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Evaluation of Hydromulches as an Erosion Control Measure Using Laboratory-Scale Experiments

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Abstract: Discharge of sediment-laden stormwater from active construction sites, such as highway construction projects, continues to be a growing concern in the construction industry. Therefore, there has been an increased interest in research efforts to test many different erosion and sediment control practices. The purpose of this research effort was to test the laboratory-scale performance of four hydromulches and two methods of mulching (crimped and tackified), normalized to a bare soil control condition using 0.6 m (2 ft) wide by 1.2 m (4 ft) long test plots. The treatments consisted of a (1) bare soil control, (2) conventional straw, crimped, (3) conventional straw, tackified, (4) wood fiber hydromulch, (5) straw and cotton hydromulch, (6) cotton fiber reinforced matrix hydromulch, and (7) bonded wheat fiber matrix hydromulch. Each treatment was subject to simulated rainfall, divided into four 15 min rainfall events with 15 min breaks in between, producing a total cumulative rainfall of 11.2 cm (4.4 in.). To determine the overall performance of each treatment, turbidity and soil loss measurements were continuously collected from plot runoff. The products tested provided a reduction in turbidity of 80%, 98%, 85%, 92%, 95%, and 99%; and a soil loss reduction of 96%, 98%, 94%, 97%, 99%, and 100%, respectively. Overall, the results showed that the four tested hydromulch practices and conventional straw applications were successful in controlling and reducing erosion under laboratory-scale simulated rainfall conditions.

Keywords: erosion control; laboratory-scale testing; simulated rainfall; runoff

1. Introduction

The discharge of sediment-laden stormwater from active construction sites, such as highway construction projects, is a growing concern in the construction industry [1]. The United States Environmental Protection Agency (USEPA) labels such discharge as nonpoint source (NPS) pollution, which is defined as land runoff, precipitation, atmospheric deposition, seepage, or hydrologic modification that does not meet the legal definition of 'point source' in Section 502 (14) of the Clean Water Act [2].

Soil erosion is considered the largest contributor to NPS pollution in the U.S. [3]. Construction sites are known to be a significant contributor to soil erosion by exhibiting soil loss rates that are 20 times greater from construction sites than agricultural lands, and 1000 to 2000 times greater than forest lands [4,5]. Studies have shown that erosion rates on cut slopes of roadways has varied from 5.93 mm/ha (0.09 in./ac. or in./ac.) up to 70 mm/ha (1.12 in./ac.) [6]. When soil is eroded from construction sites, other harmful particulates such as fertilizers, pesticides, metals, and fuels attach to the soil and are transported into municipal separate storm sewer systems (MS4s) [7,8]. Polluted

MS4s transport construction site runoff directly to surface waters, ultimately causing sedimentation. In the U.S. alone, "sedimentation impairs 84,503 river and stream miles (12% of the assessed river and stream miles and 31% of the impaired river and stream miles)" [9]. Sedimentation of surface water can lead to deterioration of aquatic habitats, rapid loss of storage capacity of reservoirs, eroded streambanks, and increased turbidity of the waters thereby reducing photosynthesis, and clogging fish gills [10]. An annual estimate of $17 billion is spent in the U.S. alone in an effort to control onsite sedimentation, bringing the national total to nearly $60 billion in erosion and sediment control activities [11]. Thus, the combination of environmental and economic downfalls related to erosion and sedimentation in the construction industry has developed a need for scientific research to be performed to understand the overall performance of erosion and sediment control (ESC) practices used at the federal, state, and local levels.

Within the construction industry, there are numerous types of erosion controls. The focus of this research effort is to test the performance of the following surface cover treatments: (1) conventional straw, crimped, (2) conventional straw, tackified, (3) wood fiber hydromulch (HM) (Excel® Fibermulch II), (4) straw and cotton hydromulch (Geoskin®), (5) cotton fiber reinforced matrix hydromulch (FRM) (HydraCX^{2}®), and (6) bonded wheat fiber matrix hydromulch (FM) (Hydrostraw® BFM).

1.1. Mulching as an Erosion Control

Mulching is defined as an erosion control practice that uses materials such as shredded paper, grass, hay, wood chips, wood fibers, straw, or gravel to stabilize exposed or recently planted soil surfaces [12,13]. Surface mulch has been found to be one of the most effective, practical means of controlling runoff and erosion on disturbed land prior to vegetation establishment; however it is most effective when used in conjunction with vegetation [12,14,15]. Researchers [16–19] have reported that mulches used to control erosion have a two-fold advantage: (1) reduce soil loss and (2) protect grass seeds and soil amendments from being washed away. Additionally, mulches are capable of reducing solar radiation, suppressing fluctuations of soil temperature, reducing water loss through evaporation, increases interception storage capacity, dissipating the kinetic energy from the raindrops impact, and helping to prevent soil crust formation [17,18,20–23]. Research has also shown that mulching can reduce sediment yields by over 80% when applied at a rate of 2000 kg/ha (1784 lb./ac.) [23,24].

The purpose of testing conventional straw was to have a traditional, low-cost, widely used erosion control practice to compare to the performance of hydromulch products. Straw is one of the most widely used ground covers used to reduce erosion on construction sites [25], and has been reported to reduce erosion rates by more than 90% if applied at sufficient rates [22,26–28]. Turgeon [21] states that straw is also capable of encouraging grass establishment by reducing runoff, increasing infiltration, and improving soil conditions.

Straw crimpers are typically used to crimp or punch straw into the soil when the soil is not too sandy [29]. If crimpers are not available or necessary, liquid mulch binders are used to 'tack' mulch by spraying the tack on top of the straw [15].

There are advantages and disadvantages to using straw mulch for erosion control. The advantages are that it is inexpensive, quick, and easy to apply using a straw-blower, capable of achieving efficient grass growth, and water is not needed for application. Straw mulch has also been found to perform as well as or better than hydromulch products when applied at sufficient rates [30]. Other studies have shown straw mulch to not only reduce soil erosion in the short term, but also by aiding in vegetation establishment through the long-term reduction of soil erosion [31]. Conversely, disadvantages of conventional straw include that it does not prevent soil loss as well as more expensive erosion products (e.g., erosion control blankets, compost, etc.), is susceptible to wind if not properly anchored, may introduce weed seeds, and fines from straw blowers can drift long distances [29].

1.2. Hydraulically Applied Mulch (As Known as Hydromulch)

Hydraulically applied mulches, referred to herein as 'hydromulches', have shown continuous evolution and improvement over the past 50 years. Advancements in technology have resulted in the production of equipment and materials that offer enhanced performance and greater productivity over many traditional methods of erosion control. Hydromulch has been shown to meet the required planting depth for small seeded species [32]. In other studies, hydromulch has been shown to reduce the sediment yield by about 75% when compared to bare plots [33]. There is a knowledge gap between the cost-effectiveness and performance benefits of new products [18,34–36] such as hydromulches, largely due to newly evolving technologies as well as a lack of research involving hydromulch products.

The introduction of water, refined fiber matrices, tackifiers, super-absorbents, flocculating agents, man-made fibers, plant biostimulants, and other performance enhancing additives to hydromulching practices on slopes has forced federal, state, and local governments to develop hydromulch guidelines. ASTM International (ASTM) has proposed new standards for testing hydraulically applied erosion control products (HECPs). Additionally, the Erosion Control Technology Council (ECTC) has divided HECPs into five distinct categories, relevant to their corresponding functional longevity, erosion control effectiveness, and vegetative establishment [29,37]. Specific to this study, the addition of a tackifier to a hydromulch has been shown to increase the effectiveness of the hydromulch as a soil cover due to the tackifier bonding with the soil particles and creating a more hydrophobic environment [38]. Prats et al. [23] determined that the initial reduction in soil erosion on a plot treated with hydromulch was attributed to the initial protective cover provided by the mulch to minimize splash erosion.

McLaughlin and Brown [27] conducted large- and laboratory-scale tests on four ground cover practices: straw mulch, straw erosion control blanket, wood fiber, and a mechanically bonded fiber matrix (MBFM) hydromulch. In their study, it was reported that the ground covers reduced runoff turbidity by a factor of four or greater when compared to bare soil. More specifically, on the controlled, laboratory-scale tests, the MBFM reduced average turbidity by approximately 85% and sediment loss by about 86% in comparison to a bare soil control.

Holt et al. [39] performed laboratory-scale tests on six hydromulch treatments using 0.6 m (2 ft) wide by 3.05 m (10 ft) long by 7.62 cm (3 in.) deep trays at a 15.7% slope. The following six hydromulches were applied by hand at 1120 kg/ha (1000 lb./ac.) and 2240 kg/ha (2000 lb./ac.): wood hydromulch, paper hydromulch, cottonseed hulls hydromulch, cotton byproduct (COBY) hydromulch produced from stripper waste (COBY Red), COBY produced from picker waste (COBY Yellow), and COBY produced from ground stripper waste (COBY Green). COBY is a term used in Holt's report to represent a patented cotton by product of cottonseed hulls [40]. The respective soil treatments with an application rate of 1120 kg/ha (1000 lb./ac.) achieved soil loss reductions of 35%, 58%, 84%, 90%, 80%, and 80% for wood, paper, cotton-seed hulls, COBY red, COBY yellow, and COBY green. When the application rate was increased to 2240 kg/ha (2000 lb./ac.), the respective soil treatments achieved soil loss reductions of 19%, 32%, 79%, 88%, 88%, and 68% for wood, paper, cotton-seed hulls, COBY red, COBY yellow, and COBY green.

In 2002, Landloch [41] studied the performance of four hydromulch treatments using 15 plots that were 5 m long by 1.5 m wide (16.4 ft long by 4.9 ft wide) at a 25% slope. The four hydromulches tested were paper hydromulch, flax hydromulch, flax plus paper hydromulch, and sugar cane hydromulch, applied at a rate of 1000 (893 lb./ac.), 2500 (2232 lb./ac.), 3250 (2900 lb./ac.), and 5000 kg/ha (4464 lb./ac.), respectively. The respective treatments achieved soil loss reductions of 80%, 85%, 96%, and 96% for paper, flax, flax plus paper, and sugar cane.

Benik et al. [42] developed a study comparing the effectiveness of five treatments, including Soil Guard® which is a bonded fiber matrix (BFM). In their experiments, the BFM was applied at a minimum rate of 3360 kg/ha (3000 lb./ac.). The BFM reduced average sediment yield by approximately 94%.

Buxton and Caruccio [43] evaluated 19 soil stabilizing and erosion control treatments, four of them were hydromulches without tackifiers. The plot sizes used were approximately 1.5 m (5 ft) wide by 3 m (10 ft) long at a 12% to 15% slope. The four hydromulches tested were Conwed wood fiber mulch, Superior wood fiber mulch, Silva wood fiber mulch, and Pulch; each hydromulch was applied at a rate of 1344 kg/ha (1200 lb./ac.). In the study of Buxton and Caruccio [43], effectiveness of the hydromulches were measured using a vegetative maintenance (VM) and erosion control value, which in 1979 was a new parameter in the Universal Soil Loss Equation (USLE), and represented total loss ratio expressed as a decimal. These values ranged from 0.0 to 1.0, where a value of 1.0 means the erosion control practice had no effect in reducing erosion. The VM values for Buxton and Caucci's [43] report were translated below in Table 1 to measure erosion control performance in soil loss reduction percentage.

Babcock and McLaughlin [25] evaluated straw mulch, with and without polyacrylamide (PAM), and a wood fiber hydromulch, with and without PAM, on the effectiveness of reducing erosion and improving the water quality of the runoff. The plot sizes used were 1 m by 2 m (3.3 ft by 6.6 ft) on a −33% slope. The plots were subjected to a total rainfall of 3.05 cm (1.2 in.) at an intensity of 3.7 cm/h (1.5 in./h). The mulch was applied at a rate of 2240 kg/ha (1998 lb./ac.), while the hydromulch was applied at two separate application rates: 1970 kg/ha (1758 lb./ac.) and 2940 kg/ha (2623 lb./ac.). This study found that hydromulch applied at a rate of 2940 kg/ha (2623 lb./ac.) provided a soil loss reduction of 8% and hydromulch applied at a rate of 1970 kg/ha (1758 lb./ac.) provided a soil loss reduction of 19% when normalized to a straw mulch application of 2240 kg/ha (1998 lb./ac.).

Robichaud et al. [44] developed a study to evaluate the performance of wheat straw mulch and wood hydromulch when used in a post-fire condition to reduce erosion. This study utilized natural rainfall over several years to evaluate the products. Two separate tests were performed in two different locations. At the first location, the application rate of the wheat straw was 2200 kg/ha (1963 lb./ac.) and the hydromulch was 1100 kg/ha (981 lb./ac.). The soil loss reduction rates of the wheat straw mulch and the hydromulch were found to be 97% and 65%, respectively, for the first year of the study. At the second location, the application rate of the wheat straw was 4500 kg/ha to 6700 kg/ha (4015 lb./ac. to 5978 lb./ac.) and the hydromulch was 600 kg/ha (535 lb./ac.). The soil loss reduction rates of the wheat straw mulch and the hydromulch were found to be 99% and 19% for the first year, respectively.

Table 1. Summary of reviewed hydromulch practices.

Study	Type of Hydromulch	Test Scale	Slope	Application Rate (kg/ha)	Soil Loss Reduction (%)
McLaughlin and Brown [27]	MBFM	Large and laboratory	10% and 20%	3360	86
Holt et al. [39]	Wood	Laboratory	15.7%	1120	35
	Paper				58
	Cotton-seed hulls				84
	COBY red				90
	COBY yellow				80
	COBY green				80
	Wood			2240	19
	Paper				32
	Cotton-seed hulls				79
	COBY red				88
	COBY yellow				88
	COBY green				68
Benik et al. [42]	BFM	Large	35%	3360	94
Landloch [41]	Paper	Large	25%	1000	80
	Flax			2500	85
	Flax plus paper			3250	96

	Sugar Cane			5000	96
Buxton and Caruccio [43]	Conwed *	Large	12% to 15%	1344	77
	Superior *				73
	Silva *				35
	Pulch *				72
Babcock and McLaughlin [25]	Wood	Laboratory	33%	1970	19
				2940	8
Robichaud et al. [44]	Wood	Large	Various	1100	65
				600	19

* All are wood-fiber hydromulches.

This research aims to evaluate the effectiveness of six different ground cover treatments, normalized to a control treatment, when evaluated under simulated rainfall on laboratory scale plots. The process will include a standard and repeatable methodology that is consistently applied across the treatments under evaluation. The expected outcome is to confirm the effectiveness of the treatments.

2. Test Methods and Procedures

The validity of this research effort relies heavily on the amount of reproducible data that is collected during experiments that can be used for comparative analyses to evaluate erosion control practice and product performance and effectiveness. The test plots and rainfall simulator constructed for this research effort were replicas of Shoemaker's [45] experiments with the exception of the runoff collection device. Each test plot is 0.6 m in width by 1.2 m in length (2 ft by 4 ft) by 7.62 cm (3.5 in.) in depth. The sizes of the test plots were constructed with the purpose of testing erosion control practices with ease, speed, accuracy, and mobility throughout the experiment. The rainfall simulator was constructed using a single FullJet™ 1/2 HH—30 WSQ nozzle, with a wide angle uniform square spray area, and medium to large drop size distribution. To regulate flow rate, the inlet hose was attached to a Norgren™ R43-406-NNLA pressure regulator with 1.27 cm (1/2 in.) port sizes. To maintain a consistent pressure specific to the desired rainfall event, a pressure gauge was attached to the pressure regulator to observe and regulate operating water pressure. The simulator was suspended approximately 1.5 m (5 ft) from the building wall, and 3 m (10 ft) from the floor as shown in Figure 1, and rainfall covers approximately a 2.4 m by 2.4 m (8 ft by 8 ft) area.

Figure 1. Illustration of rainfall simulator and test plots.

Shoemaker's research efforts determined the Christiansen Uniformity Coefficient (CUC) [46] over the 2.4 m by 2.4 m (8 ft by 8 ft) spray area to range from 83% to 88% [45]; generally in the center 1.2 m by 1.2 m (4 ft by 4 ft) area.

For this study, the rainfall in 24 h for a return period of 2 years for Auburn, Alabama, was selected. The rainfall regime was designed using data available from Shoemaker [45]. The rainfall regime consisted of four separate 15-min rainfall events, each with a rainfall amount of 2.8 cm (1.1 in.) for a total rainfall amount of 11.2 cm (4.4 in.). The rainfall intensity for this regime is 11.2 cm/h (4.4 in./h). There was a 15-min period of no rainfall between two test events utilized by the researchers for data collection.

2.1. Soil Analysis

Soil for the research effort herein was provided by a local grading contractor from a construction site near the Auburn University—Erosion and Sediment Control Testing Facility (AU-ESCTF) located in Opelika, Alabama (32°33′5″ N, 85°20′28″ W, approximately 22.9 km (14.2 mi.) from Auburn, Alabama). A soil analysis was conducted by the Auburn University Soil Testing Laboratory to determine the soil composition. The experimental soil presented a "sandy clay loam" textural class according to the United States Department of Agriculture textural classification system with respective composition of 67.5%, 2.5%, and 30% of sand, silt, and clay.

After classifying the soil, a compaction test was conducted. In accordance with local standards for highway construction [47] on a typical highway embankment, slopes were compacted to 95% compaction. Given the scale of this experiment, hand tamping was selected to be used on the box plots to achieve optimum compaction. To determine the number of drops required to compact the soil, two compaction tests were completed. The first soil compaction test was to determine the optimum moisture content (OMC) or gravimetric water content of the soil. This was completed using a modified Proctor test, as specified in ASTM D1557-09, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort [48]. The modified Proctor test enabled researchers to develop a Proctor curve representing the moisture content of the soil versus the dry unit weight of the soil, as shown in Figure 2.

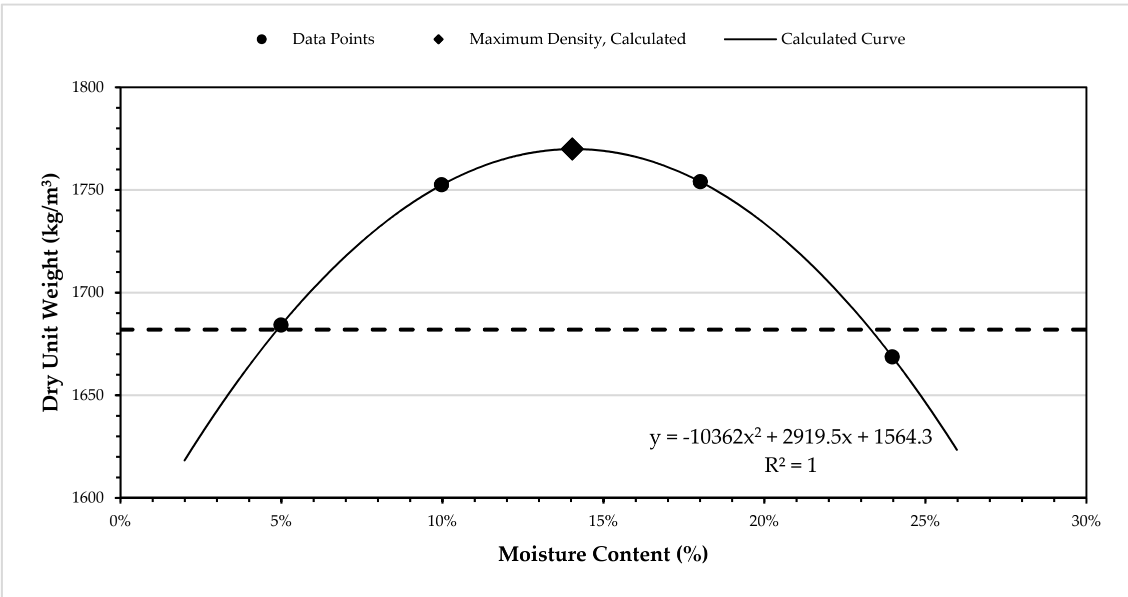

Figure 2. Proctor curve for experimental soil.

The Proctor curve shown in Figure 2 illustrates four determined moisture contents (MC) to achieve a specific dry unit weight for the tested soil. An OMC was determined to be 1762 kg/m^3 (111 lbm/ft^3 or pcf) at 14% MC by locating the maximum dry unit weight on the Proctor curve. The dotted line shown in Figure 2 represents the minimum dry unit weight of 1682 kg/m³ (105 pcf) required to reach the specified 95% compaction rate over a MC range of 5% to 23%.

The second compaction test, also adopted from Shoemaker [45], was created to test the number of drops of the hand tamper required to achieve 95% compaction. The purpose of this compaction test was to drop the hand tamper a specified number of times upon a known volume of compacted soil to determine a corresponding unit weight. Soil with a MC of approximately 14% was loaded into the testing apparatus and a hand tamper was dropped approximately 30.5 cm (12 in.) from the soil surface in a series of 5 sets: 10, 20, 30, 50, and 60 drops. After each set of drops, the known volume of soil was weighed, and a dry unit weight was calculated, and plotted on a graph, shown in Figure 3.

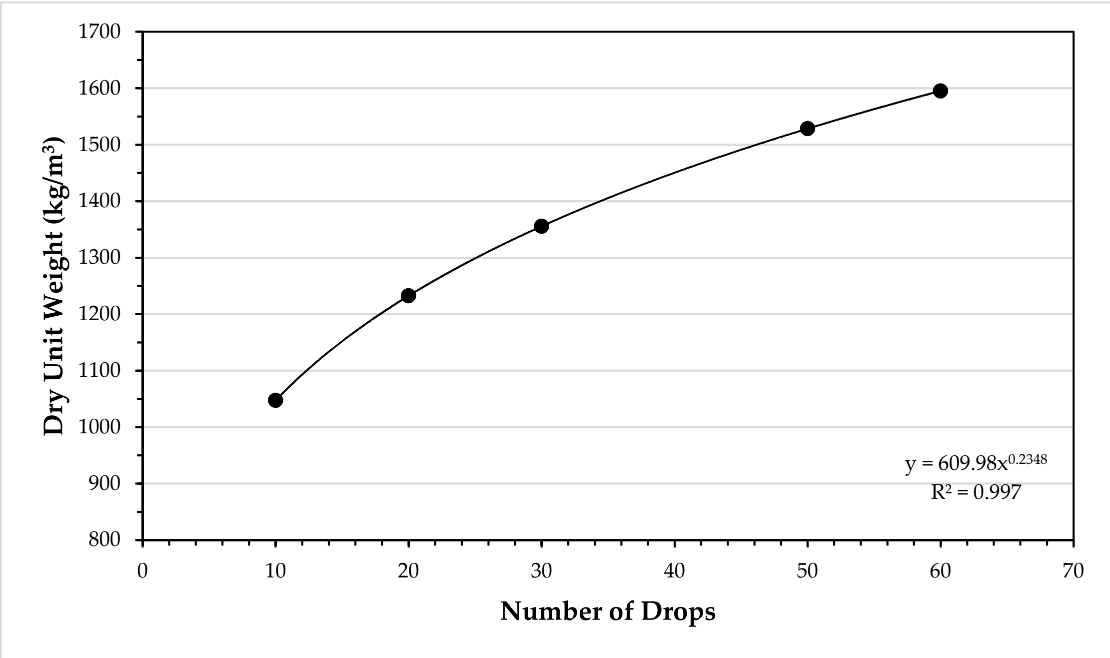

Figure 3. Number of drops with a hand tamper in relation to dry unit weight.

When compacted, soil will approach a point where it has reached maximum compaction, preventing any further compaction. A regression curve of power function was developed using the five measured points. When soil is no longer further compacted, the soil has reached maximum compaction and the dry unit weight levels off, regardless of energy applied by hand tamping. Using the power function, the specified number of drops of the hand tamper required to reach optimum compaction was calculated (Table 2).

Table 2. Calculated dry unit weight (kg/m³) and number of required drops.

Number of Drops	Dry Unit Weight, kg/m³ (pcf)
10	1048 (65.4)
20	1232 (76.9)
30	1355 (84.6)
40	1450 (90.5)
50	1528 (95.4)
60	1596 (99.6)
70	1655 (103.3)
80	1706 (106.5)
90	1754 (109.5)
100	1799 (112.3)

To obtain a minimum of 95% compaction, a minimum dry unit weight of 1682 kg/m^3 (105 pcf) was required, which corresponded to approximately 80 drops of the hand-tamper.

2.2. Experimental Design

Seven treatments were tested for this research effort: (1) one bare soil control; (2) conventional straw, crimped; (3) conventional straw, tackified; (4) wood fiber hydromulch; (5) straw and cotton hydromulch; (6) cotton fiber reinforced matrix hydromulch; and (7) bonded wheat fiber matrix hydromulch. Two of these treatments are classified as not having tackifiers: conventional straw, crimped and wood fiber hydromulch. The remainder of the products contain a tackifier component to the product. The bare soil treatment serves as the control, and conventional straw treatments were developed as a baseline condition for comparison of traditional mulching practices to newer hydromulch technologies currently being used in the industry. Given the application area of the rainfall simulator, two plots with the same treatment were always tested simultaneously (Figure 1) over the full experiment (four 15-min events). For each of the seven treatments tested, two separate experiments were administered; therefore, there were a total of four replicate plots for each treatment. The data for the four replicates of each treatment were averaged first before performing any further analysis.

2.3. Test Plot Preparation Prior to Condition Application

To perform this test, the soil was tested to verify the proper moisture content and then loaded into the test plots. The test plots were then compacted in a single layer of 7.62 cm (3 in.) to a density of 95% and scoured with a hand rake to a depth of 6.35 mm (1/4 in.). Once the test plots were prepared, the selected products were applied as per the manufacturer's recommended rates.

For each hydromulch product, testing was conducted using a commercially available hydroseeder (TurfMaker 380). Test boards were used to determine the number of passes required over the test plots to provide the manufacturer's specified application rates for each product. The test boards consisted of plywood with the same dimensions (0.6 m by 1.2 m (2 ft by 4 ft)) as the test plots, without the compacted soil. The applied products were scraped from the test boards and weighed to verify the application rates. The results of this testing are shown below in Table 3.

Table 3. Summary application rates for each hydromulch product.

Hydromulch Product	Manufacturer Required Dry Application Rate kg/ha (lb./ac.)	Equivalent Test Plot Required Dry Application Rate (g/plot)	Averaged Factors [1]	Minimum Number of Sprays Required
Straw and cotton HM	2241 (2000)	≈167	10.1	6
cotton FRM	3923 (3500)	≈292	9.7	7
Wood fiber HM	2241–2802 (2000–2500)	≈167–209	9.3	9
Bonded wheat FM	3362 (3000)	≈250	8.9	3

[1] Averaged factors is the product wet weight divided by the dry weight.

Once the minimum number of sprays was determined for each hydromulch product, each product was ready to be applied to test plots and tested accordingly. In order to verify application rates during the testing procedure, test boards were also sprayed in conjunction with the test plots. After the minimum number of sprays were applied to the two test boards and the two test plots, the test boards were scraped and weighed to check for application consistency to ensure manufacturer recommended rates were achieved on the test plots.

After the test plots were sprayed with the manufacturer specified application rate of the hydromulch, the test plots required time for the products to dehydrate and cure. After applying the product to the test plots, a structure was constructed, shown in Figure 4a, to hold four, 250 Watt ultraviolet-ray bulbs for the purpose of simulating natural sunlight. To ensure consistent drying, the bulbs were oriented on the structure to hang at a 3H:1V slope, which mimics the test plot setup. Lastly, the distance (approximately 45.7 cm (18 in.)) between the bulbs and the hydromulch on the test plots were measured and adjusted to ensure all bulbs were equidistant to the hydromulch surface, as illustrated in Figure 4a. The hydromulch test plots were left to dry for 48 h.

(**a**) (**b**)

Figure 4. (**a**) Drying of test plots during hydromulch testing; (**b**) collection from runoff for each test plot.

2.4. Data Collection

Collected data for this research included (1) soil loss, (2) runoff volume, and (3) turbidity. The focus was primarily on runoff generated from test plots during rainfall events. Runoff volume and mass for each 'left' and 'right' test plot (Figure 4b) was collected throughout the rain event. Instantaneous turbidity was recorded with a turbidity meter. The runoff volume and turbidity observations were recorded every minute and there were a total of 1680 observations for seven treatments on four plots for four replicates (7 × 4 × 4 × 15). The soil loss observations were recorded every 3 min (560 records = 7 × 4 × 4 × 5). Turbidity measurements were recorded from thoroughly stirred runoff collected at 1-min intervals using 4.7 L (5.0 quart) buckets.

To calculate the total soil loss, the runoff volume collected from the plots was filtered through Hayward single-length bags with one micron size pores. Once all samples were filtered, the bags were placed in an oven at 71.1 °C (160° F) and dried for 24 h. After drying, the bags were compared to the weight of the empty bags recorded prior to filtering to determine the amount of eroded soil from each test plot contained within each bag.

2.5. Statistical Analyses

The Tukey–Kramer method, a single-step multiple comparison procedure and statistical test, was used to analyze the recorded data and establish statistical significance between treatments [45].

3. Results and Discussion

3.1. Turbidity Variations

Using the previously outlined procedures, turbidity measurements were recorded for each series of tests from a thoroughly stirred bucket of runoff collected at 1-min intervals. A summary of the collected results is provided below in Table 4. Average turbidity of all four replicate plots for each minute and each treatment is presented in Figure 5 for four 15-min events for the bare soil (Control) and six erosion control treatments. When compared to the bare soil treatment, labeled 'Control', turbidity was reduced by at least a factor of 6 for all treatments by the end of the 60 min test ('Event 4').

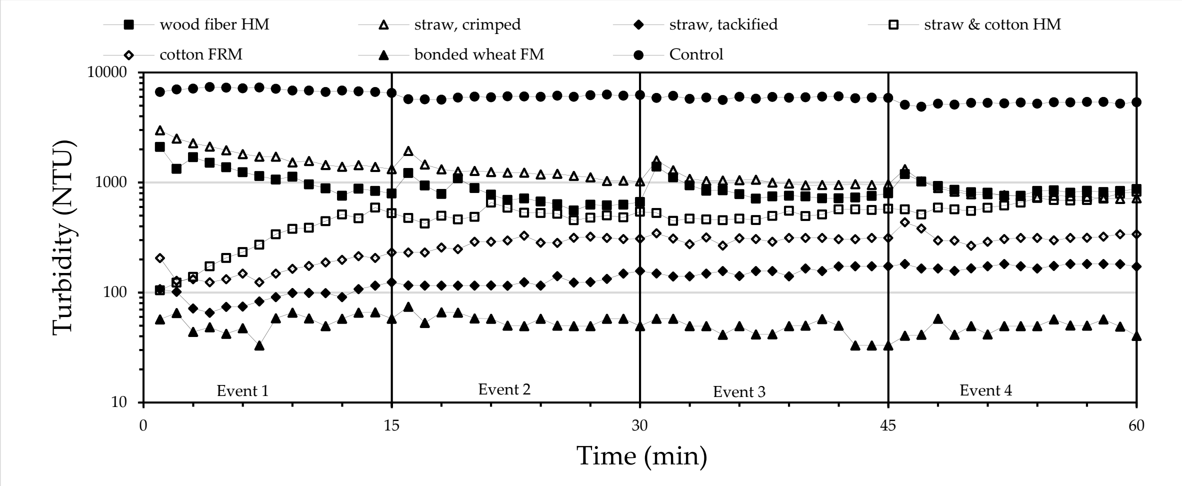

Figure 5. Average turbidity of surface runoff vs. time. Average turbidity for each minute was calculated for all four replicate plots for each treatment.

As shown in Figure 5, each hydromulch with the exception of the wood fiber HM and the straw and cotton HM were capable of reducing turbidity levels to under 500 NTUs. Two observations can be made from Figure 5: (1) the treatments without a polymer-enhanced tackifier (e.g., conventional straw, crimped, and wood fiber HM) had higher turbidity values during 'Event 1' and 'Event 2', whereas the turbidity decreased slightly during the last two rainfall events in comparison to treatments with a tackifier; (2) the treatments with tackifiers started with very low turbidity values and steadily increased over the four, 15 min rainfall events. The bonded wheat FRM was the only product to maintain a steady turbidity of about 60 NTUs throughout the four rainfall events. The improved performance of the treatments containing a tackifier in comparison to the treatments without a tackifier is likely due to the bonding of the tackifier with the soil particles, which in turn creates a more hydrophobic environment [38].

Table 4 shows average turbidity measurements, standard deviation of the average turbidity, and a percent reduction, normalized for the control condition. As shown, the bonded wheat FRM is the most effective treatment in reducing average turbidity of nearly 99%, followed by straw, tackified, cotton FRM, straw and cotton HM, wood fiber HM, and straw, crimped with percent reductions of 98%, 95%, 92%, 85%, and 80% respectively. A statistical analysis was conducted and the values for average turbidity were compared to determine if the results were statistically significantly different. The results are denoted by different letters as shown in Table 4: [a] represents significantly different to the control; [b] represents significantly different to straw and cotton HM; [c] represents significantly different to straw, crimped; [d] represents significantly different to cotton FRM; [e] represents significantly different to wood fiber HM; [f] represents significantly different to bonded wheat FM. Shoemaker [35] also computed and reported the lower and upper bounds of confidence intervals for all comparisons.

Table 4. Average turbidity, standard deviation, and percent reduction of each treatment with respect to the control of four 15-min events for surface runoff.

Treatment	Average Turbidity (NTU) [1]	Standard Deviation (NTU)	Percent Reduction
Control	6060	638	-
Straw and cotton HM	501 [a]	150	92%
Straw, crimped	1240 [ab]	468	80%
Cotton FRM	277 [ac]	71	95%

Wood fiber HM	930 [abd]	285	85%
Bonded wheat FM	59 [abce]	10	99%
Straw, tackified	148 [abcef]	35	98%

[1] Letters following the value show whether it is significantly different ($p < 0.05$) to the referenced treatment: [a] represents significantly different to the control; [b] represents significantly different to straw and cotton HM; [c] represents significantly different to straw, crimped; [d] represents significantly different to cotton FRM; [e] represents significantly different to wood fiber HM; [f] represents significantly different to bonded wheat FM.

Hydromulches typically include tackifying or bonding agents to bond the mulch particles to the soil surface. Once the hydromulch dries on the soil surface, a crusted, rough surface is formed which is typically a more hydrophobic environment. The crusted surface is designed to absorb the rainfall and serve as a filtration system to capture soil particles suspended in the stormwater runoff. When the tackifier or bonding agents have been washed away or begin to degrade due to stormwater runoff, the turbidity observed began to increase slightly as shown in Figure 5 above for the straw, tackified, cotton FRM, and straw and cotton HM. However, products with stronger tackifying agents such as bonded wheat FM take longer to deteriorate.

The treatments without a tackifier, straw, crimped and wood fiber HM, rely primarily on the mulch material by itself to minimize erosion from the plots. From a soil erosion perspective, these treatments are functioning as a protective layer to minimize the splash erosion created by the rainfall. Splash erosion has been found to be the initial cause of erosion [49]. An observation was made from Figure 5 during the first two rainfall events, which was that the treatments that do not have a tackifying agent applied experienced a higher rate of erosion due to the absence of a tackifying agent to bond the soil particles to the treatment. This initial large concentration of soil in the runoff at the beginning of a rainfall event is due to the splash erosion caused by the raindrops impacting the soil surface. The treatments which contain a tackifying agent lessen this initial erosion by bonding the soil particles with the other material. On the other hand, the products without a tackifying agent lessen the amount of splash erosion by providing a surface cover over the soil particles when compared to the bare soil treatment.

A statistical analysis was completed to confirm observed differences between the control and treatments for turbidity measurements of stormwater surface runoff. ANOVA tables were created using Tukey–Kramer comparison tests to determine statistical significance between individual pairs of groups, as illustrated in Table 4. As observed, this table demonstrated that the average turbidities had statistically significant differences between the control and all treatments. All treatments showed significant differences between them in the average turbidity except for straw and cotton HM and cotton FRM. Additionally, no significant statistical difference was observed between cotton FRM and bonded wheat FM, cotton FRM and straw, tackified, and bonded wheat FM and straw, tackified. All other treatment comparisons proved to show a statistically significant difference as shown in Table 4.

3.2. Soil Loss

Samples used to calculate soil loss were collected from simulated rainfall runoff every 3 min for all experiments conducted. Based on the data collected, it was observed that all treatments had significantly smaller levels of soil loss when compared to the bare soil (control). The control condition and the treatments without a tackifying agent (i.e., straw, crimped, and wood fiber HM) experienced an initial surge of soil loss due to the breakage of soil aggregates by the impact of raindrops, with the consequent dispersion of fine particles (splash erosion). However, the treatments with tackifiers did not have this surge; a steady increase in soil loss over time for each rainfall event was observed for these treatments. As shown in Figure 6, the most effective treatment in reducing soil loss was bonded wheat FM. After the first rainfall event, it was observed that soil loss measurements remained consistent for the remainder of the experiment. The summarized data is provided in Figure 6 below.

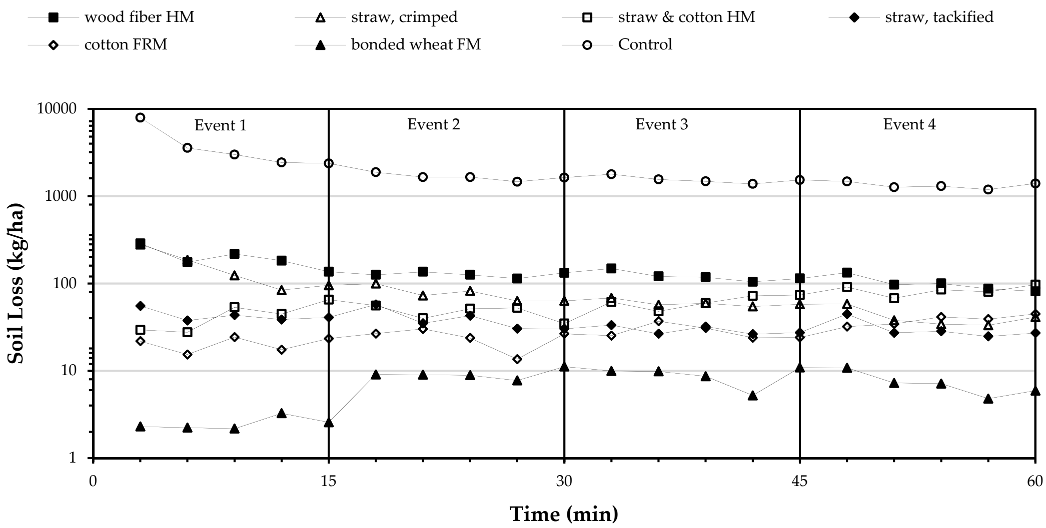

Figure 6. Three-minute soil loss vs. time for all treatments as compared to the control.

The control recorded more soil loss than all of the treatments in the first rainfall event by a factor of 17. The most consistent and effective erosion control treatment was bonded wheat FM, maintaining an average soil loss of approximately 11.2 kg/ha (10 lb./ac.) over the entire experiment. Wood fiber HM was observed to produce the largest consistent amount of eroded soil, starting at approximately 1008 kg/ha (900 lb./ac.), and decreasing to approximately 504 kg/ha (450 lb./ac.) by the last rainfall event. Straw and cotton HM showed initial signs of strength in controlling erosion with 224 kg/ha (200 lb./ac.) of cumulative eroded soil, however steadily increased to almost 448 kg/ha (400 lb./ac.) by 'Event 4', nearly doubling its initial amount. It was also observed that straw, crimped began with approximately the same amount of cumulative soil loss as wood fiber HM; however after the first two rainfall events, steadily decreased to nearly 224 kg/ha (200 lb./ac.), which are soil loss levels similar to that of straw, tackified, and cotton FRM. The cotton FRM averaged 112 kg/ha (100 lb./ac.) over the entire experiment. This data is shown in Figure 7 below.

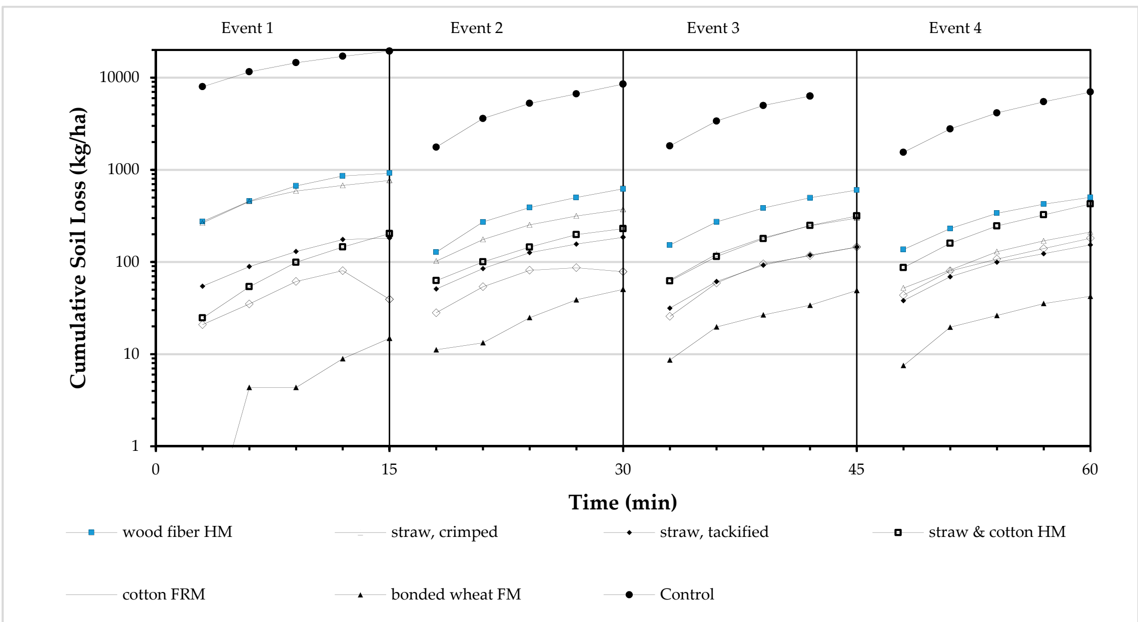

Figure 7. Cumulative soil loss vs. time for six treatments as compared to the control.

Table 5 presents specific values of average soil loss, standard deviation, and percent reduction for each treatment during each rainfall event. The straw, crimped treatment, when normalized to the control, reduced erosion during the first rainfall event by nearly 96% and increased to approximately 98.9% by the fourth rainfall event. Similarly, straw, tackified, and wood fiber HM increased in percent reduction from 'Event 1' to 'Event 4' by 98.9% to 99.2% and 94.9% to 97.4%, respectively. The hydromulches with tackifying agents reacted in a dissimilar way when normalized to the control. Over the rainfall events, percent reductions decreased from 98.9%% to 97.8%, 99.5 to 99.1%, and 99.9% to 99.7% for straw and cotton HM, cotton FRM, and bonded wheat FM, respectively. It was observed that this reduction was due to the degradation of the tackifying bonds between the soil and the mulch; contrarily, the increased performance of the non-tackified treatments was observed to be due to the 'flush effect' of the scoured surface in the first events, exposing the less erodible, compacted, underlying soil.

Table 5. Average soil loss over each 15-min rainfall event due to surface runoff.

Condition	Soil Loss [1] (kg/ha)	Standard Deviation [2] (kg/ha)	Percent Reduction [3], (%)
1st 15-min rainfall event			
Control	3889	3000	-
Straw, crimped	155.4	108.0	96.0
Straw, tackified	42.8	39.6	98.9
Wood fiber HM	198.9	158.4	94.9
Straw and cotton HM	42.8	50.1	98.9
Cotton FRM	20.7	12.9	99.5
Bonded wheat FM	3.81	2.9	99.9
2nd 15-min rainfall event			
Control	1694	212.7	-
Straw, crimped	77.6	24.3	98.0
Straw, tackified	38.3	38.7	99.0
Wood fiber HM	127.1	84.7	96.7
Straw and cotton HM	46.9	39.5	98.8
Cotton FRM	23.8	16.9	99.4
Bonded wheat FM	11.2	3.70	99.7
3rd 15-min rainfall event			
Control	1602	264.9	-
Straw, crimped	62.0	135.6	98.4
Straw, tackified	30.2	26.7	99.2
Wood fiber HM	121.4	84.4	96.9
Straw and cotton HM	64.3	53.1	98.3
Cotton FRM	29.7	18.3	99.2
Bonded wheat FM	10.5	5.8	99.7
4th 15-min rainfall event			
Control	1377	217.5	-
Straw, crimped	44.1	13.8	98.9
Straw, tackified	31.7	28.4	99.2
Wood fiber HM	101.8	78.0	97.4
Straw and cotton HM	84.3	56.3	97.8
Cotton FRM	36.7	24.5	99.1
Bonded wheat FM	10.3	3.7	99.7

[1]—Average of 3-min soil loss (Figure 6) for each 15-min rainfall event. [2]—Standard deviation for average soil loss over an event. [3]—Denotes values normalized by control condition.

Continuing the statistical analysis used throughout this research effort, ANOVA procedures with Tukey–Kramer multiple comparison tests were used for the recorded amounts of soil loss. Table

6 illustrates statistically significant and insignificant results of average soil loss throughout the experiments. The statistical analysis compared all treatments to the control and each other. The control proved to be statistically different to all treatments; therefore, each treatment had a significant effect in reducing soil loss when compared the bare soil. No significant differences were found between the comparison to the other treatments. Therefore, it can be concluded from Table 6 that statistically, each treatment is capable of significantly reducing and controlling erosion on 3H:1V, compacted fill slopes.

Table 6. Cumulative soil loss for four, 15-min rainfall events (A) and calculated soil loss ratio per treatment.

Treatment	Cumulative Soil Loss (A) (grams/plot) [2]	Cumulative Soil Loss (A) (g/m^2)	* Calculated Soil Loss Ratio [1]
Straw, crimped	126 [a]	169.5	0.040
Straw, tackified	53 [a]	71.3	0.017
Wood fiber HM	204 [a]	274.4	0.064
Straw and cotton HM	89 [a]	119.7	0.028
Cotton FRM	41 [a]	55.2	0.013
Bonded wheat FM	13 [a]	17.5	0.004

[1] Soil loss ratio normalized to a bare soil value of 4281 g/m^2. * Soil loss ratio calculation: SLR = A/Control [1].
[2] The letter [a] following the values show that they are significantly different ($p < 0.05$) to the control.

3.3. Cover-Factor

Several studies [39,41,43,50,51] used a 'cover-factor' to report erosion control performance. The cover factor is a parameter in the Revised Universal Soil Loss Equation (RUSLE) to represent a comparison of soil loss occurring with the treatment in place to that which occurs in the bare, unprotected condition [51]. The RUSLE allows researchers to calculate cover-factors for treatments without testing a bare soil using several different parameters based upon soil type, slope, and rain regimes; ECTC [50] and Clopper et al. [51] used the RUSLE to calculate cover-factors. However, in this study, the treatment results were compared to the results of the bare soil control test. This comparison is defined as the "Soil-Loss Ratio". Table 6 summarizes the soil loss ratio calculated in this research effort. According to calculated soil loss ratios of 0.004, 0.013, 0.017, 0.028 0.040, and 0.064 in Table 6, the hydromulches can be ranked from most to least effective erosion control practices accordingly: (1) bonded wheat FM, (2) cotton FRM, (3) straw, tackified, (4) straw and cotton HM, (5) straw, crimped, and (6) wood fiber HM.

4. Conclusions

Twenty eight experiments were conducted to examine the ESC effectiveness of seven treatments: (1) control (bare soil), (2) conventional straw, crimped, (3) conventional straw, tackified, (4) wood fiber HM, (5) straw and cotton HM, (6) cotton FRM, and (7) bonded wheat FM. Performance was evaluated using data collection from experiments, which included surface runoff volume, soil loss, and turbidity.

Turbidity measurements were recorded from samples that were collected every minute of each of the four, 15 min rainfall events. The order of the six treatments ranked from most to least effective according to an averaged percent reduction when normalized by the bare soil condition were (1) bonded wheat FM (99% reduction), (2) straw, tackified (98% reduction), (3) cotton FRM (95% reduction), (4) straw and cotton HM (92% reduction), (5) wood fiber HM (85% reduction), and (6) straw, crimped (80% reduction). The erosion control practices without tackifiers (conventional straw, crimped, and wood fiber HM) experienced a significant increase in the amount of eroded sediment during the first two rainfall events, likely caused by the lack of the bonding between soil particles;

however, each treatment steadily improved sediment control over time. Contrarily, the surface cover practices with tackifying agents provided excellent initial sediment control due to the bonds between soil particles and the mulching materials, but over the four rainfall events, the chemical bonds began to deteriorate, showing a steady decrease in performance.

Approximately, 100%, 99%, 98%, 97%, 96%, and 94% soil loss reduction for bonded wheat FM, cotton FRM, straw-tackified, straw and cotton HM, straw-crimped, and wood fiber HM were observed, respectively. Cumulative soil losses were also used in this research to calculate the soil loss ratios (SLR) between treated and untreated conditions; calculated ratios mimicked percent reduction performances, ranging in value from 0.004 for bonded wheat FM to 0.064 for wood fiber HM.

Literature reviewed and results from this research effort suggest that conventional straw crimped or tackified as well as hydromulches are very effective erosion control measures, when applied at the proper application rates.

4.1. Recommended Future Research

Results and conclusions presented in this study show that conventional straw (crimped or tackified) and hydromulches are effective means of reducing erosion and sedimentation caused by sediment laden runoff. However, using soil specific polyacrylamide would likely result in greater erosion control than the non-soil specific polymers that make up many of the tackifying agents used on straw and that are a part of many hydromulch products. Therefore, further research should be conducted to examine how the addition of polyacrylamide to these practices could potentially improve in-field performance.

Additionally, the conclusions derived in this study are based on laboratory-scale test plots. It would be beneficial if the performance of these treatments were tested at field-scale conditions to validate laboratory-scale results provided in this research. Laboratory-scale experiments allow researchers to test the performance of erosion control practices at a faster rate than most field-scale experiments; therefore, if field-scale test results are similar to laboratory-scale test results, a larger quantity of products could be effectively evaluated in a shorter period of time using laboratory-scale tests.

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References

1. Zech, W.C.; Halverson, J.L.; Clement, T.P. Development of a Silt Fence Tieback Design Methodology for Highway Construction Installations. *J. Transp. Res. Board Transp. Res. Rec.* **2007**, *2011*, 21–28.
2. United States Environmental Protection Agency (US EPA) Clean Water Act Section 502: General Definitions Available online: https://www.epa.gov/cwa-404/clean-water-act-section-502-general-definitions (accessed on 19 December 2019).
3. United States Enviromental Protection Agency (US EPA). *Innovative Uses of Compost: Erosion Control., Turf Remediation and Landscaping*; United States Enviromental Protection Agency: Washington, DC, USA, 1997.
4. United States Environmental Protection Agency (US EPA). *Stormwater Phase II Final Rule: Construction Site Runoff Control Minimum Control Measure*; United States Enviromental Protection Agency: Washington, DC, USA, 2005.
5. Scholl, B.N.; Holt, G.; Thornton, C.; Duke, S. Hydromulch blends using agricultural byproducts: Performance implications of cotton quantity. *J. Cotton Sci.* **2013**, *17*, 302–308.

6. Megahan, W.F.; Wilson, M.; Monsen, S.B. Sediment production from granitic cutslopes on forest roads in Idaho, USA. *Earth Surf. Processes Landf.* **2001**, *26*, 153–163.
7. Risse, M.; Faucette, B. *Compost Utilization for Erosion Control*; University of Georgia: Athens, GA, USA, 2001.
8. United States Environmental Protection Agency (US EPA). *Stormwater Phase II Final Rule: An Overview*; United States Environmental Protection Agency: Washington, DC, USA, 2005.
9. United States Environmental Protection Agency (US EPA). *2000 National Water Quality Inventory*; United States Environmental Protection Agency: Washington, DC, USA, 2000.
10. Novotny, V. *Water Quality: Diffuse Pollution and Watershed Management*; John Wiley & Sons, Inc.: New York, NY, USA, 2003.
11. Brady, N.C.; Weil, R.R. *The Nature and Properties of Soils*, 14th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2014.
12. District, M.H.F. Chapter 7 Construction BMPs. Available online: https://udfcd.org/wp-content/uploads/uploads/vol3 criteria manual/Chapter 7 Construction BMPs.pdf (accessed on 24 November 2019).
13. Scholl, B.N.; Holt, G.; Thornton, C. Screening study of select cotton-based hydromulch blends produced using the Cross-Linked biofiber process. *J. Cotton Sci.* **2012**, *16*, 249–254.
14. Tyner, J.S.; Yoder, D.C.; Chomicki, B.J.; Tyagi, A. A Review of Construction Site Best Management Practices for Erosion Control. *Trans. ASABE* **2011**, *54*, 441–450.
15. Alabama Soil and Water Conservation Committee (ASWCC). *Alabama Handbook for Erosion Control., Sediment Control, and Stormwater Management on Construction Site and Urban Areas: Volume 2*; Alabama Soil and Water Conservation Committee: Montgomery, AL, USA, 2009.
16. Box, J.E.J.; Bruce, R.R. The effect of surface cover on infiltration and soil erosion. In *Soil Erosion, Conservation and Rehabilitation*; Aggasi, M., Ed.; Dekker: New York, NY, USA, 1996; pp. 107–123.
17. Bruce, R.R.; Langdale, G.W.; West, L.T.; Miller, W.P. Surface Soil Degradation and Soil Productivity Restoration and Maintenance. *Soil Sci. Soc. Am. J.* **1995**, *59*, 654–660.
18. Sutherland, R.A. Rolled erosion control systems for hillslope surface protection: A critical review, synthesis and analysis of available data. I. Background and formative years. *Land Degrad. Dev.* **1998**, *9*, 465–486.
19. Sutherland, R.A.; Ziegler, A.D. Hillslope runoff and erosion as affected by rolled erosion control systems: A field study. *Hydrol. Processes Int. J.* **2006**, *20*, 2839–2855.
20. Rickson, R.J. Simulated vegetation and geotextiles. In *Slope Stabilization and Erosion Control: A Bioengineering Approach*; Morgan, R., Rickson, R., Eds.; Spon: London, UK, 1995; pp. 95–131.
21. Turgeon, A.J. Turfgrass Management. In *Turfgrass Management*; Prentice Hall: Upper Saddle River, NJ, USA, 2002.
22. Singer, M.T.; Matsuda, Y.; Blackard, J. Effect of Mulch Rate on Soil Loss by Raindrop Splash. *Soil Sci. Soc. Am. J.* **1981**, *45*, 107–110.
23. Prats, S.A.; Malvar, M.C.; Vieira, D.C.S.; MacDonald, L.; Keizer, J.J. Effectiveness of Hydromulching to Reduce Runoff and Erosion in a Recently Burnt Pine Plantation in Central Portugal. *Land Degrad. Dev.* **2016**, *27*, 1319–1333.
24. Keizer, J.J.; Silva, F.C.; Vieira, D.C.S.; González-Pelayo, O.; Campos, I.; Vieira, A.M.D.; Valente, S.; Prats, S.A. The effectiveness of two contrasting mulch application rates to reduce post-fire erosion in a Portuguese eucalypt plantation. *Catena* **2018**, *169*, 21–30.
25. Babcock, D.; McLauglin, R.A. Erosion control effectiveness of straw, hydromulch, and polyacrylamide in a rainfall simulator. *J. Soil Water Conserv.* **2013**, *68*, 221–227.
26. Mannering, J.V.; Meyer, L.D. The Effects of Various Rates of Surface Mulch on Infiltration and Erosion. *Soil Sci. Soc. Am. J.* **1963**, *29*, 84–85.
27. McLauglin, R.A.; Brown, T.T. Evaluation of erosion control products with and without added polyacrylamide. *J. Am. Water Resour. Assoc.* **2006**, *42*, 675–684.
28. Meyer, L.D.; Wischmeier, W.H.; Foster, G.R. Mulch Rates Required for Erosion Control on Steep Slopes. *Soil Sci. Soc. Am. J.* **1970**, *34*, 928–930.
29. Babcock, D.; McLauglin, R.A. Mulch Options for Erosion Control on Construction Sites. Available online: https://content.ces.ncsu.edu/mulch-options-for-erosion-control-on-construction-sites (accessed on 24 November 2019).
30. Lee, G.; McLaughlin, R.A.; Whitely, K.D.; Brown, V.K. Evaluation of seven mulch treatments for erosion control and vegetation establishment on steep slopes. *J. Soil Water Conserv.* **2018**, *73*, 434–442.

31. Babcock, D.L.; McLauglin, R.A. Runoff water quality and vegetative establishment for groundcovers on steep slopes. *J. Soil Water Conserv.* **2011**, *66*, 132–141.
32. McCullough, S.A.; Endress, B.A. Do postfire mulching treatments affect plant community recovery in California coastal sage scrub lands? *Environ. Manag.* **2012**, *49*, 142–150.
33. Eck, B.; Barrett, M.; McFarland, A.; Hauck, L. Hydologic and Water Quality Aspects of Using a Compost/Mulch Blend for Erosion Control. *J. Irrig. Drain. Eng.* **2010**, *136*, 646–655.
34. Morgan, R.; Rickson, J. Soil erosion control: Importance of geomorphological information. In *Geomorphology in Environmental Planning*; Hooke, J.M., Ed.; Wiley: Chichester, UK, 1988; pp. 51–60.
35. National Cooperative Highway Research Program (NCHRP). *Erosion Control During Highway Construction—Research Report*; National Cooperative Highway Research Program: Washington, DC, USA, 1980.
36. Weggel, J.R.; Rustom, R. Soil erosion by rainfall and runoff—State of the art. *Geotext. Geomembr.* **1992**, *11*, 551–572.
37. Erosion Control Technology Council (ECTC) Erosion Control Product Categories. Available online: https://www.ectc.org/product-selection-by-category (accessed on 24 November 2019).
38. Vaughn, S.F.; Kenar, J.A.; Felker, F.C.; Berhow, M.A.; Cermak, S.C.; Evangelista, R.L.; Fanta, G.F.; Behle, R.W.; Lee, E. Evaluation of alternatives to guar gum as tackifiers for hydromulch and as clumping agents for biodegradable cat litter. *Ind. Crops Prod.* **2013**, *43*, 798–801.
39. Holt, G.A.; Buser, M.; Harmel, D.; Potter, K.; Pelletier, M. Comparison of Cotton-based Hydro-mulches and Conventional Wood and Paper Hydro-mulches-Study 1. *J. Cotton Sci.* **2005**, *9*, 121–127.
40. Holt, G.A.; Laird, J.W. COBY Products and A Process for Their Manufacture 2002. U.S. Patent 6,383,548, 7 May 2002.
41. Landloch. *Studies of Hydromulch Effectiveness*; National Center for Engineering in Agriculture: Toowoomba, Australia, 2002.
42. Benik, S.R.; Wilson, B.N.; Biesboer, D.D.; Hansen, B.; Stenlund, D. Performance of erosion control products on a highway embankment. *Trans. ASAE* **2003**, *46*, 1113–1119.
43. Buxton, H.; Caruccio, F.T. *Evaluation of Selective Erosion Control. Techniques*; United States Environmental Protection Agency: Washington, DC, USA, 1979.
44. Robichaud, P.R.; Lewis, S.A.; Wagenbrenner, J.W.; Ashmun, L.E.; Brown, R.E. Post-fire mulching for runoff and erosion mitigation Part I: Effectiveness at reducing hillslope erosion rates. *Catena* **2013**, *105*, 75–92.
45. Shoemaker, A.L. Evaluation of Anionic Polyacrylamide as an Erosion Control Measure Using Intermediate-Scale Experimental Procedures. Master's Thesis, Auburn University, Auburn, AL, USA, 2009.
46. ASTM International. *Standard Test Method for Determination of Rolled Erosion Control Product Performance in Protecting Hillslopes from Rainfall-Induced Erosion*; ASTM International: West Conshohocken, PA, USA, 2019.
47. ALDOT. *Standard Specifications for Highway Construction*; Alabama Department of Transportation: Montgomery, AL, USA, 2018.
48. ASTM International. *ASTM D1557-09, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2700 kN-m/m3))*; ASTM International: West Conshohocken, PA, USA, 2009.
49. Angulo-Martínez, M.; Beguería, S.; Navas, A.; Machín, J. Splash erosion under natural rainfall on three soil types in NE Spain. *Geomorphology* **2012**, *175–176*, 38–44.
50. Erosion Control Technology Council (ECTC). Comparison of Erosion Control Technologies: Blown Straw vs. Erosion Control Blanket, Quantification of Performance and Value. Available online: https://www.ectc.org/assets/docs/Whitepapers/ectc_june2015_blown%20straw%20vs%20recp.pdf (accessed on 11 February 2020).
51. Clopper, P.E.; Vielleux, M.; Johnson, T. Quantifying the Performance of Hillslope Erosion Control Best Management Practices. World Water and Environmental Resources Congress: Orlando, FL, USA, 2001.