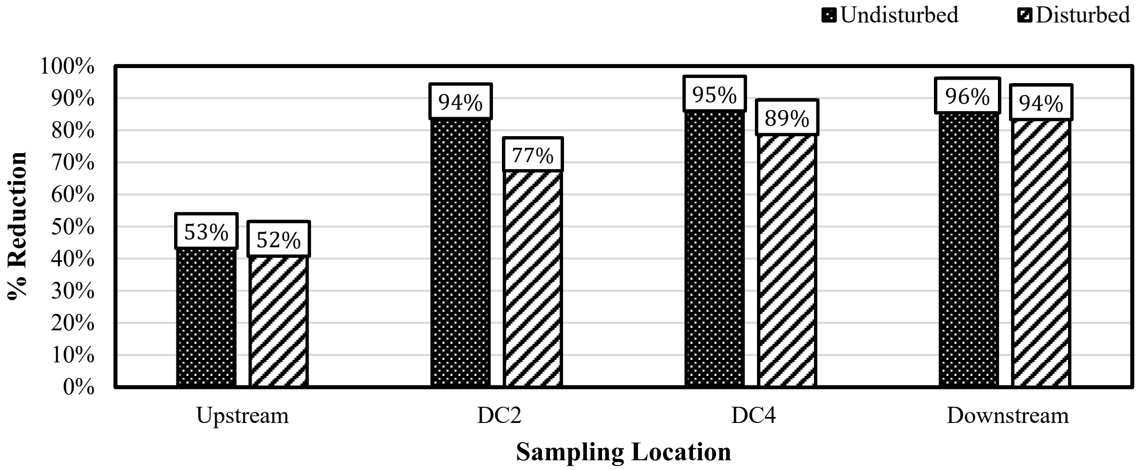
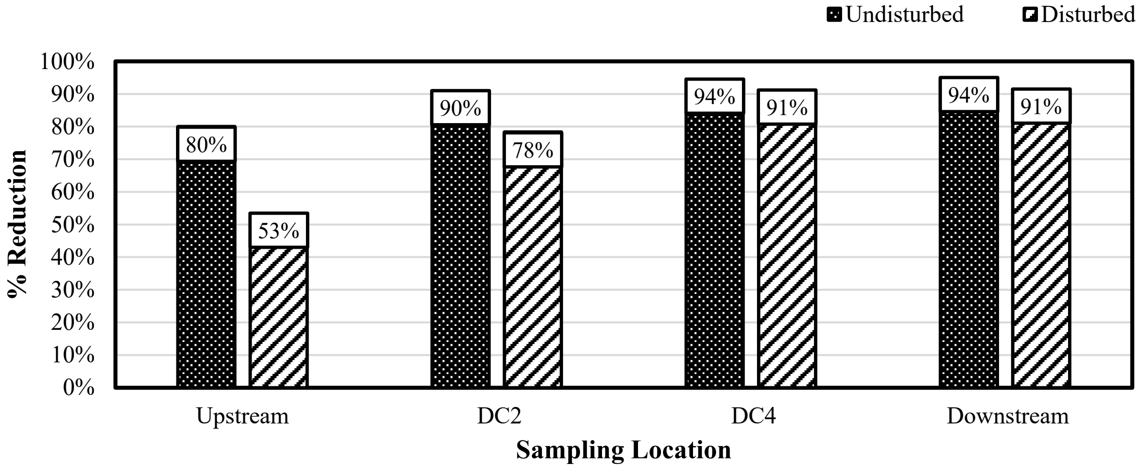


Figure 61 Residual concentration results for SB treatment.

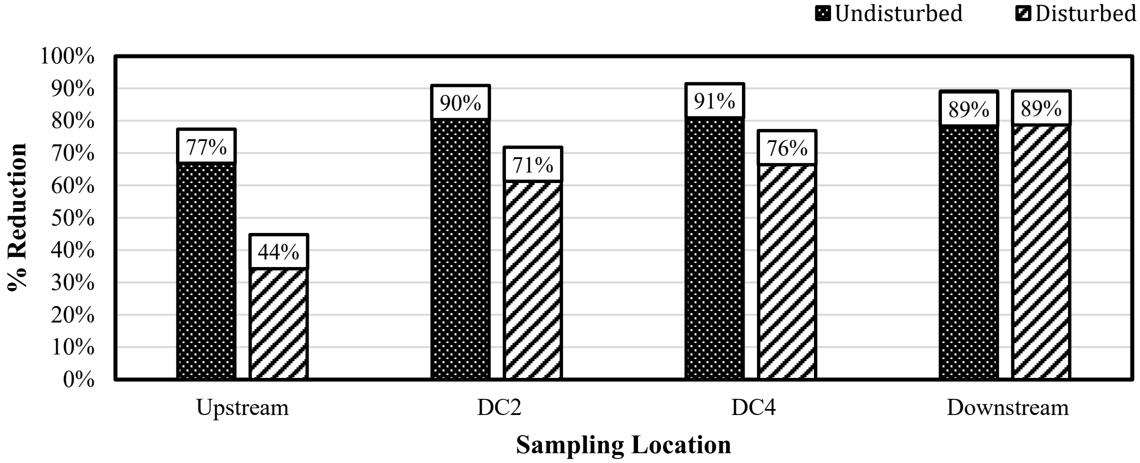
Turbidity reduction data implied highly effective agitation and mixing in block form introduction experiments by providing up to 96% turbidity reduction in undisturbed samples. Figure 62 displays %flocculant reduction results for the SB experiments. Again, the disturbed upstream samples showed lower 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 62(a) and (b). However, it can be observed in Figure 62(c) that the system overdosed itself 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 overdose conditions was also observed in the bench-scale phase of this research. These results also validated the bench-scale experiment findings on overdoses through large-scale flume observations.



(a) results for in 3-minute samples



(b) results for in 6-minute samples



(c) results for 9-minute samples

Figure 62 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.

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 63.

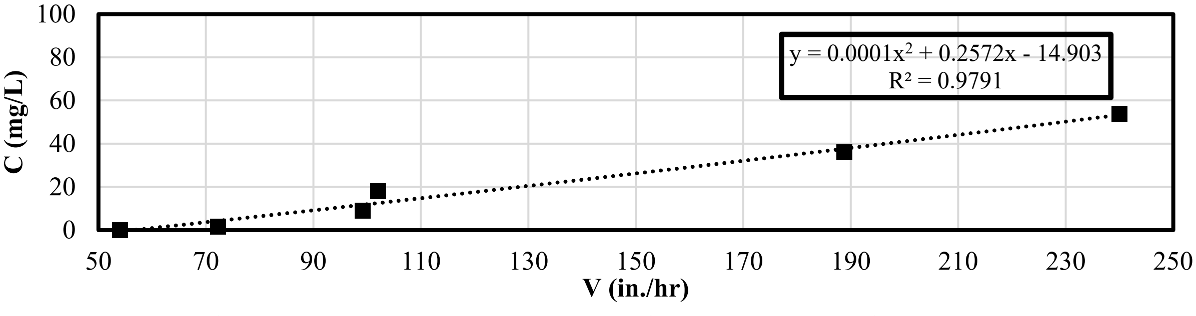


Figure 63 Product-I standard residual concentration plot.

Estimated concentration values for CS and SS treatments are presented in Table 11. 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 11 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 64. 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.

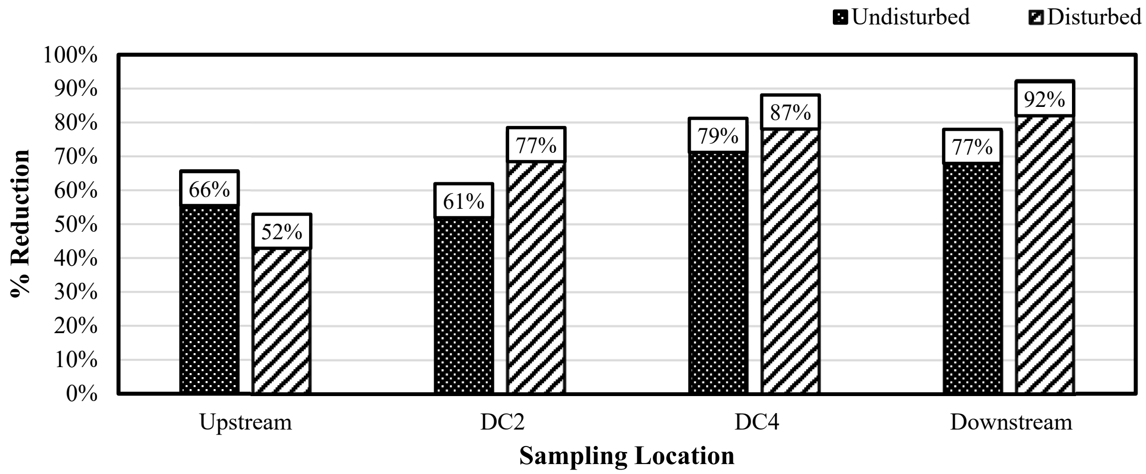


Figure 64 Turbidity reduction results for SS treatment 9-minute samples.

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 57.

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 65.

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.

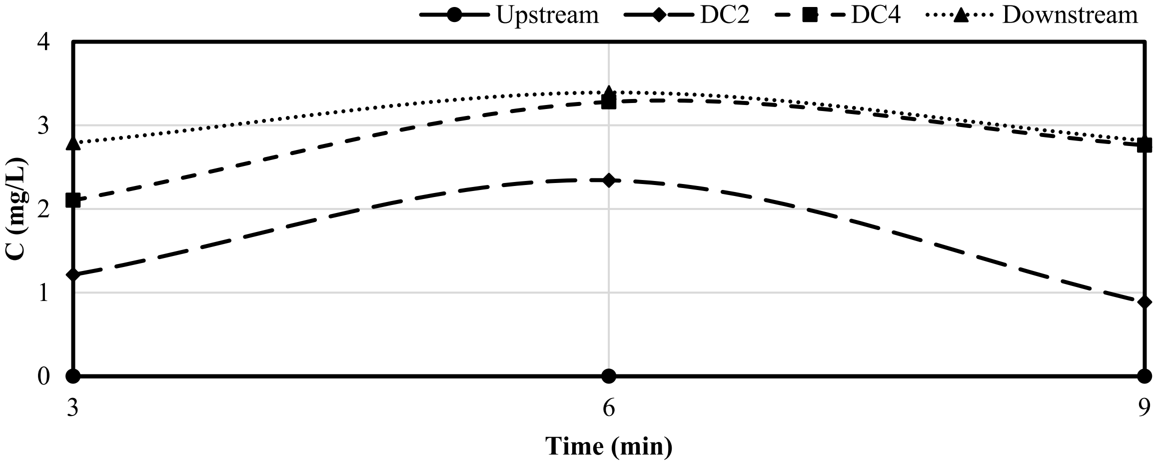


Figure 65 Residual concentration results for SA treatment.

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 65 provides evidence for proper agitation and mixing by displaying turbidity reduction rates higher than 90% in downstream disturbed and undisturbed samples.

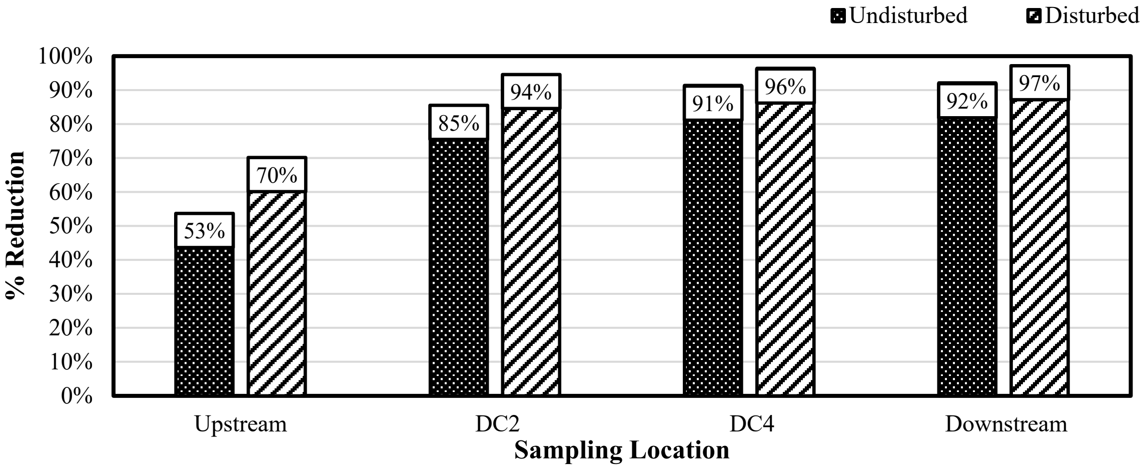


Figure 66 Turbidity reduction results for SA treatment 9-minute samples.

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 12.

Table 12 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.

5.2.4.2 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 13.

Table 13 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 67 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.

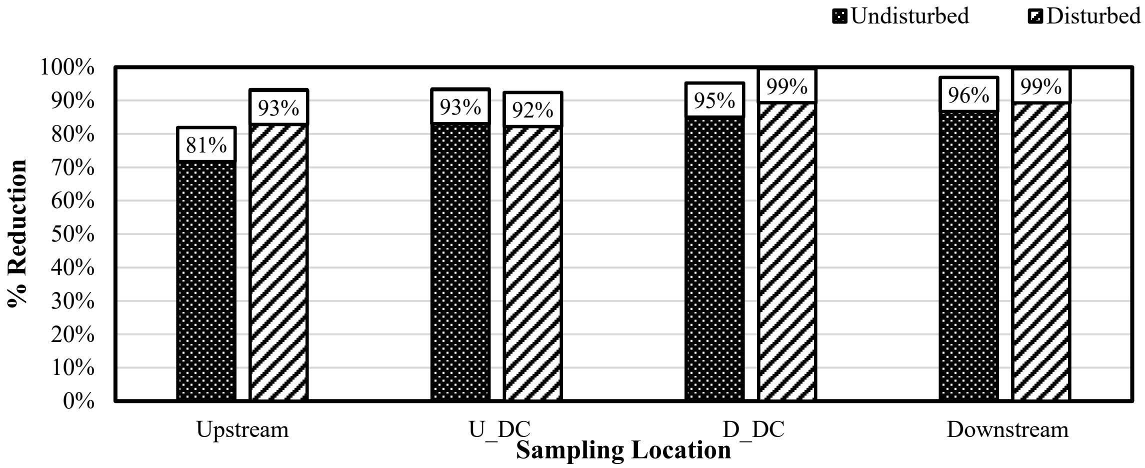


Figure 67 Turbidity reduction results for SG 9-minute samples in subcritical flow.

5.2.4.3 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 68 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.

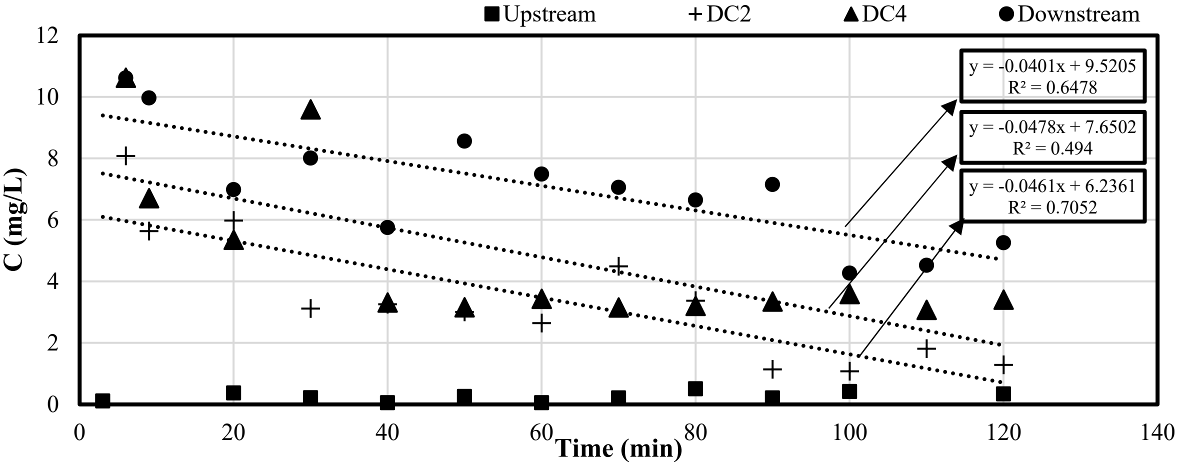


Figure 68 Longevity test results for the granular form.

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 14 presents the longevity of the granular product in each sampling location.

Table 14 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)

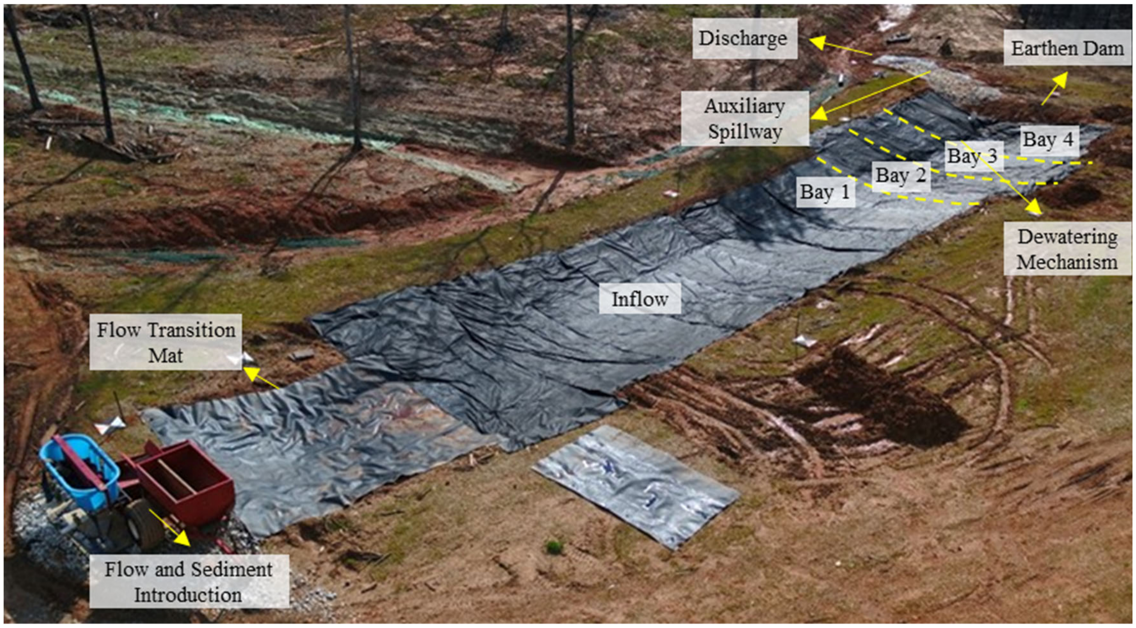
Results indicated that the complete wash-off condition would be achieved in 3 hours 57 minutes in the entire channelized flow flume setup by treating 1,422 ft^3 (40.3 m^3) turbid water. This longevity result indicated that 27,346 ft^3 (1.67 m^3) of volume could be treated before reapplication of flocculant 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.

5.3 FLOCCULANT APPLICATION ON LARGE-SCALE SEDIMENT BASIN TESTING

Sediment basins are designed to promote settling in suspended soil particles to effectively treat construction stormwater prior to off-site discharge. However, typical sediment basin treatments often fail to provide rapid capture of fine-sized soil particles and require extensive detention periods. The use of flocculant in sediment basin applications has to potential to enhance the capture of fine-sized sediment particles and decrease the detention time. This collaborative research effort evaluated flocculant introduction in sediment basins through large-scale testing at AU-SRF. The objectives of this study were to (1) implement proper dosage delivery, (2) identify turbidity reduction performance of flocculants, and (3) monitor discharge residual flocculant concentrations through testing conducted on the large-scale sediment basin apparatus.

5.3.1 OVERVIEW OF AU-SRF SEDIMENT BASIN APPARATUS

The sediment basin apparatus used in this study was built for a comprehensive sediment basin research funded 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 *(Schussler 2022)*. Figure 69 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 69 (a). Controlled flow and sediment introduction provided mimicked construction conditions in the basin and different treatments were evaluated for the basin performance by Schussler *(2022)*.



(a) basin components

(b) MFE-I configuration

Figure 69 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 69(b). Research collaboration efforts in this study took place during flocculants implementation with the most feasible and effective installation treatment phase.

5.3.2 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 70. 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 70 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 *(Schussler 2022).* 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 (Schussler 2022). 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.

5.3.3 RESULTS AND DISCUSSION

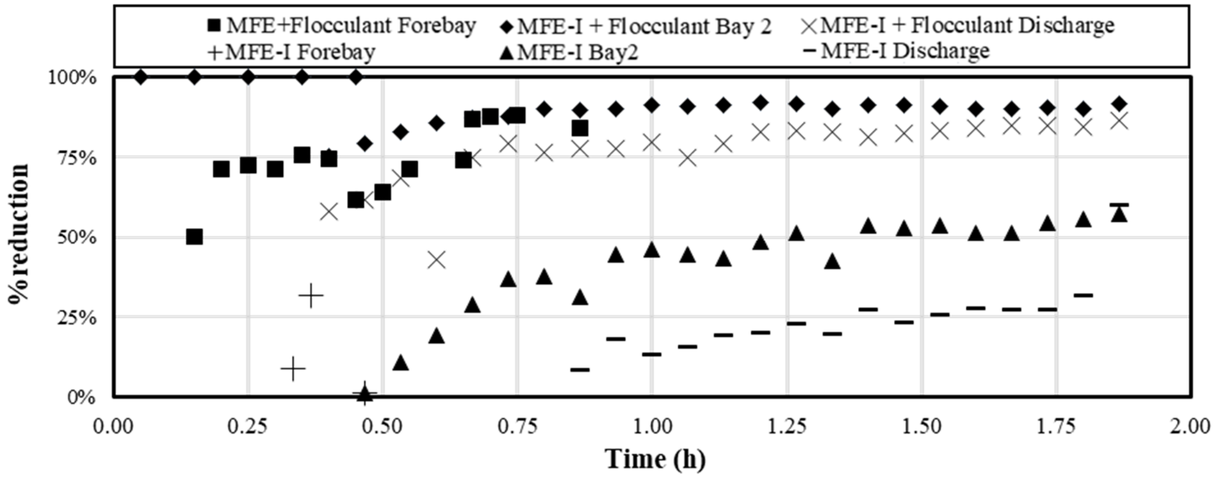
Flocculant application on the sediment basin apparatus provided an opportunity to evaluate block form dosage delivery mechanism performance in large-scale testing conditions. This section elaborates on the data analysis and results collected in this collaborative research effort from the flocculant performance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

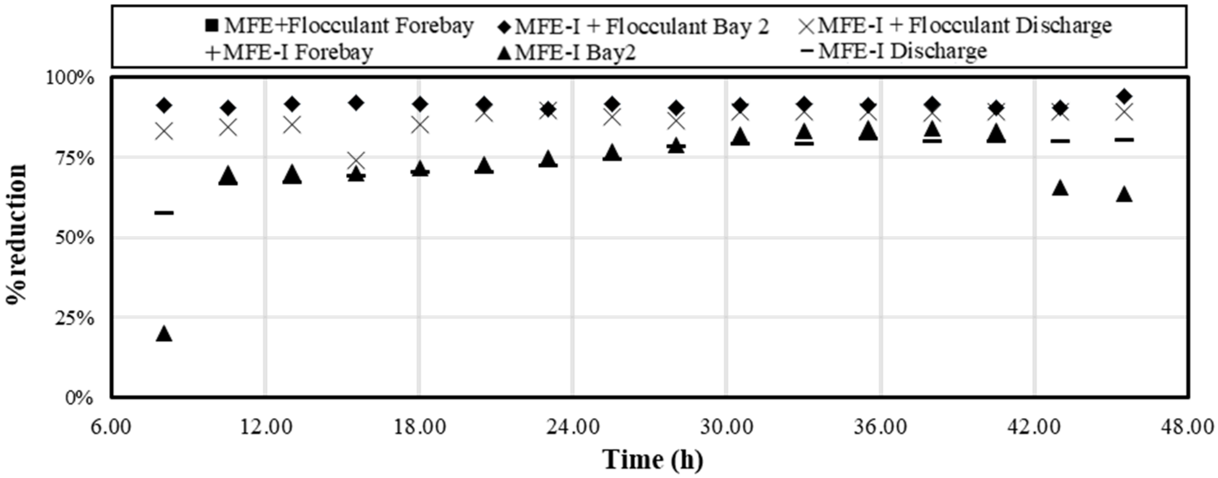
Proper dosage delivery was achieved in this study by ensuring complete flow contact throughout the testing and introducing flocculants prior to forebay in the sediment basin. The location of the flocculant introduction area within the basin apparatus had a significant role in promoting proper agitation 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. On the other hand, MFE-I treatment 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 71 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 71 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 71(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 71(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 72 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 1500 +/- 300 NTU turbid water during the bench-scale phase of this research.

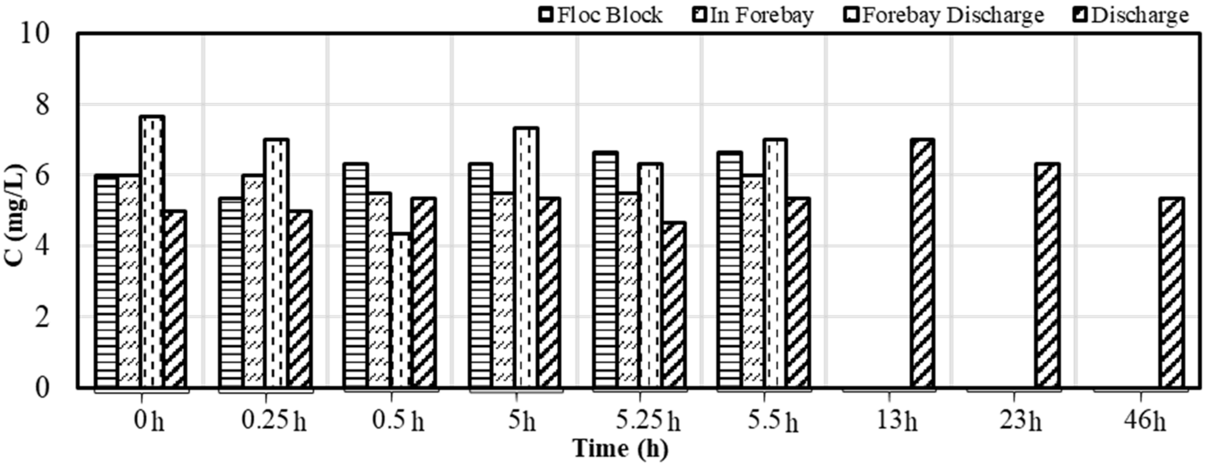


Figure 72 Residual concentration monitoring results.

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 requires 83% less of the block. However, it is important to consider that not all introduced flow was contacting with the blocks. Therefore, it was important to increase the number of the 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 large-scale experiments, block forms typically provide a steady dosage and promote effective turbidity reduction with proper agitation and mixing techniques. This feature of the block forms 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 overdose throughout the 48 hours monitoring period.

5.4 CONCLUSIONS

Flocculants promote improvement in the performance of temporary sediment control practices when applied with proper product selection and effective dosage delivery mechanisms. This work has identified requirements for proper dosage delivery mechanisms by validating bench-scale phase findings of this research through large-scale application evaluations. Large-scale flocculant application evaluations were conducted in two separate studies presented in this chapter: optimum dosage delivery flume experiments and collaborative research on sediment basin testing. Large-scale testing in this research was accomplished by utilizing tools and testing sources available at AU-SRF.

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 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.

Following the optimum dosage delivery flume experiments, a collaborative research effort was pursued to implement flocculants on a large-scale sediment basin apparatus. This section of the dissertation 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.

Large-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. 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 overdosage monitoring, but also for identifying the agitation needs of the flocculant applications. Additional work is needed to determine optimum dosage delivery requirements of other flocculant forms through testing conducted on large-scale testing apparatus. Future research is needed to produce methods for improving the application techniques of each flocculant form through large-scale testing. Future research should also focus on how to implement flocculants on different large-scale testing apparatuses different than sediment basins. Moreover, the findings of this research would potentially pave the way for a future field monitoring study for flocculant application on active construction sites.

CHAPTER SIX:
CONCLUSIONS

6.1 INTRODUCTION

Flocculants have become a point of interest in construction stormwater management for improving the sediment capture performance of temporary E&SC practices. Nation and statewide environmental regulations require protection of the downstream water bodies from sediment-laden discharge related to construction activities. Capturing fine-sized sediment particles through settlement facilitated through flocculation mechanism promotes turbidity reduction in construction stormwater runoff. However, the existing knowledge gap in the proper dosage, agitation, and application of flocculants creates challenges in flocculant implementation on construction sites due to the negative impact of potential overdosing on the environment and aquatic life. The research in this dissertation aimed to fill this knowledge gap by conducting a state-of-the-practice survey, developing bench-scale experiments, and providing large-scale evaluations on flocculant application.

6.2 CONCLUSIONS

This section summarizes the conclusions of each of the investigated research content in this dissertation. The presented research identified common unknowns in flocculant application for construction stormwater treatment and developed methods to provide specialized guidance to practitioners. The major findings of this research will ultimately promote proper flocculant implementation on construction sites and enhance the sediment capture function of temporary E&SC controls for protecting the nation’s waterbodies.

6.2.1 STATE-OF-THE-PRACTICE SURVEY: FLOCCULANT USAGE IN CONSTRUCTION STORMWATER MANAGEMENT

To achieve the first objective of this dissertation, 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 comprehensive literature review conducted in this research and distributed to 51 DOTs in the U.S. The survey was distributed through an online survey platform and 73% of the target audience responded to the survey questions.

Survey findings provided a detailed overview of flocculant usage in construction stormwater management and identified improvement needs. Results showed that only 39 % of the state agencies were allowing the use of flocculants on their active construction projects. Most DOTs are hesitant to use these chemical agents for construction stormwater treatment due to the liability of potentially polluting receiving waters. Another major finding of the survey was about dosage guidance on flocculant usage, which identified that most agencies were dependent on manufacture 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.

The survey study contributed to the bench-scale and large-scale phase of this research by outlining investigation needs for flocculant usage in construction stormwater management. 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 large-scale application phase of this research on investigating flocculant usage for the most commonly implemented sediment control practices.

6.2.2 BENCH-SCALE EVALUATION OF OPTIMUM DOSAGE AND RESIDUAL CONCENTRATIONS

The second objective of this dissertation was accomplished through the development of bench-scale testing methods for catering guidance on product selection, dosage, and residual concentration monitoring. The study evaluated 14 different flocculant products on various soil samples collected across Alabama to identify product selection and optimum dosage requirements of flocculants. In addition, the study presented a field applicable method for identifying residual flocculant concentrations in construction stormwater runoff.

The 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 testing soil. The match test procedures identified the top three best performing products based on developed color, floc formation, size floc, and settling velocity point system. These products were evaluated in the dosage experiments to identify dosage rates that provide effective treatment. Results of the match test phase indicated that PAM and chitosan products were the most effective flocculant types on the soil samples used in this study. Dosage experiment results revealed that completely relying on manufacturer guidance might falsify proper flocculant dosage on construction sites due to soil-dependent characteristics of flocculants. During dosage experiments, manufacturers' recommended dosage concentrations were ranged between 0% and 200% to evaluate underdosing and overdosing conditions across different soil samples. Results identified that using only 20% of the manufacturer's recommended dosage rates on most products provided adequate flocculation.

The development of the residual concentration detection method enabled a field applicable method for monitoring residual flocculant concentrations of various flocculant products on construction sites. The study findings showed that settling velocity observations can be related to flocculant concentrations regardless of the difference in flocculant types. Settling velocity of various flocculant products was observed for samples with known flocculant concentrations. Standard flocculant concentration plots were prepared based on these known concentration observations. Higher concentrations of flocculants corresponded to increased settling velocity and a decreased settling time. 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 the estimated residual concentrations.

Findings of the bench-scale study allowed the development of a spreadsheet-based tool FlocSpread intended to provide useful guidance on product selection and dosage. The developed tool was capable of identifying suitable products based on soil-dependent characteristics of flocculants and recommending dosage and associated cost estimates based on the user input. The resulting workbook utilized the knowledge gained in the bench-scale phase for an effective flocculant selection procedure. The tool provided the potential to improve decision-making procedures for practitioners while implementing flocculants in construction stormwater.

The bench-scale evaluation phase of this dissertation was a well-rounded study, which outlined optimum dosage requirements of flocculant usage in construction stormwater management. Results of this phase provided a strong basis for the large-scale testing phase of this research for proper product selection and agitation evaluation. Furthermore, the findings of this research should allow 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.

6.2.3 LARGE SCALE APPLICATION EVALUATIONS

The final objective was fulfilled by conducting large-scale experiments to identify the agitation and mixing requirements of proper flocculant implementation. Large-scale testing was conducted at AU-SRF by using the testing capabilities and resources of the research center. Optimum dosage delivery requirements were identified through flume experiments that mimicked channelized flow conditions. In addition, the large-scale evaluation of flocculants included a collaborative study for investigating flocculant usage in sediment basin applications.

Flume experiments were conducted in a 40-ft long flume that was constructed at AU-SRF for flocculant evaluations. The slope of the flume was adjusted to allow supercritical and subcritical flow conditions. Performances of flocculants including granular, block, sock, and aqueous solution forms were evaluated under supercritical conditions. Granular product was tested for subcritical flow conditions and longevity experiments. Turbidity reduction results of undisturbed samples of flume were compared to disturbed samples in the mixing machine, which represented the best-case scenario for proper agitation and mixing. In addition, residual flocculant concentrations were monitored to evaluate adequate dosage delivery requirements throughout the testing. The aqueous solution, granular and block forms were identified as well-performing flocculant forms in promoting effecting dosing and agitation in channelized flow based on the results of this study. Granular and block forms performed similarly in meeting the agitation requirements for effective treatment in supercritical flow conditions. However, the granular form improved its dosage delivery and agitation performance in subcritical flow experiments by having up to 96% turbidity reduction in undisturbed samples.

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 them 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.

Large-scale application evaluations in this research provided an opportunity to carry bench-scale testing findings into real-life applications and identify suitable conditions for proper dosage delivery and agitation. The findings of this research contributed to preparing guidance for proper flocculant implementation on construction sites by identifying the most effective dosage delivery mechanisms.

6.3 LIMITATIONS AND RECOMMENDED FURTHER RESEARCH

The following section describes the general limitations of the research performed and explores avenues by which the knowledge base can be expanded by performing additional studies and investigations.

6.3.1 STATE-OF-THE-PRACTICE SURVEY: FLOCCULANT USAGE IN CONSTRUCTION STORMWATER MANAGEMENT

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. Non-participating states created a limitation in the study to have a complete dataset for evaluating the perspectives of state agencies on flocculant usage in construction stormwater management. To minimize the impact of this limitation on the survey results, E&SC manuals of these agencies were reviewed and included in survey data for identifying flocculant usage in the U.S. However, information about these states was not included in the rest of the survey data.

Another limitation of the survey was inaccurate information provided by the state DOT professionals on some of the survey questions that do not match with their agency's E&SC manuals. Identifying the stormwater professionals for the survey target audience becomes challenging due to this limitation. However, several distribution cycles improved the accuracy of the survey data. Further studies on flocculants should update the survey for having up-to-date survey data that would guide further research agendas on improvement needs. An additional survey distributed to flocculant manufacturers would provide a further understanding of their dosage recommendation perspective.

6.3.2 BENCH-SCALE EVALUATION OF OPTIMUM DOSAGE AND RESIDUAL CONCENTRATIONS

Bench-scale optimum dosage evaluations were conducted on 15 different soil samples collected across Alabama from active ALDOT construction sites. The purpose of this soil sampling method was to provide dosage guidance on the soils that were existing on active job sites. However, most of the sites contained similar soil samples that were classified in the left bottom corner of the USDA soil texture triangle. Hence, the soil collection method created a limitation for evaluating several different soil textures and having a complete evaluation of the USDA texture triangle. To minimize this limitation, additional soil samples were included in the study to extend the scope of the optimum dosage evaluation.

Evaluated concentration ranges in dosage experiments were identified based on the dosage recommendations received from manufacturers of the evaluated products. Misleading information provided by manufacturers squawked the targeted concentration evaluation in the study. The wide range of evaluations in dosage experiments allowed the investigation of the recommended concentration value within the dosage experiment dataset.

Additionally, standard jar testing procedures required the preparation of homogenous stock solutions for flocculant injection in dosage experiments. Stock solutions for the products were also prepared based on manufacturer guidance. However, some of the flocculant products did not form homogeneous stock solutions based on the concentrations recommended by the manufacturers. This limitation was eliminated by injecting these products in granular form in this research. The discussed limitations provided evidence for the possible misguidance of manufacturer recommendations and showed the need for proper dosage guidance in construction stormwater management.

Standard residual concentration plots were developed based on the settling velocity of evaluated flocculant products with known concentrations. Among all tested flocculant types, alum and agricultural gypsum 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 phase of the study. Another limitation of this study was identifying a standard testing soil for settling velocity observations. This study can be easily adapted for different testing soils; however, using a specific 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.

Results of the bench-scale phase of this research led to the development of the FlocSpread tool for dosage and product selection guidance. The tool provided a user-friendly approach for identifying appropriate products and dosages for different soil samples. Currently, the tool uses the dataset formed based on the evaluated soil samples in this study for soil-dependent product selection. Future studies should focus on expanding the dataset by increasing the number of evaluated soil samples. A further enhancement of the FlocSpread tool would be to integrate a user input wizard to guide practitioners through the step-by-step explanation of product selection and dosage. Lastly, it would be useful to incorporate dosage guidance for different flocculant forms than granular. This would improve the dosage guidance capability of the tool by including information on the required amount of block, sock, and aqueous solution forms.

6.3.3 LARGE SCALE APPLICATION EVALUATIONS

The large-scale testing efforts of this research focused on evaluating optimum dosage delivery and agitation requirements of flocculants through flume and sediment basin testing. Flume experiments aimed to evaluate a certain PAM product in different forms. However, PAM products were not commercially available in sock form. Hence, a bentonite-based product had to be selected for the sock form flume evaluations. This created a limitation for the study while comparing the performance of the flocculant forms. Incorporating a PAM product in sock form would enhance the comparison of flocculant forms. Further research should include a PAM-based sock product if it becomes commercially available.

The collaborative research effort on large-scale flocculant application focused on introducing flocculants in a sediment basin testing apparatus. The block form flocculant products were used in this study to identify dosage delivery requirements in large-scale testing conditions. It would be helpful to investigate the integration of other flocculant forms through further research. This would enhance the findings of this study by providing a comparison between different flocculant forms. Methods used in this research can be utilized for flocculant application evaluation on other large-scale testing apparatuses focusing on inlet protection, ditch check, and perimeter control applications.

6.4 ACKNOWLEDGMENTS

This research is based on a study sponsored by ALDOT and the Auburn University Highway Research Center. The author gratefully acknowledges this financial support. The findings, opinions, and conclusions expressed in this dissertation are those of the author and do not necessarily reflect the view of the sponsor.

REFERENCES

1. Al Momani, F. A., & Örmeci, B. (2014). Measurement of polyacrylamide polymers in water and wastewater using an in-line UV-vis spectrophotometer. *Journal of Environmental Chemical Engineering,* Vol. 2, No. 2. https://doi.org/10.1016/j.jece.2014.02.015

2. Alabama Department of Transportation (2013). Alabama Standard Specifications- Section 672 Stormwater Turbidity Control. Montgomery, AL.

3. Alabama Department of Transportation (2014). Approved Materials List II-24: Temporary Erosion and Sediment Control Products. Montgomery, AL.

4. Alabama Department of Transportation (2015). Ahead History of ALDOT. Montgomery, AL.

5. Alabama Department of Transportation (2015). Standard Best Management Practices. Montgomery, AL.

6. Alabama Department of Transportation (2016). ALDOT Construction Manual. Montgomery, AL.

7. Alaska Department of Transportation. (2016). Alaska DOT Construction General Permit. Juneau, Alaska.

8. Applied Polymer Systems Inc. (Accessed July 16, 2020) APS 700 Series Silt Stop. https://www.siltstop.com/p.php?go=pinfo&PID=4-aps_ 700_ series_silt_stop.

9. ASTM Standard D2035-19. (2019) Standard Practice for Coagulation-Flocculation Jar Test of Water. ASTM International, West Conshohocken, PA.

10. ASTM Standard D4318, D 4318-10, & D4318-05 (2005). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA.

11. ASTM Standard D6913-04R2009. (2004). Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International, West Conshohocken, PA.

12. ASTM Standard D7928. (2017). Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. ASTM International, West Conshohocken, PA.

13. ASTM Standard D3977-97(19). (2019). Standard test methods for determining sediment concentration in water samples. ASTM International, West Conshohocken, PA.

14. ASTM Standard D5907-18. (2018). Standard Test Methods for Filterable Matter (Total Dissolved Solids) and Nonfilterable Matter (Total Suspended Solids) in Water. ASTM International, West Conshohocken, PA.

15. Auckland Regional Council. (2004). The use of flocculants and coagulants to aid the settlement of suspended sediment in earthworks runoff: trials, methodology, and design (Draft). Technical publication 227. Auckland Regional Council, New Zealand.

16. Badawy, M. E. (2012). A New Rapid and Sensitive Spectrophotometric Method for Determination of a Biopolymer Chitosan. *International Journal of Carbohydrate Chemistry*, https://doi.org/10.1155/2012/139328

17. Beim A. A. & Beim A.M. (1994). Comparative Ecological – Toxicological Data on Determination of Maximum Permissible Concentrations (MPC) for Several Flocculants *Environmental Technology* Vol. 15 pp 195-198, https://doi.org/10.1080/09593339409385420

18. Bhardwaj, A. K., & McLaughlin, R. A. (2008). Simple polyacrylamide dosing systems for turbidity reduction in stilling basins. *Transactions of the ASABE*, *51*(5), 1653-1662.

19. Biesinger, K. E., & Stokes, G. N. (1986). Effects of synthetic polyelectrolytes on selected aquatic organisms. *Journal of the Water Pollution Control Federation*, 58(3), 207–213.

20. Buczek, S. B., Cope, W. G., McLaughlin, R. A., & Kwak, T. J. (2017). Acute toxicity of polyacrylamide flocculants to early life stages of freshwater mussels. *Environmental Toxicology and Chemistry*, 36(10), 2715–2721. https://doi.org/10.1002/etc.3821

21. California Department of Transportation. (2010). Stormwater Quality Handbook - Project Planning and Design Guide. Sacramento, CA.

22. California Department of Transportation (2003). Erosion Control New Technology Report CTSW-RT-03-049. Sacramento, CA.

23. Chatsungnoen, T., & Chisti, Y. (2019). Flocculation and Electroflocculation for Algal Biomass Recovery. *Biofuels from Algae*, Elsevier B.V. 2nd Edition, 257–286.

24. Chibowski, E. (2014). Flocculation and Dispersion Phenomena in Soils. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3585-1

25. Cirtex Industries Ltd. (Accessed June 16, 2020). Large Floc Shed Assembly and Maintenance Guide. https://3724441.app.netsuite.com/core/media/media.nl?id=3361931&c=3724441&h=b636d3be49d06d383b05&_xt=.pdf

26. Connecticut Department of Transportation (2004). Connecticut Stormwater Quality Manual. CTDOT, Newington, CT.

27. Covington, A. K., Bates, R. G., and Durst, R. A. (1985). Definition of pH Scales, Standard Reference Values, Measurement of pH, and Related Terminology. *Pure & Applied Chemistry*, 57(3), 531–542.

28. Dao, V. H., Cameron, N. R., & Saito, K. (2016). Synthesis, properties, and performance of organic polymers employed in flocculation applications. *Polymer Chemistry*, 7(1), 11–25. https://doi.org/10.1039/c5py01572c

29. De Milieux, Z. (2003). Water Treatment Coagulation -Flocculation. 33, 10.

30. Davies-Colley, R. J., and Smith, D. G. (2001). Turbidity, Suspended Sediment, and Water Clarity: A Review. American Water Resources Association, 37(5), 1085–1101.

31. Department of Energy and Environment (2017). District of Columbia Erosion and Sediment Control Manual. DOEE, Washington D.C.

32. Dobrynin, A. V., Colby, R. H., & Rubinstein, M. (2004). Polyampholytes. *Journal of Polymer Science*, *Part B: Polymer Physics,* 42(19), 3513–3538. https://doi.org/10.1002/polb.20207

33. Donald, W. N., Zech, W. C., Fang, X., & Perez, M. A. (2016). Hydraulic method to evaluate the performance of ditch check practices and products. *Journal of Hydrologic Engineering*, 21(11), 1–9. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001311

34. Donohue, I., and Garcia Molinos, J. (2009). Impacts of increased sediment loads on the ecology of lakes. *Biological Reviews*, 84(4), 517–531. https://doi.org/10.1111/j.1469-185x.2009.00081.x

35. Douglas, F. J., & Enos, S. L. (1995). Impact of toxicities and potential interactions of flocculants and coagulant aids on whole effluent toxicity testing. *Water Environment Research*, 67(6), 921–925. https://doi.org/10.2175/106143095X133149

36. Druschel, S. J. (2014). Flocculation Treatment BMPs for Construction Water Discharges. Minnesota Department of Transporation, St. Paul, MN.

37. Duggan, K. L., Morris, M., Bhatia, S. K., Khachan, M. M., & Lewis, K. E. (2019). Effects of Cationic Polyacrylamide and Cationic Starch on Aquatic Life. *Journal of Hazardous, Toxic, and Radioactive Waste*, 23(4), 1–12. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000467

38. Floc Systems Inc. Tigerfloc Flocculant Belts/ Socks. (Accessed July 16, 2020) https://www.flocsystems.com/product/tigerfloc-flocculant-belts-socks.

39. Florida Department of Transportation. (2013). “Erosion and Sediment Control Designer and Reviewer Manual” Tallahassee, FL.

40. Fisher Scientific Inc. (2022a). “United Scientific Supplies Secchi Disktle.” https://www.fishersci.ca/shop/products/united-scientific-secchi-disk/s12871 (Accessed March 6, 2022b).

41. Fisher Scientific Inc. (2022b). “GSC Turbidity Tube.” (Accessed March 6, 2022). https://www.fishersci.com/shop/products/turbidity-tube-3/S38986

42. Fisher Scientific Inc. (2022c). “FisherbrandTM accumetTM AE150 Benchtop pH Meter.” (Accessed March 8, 2022). https://www.fishersci.com/shop/products/fisher-scientific-accumet-ae150-ph-benchtop-meter-bio-set/13636AE152?ef_id=Cj0KCQiAmpyRBhC-ARIsABs2EArem5yTVFBPVZpKzBz9C48i9rgfiC-WY-ymgSohv1NZkc0mKMziqK4aAlVUEALw_wcB:G:s&ppc_id=PLA_goog_2086145671_83549638768_1363.

43. Fisher Scientific Inc. (2022d). “Thermo ScientificTM OrionTM Standard All-in-OneTM pH Buffer Kit.” (Accessed March 8, 2022). https://www.fishersci.com/shop/products/orion-standard-all-in-one-ph-buffer-kit/13624500?ef_id=Cj0KCQiAmpyRBhC-ARIsABs2EApO9VYjwOmxW1lyWsBqAB1GH0SEGyWDXIl6HKW_lk8MM3F7Lv6-v8AaAvNBEALw_wcB:G:s&ppc_id=PLA_goog_2086145665_75666497494_13624500__375381481635_3.

44. Grainger Supply Inc (2022). “Ricca Chemical pH Test Strips: 2 to 9 pH.” (Accessed March 8, 2022). https://www.grainger.com/product/45D967?ef_id=Cj0KCQiAmpyRBhC-ARIsABs2EAoU81t0g_IUrhnvmW6kugoUDgFVAH28mjgS0vcu7WmVZXcrE-0YjR8aAtBXEALw_wcB:G:s&s_kwcid=AL!2966!3!496359976069!!!g!469712068256!&gucid=N:N:PS:Paid:GGL:CSM-2293:99F1R6:20501231&gclid=Cj0KCQiAmp

45. Gregory, J. (2004). “Monitoring floc formation and breakage.” *Water Science and Technology*, 50(12). https://doi.org/10.2166/wst.2004.0709

46. Hach Inc. (2022a). “TL23 Series Laboratory Turbidimeters.” (Accessed March 6, 2022) https://www.hach.com/turbidimeters/tl23-series-laboratory-turbidimeters/family?productCategoryId=50908490523 (Mar. 6, 2022).

47. Hach Inc (2022b). “2100Q Portable Turbidimeter.” (Accessed March 6, 2022) https://www.hach.com/turbidimeters/2100q-portable-turbidimeter/family?productCategoryId=35547372710

48. Hach Inc (2022c). “Pocket Pro pH Tester.” (Accessed March 8, 2022) https://www.hach.com/pocket-pro-ph-tester/product?id=17990686202

49. Hansen, Z. K., and Libecap, G. D. (2004). "Small farms, externalities, and the dust bowl of the 1930s." *Journal of Political Economy*, 112(3), 665–694. https://doi.org/10.1086/383102

50. Harper, H. H., Herr, J. L., & Livingston, E. H. (1999). Alum Treatment of Stormwater: The First Ten Years. *Journal of Water Management Modeling*. https://doi.org/10.14796/JWMM.R204-09

51. Hunter, R. J. (1986). Foundations of Colloid Science. *Oxford Science*, Vol. 1. Oxford, UK. ISBN: 0198551886

52. Illinois Department of Transportation (2010). Erosion and Sediment Control Field Guide for Construction Inspections. IDOT, Springfield, IL.

53. Jung, J., Jungyeon, J., & Jaehun, A. (2016). Characterization of a Polyacrylamide Solution Used for Remediation of Petroleum Contaminated Soils. *Materials.* https://doi.org/10.3390/ma9010016

54. Kajihara, M. (1971). "Settling velocity and porosity of large suspended particle." *Journal of the Oceanographical Society of Japan*, 27(4), 158–162.

55. Kang, J., & McLaughlin, R. A. (2016). Simple systems for treating pumped, turbid water with flocculants and a geotextile dewatering bag. *Journal of Environmental Management*, 182, 208–213. https://doi.org/10.1016/j.jenvman.2016.07.071

56. Kang, J., Sowers, T. D., Duckworth, O. W., Amoozegar, A., Heitman, J. L., & McLaughlin, R. A. (2013). Turbidimetric Determination of Anionic Polyacrylamide in Low Carbon Soil Extracts. *Journal of Environmental Quality*, 42(6), 1902–1907. https://doi.org/10.2134/jeq2013.07.0279

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

58. Kazaz, B., Perez M. A., & Donald W. N. (2021). State-of-the-Practice Review on the Use of Flocculants for Construction Stormwater Management in the United States. *Transportation Research Record: Journal of the Transportation Research Board.* http://doi.org/10.1177/0361198121995192

59. Kazaz, B., Schussler, J. C., Dickey, L. C., and Perez, M. A. (2022). "Soil Loss Risk Analysis for Construction Activities." Transportation Research Record: Journal of the Transportation Research Board, https://doi.org/10.1177/03611981221075027

60. Kurenkov, V. F., Hartan, H.-G., & Lobanov, F. I. (2002). Application of Polyacrylamide Flocculants for Water Treatment. *Chemistry and Computer Modeling*, 3(31), 31–40.

61. Lee, C. S., Robinson, J., & Chong, M. F. (2014). A review on application of flocculants in wastewater treatment. *Process Safety and Environmental Protection*, 92(6), 489–508. https://doi.org/10.1016/j.psep.2014.04.010

62. Lee, S. (2021) United Soil Classification System (Accessed March 5, 2022) https://www.dropbox.com/scl/fi/ycfu2rxwyg8rs669344la/USCS-for-engineering-purpose-ASTM-D-2487.xlsx?dl=1&rlkey=716vp0xppm2c3m49000yz2vhb

63. Lentz, R. D., & Sojka, R. E. (1994). Field results using polyacrylamide to manage furrow erosion and infiltration. *Soil Science*, 158(4), 274–282. https://doi.org/10.1097/00010694-199410000-00007

64. Lentz, R. D., Sojka, R. E., & Foerster, J. A. (1996). Estimating Polyacrylamide Concentration in Irrigation Water. *Journal of Environmental Quality*, 25(5), 1015–1024. https://doi.org/10.2134/jeq1996.00472425002500050013x

65. Li, B., Zhang, J., Bu, F., & Xia, W. (2013). Determination of chitosan with modified acid hydrolysis and HPLC method. *Carbohydrate Research*, 366, 50–54. https://doi.org/10.1016/j.carres.2012.11.005

66. Lords World Inc. Lords World Flocculant Liquid Clarifier. (Accessed July 16, 2020) https://lordsworld.eu/gb/swimming-3 pool/5lt-flocculant-liquid-clarifier-swimming-pool-water-anti-turbidity.

67. McFalls, J., Yi, Y.-J., Storey, B., Barrett, M., Lawler, D., Eck, B., Rounce, D., Cleveland, T., Murphy, H., Dalton, D., Morse, A., and Herrmann, G. (2014). Performance Testing of Coagulants To Reduce Stormwater Runoff Turbidity. Texas Department of Transportation.Austin, TX.

68. Mclaughlin, R. A., & Zimmerman, A. (2008). Best Management Practices for Chemical Treatment Systems for Construction Stormwater and Dewatering. Report No. FHWA-WFL/TD-09-001. Federal Highway Administration, Vancouver, WA.

69. Miao, Q., Cui, Y., Zhang, J., Mi, Y., Tan, W., Li, Q., Gu, G., Dong, F., & Guo, Z. (2020). Determination of chitosan content with ratio coefficient method and HPLC. *International Journal of Biological Macromolecules*, 164, 384–388. https://doi.org/10.1016/j.ijbiomac.2020.07.013

70. Miller, B. (2014). USDA Soil Texture Class Macro. (Accessed March 5, 2022) http://glsi.agron.iastate.edu/2014/03/10/usda-soil-texture-class-macro/

71. Mitchell, Charles C. (2008). Natural resources conservation services soil areas in Alabama. *The United States Department of Agriculture.* (Accessed April 5, 2020). <nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr7/?cid=nrcs142p2_047868 >.

72. New York State Department of Environmental Conservation. (2016). New York Standards and Specifications for Erosion and Sediment Control. NYSDEC, Albany, NY.

73. North Carolina Department of Environmental Quality (2019). North Carolina Administrative Code Surface Water and Wetland Standards. NC DEQ, Raleigh, NC.

74. North Carolina Department of Transportation (2014). "Erosion and Sediment Control Design and Construction Manual." Raleigh, NC.

75. Natural Resources Conservation Service (2021). "Honoring 86 Years of NRCS – A Brief History." (Accessed March 5, 2022) https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/about/history/?cid=nrcs143_021392

76. Oregon Department of Transportation (2019). "Erosion Control Manual: Guidelines for Developing and Implementing Erosion and Sediment Controls" Salem, OR.

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

78. Parsapour, G. A., Hossininasab, M., Yahyaei, M., and Banisi, S. (2014). Effect of settling test procedure on sizing thickeners. *Separation and Purification Technology*, Elsevier B.V., 122, 87–95. http://dx.doi.org/10.1016/j.seppur.2013.11.001

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

80. Perez, M.A., Zech, W. C., Donald, W. N., & Fang, X. (2015). Installation Enhancements to Common Inlet Protection Practices Using Large-Scale Testing Techniques. *Transportation Research Record: Journal of the Transportation Research Board*, 2521(1), 151–161. https://doi.org/10.3141/2521-16

81. Perez, M. A., Zech, W. C., Donald, W. N., and Fang, X. (2016a). Design Methodology for the Selection of Temporary Erosion and Sediment Control Practices Based on Regional Hydrological Conditions. *Journal of Hydrologic Engineering*, 21(4), 05016001. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001328.

82. Perez, M. A., Zech, W. C., Fang, X., & Vasconcelos, J. G. (2016b). Methodology and development of a large-scale sediment basin for performance testing. *Journal of Irrigation and Drainage Engineering*, 142(10), 1–9. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001052

83. Pillai, J., (2013). Flocculants and Coagulants: The Keys to Water and Waste Management in Aggregate Production. Nalco, Naperville, IL.

84. ProTech General Contracting Services Inc. (2004). Polymer Coagulants and Flocculants for Stormwater Applications. ProTech.

85. Przepiora, A., Hesterberg, D., Parsons, J. E., Gilliam, J. W., Cassel, D. K., & Faircloth, W. (1997). Calcium Sulfate as a Flocculant to Reduce Sedimentation Basin Water Turbidity. *Journal of Environmental Quality*, 26(6), 1605–1611. https://doi.org/10.2134/jeq1997.00472425002600060021x

86. Przepiora, A., Hesterberg, D., Parsons, J. E., Gilliam, J. W., Cassel, D. K., & Faircloth, W. (1998). Field Evaluation of Calcium Sulfate as a Chemical Flocculant for Sedimentation Basins. *Journal of Environmental Quality*, 27(3), 669–678. https://doi.org/10.2134/jeq1998.00472425002700030026x

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

88. Rabiee, A. (2010). Acrylamide-based anionic polyelectrolytes and their applications: A survey. *Journal of Vinyl and Additive Technology*. https://doi.org/https://doi.org/10.1002/vnl.20229

89. Reinke, E. A. (1951). Water Quality and Treatment. *American Journal of Public Health and the Nation's Health* 41(9).

90. Rhode Island State Conservation Committee (2014). Rhode Island Soil Erosion and Sediment Control Handbook. RISCC, Jamestown, RI.

91. Rounce, D., Eck, B., Lawler, D., and Barrett, M. (2012). "Reducing turbidity of construction site runoff via coagulation with polyacrylamide and chitosan." *Center for Research* 2309(December), 171–177.

92. Salehizadeh, H., Yan, N., & Farnood, R. (2018). Recent advances in polysaccharide bio-based flocculants. *Biotechnology Advances*, 36(1), 92–119. https://doi.org/10.1016/j.biotechadv.2017.10.002

93. Schussler, J.C. (2022) Improvements in Stormwater Detention Technologies through Large-Scale Testing [Under review doctoral dissertation]. Auburn University. Auburn, AL.

94. Schussler, J. C., Kazaz, B., Perez, M. A., Whitman, J. B., and Cetin, B. (2021). Field Evaluation of Wattle and Silt Fence Ditch Checks. *Transportation Research Record:*

Journal of the Transportation Research Board, 2675(6) https://doi.org/10.1177/0361198121992073.

95. Schussler J.C., Perez M. A., Donald W. N., Whitman J.B., Zech W.C., Fang X. and Fagan B. (2022). Decade of Research in Review at the Auburn University Stormwater Research Facility. *Transportation Research Record: Journal of the Transportation Research Board,* https://doi.org/10.1177/03611981221076449

96. Shaw, J. N., Hajek, B. F., & Beck, J. M. (2010). Highly weathered mineralogy of select soils from Southeastern U.S. Coastal Plain and Piedmont landscapes. *Geoderma*, 154(3–4), 447–456. https://doi.org/10.1016/j.geoderma.2009.01.019

97. Singh, R., and Adhikari, R. (2018). “Generalized Stokes laws for active colloids and their applications.” *Journal of Physics Communications*, IOP Publishing, 2(2). https://doi.org/10.1088/2399-6528/aaab0d

98. Sojka, R. E., Bjorneberg, D. L., Entry, J. A., Lentz, R. D., & Orts, W. J. (2007). Polyacrylamide in Agriculture and Environmental Land Management. *Advances in Agronomy*, 92(04), 75–162. https://doi.org/10.1016/S0065-2113(04)92002-0

99. Stechemesser, H., & Dobiáš, B. (2005). Coagulation and flocculation. Second Edition, CRC Press, 1–862. https://doi.org/10.1680/bwtse.63341.061

100. Stephan, C. (2009). Methods for Calculating an LC. *Aquatic Toxicology and Hazard Evaluation*, 65-65–20. https://doi.org/10.1520/stp32389s

101. Swift, T., Swanson, L., Bretherick, A., and Rimmer, S. (2015). “Measuring poly(acrylamide) flocculants in freshwater using inter-polymer complex formation.” *Environmental Science: Water Research and Technology, Royal Society of Chemistry*, 1(3), 332–340. https://doi.org/10.1039/C4EW00092G

102. Tan, S., Saito, K., & Hearn, M. T. (2018). Stimuli-responsive polymeric materials for separation of biomolecules. *Current Opinion in Biotechnology*, 53, 209–223. https://doi.org/10.1016/j.copbio.2018.02.011

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

104. Tyler, J. E. (1968). “The Secchi Disk.” Limnology and Oceanography, XIII. https://doi.org/10.4319/lo.1968.13.1.0001

105. United States Census Bureau. (2022). Monthly Construction Spending, CB22-32, Economic Indicator Division, Construction Expenditures Branch January 2022.

106. United States Congress. (2002). Federal water pollution control act. 33 U.S.C. 1251 et Seq., U.S. Congress, 234.

107. United States Department of Agriculture (1930) A Pipette Method of Mechanical Analysis of Soils Base on Improved Dispersion Procedure. Technical Bulletin No. 170, January 1930, Washington D.C.

108. United States Department of Agriculture (2022) A soil profile (Accessed March 17, 2022) Natural Resources Conservation Service Soils https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054308

109. United States Environmental Protection Agency. (1998). Federal Register. 75, 56928–56935. Environmental Protection Agency, Washington D.C.

110. United States Environmental Protection Agency. (2017a). Causal Analysis/Diagnosis Decision Information System (CADDIS). *Volume 2: Sources Stressors and Responses: pH*, (Accessed March 8, 2022) https://www.epa.gov/caddis/basic-information-about-caddis#cite

111. United States Environmental Protection Agency (2017b). Construction General Permit (CGP). Environmental Protection Agency, Washington D.C.

112. United States Environmental Protection Agency (2007). Developing Your Stormwater Pollution Prevention Plan: A Guide for Construction Sites. Environmental Protection Agency, Washington D.C.

113. United States Environmental Protection Agency (1999). National Pollutant Discharge Elimination System—Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges. Environmental Protection Agency, Washington D.C.

114. United States Environmental Protection Agency. (2002). Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms. Environmental Protection, Washington D.C.

115. United States Environmental Protection Agency. (2016). National Nonpoint Source Program. EPA 841-R-16-009. Environmental Protection Agency, Washington D.C.,1–24.

116. United States Environmental Protection Agency. (2005). National Management Measures to Control Nonpoint Source Pollution from Urban Areas. 518.

117. United States Environmental Protection Agency (2017c). National Water Quality Inventory: Report to Congress, EPA 841-R-16-011. Environmental Protection Agency, Washington D.C.

118. United States Environmental Protection Agency (2013). Stormwater Best Management Practice Polymer Flocculation. Environmental Protection Agency, Washington D.C.

119. United States Environmental Protection Agency. (2000). Stormwater Phase II Final Rule: Post Construction Runoff Control Minimum Control Measure. Environmental Protection Agency, Washington D.C.

120. Vajihinejad, V., Gumfekar, S. P., Bazoubandi, B., Rostami Najafabadi, Z., & Soares, J. B. P. (2019). Water-Soluble Polymer Flocculants: Synthesis, Characterization, and Performance Assessment. *Macromolecular Materials and Engineering*, 304(2), 1–43. https://doi.org/10.1002/mame.201800526

121. Vold, M. J. (1963). "Computer simulation of floc formation in a colloidal suspension." *Journal of Colloid Science*, 18(7), 684–695. https://doi.org/10.1016/0095-8522(63)90061-8

122. Wakema, J. R., & Tarleton, S. (2007). Pretreatment of Suspensions in Solid/Liquid Separation Equipment Selection and Process Design. 126–151, Elsevier Science. https://doi.org/https://doi.org/10.1016/B978-1-85617-421-3.X5000-7

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

124. West Virginia Department of Transportation. (2003). Erosion and Sediment Control Manual. WVDOT, Charleston, WV.

125. Whitman, J. B., Zech, W. C., & Donald, W. N. (2019). Improvements in small-scale standardized testing of geotextiles used in silt fence applications. *Geotextiles and Geomembranes*, 47(5), 598–609. https://doi.org/10.1016/j.geotexmem.2019.04.002

126. Whitman, J. Blake, Zech, W. C., Donald, W. N., & LaMondia, J. J. (2018). Full-Scale Performance Evaluations of Various Wire-Backed Nonwoven Silt Fence Installation Configurations. *Transportation Research Record: Journal of the Transportation Research Board*, 2672(39), 68–78. https://doi.org/10.1177/0361198118758029

127. Xiong, B., Loss, R. D., Shields, D., Pawlik, T., Hochreiter, R., Zydney, A. L., & Kumar, M. (2018). Polyacrylamide degradation and its implications in environmental systems. *Nature Partner Journals Clean Water*, 1(1). https://doi.org/10.1038/s41545-018-0016-8

128. Yang, R., Li, H., Huang, M., Yang, H., & Li, A. (2016). A review on chitosan-based flocculants and their applications in water treatment. *Water Research*, 95(2015), 59–89. https://doi.org/10.1016/j.watres.2016.02.068

129. Zeng, D., Wu, J., & Kennedy, J. F. (2008). Application of a chitosan flocculant to water treatment. *Carbohydrate Polymers*, 71(1), 135–139. https://doi.org/10.1016/j.carbpol.2007.07.039

APPENDICES

Appendix A:	Soil Assessment Reports
Appendix B:	Match Test Procedures
Appendix C:	Dosage Test Procedures
Appendix D:	Residual Testing Procedures
Appendix E:	Dosage Test Data
Appendix F:	Product Identification

APPENDIX A

SOIL ASSESSMENT 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

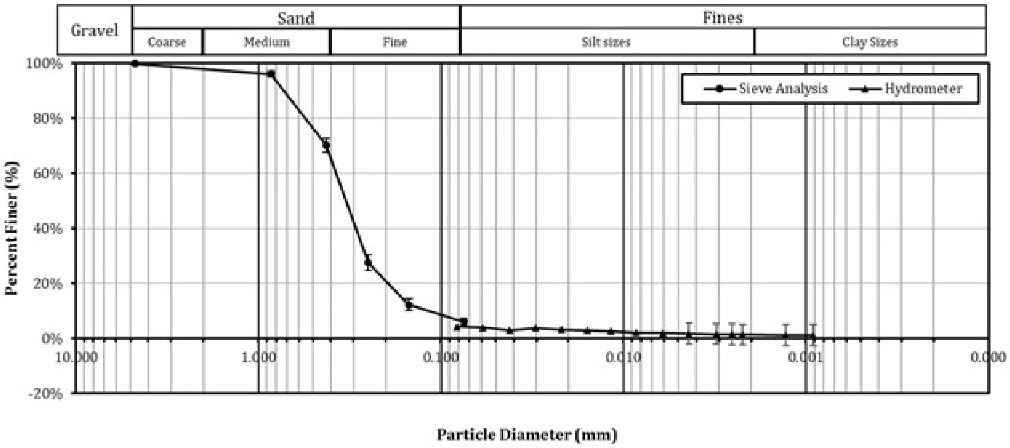


Figure 3- Particle Size Distribution Curve

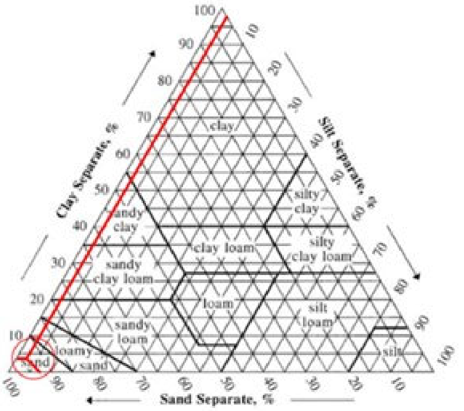
Soil Classification

% 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		

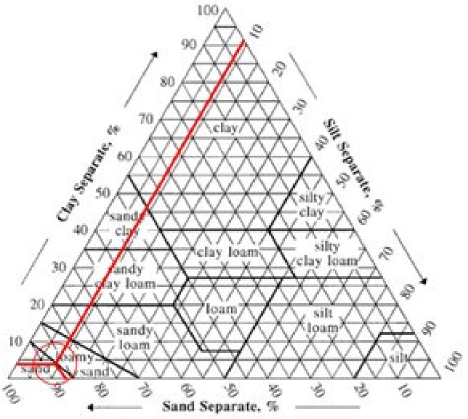
Pipette Testing (PSA) Results

% 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

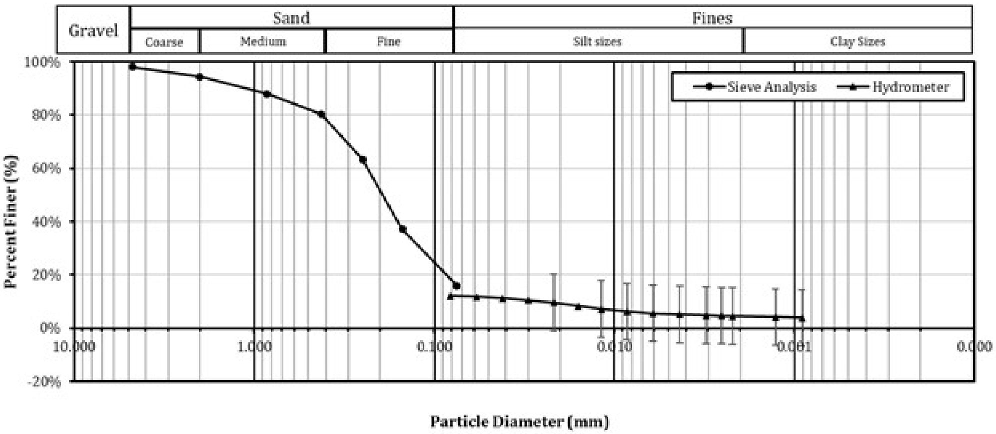


Figure 3- Particle Size Distribution Curve

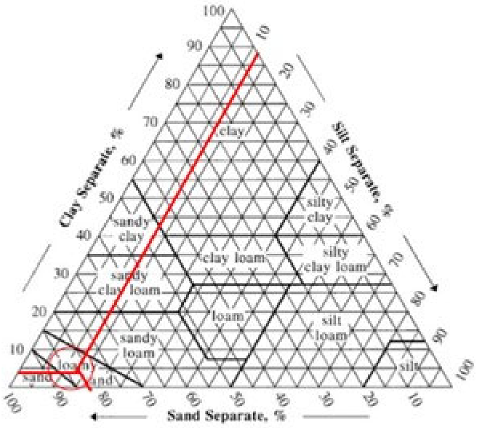
Soil Classification

% sand	82.10	**AASHTO**	**A-2-6** Silty or clayey gravel and sand
%silt	11.70	**USCS**	**SC** Clayey sand
% clay	4.20		

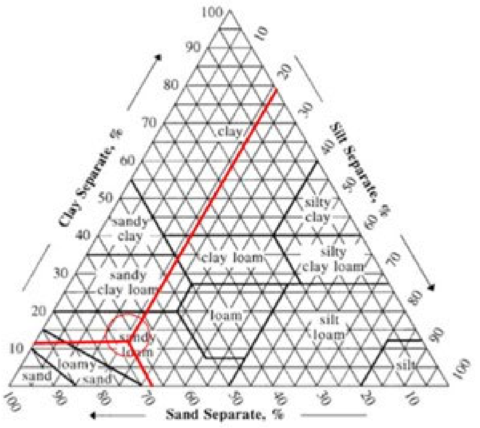
Pipette Testing (PSA) Results

% 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

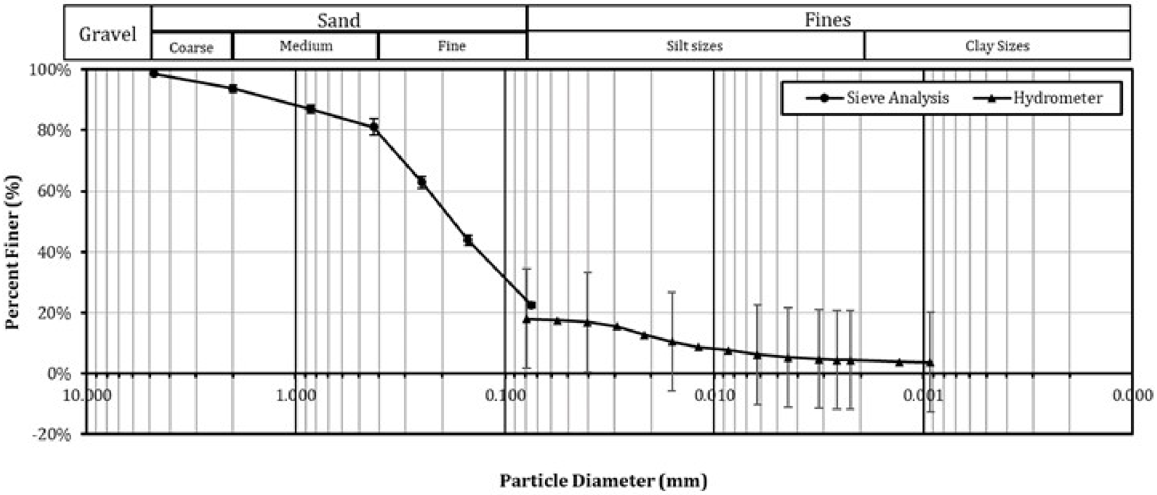


Figure 3- Particle Size Distribution Curve

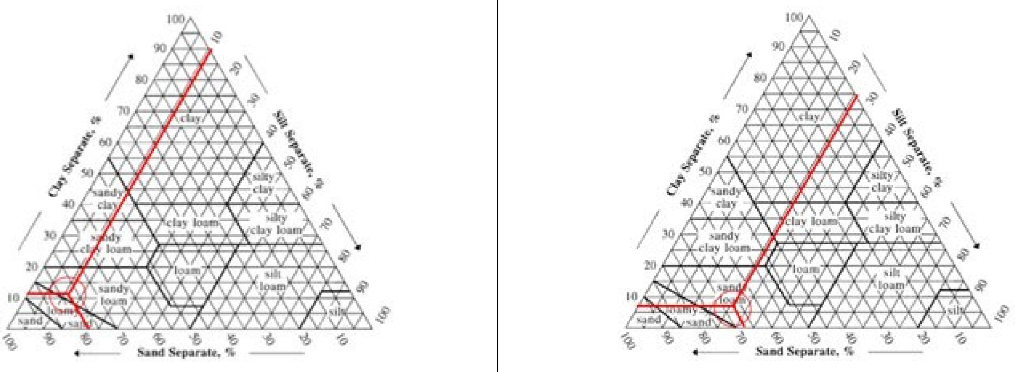
Soil Classification

% 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

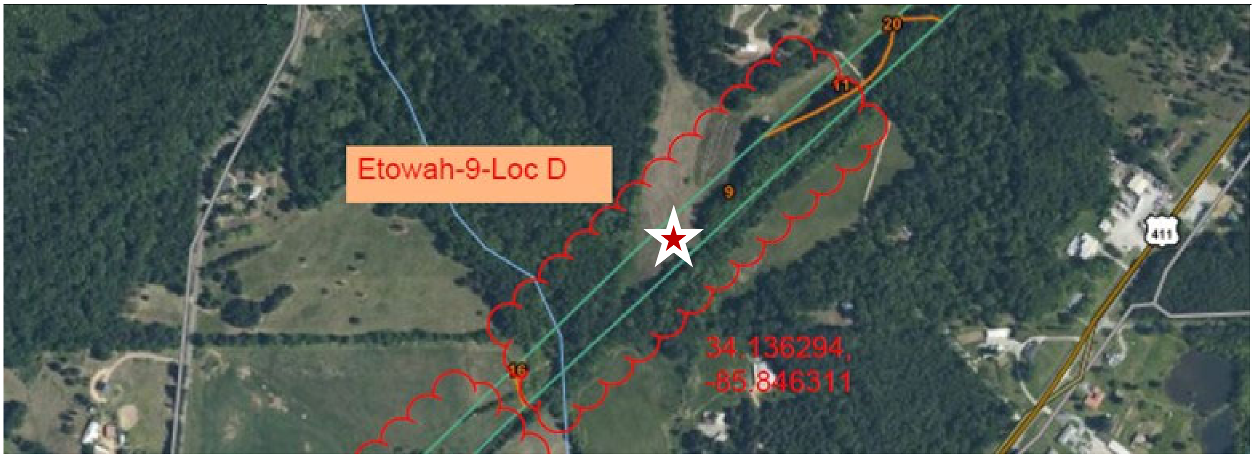


Figure 2- Sampling Location Aerial Image

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** **Tested by**	4/10/2021 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

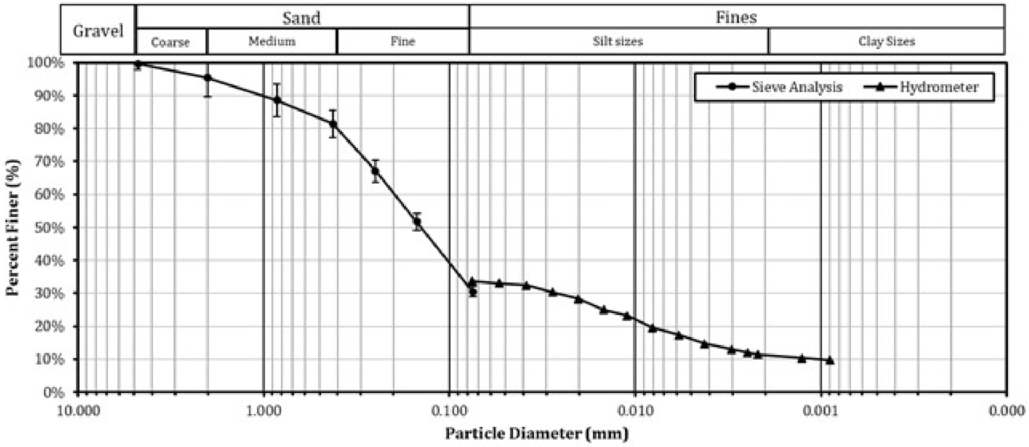
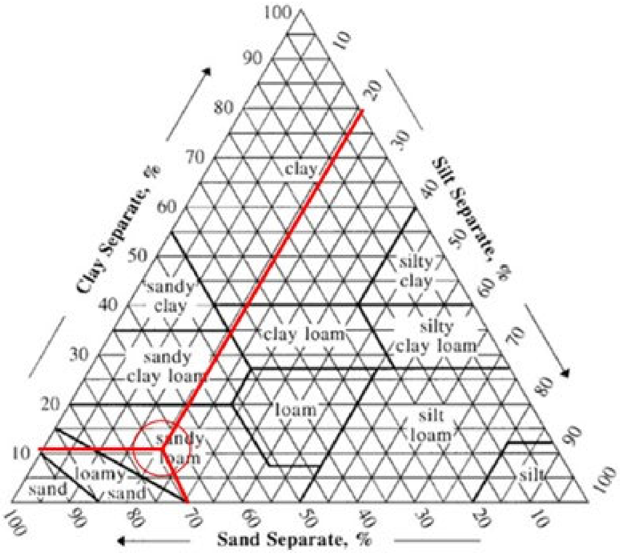


Figure 3- Particle Size Distribution Curve

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

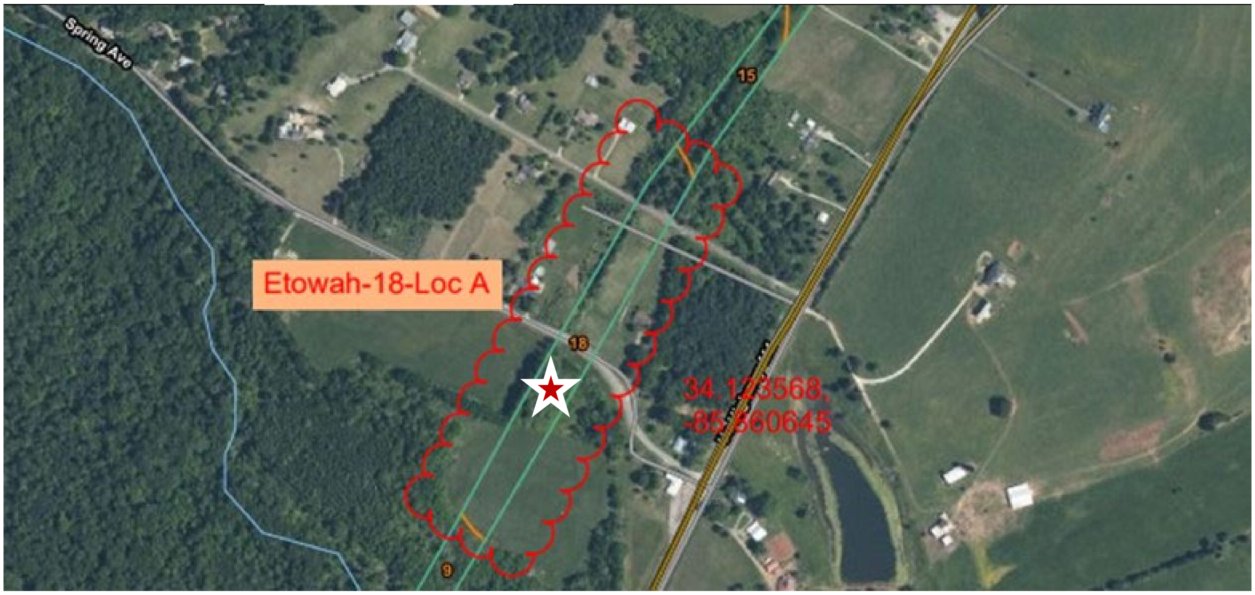


Figure 2- Sampling Location Aerial Image

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** **Tested by**	05/05/2021 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

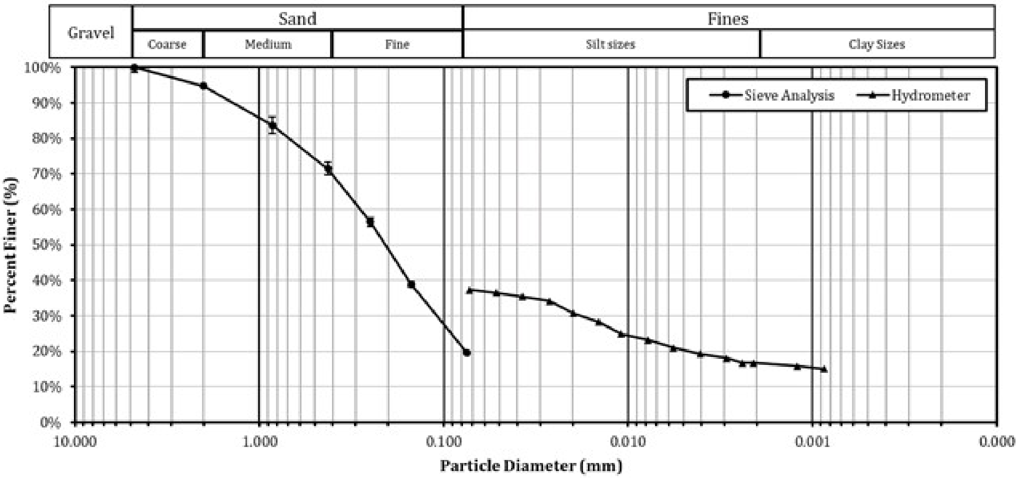
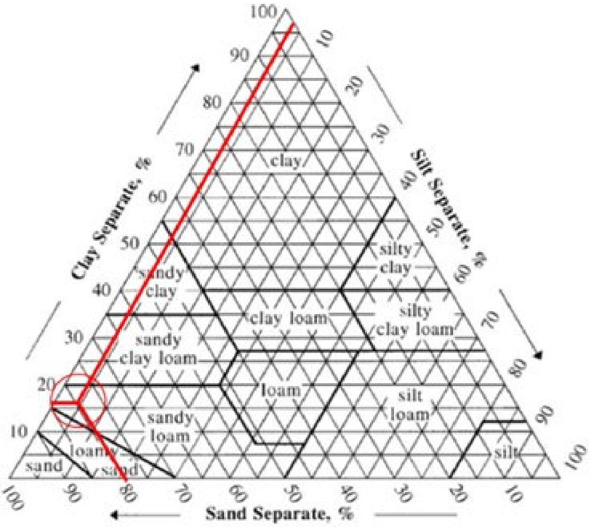


Figure 3- Particle Size Distribution Curve

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

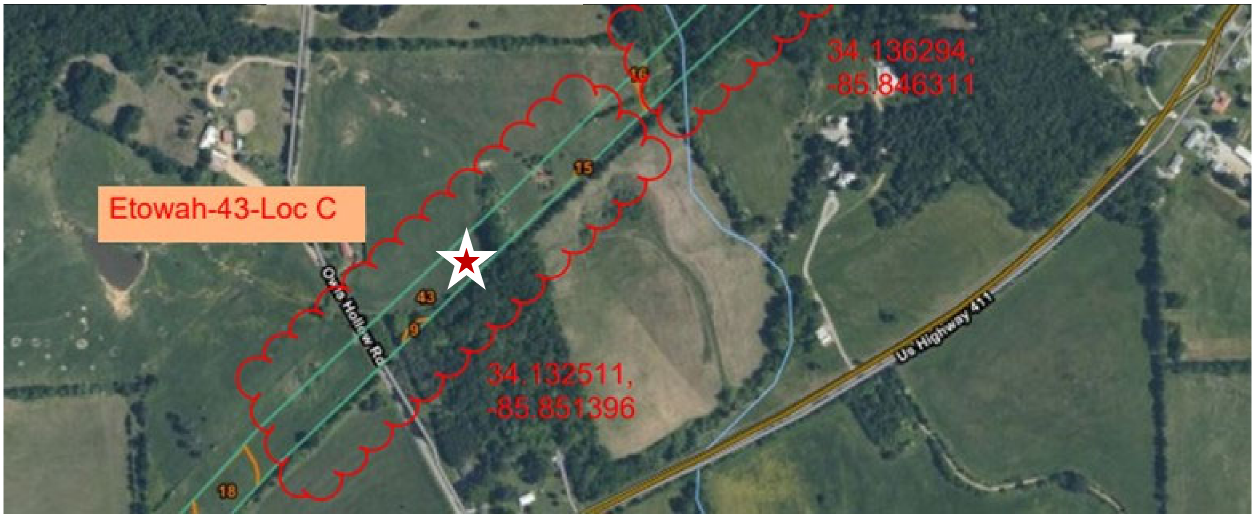


Figure 2- Sampling Location Aerial Image

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** **Tested by**	5/12/2021 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

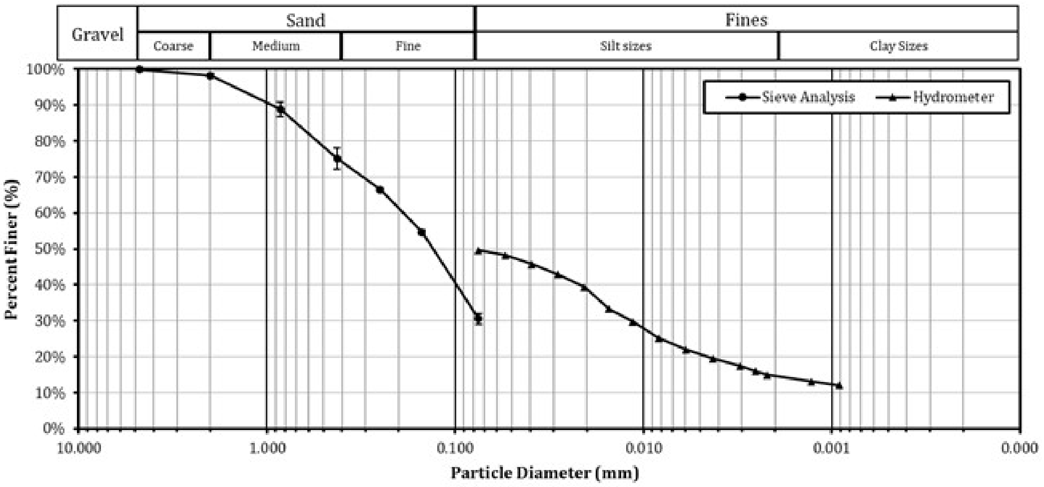
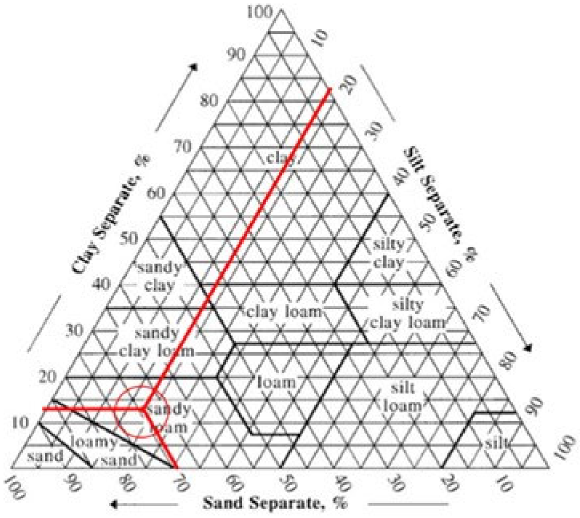


Figure 3- Particle Size Distribution Curve

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

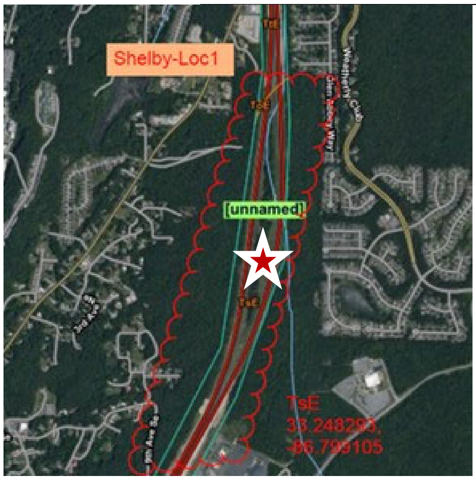


Figure 2- Sampling Location Aerial Image

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** **Tested by**	5/25/2021 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

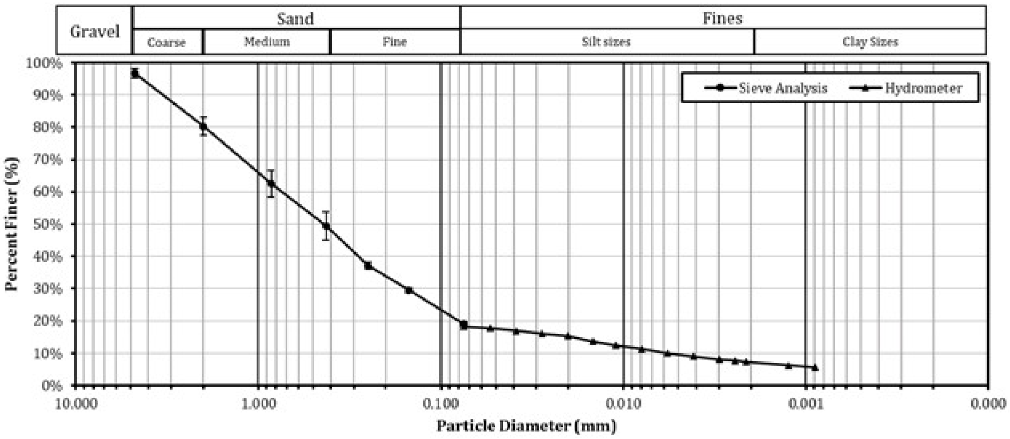
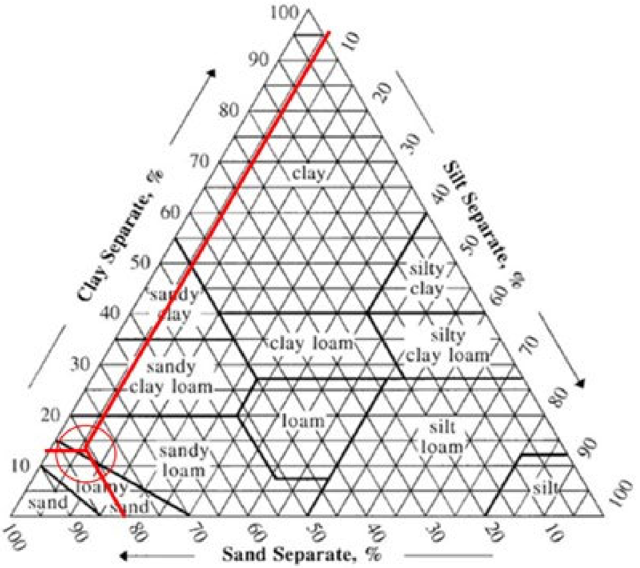


Figure 3- Particle Size Distribution Curve

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** **Tested by**	5/12/2021 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

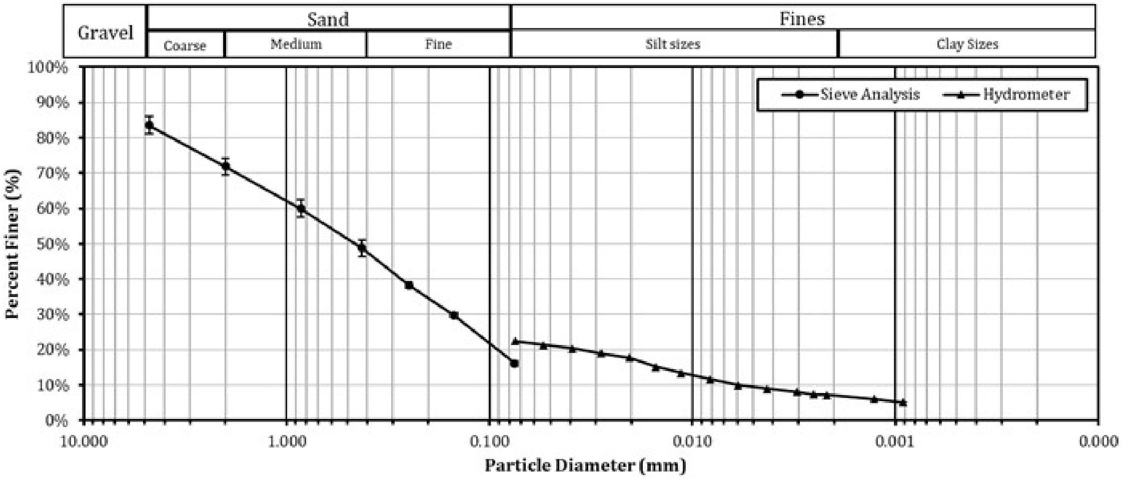
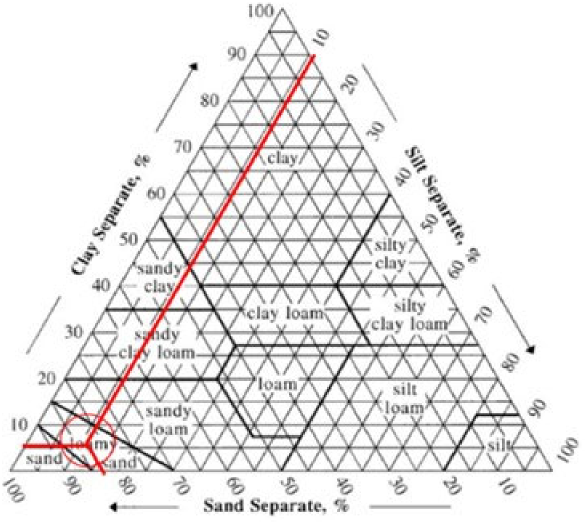


Figure 3- Particle Size Distribution Curve

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** **Tested by**	06/08/2021 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

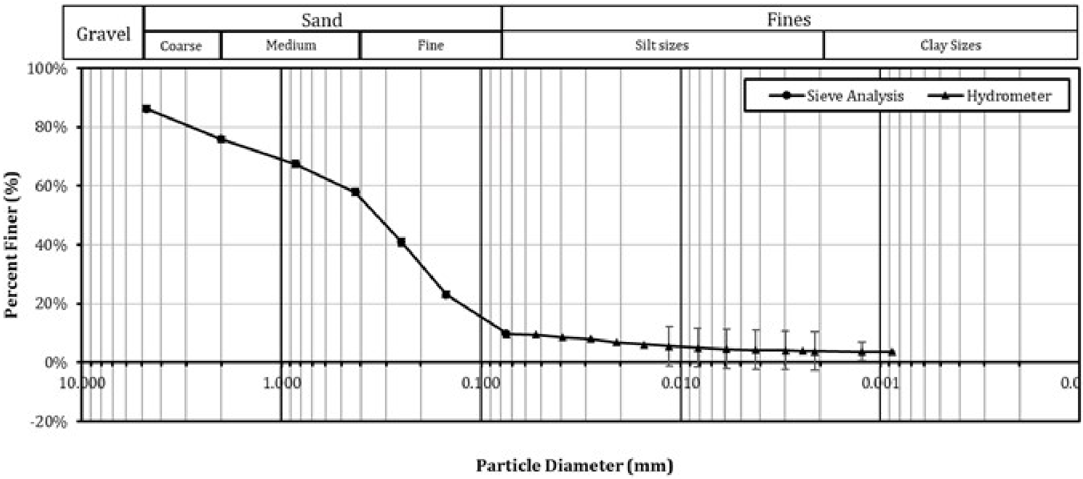
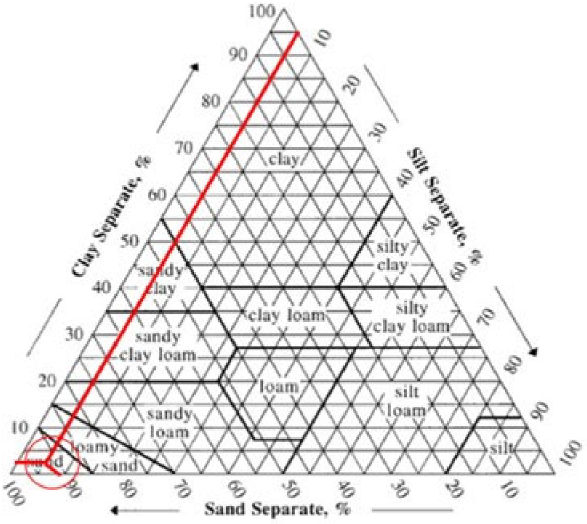


Figure 3- Particle Size Distribution Curve

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

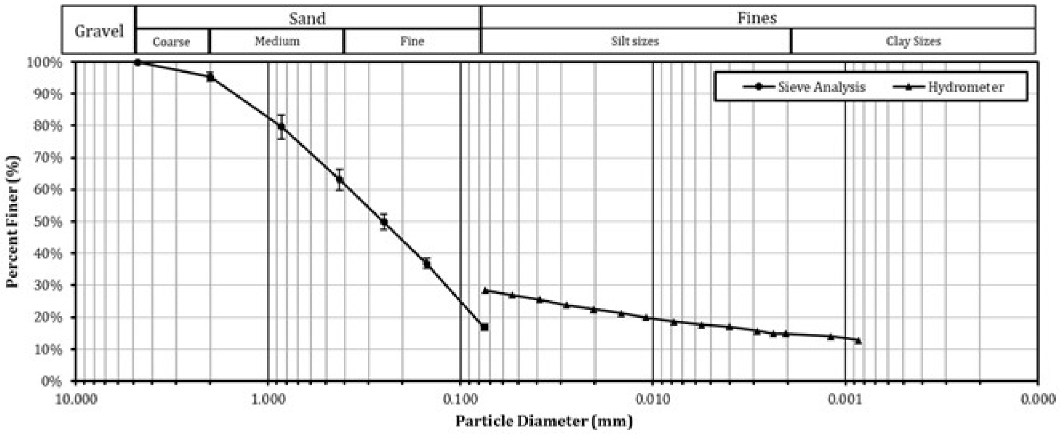
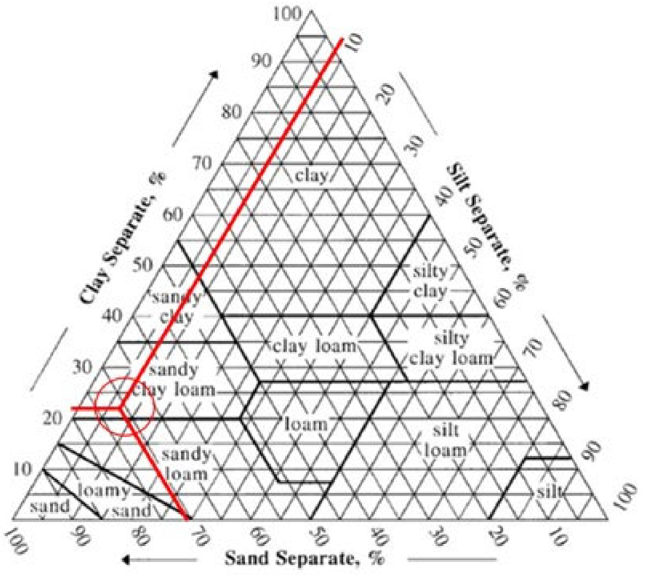


Figure 3- Particle Size Distribution Curve

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

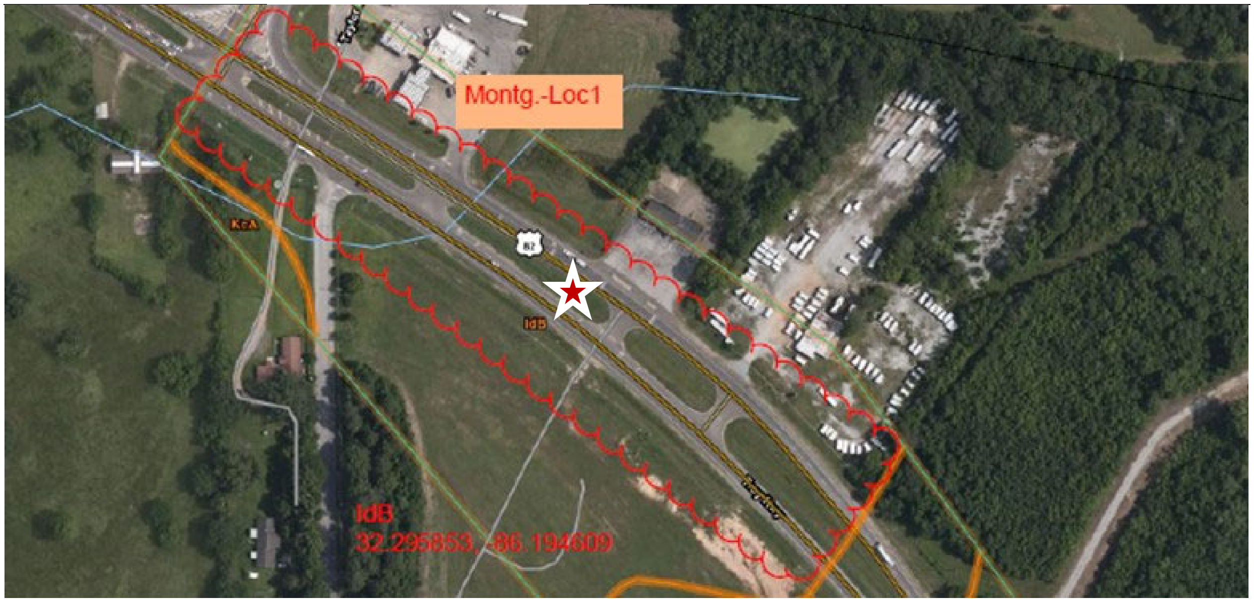


Figure 2- Sampling Location Aerial Image

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

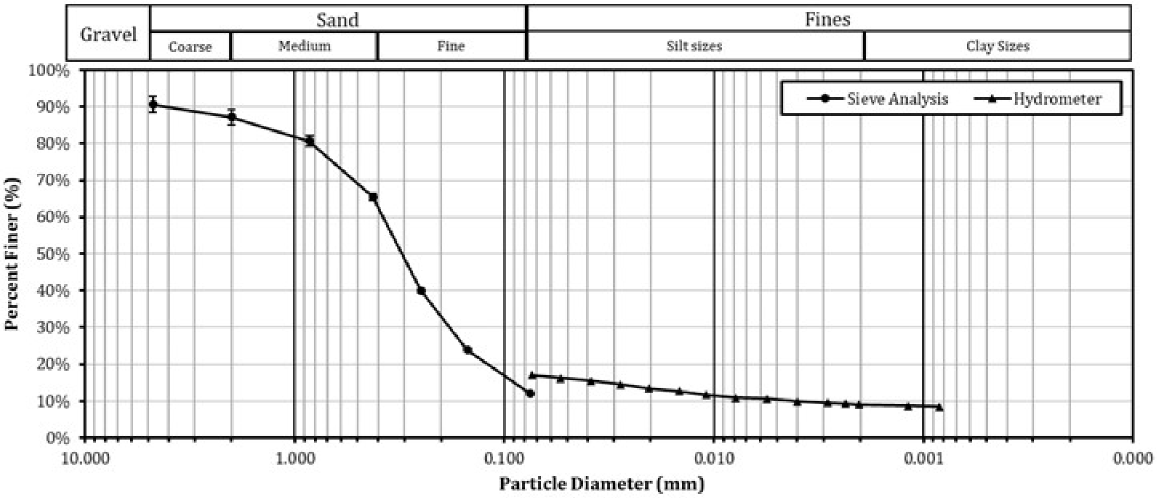
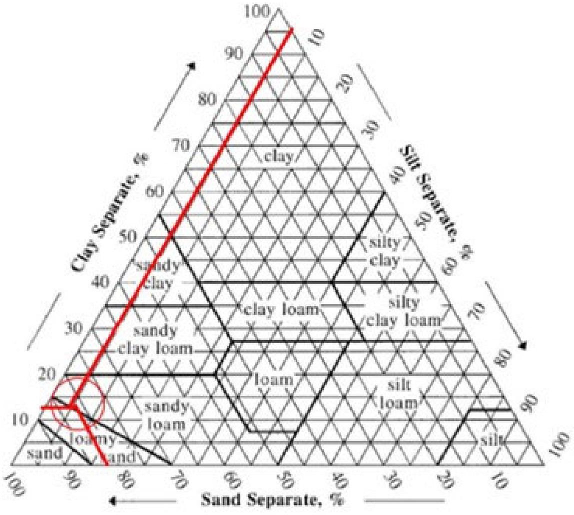


Figure 3- Particle Size Distribution Curve

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** **Tested by**	05/25/2021 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

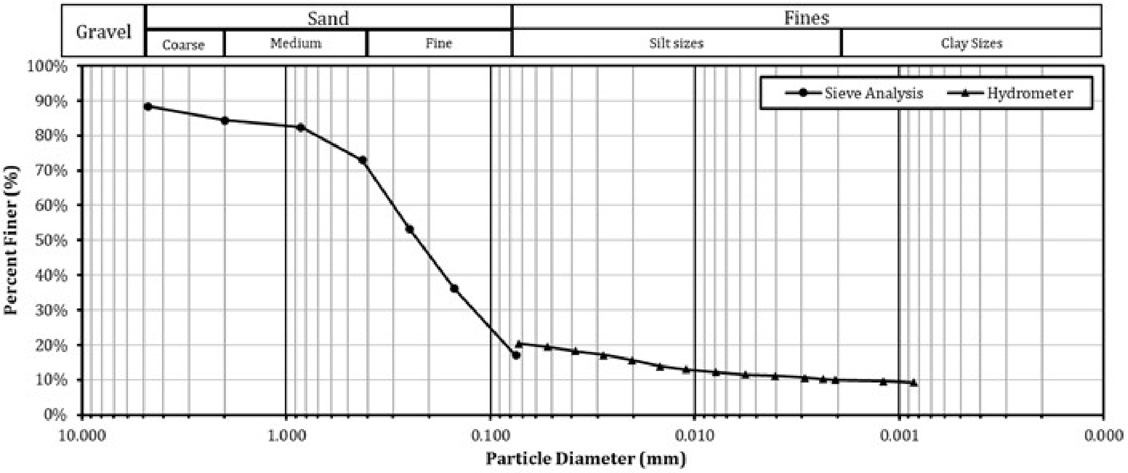
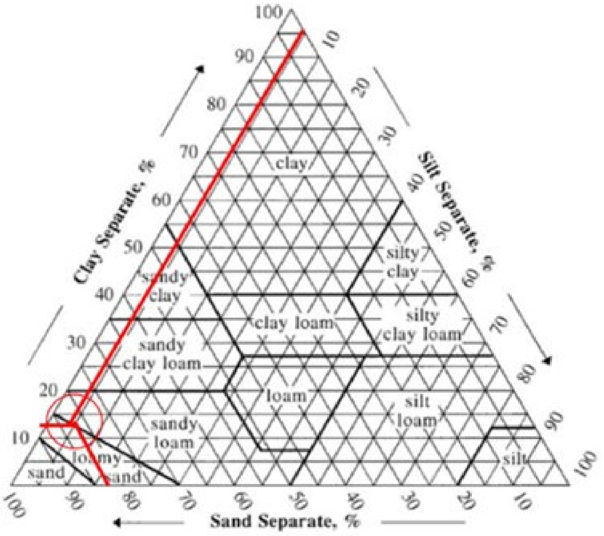


Figure 3- Particle Size Distribution Curve

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** **Tested by**	01/27/2020 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

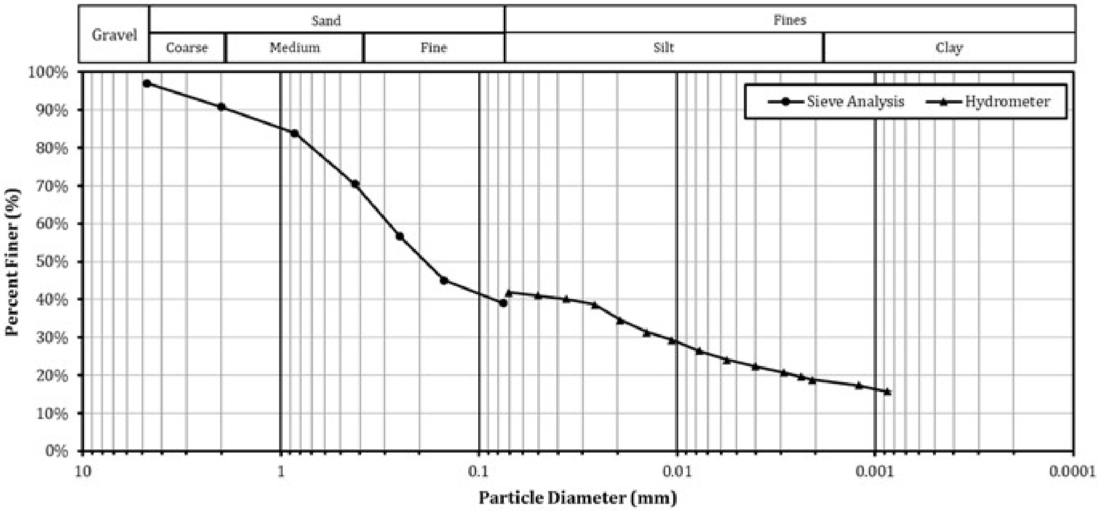
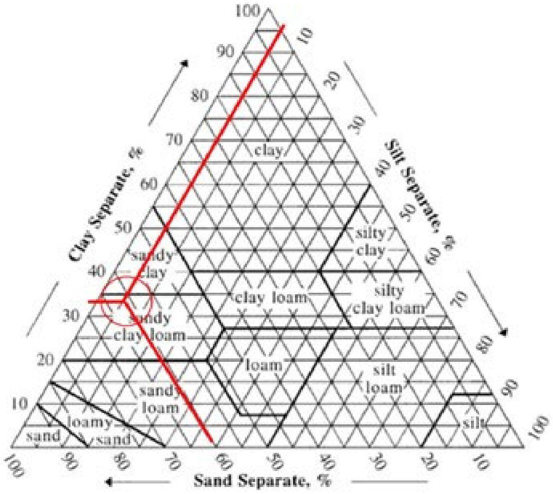


Figure 3- Particle Size Distribution Curve

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

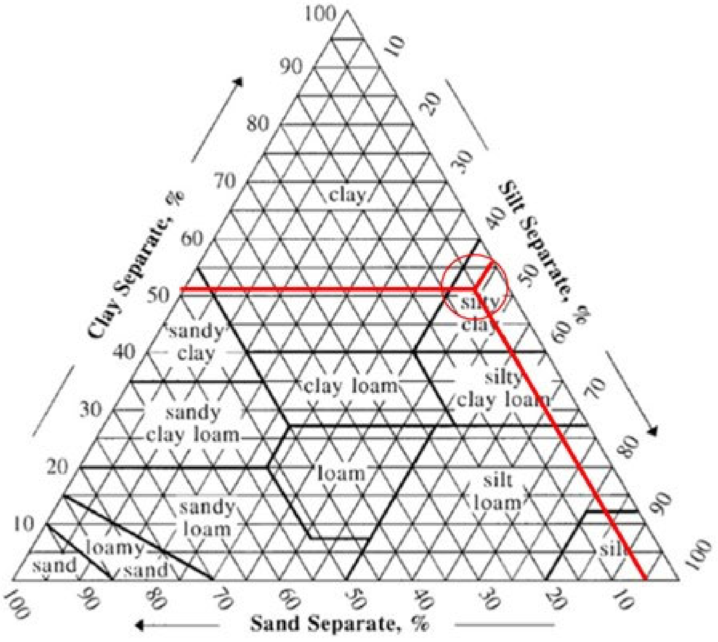
SOIL ANALYSIS

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

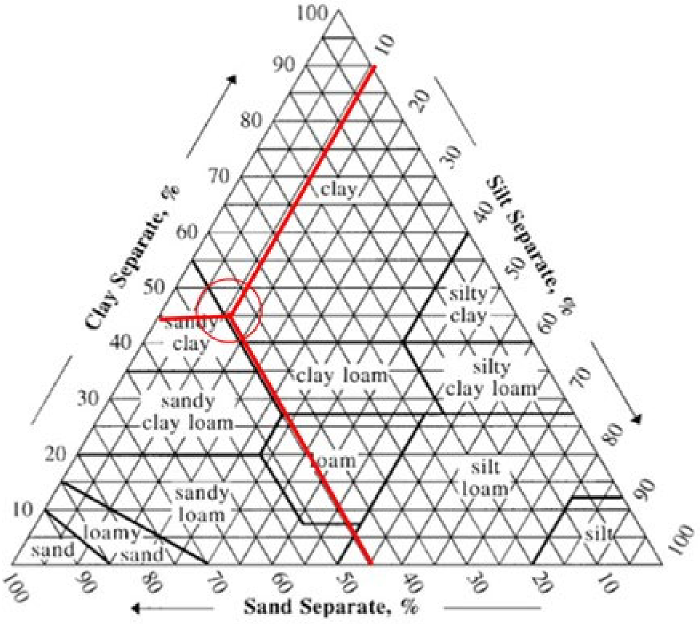
SOIL ANALYSIS

Testing method	• Dry and Wet sieve analysis • Atterberg limit test LL ☒ PL ☒ • Hydrometer

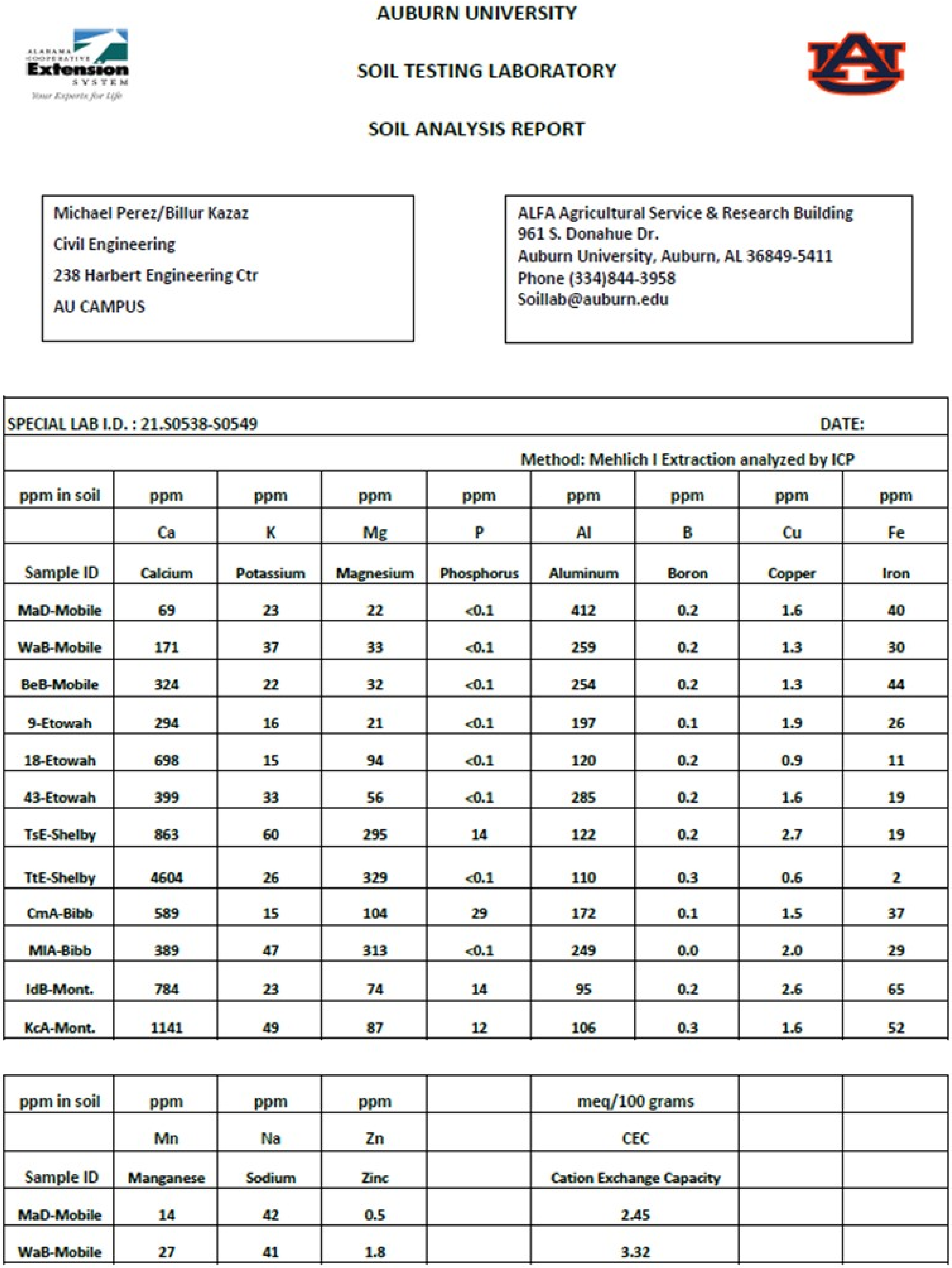
Soil Classification

% 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

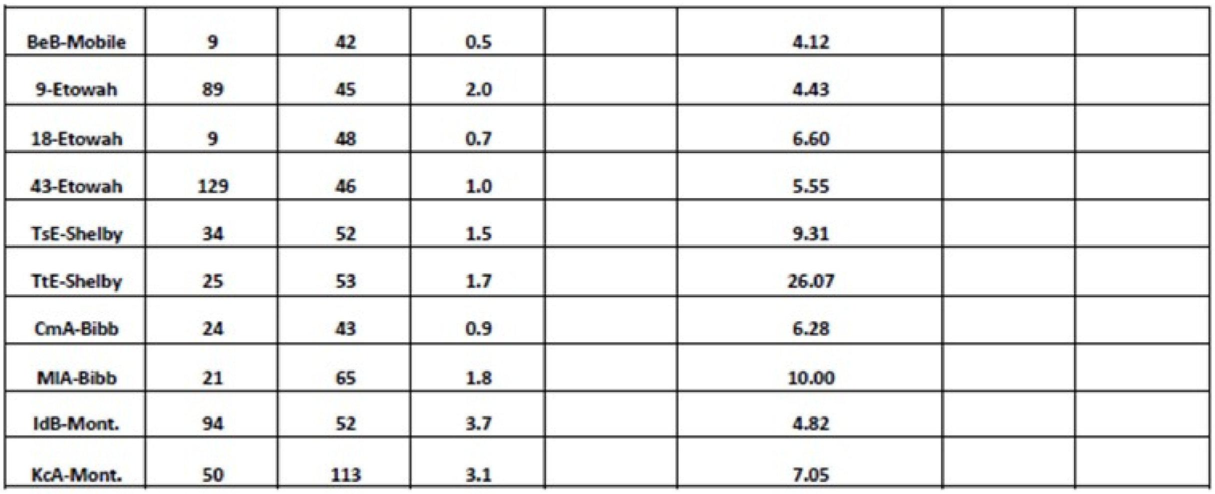
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

SPECIAL LAB I.D. : 21.S0538-S0549 DATE:

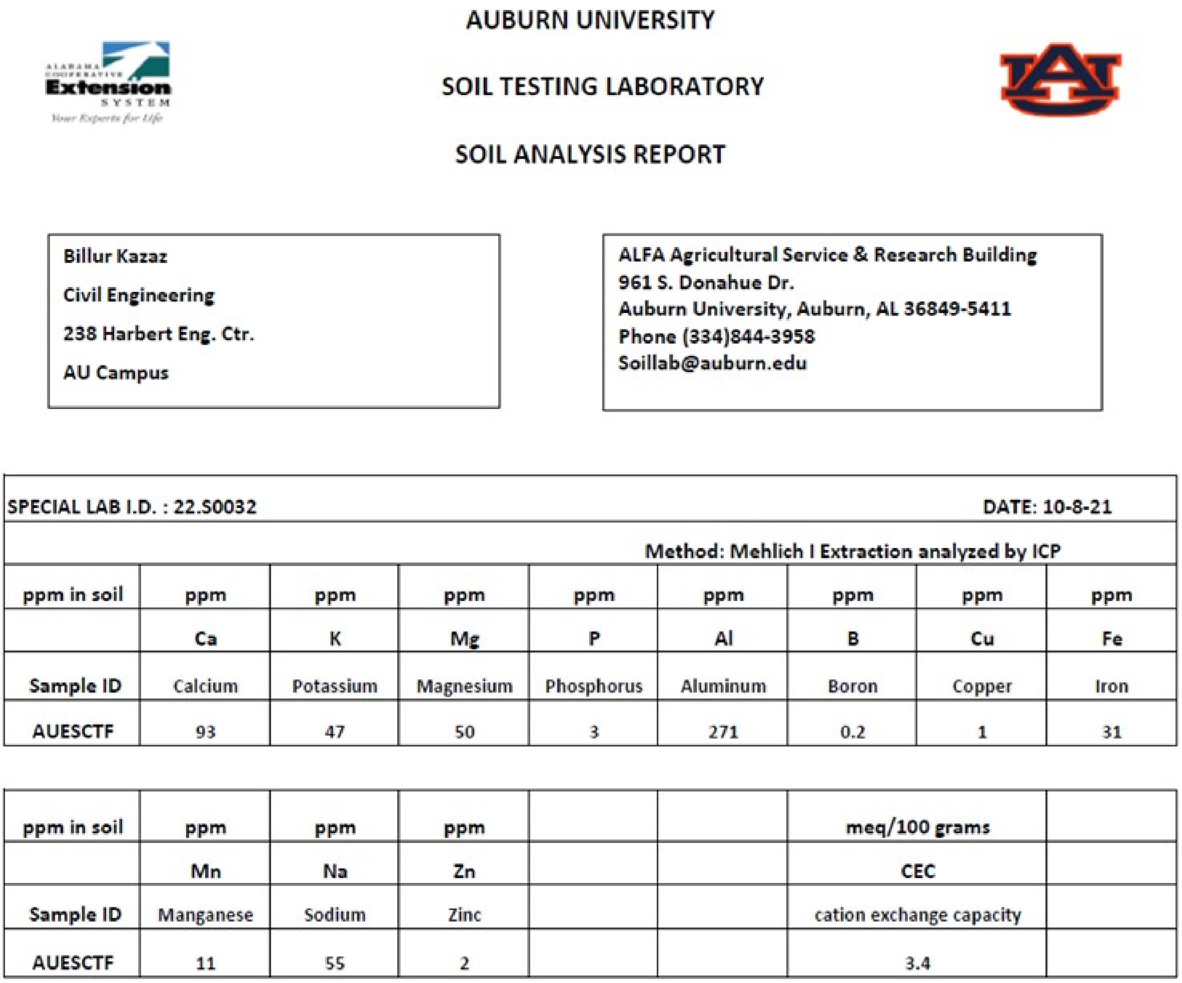
Method: Mehlich I Extraction analyzed by ICP

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

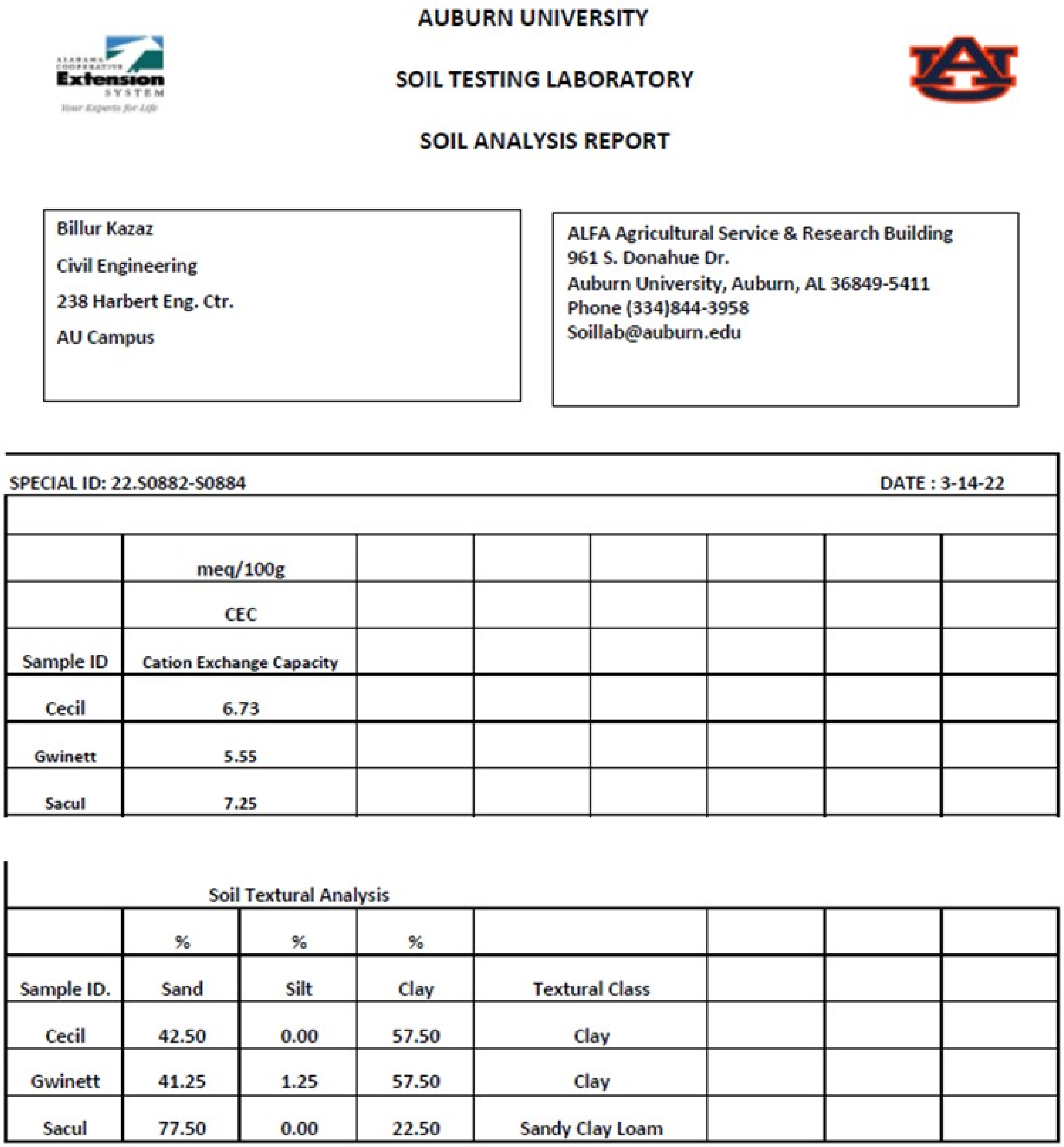
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

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

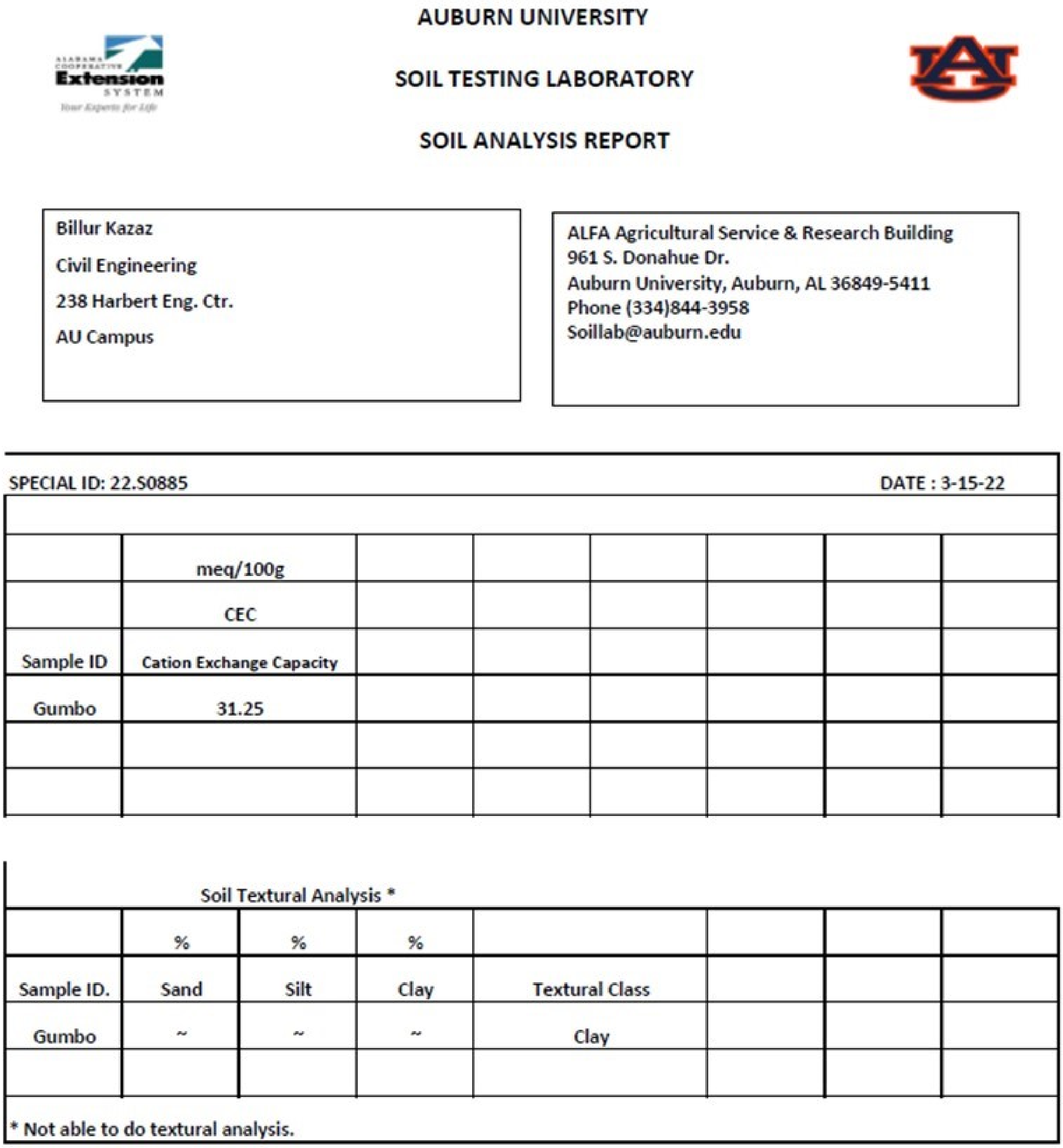
ALFA Agricultural Service & Research Building
961 S. Donahue Dr.
Auburn University, Auburn, AL 36849-5411
Phone (334)844-3958
Soillab@auburn.edu

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 B

MATCH TEST PROCEDURES

Match Test Procedures

Equipment

1- Magnetic Stirrer (20 to 150 rpm) and magnets
2- Jar Test Multiple Stirrer
3- Beakers (Min. 1000 mL, all same size and shape)
4- Reagent Rack
5- Pipets
6- Pipet Filler

Pre-Test

1- Fill the beakers with cold tap water (1000 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 C

DOSAGE TEST PROCEDURES

DOSAGE TEST PROCEDURES

Equipment

1- Magnetic Stirrer (20 to 150 rpm) and magnets
2- Jar Test Multiple Stirrer
3- Beakers (Min. 1000 mL, all same size and shape)
4- Reagent Rack
5- Pipets
6- Pipet Filler

Pre-Test

1- Fill the beakers with cold tap water (1000 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 D

RESIDUAL CONCENTRATION TESTING PROCEDURES

RESIDUAL TESTING PROCEDURES

Equipment

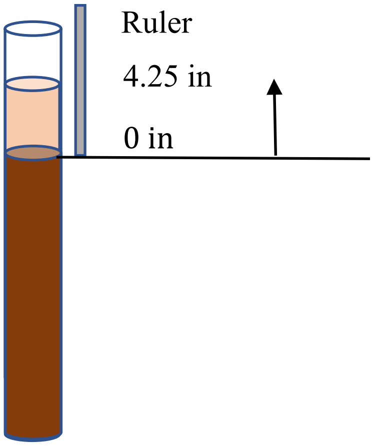
1- Jar Test Multiple Stirrer
2- Beakers (Min. 1000 mL, all same size and shape)
3- Stopwatch
4- Ruler
5- Graduated cylinder

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 E

DOSAGE TEST DATA

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**

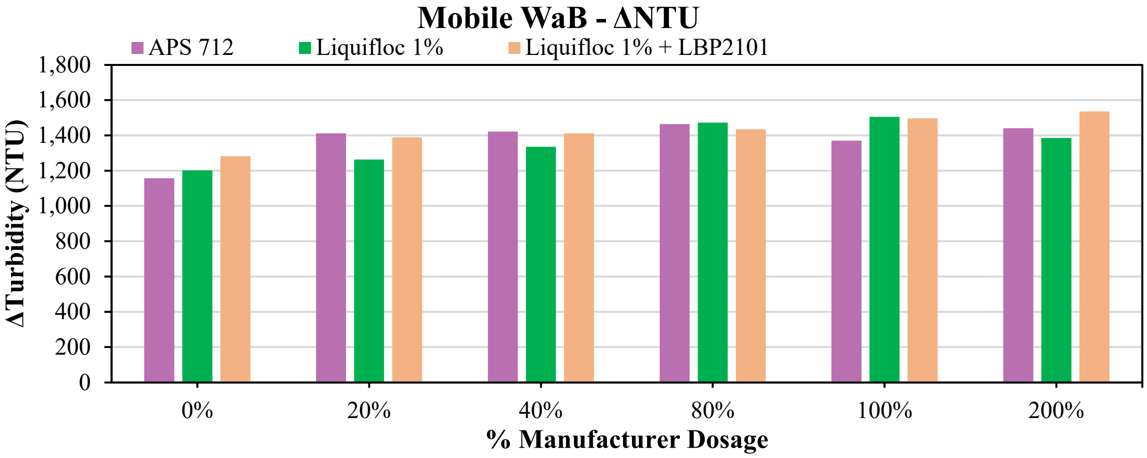
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,157.3	1,411.7	1,421.8	1,463.9	1,370.1	1,440.4
ΔpH	0.09	0.04	0.03	0.04	0.04	0.05
ΔTemperature	0.7	0.1	0.1	0.1	0.0	0.1
ΔColor	2	3	3	3	3	3

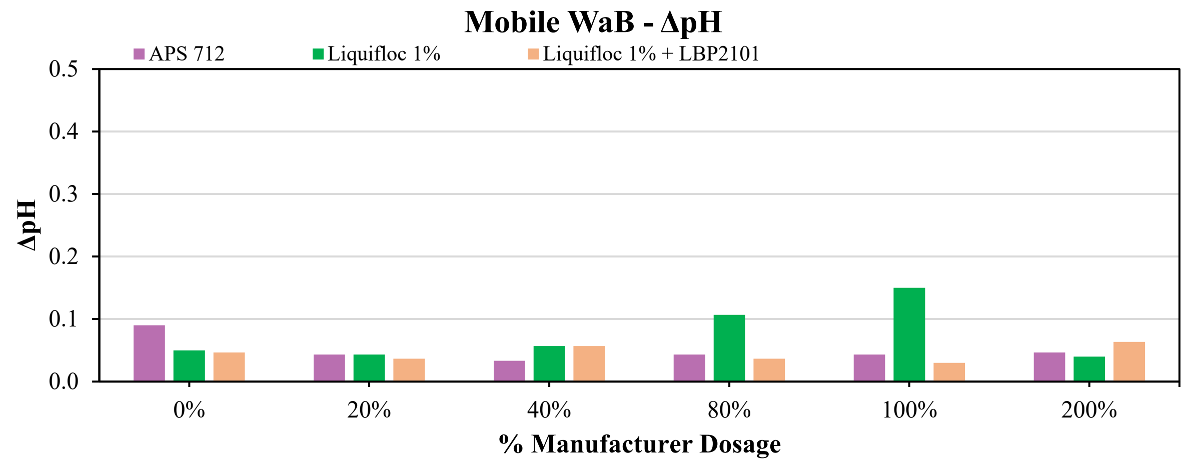
Product: **Liquifloc 1%**

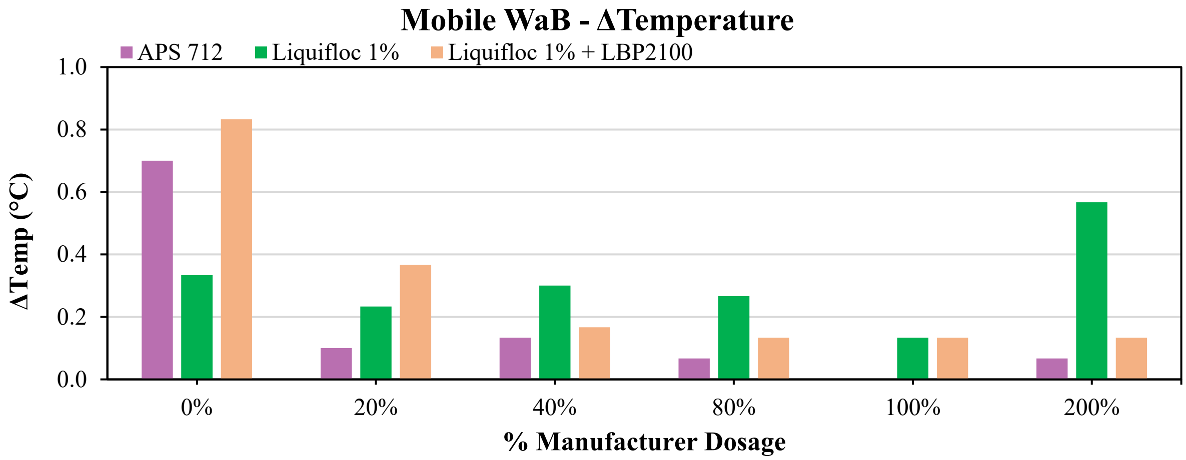
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,201.0	1,263.3	1,335.8	1,472.5	1,504.9	1,385.5
ΔpH	0.05	0.04	0.06	0.11	0.15	0.04
ΔTemperature	0.3	0.2	0.3	0.3	0.1	0.6
ΔColor	1	2	2	4	4	4

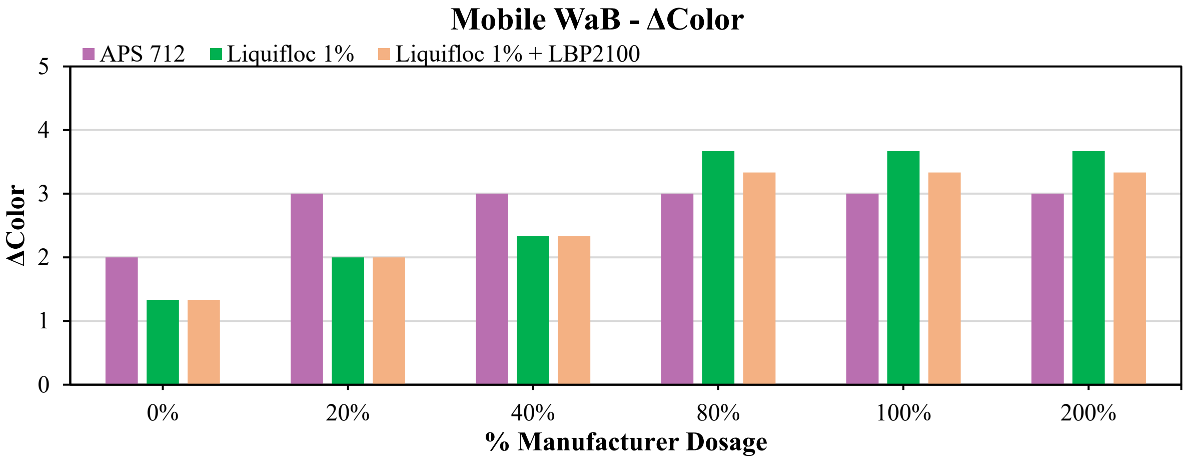
Product: **Liquifloc 1% + LBP 2101**

	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 - ΔpH
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2101
ΔpH
0.0
0.1
0.2
0.3
0.4
0.5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile WaB - ΔTemperature
APS 712
Liquifloc 1%
Liquifloc 1% + LBP2100
ΔTemp (°C)
0.0
0.2
0.4
0.6
0.8
1.0
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**

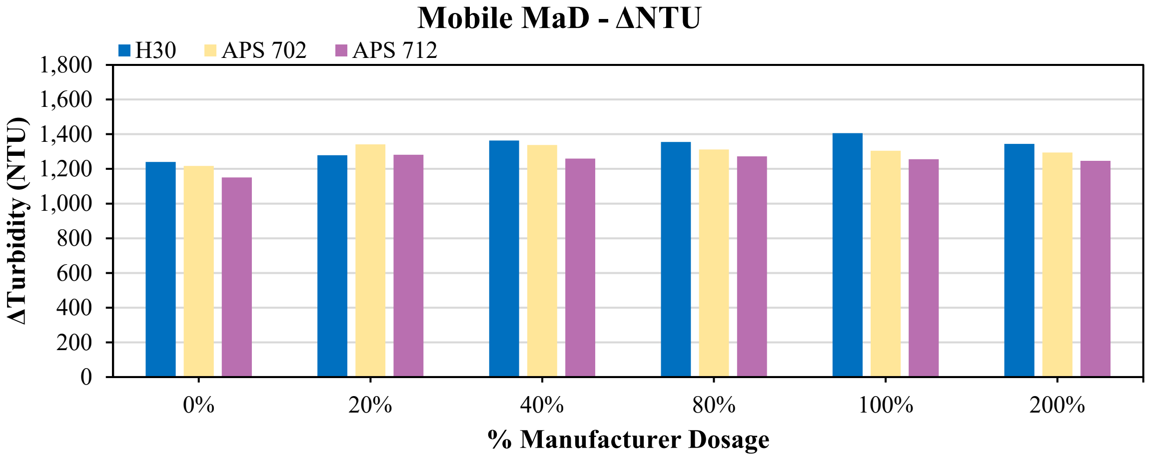
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,240.0	1,278.9	1,363.5	1,355.3	1,405.5	1,344.5
ΔpH	0.04	0.05	0.07	0.08	0.05	0.07
ΔTemperature	0.8	0.1	0.1	0.2	0.2	0.2
ΔColor	1	2	2	2	2	2

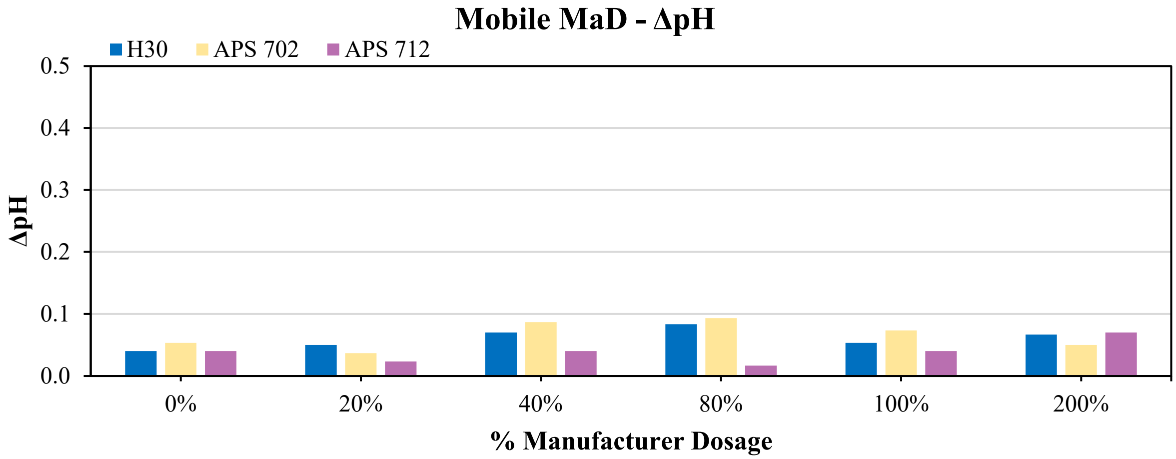
Product: **APS 702**

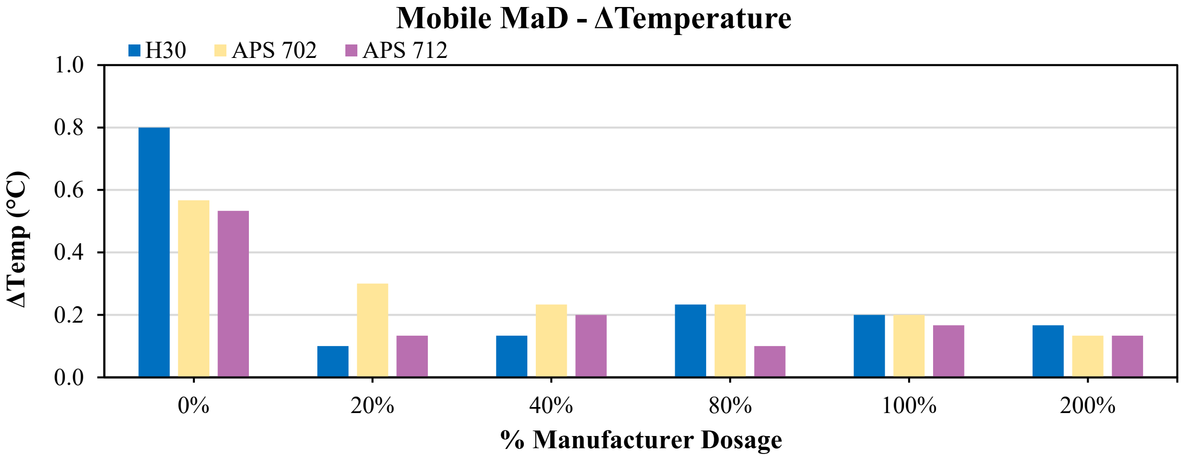
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,217.0	1,341.0	1,337.8	1,312.3	1,304.3	1,294.6
ΔpH	0.05	0.04	0.09	0.09	0.07	0.05
ΔTemperature	0.6	0.3	0.2	0.2	0.2	0.1
ΔColor	1	2	2	2	2	2

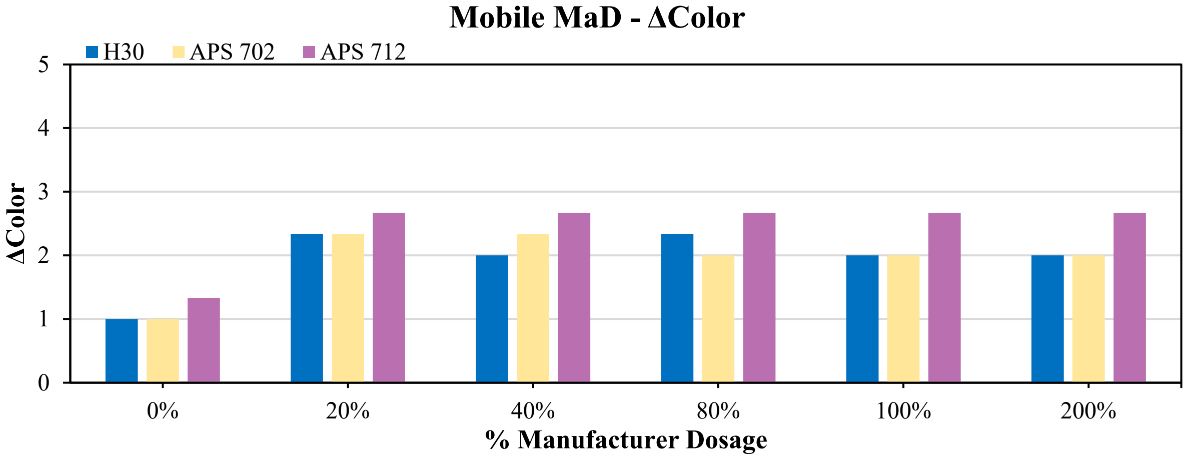
Product: **APS 712**

	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 - ΔpH
■ H30 ■ APS 702 ■ APS 712
ΔpH
0.0
0.1
0.2
0.3
0.4
0.5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile MaD - ΔTemperature
■ H30 ■ APS 702 ■ APS 712
ΔTemp (°C)
0.0
0.2
0.4
0.6
0.8
1.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Mobile MaD - ΔColor
■ H30 ■ APS 702 ■ 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:	**BeB**	**Sampling Location:**	**Mobile, AL**

Product: **H30**

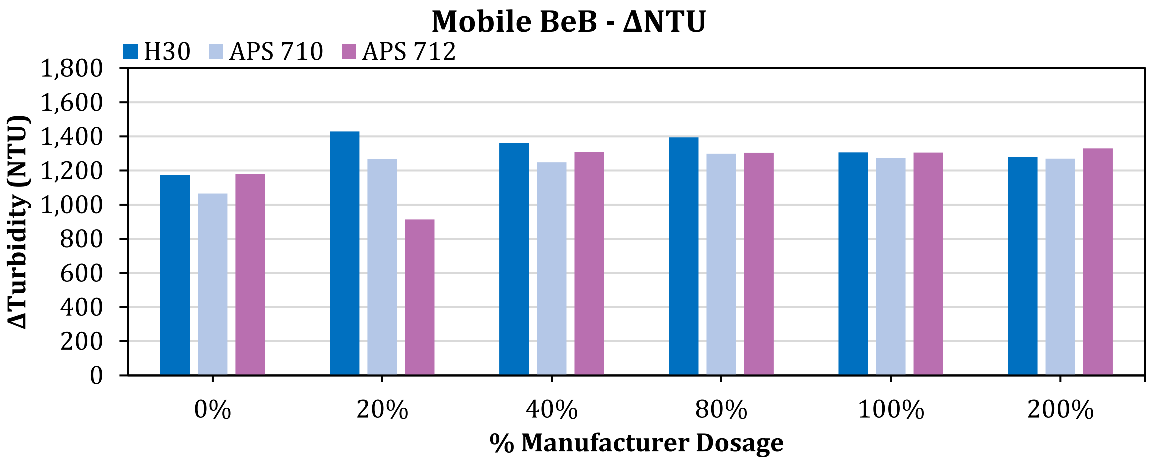
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,172.7	1,428.6	1,362.1	1,394.1	1,306.0	1,278.2
ΔpH	0.02	0.06	0.04	0.05	0.03	0.04
ΔTemperature	0.2	0.2	0.2	0.3	0.1	0.1
ΔColor	1	3	3	3	3	3

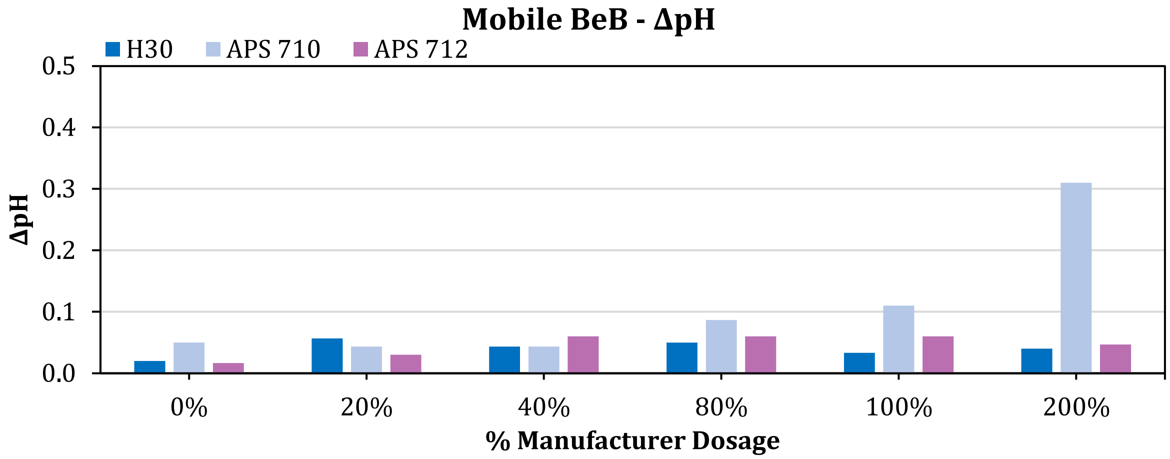
Product: **APS 710**

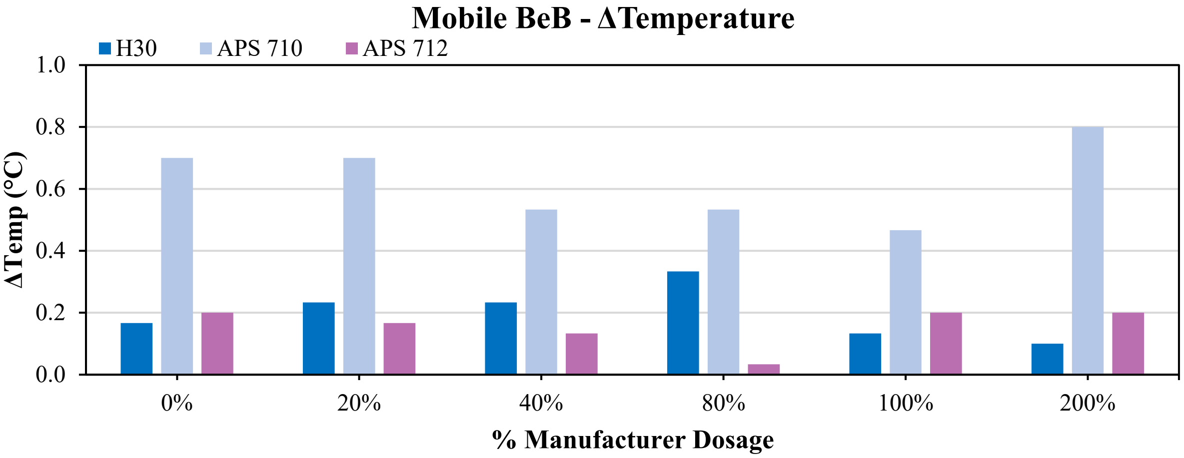
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,065.7	1,267.5	1,248.4	1,299.1	1,273.4	1,269.6
ΔpH	0.05	0.04	0.04	0.09	0.11	0.31
ΔTemperature	0.7	0.7	0.5	0.5	0.5	0.8
ΔColor	1	2	2	2	2	2

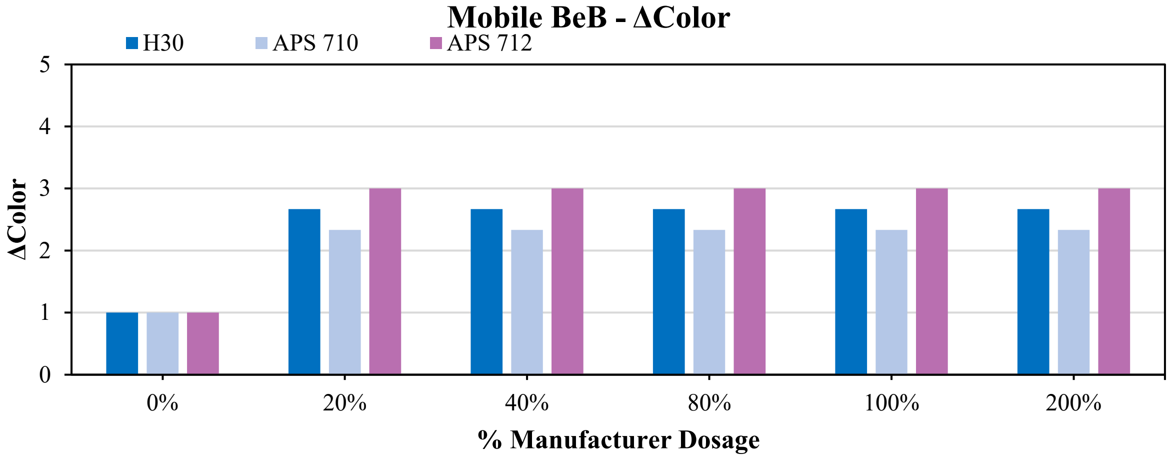
Product: **APS 712**

	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 - 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
ΔColor
5
4
3
2
1
0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage

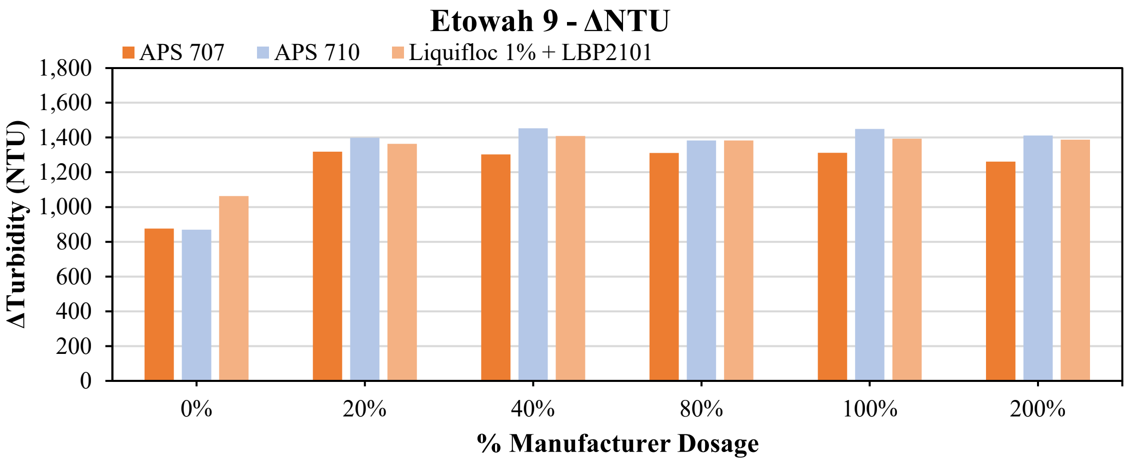
Project: Best Practices for Construction Stormwater Treatment Using Flocculants **Date:** 10/08/2021
Prepared By: Billur Kazaz

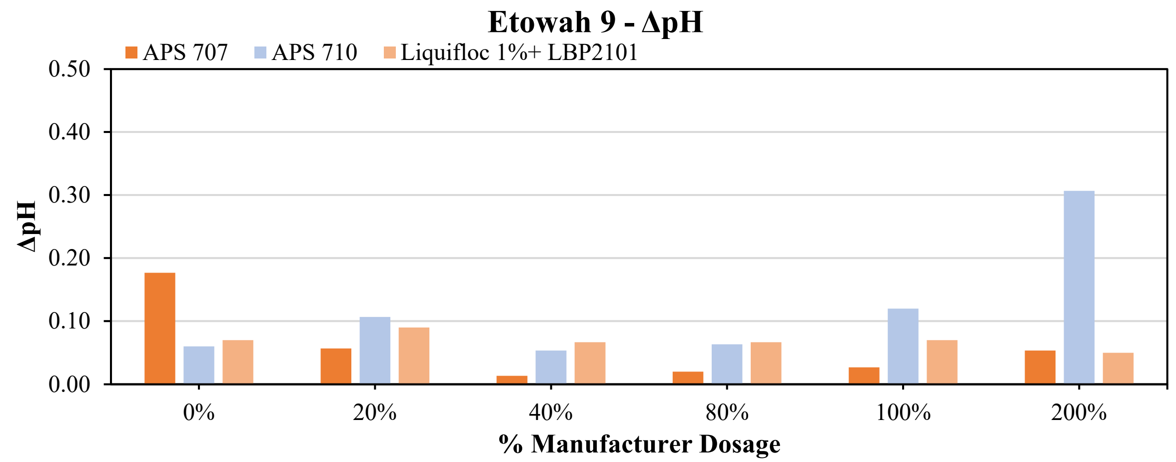
Soil ID:	**9**	**Sampling Location:**	**Etowah, AL**

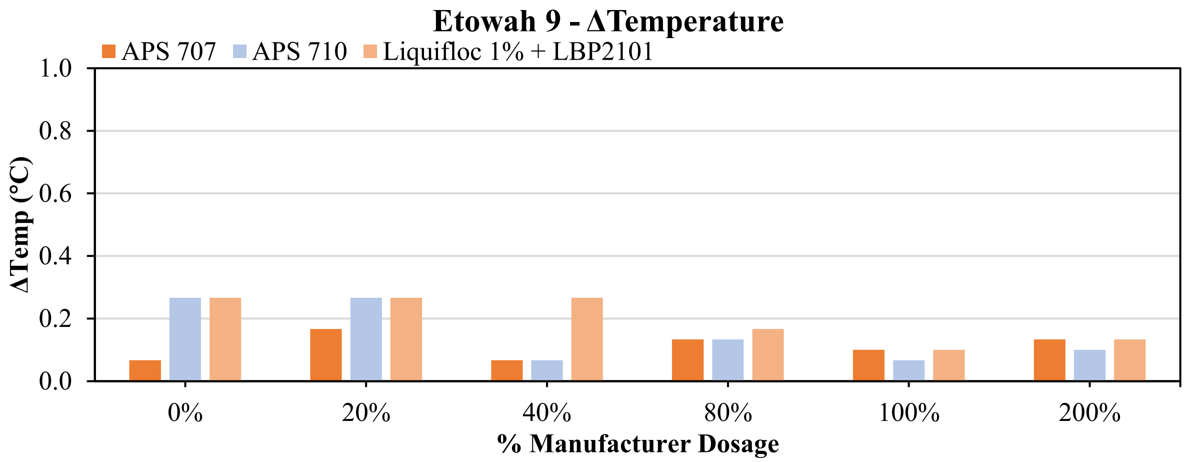
Product:	**APS 707**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	876.0	1,318.7	1,302.6	1,310.7	1,312.0	1,261.5
ΔpH	0.18	0.06	0.01	0.02	0.03	0.05
ΔTemperature	0.1	0.2	0.1	0.1	0.1	0.1
ΔColor	1	3	3	3	3	2

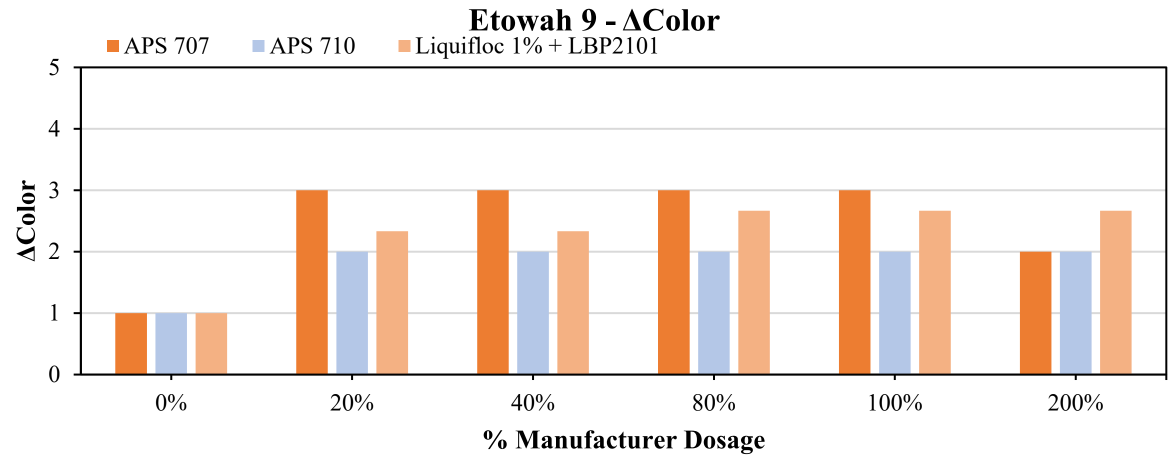
Product:	**APS 710**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	869.7	1,398.9	1,452.8	1,382.5	1,449.3	1,411.6
ΔpH	0.06	0.11	0.05	0.06	0.12	0.31
ΔTemperature	0.3	0.3	0.1	0.1	0.1	0.1
ΔColor	1	2	2	2	2	2

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 - 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
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:	**18**	**Sampling Location:**	**Etowah, AL**

Product: **APS 710**

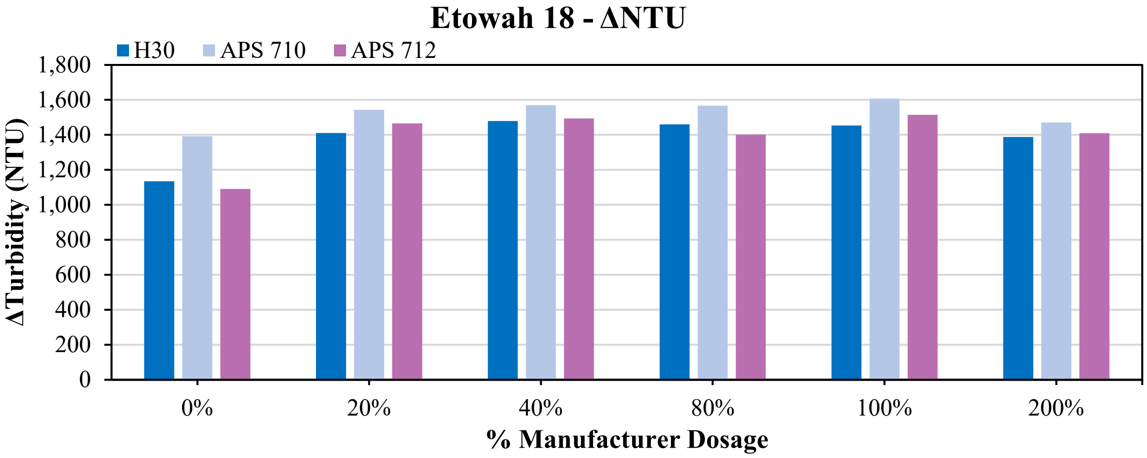
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,391.6	1,542.8	1,568.9	1,566.3	1,606.6	1,470.8
ΔpH	0.16	0.07	0.08	0.12	0.14	0.24
ΔTemperature	0.5	0.1	0.1	0.2	0.1	0.3
ΔColor	1	3	3	3	3	2

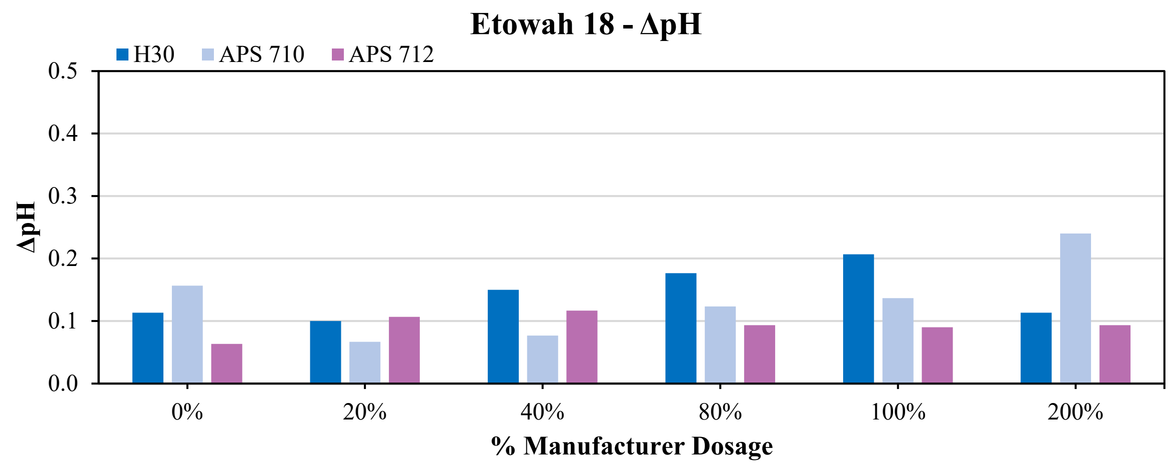
Product: **APS 712**

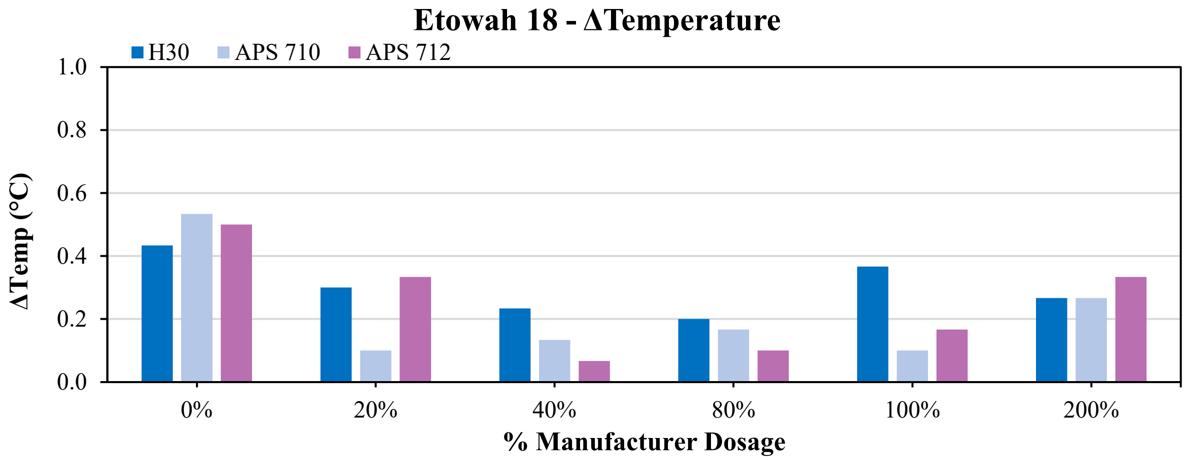
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,090.7	1,464.6	1,493.5	1,400.8	1,514.3	1,409.5
ΔpH	0.06	0.11	0.12	0.09	0.09	0.09
ΔTemperature	0.5	0.3	0.1	0.1	0.2	0.3
ΔColor	1	3	3	3	3	3

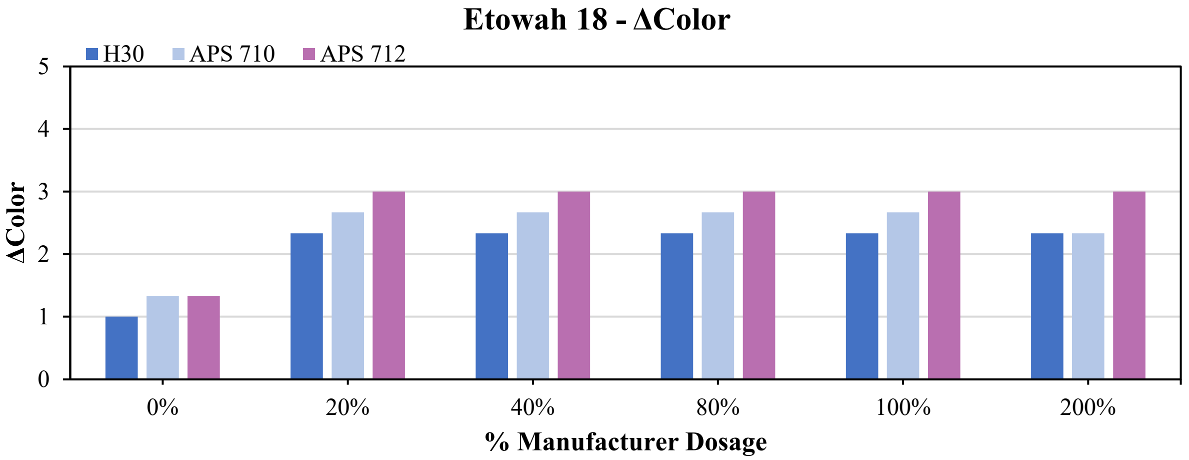
Product: **H30**

	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 - ΔpH
H30
APS 710
APS 712
ΔpH
0.0
0.1
0.2
0.3
0.4
0.5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Etowah 18 - ΔTemperature
H30
APS 710
APS 712
ΔTemp (°C)
0.0
0.2
0.4
0.6
0.8
1.0
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**

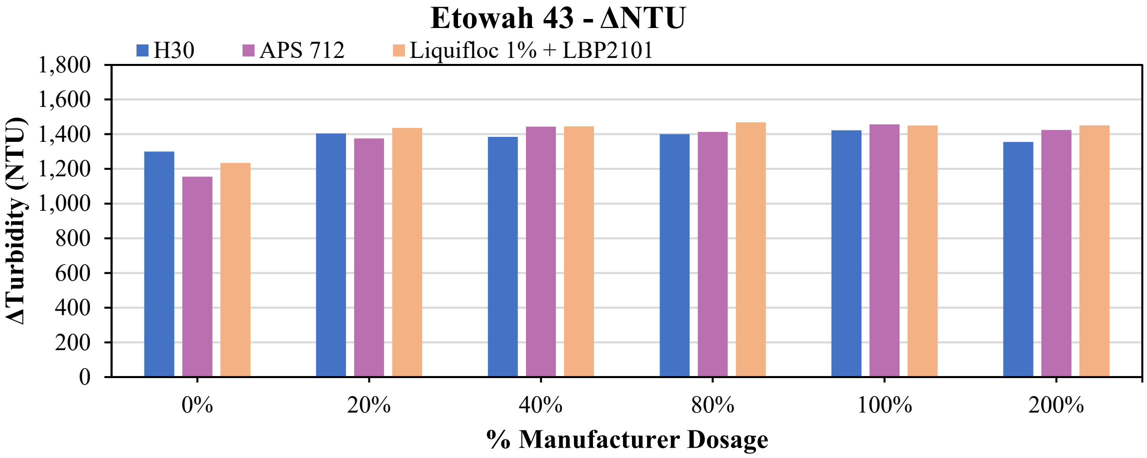
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,300.0	1,403.7	1,385.0	1,400.6	1,422.8	1,355.1
ΔpH	0.09	0.15	0.20	0.21	0.16	0.23
ΔTemperature	0.5	0.4	0.3	0.2	0.2	0.3
ΔColor	1	3	2	2	2	2

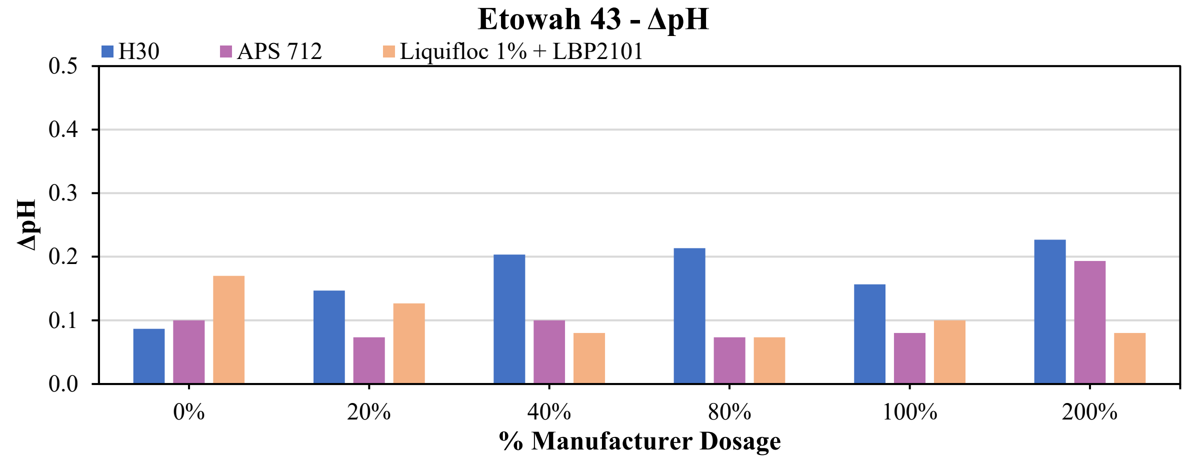
Product: **APS 712**

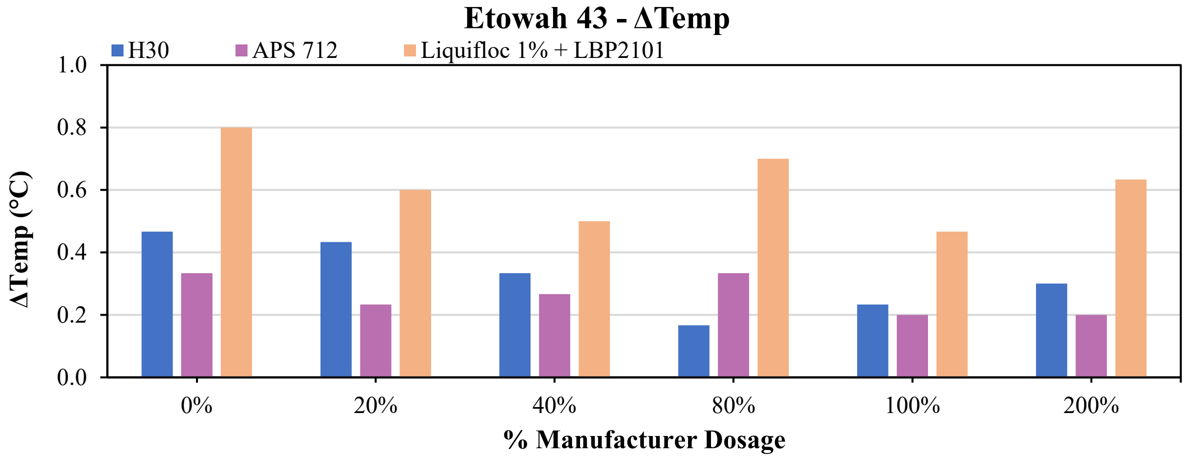
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,155.0	1,375.5	1,444.1	1,413.1	1,456.5	1,424.4
ΔpH	0.10	0.07	0.10	0.07	0.08	0.19
ΔTemperature	0.3	0.2	0.3	0.3	0.2	0.2
ΔColor	1	3	3	3	3	3

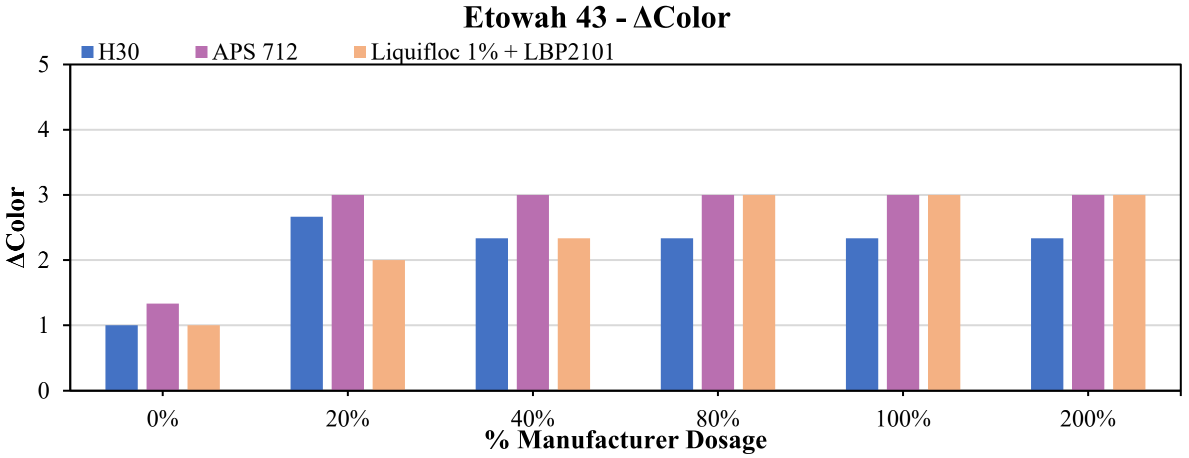
Product: **Liquifloc 1% + LBP 2101**

	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 - 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**

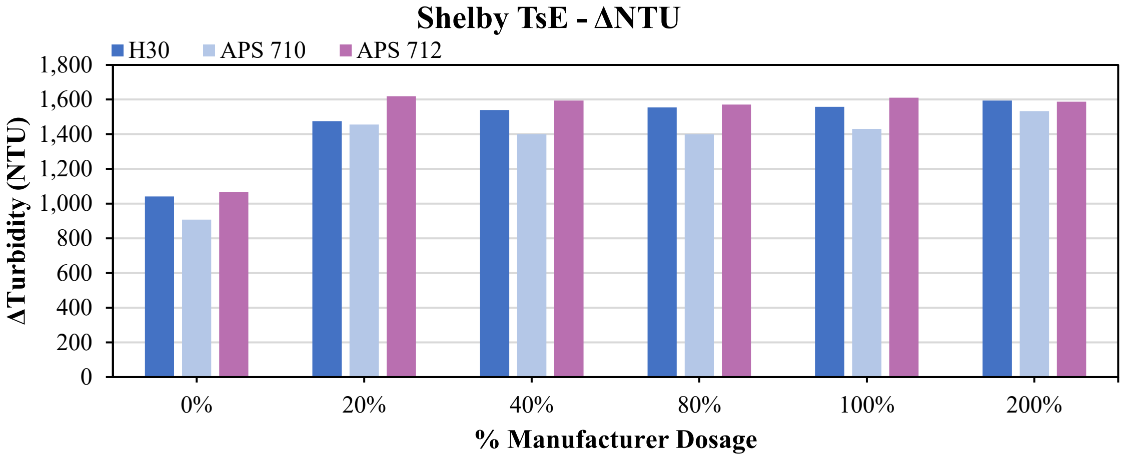
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,041.3	1,475.3	1,539.7	1,553.9	1,558.2	1,593.6
ΔpH	0.05	0.08	0.11	0.09	0.07	0.05
ΔTemperature	0.4	0.1	0.2	0.2	0.2	0.3
ΔColor	1	2	2	2	2	2

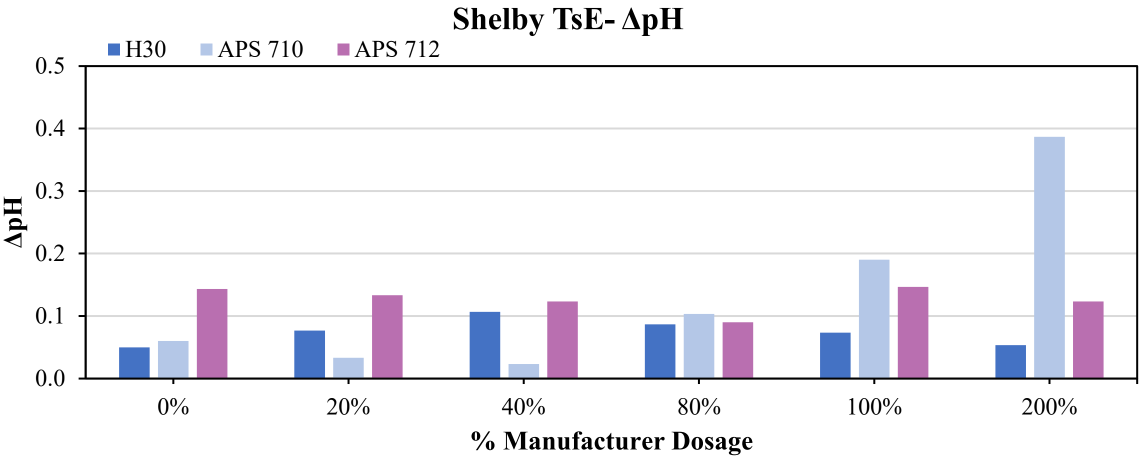
Product: **APS 710**

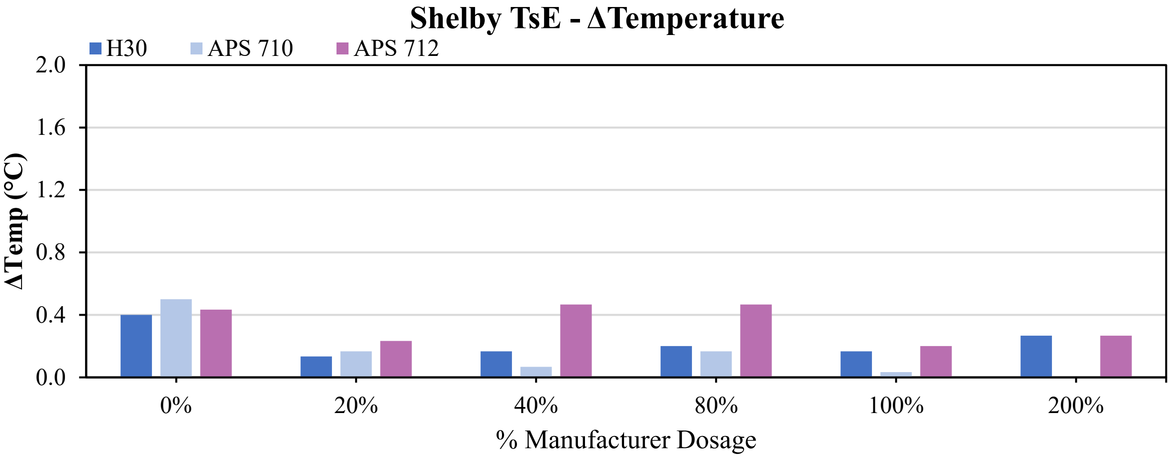
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	907.7	1,455.7	1,400.8	1,399.2	1,430.8	1,532.8
ΔpH	0.06	0.03	0.02	0.10	0.19	0.39
ΔTemperature	0.5	0.2	0.1	0.2	0.0	0.0
ΔColor	1	2	2	2	2	2

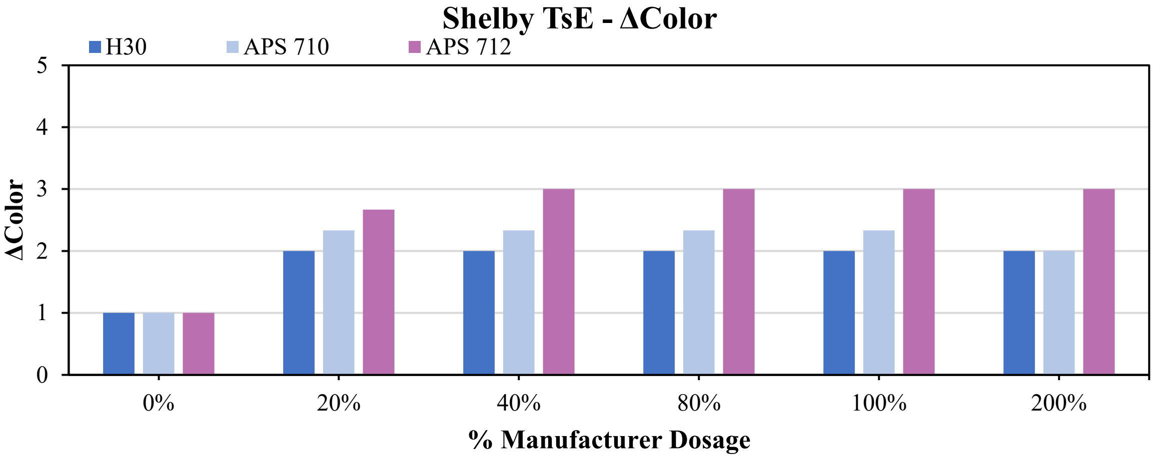
Product: **APS 712**

	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- 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
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:	**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**

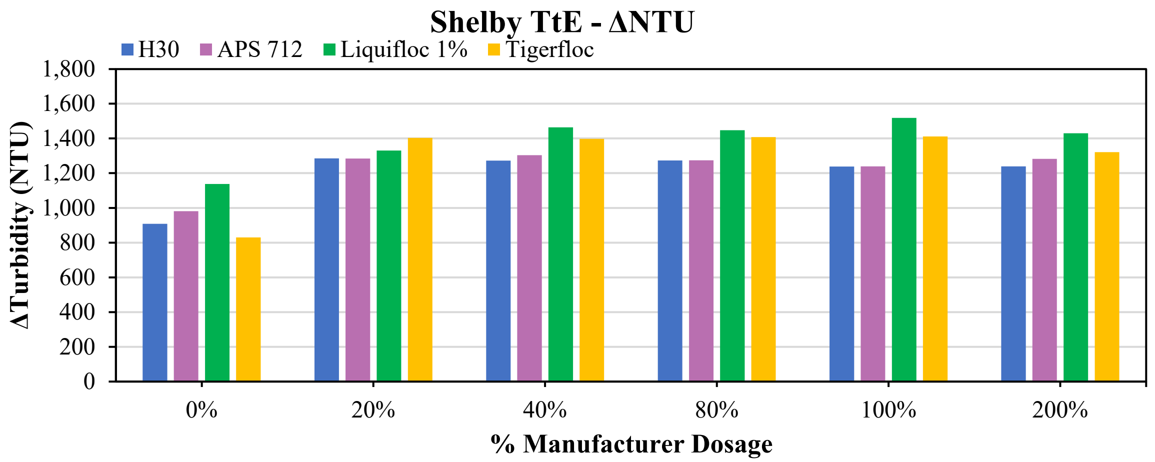
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	981.3	1,284.2	1,303.4	1,273.8	1,239.4	1,282.4
ΔpH	0.06	0.07	0.06	0.08	0.10	0.07
ΔTemperature	0.2	0.2	0.1	0.2	0.1	0.0
ΔColor	1	3	3	3	3	3

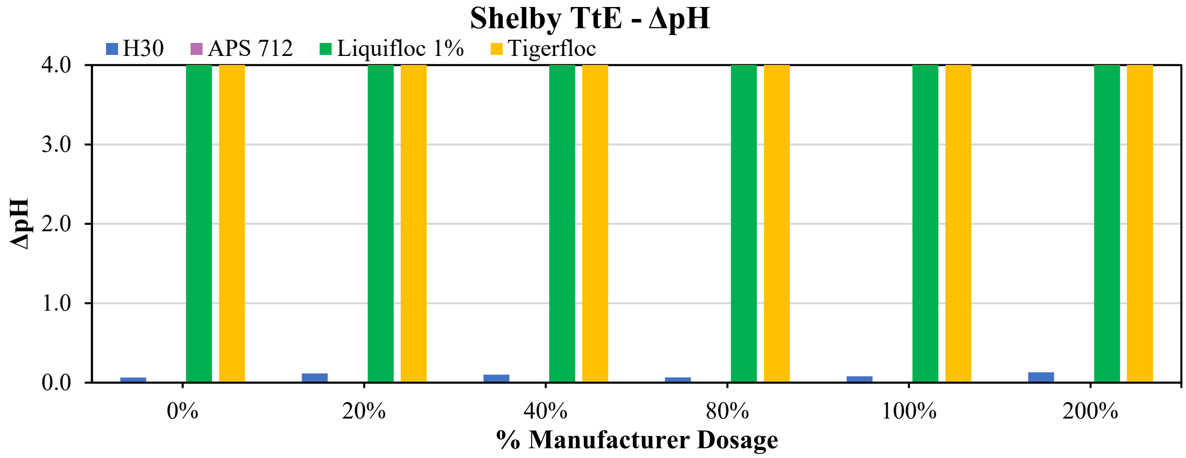
Product: **Liquifloc 1%**

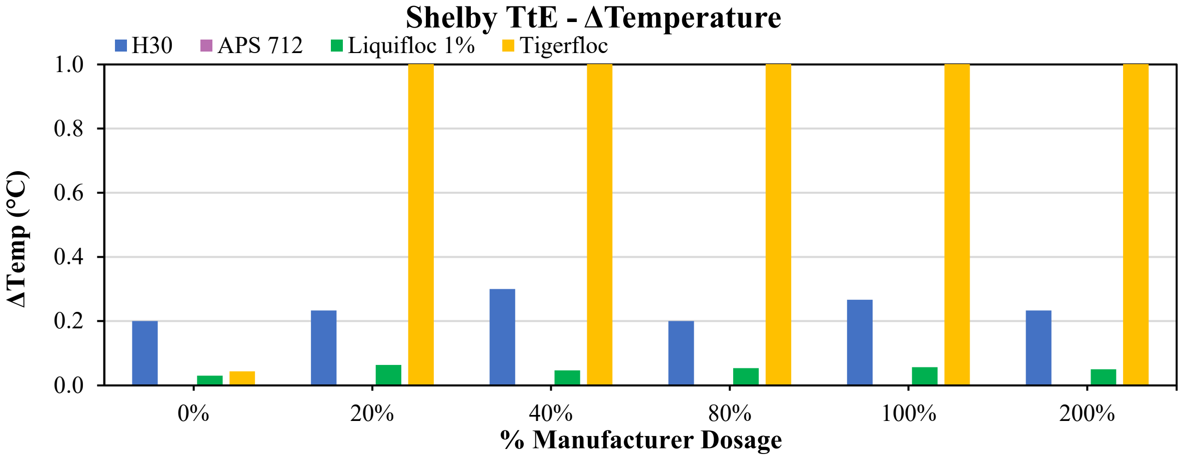
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	20	40	80	100	200
ΔNTU	1,138.0	1,330.4	1,463.7	1,447.3	1,518.3	1,429.5
ΔpH	0.03	0.06	0.05	0.05	0.06	0.05
ΔTemperature	0.1	0.1	0.1	0.3	0.2	0.3
ΔColor	1	2	2	3	3	3

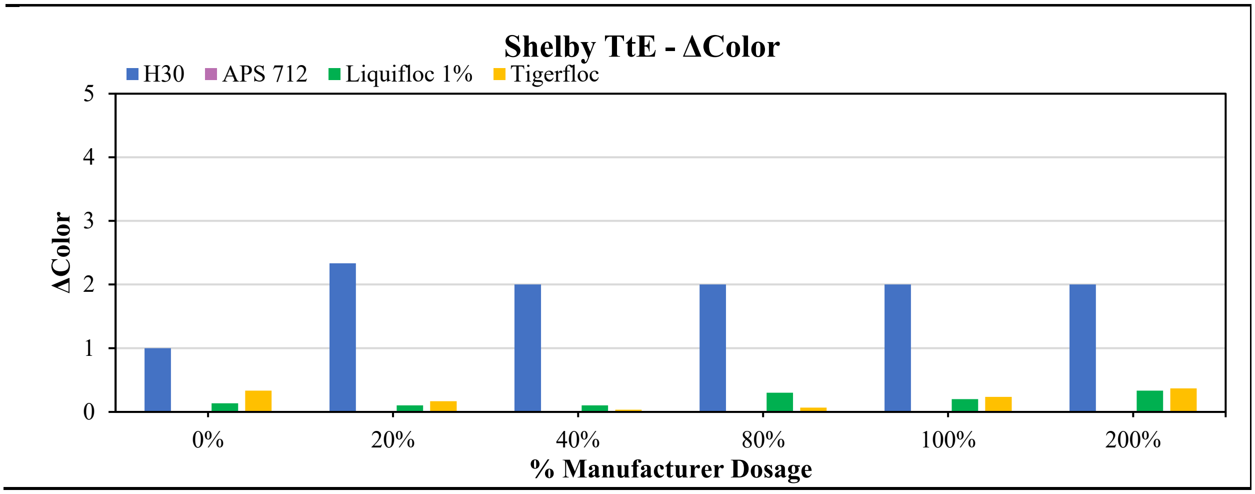
Product: **Tigerfloc**

	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 - ΔNTU
H30
APS 712
Liquifloc 1%
Tigerfloc
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 TtE - ΔpH
H30
APS 712
Liquifloc 1%
Tigerfloc
ΔpH
4.0
3.0
2.0
1.0
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Shelby TtE - ΔTemperature
H30
APS 712
Liquifloc 1%
Tigerfloc
ΔTemp (°C)
1.0
0.8
0.6
0.4
0.2
0.0
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


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**

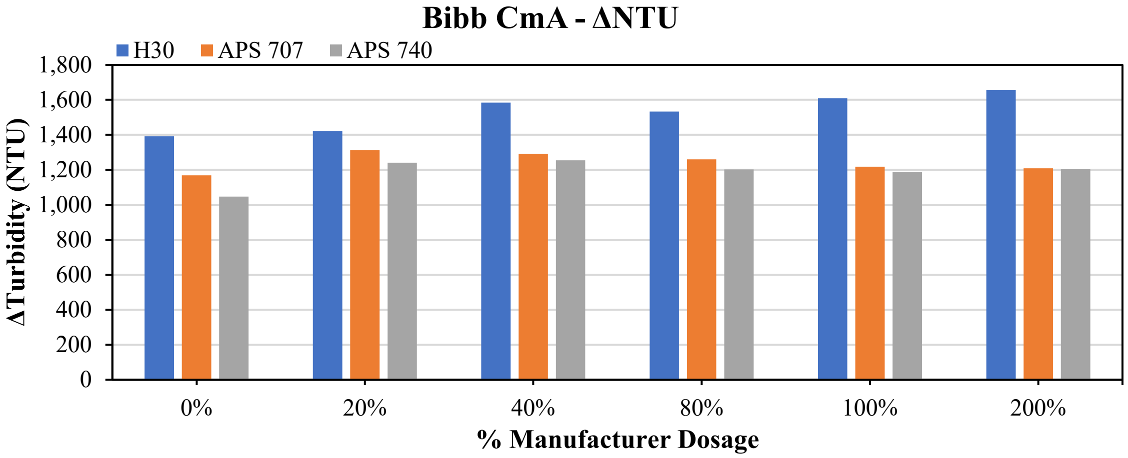
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,391.7	1,422.4	1,584.1	1,532.2	1,609.6	1,656.6
ΔpH	0.15	0.13	0.16	0.12	0.11	0.15
ΔTemperature	0.5	0.5	0.4	0.4	0.5	0.5
ΔColor	1	2	2	2	2	2

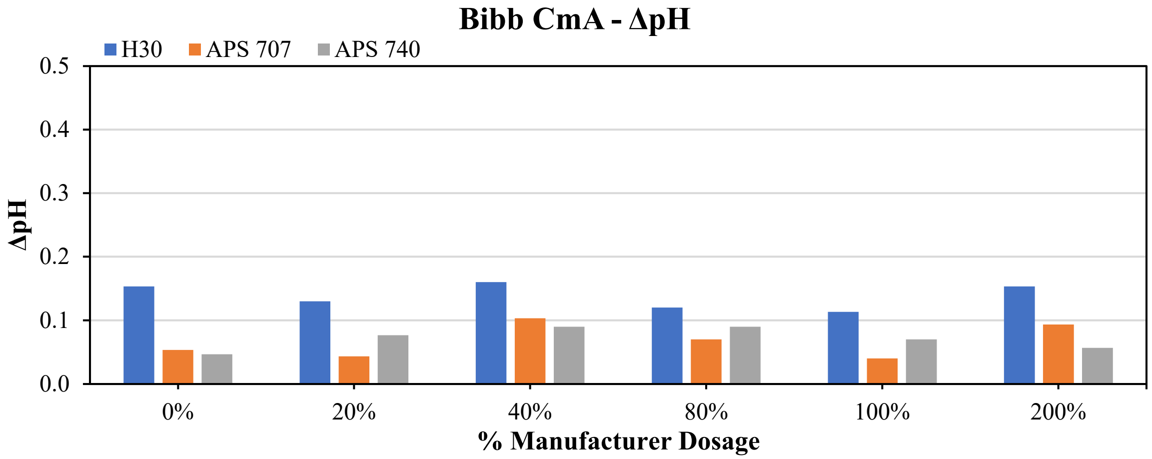
Product: **APS 707**

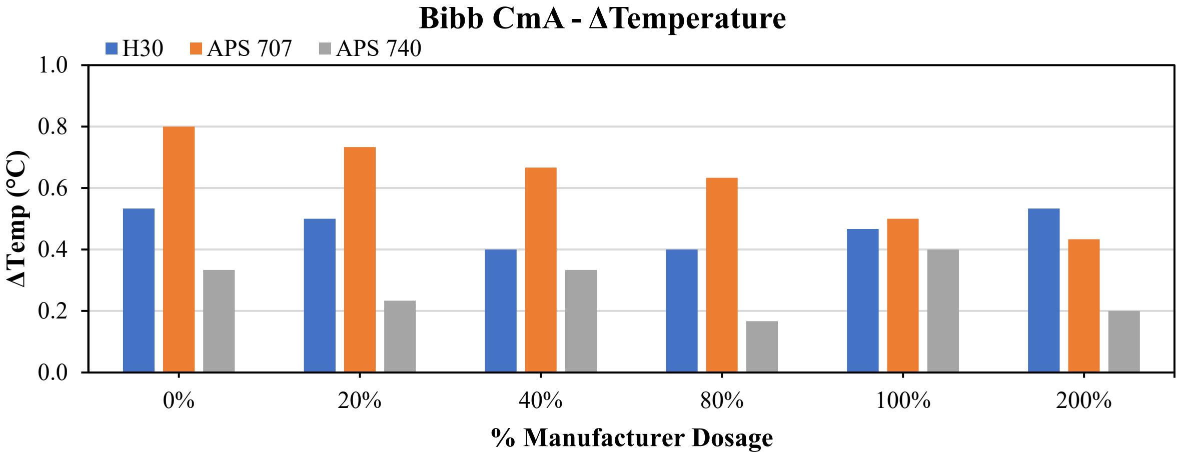
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,168.4	1,313.6	1,291.1	1,259.2	1,217.1	1,208.4
ΔpH	0.05	0.04	0.10	0.07	0.04	0.09
ΔTemperature	0.8	0.7	0.7	0.6	0.5	0.4
ΔColor	1	3	3	2	2	2

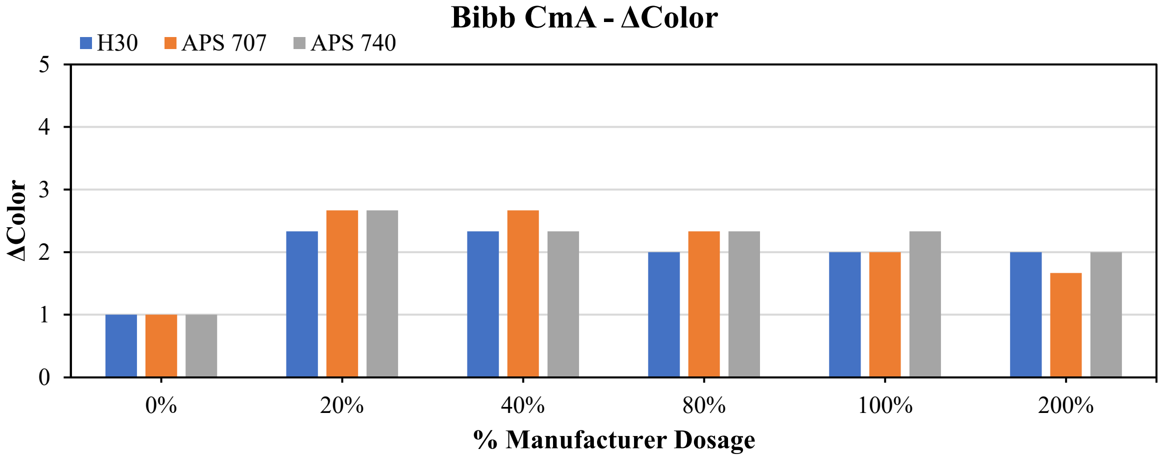
Product: **APS 740**

	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 - ΔpH
H30
APS 707
APS 740
0.5
0.4
0.3
0.2
0.1
0.0
ΔpH
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb CmA - ΔTemperature
H30
APS 707
APS 740
1.0
0.8
0.6
0.4
0.2
0.0
ΔTemp (°C)
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Bibb CmA - ΔColor
H30
APS 707
APS 740
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:	**MIA**	**Sampling Location:**	**Bibb, AL**

Product: **H30**

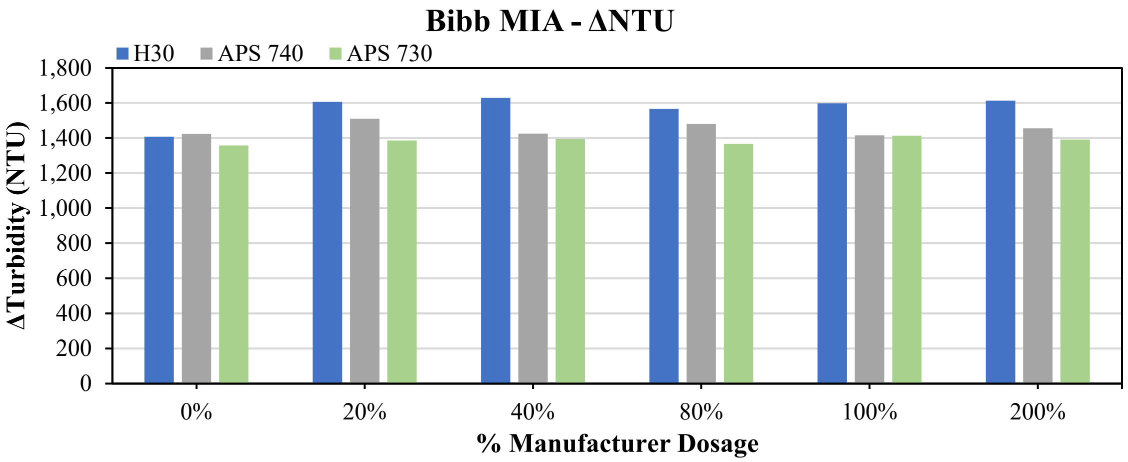
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,408.5	1,606.5	1,628.9	1,566.7	1,598.1	1,613.8
ΔpH	0.29	0.46	0.37	0.37	0.26	0.24
ΔTemperature	0.3	0.5	0.1	0.1	0.1	0.1
ΔColor	2	3	3	3	3	3

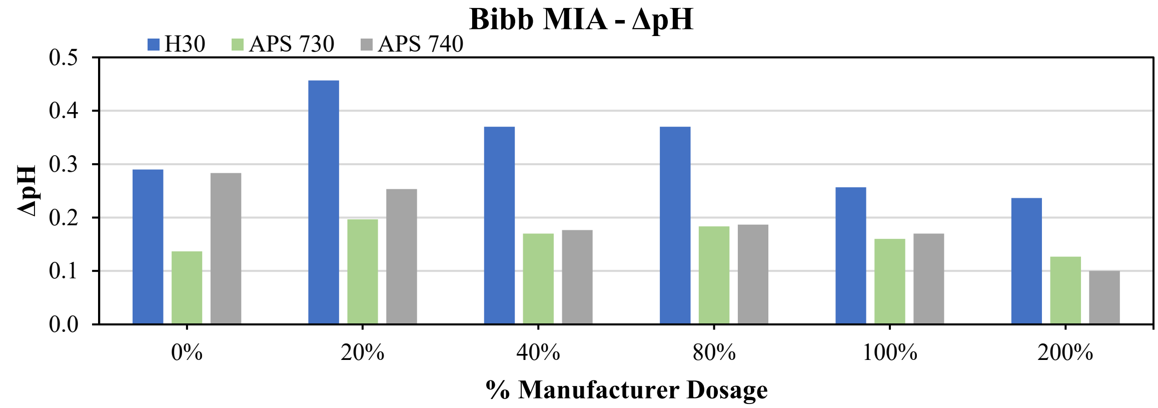
Product: **APS 730**

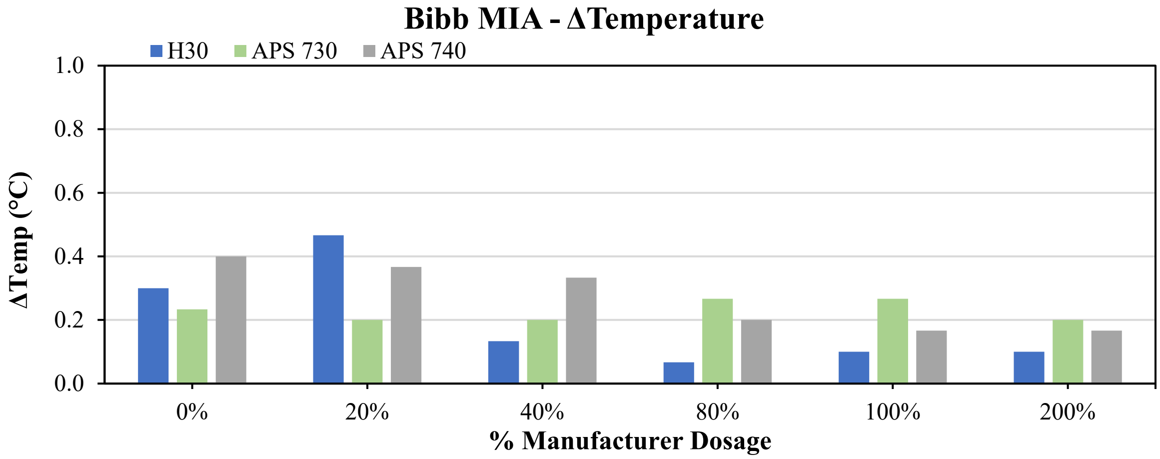
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,358.4	1,386.8	1,394.6	1,366.1	1,413.5	1,392.3
ΔpH	0.14	0.20	0.17	0.18	0.16	0.13
ΔTemperature	0.2	0.2	0.2	0.3	0.3	0.2
ΔColor	1	3	3	3	3	3

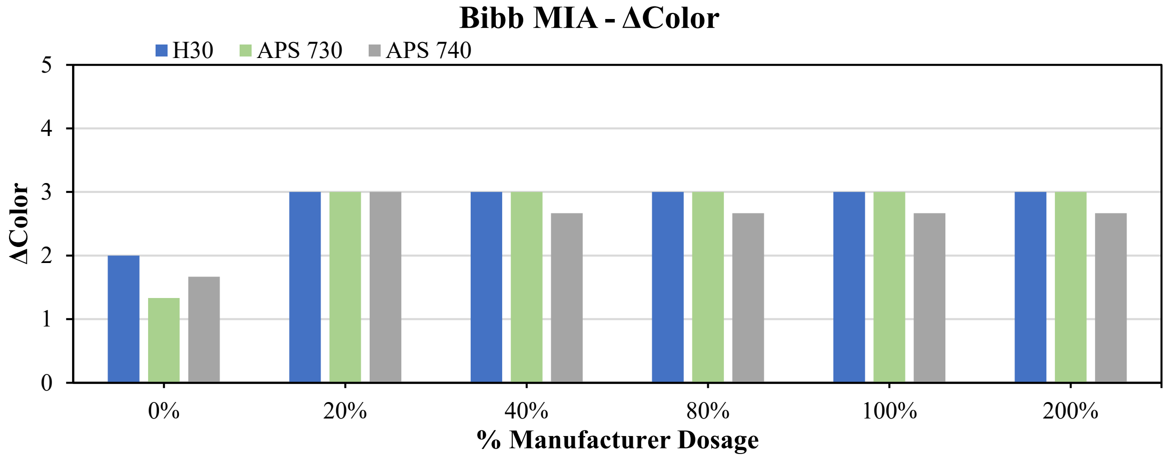
Product: **APS 740**

	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 - 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
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:	**IdB**	**Sampling Location:**	**Montgomery, AL**

Product: **H30**

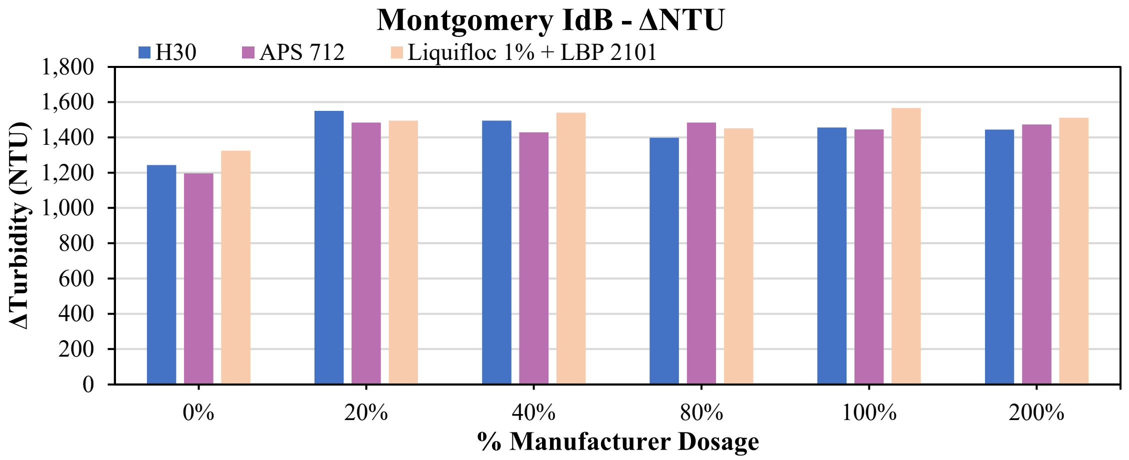
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,242.7	1,549.9	1,495.3	1,398.0	1,456.3	1,444.5
ΔpH	0.10	0.12	0.11	0.13	0.12	0.08
ΔTemperature	0.5	0.5	0.4	0.3	0.4	0.4
ΔColor	1	3	3	3	2	2

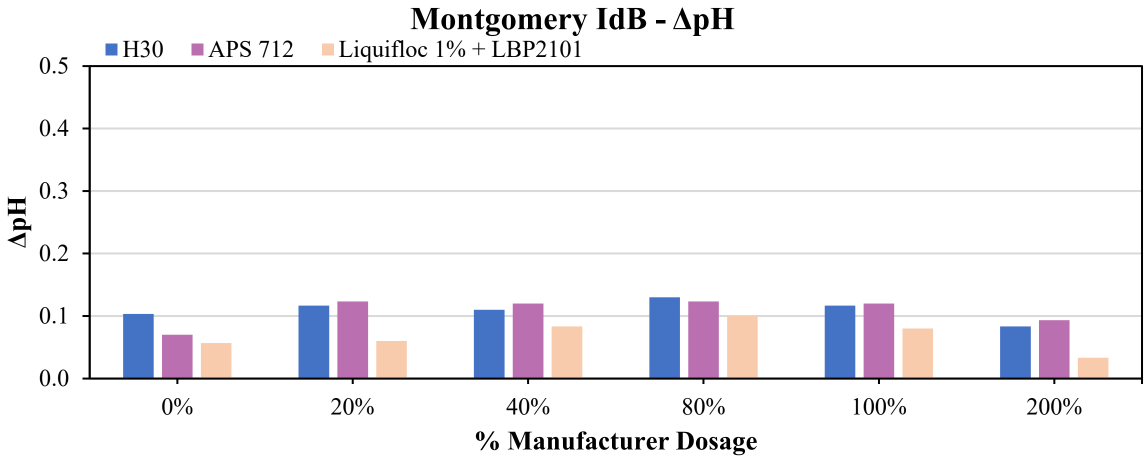
Product: **APS 712**

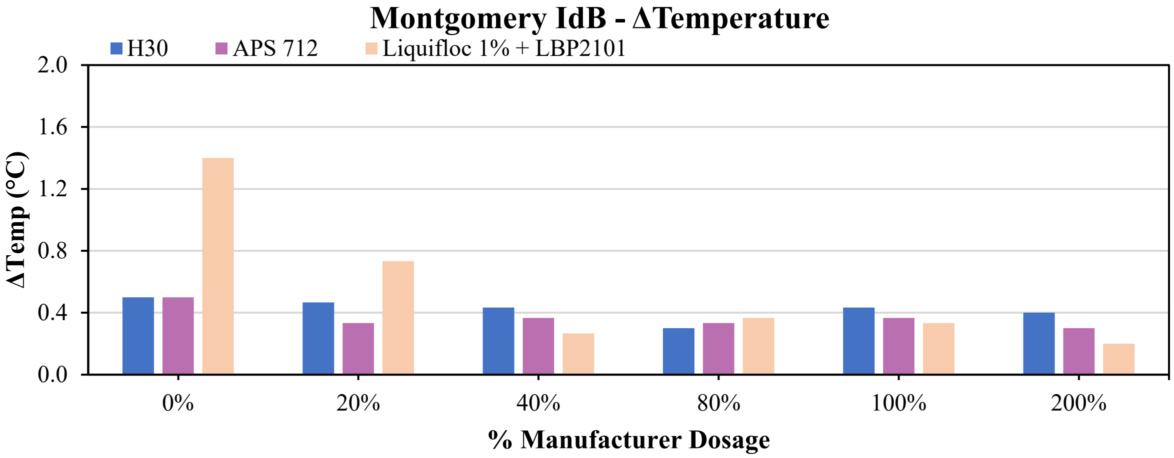
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,196.3	1,484.1	1,428.4	1,483.7	1,445.4	1,473.3
ΔpH	0.07	0.12	0.12	0.12	0.12	0.09
ΔTemperature	0.5	0.3	0.4	0.3	0.4	0.3
ΔColor	1	3	3	3	3	3

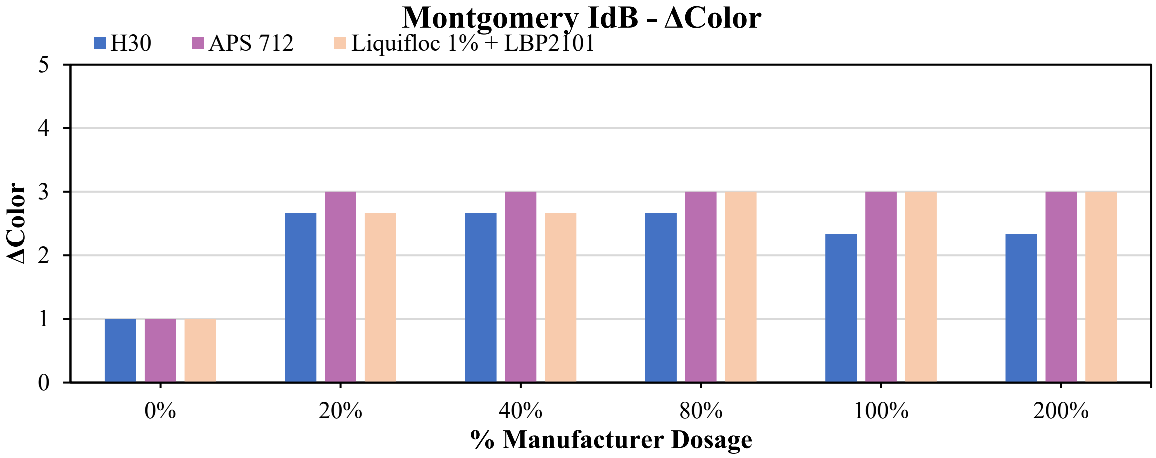
Product: **Liquifloc 1% + LBP 2101**

	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 - ΔpH
H30
APS 712
Liquifloc 1% + LBP2101
ΔpH
0.0
0.1
0.2
0.3
0.4
0.5
0%
20%
40%
80%
100%
200%
% Manufacturer Dosage


Montgomery IdB - ΔTemperature
H30
APS 712
Liquifloc 1% + LBP2101
ΔTemp (°C)
0.0
0.4
0.8
1.2
1.6
2.0
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**

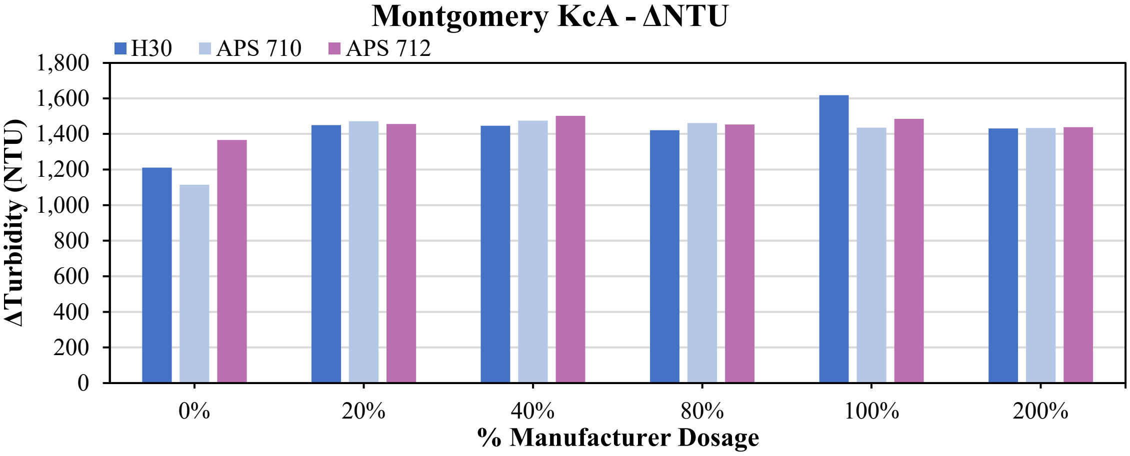
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1,210.7	1,449.7	1,445.9	1,421.4	1,617.6	1,430.5
ΔpH	0.05	0.07	0.09	0.08	0.08	0.09
ΔTemperature	0.2	0.1	0.1	0.0	0.1	0.1
ΔColor	1	3	3	3	3	3

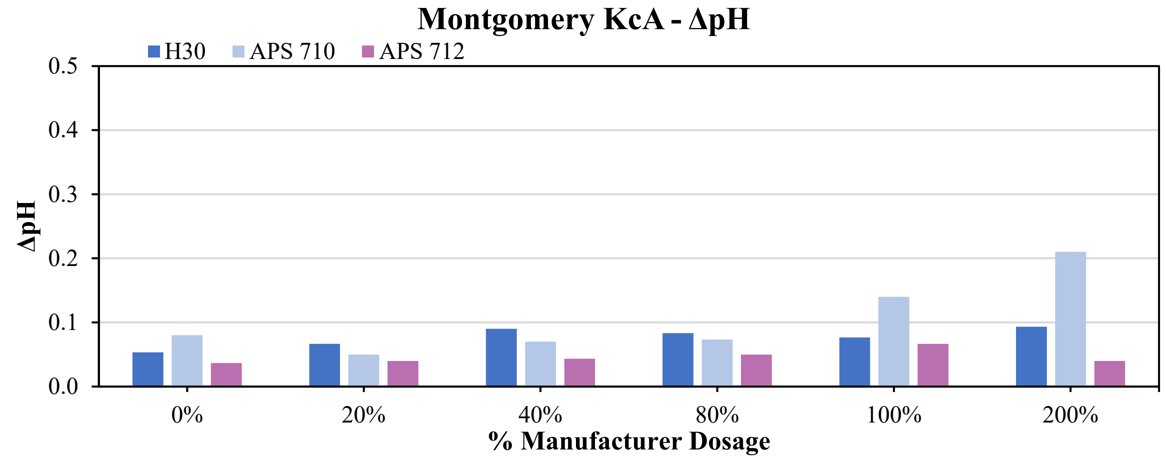
Product: **APS 710**

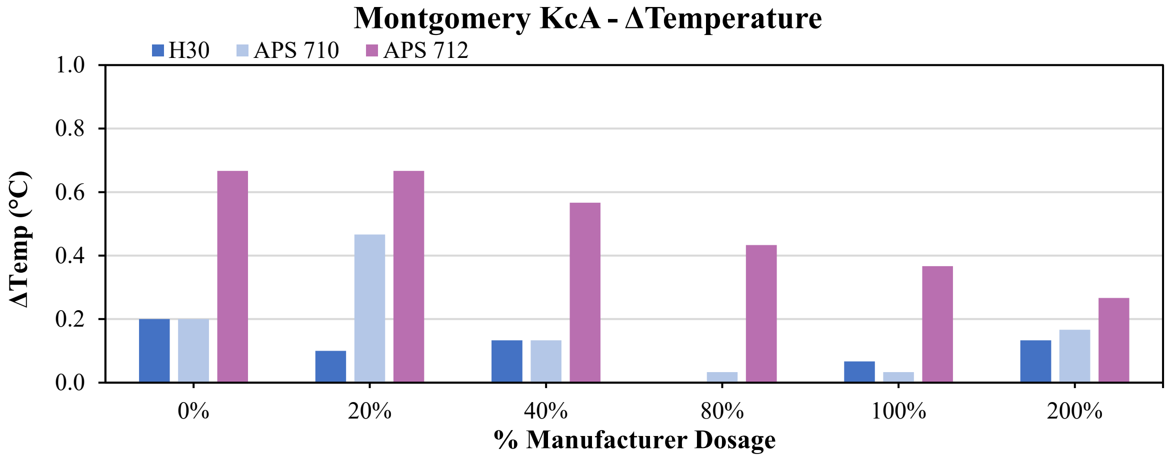
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1,114.7	1,471.3	1,474.7	1,461.2	1,435.7	1,434.1
ΔpH	0.08	0.05	0.07	0.07	0.14	0.21
ΔTemperature	0.2	0.5	0.1	0.0	0.0	0.2
ΔColor	1	3	3	3	3	2

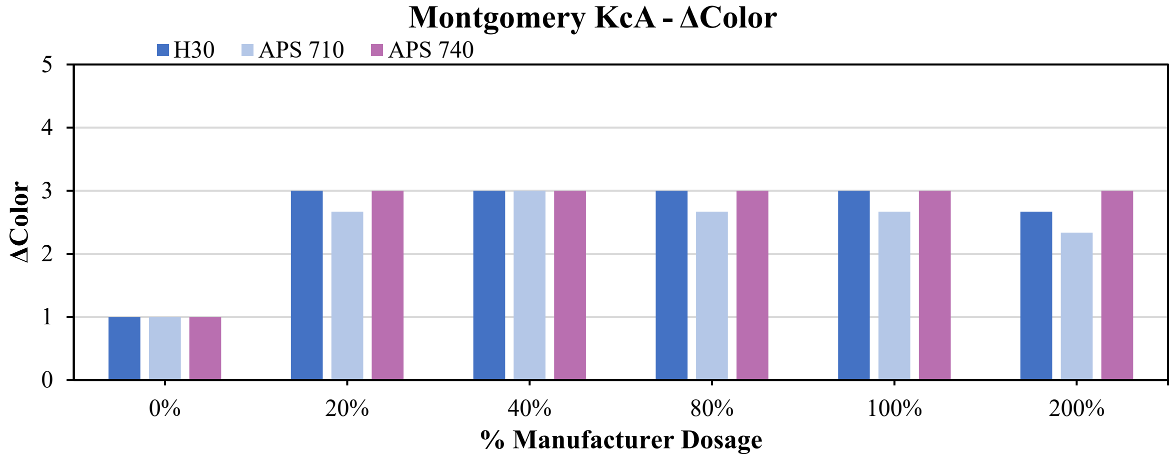
Product: **APS 712**

	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 - 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
5
4
3
2
1
0
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**

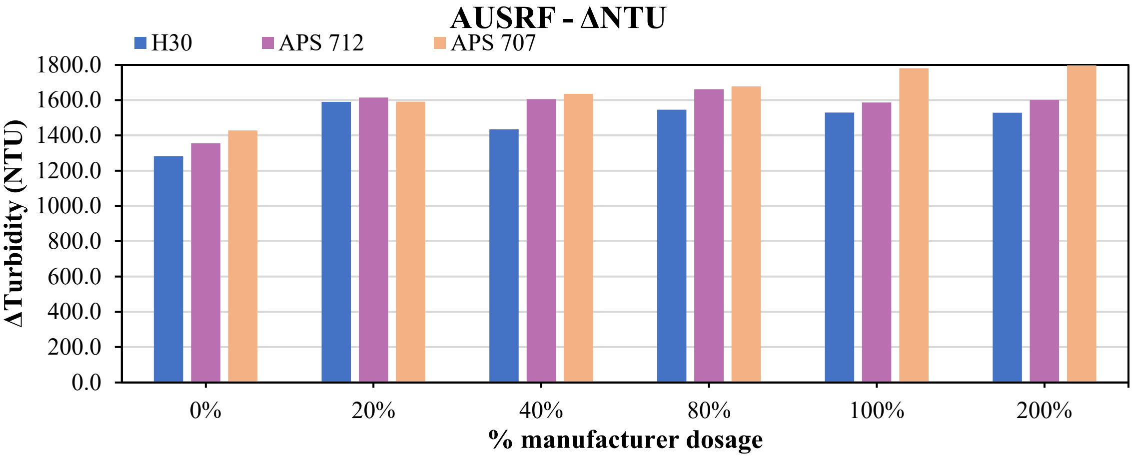
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1281.7	1589.8	1434.2	1546.0	1529.1	1528.8
ΔpH	0.49	0.09	0.07	0.10	0.15	0.54
ΔTemperature	0.8	0.8	0.8	0.8	1.3	1.8
ΔColor	1	3	3	3	3	3

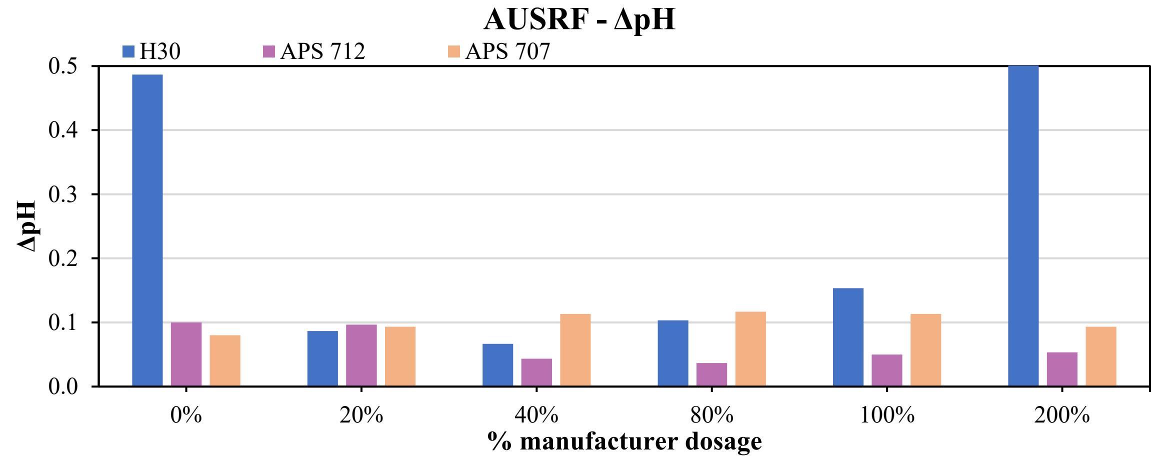
Product: **APS 712**

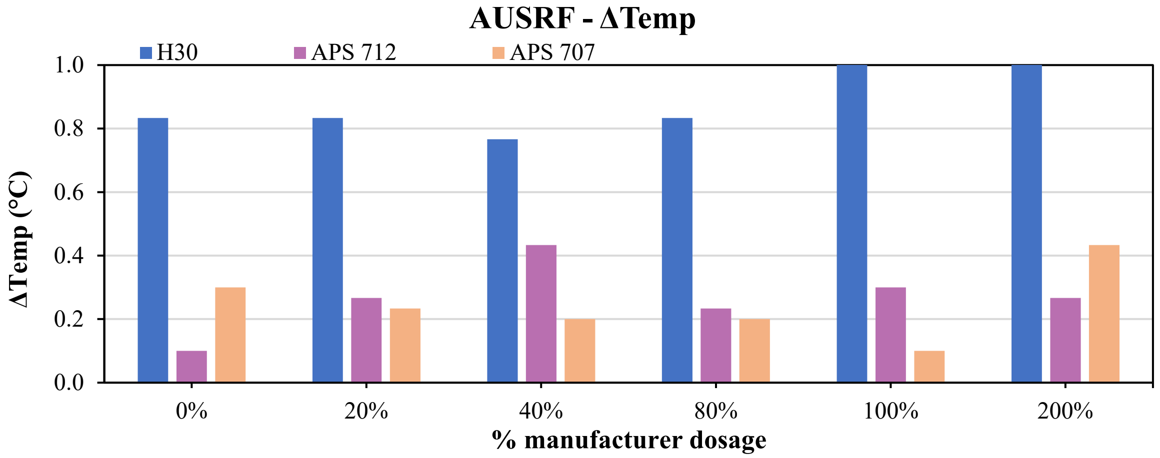
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1355.0	1614.3	1605.1	1661.5	1586.4	1600.6
ΔpH	0.10	0.10	0.04	0.04	0.05	0.05
ΔTemperature	0.1	0.3	0.4	0.2	0.3	0.3
ΔColor	1	3	3	3	3	3

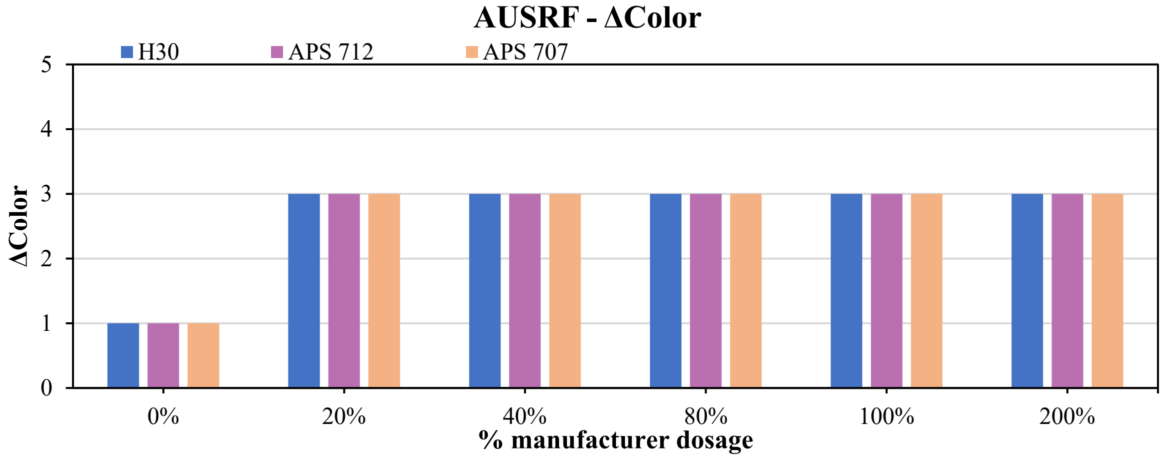
Product: **APS 712**

	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 - ΔpH
H30
APS 712
APS 707
ΔpH
0.0
0.1
0.2
0.3
0.4
0.5
0%
20%
40%
80%
100%
200%
% manufacturer dosage


AUSRF - ΔTemp
H30
APS 712
APS 707
ΔTemp (°C)
0.0
0.2
0.4
0.6
0.8
1.0
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

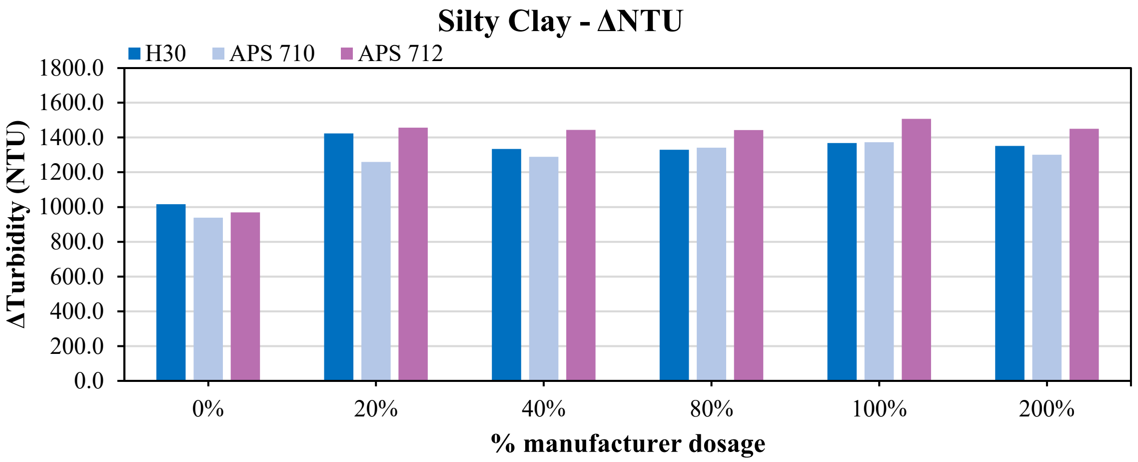
Project: Best Practices for Construction Stormwater Treatment Using Flocculants **Date:** 03/18/2022
Prepared By: Billur Kazaz

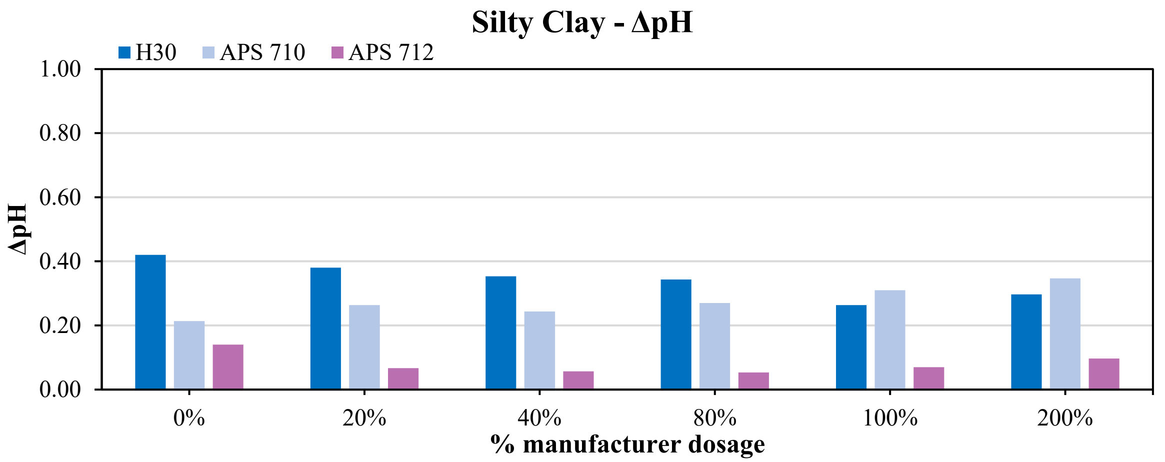
Soil ID:	**Silty Clay**	**Sampling Location:**	**Montgomery, AL**

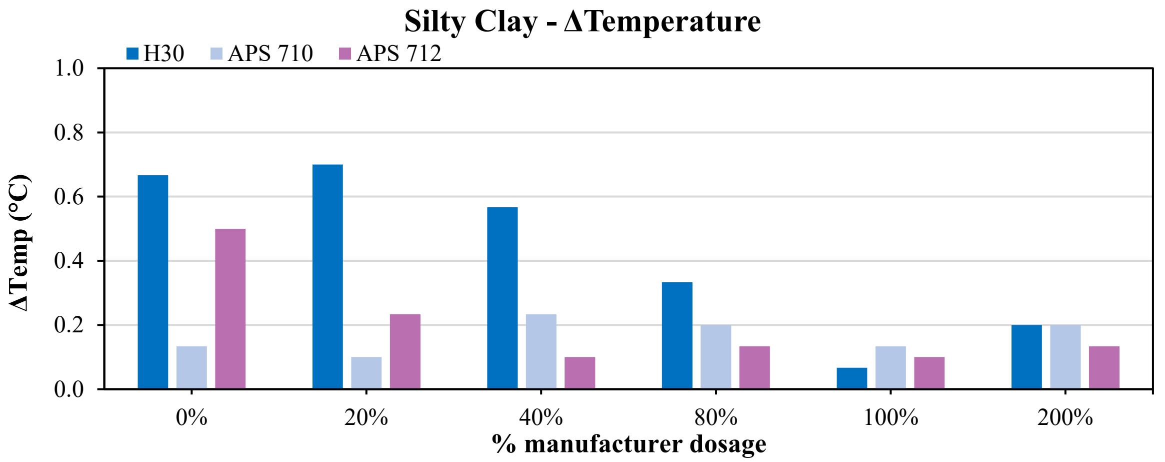
Product:	**H3O**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1016.3	1423.8	1334.4	1329.8	1368.3	1351.5
ΔpH	0.42	0.38	0.35	0.34	0.26	0.30
ΔTemperature	0.7	0.7	0.6	0.3	0.1	0.2
ΔColor	1	2	2	2	2	2

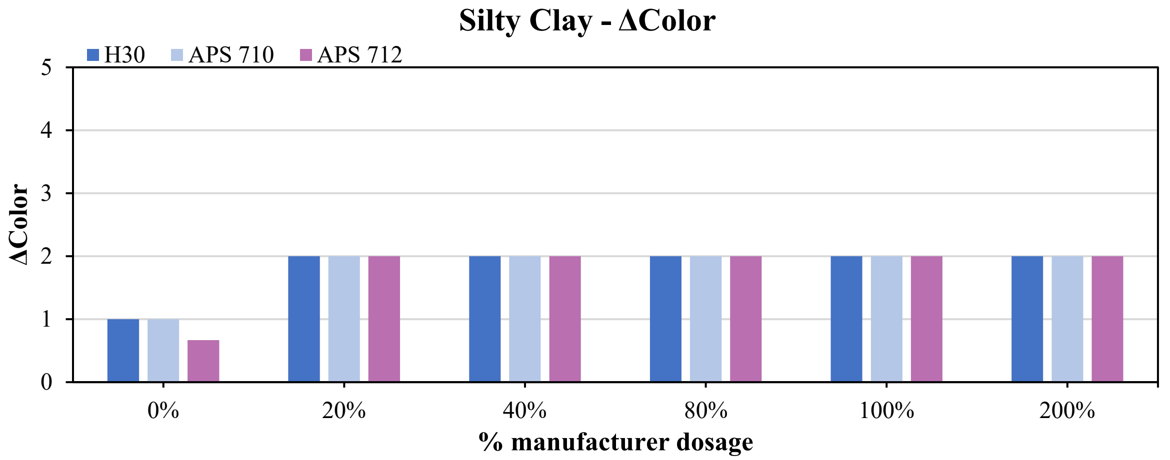
Product:	**APS 710**					
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	938.7	1259.1	1288.8	1341.3	1373.1	1300.8
ΔpH	0.21	0.26	0.24	0.27	0.31	0.35
ΔTemperature	0.1	0.1	0.2	0.2	0.1	0.2
ΔColor	1	2	2	2	2	2

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 - 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
5
4
3
2
1
0
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**

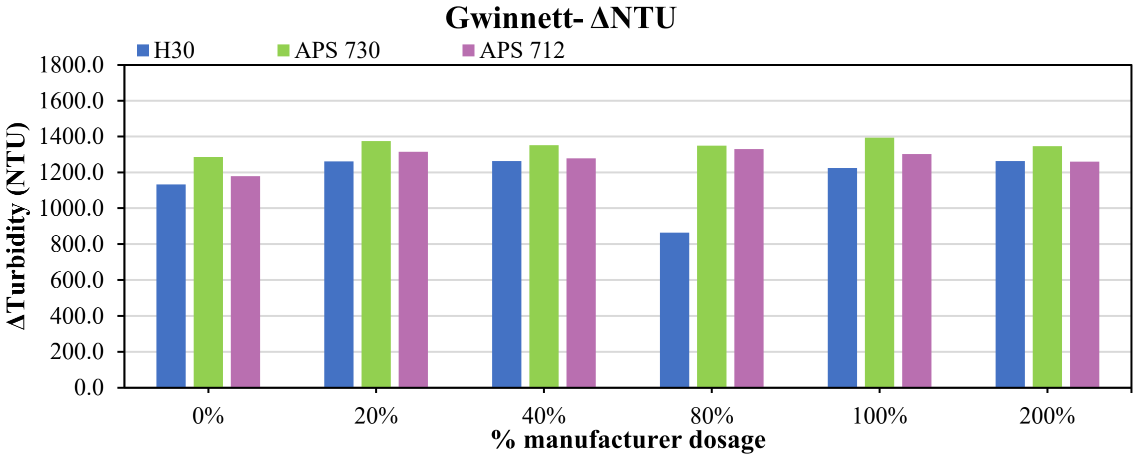
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	1	2	4	5	10
ΔNTU	1132.7	1261.5	1263.7	864.3	1225.8	1264.1
ΔpH	0.09	0.14	0.17	0.20	0.20	0.14
ΔTemperature	0.5	0.4	0.6	0.2	0.4	0.5
ΔColor	1	3	3	3	3	3

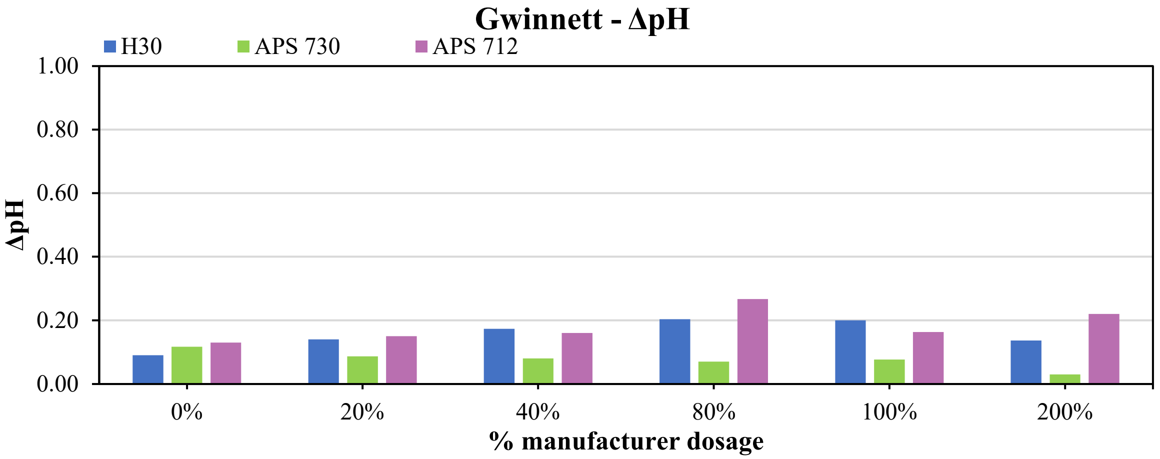
Product: **APS 730**

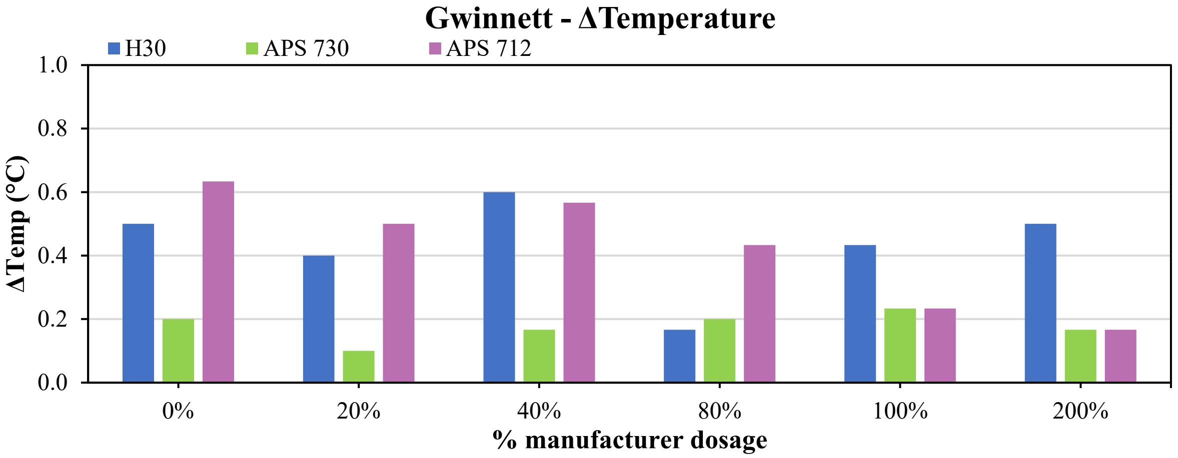
	JAR NUMBER					
	1	**2**	**3**	**4**	**5**	**6**
Flocculant (mg/l)	0	10	20	40	50	100
ΔNTU	1287.1	1375.1	1351.4	1349.4	1393.5	1345.9
ΔpH	0.12	0.09	0.08	0.07	0.08	0.03
ΔTemperature	0.2	0.1	0.2	0.2	0.2	0.2
ΔColor	1	3	3	3	3	3

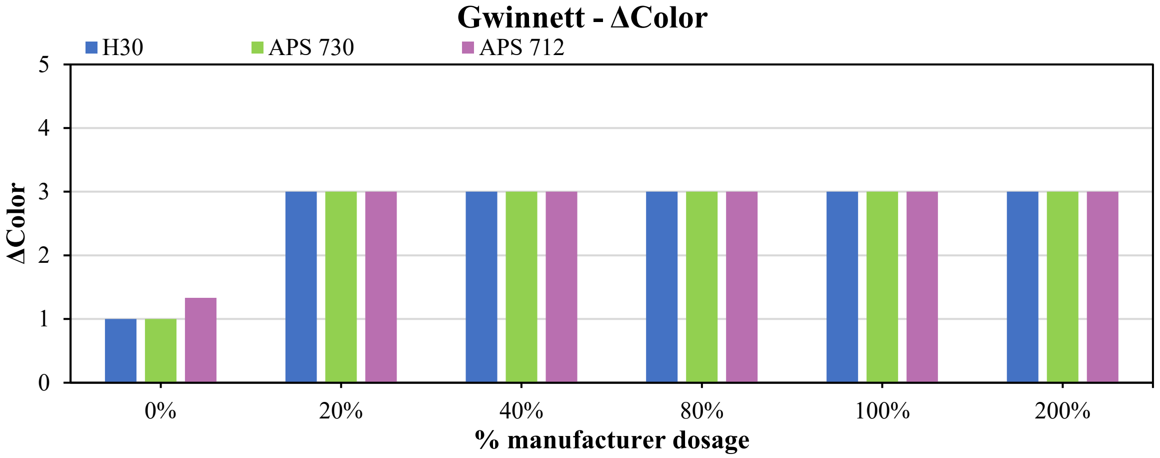
Product: **APS 712**

	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 - ΔpH
H30
APS 730
APS 712
1.00
0.80
0.60
0.40
0.20
0.00
ΔpH
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Gwinnett - ΔTemperature
H30
APS 730
APS 712
1.0
0.8
0.6
0.4
0.2
0.0
ΔTemp (°C)
0%
20%
40%
80%
100%
200%
% manufacturer dosage


Gwinnett - ΔColor
H30
APS 730
APS 712
5
4
3
2
1
0
ΔColor
0%
20%
40%
80%
100%
200%
% manufacturer dosage

APPENDIX F

PRODUCT IDENTIFICATION

Product Identification

Product ID	Product	Manufacturer ID	Manufacturer	Flocculant	Dosage (mg/L)
A	H30	I	Carolina Hydrologic, LLC.	PAM	5
B	APS 702	II	Applied Polymer Systems	PAM	50
C	APS 705	II	Applied Polymer Systems	PAM	50
D	APS 707	II	Applied Polymer Systems	PAM	50
E	APS 710	II	Applied Polymer Systems	PAM	50
F	APS 712	II	Applied Polymer Systems	PAM	50
G	APS 730	II	Applied Polymer Systems	PAM	50
H	APS 740	II	Applied Polymer Systems	PAM	50
I	FLOC	III	Innovative Turf Solutions	Bentonite-based	180
J	Liquifloc 1%	IV	Dober	Chitosan	100
K	Liquifloc 1% + LBP 2101	IV	Dober	Chitosan + coagulant	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