Evaluation of ALDOT Erosion Control Practices using Rainfall Simulation – Final Report

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16. Abstract
The rainfall simulator at the Auburn University Erosion and Sediment Control Test Facility (AU-ESCTF) was used to produce 2, 4, and 6 in. per hr rainfall intensities and has test plot dimensions of 8 ft. wide by 40 ft. long on a 3H:1V slope. Each rainfall experiment was an hour long with three sequential 20-minute rainfall intervals of increasing rainfall intensities of 2, 4, and 6 in. per hr, following ASTM D6459-19. Calibration testing was performed on each rainfall intensity to verify the rainfall drop size distribution, intensity, and uniformity. The test plots of bare soil (control test), loose, tacked, and crimped straw along with four hydraulically applied mulches and one dry applied hydraulic mulch, four erosion control blankets, two soil conditioners, and bare soil control tests were evaluated. Following the completion of testing, the Revised Universal Soil Loss Equation (RUSLE) was used to calculate the product C-factor from the incremental rainfall depth and soil loss results. The rainfall simulation tests performed on the sandy loam soil resulted in an average soil loss of 738 lb for bare soil, 143 lb for loose straw, 97 lb for loose straw with Tacking Agent 3, and 169 lb for crimped straw. Longevity testing was performed on the straw applications following the initial product test resulting in a total soil loss 611 lb for bare soil, 287 lb for loose straw, 131 lb for loose straw with Tacking Agent 3, and 82 lb for crimped straw. The initial and longevity test results were combined to determine which practice reduced the overall soil loss. The loose straw with Tacking Agent 3 resulted in the highest reduction in soil loss of 83% (i.e., 17% soil loss of the control test–bare soil), which was closely followed by the crimped straw with a reduction in soil loss of 81%. Hydraulic mulches, erosion control blankets, and soil conditioners (i.e., polyacrylamide and agricultural gypsum) were evaluated on a loam soil. The three of the hydraulic mulches resulted in similar *C*-factors of 0.55 for Eco-Fiber, 0.46 for Soil Cover, and 0.53 for Terra-Wood. The premium product, ProMatrix was able to control erosion better, resulting in a *C*-factor of 0.33. The Edge Pellets dry applied hydraulic mulch also resulted in a *C*-factor of 0.33. Erosion control blankets tests resulted in C-factors of 0.05 for Curlex I, 0.14 for S150, and 0.12 for ECX-2. The jute blanket tested as part of the soil conditioner study resulted in a *C*-factor of 0.41. The combination of PAM and jute as well as the combination of gypsum and jute resulted in *C*-factors of 0.56 and 0.1 respectively.

17. Key Words: Rainfall simulation, erosion control, rolled erosion control products, hydraulic mulch, soil conditioners, RUSLE

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EXECUTIVE SUMMARY

The rainfall simulator at the Auburn University Erosion and Sediment Control Test Facility (AU-ESCTF) follows the ASTM D6459-19 standard: *The Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall Induced Erosion requirements*. The rainfall simulator was constructed to produce 2, 4, and 6 in. per hr rainfall intensities and has test plot dimensions of 8 ft. wide by 40 ft. long on a 3H:1V slope. Each rainfall experiment was an hour long with three sequential 20-minute rainfall intervals of increasing rainfall intensities of 2, 4, and 6 in. per hr. Calibration testing was performed on each rainfall intensity to verify the rainfall drop size distribution, intensity, and uniformity.

The test plots of bare soil (control test), loose, tacked, and crimped straw along with various erosion control blankets, hydraulic mulches and soil conditioners were evaluated under rainfall simulation. The straw mulch practices and some bare soil plots were evaluated under initial (one hour) and longevity (one more hour) performance testing while the erosion control blankets, hydraulic mulches, and soil conditioners and their accompanying bare soil control tests followed ASTM D 6459-19. Following the completion of the straw mulch testing, the soil type of the test slope was changed to a loam soil, which better followed the ASTM D6459 standard. During this time, the test procedure was altered to calculate the product C-factor. Four hydraulically applied mulches and one dry applied hydraulic mulch, four erosion control blankets, two soil conditioners, and bare soil control tests were evaluated under the new test procedure. Following the completion of testing, the Revised Universal Soil Loss Equation (RUSLE) was used to calculate the product C-factor from the incremental rainfall depth and soil loss results.

The rainfall simulation tests performed on the sandy loam soil resulted in an average soil loss of 738 lb for bare soil, 143 lb for loose straw, 97 lb for loose straw with Tacking Agent 3, and 169 lb for crimped straw. Longevity testing was performed on the straw applications following the initial product test resulting in a total soil loss 611 lb for bare soil, 287 lb for loose straw, 131 lb for loose straw with Tacking Agent 3, and 82 lb for crimped straw. The initial and longevity test results were combined to determine which practice reduced the overall soil loss. The loose straw with Tacking Agent 3 resulted in the highest reduction in soil loss of 83% (i.e., 17% soil loss of the control test–bare soil), which was closely followed by the crimped straw with a reduction in soil loss of 81%. This concluded that anchoring the straw mulch reduced the overall soil lose better than the other non-anchored straw applications.

Hydraulic mulches, erosion control blankets, and soil conditioners (i.e., polyacrylamide and agricultural gypsum) were evaluated on a loam soil with a new test procedure that allows for the calculation of product *C*-factors. The loam soil had higher total soil loss rates than the sandy loam soil with an average total soil loss of 2,333 lb. The three of the hydraulic mulches resulted in similar *C*-factors of 0.55 for Eco-Fiber, 0.46 for Soil Cover, and 0.53 for Terra-Wood. All three of these hydraulic mulches experienced high erosion rates caused by the product washing from the test plot when the rainfall intensity was increased to 4 and 6 in./hr. The premium product, ProMatrix was able to control erosion better, resulting in a *C*-factor of 0.33. The Edge Pellets dry applied hydraulic mulch also resulted in a *C*-factor of 0.33. Erosion control blankets tests resulted in C-factors of 0.05 for Curlex I, 0.14 for S150, and 0.12 for ECX-2. All these blankets resulted in lower C-factors than the three hydraulic mulches. The Curlex I blanket provided the best test plot coverage resulting in the lowest C-factor. The jute blanket tested as part of the soil conditioner study resulted in a *C*-factor of 0.41. The combination of PAM and jute as well as the combination of gypsum and jute resulted in *C*-factors of 0.56 and 0.1 respectively. Residual testing of PAM was also performed to determine the amount of PAM lost during product testing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Construction activities, specifically those associated with clearing, grubbing, excavating, and grading create areas of high erosion potential when subjected to rainfall and stormwater runoff. Construction sites have measured erosion rates of approximately 20 to 200 tons per acre per year (Pitt et al., 2007). Studies have shown that construction operations disturbing in-situ soil material increase sediment yields by as much as 10,000 times when compared to natural, undisturbed sites (Haan et al., 1994). Further construction development creates impervious surfaces (i.e., driveways, sidewalks, parking lots, and roads) and near impervious areas (i.e., temporary roads and compacted subgrade) reducing infiltration of rainfall and stormwater runoff, thereby increasing runoff quantity and peak discharge thus increasing vulnerability of on-site erosion (Clark, 1999). Sediment emanating from slope and channel erosion is typically transported into existing (temporary or permanent) stormwater conveyance systems. Other pollutants stemming from the improper use and disposal of chemicals and hydrocarbons during construction often attach to sediment particles and are introduced to the local environment. Better methods and practices for controlling erosion, sedimentation, and other pollutants from construction sites are needed to meet the demands of increasing growth and development throughout the U.S., without compromising the integrity of nearby waterways.

Due to a lack of relevant third party data, the Auburn University – Erosion and Sediment Control Testing Facility (AU-ESCTF) was tasked by the Alabama Department of Transportation (ALDOT) to investigate the performance of different erosion control practices that are currently used or be potentially on ALDOT construction projects. Erosion control practices are used to temporarily or permanently stabilize earthen material to reduce pollutant loads on local water bodies. Erosion control practices consist of rolled erosion control products (RECPs), hydraulic erosion control products (HECPs), mulching, tackifiers, netting, slope interrupters, and vegetation. Using ALDOT's approved products lists, RECPs, HECPs, and soil amendments were identified in conjunction with the Project Advisory Committee (PAC).

1.2 EROSION CONTROLS

A cost effective approach to prevent the erosion of soil from a slope is to develop an erosion control plan that will minimize on-site erosion. Erosion control practices are an effective way to minimize sediment loss by mitigating the erosive energy generated by raindrop impacts. Erosion controls typically consist of RECPs, HECPs, mulching, tackifiers, netting, and slope interrupters installed on an unvegetated slope to aid in the establishment of temporary or permanent vegetation. Properly installed erosion controls will have the greatest effect on sediment-laden runoff by minimizing erosion and reducing the amount of sediment transport, both on and off site.

RECPs are rolled down a slope and secured using sod staples once in place. These products provide a protective barrier between raindrops and soil, thereby minimizing the transfer of energy from the raindrop to the soil.

Straw mulching is a commonly used erosion control that quickly provides cover. This practice can be manually or mechanically spread along an exposed slope and provide a barrier between raindrops and the soil. Straw mulching, however, has limitations when used singularly without some type of crimping, tackifier, or netting to anchor it in place. Other erosion control practices include HECPs that must be installed and specified correctly to perform as intended; and temporary and permanent vegetation, which require a stable soil matrix to promote germination and growth. The marketplace for new erosion control practices is growing rapidly; however, the effectiveness and performance of such practices in common field situations may be unknown or may be solely based on manufacturers' claims. There is a need for independent, third-party evaluations of the performance characteristics of erosion control practices used on construction sites.

To gain insight on the performance, durability, and maintenance needs of erosion control products and practices, reproducible large-scale experiments or tests are necessary to evaluate and compare the performance of different products (having different materials or manufacturing methods) and practices typically employed in the field using simulated rainfall.

1.3 TESTING PROCEDURES

To evaluate the performance of an erosion control product or practice properly, several water quality parameters should be monitored throughout the experimental process. Determining the effectiveness of these products and practices is difficult when monitoring in-field installations at construction sites. This is because "uncertainty of runoff quantity and quality due to weather patterns and construction activities makes objective, replicated experiments very difficult" (McLaughlin et al., 2001). Secondly, comparing the in-field effectiveness and overall performance of various erosion control practices would be particularly difficult due to the dissimilar conditions (slope, soil type, installation, and climate) the erosion controls may be exposed to at different evaluation sites.

Therefore, the focus of this study was to employ reproducible, large-scale experimental techniques to evaluate the performance of erosion control products and practices under controlled, simulated rainfall conditions.

1.3.1 ASTM D6459-19 Standard Test Method

The ASTM Standard D6459-15, entitled "Standard Test Method for Determination of Rolled Erosion Control Products (RECP) Performance in Protecting Hillslopes from Rainfall Induced Erosion" was originally to be used for testing of different erosion control practices. However, this standard underwent minor updates based upon the required ASTM review period, and therefore ASTM D6459-19 was used for erosion control testing for this project. ASTM D6459 describes the test method for determining the effectiveness of RECPs using rainfall simulation (ASTM D6459, 2019). This method describes the procedure for conducting an experiment and quantifying the ability of a RECP to minimize erosion and retain soil on a slope. As part of this study, the ASTM test method was used to evaluate various erosion control practices including different types of straw applications, RECPs, HECPs, flocculants, and soil conditioners.

The ASTM D6459-19 test method requires that simulating rainfall intensities of 2, 4, and 6 in. per hr be simulated for 20 minutes each in intervals of increasing intensity to induce rill erosion on a test plot. This results in a precipitation depth of 4 in. within a 1-hour period. The test plot is specified to be 8 ft wide by 40 ft long on a 3:1 (H:V) slope. The test plot consists of a sandy loam (as classified by the USDA soil texture method) subsoil. A sandy loam test soil was used for testing the straw applications and a loam soil was used for testing all other erosion control products. A detention basin, at the base of the slope, collects runoff emanating from the test plot. Grab samples were collected from the runoff to determine suspended sediment concentrations, while the weight of the total soil eroded and captured in the detention basin was also quantified to measure performance.

1.4 PROJECT OJECTIVES

The primary purpose of this project was to evaluate the performance of commonly used ALDOT erosion control practices. To further this effort, the AU-ESCTF sought to: (1) determine the performance and effectiveness of erosion control practices and products, and (2) seek accreditation for testing ASTM D6459-15 by the American Association of State Highway and Transportation Officials (AASHTO) National Transportation Product Evaluation Program (NTPEP).

Phase II, which has been approved and is currently underway, is to increase the ability to evaluate erosion controls products seeking ALDOT approval, by constructing additional test plots each with a separate rainfall simulator, in addition to a secondary water supply. The addition of new plots will increase the productivity of the AU-ESCTF to expedite ALDOT's testing needs and provide alternative methods for testing erosion control practices and products. By varying soil types, rainfall intensities, and other conditions on these additional plots, the AU-ESCTF will be able to provide ALDOT with a better understanding of the products and practices used on ALDOT construction sites that can vary in site conditions throughout the state. The primary objectives of Phase I, which is the focus of this report, is listed below:

Phase I: Evaluation of ALDOT Erosion Control Practices using Rainfall Simulation (proposed)

Primary Objectives:
(1) Evaluate the performance of ALDOT erosion control practices and determine their overall effectiveness. Through this, compare these performance results to published results.
(2) Determine prescribed cover factors (C-factors) for each practice or product to provide designers with Alabama specific expected soil losses based upon ASTM D6459-19 and the soil type used for testing.
(3) Provide recommendations based upon effectiveness, as well as, considering installation requirements and potential cost considerations, that will help a designer better specify a practice or product that best suits the needs of a project.
(4) Pursue accreditation to perform ASTM D6459-19 tests through the Geosynthetic Accreditation Institute (GAI), to ensure high quality data collection for ALDOT.
(5) Design additional rainfall simulators and an additional water source to provide ALDOT with greater productivity and testing options for evaluating erosion control products and practices.

1.5 PROJECT METHODOLOGY

Phase I project methodology was divided into separate tasks that were performed to satisfy the abovementioned research objectives. Each individual task is described below:

Task 1: Literature Review

The purpose of this task was to identify, describe, evaluate, and assess previous research and current testing methodologies used for testing and evaluating erosion control practices/products. Additionally, the researchers evaluated and assessed current laboratory methods used to determine soil loss from erosion plots to ensure these methods align with ASTM and NTPEP requirements. Furthermore, the researchers investigated the requirements for pursuing accreditation as an ASTM certified laboratory.

Task 2: Design of Additional Rainfall Simulator Plots

Design a new system that will provide ALDOT with a greater ability to evaluate new and innovative erosion control products or practices that help minimize sediment loss during construction. Design requirements included locating a proposed area within the existing NCAT/AU-ESCTF property that was easily modified to meet the testing needs. This also included finding an on-site location that can be used to collect and store stormwater runoff to provide an additional water source to support these testing activities. Expansion of the AU-ESCTF has been performed and new plots are being constructed.

Tasks 3 – 8: Testing and Accreditation

Table 1.1 shows the products and practices tested to meet project testing requirements.

Table 1.1 – Products an practices tested during project Phase I.

Erosion Control Type	Product or Practice	Manufacturer
Blown Straw	Loose Straw	N/A
	Straw with Tacking Agent 3r	Profile Products
	Crimped Straw	N/A
Rolled Erosion Control Products	Jute	L&M Supply
	Curlex-I	American Excelsior
	ECX-2	East Coast Erosion
	S-150	North American Green
Hydraulic Erosion Control Products	ProMatrix	Profile Products
	EcoFiber	Profile Products
	Soil Cover	Profile Products
	Terra Wood	Profile Products
	Edge Pellets	Terra Novo
Flocculants and Conditioners	Polyacrylamide	Applied Polymer Solutions
	Gypsum	USA Gypsum

Task 3: Testing of Bare Soil Control

This task provided the AU-ESCTF a benchmark for comparison of a bare soil slope condition to a stabilized slope for determining soil retention of the tested erosion control products. These tests also allowed the AU-ESCTF to develop the required documentation for seeking accreditation to perform ASTM D 6459-15 from the AASHTO recognized accreditor: Geosynthetic Accreditation Institute (GAI). Each product or practice tested was accompanied by one control test to ensure comparison between a recently run control was available to account for any soil variability.

Task 4: Seek Laboratory Accreditation for ASTM D 6459-15

Accreditation from the GAI was successfully pursued with the intent to meet the requirements for participation in the AASHTO NTPEP program by becoming a NTPEP contracted laboratory. Accreditation was achieved from GAI, however, we have been unsuccessful at becoming a NTPEP laboratory, specifically because NTPEP will not communicate with us regarding how to accomplish this. We are still trying to identify other avenues regarding becoming a NTPEP lab.

Task 5-8: Testing of Straw Mulch, Hydraulic Mulch, and Short Term RECPs

The purpose of these tasks was to test and evaluate the performance of erosion control practices using field-scale rainfall simulation techniques. Table 1.2 provides a summary of the proposed testing regime as part of this study consisting of 50 tests. Through ongoing advisement from the project advisory committee (PAC), this table evolved into Table 1.1. Table 1.1 does not show the number of control tests, however since one control test is required with each product, 14 control tests were actually run. The experimental setup and the testing of erosion control practices followed the ASTM D6459-19 standard testing methodology unless otherwise discussed within this report.

Table 1.2: Summary of Rainfall Simulation Tests

Group	Proposed Erosion Controls for Testing	ALDOT Approved Materials List	No. of Installations	Replications	No. of Tests
Control	Bare Soil Control	--	8	1	8
1	Straw Mulching – w/Crimping	LIST II-20	3	1	3
	Straw Mulching– w/Tackifier		3	1	3
	Straw Mulching– w/Netting		3	1	3
2	Hydraulic Mulch 1		3	1	3
	Hydraulic Mulch 2		3	1	3
	Hydraulic Mulch 3		3	1	3
	Hydraulic Mulch 4		3	1	3
3	Hydraulic Mulch 5		3	1	3
	Hydraulic Mulch 6		3	1	3
	Hydraulic Mulch 7		3	1	3
	Hydraulic Mulch 8		3	1	3
4	RECP 1 – TYPE S3 – 3 months	LIST II-11	3	1	3
	RECP 2 – TYPE S3 – 3 months		3	1	3
	RECP 3 – TYPE S3 – 3 months		3	1	3
			Total Number of Proposed Tests =		**50**

Task 9: Development of Final Report

The purpose of this task was to develop a final report that documents the results from the testing efforts. Results include sediment loss reductions and appropriate cover factors for designers to use when specifying erosion control practices for ALDOT projects. Results also include installation techniques and requirements that will assist the designers in understanding possible site specific requirements to better implement successful usage of the erosion control practices and products evaluated as part of this effort. This information will be provided in the product reports that were individually developed for all products tested. This final report provide a summary of all testing while individual testing reports with greater data detail are also provided.

CHAPTER 2: LITERATURE REVIEW

2.1 RAINFALL SIMULATOR TYPES

Rainfall simulators are playing a major role in evaluating the performance of erosion control measures and through the analysis of varying rainfall parameters (Elbasit et al. 2015). There are two main rainfall simulator types consisting of dripper and nozzle simulators (Robeson et al 2014).

2.1.1 Dripper Rainfall Simulators

The dripper rainfall simulators allows water to accumulate on the tip of the drop emitter until the weight of the drop overcomes the surface tension and falls to the ground with an initial velocity of zero (Pall et al. 1983). There have been varying types of drop emitters used in rainfall simulators consisting of hanging yarns, glass capillary tubes, hypodermic needles, polyethylene tubing, and stainless steel tubes (Bubenzer and Jones Jr. 1971). Since the raindrops have an initial velocity of zero, the dripper rainfall simulators must be taller than nozzle rainfall simulators to allow the drops to reach terminal velocity before impacting the test plot (Elbasit et al. 2015). The dripper rainfall simulators generate a uniform drop size distribution with larger drop sizes, which commonly range from 2.2 to 5.5 millimeters (Pall et al. 1983).

2.1.2 Nozzle Rainfall Simulators

Nozzle rainfall simulators generate a wide range of drop size distributions, which are controlled by the nozzle characteristics, pressure, and spray pattern (Pall et al. 1983). The sprinklers used for nozzle rainfall simulators have a rotating disk that evenly spreads and shapes the drops over the test plot area (Robeson et al 2014 and Pall et al. 1983). Raindrops leaving the nozzles have an initial velocity, allowing the raindrops to reach terminal velocity over a shorter distance. Therefore, nozzle rainfall simulators do not need to be as tall as dripper simulators but have a smaller raindrop size distribution (Elbasit et al. 2015).

2.2 CALIBRATION TESTING

Prior to rainfall simulation testing, initial calibration tests consisting of rainfall intensity, uniformity and drop size distribution are evaluated to ensure the simulator meets specifications (Cabalka et al.). There are many factors influencing the intensity and uniformity for rainfall simulators consisting of the sprinkler spacing and wind speed. The rainfall intensity of a rainfall simulator is measured by collecting the rainfall for a predetermined length of time in a rain gauge or other container with known volume. The rainfall uniformity produced by a simulator is determined through the application of the Christiansen Uniformity Coefficient (Pall et al. 1983).

2.3 DROP SIZE DISTRIBUTION

Rainfall simulators have been designed and constructed for field and laboratory studies of soil erosion. These simulators are designed to mimic the drop size, drop shape, and the terminal velocity of natural rainfall (Jayawardena et al. 2000 and Elbasit et al. 2015). Raindrop size distribution testing was first tested in 1895 by J. Wiesner who used his absorbent paper method.

Over the past one hundred and twenty years, various drop size distribution testing procedures have been developed such as the flour pan method, stain method, laser method, momentum method, and the oil method.

2.3.1 Flour Pan Method

In 1904, Wilson Bentley developed the flour pan method to determine the drop size distribution of rainfall (Eigel and Moore 1983). The flour pan method uses ten-inch diameter pans that are one-inch thick. The pans are filled with sifted flour and leveled off across the top of the pan. Prepared pans are not allowed to sit for more than two hours before being tested. Before the flour pan was exposed to rainfall, the flour was covered and moved to a level surface under the rainfall. The cover was removed from the pan allowing the flour to be exposed to rainfall for time intervals of a few seconds to minute's depending on the rainfall intensity (Laws and Parsons 1943).

The flour pan with raindrops was allowed to air dry overnight. The air dried pellets were sieved through a #70 mesh sieve to remove all excess flour. The remaining pellets and flour were placed in an oven at 110oC for 60 minutes. Once dry, the pellets were sieved through a stack of sieves including #8, #10, #14, #20, #28, and #35 for two minutes. The pellets retained on each sieve were weighed and counted. In order to properly determine the mass of the drop, the mass of the flour pellets must be converted through the application of a mass ratio. A mass ratio curve was developed by evaluating drops of known size. The same number of drops were collected in a cup and flour to compare the drop and pellet masses.

The mass of the average pellet was multiplied by the corresponding mass ratio value from Laws and Parsons (1943) to calculate the mass of the average drop. The diameter of the average drop was calculated using the average drop mass in Equation 2.1.

$$D_r = \sqrt[3]{\left(\frac{6}{\pi}\right) m} \tag{2.1}$$

where,

Dr = diameter of average drop (mm)
m = mass of average drop (mg)

2.3.2 Laser Method

The advancement in laser technology provides an opportunity for high-speed data collection for determining the drop size distribution of rainfall. The laser projects a horizontal beam across a surface and measures the quantity of drops and the raindrop sizes ranging from 0.2 to 13 millimeters in diameter. Lasers are also capable of calculating the velocity of raindrops as they pass through the laser beam. When multiple drops simultaneously pass through the laser, an error occurs by combining the two-drop sizes to record a larger drop. Another error with lasers occurs when large drops that become distorted are measured at their maximum horizontal diameter (Kincaid et al 1996).

2.3.3 Momentum Method

Piezoelectric force transducers produce voltage pulses that represents one water drop. The magnitude of the pulse correlates to the drop size, kinetic energy, and momentum of the drops (Jayawardena et al. 2000). The force transducer uses a crystalline quartz plate covered by a steel plate to measure voltage pulses (Elbasit e. al. 2015). Since measurements are recorded based on time, the raindrop data can be examined for any time during a storm event (Jayawardena et al. 2000).

2.3.4 Oil Method

The oil method is founded on the principal that water droplets will maintain their shape in a less dense, but more viscous fluid. This method combines STP oil treatment and heavy mineral oil at a 2:1 ratio mixture. Immediately after the oil mixture is exposed to raindrops, a photograph is taken with a scale placed within the picture for size reference. The photographs were projected onto a smooth screen and the water droplets are measured while incorporating an enlargement factor determined from the scale in the image (Eigel and Moore 1983).

2.3.5 Stain Method

The stain method uses absorbent paper with water-soluble dye to measure the size of the raindrops. The paper with dye is placed under rainfall for a few seconds. When the raindrops come in contact with the paper, the dye leaves a permanent mark on the paper (Kathiravelu et al. 2016). The size and quantity of the drops are measured. A factor to consider when measuring the stains is that the relationships between the drop diameter and the stain diameter will be different. The difference in drop diameter and the stain diameter can be determined by prior testing of drops with known size. A difficulty with this procedure is that large drops tend to splash upon impact causing inaccurate results (Hall 1970).

2.4 MULCHES

Mulching is the application of plant residues to the soil surface to reduce the impact of erosive forces of raindrop impacts and reduces the velocity of overland flow. The application rate of straw mulches varies depending on the state or municipality design specifications, site characteristics, and whether the mulch is installed with or without seed. The target percentage soil cover rate for straw is 75% when installed with seed and 100% when installed without seed. The Alabama Department of Environmental Management (ADEM) specifies a straw application rate of 1.5 to 2.0 t/ when installed with seed and 2.5 to 3.0 t/ac without seed. The mulching application rates specified by the Alabama Soil and Water Conservation Committee are depicted in Table 2.1 (AL-SWCC 2018).

TABLE 2.1: AL-SWCC Mulch Application Rates

Material	Rate Per Acre and (Per 1000 ft^2)	Notes
Straw with Seed	1 1/2 - 2 tons (70 lbs-90 lbs.)	Spread by hand or machine to attain 75% groundcover; anchor when subject to blowing.
Straw Alone (no seed)	2 1/2-3 tons (115 lbs-160 lbs.)	Spread by hand or machine; anchor when subject to blowing.
Wood Chips	5-6 tons (225 lbs-270 lbs.)	Treat with 12 lbs. nitrogen/ton.
Bark	35 cubic yards (0.8 cubic yard)	Can apply with mulch blower.
Pine Straw	1-2 tons (45 lbs-90 lbs.)	Spread by hand or machine; will not blow like straw.
Peanut Hulls	10-20 tons (450 lbs-900 lbs.)	Will wash off slopes. Treat with 12 lbs. nitrogen/ton.
HECPs	0.75 - 2.25 tons (35 lbs. - 103 lbs.)	Refer to ECTC or Manufacturer's Specifications.

When loose straw is exposed to high winds and overland flow, it can be blown offsite. Therefore, when straw mulch is exposed to strong winds and flow rates, it should be anchored to ensure the effectiveness of the straw cover is maintained. A tackifier is a straw anchoring method used on steep slopes to hold the straw in placed (AL-SWCC 2018).

Crimping is an anchoring method used to imbed the loose straw into the soil surface. The state of Alabama requires that the straw must be imbedded 2.0 inches (5.08 cm) into the soil by a ¼ inch flat edged coulter blade. The coulter blades must be spaced a maximum of 8 inches apart. The crimper is pulled behind a tractor, allowing the weight of the crimper to embed the straw into the soil surface in the perpendicular direction to flow. Crimping should not be performed on slopes greater than 3H:1V for equipment safety purposes (ALDOT 2018).

2.5 STRAW MULCH TESTING

Khan et al. (2016) created a dripper type rainfall simulator to evaluate the performance of mulches on the purple soil of South-Western Sichuan Province, China. The dripper type rainfall stimulator was constructed of 324 rain needles that vibrated to produce rain like conditions. The average drop size for the rain needles was 1.7-2.8 mm. The test plot size was 3.3 ft (1 m) long by 1 ft (0.3 m) wide by 1.3 ft (0.4 m) deep with a slope of 5˚, 15˚, or 25˚. The rainfall simulator was designed to produce four different rainfall intensities of 1.29, 2.13, 3.70, and 4.72 in./hr (33, 54, 94, and 120 mm/hr).

Khan et al. (2016) installed wheat straw to a depth of 1.6 in. (4 cm) to evaluate under the varying rainfall intensities and slopes. The results of the straw were compared with the results from a bare soil control test. During the experiments, the total soil loss significantly increased as the slope increased from 5˚ to 25˚. The addition of wheat straw considerably reduced the sediment losses by 81-100% as compared to the bare soil control conditions. The most notable improvement was from the 25˚

slope at 3.70 in./hr rainfall intensity. The soil loss decrease from 0.18 lb/ft^2 un-mulched to 0.007 lb/ft^2, which is a 96% improvement. The total amount of infiltration was measured for each experiment. It was determined that under all testing conditions that the infiltration rate was higher on mulched slopes than under bare soil conditions.

Wilson et al. (2010) evaluated the performance of straw mulch and hydraulic mulches under small-scale rainfall simulation at the AU-ESCTF. The rainfall simulation was constructed using one FullJet ½ HH-30WSQ nozzle and a 10 psi Norgren R43-406-NNLA pressure regulator. The test plots were 2 ft wide by 4 ft long by 3.5 inches in depth and were supported by saw horses which created a testing slope of 3H:1V. The rainfall simulator test consisted of four 15-minute rainfall events and was calibrated to generate a total rainfall depth of 4.4 inches.

Wilson et al. (2010) evaluated six erosion control products and practices consisting of: conventional crimped straw, conventional straw mulch with tackifier, and four hydromulches. During the rainfall experiment, the slope runoff was diverted by a metal apron to a single location for collection to evaluate the total soil loss and the runoff turbidity over time. The data collected for each product was compared to a bare soil control test to calculate the percent reduction in soil loss and turbidity. The crimped straw was the worst performing product with a percent reduction in turbidity of 80% and soil loss of 98%. The straw with tackifier performed at a much higher rate than the crimped straw with a percent reduction in turbidity of 98% and soil loss of 99%. The hydraulic mulch performance ranged from a percent reduction in turbidity of 85-99% and soil loss of 95-99%.

Rainfall simulation testing was performed at the Sediment and Erosion Control Laboratory at Texas A&M Transportation Institute (TTI) to evaluate the performance of crimped straw under varying application rates, soil types and slopes. The test plot was 30 ft long by 6 ft wide by 9 in deep. The test plot was evaluated at a 2H:1V and 3H:1V slopes. Each rainfall simulation experiment consisted of three, 30 minute storm events with a rainfall intensity of 3.5 in./hr. Wheat straw was installed to the test slope at application rates of 1, 2, 3, and 4 ton/acre. The average sediment loss for each application rate was compared to the Texas Department of Transportation (TxDOT) allowable threshold for a RECP to determine if the application was as effective as an RECP. All four of the application rates tested on the 3H:1V slope met the threshold of 0.79 lb/10 ft^2 for clay and 28.47 lb/10 ft^2 for sand. However, on the 2H:1V slope, the 3 and 4 ton/acre were the only two application rates that met the required thresholds for both soils (Ming-Han 2014).

Barnett et al. (1967) evaluated several mulching applications on seeded highway backslopes in Oconee, Peach, and Wilkes Counties, Georgia. Each test slope was graded to 2.5H:1V and seeded. Bare soil conditions, surface applied mulch with a tackifier, and crimped mulch were evaluated. A grain straw mulch was installed at an application rate of 2 ton/acre. Two 30-minute increments of 2.5 in./hr rainfall intensities were performed for each experiment. The soil loss rate for the bare soil plots averaged 96.57 ton/acre. The straw with asphalt tackifier decreased the average soil loss rate to 31.54 ton/acre, while the crimped straw decreased the soil loss rate to 9.88 ton/acre. This experiment concluded that crimping straw was on average the most effective erosion control method as compared with straw with an asphalt tackifier.

Foltz and Dooley (2003) evaluated the performance of straw, wide wood strands, and narrow wood strands on a small-scale rainfall simulator and compared their results to bare soil control tests. The straw and wood applications were installed at a target cover factor of 70%. The test plot was a 4.07

ft (1.24 m) wide by 13.12 ft (4.0 m) long filled with a gravely sand and had a slope of 30%. Each rainfall experiment consisted of a 15-minute storm event of 1.97 in./hr (50 mm/hr) rainfall intensity followed by the same rainfall intensity and an inflow of 0.26 gpm (0.97 L/min) for 5 minutes. The second inflow consisted of the same rainfall intensity and an inflow of 1.08 gpm (4.1 L/min) for 5 minutes.

The loose straw and wood strands all resulted in a 98 to 100% improvement as compared to the bare soil control test. The average sediment loss under the second inflow for a bare soil control test was 64.82 while the loose straw averaged a total sediment loss of 1.17 lb and the wide wood strands was 0.86 lb. The wide wood strand was the best performing product with a 98% improvement from bare soil control tests for the second inflow. The study found that the majority of the soil loss occurred during the second inflow (Foltz and Dooley 2003).

Gholami et al. (1994) evaluated the performance of straw mulch under rainfall simulation at the Faculty of Natural Resources of Tarbiat Modares University, Noor, Iran. The rainfall simulator test plots were 19.7 ft (6 m) long by 3.3 ft (1 m) wide by 1.64 ft (0.5 m) deep with a slope of 30%. The rainfall simulator produced rainfall intensities of 1.18, 1.97, 2.76, and 3.54 in./hr (30, 50, 70, and 90 mm/hr) from 27 calibrated nozzles. The average raindrop size for this simulator is 1.3 mm with a fall height ranging between 13.1 ft and 19.7 ft (4 m and 6 m). The variation in drop fall height is due to the slope of the plot changing the distance from the top and bottom to the sprinklers. Each experiment had a duration of 15 minutes with one rainfall intensity. The performance of the test plots under varying rainfall intensities was compared with the same straw application rate. Rice straw mulch was installed on each test plot at an application rate of 0.10 lb/ft2 (0.5 kg/m2) with a target of 90% cover. During each experiment, three test plots were evaluated simultaneously. The slope runoff was collected and oven dried to determine the total sediment yield for each test plot. Each test plot was compared to a bare soil control test to determine the effectiveness of the rice straw. The 1.18 in./hr (30 mm/hr) rainfall intensity resulted in an average of 54% improvement from bare soil conditions. The highest percentage improvement occurred with the 3.54 in./hr (90 mm/hr) rainfall intensity with an improvement of 63%. The rice straw was not as effective with the 1.96 and 2.76 in./hr (50 and 70 mm/hr) intensities resulting in a percent improvement of 47% and 45%.

Bjorneberg et al. (2000) evaluated the performance of polyacrylamide under small-scale rainfall simulation. The rainfall simulator was 4.92 ft (1.5 m) long by 3.94 ft (1.2 m) wide by 0.66 ft (0.2 m) deep with a 2.4% slope. Veejet nozzles were mounted 9.84 ft (3 m) above the soil surface and produced a drop size of 1.2 mm and a rainfall intensity of 3.15 in./hr (80 mm/hr). The rainfall simulation test lasted for a duration of 15 minutes exposing the soil to 0.79 inches (20 mm) of total rainfall. Wheat straw was installed on the test plots at an application rate of 2230.45 lb/ac (2500 kg/ha) with a target of 70% cover factor. Each experiment consisted of three 15-minute irrigations. The polyacrylamide (PAM) was installed during the first irrigation onto the bare soil control test and the straw test at an application rate of 0, 1.78, and 3.57 lb/ac (0, 2, and 4 kg/ha). The cumulative soil loss for the bare soil with PAM significantly decreased as the amount of PAM was increased from 0 to 3.57 lb/ac (0 to 4 kg/ha). The bare soil test with no PAM had a cumulative soil loss of 1811 lb/ac (2030 kg/ha) while the bare soil with PAM installed at an application rate of 0.57 lb/ac was 704.82 lb/ac (4 kg/ha was 790 kg/ha). The straw installed without PAM decreased the cumulative soil loss to 122 lb/ac (137 kg/ha). The straw with PAM installed at an application rate of 1.78 lb/ac (2 kg/ha) had a cumulative soil loss of 50 kg/ha and the straw with PAM installed at an application rate of 3.57 lb/ac (4 kg/ha) resulted in 50.85 lb/ac (57 kg/ha) soil loss. The PAM decreased the runoff by 85% with straw and decreased runoff by 40% with bare soil.

This study concluded that adding straw to bare soil instead of PAM was a more effective method in reducing soil loss.

Holt et al. (2005) developed a pressurized rainfall simulator to compare the performance of cotton, wood, and paper hydraulic mulches. The rainfall simulator consisted of three test plots measuring 10 ft long by 2 ft wide by 3 inches deep with a slope of 9%. The rainfall simulator produced a single rainfall intensity of 4.1 in./hr. The recycled cotton products from stripper waste, picker waste, and ground stripper waste were compared to traditional hydro-mulches. Each experiment lasted for a duration of 30 minutes once runoff started. The COBY red was the best performing mulch with a soil loss of 3.80 t/ac. The peanut hulls was the second best performing product with a sediment loss of 5.07 t/ac. The worst performing product was the paper hydromulch with a sediment loss of 12.12 t/ac. This study found that the cotton-based hydromulches performed equal to if not better than the traditional wood and paper hydromulches.

2.6 ROLLED EROSION CONTROL PRODUCTS

Rolled erosion control products (RECPs) are used to reduce erosion from unprotected slopes and channels. RECPs are made of a variety of practices including straw, wood, jute, plastic, nylon, paper, and cotton. RECPs are commonly installed as an alternative to mulching practices where a more structured erosion control product is required. The selection of RECP type is determined by site characteristics such as steepness of slope, length of slope, and the required product longevity. RECPs are divided into two main categories consisting of erosion control blankets (ECB) and turf reinforcement mats (TRM). An ECB is a temporary blanket used to protect the seed and soil from raindrop impacts, promote germination, vegetation establishment, and prevent soil erosion. Since ECBs are temporary, the establishment of vegetation is crucial for erosion prevention beyond the product longevity. TRMs are permanent ECBs used to provide permanent soil stabilization most commonly on steep slopes and channels. TRMs are constructed of a permanent matrix, which aids in the stabilization of vegetation root structure. This process allows the vegetation to withstand higher flow rates, hydraulic uplift, and shear forces (AL-SWCC 2018).

The Alabama Department of Transportation (ALDOT) Standard Specifications for Highway Construction specifies which classification of RECPs shall be used based on site characteristics. The maximum slope or the maximum shear stress are the two factors used for product selection as depicted in Table 2.2.

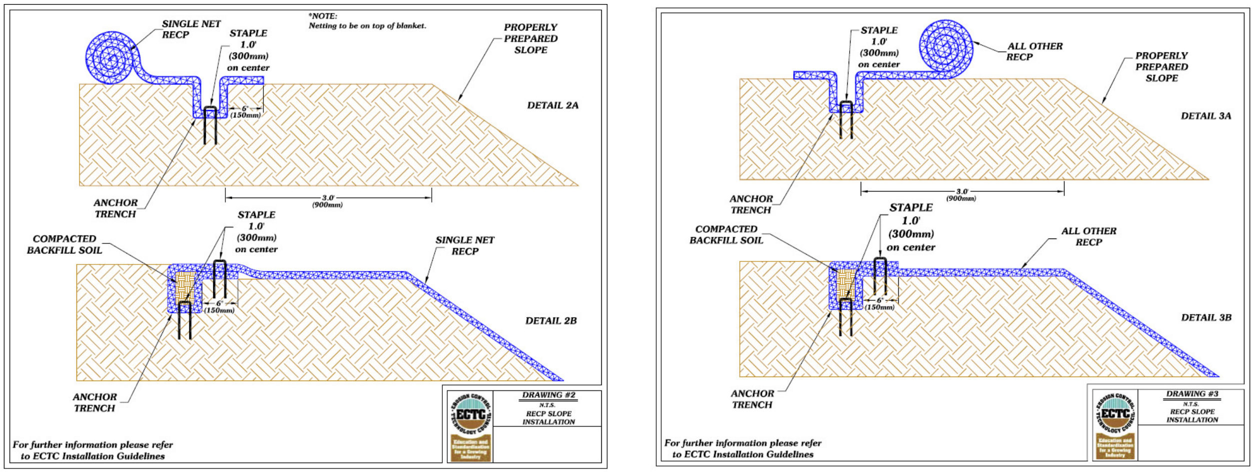
TABLE 2.2: Erosion Control Product Classification (ALDOT 2018)

Product Application	ECP Type	Maximum Slope (H:V)	Maximum Anticipated Channel Shear Stress (Pounds per Square Foot)
Slope	S4	4H:1V	-
	S3	3H:1V	-
	S2	2H:1V	-
	S1	1H:1V	-
Channel	C2	-	2.0
	C4	-	4.0
	C6	-	6.0
	C8	-	8.0
	C10	-	10.0

2.7 RECP INSTALLATION PROCEDURES

The AL-SWCC references the general installation guidelines created by the Erosion Control Technology Council (ECTC), but requires that product guidelines created by the product manufacturers be followed over the general guidelines developed by ECTC. Prior to RECP installation, the site must be properly prepared for optimal product performance. The site preparation consists of grading and the removal of debris such as weeds, sticks, stones, and roots. Soil amendments and seed shall be incorporated into the soil as needed for site-specific soil conditions. RECPs must be rolled in the direction of flow to reduce the amount of erosion. RECPs must also maintain close contact with the soil and must not be stretched for optimal erosion prevention. Temporary ECBs use a U-shape 11 gauge wire staple with a minimum 6-inch length and 1-inch width. TRMs must be anchored using one of the following two methods. The first is by using a minimum 8-inch long by 2-inch wide 11 gauge wire U-shaped staples. The second consists of a 1-inch by 3-inch wooden stake with a length of 12 to 18 inches depending on soil compaction rates. The stakes must be spaced 4 ft on center along the edge of the TRM (AL-SWCC 2018).

Prior to installing the RECP, a 6-inch wide by 6-inch deep trench must be created at the top of the slope. Under ideal conditions, the trench will be located 3 ft from the crest of the slope. The RECPs will be anchored to the bottom of the trench with U-shape staples spaced at 12 inches on center. Once the blanket was anchored in the trench, the trench was backfilled and compacted. There are two primary methods for trenching the blanket into the trench. The first leaves an extra 12 inches of blanket downslope of the trench while the rest of the blanket was rolled from the upslope side of the trench over the trench and down the slope. The second method leaves 12 inches of extra blanket upslope of the trench and is laid over the trench and stapled downslope of the trench (ECTC 2014). These trenching procedures are depicted in Figure 2.6.



(a) Trenching Method 1 (b) Trenching Method 2

FIGURE 2.6: RECP Anchoring Methods (ECTC 2014)

Once the RECP is anchored, the blanket can be rolled down the slope with the guidance of an installer. The blanket shall be gently pulled to remove any slack at 20 to 25 ft increments down the slope. Once the blankets have been rolled out to the end of the slope, the stapling pattern designated by the product manufacturer should be followed. The Federal Highway Administration (FHWA) FP-03 specifies that an RECP should have a minimum stapling rate of 1.5 staples per square yard. The staples are most commonly staggered 18 to 24 inches horizontally across the slope and the edges of the blankets shall be connected or overlapped to adjacent blankets as specified by the product manufacturer. The terminal end of the blanket should be trenched into the ground following the same procedures as the upslope trench. The downslope trench and stapling patterns are depicted in Figure 2.7 (ECTC 2014).

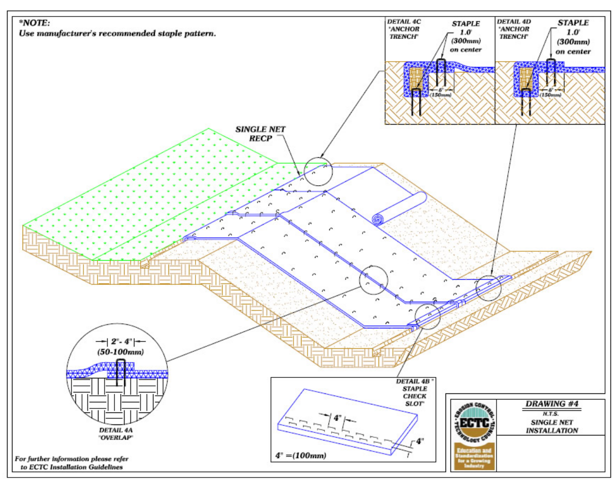


FIGURE 2.7: Downslope RECP Anchoring (ECTC 2014)

2.8 RECP TESTING

Ming Han et al. (2013) evaluated the erosion control product performance of under indoor rainfall simulator at the Texas A&M Transportation Institute (TTI). The indoor rainfall simulator was 30 ft (9.1 m) long by 6 ft (1.83) wide by 9 in (3.54 cm) deep with a 33% slope. The rainfall simulator generated rainfall intensities of 3.5 in./hr from drip emitters at a height of 14 ft (4.3 m). The average drop size for this rainfall simulator ranged from 3-4 mm. The products were evaluated for 30 minutes once every 24 hours for three tests. The products evaluated for this experiment were a straw ECB bound by jute netting, straw ECB bound by polypropylene netting, excelsior ECB, and bonded fiber matrix. The products were installed on clay and sand. The clay soil produced significantly lower erosion rates than the sand soil. The best performing erosion control product installed on the clay soil was the straw ECB with jute netting with a soil loss rate of 7.91 lb/10ft2 (1.62 kg/10 m2). The worst performing product was the bonded fiber matrix with a soil loss rate of 19.6 lb/10ft2 (4.02 kg/10 m2). The sand soil produced much larger amounts of soil loss than the clay soil. The excelsior ECB was the best performing erosion control practice on the sandy soil with a soil loss rate of 281.25 lb/10ft2 (57.6 kg/10 m2). The bonded fiber matrix was again the worst performing erosion control practice with a soil loss rate of 831.5 lb/10ft2 (170.3 kg/10 m2).

Faucette et al. (2007) constructed a small-scale pressurized rainfall simulator to evaluate the performance of erosion control blankets. The rainfall simulator test plot was 16 ft long by 3.3 ft wide with a slope of 10%. The simulator produced a rainfall intensity of 4 in./hr for a 1-hour duration at a pressure of 6 psi. The ECBs evaluated for this experiment were straw with pam, wood mulch, 1:2 blend of compost to wood mulch, 2:1 blend of compost to wood mulch, 100% yard waste compost, and compost with Bio-floc. The results from these product evaluations were compared to bare soil control conditions. The results of these products are depicted in Table 2.3.

TABLE 2.3: Faucette et al. 2007 ECB Results

Blankets	Total Solids (lb/ac)	TSS Total (lb/ac)	Turbidity (NTU)
Bare Soil	6,108	4,710	7,686
Straw w/ PAM	990	583	940
100% Wood Mulch	86	46	36
1:2 Blend	115	54	60
2:1 Blend	186	58	87
100% Compost	364	252	288
Compost with Bio-Floc	-	192	139

The best performing erosion control blanket for all three parameters was the wood mulch blanket. The wood mulch blanket had a reduction in total solids of 98.6% as compared to the bare soil control test. The wood mulch blanket had a calculated C-factor of 0.013. The straw with PAM blanket was the worst performing product with a percent reduction from bare soil control testing for total solids of 84%. The straw with PAM blanket had a C-factor of 0.189. The 100% compost blanket did not perform as well as the blended compost blankets with wood mulch (Faucette et al. 2007).

Lipscomb et al. (2006) conducted a study using a large-scale rainfall simulator following ASTM D6459 to compare the effectiveness of blown straw and an erosion control blanket. The rainfall simulator was a pressurized system that produced three sequential 20-minute rainfall segments of 2, 4, and 6 in./hr. The test plot is 40 ft long by 8 ft wide. The blown straw was installed to the test plot at an application of 2500 lb/ac. A single netted, temporary erosion control blanket was installed. The blanket was installed with U-staples at the rate recommended by the manufacturer. During each rainfall experiment, the runoff was collected to quantify the total sediment yield of the test. Unprotected bare soil control tests were performed to obtain a reference of the product performance. This study found that blown straw had little benefit on the steep slopes. The study concluded that straw was most effective when installed on shallow slopes. The single net ECB was over 98% effective on the sandy loam soil and 80% on the clay soil as compared to corresponding bare soil control tests. This experiment concluded that ECBs perform better on steep slopes due to their resistance to runoff and the minimal blanket filler displacement.

Benik (2003) created a large scale pressurized rainfall simulator to evaluate the performance of erosion control blankets on hillslopes. The simulator test plot was 32 ft long by 7.9 ft wide with a 2.8H:1V slope. The rainfall simulator had a regulated pressure of 8 psi (55 kPa) and produced a rainfall intensity of 2.4 in./hr. This experiment evaluated bare soil control, crimped straw mulch at an application rate of 0.092 lb/ft^2 , bonded fiber matrix at an application rate of 160.8 lb/ft^2, straw/coconut blanket, and a wood fiber blanket. The products were evaluated during various conditions with and without the establishment of vegetation. The sediment yield results are depicted in Table 2.4.

TABLE 2.4: Sediment Yield Results Benik (2003)

Product	Spring No Vegetation lb/ac (kg/ha)	Fall Vegetation lb/ac (kg/ha)
Bare Soil	8505 (9533)	1001 (1122)
Straw Mulch	1469 (1647)	267 (299)
Bonded Fiber Matrix	216 (242)	196 (220)
Straw/Coconut Blanket	188 (211)	137 (153)
Wood-Fiber Blanket	263 (295)	88 (99)

The spring tested evaluated the performance of the erosion control practices without the establishment of vegetation. The straw/coconut blanket was the best performing product with a sediment yield of 188 lb/ac, which is a 98% reduction in sediment yield from the bare soil control conditions. The straw mulch was the worst performing erosion control practice with a sediment yield of 1467 lb/ac, which is an 83% reduction is sediment yield from the bare soil control test. The second testing evaluated the performance of erosion control practices with the establishment of vegetation in the fall. The wood-fiber blanket was the top performing erosion control product with a sediment yield of 88.32 lb/ac, which is a 91% reduction in sediment yield from the bare soil conditions with vegetation. The straw mulch was again the worst performing erosion control practice evaluated. There was a significant difference in the sediment yield between the spring test and the fall test. The establishment of vegetation alone allowed the sediment yield for a bare soil control test to decrease by 88% (Benik 2003).

Rickson (2006) evaluated the performance of erosion control geotextiles under small-scale rainfall simulation and runoff simulation. The study evaluated the performance of geojute, fine geojute, enviramat, enkamat s, bachbett, enkamat b, and tensarmat as compared to bare soil control tests. The rainfall simulator experiments consisted of a 1.4 in./hr (35 mm/hr) rainfall intensity for 15 minutes or 4.53 in./hr (115 mm/hr) rainfall intensity for 10 minutes. The rainfall simulation was used to determine the effectiveness of the geotextiles in protecting the soil from splash erosion. The geojute, fine geojute, enviramat, bachbett were the best performing products. This study found that the higher the coverage area of the geotextile, the more effective the product was in protecting from splash erosion. The thicker geotextiles were more effective at ponding water, which aided in the reduction of splash erosion. Another factor that prevented erosion was the water holding capacity of the geotextiles. The geotextiles with the highest water holding capacity weighed more and therefore maintained good contact with the soil surface. Following the rain splash testing, a runoff experiment was conducted on a test plot measuring 6.6 ft (2 m) long by 3.28 ft (1 m) wide by 3.94 in (10 cm) deep at a 10˚ slope. The flow rate introduced to the test plot was 0.63 gpm (2.4 L/min) for 10 minutes, which is the equivalence of a 2.83 in./hr (72 mm/hr) rainfall intensity for ten minutes. The only geotextile the noticeably reduced the amount of runoff from a bare soil control test was the buried tensarmat. The results from the runoff experiment showed that geotextiles are not effective in reducing runoff.

2.9 REVISE UNIVERSAL SOIL LOSS EQUATION

The Revised Universal Soil Loss Equation (RUSLE) is an update to the original Universal Soil Loss Equation (USLE). USLE and RUSLE generate quantifiable results, which allow researchers to evaluate the performance of best management practices (BMPs). USLE was developed in 1954 at the National Runoff and Soil Loss Data Center. USLE method for quantifying soil erosion was developed from 49 locations with more than 10,000 test plots (USDA 1978 and USDA 1997). This method uses a rainfall runoff erosivity factor (R), soil erodibility factor (K), length slope steepness factor (LS), cover-management factor (C), and a support practice factor (P) to calculate the average annual soil loss in tons/acre/year. Factors LS, C, and P are dimensionless. C-factors closer to zero are considered best practices where as when C-factor equals 1, there is no cover management and the surface is bare soil and exposed to the elements. In 1992, RUSLE was released by the United States Department of Agriculture (USDA). RUSLE applied additional research to USLE by introducing new isoderent maps, a sub factor approach for evaluating the C-factor, a new equation for the LS factor and new P-factor values (USDA 1997). The RUSLE equation is depicted in Equation 2.2.

$$A=R\times K\times LS\times C\times P \tag{2.2}$$

where,

A = average annual soil loss (tons/acre/year)
R = Rainfall Erosivity Factor (hundreds of ft – tonf – in. – acre^{-1} – yr^{-1})
K = Soil Erodibility Factor (ton – acre – hr – [hundreds of acre-ft – tonf – in.]$^{-1}$)
LS = Length Slope Steepness Factor
C = Cover Management Factor
P = Support Practice Factor

2.9.1 Rainfall Erosivity Factor - R

The rainfall erosivity factor (R) quantifies the effect of the total storm kinetic energy (E) and the maximum 30-minute rainfall intensity (I_{30}) (USDA 1978). The total storm kinetic energy is calculated by determining the unit energy of the storm using the calculated rainfall intensity and the depth of rainfall for the desired storm increment (Clopper et al. 2004). I_{30} is determined by using the rainfall intensity when a time increment exceeds 30 minutes or by calculating the weighted average of varying intensities over a 30-minute interval (Early et al., 2003). Once E and I_{30} are calculated and multiplied together, the number of storms are summed together and divided by the year period to get the R-factor (USDA 1997). The runoff erosivity factor and the rainfall energy are calculated using Equations 2.3 and 2.4.

$$R = \frac{\sum_{i=1}^{J}(EI_{30})i}{N} \tag{2.3}$$

where,

R = Runoff Erosivity Factor (hundreds of ft – tonf – in. – acre^{-1} – yr^{-1})
E =total storm kinetic energy (ft – tonf – acre^{-1})
I_{30} = maximum 30-minute rainfall intensity (in./hr)
J = number of storms over N years
N = year period

The unit energy of the storm (e) is calculated using equation (2.4)

$$e = 1099(1 - 0.72e^{-1.27\times i}) \tag{2.4}$$

where,

e = rainfall energy per unit depth of rainfall per unit area (ft – tonf – acre^{-1} – in-*1*)
i = rainfall intensity (in./hr)

2.9.2 Soil Erodibility Factor – K

The soil erodibility factor (K) is the ease at which soil is eroded from splash erosion and overland flow during rainfall events. The soil erodibility factor accounts for the impact of rainfall, runoff, and infiltration on the soil loss. The K-factor is measured as "the rate of soil loss per erosion index unit as measured on a unit plot (USDA 1997)." The K-factor for a given soil can be calculated from bare soil plots, which have a cover management (C-factor) and support practice (P-factor) factors of one. The K-factor is determined by using the R-factor, LS factor, and the soil loss per test plot (A) as depicted in Equation 2.5. A new K-factor can be calculated for each R-factor (Clopper et al. 2004).

$$K = \frac{A}{(LS)(R)} \tag{2.5}$$

where,

K = Soil Erodibility Factor (ton – acre – hr – [hundreds of acre-ft – tonf – in.]$^{-1}$)
A = Average Annual Soil Loss (tons/acre/year)
LS = Length slope steepness factor
R = Rainfall Erosivity Factor (hundreds of ft – tonf – in. – acre^{-1} – yr^{-1})

2.9.3 Length Slope Steepness Factor – LS

The length slope steepness factor (LS) is dimensionless and is broken down into the slope length factor (L) and the slope steepness factor (S). LS represents the soil loss ratio of the test plot to the standard RUSLE plot (LS factor = 1.0) of 72.6 feet in length and a slope of 9% (Clopper et al. 2004). The LS factor can be less or greater than 1.0. A smaller LS factor means the plot or site topographic and geometric setting will result in less soil loss from rainfall. The slope length factor (L) is calculated using Equation 2.6.

$$L = (\frac{\lambda}{72.6})^m \tag{2.6}$$

where,

L = slope length factor
λ = horizontal projection of slope length
m = variable slope length exponent

In order to determine the L-factor, the variable slope length exponent (m) must be calculated. The slope angle is used to in Equation 2.7 to calculate the ratio of rill to interrill erosion (β), and β can then be used in Equation 2.8 to calculate m (USDA 1997).

$$\beta = (\frac{sin\theta}{0.0896})/[3.0(sin\theta)^{0.8} + 0.56] \quad (2.7)$$

where,

β = ratio of rill to interrill erosion
θ = slope angle (degrees)

$$m = \frac{\beta}{1+\beta} \quad (2.8)$$

where,

m = variable slope length exponent
β = ratio of rill to interrill erosion

The slope steepness factor (S) is calculated in Equation 2.9 or 2.10 by using the slope angle (θ). Equation 2.9 is used to calculate S on slopes that have a steepness of less than 9%, while Equation 2.10 is for slopes with a steepness greater than or equal to 9% (USDA 1997).

$$S = 10.8\ sin\theta + 0.03 \quad (2.9)$$

$$S = 16.8\ sin\theta - 0.50 \quad (2.10)$$

where,

S = slope steepness factor
θ = slope angle (degrees)

2.9.4 Cover Management Factor – C

The cover management factor (C) is a dimensionless ratio used to represent the performance of cropping and BMPs on reducing the soil loss at a scale ranging from zero to one (USDA 1997). “C represents the ratio of soil loss from an area with specified cover and management to the soil loss from a bare, unprotected, uncovered slope (e.g., titled, continuous fallow)” (Early et al., 2003). Soil that is well protected (i.e., resulting minimum or near zero soil loss) will result in a C-factor close to zero and a poorly protected soil results in a value close to one (Karpilo 2004). In order to calculate the C-factor of BMPs, the K-factor must first be determined from bare soil testing results. The least squares linear regression method can be used to determine the C-factor for the BMP. The least squares linear regression method plotted the soil loss and the R-factor to create a trendline equation to calculate the C-factor (Early et al., 2003).

2.9.5 Support Practice Factor – P

The support practice factor (P) is a dimensionless ratio of the soil loss due to support practices. The practices evaluated by P adjust the flow pattern, grade, or direction of runoff. Some commonly used P-factors consist of contouring, strip-cropping, terracing, and subsurface drainage (USDA 1997). "P represents the ratio of soil loss from an area with a support practice like contouring, stripcropping, or terracing to the soil loss from an area with straight-row farming up and down the slope" (Early et al., 2003).

2.10 RESIDUAL PAM TESTING

Interest in polyacrylamide (PAM) performance and its potential environmental impact was also a concern. Though the original proposal did not include this as an objective, through discussion with the PAC, it was suggested that residual testing of flocculants, particularly anionic PAM, be evaluated.

2.10.1 Effects on Soil and Environment

PAM was first used in agriculture in the USA, where it has been shown to reduce sediment loss and increases infiltration (Lentz 2015, Trout et. al 1995, Peterson et. al 2007). PAM can also accelerate settling of sediment when added upstream of sediment basins, reducing turbidity by up to 88% (Trout et. al 1995) and total suspended solids (TSS) by up to 75% (Peterson et. al 2007). PAM bonds mostly with the slightly charged fine clay fraction of soil (McLaughlin et. al 2007) which increases the particles' weight and stability (Flangan et. al 2003). Particle charging also increases hydraulic conductivity as well as infiltration (Xiong et. al 2018), decreasing runoff that is leaving the site. In addition, PAM contributes to coarse aggregate stability when it penetrates into void spaces, increasing mean weight diameter of the soil particles, which is important since larger soil particles are more resistant to erosion (Levy and Miller 1999).

While PAM has numerous benefits for erosion and sediment control applications, excessive quantities in runoff may be undesirable. PAM has been shown to be very safe for aquatic life, including minnows, trout, and mussels (Herth et. al 2015, Seybold 1994, Buczek et. al 2017). Toxicity does vary by product and exposure time, with the concentration resulting in fatality of 50% of the sample (LC_{50}), was as low as 14.1 mg/L for a 96-hr exposure to water fleas (Biem and Biem 1994). A principal concern for any flocculant application is the effect on water viscosity. For PAM, viscosity noticeably increases at concentrations starting at 50 mg/L, which can pose a challenge to small aquatic life. PAM may also flocculate food sources and reduce the density of algae species (Weston 2009). PAM degrades at a rate of 10% per year in soil (Entry et. al 2002) due mostly to ultraviolet exposure, and degradation can lead to more of the release of monomer amide (AMD), the toxic component which does not adsorb (Guezennec et. al 2015), than was originally present (Xiong et. al 2015). Finally, heavy metal ions such as Chromium (IV) have been demonstrated to adsorb to PAM molecules along with the intended ions such as calcium (Ca^{2+}). While this benefits downstream water quality, it also leads to possible accumulation of heavy metal pollution in soil (Wisniewska et. al 2018). PAM has also been shown to absorb organic pollutants from animal-based agriculture such as coliform (Sojka and Entry 2000), benefitting downstream water quality but having an unknown effect on soil. Thus, while PAM is typically safe and has multiple environmental benefits, very high or prolonged doses in runoff should generally be avoided. Therefore, it is important to ensure that PAM concentrations in stormwater runoff leaving construction sites are low, which require methods for testing PAM residuals.

2.10.2 Residual Detection

The best detection method for aqueous PAM depends upon the application scenario and especially upon possible interference sources. Table 2.5 summarizes the primary detection methods and their suitability for construction stormwater. The turbidimetric method (Kang et. al 2014) was developed specifically for detection at construction sites, but yielded inconsistent results when attempted for this study due to probable organic interference from the retention pond source water. The methods fall into four broad categories: (1) chemical (N-Bromination), (2) physical (viscosity measurement, flocculation), (3) chemical-physical (polarography), and (4) special methods (radioactive tagging). Most methods are developed for industrial or wastewater applications.

TABLE 2.5: Detection Methods and Construction Suitability

Method	Procedure Overview	Suitability for Construction Stormwater?
Radioactive Tagging (Lu and Wu 2003)	PAM is labeled with C-14 or Tritium	Small scale detection and sensitive to tagging unwanted material
Total Organic Carbon (TOC) (Lu and Wu 2003)	Very popular method where PAM is analyzed as carbon. It is decomposed and then measured as TOC	Inappropriate for any amount of organic matter (OM) or inorganic carbon ions
Colloid Titration (Mocchiutti and Zaruttini 2007)	Titrate with a cationic indicator such as Polydiallyldimethylammonium using a color indicator and/or spectrometry	Good candidate
Turbidimetric (Kang et. al 2014)	Change in turbidity (NTU) before and after reaction with a suspension agent correlates with dosage	Possibly subject to OM interference
Flocculation Measurement (Lu and Wu 2003)	Measure speed of settling flocs by transmittance change	Subject to OM interference
Viscosity Measurement (Jung et. al 2016)	Surface tension angle and viscosity (using a Brookfield viscometer) correlate to dosage	Small scale samples are taken and highly sensitive
Size Exclusion Chromatography (SEC)(Lu et. al 2003)	Polymer gel column filters PAM from interferences	Good candidate
Spectrometry (Momami and Ormeci 2014)	Absorbance or emittance spectra correlated with dosage	Selected for use
Amide Hydrolysis with Ammonia Detection (Lu and Wu 2003)	Hydrolysis releases ammonia from the PAM chain and is detected by a number of methods	Prohibitive equipment and expertise for application. Subject to OM interference
N-Bromination (Lu and Wu 2003)	A unique method using a series of reaction with bromine to create a starch that is passed through spectrometer	Subject to OM interference. Prohibitive equipment for application
Polarography (Betso and McLean 1976)	Current response vs. voltage are obtained at different PAM doses	Prohibitive materials and equipment for application

Of rainfall simulator experiments, only a few small-scale, low-intensity projects have attempted to detect concentrations of PAM in runoff. A study by McLaughlin et. al 2014 used 100 cm by 50 cm (3.3 ft by 1.6 ft) plots at 5% slope and a rainfall intensity of 8.3 cm/hr (3.3 in./hr) in conjunction with ultra-high performing erosion control blankets and found runoff concentrations on the order of 6-17 mg/L. Sadeghi et. al 2016 used plots of 0.5 m^2 (5.4 ft^2) at a 20% slope and a rainfall intensity of 7.2 cm/hr (2.8 in./hr) and found concentrations around 10 mg/L.

2.11 SUMMARY

This section provides an overview of how rainfall simulation testing is used to evaluate erosion control practices. This study examined dripper and pressurized rainfall simulators and how these two types of simulators vary in design and performance. The most important aspects of a rainfall simulator are the raindrop size distribution, rainfall intensity, and the uniformity. The drop size distribution of a simulator can be determined in a number of ways consisting of the flour pan, laser, momentum, oil, and stain method. Rainfall simulators have many design characteristics that effect the test results such as the rainfall simulator type, test plot dimensions, slope, experimental rainfall intensity, and the products being evaluated. These variations in rainfall simulators analyzed in this literature review are depicted in Table 2.6.

Table 2.6: Literature Review Summary

Study	Rainfall Simulator Type	Test Plot Dimensions	Slope	Rainfall Intensity	Tested Product
Khan et al. 2016	Dripper	3.28 ft x 1 ft	5˚, 15˚, and 25˚	1.29, 2.13, 3.70, and 4.70 in./hr	Wheat Straw
Wilson et al. 2010	Pressurized	4 ft x 2 ft	3H:1V	4.4 in./hr	Crimped straw Straw w/ Tackifier Hydraulic Mulches
Ming-Han 2014	Dripper	30 ft x 6 ft	2H:1V 3H:1V	3.5 in./hr	Crimped Wheat Straw
Barnett et al. 1967	Pressurized	30 ft x 6 ft	2.5H:1V	2.5 in./hr	Crimped Straw Straw w/ Tackifier
Foltz and Dooley 2003	Pressurized/Flow	4.1 ft x 13.1 ft	30%	1.97 in./hr Flow of 0.26 gpm	Loose Straw Wood Strands
Gholami et al. 1994	Pressurized	19.7 ft x 3.3 ft	30%	1.18, 1.97, 2.76, and 3.54 in./hr	Rice Straw
Bjorneberg et al. 2000	Pressurized	4.9 ft x 3.9 ft	2.4%	3.15 in./hr	Wheat Straw with PAM
Holt et al. 2005	Pressurized	10 ft x 2 ft	9%	4.1 in./hr	Cotton, wood, and paper hydraulic mulches
Ming-Han et al. 2013	Dripper	30 ft x 6 ft	2H:1V 3H:1V	3.5 in./hr	TRM, Open Weave Textile, Straw ECB, excelsior ECB, Hydraulic Mulch
Faucette et al. 2007	Pressurized	16 ft x 3.3 ft	10%	4 in./hr	Straw, wood, blend, compost ECB
Lipscomb et al. 2006	Pressurized	40ft x 8 ft	3H:1V	2, 4, and 6 in./hr	Blown straw vs. Straw ECB
Benik 2003	Pressurized	32 ft x 7.9 ft	2.8H:1V	2.4 in./hr	Straw mulch, hydraulic mulch, straw/coconut blanket, and wood fiber blanket
Rickson 2006	Pressurized	6.6 ft x 3.3 ft	10˚	1.4 and 4.53 in./hr	Geotextiles

With the large variation is design and testing procedures of the rainfall simulators, it is evident that a standardized testing procedure and rainfall simulator design should be followed to allow for comparison of results. Through the examinations of these rainfall simulation experiments, it was determined that the small-scale rainfall simulators produced lower erosion rates than the larger-scale rainfall simulators. These studies also showed that installing an erosion control with anchoring greatly increases the overall performance of the product. Based on these results, it was decided to follow a standardized testing procedure in order to produce product performance results that are comparable to other testing facilities.

CHAPTER 3: TEST OVERVIEW

3.1 INTRODUCTION

This section presents experimental procedures for the calibration, validation, and product installation of the large-scale rainfall simulator at the Auburn University Erosion and Sediment Control Test Facility (AU-ESCTF). Test methodologies and product installation procedures are based on *The Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion* (ASTM D6459), the Erosion Control Technology Council (ECTC), manufacturer recommendations, and additional ASTM test procedures.

The primary research objective of this project was to evaluate the performance of various erosion control practices used on Alabama Department of Transportation (ALDOT) projects through large-scale rainfall simulation. Calibration testing was initially performed to determine the optimal location of sprinkler risers, nozzle size, and operating pressure to achieve desirable rainfall uniformity, rainfall intensity, and drop size distribution. The flour pan method was used to evaluate the drop size distribution for each rainfall intensity. Upon completion of the calibration testing, bare soil control tests were completed to develop the slope preparation procedure, experimental testing procedure, and to evaluate bare soil performance. Each test was evaluated from the collection of water samples to determine the Total Suspended Solids (TSS) and turbidity, soil loss in the catch basin, and the discharge over time measurements. The product-testing phase of the project evaluated loose straw, loose straw with tackifier, crimped straw, hydraulic erosion control products (HECP), and rolled erosion control products (RECP).

3.2 CALIBRATION TESTING

Calibration testing was performed to verify if the designed rainfall simulator met the ASTM D6459 standards for uniformity, intensity, and drop size distribution. Nozzle size and sprinkler location were adjusted during the calibration process to achieve consistent and repeatable rainfall conditions for the 2, 4, and 6 in./hr rainfall intensities.

3.2.1 Rainfall Uniformity and Intensity

The rainfall intensity was measured by installing 20 rain gauges throughout the test plot. The layout of the rain gauges is depicted in Figure 3.1.

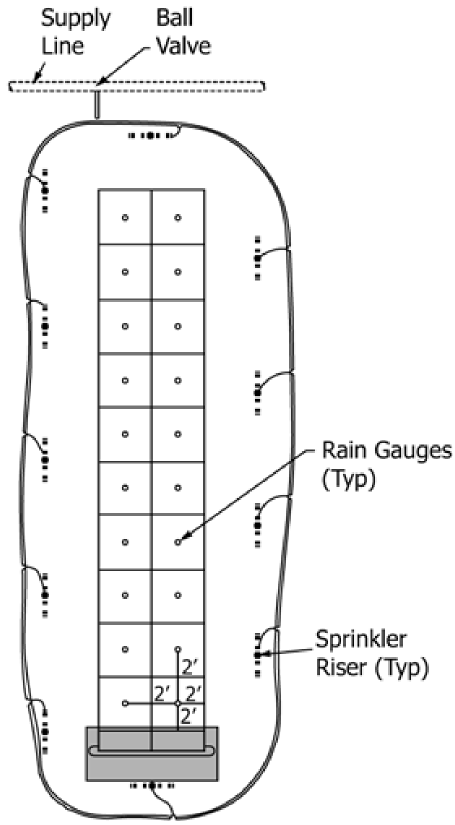


FIGURE 3.1: Rain Gauge Layout (ASTM 2019)

Prior to calibration testing, an anemometer was used to evaluate the wind speeds. If the wind speed at the time of the test exceeded 1 mile per hour, the wind curtains were installed. For the 2, 4, and 6 in./hr (51, 102, and 152 mm/hr) rainfall intensities, a group of 15-minute calibration tests was performed. Following the completion of the test, each rain gauge depth was recorded in a spreadsheet to calculate the Christiansen Uniformity Coefficient (Equation 3.1) and the rainfall intensity (Equation 3.2).

$$C_u = 100\,[\,1.0 - \sum|d| \div n\,\bar{X}] \tag{3.1}$$

where,

C_u = Christiansen uniformity coefficient
d = $X_i - \bar{X}$
n = number of observations
X = average depth caught, in.
X_i = depth caught in each rain gauge, in.

$$i = 60[\textstyle\sum_{j=1}^{J} P_j \div Jt] \tag{3.2}$$

where,

i = rainfall intensity, cm/hr
P_j = depth of rainfall, cm
J = number of rain gauges
t = time of test

Calibration tests were repeated a minimum of 10 times for each rainfall intensity to ensure consistency and repeatability of the rainfall simulator. The rain gauge layout and calibration testing is depicted in Figure 3.2.

(a) Rain gauge layout (b) Rainfall during calibration test

FIGURE 3.2: Uniformity and Intensity Testing

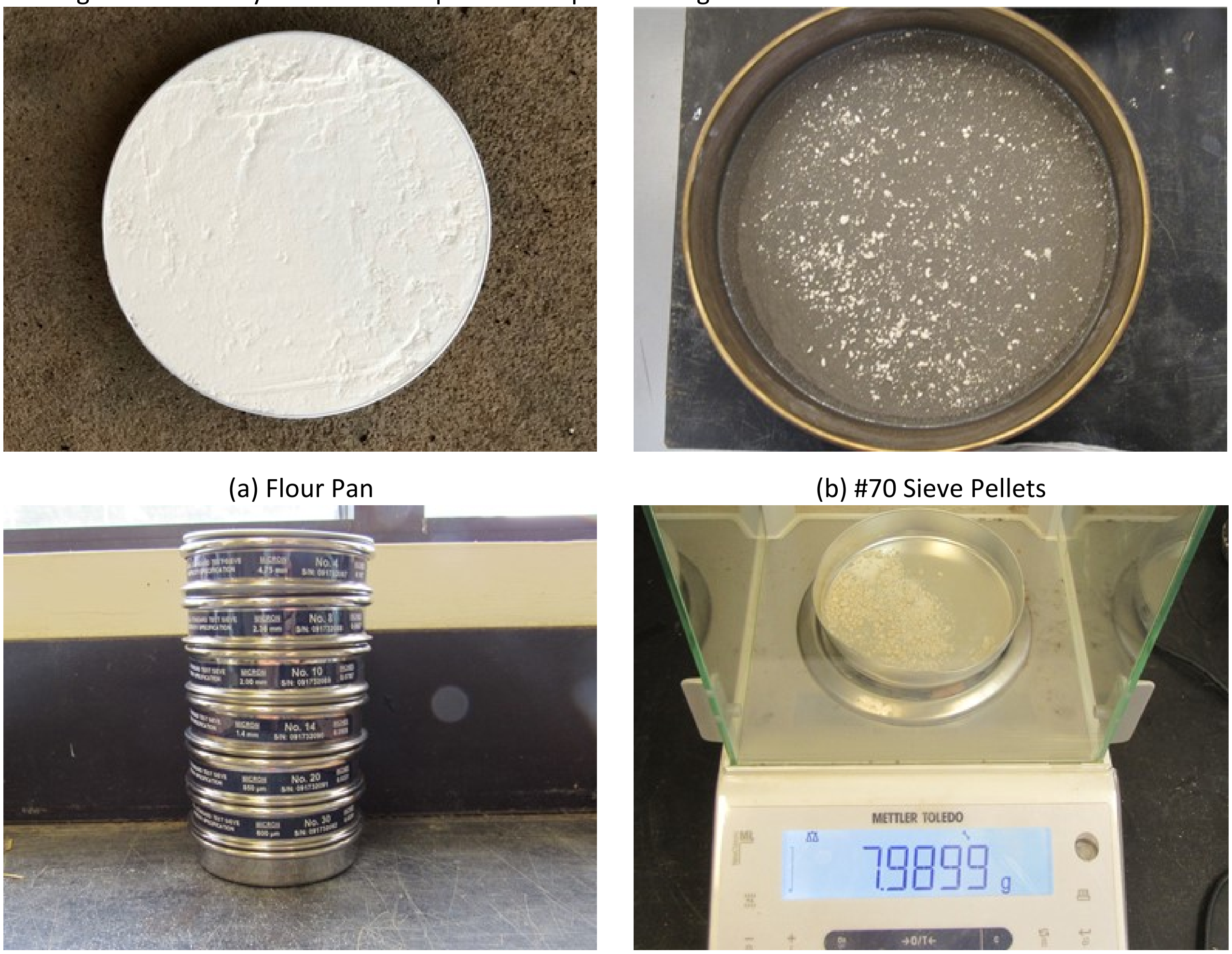
3.2.2 Drop Size Distribution

After the desired uniformity and rainfall intensity was reached, the flour pan test was used to evaluate the drop size distribution for the 2, 4, and 6 in./hr rainfall intensities (Laws and Parsons 1943). An 8.5-inch diameter aluminum pie pan was filled to the edge with sifted Pillsbury all-purpose flour. The excess flour was struck off with a straight edge to create a smooth surface along the edge of the pie pan. The rainfall simulator was turned on to the desired rainfall intensity and the covered flour pan was placed on a level wooden stand. The top of the aluminum pie pan was removed by pulling the cover toward the experimenter for 2 to 4 seconds before recovering the pan. This procedure was performed at the top, middle, and bottom of the slope for each rainfall intensity. The flour pan sampling procedure is depicted in Figure 3.3.

(a) Covered Flour Pan (b) Uncovered Flour Pan

FIGURE 3.3: Flour Pan Field Procedure

The flour was air dried for a minimum of 12 hours. The air-dried flour was gently sieved through a #70-wire mesh sieve. The pellets were inspected to remove combined or misshapen pellets and the remaining flour pellets were placed in the oven for 2 hours at 110 °F. The oven dried pellets were sieved through the #4, #8, #10, #14, #20, and #30 sieves. The flour pellets retained on each sieve were counted and weighed. The analysis of the flour pellets is depicted in Figure 3.4.



(a) Flour Pan (b) #70 Sieve Pellets

(c) Testing Sieves (d) Weighing pellet samples

FIGURE 3.4: Flour Pan Lab Testing

Each rainfall intensity collected three flour pan samples, which were all added together for drop size distribution analysis. The total weight of the flour pellets retained on each sieve was calculated by adding the weights for all three samples. The average weight of the pellets retained on each sieve is determined by dividing the total weight per sieve by the total number of pellets. The mass ratio was calculated to convert the mass of the average pellet into the mass of the average drop using Equation 3.3.

$$M_R = (0.038) * \ln(W_{avg}) + 1 \qquad (3.3)$$

where,

M_R = mass ratio
W_{avg} = average pellet weight, mg

The average diameter of the pellets was calculated by multiplying the average weight and the mass ratio as depicted in Equation 3.4.

$$D_{avg} = \sqrt[3]{\frac{6}{\pi} \times W_{avg} \times M_R} \qquad (3.4)$$

where,

D_{avg} = average drop diameter, mm
W_{avg} = average weight, mg
M_R = mass ratio

The adjusted pellet weight was calculated by multiplying the total pellet weight for each sieve by the sieves corresponding mass ratio. The adjusted mass percentage was calculated by dividing the adjusted total pellet weight per sieve by the total adjusted pellet weight for pellets retained on all the sieves. The fall velocity was calculated by developing a regression equation from the raindrop fall velocity measurements from 15 feet. The regression equation was formed by plotting the raindrop size and the corresponding fall velocity from Figure 3.5. The regression equation is depicted by Equation 3.5.

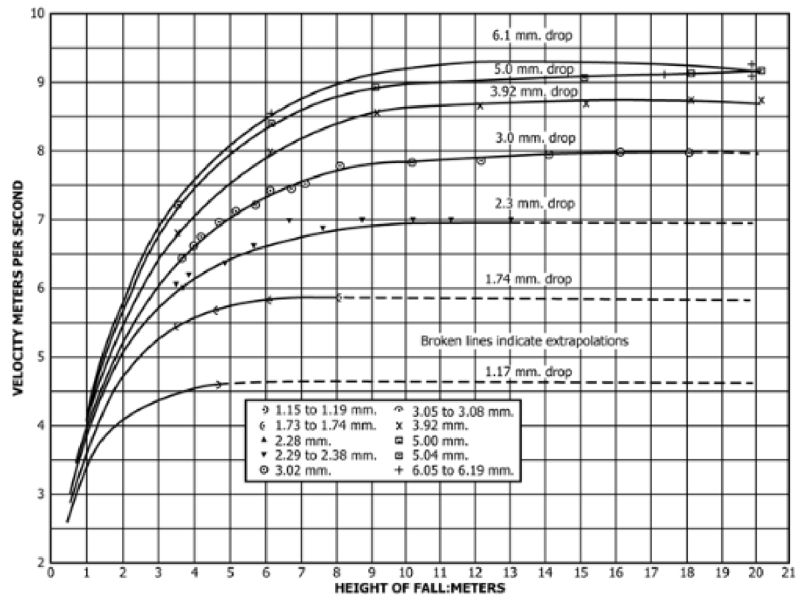


FIG. 6 Velocity of Fall of Seven Sizes of Water Drops After Heights of Fall from 0.5 to 20.0 m.

FIGURE 3.5: Raindrop Fall Velocity Chart (ASTM 2015)

$$y = -0.1667x^2 + 1.8235x + 2.8602 \quad (3.5)$$

where,

y = fall velocity, m/s
x = raindrop size, mm

The total rainfall volume for each rainfall intensity was calculated by converting the rainfall intensity to feet and multiplying by the test plot area of 320 square feet. The rainfall weight was calculated by multiplying the rainfall volume by 62.4 lb/ft^3, the density of water. The total rainfall weight was converted to slugs by dividing the weight by 32.2 ft/s^2. The incremental weight of rainfall retained on each sieve was calculated by multiplying the rainfall mass by the percentage of rainfall. The kinetic energy for each sieve was calculated by implementing Equation 3.6.

$$KE = \frac{1}{2}mv^2 \quad (3.6)$$

where,

KE = kinetic energy of sieve, lb-ft
m = incremental rainfall mass, slug

v = raindrop fall velocity, ft/s

The kinetic energy was then converted to foot-tons by dividing the original kinetic energy by 2000 lb/ton. The total kinetic energy for the test plot is calculated by dividing the KE in foot-tons by the area of the test plot in acres as depicted by Equation 3.7.

$$E = \frac{KE}{\left(\frac{A}{43560}\right)} \tag{3.7}$$

where,

E = total kinetic energy, ft-ton/acre
A = total test plot area, ft^2
KE = kinetic energy, ft-ton

The total kinetic energy for each sieve was summed together for all three-rainfall intensities. The maximum 30-minute rainfall intensity was calculated by determining the maximum possible rainfall intensity occurring during the hour-long experiment. Therefore, I_{30} was calculated using Equation 3.8.

$$I_{30} = \frac{\left(4\frac{in}{hr}\times 10\text{ min}\right)+\left(6\frac{in}{hr}\times 20\text{ min}\right)}{30\ min} \tag{3.8}$$

where,

I_{30} = maximum 30-minute rainfall intensity, in./hr

The theoretical erosivity index was calculated by multiplying the total kinetic energy with a conversion of 0.01 and I_{30}. The theoretical erosivity index was later used to aid in the Revised Universal Soil Loss Equation (RUSLE) calculations analyzing product performance.

3.3 VALIDATION PROCEDURES

Following the completion of calibration testing for the 2, 4, and 6 in/ rainfall intensities, bare soil control tests were performed to provide a benchmark comparison to erosion control product performance.

3.3.1 Slope Preparation

Prior to rainfall simulation testing, the test slope must be prepared in a consistent and repeatable manner. To remove rills or slope damage from prior testing, the entire test slope was tilled to a minimum depth of 4 inches. The tilling process is depicted in Figure 3.6.

FIGURE 3.6: Tilling Test Slope

After the slope was tilled, the soil was raked to remove any clumps and to create a level soil depth across the slope. Dry screened soil was raked into the test plot until the optimal soil elevation was reached across the entire test plot. If the soil was too dry, water was added until the optimal moisture content of 20.0±5% was reached. A 24” x 48” turf roller was placed at the bottom of the test slope against one edge of the plot. The turf roller was rolled up and down the slope with a mounted electronic winch three times. Then the turf roller was moved to the other half of the test plot and the same number of passes was performed. Lastly, the turf roller was moved to the center of the plot where one pass is performed to remove any inconsistencies from prior compacting. The desired compaction rate for the sandy loam soil is 86±6%. The compaction process is depicted in Figure 3.7.

(a) First half compacted

(b) Second half compacted

FIGURE 3.7: Slope Compaction

3.3.2 Drive Cylinder Compaction

Once the slope is compacted, the compaction and moisture content are evaluated through the *Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method* (ASTM D2937). Three numbers between 1 and 60 were selected by a random number generator to determine the drive cylinder test locations depicted in Figure 3.8.

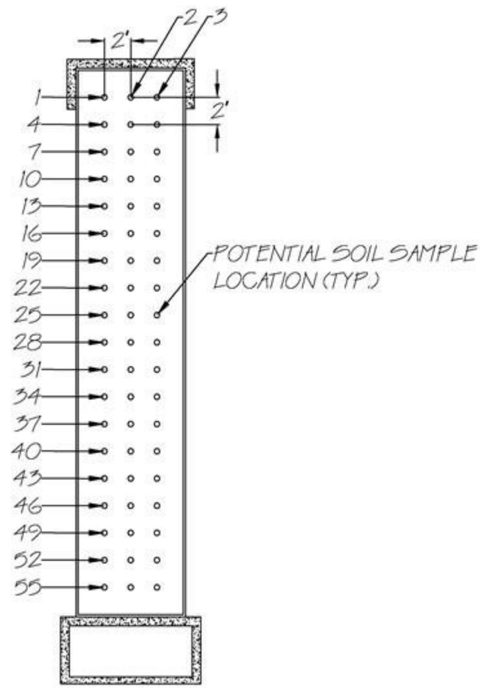
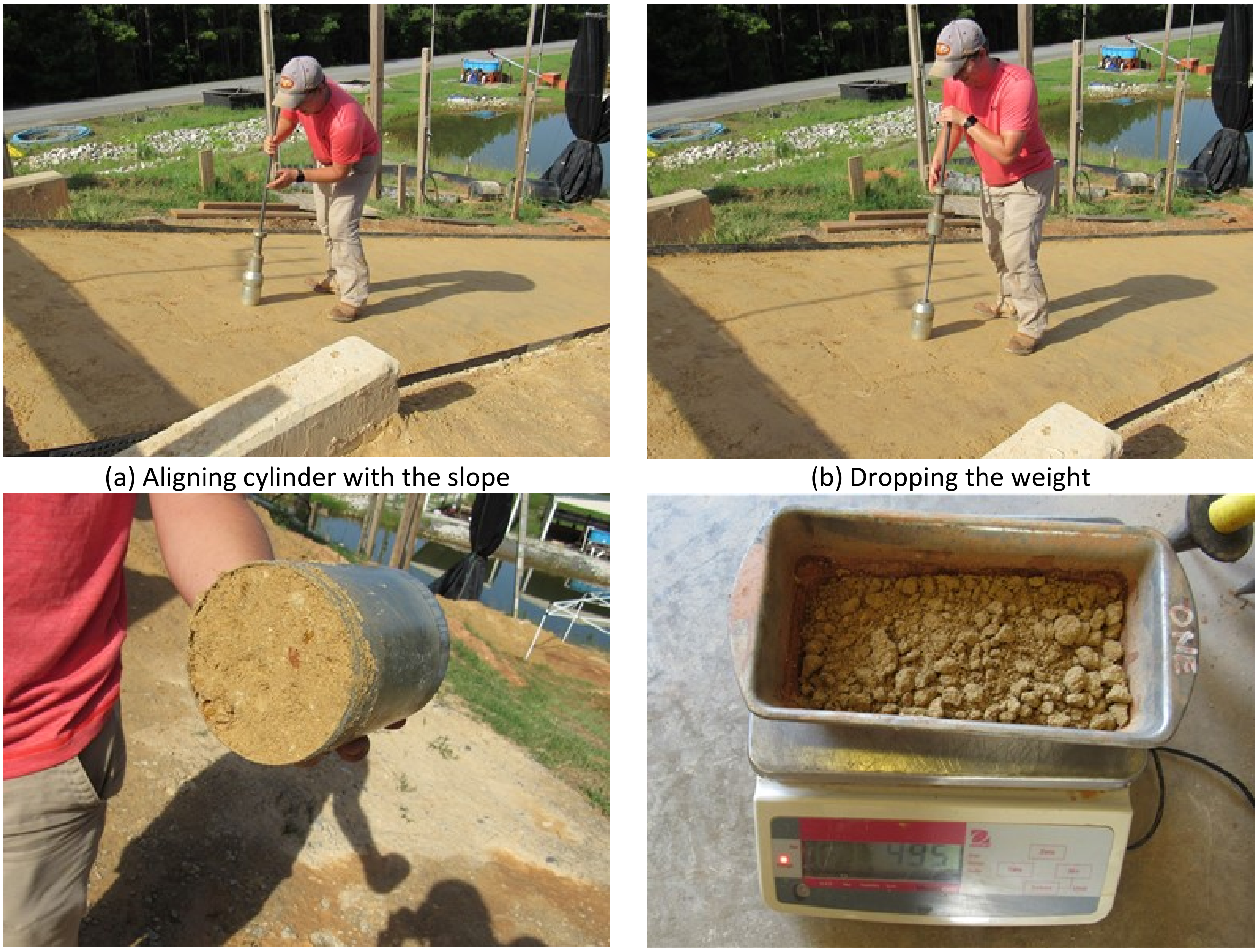


FIGURE 3.8: Drive Cylinder Test Locations (Horne et al. 2017)

The drive cylinder was driven into the slope. The cylinder was removed by digging around the front edge and picking the sample and cylinder up with a flat tool. Excess soil was removed from the bottom and cylinder edge. The approximate thickness of the soil sample was measured with a caliper. The wet soil sample was weighed before the moisture content and percent compaction were determined. The drive cylinder compaction test procedure is depicted in Figure 3.9.



(a) Aligning cylinder with the slope (b) Dropping the weight

(c)Leveled bottom (d) Weighing sample

FIGURE 3.9: Drive Cylinder Compaction Procedure

Immediately following the drive cylinder compaction test, the moisture content of the soil sample was determined by following the *Determination of Water Content of Soil by Microwave Oven Heating* (ASTM D4643). The drive cylinder soil sample was placed in a microwave safe dish, which was weighed and then heated in the microwave for 3 minutes. The sample was removed, weighed, and placed back in the microwave for 1 additional minute. This process was repeated until the change in mass was 0.1% of the initial wet mass or there is no change in mass. The final dry mass was used to calculate the moisture content in Equation 3.6.

$$w = \left(\frac{M_1 - M_2}{M_2 - M_c}\right) \times 100 \quad (3.6)$$

where,

w = water content, %
M_1 = mass container and wet soil, g
M_2 = mass container and dry soil, g
M_c = mass container, g

The allowable moisture content must be within 5% of the optimal moisture content of 20.0%. The wet density of the soil sample was calculated using Equation 3.7.

$$\rho_{wet} = \frac{(M_1 - M_2)}{V} \quad (3.7)$$

where,

ρ_{wet} = wet density, g/cm^3
M_1 = mass cylinder and wet soil sample, g
M_2 = mass cylinder, g
V = volume of cylinder, cm^3

The in-place dry density was then calculated using the wet density of the soil shown in Equation 3.8.

$$\rho_d = \frac{\rho_{wet}}{(1+\left(\frac{w}{100}\right))} \tag{3.8}$$

where,

ρ_d = dry density, g/cm^3
ρ_{wet} = wet density, g/cm^3
w = water content, %

The dry unit weight was then calculated using the in-place dry density in Equation 3.9.

$$\gamma_d = 62.4 \times \rho_d \tag{3.9}$$

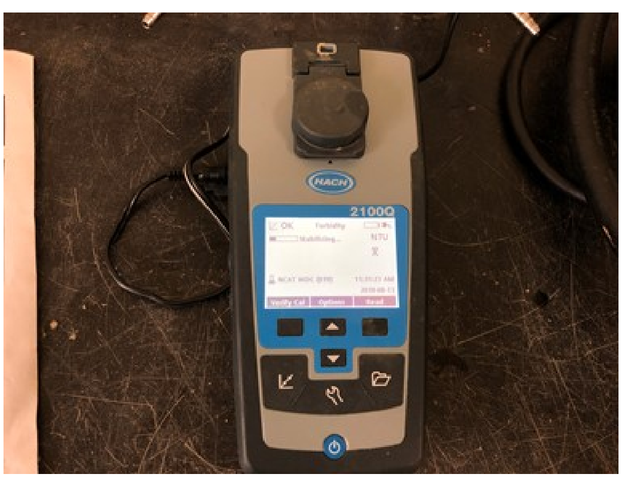
where,

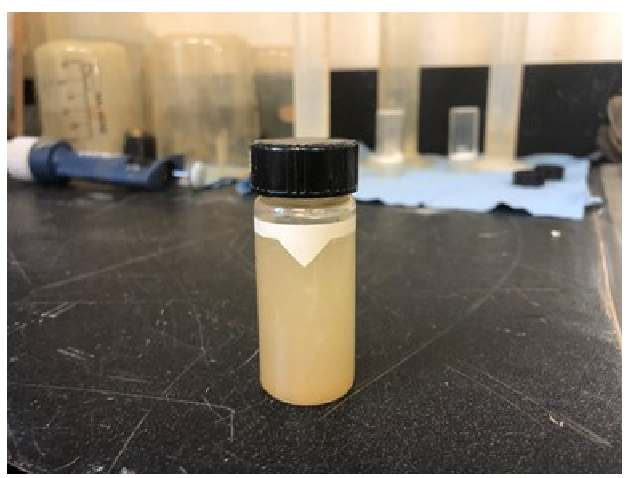
γ_d = dry unit weight, lb/ft^3
ρ_d = dry density, g/cm^3

The dry unit weight for each drive cylinder sample was divided by the maximum dry unit weight of the soil to determine the percent compaction. If the percent compaction was not within 86±6 % limits, then additional slope preparation must be performed. This process was repeated until the water content and compaction meet the desired values.

3.3.3 Turbidity

Following the completion of the rainfall simulation and the collection of water samples, the samples were transferred to the lab for testing. First, the turbidimeter was recalibrated using standard samples. Then each water sample bottle was shaken to thoroughly mix all sediment in the solution. The water sample was transferred to a 1000 mL beaker and placed on a magnetic stirrer. The sample was continuously mixed throughout the entire testing process. A pipette was used to fill the turbidity sample cell to the line with 15 mL of sample. The cell was placed in the turbidimeter and the reading was recorded. The preparation and testing of the turbidity measurements is depicted in Figure 3.10.





(a) Turbidimeter (b) Turbidity Sample

FIGURE 3.10: Turbidity Lab Testing

If the water sample over ranges, the original sample was diluted 1:2 by mixing 100 milliliters of deionized water in a beaker with 50 milliliters of sample. The cell was filled with the diluted sample and the measurement recorded. The dilution process was repeated until the turbidimeter recorded a measurement.

3.3.4 Total Suspended Solids

Following the completion of the turbidity testing, the same diluted sample was used to determine the TSS for each water sample. Before testing began, the glass microfiber filter membranes were pre-washed with 10 mL of deionized water. The filter membranes were placed in numbered aluminum crinkle dishes and placed in the oven at 103 ˚C for one hour. The crinkle dishes were removed from the oven and placed in a desiccator to cool to room temperature. Once at room temperature, the crinkle dish and filter membrane were weighed on the analytical balance and recorded to the nearest 0.0001 grams. Tweezers were used to move the filter membrane from the crinkle dish to the filtering apparatus. A pipette transferred 25 mL of diluted solution to the filter. The filtering machine was turned on to suction the water through the filter. The filtrate on the filter was rinsed with three 10 mL portions of deionized water. The filter membrane was removed from the apparatus with tweezers, placed in the assigned crinkle dish, and placed in the oven at 103˚C for one hour. Once the filter membranes were dry and have cooled to room temperature, each filter membrane and crinkle dish were weighed to the nearest 0.0001 grams. The procedure used to determine the TSS for water samples is depicted in Figure 3.11.

(a) Rinsing filters

(b) Mixing water samples

(c) Filtered sample (d) Drying samples

FIGURE 3.11: TSS Lab Testing

3.4 TEST SOIL

The AU-ESCTF soil source was classified based upon United States Department of Agriculture (USDA) and the Unified Soil Classification System (USCS) soil standards described in ASTM 6459–19. It was determined that the soil is a silt sand based upon the USCS system and a loam based upon the USDA soil texture system.

Table 3.1: AU-LOAM Soil Characteristics

Soil Characteristic Table	Test Method	Value
% Gravel	ASTM C136 ASTM 7928	0.0%
% Sand		48.0%
%Silt		41.0%
%Clay		11.0%
Liquid Limit	ASTM 4318	33
Plasticity Index		5
Soil Classification	USCS	Silty Sand
	USDA	Loam
K-Factor	ASTM 6459	0.23

3.5 TEST SLOPE PREPARATION PROCEDURE

Before rainfall simulator tests can be performed, the test plot is compacted to 86 ± 6 percent and at moisture content of 20.0 ± 4 percent. The test plot is first tilled to a minimum depth of 4 inches to remove rills. Soil is added to the slope until the desired fill mark is reached. A tiller is used to incorporate the new soil into the slope. The test plot is raked to achieve a consistent and even soil surface. A 4- foot wide turf roller is rolled up and down the test plot by an electric winch to achieve the desired compaction. The drive cylinder compaction test is performed in three randomly selected locations throughout the test plot to determine the compaction and moisture content of the slope.

3.6 PRODUCT INSTALLATION

All products were installed based either on the manufactured recommended installation or by the guidelines required by ALDOT or the Alabama "Blue Book" (ASWCC 2018). The following sections describe the installation procedures for each.

3.6.1 Loose Straw

Once the slope preparation procedure has been completed, loose dry wheat straw was applied to the slope for the blown, crimped, and tackifier straw tests. An application rate of 2 tons per acre was installed by hand as designated by the Alabama Handbook for seeding applications and ALDOT. The test plot and straw were divided into four even sections and spread by hand across the test plot to ensure a consistent application rate. The loose straw application is depicted in Figure 3.12.

(a) Straw application

(b) Finished application

FIGURE 3.12: Loose Straw Application.

3.6.2 Loose Straw with Tackifier

Once the slope preparation and loose straw application procedures were completed, a tackifier was sprayed on the straw. The tackifier was installed at an application rate of 50 lb per acre. Four metal buckets were filled with 8 gallons of water and one fourth of the tackifier to be installed. The tackifier was mixed with a drill mixer until the powder dissolved into a thick blue solution. Four gallons of tackifier solution was poured into a backpack sprayer and spread across one eighth of the test plot (40 ft^2). The powder and mixed Tacking Agent 3 are depicted in Figure 3.13.

(a) Power form Tacking Agent 3

(b) Mixed tackifier

FIGURE 3.13: Tackifier Application.

3.6.3 Crimped Straw

Once the slope preparation and loose straw application procedures were completed, the straw was crimped using the following procedure. A crimper was constructed using two notched flat coulter blades and wheelbarrow handles. Each blade was spaced eight inches apart as specified by Section 656 in the ALDOT Standard Specifications for Highway Construction. The crimper was rolled across the straw covered slope perpendicular to the flow direction. The straw was imbedded a minimum of two inches into the soil. The crimping procedure is depicted in Figure 3.14.

(a) Crimping perpendicular to slope (b) Crimped straw

FIGURE 3.14: Crimping Straw.

3.6.4 Hydraulic Mulch

The AU-ESCTF uses a 300-gallon Turf Maker for the mixing and application of hydraulically applied erosion control products. A 50-pound bale of the hydraulic mulch is hand shredded into a container prior to the mixing process. The shredded hydraulic mulch is added to the Turf Maker and mixed for 20 minutes.

Once the mixing process is complete, the hose is moved to the bottom of the slope and the product is sprayed onto the slope at an application rate of 2,500 pounds per acre. The product is then sprayed in the opposite direction down the slope. To verify the desired application rate is being achieve, 2-foot by 4-foot plywood boards are placed along the side of the slope and sprayed at the same time as the test slope. The product on the boards is dried and weighed to verify the application rate. The hydraulic mulch is allowed to cure a minimum of 24 hours before testing.

(a) Bottom install (b) Top install

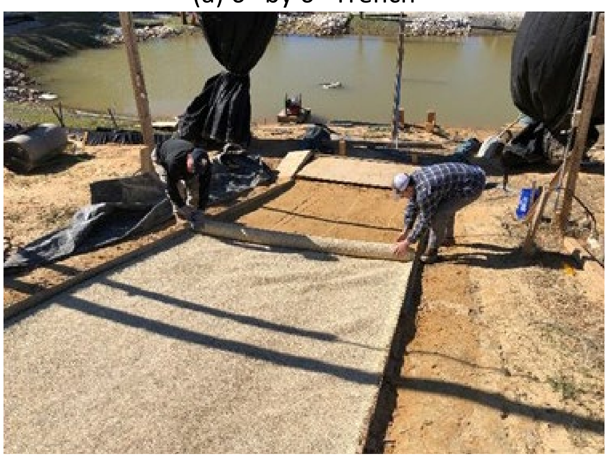
FIGURE 3.15: Hydraulic Mulch Application.

3.6.5 Erosion Control Blanket

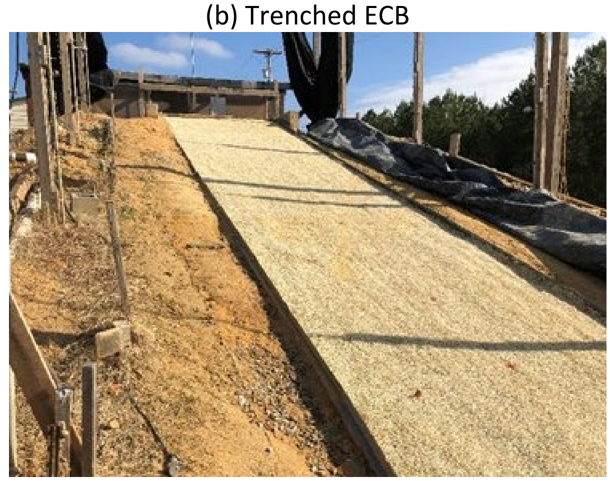
Following the test slope preparation, a 6-inch by 6-inch trench was excavated horizontally across the top of the test slope. The erosion control blanket (ECB) was anchored into the trench with 12-inches of blanket downhill of the trench. Once the blanket was anchored tot eh bottom of the trench, the trench was backfilled and compacted. The ECB was rolled over the trench and down the slope. The anchoring pattern provided by the manufacturer was used for the product installation. Once the blanket was anchored, the blanket was cut flush with the bottom of the test slope. The installation process is depicted in Figure 1.

(a) 6” by 6” Trench

(b) Trenched ECB



(c) Installing ECB



(d) Anchored ECB

FIGURE 3.16: Erosion Control Blanket Installation

3.6.6 PAM with jute matting

For the first three tests, polyacrylamide was applied directly to the soil as a dry granular powder at a rate of 25 pounds per acre. Jute matting was then applied on top of the soil and secured with 6” sod staples. To begin jute installation, a 6” by 6” trench was dug at the top of the slope and the matting was placed inside the trench and then buried. Then, the matting was overlapped on top of the trench and allowed to continue down the slope in the so-called “reverse trench” installation process. One vertical seam down the middle of the test slope was overlapped 6” and stapled every 12”. The matting was stapled every 12” at the edges of the plot and once per yard in the field.

3.6.7 Gypsum

The gypsum was applied in dry powder form directly to the soil at a rate of 32 lb/acre, consistent with literature (Miller 1987, Ben-Hur 1992). Jute matting was then installed on top of the gypsum, secured at the top of the slope with the reverse trenching technique, and anchored with sod staples at a minimum of one per yard. When using soil amendments for erosion control, it is recommended to use them in conjunction with another erosion control practice and jute was selected for use to be consistent with prior soil amendment testing and sponsor recommendation.

3.7 SOIL ERODABILITY FACTOR: *K*-FACTOR

The *K*-Factor was calculated using the rain gauge measurements and soil loss (lb) for each 20-minute rainfall intensity interval of the bare soil control test. The rain gauge measurements were used to calculate the average rainfall in inches and the maximum 30-minute rainfall intensity (I_{30}). The total soil loss for each rainfall intensity was inserted and converted from pounds to tons. The average soil loss (*A*) in tons/acre was calculated for each intensity by dividing the soil loss (tons) by the acreage of the rainfall simulator test plot.

Following these calculations, a graph is created plotting the incremental R-factor vs. the incremental *A* (tons/acre). From the three points plotted on the graph, a linear trendline is used to determine the trendline equation. The slope of the trendline equation is equal to *A*/*R*. The theoretical *R*-factor is used in the trendline equation to calculate the average *A* (tons/acre) from the entire experiment. The RUSLE equation is reformatted to solve for the *K*-factor as depicted in Equation 3.13.

$$K = \frac{A}{R \times LS \times C \times P} \tag{3.13}$$

where,

K = Soil Erodibility Factor (ton – acre – hr – [hundreds of acre-ft – tonf – in.]$^{-1}$)
A = Average Annual Soil Loss (tons/acre)
LS = Length slope steepness factor
R = Rainfall Erosivity Factor (hundreds of ft – tonf – in. – acre^{-1})
C = cover management factor
P = support practice factor

Since a bare soil control test was being evaluated, the *C*-factor and *P*-factor are 1.0. The *LS* value is the calculated value for the length and steepness of the test plot. For the current test plot (40 ft slope length on 3H:1 V slope), LS = 2.86. Once all of the equation values are determined, the *K*-factor was calculated. This *K*-factor will be used to determine the cover management factor C for the three product tests that it was paired with. A bare soil control test was performed for every three product experiments.

3.8 COVER MANAGEMENT FACTOR: *C*-FACTOR

The *C*-factor for a product was calculated by inserting the incremental rain gauge measurements and the incremental soil loss data into the drop size distribution data from section 3.2.1. This will calculate the incremental EI_{30} value (*R*). The incremental average soil loss (*A*) was calculated by dividing the soil loss in tons by the acreage of the test plot. Once these values were calculated, a graph was created to plot the *R*-factor vs. *A* (ton/acre). The three data points on this graph are used to create a linear trendline equation. The slope of the linear trendline equation equals *A*/*R*. The average *A* (tons/acre) for the experiment was calculated by solving the trendline equation with the theoretical *R*-value. The RUSLE equation was arranged to solve for the *C*-factor. The *C*-factor for the product was calculated using the slope of the trendline *A*/*R* and a *P*-factor of 1.0.

Once three experiments of the same product have been completed, the average *C*-factor for the product must be determined. Two separate methods were used to calculate the *C*-factor for each erosion control product. The first method plotted the incremental *C*-factor versus the incremental *R*-factor for all three of the products experiments. The 2 inch per hour rainfall intensity data was not included because the *C*-factor was near zero resulting in a skewed trendline equation. A linear trendline equation was fit to the 4 and 6 inch per hour data points. The resulting trendline equation was used to calculate the *C*-factor of the product by solving for the theoretical *R*-factor of 182.02.

The second method used to solve for the product *C*-factor plotted the incremental soil loss (*A*) tons/acre versus the incremental *R*-factor for each individual experiment. A trendline equation was determined for each of the graphs and used to calculate the A in tons/acre for each test that correlates with the theoretical *R*-factor of 182.02. The resulting *A*-factor was averaged for all of the experiments and used in the RUSLE equation.

3.9 TEST PROCEDURES

Prior to testing, six rain gauges are placed on the slope at 10, 20 and 30 feet from the top of the slope. The test slope is exposed to three sequential 20-minute durations of 2, 4, and 6 in./hr rainfall intensities. Between each rainfall intensity, the rain gauge depths are measured, soil conditions are photographed, runoff is directed to a new container and an additional switch is turned on. Water samples are collected every three minutes once runoff is initiated for the duration of the experiment. Slope runoff from the 2, 4, and 6 in./hr rainfall intensities are separated into three separate containers to determine the total sediment lost during each rainfall intensity. The discharge as a function of time for the duration of the test is determined by recording the amount of time it takes for one gallon of runoff to be collected at two-minute increments throughout the test.

CHAPTER 4: SUMMARY RESULTS AND CONCLUSIONS

The following section provides a summary discussion of calibration and testing results. Full testing results for all products and practices are included in full test reports.

4.1 CALIBRATION RESULTS

The data recorded from calibration testing was used to calculate the experimental rainfall intensity, uniformity, and drop size distribution for each target rainfall intensity of 2, 4, and 6 in./hr.

4.1.1 Uniformity and Intensity

The initial rainfall simulator consisted of six risers each with four sprinklers designed to produce a 2-year, 24-hour storm event for Alabama. During the calibration process, the rainfall simulator was redesigned to have eight riser each with three sprinklers to product the 2, 4, and 6 in. per rainfall intensities. Calibration testing determined that the top and bottom of the test plot was not receiving the same rainfall coverage as the rest of the test plot. Therefore, two additional risers were placed at the uphill and downhill sides of the test plot. Following the placement of two additional rainfall risers, calibration tests were performed to verify that the riser placement was producing uniform rainfall throughout the test plot. Once the riser placement was finalized, a total of 30, 15 minute calibration tests were performed with 20 rain gauges installed on the test plot. A minimum of ten calibration tests were performed for each rainfall intensity. If the standard deviation between the ten tests was less than 0.1 in. per hr, no additional calibration testing was required. Each rainfall intensity in this experiment had a standard deviation less than 0.1 in. per hr and therefore only required ten tests. During the calibration process, 6 psi and 10 psi pressure regulators were installed to determine which pressure resulted in the best rainfall conditions. The 6 psi pressure regulator was selected for testing because it generated larger drop sizes as well as a higher rainfall uniformity. The calibration summary results are depicted in Table 4.1.

TABLE 4.1: Rainfall Intensity Results

Theoretical Rainfall Intensity	2 in. per hr	4 in. per hr	6 in. per hr
Experimental Intensity (in./hr)	2.08	4.12	6.07
Rainfall Intensity Percent Error (%)	4.00	3.00	1.17
Standard Deviation	0.04	0.06	0.07
Number of Tests	10	10	10

The experimental rainfall intensity for each calibration test was averaged and compared to the theoretical rainfall intensity to calculate the percent error. If the percent error was greater than 5%, changes were made to the nozzle size attached to the sprinklers. Upon final calibration testing, the rainfall intensity percent error was greatest for the 2 in. per hr rainfall intensity at 4.0% and the lowest for the 6 in. per hr rainfall intensity at 1.17%. The standard deviation between the calibration tests for each rainfall intensity ranged from 0.043 to 0.07 in. per hr. As the rainfall depth data was recorded, the rainfall uniformity was calculated using the Christiansen Uniformity Coefficient (Equation 3.1). The results for the uniformity calculations for each rainfall intensity are depicted in Table 4.2.

TABLE 4.2: Rainfall Uniformity Results

Intensity	2 in. per hr	4 in. per hr	6 in. per hr
Experimental Intensity (in. per hr)	2.08	4.12	6.07
Christianson Uniformity Coefficient, C*u* (%)	85.67	87.49	87.51

For the rainfall simulator to meet the ASTM D6459 requirements, the rainfall uniformity for each rainfall intensity had to be a minimum of 80%. The results of the calibration testing concluded that the average rainfall uniformity ranged between 85 to 87%. After reviewing the calibration data, it was determined that the rainfall simulator met the ASTM D6459-19 requirements for intensity and uniformity, however, an additional analysis was performed on the calibration results.

4.1.1.1 Calibration Statistical Analysis

ANOVA testing was performed on each rainfall intensity to determine if each of the ten calibration test means were equal. If the *p*-value of the ANOVA test was greater than the alpha value of 0.05, then the null hypothesis was accepted, concluding that the means were equal. The results of the three ANOVA tests is summarized in Table 4.3.

TABLE 4.3: Calibration Testing ANOVA Test Results

Rainfall Intensity	No. of Rain Gauges	Alpha Value	*P*-Value
2 in./hr	20	0.05	0.951
4 in./hr	20	0.05	0.983
6 in./hr	20	0.05	0.994

All three of the ANOVA tests resulted in *p*-values greater than the alpha value of 0.05. Therefore, the null hypothesis that the ten calibration tests for each rainfall intensity had equal means is true. This analysis concludes that the rainfall simulator was producing consistent and repeatable rainfall events for the 2, 4, and 6 in./hr (51, 102, and 152 mm per hour) rainfall intensities.

4.1.2 Drop Size Distribution

The flour pan method was used to determine the drop size distribution for each rainfall intensity of the AU-ESCTF rainfall simulator. The procedure defined in section 3.2.1 was followed to calculate the fall velocity of the raindrops as well as the total kinetic energy from the storm event. ASTM D6459 requires the average raindrop diameter to range from 0.04 to 0.24 inches (1 to 6 mm). The average raindrop size and fall velocity retained on each sieve for each rainfall intensity are summarized in Table 4.4.

TABLE 4.4: Raindrop Fall Velocity

Particle Diameter Range (mm)	2 in./hr		4 in./hr		6 in./hr	
	Average Raindrop Size (mm)	Fall Velocity (ft/s)	Average Raindrop Size (mm)	Fall Velocity (ft/s)	Average Raindrop Size (mm)	Fall Velocity (ft/s)
4.76+	6.03	25.57	5.29	25.73	5.78	25.69
4.76–2.38	3.79	24.21	3.52	23.68	3.65	23.93
2.38–2.0	2.50	20.92	2.59	21.22	2.28	20.17
2.0–1.41	1.81	18.42	2.00	19.16	1.76	18.22
1.41–0.841	1.21	15.84	1.21	15.81	1.55	17.36
0.841–0.59	0.91	14.39	0.89	14.27	0.95	14.59

The average size of the pellets retained on each sieve was calculated by inserting the average pellet weight and the mass ratio of the pellet size into Equation 3.4. The mass ratio converts the mass of the flour pellet to the mass of a raindrop of equal size. The largest drop size was recorded for the 2 in. per hr (51 mm per hr) rainfall intensity with a diameter of 0.24 inches (6.03 mm). The fall velocities for each of the three rainfall intensities were similar for each sieve size. The average raindrop size for each sieve and the percent of rainfall by mass were plotted to get the drop size distribution for each rainfall intensity. The drop size distribution is depicted in Figure 4.1.

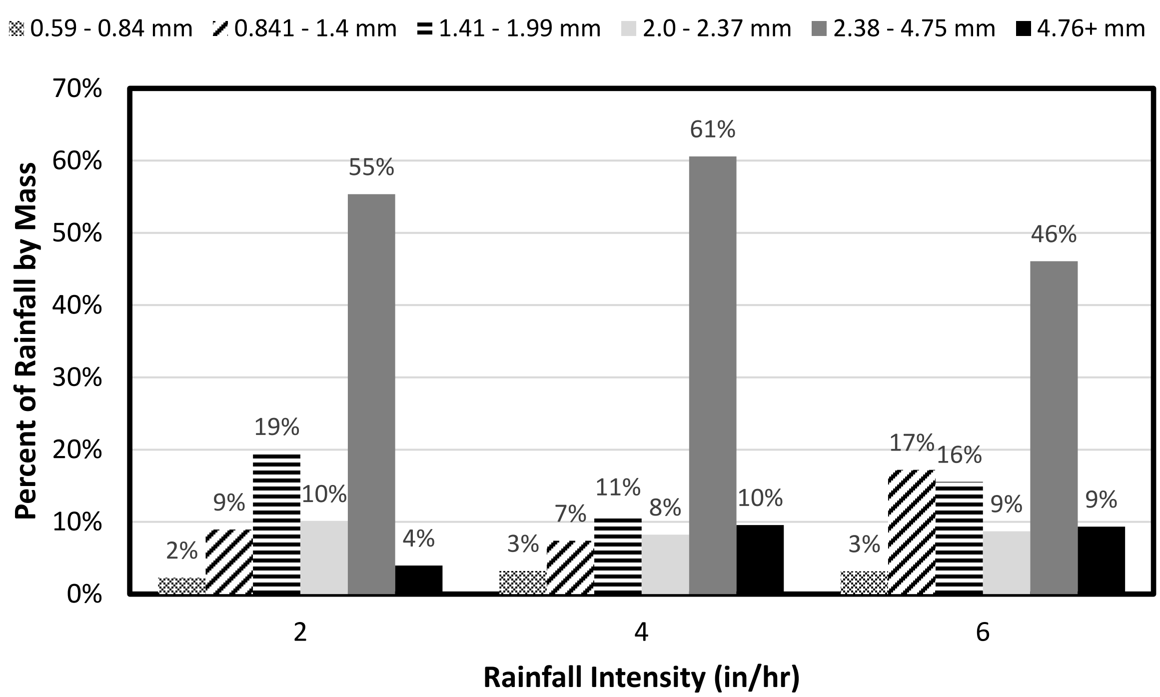


FIGURE 4.1: Drop Size Distribution by Mass.

The drop size distribution for each of the three rainfall intensities follows a similar trend. The No. 8 sieve (2.38 to 4.75 mm) retained the highest percentage of rainfall by mass produced by the rainfall simulator. The drop size distribution data and the average experimental rainfall depth for each rainfall intensity were used to calculate the total storm kinetic energy. The total energy produced by the rainfall during the one-hour experiment is depicted in Table 4.5.

TABLE 4.5: Rainfall Simulator Storm Energy

Rainfall Intensity	2 in. per hr	4 in. per hr	6 in. per hr	Total
Kinetic Energy Rainfall (ft-lbf)	8,729	17,704	24,266	50,699
Total Storm Energy, E (ft-tonf/acre)	594	1,205	1,652	3,451

The total storm energy incrementally increases with each new rainfall intensity. The total storm energy (E) for the calibration test results is 3,451 ft-ton/acre (2600 m-metric ton/ha). The rainfall erosivity factor (R) is calculated by multiplying the E with the maximum 30-minute rainfall intensity (I_{30}). The I_{30} was calculated using the experimental rainfall intensities of 4.12 and 6.07 in./hr (105 and 154 mm per hr). The I_{30} was calculated to be 5.42 in./hr (138 mm). The resulting experimental R-factor for the calibration test results was 187, while the theoretical R-factor is 182. Therefore, the rainfall simulator is generating a slightly larger R-factor than the theoretical storm event of ASTM D6459. The drop size distribution and total storm energy calculations are used to calculate erosion control product C-factors.

4.1.3 Soil Summary

The two soils evaluated during this study were classified as a sandy loam and loam for the USDA classification system and both were classified as a silty sand for the USCS classification system. The soil characteristics are summarized in Table 4.8.

TABLE 4.6: Soil Analysis Summary

Soil Property	Sandy Loam	Loam
% Sand	73	48
% Silt	15	41
% Clay	12	11
Maximum Dry Unit Weight (lb/ft^3)	113.6	96.0
Optimum Moisture Content (%)	13.5	20.0

The sandy loam soil had a higher percentage of sand particles than the loam soil and the loam soil had a higher percentage of silt particles. Due to these differences in soil composition, the maximum dry unit weight was much higher than the loam soil. The sandy loam soil was used initially in the straw mulch testing, however, prior to testing manufactured products, the sandy loam soil was removed and a loam soil that aligned with ASTM D6459 was installed on the rainfall plots.

4.1.4 Straw Testing Summary

Three straw mulching applications were evaluated under the AU-ESCTF rainfall simulator to compare the erosion control practice performance to bare soil control tests on a sandy loam soil. The straw mulch was installed as a loose straw, loose straw with Tacking Agent 3, and crimped straw. The turbidity of the test plot runoff is summarized for each straw mulch application and the bare soil control tests in Figure 4.26 and the soil loss for each application is summarized Table 4.7. The soil loss ratio is calculated as the soil loss from the test plot with a product or practice versus the soil loss from bare soil control test, e.g., 143 lb/738 lb = 0.19 for loose straw. The % improvement is calculated as the percent reduction (i.e., improvement) of soil loss from a product or practice in comparison to the bare soil test plot, e.g., (738 – 143) lb/738 lb = 81% for loose straw.

TABLE 4.7: Straw Mulch Soil Loss Results

Product	Soil Loss (lb)	Soil Loss Ratio	% Improvement
Bare Soil Control	738	-	-
Loose Straw	143	0.19	81%
Loose Straw with Tacking Agent 3	97	0.13	87%
Crimped Straw	169	0.23	77%

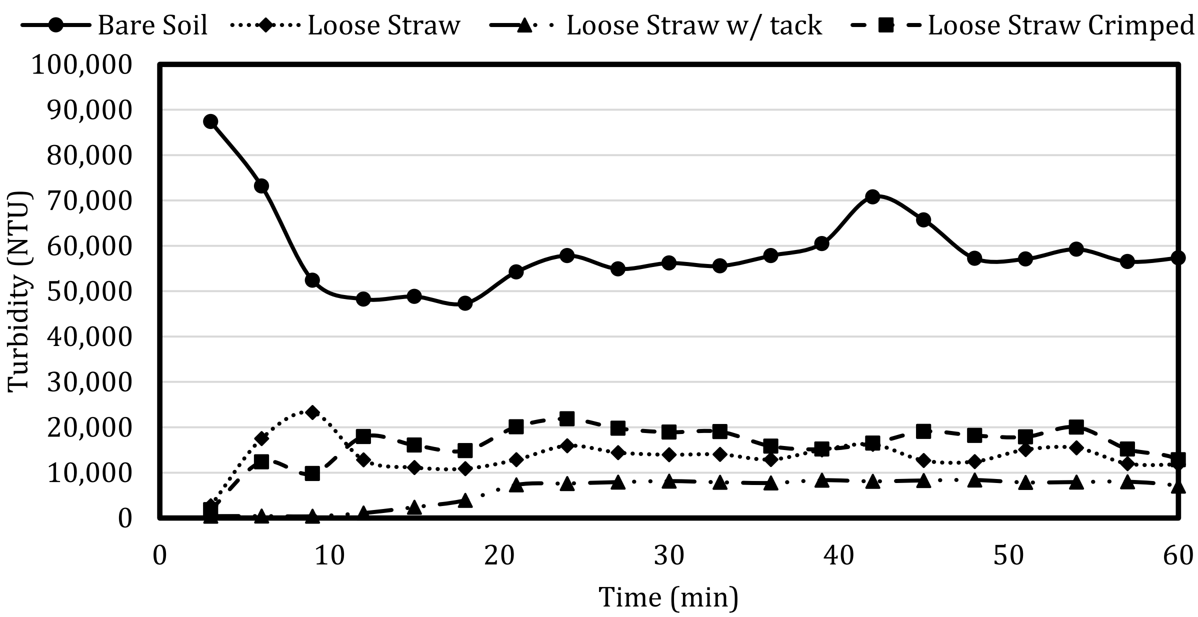


FIGURE 4.2: Straw Mulch Turbidity Summary.

All three of the straw applications showed substantial reduction in turbidity throughout the entire experiment. The best performing straw application under initial performance testing was the loose straw with Tacking Agent 3 with a total soil loss of 97 lb, which was an 87% improvement from bare soil conditions. The crimped straw was the relatively lowest performing straw mulch application under initial product performance testing. The crimped straw had a total soil loss of 169 lb, which was a 77% improvement from bare soil conditions. The test plot conditions following the initial product test is depicted in Figure 4.3.

(a) Bare soil (sandy loam) (b) Loose straw

(c) Loose straw with Tacking Agent 3 (d) Crimped straw

FIGURE 4.3: Straw Mulch Product Results.

The straw mulch applications and bare soil were exposed to a second rainfall event following the 2, 4, and 6 in./hr of rainfall for 20 minutes each after the first (initial) event (60 minutes) to evaluate the longevity performance of the erosion control applications. The soil loss results for the second rainfall event and the water quality curves are depicted in Table 4.8 and Figure 4.4.

TABLE 4.8: Straw Mulch Longevity Soil Loss

Product	Soil Loss (lb)	Soil Loss Ratio	% Improvement
Bare Soil Control	611	-	-
Loose Straw	287	0.47	53%
Loose Straw with Tacking Agent 3	131	0.21	79%
Crimped Straw	82	0.13	87%

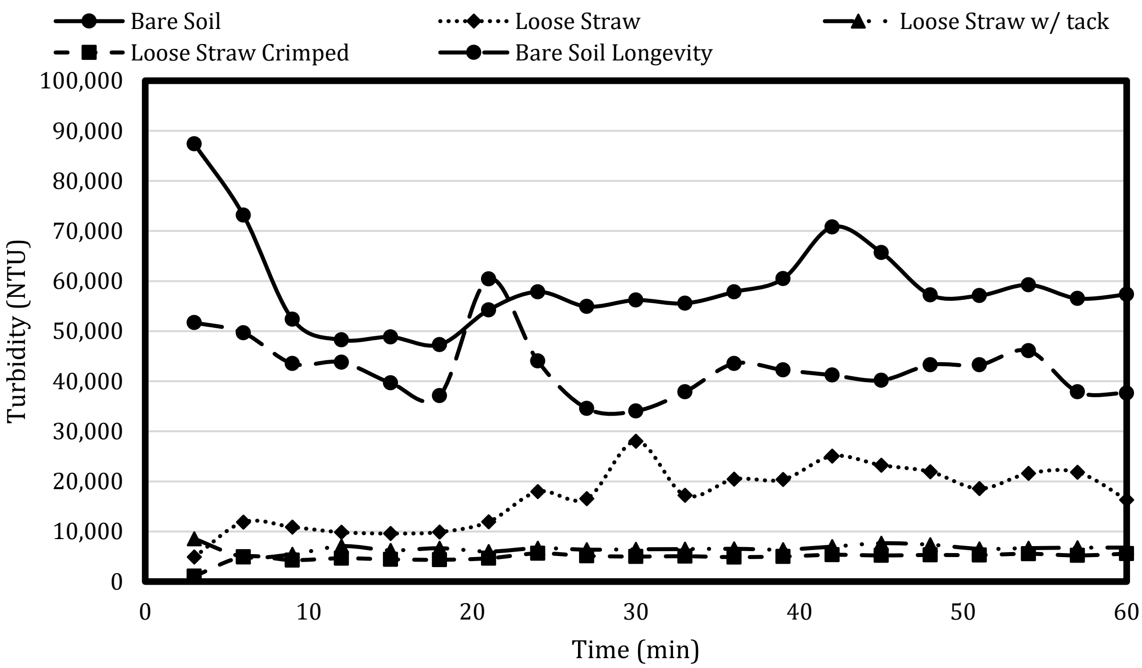


FIGURE 4.4: Straw Mulch Longevity Water Quality Results.

The longevity testing of the straw mulch applications resulted in different results from the initial product testing. Unlike in the initial test, the crimped straw was the best performing straw mulch application with a total soil loss of 82 lb, which is an 87% improvement from the longevity bare soil results. The crimped straw and the loose straw with Tacking Agent 3 had similar turbidity measurements throughout the duration of the longevity experiments. The loose straw was the worst performing straw mulch application with a total soil loss of 287 lb, which is a 53% improvement from bare soil conditions. The loose straw with Tacking Agent 3 did not perform as well under longevity testing as under initial product testing. The total soil loss for the loose straw with tackifier under longevity testing was 131 lb, which is a 79% improvement from the bare soil conditions. The reason for the drop off in performance of the loose straw with tackifier is likely caused by the tackifier being washed from the test plot. The crimped straw had an increased performance because the loose soil that was disturbed by the crimping process had been washed form the site and the voids caused by the crimper had been filled with sediment.

The initial and longevity soil loss results were combined to determine the overall effectiveness of each straw mulch application. The soil loss data for the combined results is depicted in Table 4.9.

TABLE 4.9: Combined Straw Mulch Results

Straw Application	Combined Soil Loss (lb)	Soil Loss Ratio	% Improvement
Bare Soil	1,349	-	-
Loose Straw	430	0.32	68%
Loose Straw w/ Tackifier	228	0.17	83%
Crimped Straw	251	0.19	81%

The combination of the initial and longevity results shows that anchoring straw reduces the amount of erosion. The loose straw with Tacking Agent 3 was the best performing straw mulch practice with an 83%

improvement from the bare soil conditions. The crimped straw was the second best straw application with an 81% improvement from bare soil conditions. The crimped straw and loose straw with Tacking Agent 3 were similar in performance with only a 23 lb (10.4 kg) difference in combined soil loss. The loose straw application resulted in a 68% improvement from bare soil conditions. The results found in this study prove that anchored straw applications provided the greatest erosion reduction occurring on steep slopes.

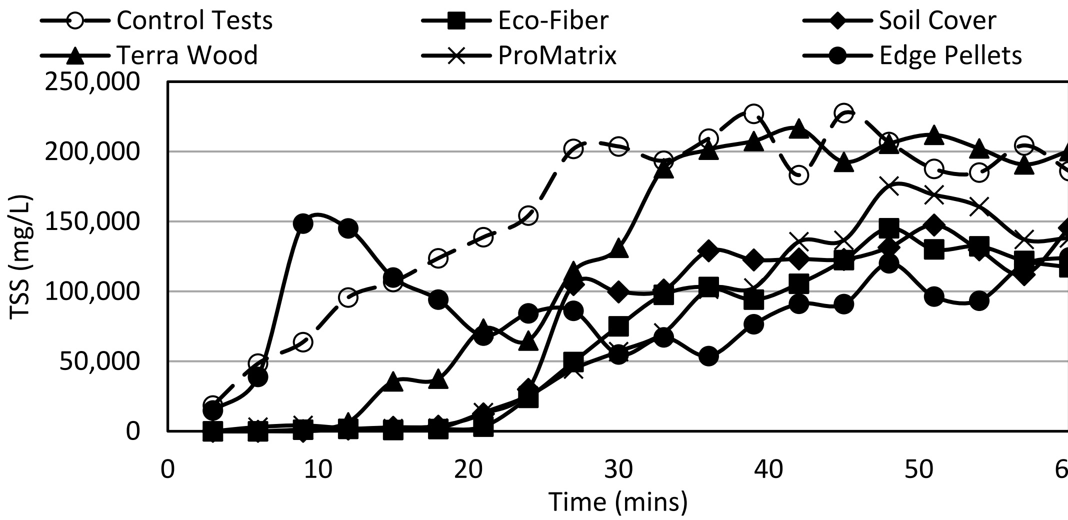
4.2 HYDRAULIC EROSION CONTROL PRODCUTS

At the conclusion of straw mulch testing, the rainfall simulator slope was rebuilt and a new loam soil was used for constructing the slope to meet ASTM D6459-19. The loam soil was then used to determine the performance of three hydraulic mulch products as compared to bare soil control tests. The four hydraulically applied mulches were tested: 1) Eco-Fiber plus Tackifier, 2) Soil Cover Wood Fiber with Tack, 3) Terra-Wood with Tacking Agent 3, and 4) Promatrix EFM. A pelletized mulch called EDGE Pellets was also tested that is similar in nature to a hydraulic mulch, however, the pellets are dry applied to the slope and the rainfall hydrates the pellets. The data collected for each product was used to calculate the cover-factor (*C*-factor) of the product. Initially the Eco-Fiber, Soil Cover, and Terra-Wood were tested based upon initial proposed efforts. The average soil loss for these products and controls are shown in Table 4.10

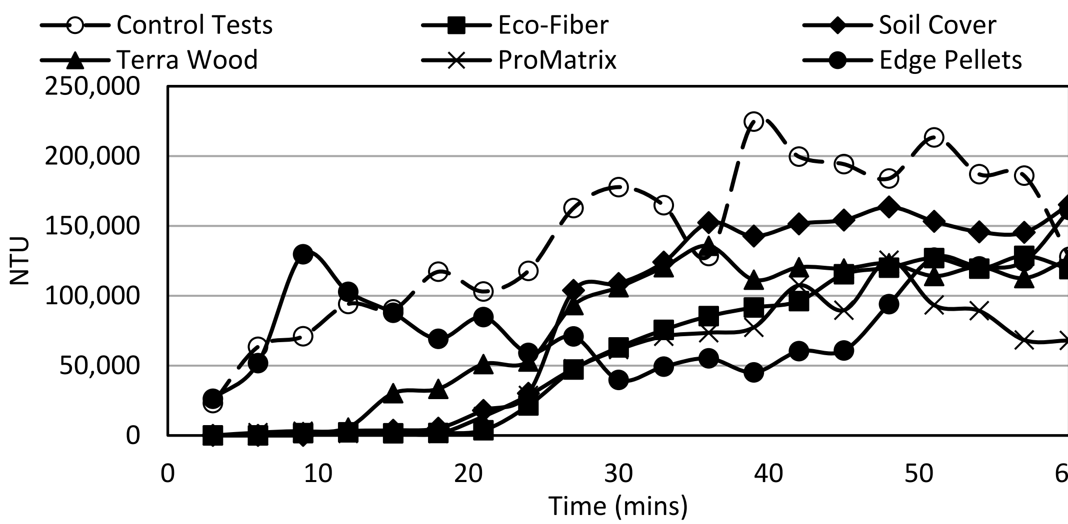
TABLE 4.10: Hydraulic Mulch Soil Loss Results

Product	Soil Loss (lb)
Avg. Bare Soil Control	2,333
Eco-Fiber	1,038
Soil Cover	1,164
Terra-Wood	1,294
ProMatrix	928
Edge Pellets	610

The Edge Pellets resulted in the lowest soil loss. The Terra-Wood hydraulic mulch experiments resulted in the highest average soil loss of 1,294 lb. The average turbidity and TSS curves for each product is depicted in Figure 4.5.



(a) Total Suspended Solids



(b) Turbidity

FIGURE 4.5: Hydraulic Mulch Water Quality Summary.

The four hydraulically applied mulches started at close to zero turbidity and TSS for the first 2o minutes of testing which encompassed the 2 in./hr intensity of the test. Once the intensity increased to 4 in./hr, the products began losing soil. The Edge Pellets product resulted in higher turbidity initially likely due to its dry application, however, once the product hydrated, it resulted in a lower TSS concentration and turbidity in the 4 in./hr intensity and began to lose its effectiveness halfway through the 6 in./hr intensity. That improved performance during the higher intensity storm events is the most likely reason for its reduction in sediment volume loss. However, since its performance had begun to reduce, it would likely begin losing soil at an increased rate that is comparable to the other hydraulic mulches.

The *C*-factor for each hydraulic mulch was determined from the test specific soil loss and total rainfall depth. The resulting *C*-factor for each product is summarized in Table 4.11. The soil loss ratio was also determined for convenience to compare to the straw mulch tests.

TABLE 4.11: Hydraulic Mulch *C*-Factor Results

Product	*K*-factor	*C*-factor (Regression Method)	*C*-Factor (RUSLE Method)	Soil Loss Ratio
Eco-Fiber	0.29	0.55	0.55	0.55
Soil Cover	0.33	0.45	0.46	0.49
Terra-Wood	0.31	0.53	0.54	0.55
ProMatrix	0.37	0.42	0.33	0.39
Edge Pellets	0.24	0.46	0.33	0.38

The hydraulic mulch that resulted in the best performing *C*-factor was the ProMatrix with a *C*-factor of 0.33 using the RUSLE Method. The soil loss ratio was slightly higher than the Edge Pellets, likely due to better performance during the 4 in./hr intensity. However, the ProMatrix seemed maintain a more stable slope for a longer time period based upon the water quality data collected. The worst performing hydraulic mulch was the Eco-Fiber mulch with a *C*-factor of 0.55. However, one of the Eco-Fiber experiments was exposed to excess rainfall due to the covers being blown off the test plot. Eco-Fiber had the lowest average soil loss between the three hydraulic mulch products, but resulted in the highest *C*-factor. The high *C*-factor was caused by the second Eco-Fiber test, which was exposed to excess rainfall. The exposure to excess rainfall resulted in around 900 lb. (408 kg) more soil loss than the other two Eco-Fiber experiments. If the second experiment was removed from the *C*-factor calculations, the Eco-Fiber *C*-factor would be 0.472 for the regression method and 0.465 for the RUSLE method.

4.3 ROLLED EROSION CONTROL PRODUCTS

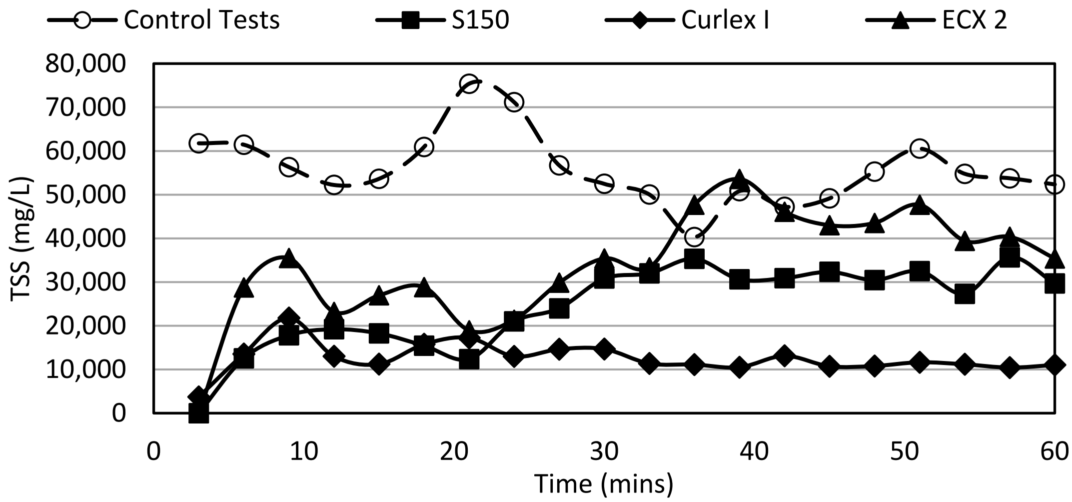
Four rolled erosion control products were evaluated as part of this project. Two blankets are excelsior blankets (Curlex I and ECX-2), one is a straw blanket (S150) and one is a jute blanket. The jute blanket was tested as a way to determine the performance of the polymer enhanced soft armoring technique that uses polyacrylamide (PAM) as a soil binding agent.

The average soil loss results for the products are depicted in Table 4.12.

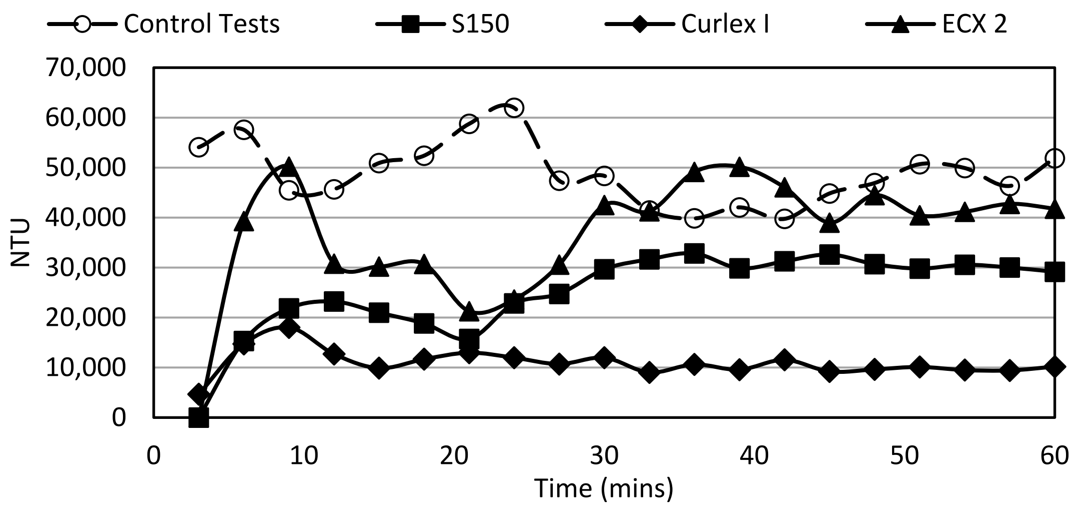
TABLE 4.12: Erosion Control Blanket Soil Loss Summary

Product	Soil Loss (lb)
Avg. Bare Soil Control	2,008
Curlex I	90
S150	292
ECX-2	231
Jute	859

Curlex I resulted in the lowest total soil loss of 90 lb, which was 141 lb less than the second best blanket. The S150 and the ECX-2 blankets were relatively similar in performance when compared to the Curlex and jute blankets. The jute blanket was the worst performing blanket with an average soil loss of 859 lb. The average water quality measurements for straw and excelsior products are depicted in Figure 4.6. The jute blanket was added at a later date for testing with PAM. The performance of it in conjunction with the PAM will be discussed in the next section.



(a) Total suspended Solids



(b) Turbidity

FIGURE 4.6: ECB Water Quality Results.

All three of the blankets had an initial flush, but were followed by different results for the remainder of the experiment. ECX-2 had the highest initial flush of 50,000 NTU and resulted in the highest turbidity measurements throughout the remainder of the experiment. Curlex I had an initial flush of only 18,000 NTU and then stabilized at roughly 10,000 NTU for the remainder of the experiment. The rainfall depth and soil loss data for each blanket was used to calculate the product *C*-factor. The *C*-factor was calculated using the regression and the RUSLE method, which is depicted in Table 4.13. The soil loss ratio was also determined for convenience to compare to the straw mulch tests.

TABLE 4.13: ECB *C*-factor Results

Product	*K*-factor	*C*-factor (Regression Method)	*C*-Factor (RUSLE Method)	Soil Loss Ratio
Curlex I	0.23	0.05	0.05	0.05
S150	0.27	0.14	0.14	0.14
ECX-2	0.24	0.12	0.12	0.12
Jute	0.27	0.34	0.41	0.41

The excelsior and straw blankets resulted in lower *C*-factors than the hydraulic mulches. Curlex I, which had the lowest soil loss results, had the lowest *C*-factor of 0.05. S150, which had the highest average soil loss, had the highest *C*-factor of 0.14. The S150 and ECX-2 blankets both had bare spots within the blanket where there was minimal to no product. The lack of soil coverage in these areas resulted in higher amounts of erosion. The Curlex I blanket did not have any bare spots resulting in a better product performance than the other two blankets. If the bare spots in the ECX-2 and S150 blankets were filled, the blanket performance would likely increase resulting in lower *C*-factors. The jute blanket is an open weave blanket that results in substantial soil exposure. The addition of a soil conditioner such as PAM was also investigated to determine if its performance could create better results.

4.4 SOIL CONDITIONERS

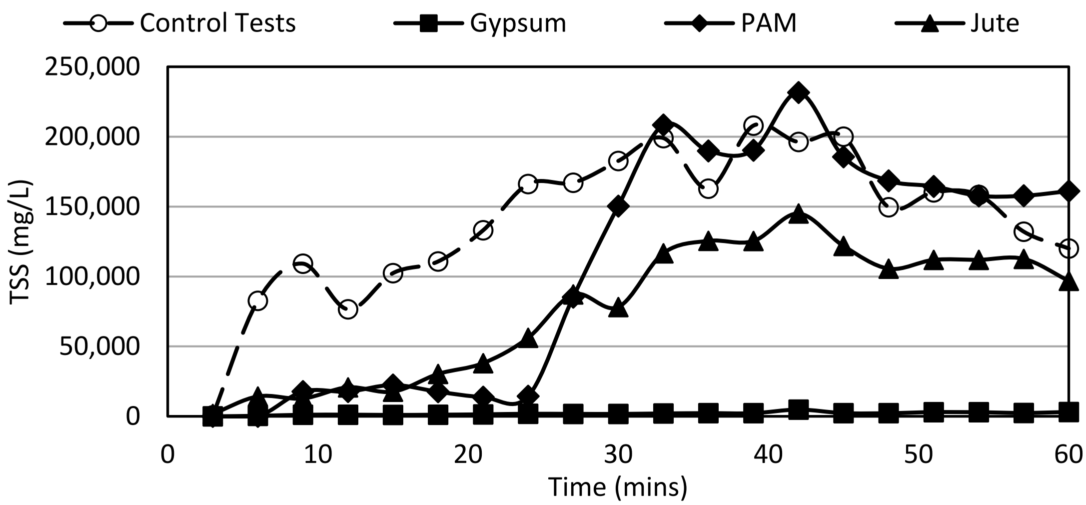
PAM was applied directly onto the soil at a rate of 25 lb/acre, as determined through recommendation from a technical statement from the manufacturer. The PAM product used was Applied Polymer Systems Silt Stop 715, selected from the 700 series through jar testing performed by the manufacturer with a sample of the loam soil from the plot. The product was applied in a dry, white, granular powder form. Jute matting was then applied on top of the soil and secured with 6 in. sod staples as an additional erosion control measure, as recommended.

Gypsum as a soil stabilizer was also evaluated in conjunction with the jute blanket as a potential replacement for the PAM product. The gypsum requires a much higher application rate of 4,450 lb/ac. Just as with the PAM, the gypsum was dry applied to the soil surface and covered with the jute blanket. Both products exhibited less runoff than the jute blanket throughout the test. Gypsum and PAM continued to reduce runoff more than the jute blanket throughout the test. Thus, both products did appear to improve infiltration as advertised by their manufacturers.

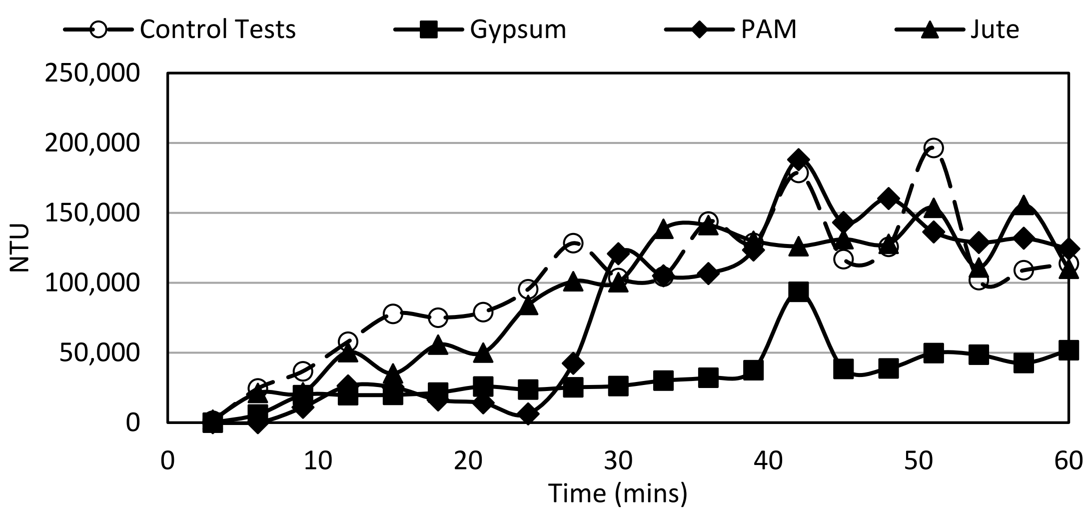
The gypsum demonstrated the best water quality of all three conditions as evidenced by substantially lower turbidity and TSS than jute blanket. The PAM exhibited lower turbidity than jute blanket only during the first half of testing. However, turbidity climbed after about the halfway point and was comparable to the jute for the rest of the test. Similarly, PAM exhibited lower TSS than the jute only during the 2 in./hr simulation, but actually exhibited a higher average than the jute only for the remainder of the test. It is important to note that all PAM water samples demonstrated a high degree of flocculation, but settling time was not measured. Thus there may be an important aspect of runoff quality improvement due to PAM, namely, improved settling time, which is not captured in these results. The *C*-factor was calculated using the regression and the RUSLE method, which is depicted in Table 4.14. The soil loss ratio was also determined for convenience to compare to the straw mulch tests. Water quality performance is shown in Figure 4.7.

TABLE 4.14: Soil Conditioner *C*-factor Results

Product	*K*-factor	*C*-factor (Regression Method)	*C*-Factor (RUSLE Method)	Soil Loss Ratio
Gypsum w/ Jute	0.22	0.12	0.10	0.09
PAM w/ Jute	0.26	0.45	0.56	0.61



(a) Total suspended Solids



(b) Turbidity

FIGURE 4.7: Soil Conditioners Water Quality Results.

4.4.1 Residual Testing

This study aimed to select a detection method based on four main criteria: (1) free from interference from organic matter, (2) robust to high sediment concentrations, (3) have a high upper detection limit, and (4) be accessible for others in the construction industry. The concern over organic matter interference is due to the fact that the source water for testing is a small retention pond that contains algae and other aquatic life. The concern over sediment concentrations comes from the fact that the runoff samples from the ASTM D6459-19 simulator typically contain high amounts of soil. The concern over detection sensitivity arises from the goal of the study. Some methods are highly sensitive and can only detect very small concentrations, which may not be adequate for the quantities anticipated. Lastly, the concern over accessibility is for the method to not be prohibitive to replicate so that others may easily adapt it to different circumstances as needed, and that the method should be adaptable to other site conditions such as other soils and other water sources.

The spectroscopic method following Momami and Ormeci 2004 was selected for use as a detection method in this study. This method was intended to fulfill the research objectives outlined above: (1) it is not sensitive to organics, (2) sediment interference can be eliminated through centrifuging, (3) it can detect higher concentrations if needed, and (4) it may be adapted to varying site conditions such as different soil concentrations or water properties. In the spectroscopic method used for this study, solutions of PAM at known concentrations were passed through a UV-Visible spectrum spectrometer and absorbance was measured from 200 nm to 750 nm, the breadth of the ultraviolet and visible spectrum. A regression relationship was then established between concentration of PAM and absorbance at 200 nm from these calibration samples. Absorbance at 200 nm was selected for comparison because it represented the greatest magnitude of difference between samples as per example of Momami and Ormeci. The absorbance from a sample of unknown concentration could then be measured and its concentration estimated using the calibration relationship. Calibration samples were prepared with source water and PAM at concentrations of 120, 90, 60, 40, 20, and 0 mg/L. Absorbance at 200 nm was plotted and a linear relationship obtained with an R^2 value of 0.99. Figure 3.1 illustrates absorbance curves at these values and also plots absorbance vs. concentration at 200 nm. The regression equation obtained from Figure 4.8 was used to estimate concentration of test samples by using measured absorbance and solving for concentration.

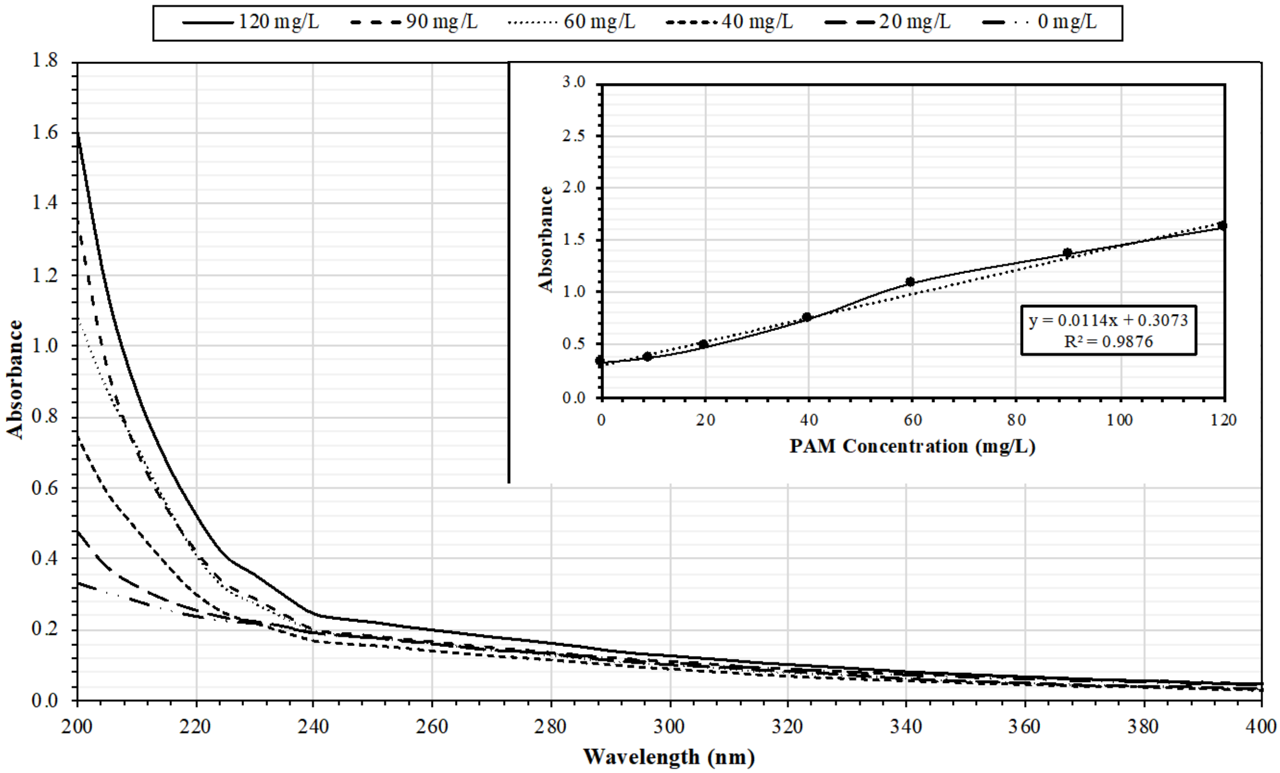


FIGURE 4.8: Calibration Curves

4.4.2 Validity Analysis

Centrifuging was used to remove sediment from runoff samples from the ASTM plot, isolating only the runoff, before spectrometer analysis. Samples were centrifuged at 1,200 relative centrifugal force (RCF) for 10 minutes to remove sediment and then only the supernatant was run through the spectrometer. Figure 4.9 depicts the centrifuging process.

(a) Eppendorf machine (b) Sediment removal post-centrifuge

FIGURE 4.9: Centrifuging

The following two paragraphs address the validity of the results with centrifuging. First, soil removal must be complete for accurate PAM detection, in other words, there should be no soil interference remaining after centrifuging. To determine if residual soil interference affected results, turbidities were compared between calibration samples and supernatant of field samples. The average turbidity of 56 field samples was 8.6 NTU with a standard deviation of 4.2 and the average turbidity of nine calibration samples was 8.4 NTU with a standard deviation of 2.3. There was a weak correlation between concentration and turbidity, with a correlation coefficient of -0.3, suggesting that the flocculant tended to reduce background turbidity but not consistently. A T-test between the calibration and field samples yielded a t-statistic of 0.87 and a corresponding p-value of 0.39. Because there is not sufficient evidence that the turbidities of the field samples and the calibration samples differed, it is not believed that soil interference was a concern in the analysis. Removing soil interference is a significant advantage of this method because some samples contained up to one part soil per four parts solution by weight.

There is an additional concern that the centrifuging process may remove PAM from solution along with the soil. To determine if centrifuging removed PAM from the supernatant, a solution was prepared with 100 mg/L PAM and deionized water and its absorbance read at 200 nm in the spectrometer. Then the sample was centrifuged and the topmost portion of the sample was read again. A T-test between the raw and centrifuged samples yielded a t-statistic of 2.78 and a corresponding p-value of 0.12. At the 90% confidence level, there is not sufficient evidence that the means between the centrifuged and raw samples differed and therefore it is not believed that centrifuging PAM out of solution was a concern.

A reading at 2 mg/L was added to the blank calibration solutions to determine whether a detection limit might be valid at that level. A T-test between the means of the absorbances at 200 nm of the 0 mg/L and the 2 mg/L sample yielded a t-statistic of 8.83 and a corresponding p-value of 4.5E-4. It can be concluded that the detection limit of this method is reliably 2 mg/L. Only one reading of 52 was below this limit.

4.4.3 PAM Residual Testing Discussion

The average estimated concentration over the three trials is plotted in Figure 4.10 along with runoff rate. The first recorded absorbance value corresponds to observance of first runoff. An increase in concentration occurred immediately after first runoff was observed at approximately 12-15 minutes into the test, too large to be measured using the absorbance values constructed during calibration without extrapolation. The concentration was extrapolated at nearly 200 mg/L during trial 3. There was a subsequent decrease in concentration until about halfway through the test or minute 30, when concentration appeared to steadily fluctuate between 20-60 mg/L. The phenomenon of high initial concentration echoes the first flush effect, where the first appearance of stormwater runoff contains the highest concentration of contaminants that had been previously found on the ground surface. Then, as runoff persist and even grows, concentration decreases. Furthermore, the first runoff/high concentration points correspond to a period of no observed sediment loss during testing. Figure 4.11 compares average PAM concentration to average TSS, a metric used as a proxy for sediment loss, throughout the test. As PAM concentration decreased and the slope lost its protective coating, sediment loss increased.

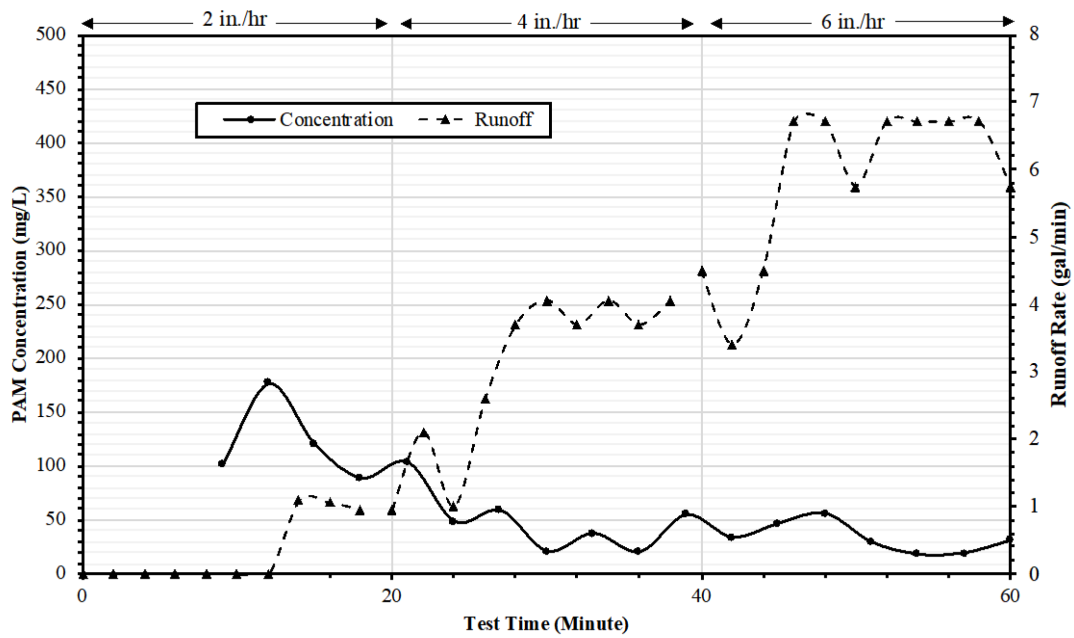


FIGURE 4.10: Estimated PAM concentration over time.

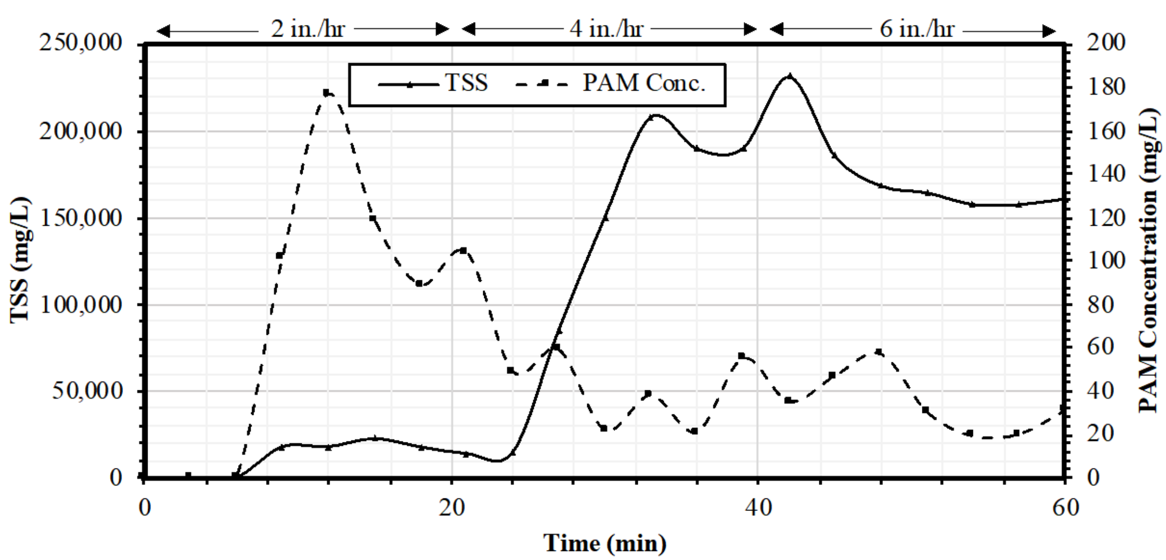


FIGURE 4.11: PAM concentration vs. TSS.

Twelve out of 52 samples displayed high (>100 mg/L) concentrations. Qualitative observations during testing confirm the likely presence of high PAM concentrations. Sediment-laden runoff from the plot during PAM testing had a visibly and unusually frothy, soap-like quality, documented in Figure 3.5. Blank PAM solutions without sediment, such as those prepared for calibration, were observed to display a thin, soapy film when agitated and tended to form lather at the surface. Furthermore, while PAM/jute offered 100% protection against soil loss during the 2 in./hr simulation – in other words, no soil loss was observed in contrast to the bare soil condition – the plots treated with PAM and jute did not exhibit statistically significantly less soil loss during the 4 in./hr and 6 in./hr simulations than the plots covered with jute alone. While also surprising, this is not without precedent. Ai-Ping (2011) and Babcock and McLaughlin (2013) found that at some doses adding PAM in a rainfall simulation either had no impact on sediment loss or led to an increase in sediment loss, and Tumsavas and Kara (2011) also found a single optimum application rate that was not the same as the maximum application rate used. Because other rainfall simulators typically do not test at intensities on the order of 4 in./hr, it is likely that this experiment is simply demonstrating the limits of the product especially after product was erased during the first flush.

Because sediment loss in this experiment was so high, it is likely that a high percentage of the applied polymer bonded to the soil ended up in the runoff. An expected concentration can be hypothesized based on total runoff volume generated from each test and amount of PAM applied to each test. Table 4.15 displays the amount of PAM applied, the runoff generated from the test, and the PAM concentration expected if all PAM washed into the runoff. It also provides an estimate of the percentage of PAM from each test that appeared in runoff, as opposed to remaining in the soil, by dividing the observed concentration by the expected concentration anticipated if all PAM washed into the runoff. As evidenced from the table, roughly half on average of product appeared in runoff.

TABLE 4.15: Runoff and Expected Concentration If All PAM Appeared in Runoff

Parameter	Test 1	Test 2	Test 3	Avg.
PAM applied to slope, g (oz.)	84 (3.0)	84 (3.0)	84 (3.0)	84 (3.0)
Total runoff from test, L (gal)	687 (181)	787 (208)	935 (247)	803 (212)
Expected concentration if all PAM (100% runoff) appeared in runoff, mg/L	122	107	90	106
Actual average concentration from test, mg/L	55	52	61	56
Percent of applied product observed in runoff	45%	49%	68%	54%

Several explanations exist for the higher concentrations found than in previous studies. First, the ASTM simulator represents a steeper, large-scale slope with high rainfall intensities. In fact, the total intensity called for over the 1-hr simulation represents approximately the 500-yr storm in the testing location of central Alabama. As suggested previously, the standard may simply be pushing the limits of the product. Second, PAM dosing is much more difficult to do on slopes than on for example sedimentation basins. Even when jar testing is performed, soil type, slope, rainfall, and other conditions can interact in such ways that make exact optimal dosing sometimes difficult. By contrast, in the sedimentation basin example, typical doses are low (1-5 mg/L) (McLaughlin et. al 2016), based on design volume (Johnson et. al 2015), and introduced in ways to maximize mixing, thus making ideal dosing easier. It is possible that in this study a sub-optimal dose was utilized which did not fully create a seal on the soil. PAM's effectiveness relies on the polymer seal that it creates against the soil surface when introduced with water and the proper dose would theoretically make the most ideal seal. Further study should evaluate the effects of different application rates. Third, and related, the soil utilized was a highly erodible type. Medium-texted soils tend to erode more than other types, leading to the high sediment loss and perhaps the additional difficulties bonding. Fourth, pre-wetting the soil before running the test could have aided in activating the product to create the seal, increasing the amount bonded and mitigating the amount in runoff. Unfortunately, based upon ASTM standard methods, soil wetting is not specified prior to testing and therefore was not performed. In the field, it is highly like that PAM would be subject to dew formation and much less intense storm events that would activate the PAM and help bind it to the so

4.5 SUMMARY OF PERFORMANCE RESULTS

As shown through testing, there are varying performance capabilities of the erosion controls tested during this project. Surprisingly the hydromulch products tended to perform poorly, especially when subjected high intensity storm events. Rolled erosion control blankets tended to perform well, particularly the Curlex I blanket. This excelsior blanket is made of fibrous material that creates substantial ground contact while also benefiting from surface anchoring with sod staples. The limitation of hydromulch is likely due to the lack of physical anchoring. The performance of the soil conditioners also yielded varying results. The PAM application with jute blanket performed poorly while the agricultural gypsum helped improve the jute blankets performance, greatly decreasing soil loss from the plot. PAM residual is a concern, but further evaluation and setup is warranted to ensure the product was not subjected to undue conditions during testing.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Erosion controls, especially those that protect against rainfall induced erosion are often the first physical line of defense for construction project to mitigate downstream pollution potential. Knowing what the erosion reduction capability of different products and practices is important for designers and planners to adequately meet the local, state, and federal pollution reduction guidelines. The testing results from this project resulted in many expected results as well as results that likely require further investigation to ensure erosion control options are adequately investigated.

5.2 CONCLUSIONS

The following sections summarize the conclusions from testing of the different erosion control products and practices under rainfall simulation. The results of the testing and published product *C*-factors are also discussed to show differences in expected versus measured performance.

5.2.1 Straw Mulch Testing

Blown straw mulch was tested based upon loose straw condition, blown straw with tackifier, and blown straw crimped. Initial performance resulted in surprising results with the crimped straw having poorer performance than all other straw applications from both a sediment loss and water quality standpoint. It was hypothesized and demonstrated that the crimping of the straw disturbed the soil surface enough to create a substantial amount of soil loss. However, longevity testing showed that soil loss greatly decreased with the crimped straw stabilizing the slope and capturing sediment that migrates down slope. The straw with tackifier loss some erosion reduction capability over time, likely due to the tackifier diluting in the rainfall and runoff. It may be of benefit to perform further longevity testing on straw with tackifier to determine loss of performance over time and potential performance improvements with additional tackifier applications. Since straw testing did not originally follow ASTM standards, it would also be beneficial to evaluate straw on the ASTM soils to determine potential performance for different soil regions within the state.

5.2.2 Hydraulic Mulch Testing

Hydraulic testing evaluated four hydraulically applied mulches and one dry applied hydraulic mulch pellets. Three of the hydraulically applied mulches had similar *C*-factors close to 0.50. However published *C*-factors for these products are closer to 0.25. However, these product specified C-factors were not determined using ASTM D 6459, so confirmation and comparison cannot be performed. The Earthgaurd Edge Pellets dry mulch does not specify a tested c-factor in its literature, however, it advertises an erosion control rating of 99.9%. Testing this product using ASTM methods resulted in a C-factor of 0.33. Performance of these products and the differences seen between published values and measured values are most likely due to differences in testing methodologies. To ensure performance characteristics are consistent for regardless of testing environment, these products should be tested on other ASTM soils that are less erosive.

5.2.3 Erosion Control Blanket Testing

Four erosion control blankets were tested. Three were tested as part of the initial project requirements (two excelsior and one straw blanket) and a jute blanket was tested as part of the soil conditioner evaluations. The Curlex I excelsior blanket resulted in the lowest *C*-factor for all products tested with a *C*-factor of 0.05. This *C*-factor was still higher than the published *C*-factor of 0.018. The *C*-factor for the North American Green S150 blanket was determined to be 0.14, however the published *C*-factor is 0.055 for a 3:1 slope between 20 and 50 ft in length. The East Coast Erosion ECX-2 excelsior blanket was determined to have a *C*-factor of 0.12. The published C-factor of slope lengths less than 50 ft and equal to 3:1 is 0.035. However the published *C*-factor for slope lengths of 3:1 to 2:1 and less than 50 ft is 0.14 which is closer to the *C*-factor determined in this study.

5.2.4 Soil Conditioners

Polyacrylamide (PAM) was evaluated with jute blanket to mimic the polymer enhanced soft armoring system. To determine the products performance, a jute blanket was also evaluated. Due to the open weave nature of the jute, substantial soil loss was observed. The addition of the PAM did not provide substantial improvement from an erosion control standpoint. Testing the PAM application followed ASTM D 6459 methodology which does not allow for pre-wetting the soil or application surface. However, based upon discussions with the manufacturer, since PAM requires wetting and activation prior to achieving desired performance, it may prudent to test PAM with jute and allow for a pre-wetting condition to help activate PAM and allow for soil anchoring to occur. This may be extremely beneficial due to the high intensity nature of the ASTM D 6459 test method. The gypsum and jute test resulted in the second lowest *C*-factor of 0.12. This is equivalent to the ECX-2 excelsior blanket performance. The gypsum and PAM both reduced runoff, giving credence to these products being soil conditioners as well as erosion controls.

5.3 EROSION CONTROL RECOMMENDATIONS

5.3.1 Straw Mulch

Straw mulch has consistently been used as an erosion control practice for temporary erosion control applications. Substantial improvement in soil loss reduction was found to occur when some type of anchoring is included as part of the practice. Though crimping had the greatest amount of soil loss, initially, longevity testing showed this practice to be the best form of anchoring. The tackifying anchoring also performed well, but loss of performance was evident over time and should be a consideration. Potential considerations should be made for reapplication of tackifying agent. This could be further investigated in future testing.

5.3.2 Erosion Control Blanket

Excelsior blankets appear to provide the most consistent erosion control based upon comparisons between products and practices. These products also have the greatest amount of labor and preparation requirement. Mulch applications typically do not require significant slope dressing since the mulch application is not affected by "tenting" that erosion control blankets tend to have issues with. However, the additional preparation and installation requirements may outweigh the potential soil loss and redressing that may be created from lesser performing mulch applications. It is apparent from testing that both soil contact and anchoring are extremely important for products to be able meet erosion control requirements. Though the ECX-2 was an excelsior blanket, similar to the Curlex I blanket, the ECX-2 had "thin spots" that resulted in substantial erosion in at those areas. It may also important to specify that blanket sections with bare spots should be cut out and the blankets should be spliced together as specified by the manufacturer installation requirements to ensure the slopes are properly protected.

5.3.3 Hydraulically Applied Mulch

The hydraulically applied mulch tested for this project resulted in measured *C*-factors substantially higher than published values. As previously mentioned, ground contact and anchoring are two of the most important mulch performance components. Hyrdomulch relies on hydration and soil bonding to anchor to the soil surface. However, if the underlying soil becomes unstable, then soil loss may be greater than expected. The ASTM D6459 test results in 4 in./hr average intensity during the entire one hour testing regime. During the initial 2 in./hr for 20 minute portion of the test, very little runoff is occurring due to the absorbent nature of the dried hydraulic mulch. As the intensity increases to 4 in.hr, the amount of absorbance the product is able to provide is exceeded causing the hydraulic mulch to liquefy and run down slope with the runoff, exposing the surface to rain drop impact and interrill and rill erosion. The combination of soil saturation, high intensity rainfall, and highly erosive soil potentially created conditions much worse than the products were exposed to in other test evaluations. Future testing of hydromulches should be performed on other soil types that are not as highly erosive as the loam soil used for this project to determine if soil erosivity affects hydraulic mulch performance. Also, since vegetation is the final goal of testing, most final erosion controls are going to be installed on topsoil, which this initial testing program did not evaluate (due to ASTM D6459 limitations). The combination of soils that are less erosive and the addition of topsoil to reduce soil runoff may result in improved product performance. This would lead to categorization of products for specific project conditions and allow the designer to best specify the products or practices that will meet the overall project needs.

5.3.4 Soil Conditioners

The use of PAM and gypsum as erosion controls and soil conditioners may be somewhat of a new concept to some contractors and designers, however there is evidence that these can be beneficial for reducing runoff volume and erosion. Gypsum, specifically had a substantially positive affect on erosion control. However, this product may not be as effective on other soil types, so testing it on other ASTM soils would be recommended. Further testing of PAM to provide the product the opportunity to hydrate and activate as potentially occurs in the field from overnight condensation development or through light rainfall amounts would also be recommended.

5.4 LIMITATIONS AND OUTCOMES FOR FUTURE RESEARCH

5.4.1 Evaluate Differences in Performance with Different Variables

This project was limited to the environment created by ASTM D 6459. The ability to test under these conditions has allowed the AU-ESCTF to become an ASTM accredited laboratory. This has, however, limited the ability to evaluate different erosion controls under more realistic circumstances. The soils used for this project is likely substantially different than that used for testing at other laboratories, therefore, evaluating performance of these products and practices on differing soil types as well as differing slopes will help create a more complete understanding of expected performance for these erosion controls.

Many of the hydraulic mulches on the market have maximum affective slope lengths of less than 40 ft, which is what the ASTM D 6459 slope requirement is. Of the hydraulic mulches tested for this research project, only ProMatrix has an allowable maximum slope length of 40 ft or greater. Other standardized methods have recently become available from ASTM, including ASTM D 8298 that has a shorter slope length requirement that is a minimum of 16.4 ft long. Future testing could potentially modify the ASTM D 6459 slopes to shorten the affective installation area and evaluate the product under the less stringent testing environment.

5.4.2 Erosion Control Testing on Different Soil Types

ASTM D 6459 also requires testing to meet specific soil type requirements. This testing was performed on a locally sourced loam soil, however, the standard also allows for testing on a clay or sand as long as certain gradation and cohesion requirements are met. This will also allow for a better understanding of expected performance under different site conditions. Also, since erosion controls are meant to preserve topsoil to enhance vegetative capabilities, it would also be important to evaluate how stabilization practices are able to perform through topsoil erosion control and preservation.

5.4.3 Erosion Control Testing under Regional Rainfall Intensities

The storm intensity requirements for ASTM D 6459 are specified to be 2 in./hr, 4 in./hr, and 6 in./hr for twenty minutes each intensity. This results in an average storm intensity of 4 in./hr for the one-hour storm duration. This would be considered a 500-year return period for this type of storm in Alabama. Therefore, it may be necessary to evaluate products and practices under more realistic storm intensities that better represent expected climatic conditions. For example, the 2-year 24-hour storm is used for evaluating various erosion and sediment control practices and could be used for the rainfall simulation. The 2-year 24-hour rainfall at Auburn is 4.16”, and the maximum rainfall depth over one hour is 1.63 in. for Type III SCS rainfall distribution.

5.5 ACKNOWLEDGEMENTS

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