RESEARCH & DEVELOPMENT

Performance of Straw Mulch Binding Agents

Richard A. McLaughlin, Ph.D.
Maria A. Polizzi, M.S.
Department of Crop and Soil Sciences
North Carolina State University

NCDOT Project 2015-17

FHWA/NC/2015-17

January 2018

Technical Report Documentation Page

1. Report No.	2. Government Accession No. *…leave blank…*	3. Recipient's Catalog No. *…leave blank…*
4. Title and Subtitle Performance of Straw Mulch Binding Agents		5. Report Date 6. Performing Organization Code *…leave blank…*
7. Author(s) Richard A. McLaughlin and Maria A. Polizzi		8. Performing Organization Report No. *…leave blank…*
9. Performing Organization Name and Address Departments of Crop & Soil Sciences North Carolina State University Campus Box 7620…???? Raleigh, NC 27695		10. Work Unit No. (TRAIS) *…leave blank…* 11. Contract or Grant No. *…leave blank…*
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Analysis Group 1 South Wilmington Street Raleigh, North Carolina 27601…..????		13. Type of Report and Period Covered Final Report August 2015 – December 2017 14. Sponsoring Agency Code 2015-17
Supplementary Notes: *…leave blank…*		

16. Abstract

Establishing vegetation at the end of construction projects is required on areas where soil is exposed. Grass is commonly the preferred vegetation, and when grown from seed, mulch is needed to protect the seeds and prevent erosion. Straw is the most widely used mulch as it is relatively inexpensive and effective for establishing grass. In order to prevent the straw from blowing away, binding agents, commonly known as tackifiers, are applied to hold straw together like a blanket until the grass is established. Emulsified asphalt has been widely used as a straw tackifier and this research was focused on testing the effectiveness of a variety of potential alternatives for preventing straw from blowing away. The primary objectives of the project were to determine the effectiveness of each potential tackifier to withstand wind and rain events, and to determine if they had any effects on grass growth. A significant portion of testing was completed using a wind tunnel to compare failure wind speeds of these products at different application rates and under a range of conditions. In general, wet straw was resistant to failure up to the maximum wind speed of 72-80 km h^{-1} (45-50 mi h^{-1}) even without tackifier. Products tested under gusty wind conditions failed at lower wind speeds than under steady conditions. Tackifier application rates below those recommended by the manufacturer were significantly less effective at withstanding wind, while applications beyond recommended did not always significantly improve stability for most products. Hydromulch products, made of paper and/or wood fiber, were as effective as asphalt in resisting failure, and some have a much lower material cost. There were few negative impacts on grass growth when these products were applied to straw. Overall, the lower cost hydromulches at 1120 kg ha^{-1} (1,000 lb ac^{-1}) and plantago at 224 kg ha^{-1} (200 lbs ac^{-1}) would be well suited for replacing emulsified asphalt on construction sites.

17. Key Words Straw, mulch, tackifier, grass, erosion, wind	18. Distribution Statement *…leave blank…*

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 62	22. Price *…leave blank…*

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Disclaimer

The contents of this report reflect the views of the author(s) and not necessarily the views of the University. The author(s) are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

Acknowledgments

The study was primarily the responsibility of graduate student Maria Polizzi and technicians Jamie Luther and Chris Niewoehner in the Department of Crop and Soil Sciences. A number of undergraduate students also provided assistance. We are always grateful for the assistance of the NC DOT Roadside Environmental Unit staff for finding potential sites for us that meet our requirements. We also greatly appreciated the assistance of project staff and contractors to get our devices deployed in a timely manner. It is only through this type of cooperation that we can conduct research on “live” construction sites, which is one reason why North Carolina is considered a leader in erosion, sediment, and turbidity control.

Executive Summary

Establishing vegetation at the end of construction projects is important, as stabilization is a requirement on areas where soil is exposed. Grass is commonly the preferred vegetation, and when grown from seed, and mulch is used to protect the seeds from displacement, provide insulation from extreme temperatures and prevent erosion. Straw is the most widely used mulch; however, in order to prevent the straw from blowing away, binding agents, commonly known as tackifiers, are applied to hold straw together until the grass is established. Emulsified asphalt has been widely used as a straw tackifier and this research was focused on testing the effectiveness of a variety of potential alternatives for preventing straw from blowing away. The main reasons for replacing emulsified asphalt are the high product costs, specialized machinery required for application, and a number of environmental concerns. The primary objectives of the project were to determine the effectiveness of each potential tackifier to withstand wind and rain events, and to determine if they had any effects on grass growth. The final goal was to find a suitable replacement tackifier for emulsified asphalt, and to provide recommendations for its implementation on construction sites and urban areas.

A significant portion of testing was completed using a wind tunnel to compare failure wind speeds of these products at different application rates and under a range of conditions. In general, wet straw was resistant to failure up to the maximum wind speed of 72-80 km h^{-1} (45-50 mi h^{-1}) even without tackifier. Products tested under gusty wind conditions (higher wind speed acceleration) failed at lower wind speeds than under steady conditions. Tackifier application rates below those recommended by the manufacturer were significantly less effective at withstanding wind, while applications beyond recommended did not always significantly improve stability for most products. Hydromulch products, made of paper and/or wood fiber, were as effective as asphalt in resisting failure, and some have a much lower material cost. Two smaller studies, outdoor and greenhouse, were conducted to determine the effect of tackifier products on grass growth, for species used by the North Carolina Department of Transportation. Neither study indicated negative impacts on grass establishment when these products were applied to straw. Overall, the lower cost hydromulches at 1120 kg ha^{-1} (1,000 lb ac^{-1}) and the plant-based product, plantago, at 224 kg ha^{-1} (200 lbs ac^{-1}) would be well suited for replacing emulsified asphalt on construction sites during the revegetation phase.

Contents

List of Figures:

List of Tables

Introduction and Literature Review

Erosion from either rainfall or wind can be a major problem on construction projects. The United States Environmental Protection Agency (USEPA) states that “soil loss rates from construction sites are 10 to 20 times that of agricultural lands” (USEPA, 2000). Once the vegetation is removed during the grading process, exposed soil can easily wash or blow away in storm events. Detached sediment then moves downwind or downslope, and can cause major problems for sensitive waterways or wetland areas. Many aquatic species are negatively affected by high turbidity, as it can reduce visibility, cause difficulty breathing, and bury rocky streambed environments where many organisms live (Grace, 2000). For this reason, the U.S. Environmental Protection Agency now mandates that graded soils may remain bare for no more than 14 days (USEPA, 2009).

The most susceptible time for sediment loss is immediately after grading (Bethlahmy and Kidd, 1966; Burroughs and King, 1989; King, 1984; Megahan, 1974; Megahan et al., 1991; Swift, 1985). Furthermore, roadside slopes may produce 70-90% of the sediment loss from construction projects (Swift, 1984b), with newly created slopes being most at risk, due to their loose, structureless nature (Grace, 2000). One of the best ways to reduce wind and water erosion on bare soil is to establish vegetation. According to the Alabama Forestry Commission (1993), establishment of vegetation is shown to reduce sediment loss from road side-slopes, and roots effectively hold soil particles together, where shoot (or above-ground) growth can lessen the impact of water droplets (Osborn, 1955). Furthermore, grasses and other vegetation can slow wind speeds at the soil surface, and consequently limit particle detachment. Therefore, complete vegetation cover is ideal.

For vegetation establishment to occur, the grass seed requires a sheltered environment, typically straw mulch for standard highway practice. Straw also reduces seed transport away from the site by intercepting rain drops and slowing sheet flows. Currently, emulsified asphalt is often used to prevent the straw from being blown away by wind, but it has a number of negative impacts. It may pose environmental concerns, primarily potential water contamination, it requires specialized equipment to apply, and it can inhibit grass establishment at high application rates. (Dudeck et al., 1970; McKee et al., 1964). The objective of this study was to find and compare potential tackifier products for their effectiveness, cost efficiency, and ease of application.

Vegetation Establishment:

Establishing a full stand of grass can prove a challenge on some landscapes, with many perennial grasses dying off within the first year (Brown and Gorres, 2011). Varying climatic conditions, soil types, slopes, and other factors can greatly affect the potential for successful grass establishment. Two of the main factors influencing germination are soil water content and the amount of seed-to-soil contact (Hauser, 1989). However, due to the small size of grass seed good contact can be difficult to achieve. To compensate, the recommended rate for grass seed application is approximately 20 live seeds to produce one viable sprout (Hauser, 1989). Furthermore, Hauser states that an optimal rate of 60 ml/m (0.62 lq oz/ft) of water applied in the seed furrow during planting can double the number of subsequent seedlings. The effect of water stress on *S. tenacissima* (commonly called esparto or needles grass) germination was tested, with -0.8 MPa greatly reducing germination, and -1.6 MPa halting it completely (Krichen, 2014).

Different species are able to withstand different soil moisture and temperature levels (Swemmer et al., 2006). One option to take advantage of this is to apply a mixture of seeds from different species, which in turn reduces the risk of stand failure (Smale, 2004). As a result of similar research, the NCDOT uses an explicit seed specification to ensure seed diversity and quality (NCDOT (1), 2017). Before any seed can be used by the NCDOT, it must first be tested by the North Carolina Department of Agriculture and Consumer Services, Seed Testing Laboratory, where it can be approved for use. Different seed mixtures are recommended depending on the county where grass establishment is required (NCDOT (2), 2017). Additionally the NCDOT recommends either warm-season or cool-season turfgrass mixes depending on the time of year or region of the state. Cool-season grasses include tall fescue, hard fescue and kentucky bluegrass, while warm-season grass contains centipedegrass, bermudagrass, zoysiagrass and Pensacola bahiagrass (NCDOT (3), 2017).

The Effect of Increased Vegetation:

Vegetation establishment is important, as it not only acts as a ground cover to protect the soil from erosion (Marques et al. 2007), but it can actually improve soil structure, infiltration, water holding capacity, and even decreased bulk density (Logsdon, 2013). Additionally, Pan et al. (2006) found that grassy slopes can reduce runoff by 8%, and that bare slopes have 45 - 85% more sediment loss than grassy slopes.

One of the main ways that construction damages soil is by compaction, often from heavy machinery, during the cut and fill process of grading (Gregory, 2006). Soil compaction increases soil strength and bulk density, decreases porosity, and creates smaller pore size distribution. This reduces the water and air flow throughout the soil, and can stress plants by limiting water availability for roots, and physically hindering root penetration (NRCS, 2000; Richard et al., 2001). Improved soil quality can help aid in the reduction of erosion, as increased infiltration allows water from a rain event to soak into the soil. This in-turn allows plants to receive more water, and possibly prevent the need for re-seeding due to drought stress.

Temporary Erosion Control:

Permanent stabilization using vegetation is generally the final goal for bare soil areas; however, until the vegetation becomes established, temporary measures must be taken to prevent erosion. There are a variety of options including rolled erosion control products (such as erosion control blankets), hydromulches and loose straw, all of which perform the same general role. Each acts as a shield to protect the soil from raindrop impact and decrease the likelihood for detachment from soil aggregates (Gholami et al., 2014). In addition, mulches protect the soil from solar radiation, keeping the soil up to 20°C cooler than bare soil (Ross et al., 1985). According to Swanson et al. (1965), mulching was very effective in stabilizing slopes and preventing soil loss, and others found increased seed germination and growth when using mulch (Gilbert and Davis, 1967; Blaser, 1962). Similarly, Lemly et al. (1982) determined the effect of mulch on grass establishment, and found that with all five treatments (jute netting, excelsior, mulch blanket, wood chips and asphalt-tacked straw) each treatment had significantly greater grass cover than bare soil.

Straw mulch may be used to protect seeds during the germination phase. NCDOT recommends 80% straw mulch coverage on all slopes (NCDOT (6), 1998), which helps to shade the seed, insulating it from extreme temperatures, and keeping the soil moist by reducing evaporation (Adams, 1966; Jordan, 1998; Grigg et al., 2006). McKee et al. (1964) found it to be one of the best mulching materials for revegetation compared to netting, hydromulches or a combination of products, particularly on steep slopes.

Straw mulch was selected for this project due to its frequency of use, affordable price, ease of application and effectiveness in erosion reduction. Meyer et al. (1970), showed that soil loss from straw-mulched plots on steep slopes (15%), was approximately one third of that on bare soil areas. Straw mulch reduced erosion by 90% compared to bare soil, with a significant increase in effectiveness with grass growth (Benik et al., 2003). Straw also functions to protect seeds during the germination phase by shading the seed, insulating it from damaging temperatures, and keeping the soil moist by preventing evaporation (Adams, 1966; Jordan, 1998). Additionally, as the wheat straw breaks down, it contributes organic matter to the soil, with a C:N ratio of approximately 80:1 (Dahmer, 2017).

Straw is spread over the site manually or by using a straw blower. These blowers can quickly stread straw up to 50 feet depending on the size of the machinery. (NCDOT (3), 2017). This can considerably reduce the time and manpower needed in comparison to erosion control blankets. NCDOT recommends 2240 – 4480 kg ha^{-1} (2000 - 4000 lbs ac^{-1}) straw mulch coverage on all slopes, and tackifiers are applied to prevent the straw from blowing off the slope.

All construction sites in North Carolina must follow soil stabilization timeframes mandated by the Construction General Permit NCG 01 (Construction General Permit NCG 01, Section II.B.2). These timeframes indicate how long a site may remain bare before temporary or permanent stabilization must be in place, generally grass seed with straw mulch and tackifier. Different slopes require stabilization timeframes that correlate with their potential for soil loss; in general, slopes steeper than 3:1 require stabilization within 7 days, whereas slopes shallower than 3:1 have up to 14 days.

Tackifier Products:

There have been a number of studies on the effectiveness of hydromulches (HM) as a cover during grass establishment but few of hydromulches being used as a tackifier. Although some studies have shown hydromulches to be effective on their own (Emanual, 1976), many others show that they often come up short in many areas. According to Faucette et al. (2005), hydroseeding may provide limited soil coverage prior to vegetation growth, as well as a slow drying period following application. In a recent study funded by NCDOT, hydromulches were not found to be consistently better or worse than straw in reducing erosion and establishing vegetation (Lee et al., 2018). It is possible that ground cover costs would be minimized by using straw at <$620 per hectare with an alternative tackifier with a cost rate from $900 - $4150 per hectare (Table 1). The cost of hydromulches alone would be close to two times the Double Rate Cost in Table 1, since the double rate for tackifying is about one half that of erosion control.

Table 1: Tackifier cost on an area basis. Costs are calculated using pricing figures from commercial retailers, specifically the suppliers for this study. Application costs are not included. See Table 2 for rates for each product.

Tackifier	**Price**	**1/2 Rate Cost**	**Full Rate Cost**	**Double Rate Cost**
	-- per kg --	----------------------USD per ha-----------------------		
PAM	$11	$310	$615	$1230
Plantago	$2.07	$115	$230	$465
Tracer	$6.30	$170	$340	$680
Bonded Fiber FGM (BF)	$1.85	$1035	$2070	$4140
Cellulose HM (CHM)	$0.40	$225	$450	$900
Wood Fiber HM (WF)	$0.55	$310	$615	$1230
Tornado Tack HM (TT)	$0.73	$205	$410	$820
Soiltac	$5 / liter	$600	$1,200	$2,400
Emulsified Asphalt	N/A	N/A	$1450	N/A

There were four main types of tackifiers that were tested in this study: wood-based, hydraulically applied mulches (cellulose HM (CHM), bonded fiber flexible growth media (BF), Tornado Tack (TT), and wood fiber HM (WF), plant-based glue (plantago), flocculants (polyacrylamide) and organic soil stabilizers (Soiltac and Tracer) (Table 2). Wood fiber products as tackifiers may be less expensive, equally as effective and more environmentally acceptable in comparison to emulsified asphalt (Kay 1978, Brown and Hallman, 1984). Many of these hydromulches obtain their fibers from the wood of aspen or alder trees, while others use recycled paper (Keammerer, 1988). Recycled products are not only more environmentally friendly, but are typically inexpensive due to the saving in raw material costs. Hydromulches are typically dyed a bright green or blue color as a visual aid for even and full coverage over the site (Keammerer, 1988).

Table 2: Products tested in this study as tackifiers.

General Name	**Product Name**	**Manufacturer**	**Mixing Rate** Kg L^{-1} (lb/gal)	**Recommended Rate** Kg ha^{-1}
Bonded Fiber FGM	FlexTerra	Profile (Buffalo Grove, IL, USA)	0.048 (0.4)	1120
Cellulose Hydromulch	Country Boy	Country Boy Seed, Inc. (Bristol, VA, USA)	0.048 (0.4)	1120
Plantago	Plantago	Ewing Irrigation (Phoenix, AZ, USA)	0.048 (0.4)	112
Polyacrylamide	APS 705	Applied Polymer Systems, (Woodstock, GA, USA)	0.00099 (0.0083)	56
Soiltac (liquid)	Soiltac (liquid)	Soilworks, LLC (Scottsdale, AZ, USA)	40:1 ratio (water to product)	117 (234 L ha^{-1} liquid product)
Tracer	Tracer	Reinco, Inc. (Plainfield, NJ, USA) *No longer commercially available*	0.0012 (0.01)	11
Tornado Tack Hydromulch	Tornado Tack	Profile (Buffalo Grove, IL, USA)	0.048 (0.4)	560
Wood Fiber Hydromulch	Conwed 1000	Profile (Buffalo Grove, IL, USA)	0.048 (0.4)	1120

Soil stabilizers, have been successful tackifiers due to their field longevity resulting from their resistance to ultraviolet radiation (Keammerer, 1988). TRACER™ (Epic Manufacturing, Greenwood, DE, USA) tackifier, used in this study, is one example of this type of soil stabilizer. It comes in a powdered form which is then added to water to create the tackifier for straw. It is described as “a water soluble blend containing: linear, anionic, copolymer of acrylamide and sodium acrylate, containing less than 0.05% acrylamide monomer; blended with one or more polysaccharides such as pre-gelatinized starch in conjunction with an inorganic salt used as a cross linking agent” (Braun, Material Safety Data Sheet (M*SD*S)). The powdered form is greenish-brown and when mixed with water it transitions to a brighter green color. It is not currently listed as a carcinogen by the International Agency for Research on Cancer (IARC), National Toxicology Program (NTP), Occupational Safety and Health Administration (OSHA) or the Association

Advancing Occupational and Environmental Health (ACGIH). Soiltac, another organic soil stabilizer used in this study, is manufactured by Soilworks for the purpose of dust control. It is composed of 55% synthetic vinyl copolymer dispersion and 45% water, with no known carcinogens or environmentally hazardous chemical components (Soiltac MSDS).

Linear polyacrylamide (PAM), although not typically used as a tackifier, was included in this study since it is used for erosion control on construction sites and in irrigated agriculture (Sojka et al., 2007), and therefore could provide two functions if it worked as a tackifier. The PAM used in erosion control, and in this project, is a linear anionic polymer which becomes sticky when wet and that suggested it could function to hold straw. PAM is also one of the ingredients in Tracer. Plantago, is a plant byproduct that has been ground into a fine powder and which becomes sticky when combined with water. Due to its inexpensive and environmentally friendly nature, plantago was included in this study. The products selected could all be applied with a standard hydroseeder, which are commonly used on construction sites.

Emulsified Asphalt

Emulsified asphalt is used as a straw tackifier, primarily due to its availability and affordable cost of the straw mulch base. By emulsifying the asphalt, it creates a product that is easier to apply, and the water will evaporate after application leaving only the asphalt behind as the tackifier (TDOT, 2006).

However, despite its widespread use it is important to note some concerns about this product. Although the application is less involved than laying asphalt for pavement, the process is still difficult because the tackifier must be kept between 40° - 70° C (104° -158° F) during application (TDOT, 2006). This raises concerns as some seed species can be damaged by high temperatures (Corbineau et. al, 2002) and contact with the hot asphalt could kill the seeds. Even if the asphalt cools quickly after initial application, its dark black color will absorb sunlight and therefore continue to warm the emerging seedlings, or could prevent sunlight from reaching the ground surface at all. Asphalt tackifier produced inferior grass growth compared to seven other mulching treatments on fill slopes (Grace, 2000), and poor grass stands have been observed in areas with generous asphalt application (McKee, 1965). Additionally, direct contact between emulsified asphalt and grass seed, for certain grass species, can decreases its growth and survival rates (Brofas et al., 2000).

Additionally, asphalt is dangerous to animals who may come into contact with the substance and are unable to remove it from their fur (Sittig and Pohanish, 2002). For the workers applying tackifiers, there are short- and long-term exposure risks in the form of burns and skin cancer. (Sittig and Pohanish, 2002). Personnel handling asphalt are required to wear personal protective equipment when handling to product to protect themselves from any risks associated with it (Sittig and Pohanish, 2002).

METHODS

Task 1. Construct a portable wind tunnel capable of generating sufficient velocities to cause the various straw/binder combinations to fail. This will require some preliminary testing as there are no previous studies on this subject. Tests will include the straw/binder combinations under wet and dry conditions.

The wind tunnel used in this study was built for the specific purpose of testing tackifier effectiveness on wheat straw. The goal was to find which tackifier products were most successful at withstanding laminar wind, and preventing straw mulch failure. We hypothesized that straw would be able to withstand higher wind speeds when using a tackifier, but we did not have any specific products that were expected to work better than others. The ultimate goal was to find any alternative tackifier products that were at least as effective at tacking straw as emulsified asphalt, and at a lower cost.

Building a wind tunnel to fit the exact specifications for this project was an additional endeavor. It was important that this tunnel was portable, and therefore relatively small, created a laminar wind pattern, and reached wind speeds representative of moderate storm events. Many portable wind tunnels found in the literature were designed for testing soil erodibility, and therefore have the actual ground surface as the “working section” of their tunnel (Pelt and Zobeck, 2013). In this project, however, the focus was on straw failure and therefore a fully enclosed tunnel was preferable. The tunnel created in this project allowed for full sample trays of soil, straw and tackifier to be freely moved in and out of the wind tunnel.

Wind Tunnel Design:

The wind tunnel in this study is an example of an open design tunnel (Advanced Thermal Systems, 2009), meaning that ambient air enters the wind tunnel and then exits into ambient air after passing through the testing chamber (Advanced Thermal Systems, 2009). There are also three components to a portable wind tunnel: a self-contained power source or engine, a fan, and transportation of wind from the fan to the working section, either an actual soil area, or an enclosed testing space (Pelt and Zobeck, 2013). For this design, a gasoline-engine powered fan was attached to the testing tunnel via a segmented wooden frame with baffles to create a laminar flow patter (Figure 1). Maximum wind speeds of 72 to 80 km h^{-1} (45-50 miles h^{-1} (mph)) were achieved with this design, with minimums between 24-32 km h^{-1} (15-20 mph).

Figure 1: Fully operational wind tunnel with the fan properly attached and a bare soil box inside. The orange wind speed meter sits on top, exterior to the box, with only the probe on the inside.

The floor of the tunnel was covered in a base layer of wheat straw glued in place to simulate bare soil with straw applied to it. In the center was a cutout for removable wood boxes which served as the test plots (Figure 2). The boxes sat flush with the floor of the tunnel to prevent interference with the air flow. The purpose was to create an environment similar to straw applied to a slope and to avoid any discontinuity in the straw layer.

Flow Pattern:

To examine the flow pattern within the wind tunnel a series of videos were taken using colorful smoke emitters (Burst Wire-Pull Smoke Grenades, Enola Gaye, Pahrump, NV, USA). These emitters were fastened to the wind tunnel such that either one or two emitters were suspended in the middle of the tunnel entrance.

Figure 2: Test box filled with soil and installed in the wind tunnel. During testing, the box also has straw with or without tackifier applied to the soil.

Once they were securely fastened, the plug was pulled, video camera started and the fan was set to 20 mph, or the lowest speed. Slowly the wind speed was increased, and the test was only concluded when the smoke had run out. These videos were then used to determine the general wind flow pattern within the tunnel, and elucidate any areas of turbulence. Additionally a more qualitative measurment was taken to determine the wind speed distribution. Using the anemometer, wind speed was measured in various places throughout the tunnel, including 3 depths, with 5 points at each of the three cross sections (Figure 3), for a total of 45 measurments per replication. Overall for the lowest fan speed (approximately 32 km h^{-1}) the standard devation is 0.98 km h^{-1} on average, and 2.3 for the highest fan speed (80 km h^{-1}). This means that in general the speed is approximately the same throughout the tunnel.

Treatments:

Wind tunnel tests were conducted under a variety of conditions to determine the effects on the performance of the tackifiers. These conditions included tackifier

Lowest Fan Speed — Top. Front of tray closest to fan

10"	25.7	24.3	18.7	19.3	21.7
6"	24.3	22.7	18.7	19.7	23.7
2"	23.3	19.3	18.3	19.3	24.0

Highest Fan Speed — Top. Front of tray closest to fan

10"	61.0	57.3	41.0	44.0	51.0
6"	58.0	53.0	42.0	46.0	55.0
2"	54.3	46.0	42.0	44.7	48.3

Lowest Fan Speed — Middle of tray

10"	25.7	22.7	19.3	21.0	22.3
6"	24.7	22.7	19.3	21.0	23.7
2"	23.7	20.7	18.7	18.7	19.3

Highest Fan Speed — Middle of tray

10"	59.7	52.3	43.3	47.7	51.7
6"	57.3	52.3	45.0	49.0	53.7
2"	53.0	46.7	43.3	42.0	42.0

Lowest Fan Speed — End of tray

10"	26.3	22.7	20.7	22.3	23.0
6"	25.3	23.3	21.0	21.7	23.7
2"	23.0	22.0	20.3	19.0	19.7

Highest Fan Speed — End of tray

10"	60.7	51.3	47.3	51.7	53.0
6"	58.7	54.3	48.0	50.0	53.3
2"	53.7	50.3	47.7	44.0	44.0

Figure 3: Distribution of wind speeds (mi h^{-1}) throughout the wind tunnel. This figure shows the average of three replications and should be observed as if looking from the fan into the wind tunnel. The top set of columns shows the wind tunnel cross section

that is closest to the fan, while the bottom set of columns shows the furthest away. Height is measured from the tray floor.

application rate, straw application rate, wet vs. dry straw, and gusty vs. steady wind. Application rates were tested under dry and steady wind conditions at the rate recommended by the manufacturer as well as at half and double that rate, while straw application was tested at 2240 kg ha^{-1} (2000 lb ac^{-1}) and 4480 kg ha^{-1} (4000 lb ac^{-1}). Dry samples were tested directly after the two day drying period. Wet samples were dried for two days and then placed under a rainfall simulator (5 cm h^{-1}) for ten minutes prior to testing, with only the higher straw rate included. Steady wind testing involved increasing wind speed by 8 km h^{-1} (5 mi h^{-1}) every minute until failure. Gusty tests were increased by 16 km h^{-1} (10 mi h^{-1}) every twenty seconds, with the fan being turned off between wind speed increases. For instance, if the starting wind speed was 40 km h^{-1} (25 mi h^{-1}) and no failure occurred, the fan would be stopped and restarted at 56 km h^{-1} (35 mi h^{-1}) , so a 0 – 56 km h^{-1} (0 – 35 mi h^{-1}) gust was created. Only the 4480 kg ha^{-1} (4000 lbs ac^{-1}) straw rate was included in the gusty testing.

<u>Box Preparation and Testing:</u>

Each box was 0.27 x 1.18 m (0.88 x 3.88 ft) and 0.05 m (2 in) deep. They were filled with a clay loam soil to the top edge to create an even surface. Each box then received straw with or without tackifier, which were both spread by hand evenly over the surface of the soil. Each tackifier was tested at 50%, 100%, and 200% of the manufacturer's recommend rates (Table 2). After tackifier application, each soil box was left for a minimum of two days after the liquid tackifier application, which allowed time for moisture to evaporate. All combinations of treatments were tested in triplicate.

Each steady flow test was started at 24-32 km h^{-1} (15-20 mph), the lowest wind speed with the motor running, and the throttle was manually adjusted to result in an 8 km h^{-1} (5 mph) increase in speed every minute. For gusted flow tests, wind speeds began at 40 km h^{-1} (25 mi h^{-1}) and were increased by 16 km h^{-1} (10 mi h^{-1}) every 20 seconds. Additionally, instead of increasing the wind speed while the fan was running, like in the steady flow test, the fan was turned off after each 20 seconds, and then started again from and rapidly brought to the desired speed. This created a faster acceleration of wind speed in the gusty tests, as compared with the steady flow. Testing was completed when either a failure occurred or maximum wind speed (72-80 km h^{-1} (45-50 mph)) was reached. Each test was monitored with an anemometer as well as a video camera. The anemometer recorded wind speed continuously and showed the current wind speed on a display during the testing. The video camera recorded both the wind tunnel and the wind gauge, which was later used as a reference when needed. During the first 15 seconds of each video a sign was placed in view to denote which test was being run. In addition, any notable observations during the test were also recorded by hand, and the failure wind speed was documented. If the straw/tackifier combination was not a full failure, a brief description was added, to provide a more detailed analysis. A failure was defined as the point at which more than 50% of the straw had blown off (Figure 4). After the test was completed each box was photographed to record the amount of failure.

Figure 4: A before (left) and after (right) view of a soil test box with an application of hydraulic tackifier. This illustrates a "failure" with less than 50% of the straw remaining.

Task 2. Using the portable rain simulator constructed as part of a currently funded project, test the straw/binder combinations on 2:1 slopes and sheet erosion conditions.

A very brief preliminary test addressed task 2. Three test boxes were set up below the rain simulator, with only straw covering the soil. The rainfall simulator rained approximately 5 cm h^{-1} (2 in h^{-1}), and ran for one hour. Every ten minutes observations were made to determine at what point the straw mulch would fail due to sheet erosion.

Task 3a. Conduct vegetation establishment studies for the most successful binders under a variety of conditions: outdoor conditions.

The goal of the field vegetation study was to determine if any tackifiers which were successful in preventing straw failure in the wind tunnel testing affected grass germination or growth. We expected that emulsified asphalt would negatively impact growth more than other tackifiers, due to its dark color and ability to obscure light penetration to the ground surface. Studies by Grace (2000) and McKee (1965) found that emulsified asphalt performed significantly worse than other mulch treatments, and that high applications of asphalt can hinder growth. Previous tests of hydromulches alone at a full erosion control rate suggested they can inhibit grass growth (Lee, 2012). This study allowed for natural weather patterns, soil conditions and wind to influence the study and create a simulation of actual construction site conditions.

Methods:

Two locations were used for the grass establishment study, one being the Lake Wheeler Field Laboratory (LWFL), and the other was a North Carolina Department of Transportation (NCDOT) project site in Apex, NC. The LWFL plots were replicated in the spring and fall, whereas the Apex site was only tested in the fall. The LWFL site was initially prepared by scraping the existing grass off with a motor grader then rotary tilling the area to 12-15 cm (5-6 in). The area sloped southward at approximately 4%. The Apex site was a fill slope on the inside curve of a highway interchange under construction, with approximately 10% slope facing northeast.

Lake Wheeler Field Laboratory Site

The grass establishment study at LWFL was conducted twice, one beginning in mid-April 2016, and the other in late September. Prior to test initiation, the entire site 6.1 x 30.5 m (20 x 100 sq. ft.) received DOT specification lime and fertilizer applications followed by tillage. Fertilizer was applied at 560 kg ha^{-1} (500 lbs/ac) of 10-20-20 (N-P-K) and 4482 kg ha^{-1} (4000 lbs ac^{-1}) of lime. The grass seed mix is specified under the NCDOT eastern North Carolina seeding and mulching requirements for "shoulder and median areas", with slight variations depending on the season. The two seasonal mixes are composed of 56 kg ha^{-1} (50 lbs/ac) tall fescue, 11 kg ha^{-1} (10 lbs/ac) centipede, and either 28 kg ha^{-1} (25 lbs/ac) bermudagrass (hulled) or 39 kg ha^{-1} (35 lbs/ac) bermudagrass (unhulled) for March 1- August 31 or September 1- February 28, respectively (NDOT (6), 2016). Since all the testing conducted in this study occurred between August 1st and June 1st, only the fall mix was used. The seed, fertilizer and lime information are provided in Table 3.

Table 3: Source and pricing information for grass seed, fertilizer and lime used in this project.

Eastern NC DOT Grass Mix	Application Rate	Price per kg	Price per ha.	Variety	Source
	---kg ha^{-1}---	-------USD-------			
Tall Fescue	56	$5	$280	Raptor II	Wyatt Quarles Seed Company (Garner, NC)
Centipede	11	$79	$870	N/A	Burke Brothers Hardware (Raleigh, NC)
Bermudagrass (hulled)	28	$11	$310	RFLB	Corr Farm Supply (Smithfield, NC)
Fertilizer	560	$1	$560	10-20-20	Corr Farm Supply (Smithfield, NC)

Limestone	4480	0.22	$990	Rocky Dale Ground Lime (0.5 #)	Corr Farm Supply (Smithfield, NC)

After the grass seed was applied on April 4th and September 15th 2016, wheat straw was applied with a commercial straw blower to create an even distribution of approximately 2240 to 4480 kg ha^{-1} (2000 – 4000 lbs/ac). An acceptable application, according to the NCDOT, allows some sunlight to reach the soil, while still partially shading the ground, which helps to reduce erosion and conserve soil moisture (NCDOT (5), 1998). Since each bale of straw is of variable weight, this range is rather wide, and most contractors apply straw by sight, rather than a set number of bales or weight. However, based on average bale weight for the straw used for these tests, 86 bales was approximately the correct amount for one hectare (35 bales per acre). A cost breakdown for each grass type is included in Table 3, along with the specific brand and variety information. All pricing information is based upon the rates that were paid during this project, so certain products may be less expensive if purchased in bulk. Under this pricing scheme, and the estimated 86 bales of straw at $6 per bale, the total cost prior to tackifier application was approximately $3,526 per hectare.

Table 4: List of tackifiers and application rates used at the Lake Wheeler Field Laboratory for the outdoor vegetation tests.

Tackifier	**Application Rate: Kg ha^{-1}**
No Tackifier	0
Emulsified Asphalt	N/A
Polyacrylamide	112
Wood Fiber HM	560
Wood Fiber HM	1120
Wood Fiber HM	2240
Bonded Fiber HM	560
Bonded Fiber HM	1120
Bonded Fiber HM	2240
Cellulose HM	560
Cellulose HM	1120
Cellulose HM	2240

Plantago	224
Tornado Tack (Fall Only)	500
Soiltac	117
Soiltac	234

Tackifier treatments were selected using results from the wind tunnel testing to select tackifiers and rates that were effective at withstanding wind speeds of over 48 km h^{-1} (30 mi h^{-1}; Table 4). For this reason, some tackifiers were tested at multiple application rates. Each treatment was replicated four times in a completely randomize block design. Each plot was 0.46 x 0.46 m (5 x 5 ft.), and all plots were marked with colored flags to denote boundaries and to designate tackifier treatments.

The tackifiers were carefully applied by hand immediately following the straw application, to prevent it from being blown away. A commercial operator applied the emulsified asphalt to those plots using their standard equipment. Both aerial and ground photography were used to track the grass germination and growth. The aerial photographs were processed using ArcGIS (version 10.3.1; ESRI, Redlands, CA, USA) to determine the vegetation cover for each plot. No specific time interval was set to record data for these sites, as it was collected according to grass growth. When the grass appeared to be fully established, i.e. the vegetation cover was constant, the study was concluded with the final survey. Lastly, to account for any variability in fertility or pH conditions, soil samples were taken from four locations within each block.

Apex Active DOT Site

Four tackifiers which were at least partially successful in the wind tunnel tests and which represented different product types were selected for testing at the Apex construction site. These tackifiers were plantago (200% application rate), cellulose HM (100%), Soiltac (100%) and PAM (200%). Fertilizer, lime, grass seed and straw were applied by the DOT. Plots were 3 x 6 m (10 x 20 ft) and were installed at the top of the short slope below the pavement. Due to the larger plot size, cellulose HM, Soiltac and PAM were applied with a hydroseeder. To determine the application rates for each product, the spray rate was measured briefly prior to application and the approximate spray time was calculated to apply the appropriate amount of product. Plantago was applied by hand due to its lower application rate. An additional 0.93 x 1.89 m^2 (10 X 20 ft^2) area, adjacent to the 12 test plots, was tackified with emulsified asphalt applied by the contractor, and used for comparison of grass growth. Tackifier was applied on September 16th, 2016 and aerial photographs for this site were taken on September 29th and October 31st, 2016.

After collecting aerial images from the field, the photographs were analyzed using ArcMap (Esri, version 10.3.1) to determine the amount of vegetation cover. This is determined by assigning designations to specific colors, for instance green is grass, brown is soil, etc., and then calculating the percentage at which each color is present.

Task 3b. Conduct vegetation establishment studies for the most successful binders under a variety of conditions: greenhouse conditions.

The objective of this study was to expand upon the outdoor vegetation testing of the potential for tackifiers to inhibit grass growth, but under more controlled conditions. Each sample used the same soil, in the same sized tray, received the same amount of water, approximately the same amount of light, and did not experience any wind. This study also delved deeper into potential growth inhibition by separating the grass species in order to observe any differences for each species. After observing few differences during the outdoor vegetation study, tackifiers were hypothesized to have no effect on grass growth.

Methods:

The greenhouse bioassay study was initiated in December 2016 (Figure 5). Instead of using a grass seed mix, each grass species was tested individually so

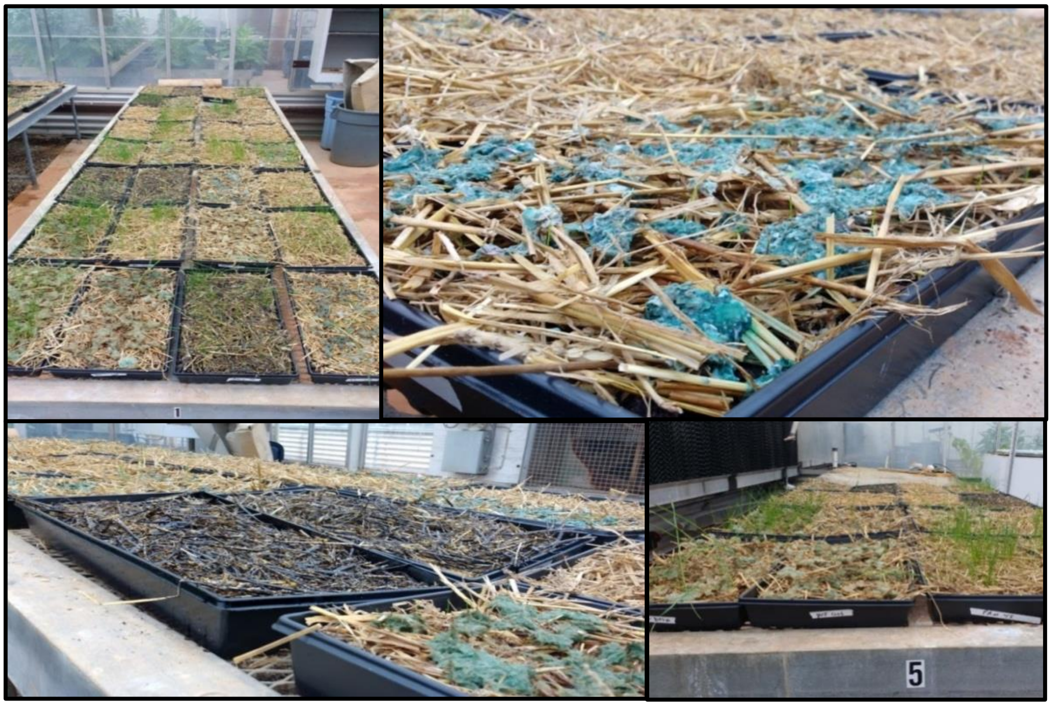


Figure 5: Photographs of the greenhouse bioassay project in progress, showing one bench (block).

that any species-specific effects could be isolated. The same grass species, tall fescue (Raptor II), bermudagrass (hulled, RFLB)) and centipedegrass, were used in this project as in the outdoor vegetation study, and were planted at a rate of 200 seeds per tray.

After the trays were filled with potting soil, grass seed was planted, as well as straw and tackifier, all on December 12th, 2016. Seed was applied to the surface of the soil and then gently raked in by hand, followed by straw at 4400 kg ha^{-1} (4000 lbs ac^{-1}).

The tackifiers included in this study were selected based on their successful reduction in straw failure in the wind tunnel testing. These included plantago, cellulose HM, wood fiber HM, bonded fiber HM, PAM, Soiltac, Tornado Tack, emulsified asphalt plus a no tackifier control. All were applied by hand at double the recommended rate. Each treatment was replicated three times with 3 grass species and 9 tackifiers, for a total of 81 trays. The application rate was accidentally doubled for all plantago treatments and for two replications of Soiltac. The emulsified asphalt was applied by a contractor three days after all other tackifiers. To prevent grass growth prior to asphalt application, the asphalt-tackified trays were not watered until they received the tackifier, and all data was adjusted to correct the delayed application. This correction was applied by shifting the results backwards by two days, meaning that data collected on day 18, for example, would be recorded as being collected on day 16 instead.

The trays received 335 mL of water per day (0.1 in/day) throughout the test period. Blade height and count measurements were taken on alternating days. Grass blade count included fully matured blades as well as barely visible, newly emerged blades. Blade height was measured on the tallest three blades in each tray and averaged. If less than three blades were present, the average was calculated using only the number of blades that were present. And grass emergence was calculated by dividing the number of grass blades per tray by 200 (the estimated total number of seeds planted).

Data was recorded for all grass species until January 2nd, 2017, 22 days after planting. At this time tall fescue was nearing 100% emergence; however, centipedegrass and bermudagrass had only produced a few blades per tray. Watering ceased on January 2nd; however on January 11th centipedegrass and bermudagrass appeared to have continued growing, so to included them in the assay, watering was resumed and the test was extended until January 24th (44 days) for these species. Measurement frequency for blade count was decreased during this time due to the slow growth, and height data was only recorded for the final day of testing. Blade counts were taken every three days, ending on January 20th, and on January 24th blade height was recorded for the last time.

RESULTS AND DISCUSSION

Task 1.

Wet straw was able withstand higher wind speeds than dry straw. In fact, the other factors, including tackifier, tackifier application rate, and wind condition had little effect when the straw was wet, and in many tests the maximum wind speed (80 km h^{-1} [50 mi h^{-1}]) was reached with no failure (Figure 6). An interaction was also found between tackifier type and straw application rate (p = 0.0003), indicating that

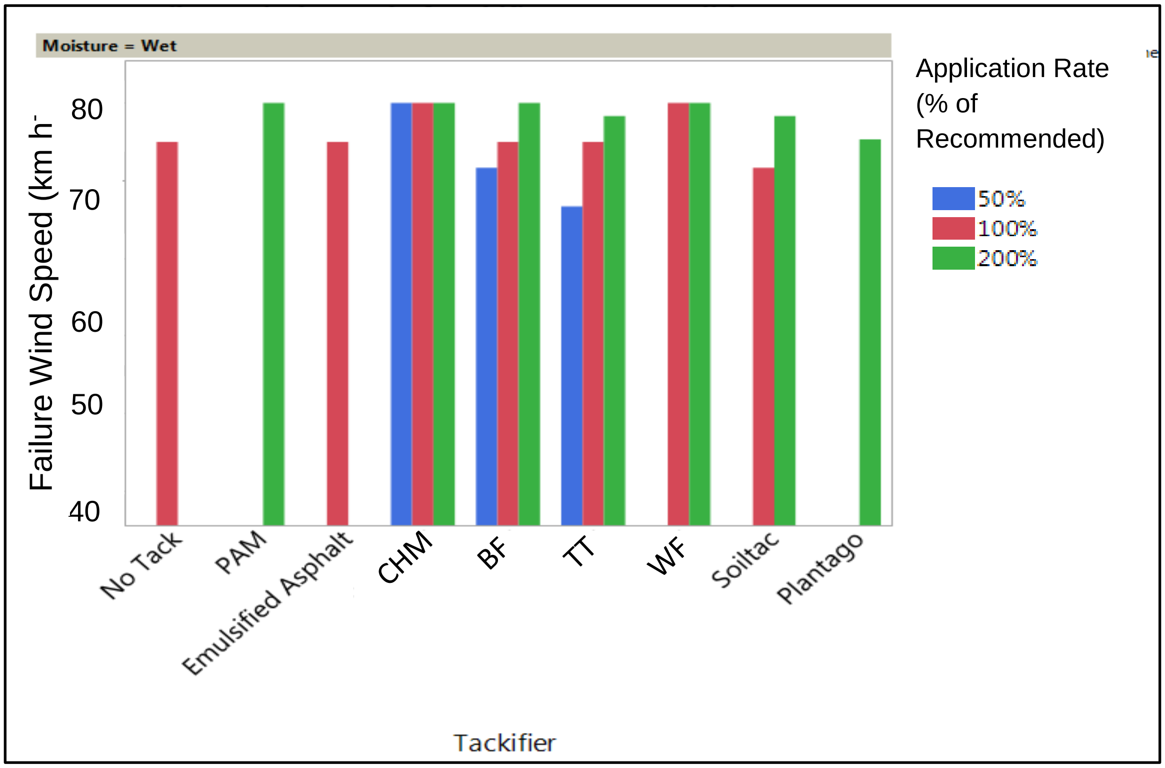


Figure 6: Effect of wet moisture conditions and tackifier application rate on tackifier treatments.

the higher straw rate resulted in different tackifier performance under dry and steady conditions.

Dry Straw and Steady Wind:

At 200% application rate the average wind speed to failure is 70 km h^{-1} (43.4 mi h^{-1}), whereas 100% and 50% are 57.5 (35.7) and 46.3 km h^{-1} (28.8 mi h^{-1}) respectively (Table 5). Differences between tackifier treatments were found at all tackifier application rates. At 50% application rate, bonded fiber HM, Tornado Tack, and emulsified asphalt could all withstand higher wind speeds than plantago, while only bonded fiber HM and emulsified asphalt could withstand higher wind speeds than bare straw and plantago. At the half rate, Soiltac, wood fiber HM, PAM, Tracer,

Table 5: Effects of tackifier treatments on failure wind speed under dry and steady conditions at three application rates. Since emulsified asphalt and "No Tack" were only applied at one rate, comparisons were made at all three rates of the other products. Differences ($p<0.05$) are indicated if values do not have a common letter.

Tackifier	**Tackifier Application Rate**		
	50%	100%	200%
	------------ Failure Wind Speed (km h^{-1}) -----------		
No Tackifier	36 cd	36 b	36 b
Emulsified Asphalt	61 a	61 a	61 a
Polyacrylamide	42 bcd	40 b	51 ab
Bonded Fiber HM	55 ab	76 a	80 a
Cellulose HM	53 abc	71 a	77 a
Plantago	35 d	39 b	68 a
Wood Fiber HM	43 bcd	64 a	79 a
Tornado Tack	55 abc	68 a	69 a
Soiltac	43 bcd	61 a	63 a
Tracer	37 bcd	39 b	42 b

plantago and bare straw performed worse than emulsified asphalt (Table 5). However, in this comparison, emulsified asphalt was applied at its recommended rate (the only rate tested throughout the study), while all other tackifiers were applied at half the recommended rate.

Cellulose HM, bonded fiber HM, Tornado Tack, wood fiber HM, Soiltac and emulsified asphalt all performed better than PAM, plantago, Tracer and bare straw samples at the recommended rate (Table 5, FigureS 7 & 8). At the 200% application rate, cellulose HM, bonded fiber HM, Tornado Tack, wood fiber HM, emulsified asphalt and plantago all performed better than Tracer and bare straw, while PAM was neither better nor worse (Table 5).

The effects of tackifier application rate for dry and steady tests were consistent with that of all dry samples, where higher tackifier application rates performed better than low rates (tackifier / application rate interaction $p= 0.0001$). There is also an interaction between tackifier and straw application rate ($p= 0.0004$).

Six tackifier treatments were unaffected by straw application rate, while cellulose HM and Tornado Tack performed better at the 2240 kg ha^{-1} (2000 lbs ac^{-1}) straw application rate (Table 6). When no tackifier was applied, the higher straw rate resisted winds up to 8 km h^{-1} higher than the lower rate.

Table 6: The effect of straw application rate for each tackifier treatment under dry and steady wind conditions. Differences ($p<0.05$) are indicated between the two straw rates if the letters following the failure wind speed are different.

Tackifier	**Mean Failure Speed: 2240 kg ha^{-1} Straw**	**Mean Failure Speed: 4480 kg ha^{-1} Straw**
	--- km h^{-1} ---	--- km h^{-1} ---
No Tackifier	32 b	40 a
PAM	42 a	47 a
Bonded Fiber HM	72 a	69 a
Cellulose HM	76 a	60 b
Emulsified Asphalt	51 a	72 a
Plantago	51 a	43 a
Wood Fiber HM	63 a	61 a
Tornado Tack	69 a	56 b
Soiltac	56 a	55 a

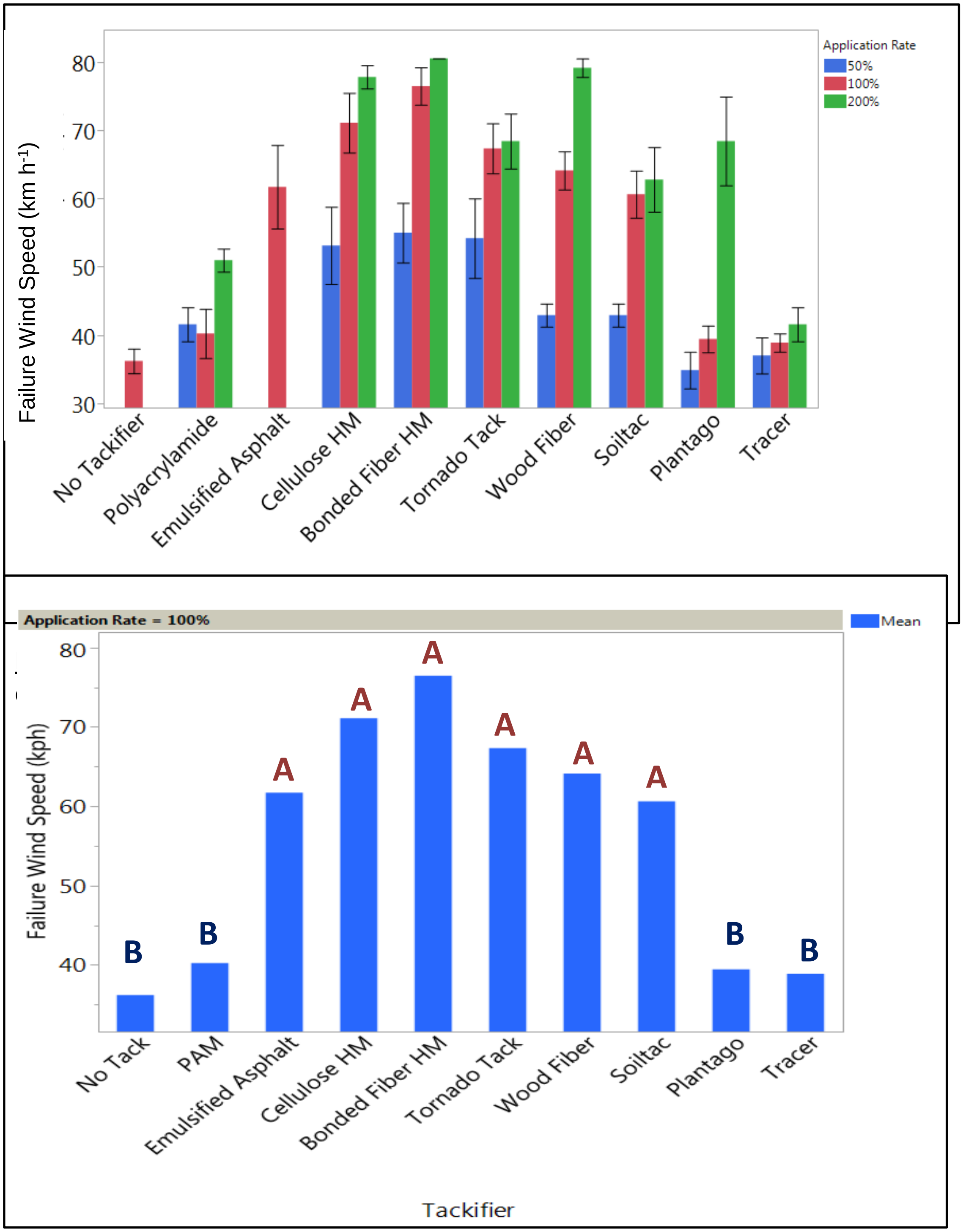


Figure 8: Differences in tackifier treatments at the recommended rate for dry straw and steady conditions. Differences ($p<0.05$) are indicated if values do not have a common letter.

Key: No Tack = No Tackifier. PAM = Polyacrylamide

Dry Straw and Gusty Wind:

Samples run in gusty wind flow conditions had no differences in failure wind speed among tackifier treatments when all rates were included (Table 10). In general, samples tested under gusty conditions failed at lower wind speeds than under steady conditions. On average, for dry samples, steady tests failed at 55.7 (34.6) vs. 51.1 (31.7 mi h^{-1}) km h^{-1} under gusty conditions. Furthermore, there were no differences at the recommended rate under gusty conditions. At the 200% application rate, plantago and bonded fiber HM withstood higher wind speeds than bare straw and PAM, while all other tackifiers performed neither better nor worse (Table 7). Additionally, there was no significant interaction between tackifier and application rate under dry and gusty conditions.

Table 7: Effects of tackifier treatments on failure wind speed (km h^{-1}) under dry straw and gusty winds with an application of 2x the recommended rate. Differences ($p<0.05$) are indicated if values do not have a common letter.

Tackifier	Mean Failure Speed
	-- km h^{-1} --
Plantago	68 a
Bonded Fiber HM	68 a
Cellulose HM	61 ab
Wood Fiber HM	56 ab
Tornado Tack	56 ab
Soiltac	45 ab
Polyacrylamide	40 b
No Tackifier	40 b
Emulsified Asphalt	60 ab

Ease of Application and Cost Analysis:

Another focus for this project is to find tackifier products that are both easy to apply and cost effective relative to asphalt. All tackifiers used in this study were tested for their ability to be applied via a hydroseeder, and all are capable of being sprayed through a 2.5 cm (1 in.) nozzle. This was determined through brief testing or according to the manufacturers when information was available. The hydroseeder used was a TurfMaker 420 (TurfMaker Corp., Rowlett, TX) with a 3.8 cm (1 ½ in.) hose attachment. The only product not applicable for hydraulic application was emulsified asphalt, which must be applied with specialized equipment to keep the mixture heated. All products require that the spray tank be cleaned thoroughly after application; however, PAM and plantago require special attention. We observed that plantago biodegrades rather quickly after application, so material left in the tank is likely to also degrade quickly. PAM becomes very viscous and sticky as it dries and this could clog the hydroseeder plumbing unless it is thoroughly rinsed.

There are a wide range of material costs depending on the type and brand of the tackifier, with national brand name hydromulches being relatively expensive, and off brand or alternative tackifier products being much cheaper (Table 1). A cost-benefit graph (Figure 9) compares product prices to their effectiveness at holding straw against wind, which can be used to determine the least cost to attain the greatest resistance to failure. From this analysis, either plantago at 200% the recommended rate or cellulose HM and wood fiber HM at the recommended rate appear to be the best options for cost and performance.

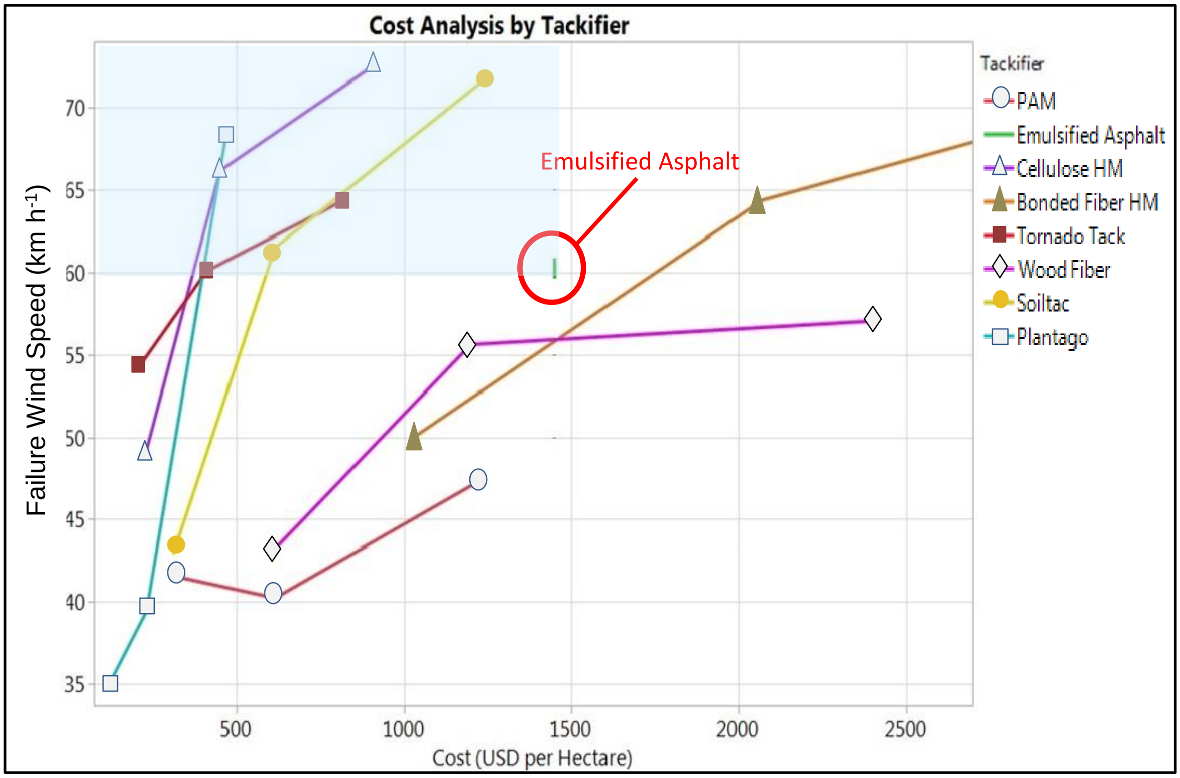


Figure 9: Cost-benefit analysis for each tackifier under dry straw conditions, at three application rates, as reflected in the cost. Emulsified asphalt is shown as a straight line since it is only applied at one rate. The light blue box represents tackifier and application rates that would be recommended to replace emulsified asphalt.

Task 2.

The three samples were observed over the course of the hour, but no straw was displaced by the rainfall simulator. Additionally, no sheet erosion occurred, and all of the straw stayed in place. Although this was only a preliminary test, since bare straw would not fail under moderate and lengthy rain events, we suspected that straw with tackifier would only perform as well or better. Therefore, straw failure by rainfall was not a major piece of this project, as it did not appear to be as much of a factor as failure via wind.

Task 3a.

During the spring evaluation at LWFL, no differences in grass cover were found between any of the tackifier treatments, application rates or blocks (Table 8). Additionally, rates (50, 100 or 200%) of application also did not affect grass stands. The aerial image used for this analysis was collected on July 29th, 2016, approximately 3 months after grass seed was planted, and on average the vegetation cover was 61%.

Table 8: Grass cover from July 29th 2016 aerial survey at the Lake Wheeler Field Laboratory. Four observations were recorded for each treatment and no differences were found ($p<0.05$).

Tackifier	Application Rate	Mean	Maximum	Minimum
	---------------------- Vegetation Cover (%) --------------------			
Cellulose HM	50	58	92	43
	100	52	70	26
	200	61	88	45
Bonded Fiber HM	50	66	100	37
	100	53	68	40
	200	79	92	73
No Tackifier	100	58	94	33
Soiltac	100	64	91	42
	200	58	78	39
Wood Fiber	50	54	91	29
	100	60	89	41
	200	58	80	41
Emulsified Asphalt	100	79	84	71
Polyacrylamide	200	47	67	29
Plantago	200	78	94	54

Lemly (1982) compared asphalt-tackified straw to jute netting, mulch blanket, wood chips and stapled excelsior blanket and found that over a 3 month period tall fescue cover was approximately 75% for the asphalt treatment, which was similar to our 79% grass cover on July 29th, also for emulsified asphalt. Although this study is not applicable to other tackifiers, it shows growth consistency to another study for the emulsified asphalt treatment, and the general range for grass cover after a three month time period.

During the fall evaluation at LWFL, there were early differences in tackifiers and application rates. In the data collected 13 days after seeding emulsified asphalt, cellulose HM, plantago, Soiltac and Tornado Tack had higher vegetation cover than bonded fiber HM, wood fiber HM and “No Tack” plots when including all rates. At the 50% application rate, bonded fiber HM had a higher vegetation cover than wood fiber HM (Table 9). Emulsified asphalt had more grass coverage than wood fiber HM, bonded fiber HM and straw alone at the 100% rate and no differences in grass establishment at the double recommended rate. However, all differences disappeared by 33 days after seeding, when the average grass cover was 56%.

Table 9: Grass cover comparison by tackifier application rate on 9/28/16. Emulsified Asphalt, Tornado Tack HM and “No Tack” are not included due to insufficient data (only one application rate).

Tackifier	**Grass Cover per Application Rate**		
	50 %	100 %	200 %
	----------------------	-%-	---------------------
BF	9 (A)	2 (B)	4
CHM	10	10	8
WF	4	6	4
Soiltac	N/A	8	7

Although there were some distinctions in grass cover between tackifiers under the recommended and 50% recommended rates, it seems likely that these effects were not due to inhibition by tackifier, but rather due to other factors. There were no differences at the 200% tackifier application rate, suggesting that the tackifiers were not inhibiting growth. No differences occurred in the spring iteration or after the initial few weeks in the fall. It is also possible that since only a few weeks had passed when the differences were found between tackifiers in the fall, these tackifiers may be positively affecting grass growth, instead of other tackifiers inhibiting growth. It is imperative that the soil retain its moisture during seed germination and early growth (Ayers, 1952), and therefore it could be possible that certain tackifiers offer more initial moisture or are better able to retain moisture.

The Apex site was prematurely terminated due to a severe erosion during Hurricane Matthew on October 8th (Figure 10), during which the estimated rainfall at the site was >20 cm (8 in). The erosion during this storm event was due primarily to the lack of a curb to protect the slope from the paved road runoff. However, one set

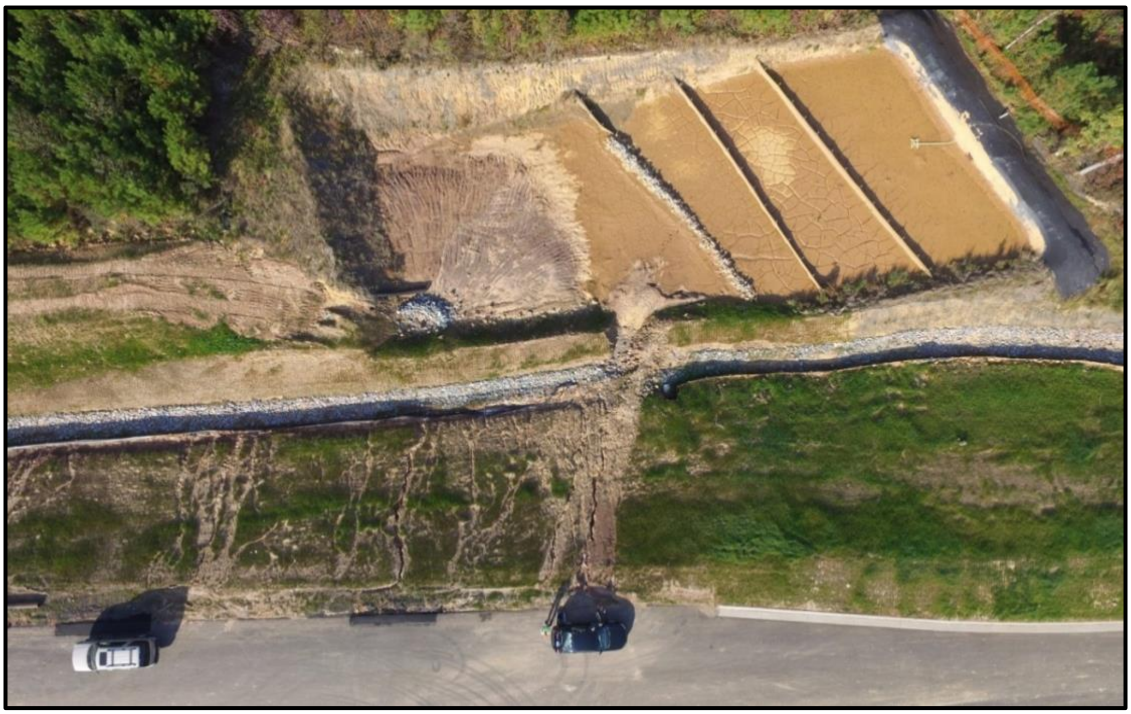


Figure 10: Aerial photograph of the Apex DOT site after Hurricane Matthew (10/31/2016).

of aerial photographs (Figure 11) was taken prior to Hurricane Matthew 13 days after planting, which was processed through the GIS software in the same manner as the LWFL plots. There were no differences in grass cover between any of the tackifier treatments (Figure 12). This indicated that these tackifier treatments did not have different effects on grass germination or growth.

Figure 11: Tackifier treatment plots located at the Apex Active site, September 29th, 2016

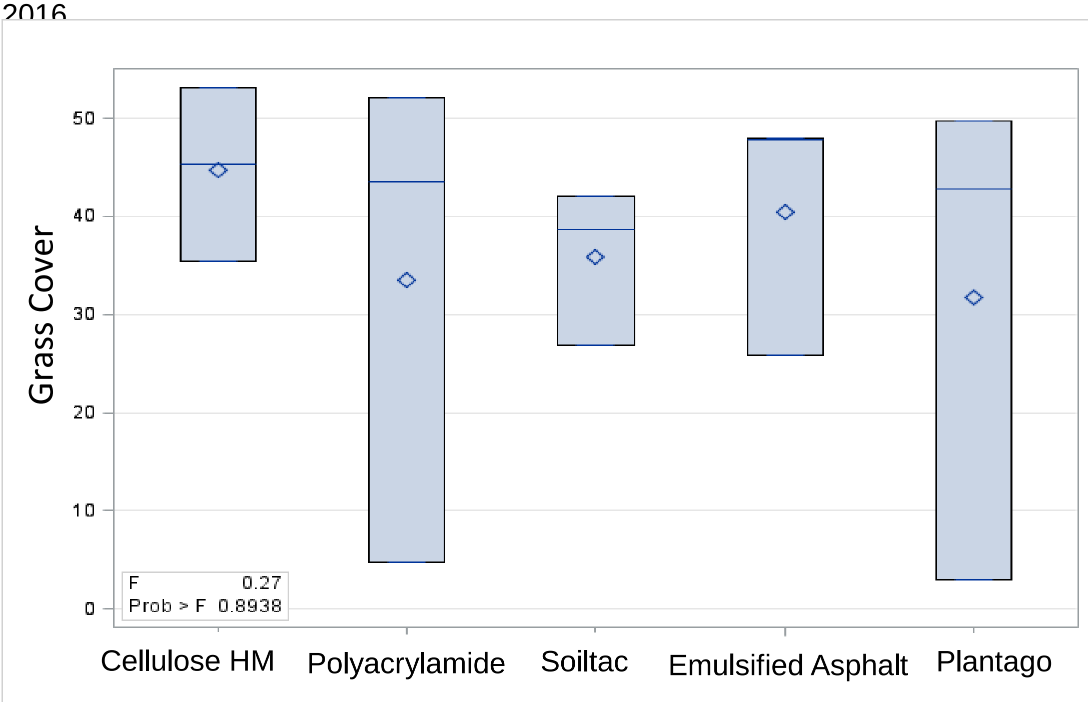


Figure 12: Grass cover results from the Apex, NC active DOT site on September 29th, 2016. For each tackifier the upper edge of the box represents the 3rd quartile (75th percentile), the line inside the box represents the median (50th percentile), the diamond represents the mean and the bottom edge of the box is the 1st quartile (25th percentile). There were no significant differences between any of the tackifier treatments ($p>0.05$).

Task 3b. Greenhouse Tests of Tackifier Inhibition

Tall Fescue:

Overall, there were few significant differences in grass establishment due to tackifier treatments effects. Differences were evident on only 37% of the eight days when blade counts were performed. Average maximum blade height only had differences 12% of the time, and seedling emergence was different for 62% of the measurement days. Overall, only 26% of the measurements for tall fescue had differences in tackifier treatments, suggesting that tall fescue growth was relatively unaffected by the tackifier applied to the straw. There were no differences in blade count between tackifiers when all days were included ($p \leq 0.05$), nor was there an interaction between tackifier and day; however, there was an day effect ($p < 0.0001$).

Differences in blade count did not occur until days 16, 18 and 20 (Table 10). The maximum average blade height was only different on day 10, with Tornado Tack having taller blades than emulsified asphalt. Differences in tall fescue grass emergence were evident on days 9, 11, 16, 18 and 20. Early emergence was generally much worse for the emulsified asphalt than the other tackifiers. Later, Tornado Tack HM tended to have higher emergence than the other tackifiers, but emergence in the emulsified asphalt caught up with all but the Tornado Tack HM. Barkley et al. (1965), compared grass emergence when mulched with straw, Turfiber (a wood cellulose fiber), saw dust, an elastomeric polymer emulsion called Soilset, and no mulch, finding it lower in the emulsion or no mulch treatments. All three grass species tested (Kentucky 31 fescue, Kentucky bluegrass, and redtop) had similar responses to the mulching treatments. These results seem related as Soilset and emulsified asphalt are both black emulsions, and although varying in composition, both had lower grass emergence. Although tall fescue was not specifically tested in the Barkley et al. experiment, the effect of tackifiers on emergence was consistent with the results from this study.

The change in number of grass blades between the measurement days indicated the rate of growth. Differences were found between days 9 and 11 as well as 11 and 14, where growth in the emulsified asphalt treatments was much less between days 9 and 11, and significantly more than other tackifiers between days 11 and 14. This result may be because emulsified asphalt was one day behind the other tackifiers, and that rapid growth generally occurs at a certain stage in the emergence process. On days 9-11, only 14 additional grass blade emerged in the emulsified asphalt treatment compared to 62 averaged among the other treatments.

However, between days 11 and 14, grass emergence increased by 108 blades in the emulsified asphalt treatment compared to only 25 blades averaged across all other treatments.

Table 10: Grass blade counts of tall fescue on days 16, 18, and 20 by tackifier. Similar letters within columns are not different at $p<0.05$. Standard deviations are shown in the columns marked S.D.

Tackifier Treatment	**Day 16**		**Day 18**		**Day 20**	
	Blade Count	S.D.	Blade Count	S.D.	Blade Count	S.D
Tornado Tack	153 a	7.6	156 a	5.2	158 a	3.8
Cellulose HM	135 b	5.9	136 b	4.9	138 b	2.5
Wood Fiber HM	137 b	11.6	140 ab	2.9	141 ab	2.0
Bonded Fiber HM	134 b	3.1	138 b	4.4	140 ab	4.5
Polyacrylamide	146 ab	8.1	150 ab	11.7	151 ab	13.1
Plantago	147 ab	7.5	150 ab	9.3	152 ab	9.1
Soiltac	145 ab	4.9	145 ab	4.9	146 ab	13.8
Emulsified Asphalt	142 ab	10.5	144 ab	12.2	150 ab	13.2
No Tack	144 ab	11.6	148 ab	13.5	153 ab	11.5

Centipede and Bermuda:

Both centipedegrass and bermudagrass species had much slower growth than tall fescue. Even after extending the test for an additional 3 weeks, the growth still did not reach the same level, with only 43 blades out of 200 (21.6%) emerged on day 40 for bermudagrass and less than 4 (1.9%) for centipedegrass on average (Figure 29). Due to this low growth, no comparisons were made for the centipedegrass species. No significant differences were found between any of the tackifier treatments for the bermudagrass.

The slower growth of both centipedegrass and bermudagrass was most likely due to the fact that these grasses are warm season grasses, whereas tall fescue is a cool-season perennial. Since the testing was conducted in December, the bermudagrass and centipedegrass did not receive enough light, due to shorter day lengths, and therefore exhibited stunted growth. This is likely due to fescue having greater growth potential under winter sunlight conditions compared to warm-season grasses (McCarty, 2001). Decreased light and photosynthetic input can cause reduced carbohydrate storage and therefore sparse stands, as seen in this study (Barrios et al., 1986 and Beard, 1969).

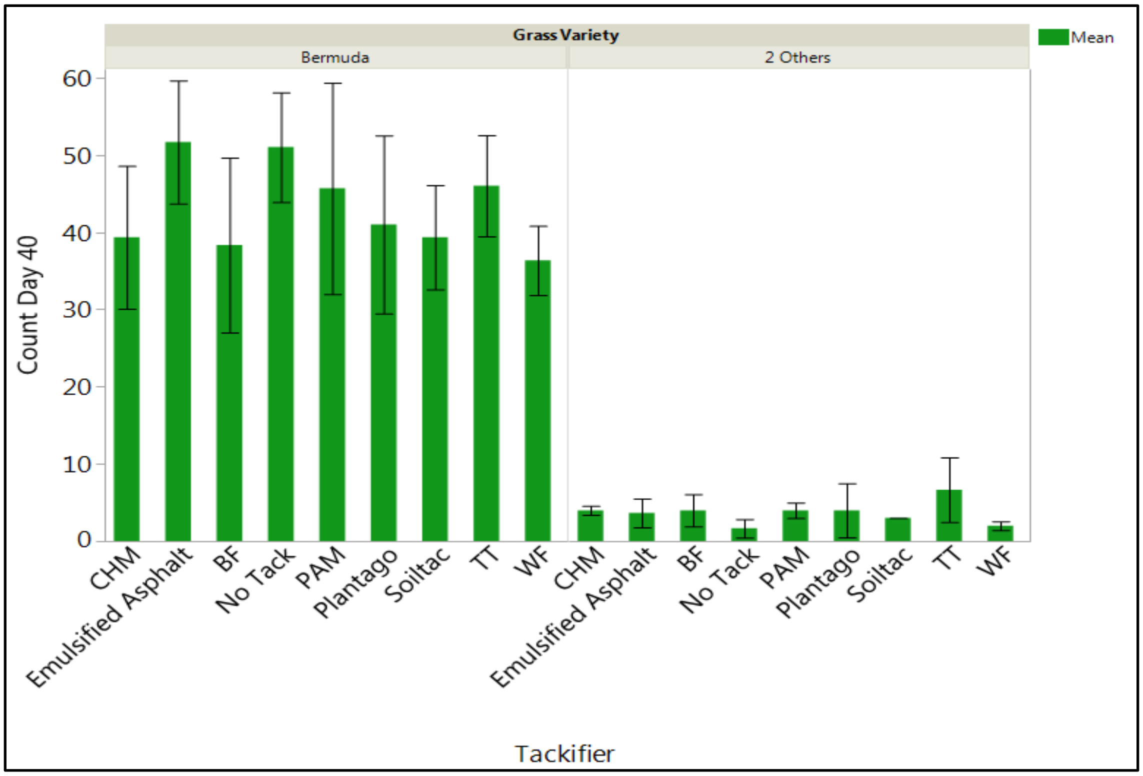


Figure 13: Blade count results for centipedegrass and Bermudagrass on day 40, the final day that grass blade count was recorded. No significant differences ($p<0.05$) in grass blade count between tackifier treatments, but bars represent standard error. Key: CHM = cellulose HM, BF = bonded fiber HM, PAM = polyacrylamide, TT = Tornado Tack, and WF = wood fiber HM.

Conclusions:

The main goal of this study was to determine viable straw tackifier options to replace emulsified asphalt. Specifically, a replacement tackifier would need to meet four main qualifications: effectively withstand wind and rain events, quick and easy application, no interference with grass germination or growth, and similar or lower cost. All tackifiers tested in this project met the ease of application qualification, as all are capable of hydraulic application with a hydroseeder, and each other aspect was tested in the three main studies conducted in this study.

There were a number of alternative tackifiers that were able to effectively withstand dry and steady winds at or above 56 km h^{-1} (35 mi h^{-1}), including cellulose HM, bonded fiber HM, wood fiber HM at the recommended 1,120 kg ha^{-1} (1,000 lb ac^{-1}), plus Tornado Tack and Soiltac at their recommended rates. Plantago also achieved good wind resistance at 2X the recommended rate (224 kg ha^{-1}; 200 lb ac^{-1}). Under dry and gusty conditions, a number of products withstood winds of 56 km h^{-1} (35 mi h^{-1}) or greater when applied at 200% of the recommended rate: plantago (42 mph), bonded fiber HM (42 mph), cellulose HM (38 mph), wood fiber HM (35 mph) and Tornado Tack (35 mph). A tackifier with an ability to withstand both steady and gusty winds is important, as gusty winds, common during storms or when frontal systems pass an area, were shown to cause straw failure at lower wind speeds. Although there was variation in the performance of these products, most of them provided similar protection from wind erosion to emulsified asphalt. Tracer and polyacrylamide were generally ineffective under most conditions, while Soiltac was only moderately effective. There was little evidence that the tested tackifiers had much effect on grass growth.

The hydromulches were generally effective at the current recommended rate of 1,140 kg ha^{-1} (1,000 lb ac^{-1}), and plantago was effective at the 2X (225 kg ha^{-1} or 200 lbs ac^{-1}) rate. Plantago costs approximately \$465 per hectare at the high rate; whereas cellulose HM (Country Boy) at the recommended rate was \$450 ha^{-1}, Tornado Tack HM was \$410 ha^{-1}, wood fiber HM (Conwed 1000) was \$615 ha^{-1} and bonded fiber FGM (FlexTerra) was \$2070 ha^{-1}. Since these were all effective, the lower cost products plantago, TT and CHM would be recommended to replace emulsified asphalt. Compared to the asphalt tackifier these products are all easier to apply, have fewer environmental concerns, do not hinder vegetation emergence or growth and are significantly less expensive. Each of these products offers protection from straw mulch failure at wind speeds up to 68 km h^{-1} (42 mi h^{-1}) under dry and steady conditions and 56 km h^{-1} (35 mi h^{-1}) under dry and gusty conditions.

Recommendations

- Phase out emulsified asphalt and begin using either cellulose HM or Tornado Tack at the recommended rates, or plantago at the double recommended rate. Examples of hydromulch application are shown in figures 14-15.

Figure 14: Example of cellulosic hydromulch applied at the recommended 1,120 kg ha^{-1} (1,000 lb ac^{-1}).

Implementation and Technology Transfer Plan

- Use a hydrodroseeder to apply tackifier to the site. Mix tackifier with the correct amount of water inside the tank and then apply evenly.
- Ensure that runoff from newly paved areas does not flow onto slopes but directed into storm drains or stabilized conveyances.
- Observe slopes on a frequent basis, specifically checking for bare soil areas. If bare areas are found, apply more straw mulch to the area. If the bare area is large, tackifier may need to be reapplied.

- Ensure that the site is receiving enough water for the grass to grow. If not, supplement your site with additional water if dry weather persists, especially with newly emerging grass.

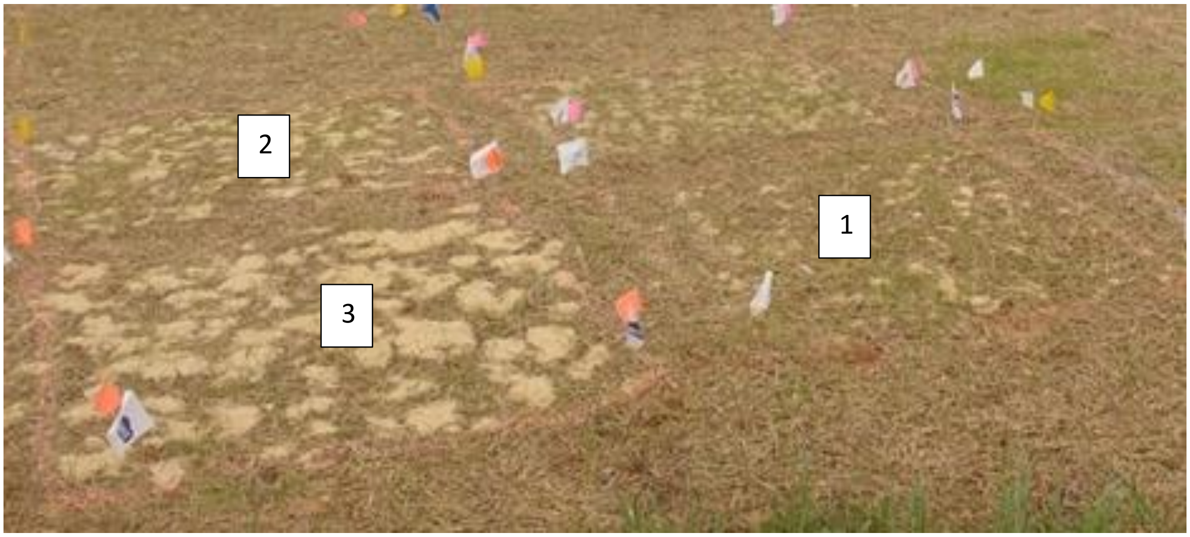


Figure 15: Examples of different rates of wood fiber hydromulch: 1. 560 kg ha^{-1} (500 lb ac^{-1}), 2. 1120 kg ha^{-1} (1,000 lb ac^{-1}), and 3. 2240 kg ha^{-1} (2,000 lb ac^{-1}). The original green color had faded at the time of the photograph.

Literature Cited:

Adams, J.E. 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Proceedings 30:110-114.

Advanced Thermal Solutions, Inc. 2012. Some basic principles of wind tunnel design. https://www.qats.com/cms/2012/07/17/some-basic-principles-of-wind-tunnel-design/

Alabama Forestry Commission. 1993. Alabama's best management practices for forestry. Alabama Forestry Commission: Montgomery, AL. http://www.forestry.alabama.gov/BMPIndex.aspx?bv=2&s=1%20.

Ayers, A. D. 1952. Seed germination as affected by soil moisture and salinity1. Agron. J. 44:82-84. doi:10.2134/agronj1952.00021962004400020006x

Barkley, D. G., R.E. Blaser, and R.E. Schmidt. 1965. Effect of mulches on microclimate and turf establishment1. Agron. J. 57:189-192. doi:10.2134/agronj1965.00021962005700020016x

Barrios, E. P., F.J. Sundstrom, D. Babcock, and L. Leger. 1986. Quality and yield response of four warm-season lawngrasses to shade conditions. Agron. J. 78:270-273. doi:10.2134/agronj1986.00021962007800020011x

Beard, J.B. 1969. Turfgrass shade adaptation. P. 273-282. In E.C. Robers (ed.) Proc. Of the 1st Int. Turfgrass Res. Conf., Alf Smith and Co., Bradford, UK. archive.lib.msu.edu/tic/turfx/article/2002jan6.pdf.

Bethlahmy, N., andW.J. Kidd Jr. 1966. Controlling soil movement from steep road fills. INT-45. USDA Forest Service, Intermountain Research Station: Ogden, UT.

Blaser, R. E. 1962. Soil mulches for grassing. p. 15-20. In: Roadside development. Pub. 1030. Highway Research Board, NAS-NRC.

Braun, George F. 2003. Material safety data sheet- Reinco Tracer Tackifier. https://www.epicmanufacturing.com/images/pdf/Reinco.../MSDS_Tracer_Tackifier.pdf

Brofas, G., and C. Varelides. 2000. Hydro-seeding and mulching for establishing vegetation on mining spoils in greece. Land Degradation & Development. 11(4):375-382. doi:10.1002/1099-145x(200007/08)11:4<375::aid-ldr400>3.3.co;2-7.

Brown, D., R. Hallman. 2009. Reclaiming disturbed lands. U.S. Department of Agriculture, Forest Service, Equipment Development Center.

Brown, R.N., and J.H. Gorres. 2011. The use of soil amendments to improve survival of roadside grasses". HortScience Vol. 46(10):1404-1410.

Burroughs, E.R. Jr., and J.G. King. 1989. Reduction of soil erosion on forest roads. INT-264. USDA Forest Service, Intermountain Research Station: Ogden, UT. https://www.fs.fed.us/rm/pubs_int/int_gtr264.pdf.

U.S. Climate Data. 2017. Climate Raleigh - North Carolina. www.usclimatedata.com/climate/raleigh/north-carolina/united-states/usnc0558.

Corbineau, F., C. Gay-Mathieu, D. Vinel and D. Côme. 2002. Decrease in sunflower (*Helianthus annuus*) seed viability caused by high temperature as related to energy metabolism, membrane damage and lipid composition. Physiologia Plantarum, 116: 489–496. doi:10.1034/j.1399-3054.2002.1160407.x.

Dahmer, Adam. n.d. Understanding the carbon: nitrogen ratio (C:N). Advance Cover Crops. Accessed 2017. www.advancecovercrops.com/understanding-the-carbon-nitrogen-ratio-cn/.

Dudeck, A.E., N.P. Swanson, L.N. Mielke and A.R. Dedrick. 1970. Mulches for grass establishment on fill slopes. Agronomy Journal 60(6): 810-8:2.

Emanual, David M. 1976. Hydromulch: a potential use for hardwood bark residue. Research Note NE- 226. Upper Darby, PA. U.S. Dept. of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Faucette, L.B., C.F. Jordan, L.M. Risse, M. Cabrera, D.C. Coleman and L.T. West. 2005. Evaluation of storm water from compost and conventional erosion control practices in construction activities. Journal of Soil and Water Conservation 60(6):288-297.

Gholami, L., K. Banasik, S.H. Sadeghi, A.K. Darvishan and L. Hejduk. 2014. Effectiveness of straw mulch on infiltration, splash erosion, runoff and sediment in laboratory conditions. Journal of Water and Land Development, 22(1), 51-60. doi:http://dx.doi.org/10.2478/jwld-2014-0022

Gilbert, W. B., and D.L. Davis. 1967. An investigation of critical problems of establishing a satisfactory sod cover along North Carolina highways. School of Engineering, N.C.S.U. and N.C. Div. of Highways. Final Report ERD-lOO-S, Raleigh, N.C.

Grace, J.M, III. 2000. Forest road sideslopes and soil conservation techniques. Journal of Soil and Water Conservation. 55: 96-101.

Grigg, A.H., G.J. Sheridan, A.B. Pearce and D.R. Mulligan. 2006. The effect of organic mulch amendments on the physical and chemical properties and revegetation success of a saline-sodic minespoil from Central Queensland, Australia. Australian Journal of Soil Research 44(2):97-105.

Hauser, V. 1989. Improving grass seedling establishment. Journal of Soil and Water Conservation. 44(2):153-156. http://www.jswconline.org/content/44/2/153.abstract.

Gregory, J.H., M.D. Dukes, P.H. Jones, G.L. Miller. 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation, 61(3):117-124.

Jordan, C.F. 1998. Working with nature: resource management for sustainability. Hardwood Academic Publishers, Amsterdam, Netherlands.

Kay, Burgess L. 1978. Mulch and chemical stabilizers for land reclamation in dry regions. *In* Reclamation of Drastically Disturbed Lands, (F.W. Schaller and P. Sutton eds.), Am. Soc. Of Agronomy, Crop Sci. Soc. Of Am., and Soil Sci. Soc. Of Am., Madison, WI, p. 467 – 483.

Keammerer, W.R., L.F. Brown and Colorado Water Resources Research Institute. 1988. High altitude revegetation workshop. Vol. 8. dspace.library.colostate.edu/bitstream/handle/10217/3138/is_59.pdf?sequence=1#page=250.

Krichen, K., H.B. Mariem and M. Chaieb. 2014. Ecophysiological requirements on seed germination of a Mediterranean perennial grass (*Stipa tenacissima* L.) under controlled temperatures and water stress. South African Journal of Botany. 94: 210-217.

Lee, G., R. A. McLaughlin, K. D. Whitely, and V. K. Brown. 2018. Evaluation of seven mulch treatments for erosion control and vegetation establishment on steep slopes. J. Soil Water Conservation (in press).

Lemly, A. Dennis. 1982. Erosion control at construction sites on red clay soils. Environmental management 6(4):343-52. https://link.springer.com/article/10.1007/BF01875066.

Logsdon, S.D. 2013. Root effects on soil properties and processes: synthesis and future research needs. In: Timlin T, Ahuja LR (eds) Enhancing understanding and quantification of soil–root growth interactions. Adv Agric Syst Model 4. ASA, CSSA, SSSA, Madison, WI. P. 173-196. doi:10.2134/advagricsystmodel4.c8

Marques, M.J., R. Bienes, L. Jiménez and R. Pérez-Rodríguez. 2007. Effect of vegetal cover on runoff and soil erosion under light intensity events. Rainfall Simulation Over USLE Plots. The Science of the total environment 378 (1-2):161-165.

McCarty, L.B. 2001. Best golf course management practices. Prentice Hall, Upper Saddle River, NJ.

McKee, W.H. Jr., R.E. Blaser and D.G. Barkley. 1964. Mulches for steep cut slopes. Highway Research Board. 53:35-42.

McKee, W.H. Jr., A.J. Powell Jr., R.B. Cooper and R.E. Blaser. 1965. Microclimate conditions found on highway slope facings as related to adaptation of species. Highway Research Board 93:38-43.

Megahan, W.F. 1974. Erosion over time on severely disturbed granitic soils: a model. INT-156. USDA Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT.

Megahan, W.F., S.B. Monsen and M.D. Wilson. 1991. Probability of sediment yields from surface erosion on granitic roadfills in Idaho. Journal of Environmental Quality 20:53-60.

NCDOT (1), Division of Highways, Roadside Environmental Unit. n.d. NCDOT general seed specification for seed quality. Accessed 2017. www.ncdot.gov/doh/operations/dp_chief_eng/roadside/soil_water/pdf/SeedQuality.pdf.

NCDOT (2), Division of Highways, Roadside Environmental Unit. n.d. Seed mix, crimping, guardrail seed to be used by county. Accessed 2017. www.ncdot.gov/doh/operations/dp_chief_eng/roadside/soil_water/pdf/SeedMixTable.pdf.

NCDOT (3), Division of Highways, Roadside Environmental Unit. n.d. Vegetation management section. Accessed 2017. www.ncdot.gov/doh/operations/dp_chief_eng/roadside/vegetation/materials/turf.html.

NCDOT (4), Division of Highways. n.d. Soil stabilization timeframes. Accessed 2017. https://www.ncdot.gov/doh/.../dp.../StabilizationGuidelinesMaintenance_detail.pdf.

NCDOT (5), Division of Highways, Roadside Environmental Unit. 1998. Soil stabilization level 2: skill block training guide REU 155. https://www.ncdot.gov/doh/operations/dp_chief_eng/roadside/vegetation/training/manuals/Skillblock2R8REU155.doc+&cd=1&hl=en&ct=clnk&gl=us.

NCDOT (6), Division of Highways, Roadside Environmental Unit. 1998. Soil stabilization level 3: skill block training guide REU 156. 21 Aug. https://www.ncdot.gov/doh/.../dp.../training/manuals/SkillBlock3R10REU156.doc.

NCDOT (7), Division of Highways, Roadside Environmental Unit. 2016. Stabilization requirements. https://connect.ncdot.gov/letting/.../Z-06-19.../DG00207PropErosionControl.pdf.

North Carolina Department of Environment and Natural Resources, Division of Water Quality. 2011. Construction General Permit NCG 01, Section II.B.2. http://portal.ncdenr.org/c/document_library/get_file?uuid=d15e7ee8-cb50-443f-9dcf-049b001337ac&groupId=38364.

Osborn, B. 1955. Effectiveness of cover in reducing soil splash by raindrop impact. Journal of Soil and Water Conservation. 10(1):70-76.

Pan, C., Z. Shangguan and T. Lei. 2006. Influences of grass and moss on runoff and sediment yield on sloped loess surfaces under simulated rainfall. Hydrol. Process., 20: 3815–3824. doi:10.1002/hyp.6158

Pelt, R.S.V. and T.M. Zobeck. 2013. Portable Wind Tunnels for Field Testing of Soils and Natural Surfaces. Wind tunnel designs and their diverse engineering applications. Intech. http://dx.doi.org/10.5772/54141.

Richard, G., I. Cousin, J.F. Sillon, A. Bruand and J. Gue'rif. 2001. Effect of compaction on soil porosity: consequences on hydraulic properties. European Journal of Soil Science 52:49-58.

Ross P.J, J. Williams and R.L. Mccown. 1985. Soil temperature and the energy balance of vegetative mulch in the semi-arid tropics. I. Static analysis of the radiation balance. Australian Journal of Soil Research 23(4):493-514.

Sittig, M., R.P. Pohanish. 2002. Asphalt Fumes. Sittig's Handbook of Toxic and Hazardous Chemicals and Carcinogens (4th Edition). William Andrew Publishing/Noyes.

Smale, M., M.R. Bellon, D. Jarvis and B. Sthaphit. 2004. Economic concepts for designing policies to conserve crop genetic resources on farms. Genetic Resources and Crop Evolution. 51: 121–135.

Soiltac safety data sheet. 2015. Scottsdale, AZ. https://www.soilworks.com/media/23415/soiltac-material-data-safety-sheets-en-.pdf.

Sojka, R.E., D.L. Bjorneberg, J.A. Entry, R.D. Lentz and W.J. Orts. 2007. Polyacrylamide in agriculture and environmental land management. San Diego: Elsevier Academic Press Inc. 92: 75-75.

State Climate Office of North Carolina. 2017 Lake Wheeler Rd Field Lab, NC (LAKE): monthly data retrieval. CRONOS Database. climate.ncsu.edu/cronos/?station=LAKE&temporal=monthly.

Swanson, N. P., A.R. Dedrick, H.E. Weakly and H.R. Haise. 1965. Evaluation of mulches for water erosion control. Trans. Am. Soc. Agric. Eng. 8:438-440.

Swemmer, A.M., A.K. Knapp and M.D. Smith. 2006. Growth responses of two dominant C4 grass species to altered water availability. International Journal of Plant Sciences. 167(5):1001-1010.

Swift, L.W. Jr. 1984. Soil loss from roadbeds and cut and fill slopes in the southern Appalachian Mountains. Southern Journal of Applied Forestry 8(4):209-215.

Swift, L.W. Jr. 1985. Forest road design to minimize erosion in the southern Appalachians. In: B.G Blackman (Ed.) Proceedings Forest and Water Quality: A mid-South symposium. University of Arkansas: Little Rock, AR. 141-151.

Texas Department of Transportation, Construction Division. 2006. Asphalt emulsions. ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/AsphaltEmulsions.pdf.

Tilley, Derek J., and St. John Loren. 2013. Hydroseeding improves field establishment of Nebraska sedge regardless of seed treatment. Home Organization Selection. Project Muse. Web. 10 July 2017. http://npj.uwpress.org/content/14/2/89.abstract.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). 2000. Urban soil compaction. Urban Technical Note No. 2. U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Quality Institute, Auburn, Alabama.

U.S. Environmental Protection Agency (USEPA). 2000. Stormwater Phase II Final Rule: construction site runoff control minimum control measure. Office of Water (4203). EPA 833-F-00-008, Fact Sheet 2.6. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (USEPA). 2009. Construction and development, final effluent guidelines. U.S. Environmental Protection Agency, Washington, D.C. https://www.epa.gov/eg/construction-and-development-effluent-guidelines.

WeatherSpark.com. 2017. Average weather in Raleigh, North Carolina, United States, year round - *Weather Spark*. weatherspark.com/y/20170/Average-Weather-in-Raleigh-North-Carolina-United-State

Appendix: Additional Figures

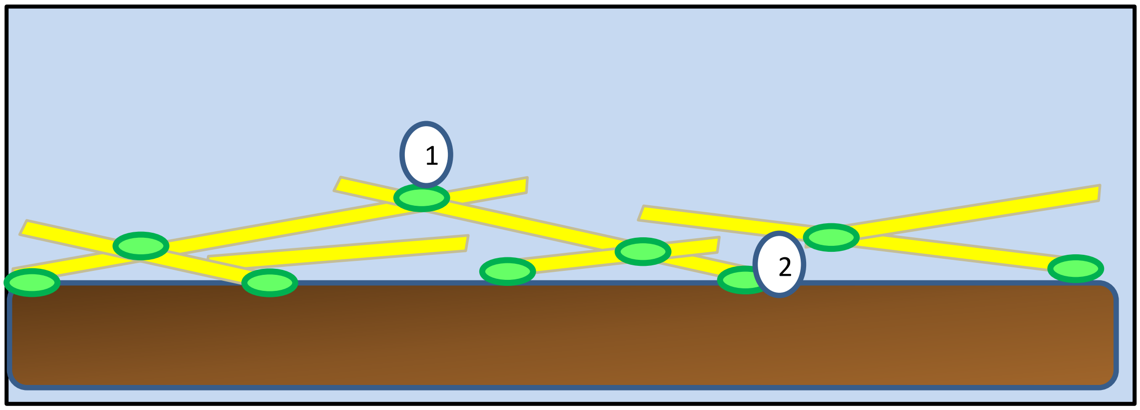


Figure A1: Illustration of tackifiers function with a straw cover. Yellow represents the straw and green the tackifier, which can both bind the straw together (1) and bind the straw to the soil (2).

Figure A2: View of the wind tunnel through the section connecting the fan to the tunnel, with laminar flow baffles.

Figure A3: View of the wind tunnel with the laminar flow baffle section attached.

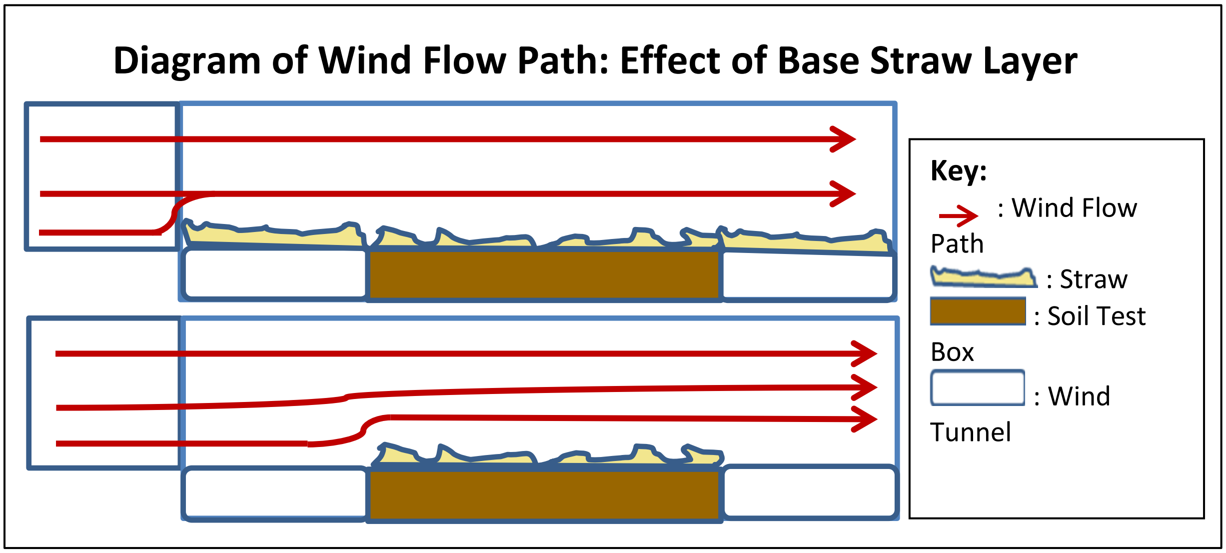
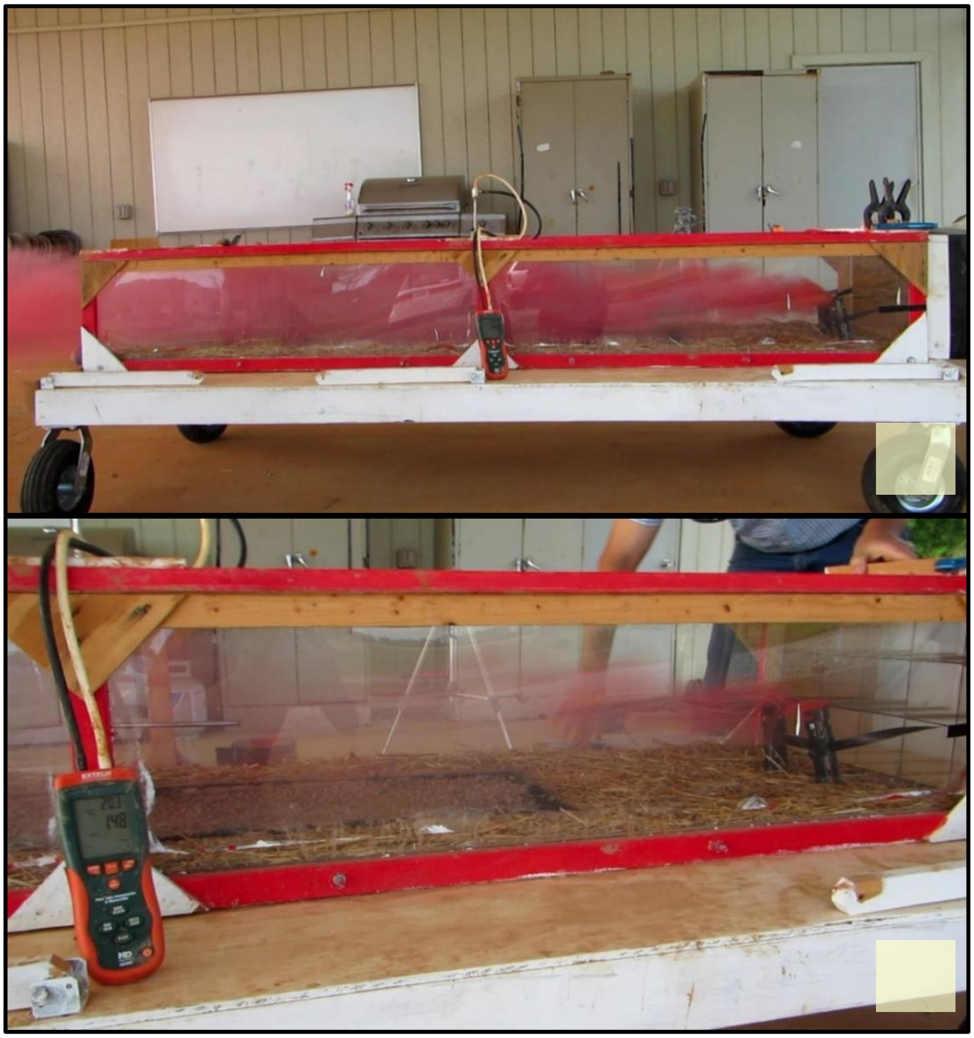


Figure A4: Illustration of potential wind flow paths with and without a base straw layer on the floor of the wind tunnel. The top figure illustrates flow paths with a base layer of straw, while the bottom figure illustrates flow paths with no straw glued to the tunnel floor.



<u>Figure A5:</u> (a) Smoke emitter affixed to the wind tunnel for testing the flow pattern. (b) Red smoke shows wind pattern inside the tunnel.

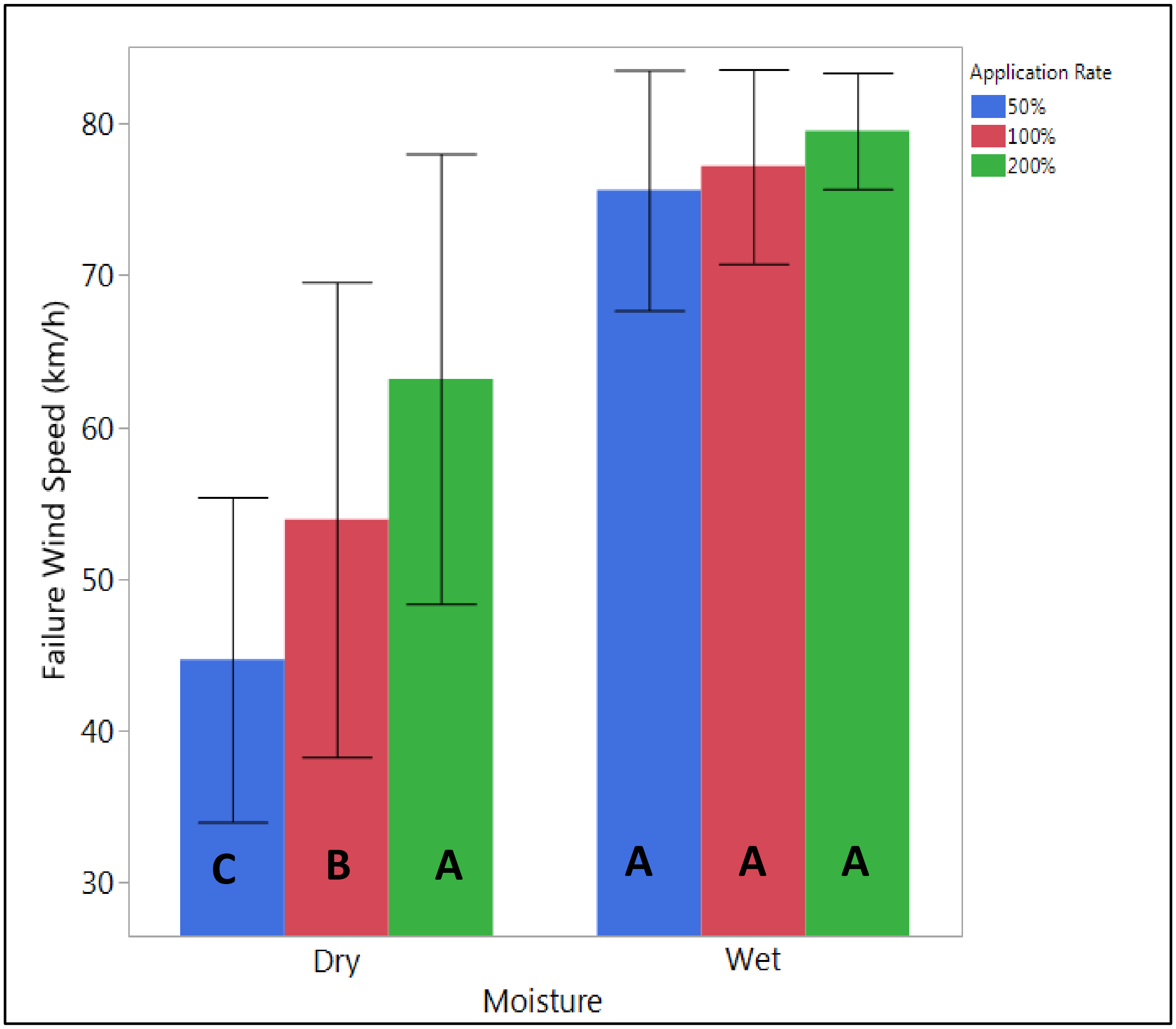


Figure A6: Variation in failure wind speed due to moisture and tackifier application rate (% of manufacturer's recommended rate).

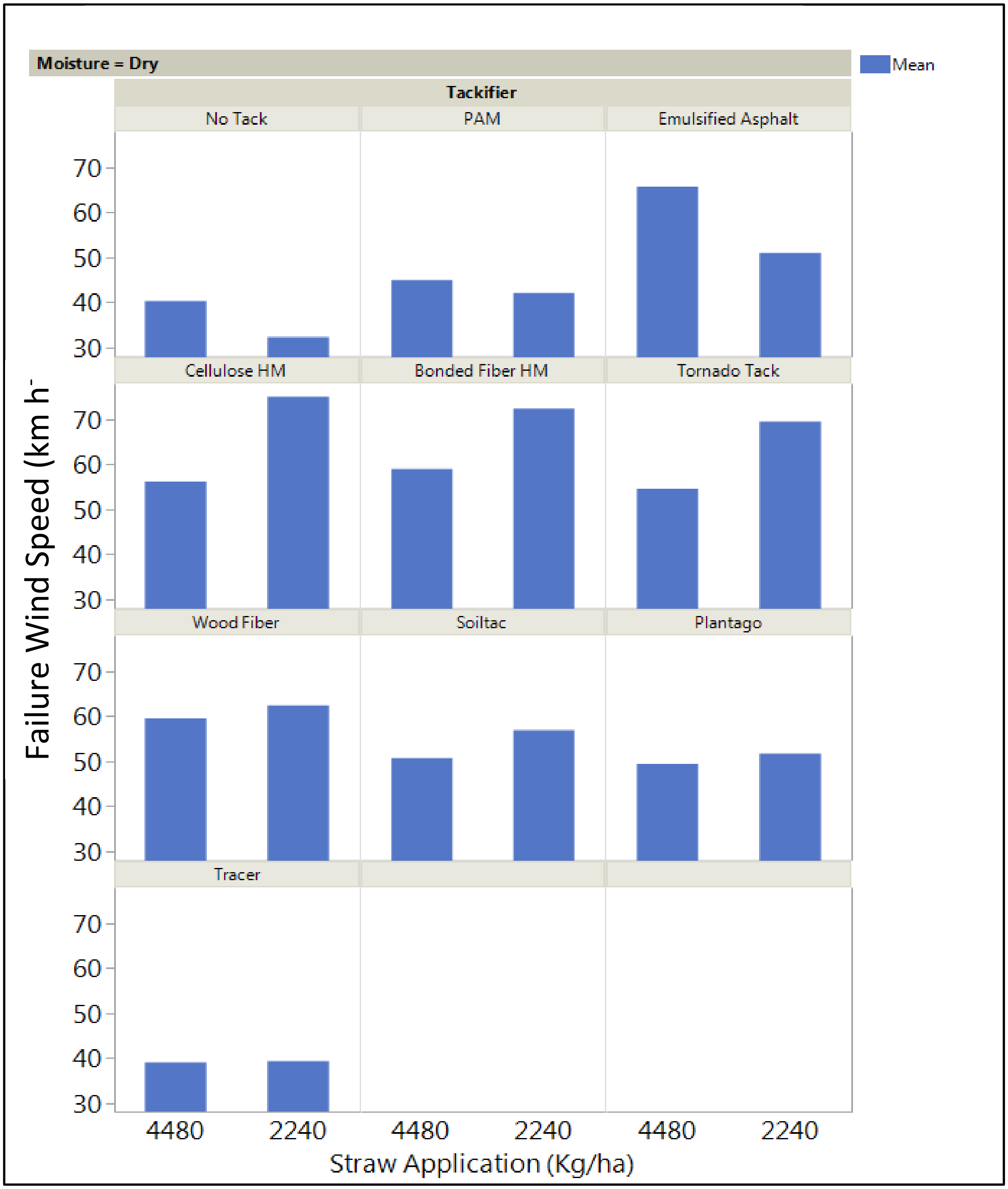


Figure A7: Effect of straw application rate on the ability for tackifiers applied under dry straw conditions, at the manufacturer's recommended rate, to withstand wind.

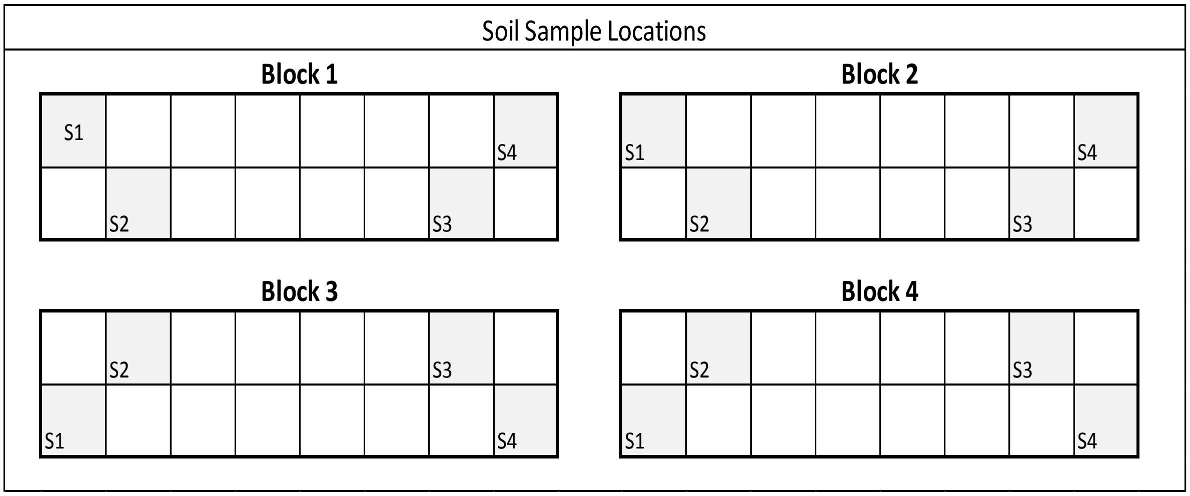


Figure A8: The locations of each of the four soil samples (S1-S4) taken in each block.

Figure A9. Aerial image of the LWFL plots, September 28, 2016.

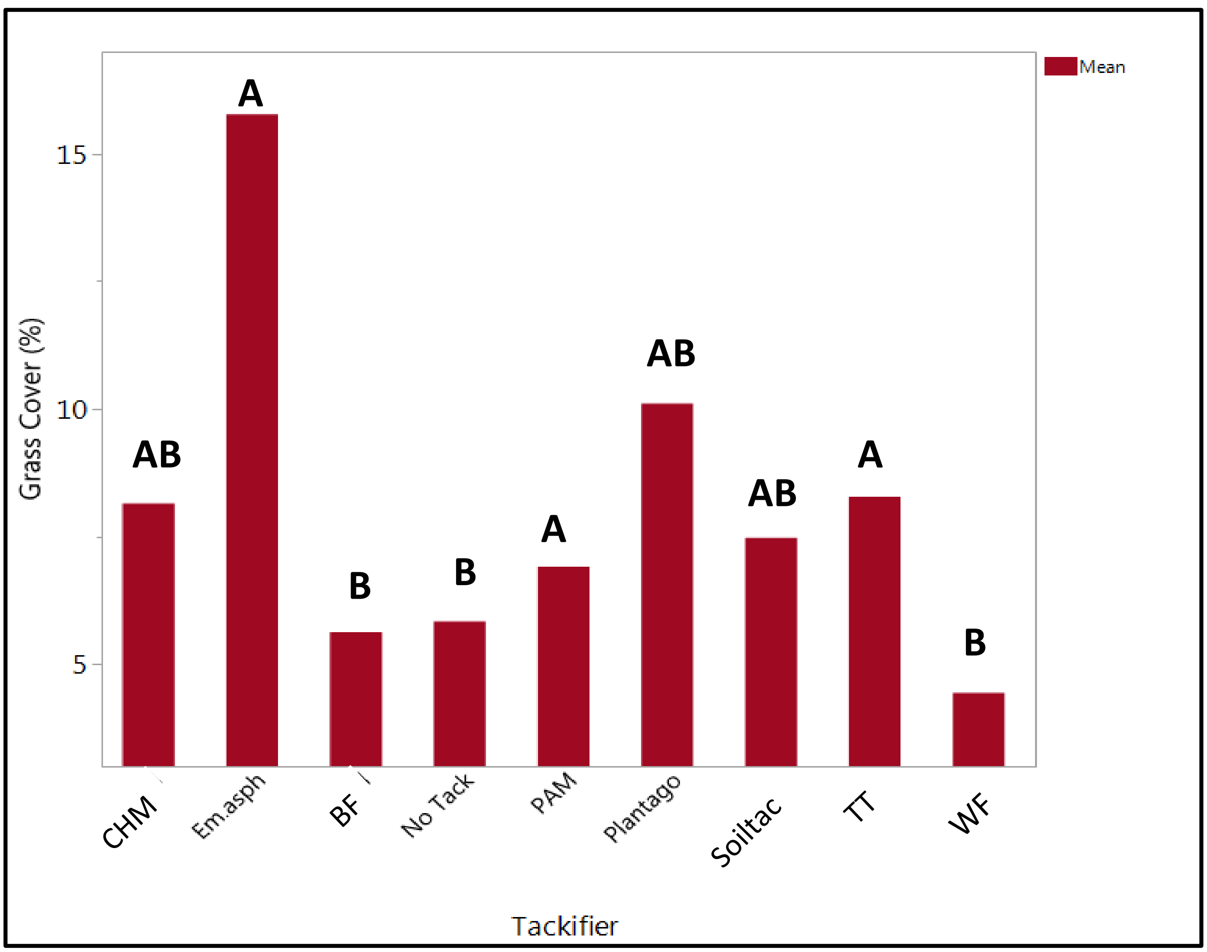


Figure A10: Grass cover results from September 28th, 2016 at the LWFL field

Figure A11: One of the gullies at the Apex site resulting from Hurricane Matthew, with a rain gauge to depict the scale.

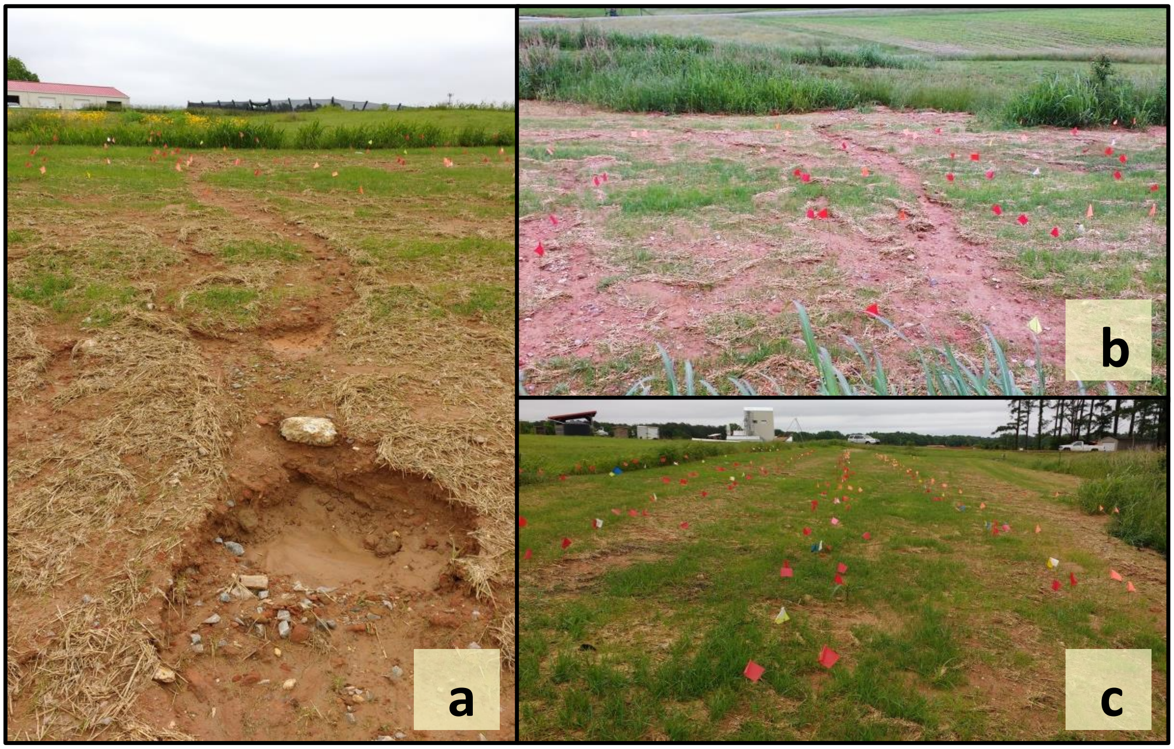


Figure A12: Photographs of the spring field test of tackifiers at the Lake Wheeler Field Laboratory, after a heavy rainstorm approximately one month after planting. The photograph on the left (a) shows the most extreme erosional damage, the top right (b) shows the plots affected by the damage and the bottom right (c) shows the entire grass stand on the same date (May 18^{th}, 2016).

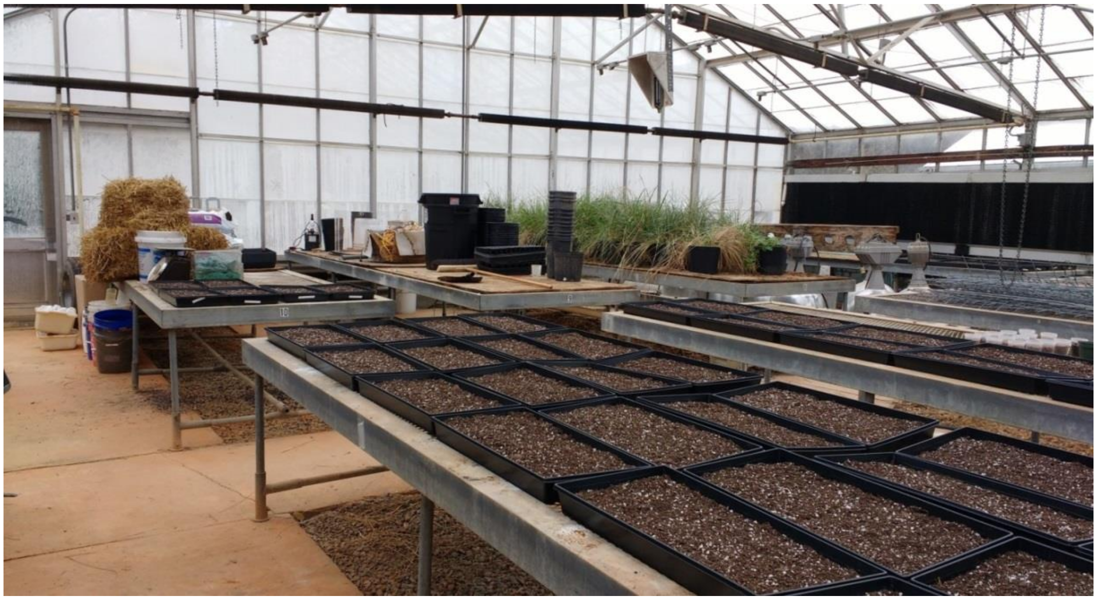


Figure A13: Photograph of the greenhouse trays prior to seed, straw and tackifier application.

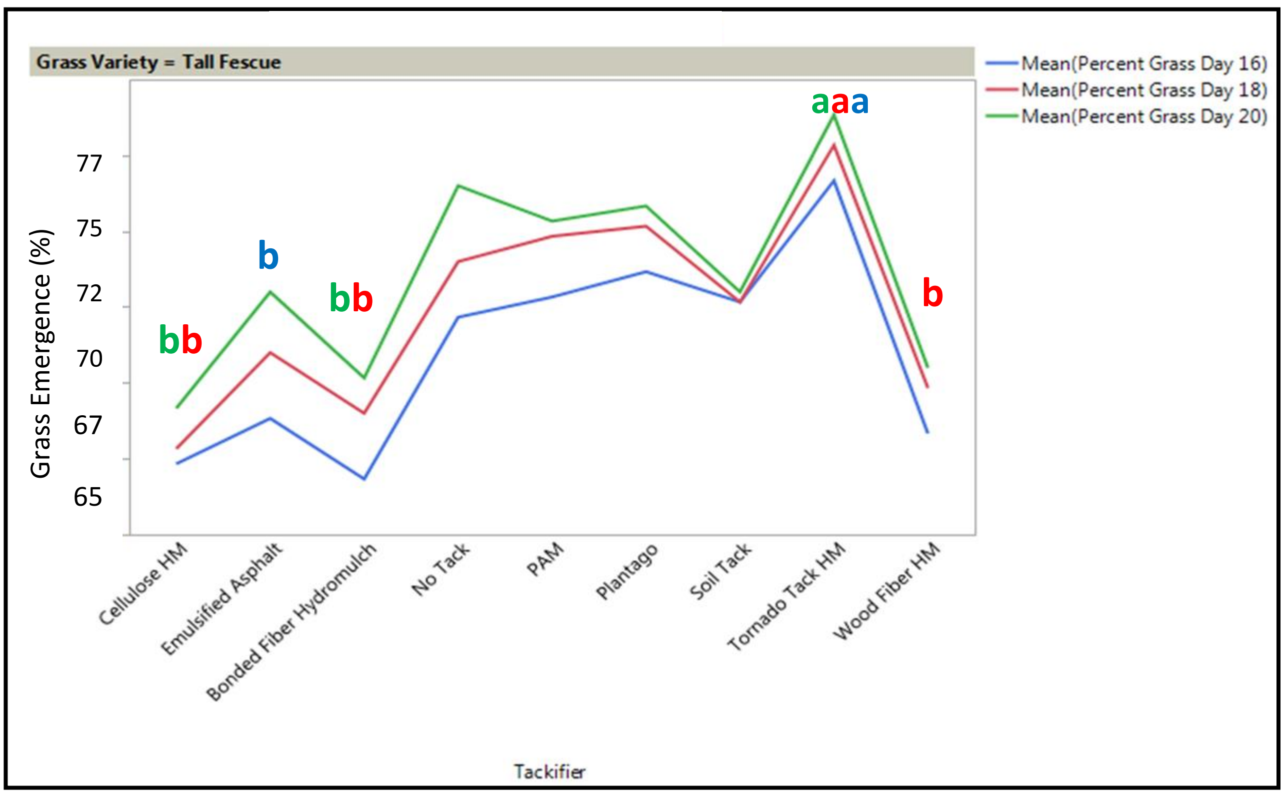


Figure A14: Grass emergence for each treatment for the three measurement periods where differences were evident. The plus symbols represent results that are significantly better, and stars indicate results that are significantly worse. The color of the symbol signifies with which sampling date the result is associated.

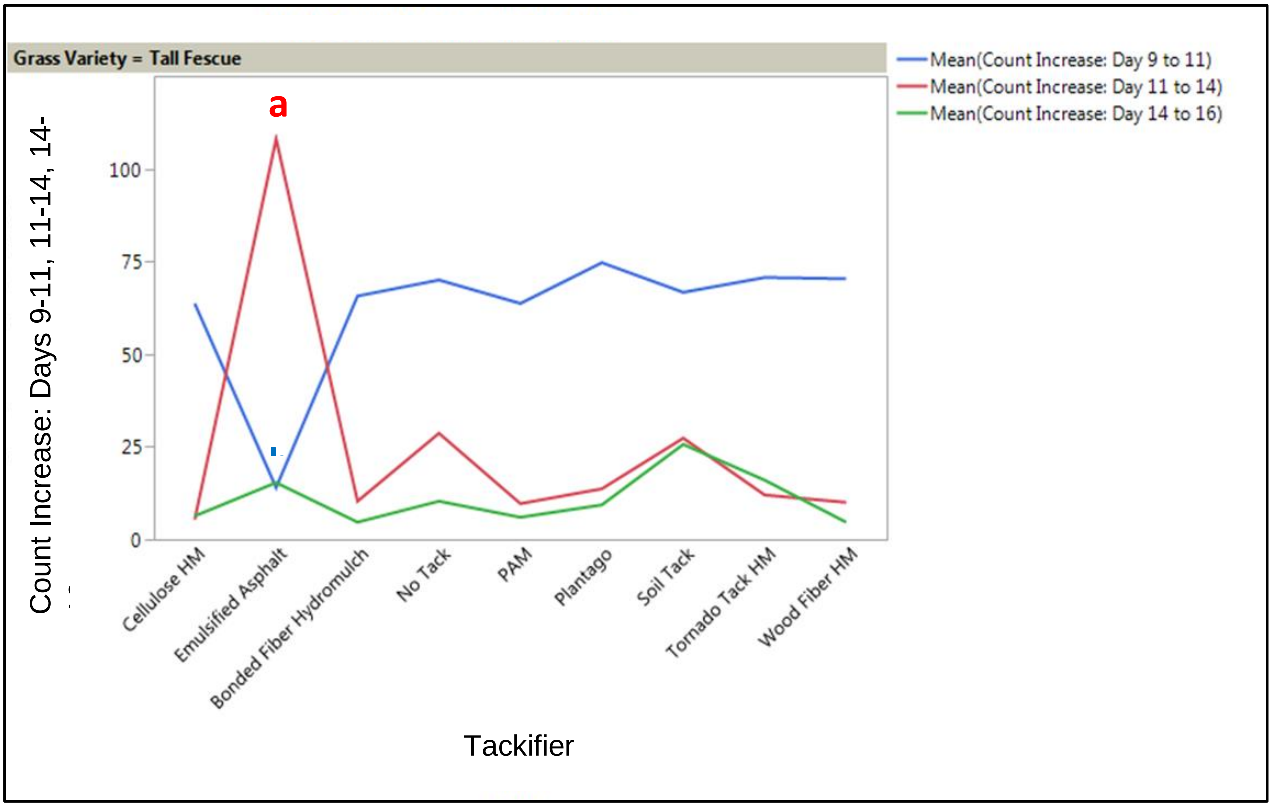


Figure A15: Tall fescue blade count increases on days 9-11, 11-14 and 14-16. Significant differences denoted with letters ($p > 0.05$).

Tables:

Table A1: Legal timeframes for Department of Transportation site stabilization in North Carolina (NCDOT (4), 2016)

Site Description	Stabilization Time (Days)	Timeframe Exceptions
Perimeter dikes, swales, ditches and slopes	7	None
High Quality Water (HQW) Zones	7	None
Slopes Steeper than 3:1	7	If slopes are 10' or less in length and are not steeper than 2:1, 14 days are allowed
Slopes 3:1 or Flatter	14	7 days for slopes greater than 50' in length
All Other Areas with Slopes Flatter than 4:1	14	None, except for perimeters and HQW zones

Table A2: Effects of tackifier treatments on failure wind speed under dry and steady conditions at two application rates of straw. Differences ($p<0.05$) are indicated if values in a column do not have a common letter.

Tackifier	Mean Failure Speed: 2240 kg ha^{-1} Straw	Mean Failure Speed: 4480 kg ha^{-1} Straw
	--- km h^{-1} ---	--- km h^{-1} ---
No Tackifier	32 b	40 a
Polyacrylamide	42 a	47 a
Bonded Fiber HM	72 a	69 a
Cellulose HM	76 a	60 b
Emulsified Asphalt	51 a	72 a
Plantago	51 a	43 a
Wood Fiber HM	63 a	61 a
Tornado Tack	69 a	56 b
Soiltac	56 a	55 a

Table A3: Results from Brookside Laboratories' soil testing by block at the Lake Wheeler Field Laboratory site. Significant differences using Tukey's HSD test between blocks were found for carbon and are denoted with letters. There are no significant differences between blocks for pH and organic matter.

Block	**Carbon**	**pH**	**Organic Matter**
	-----%-----		----%----
1	0.38 ab	7.6	1.3
2	0.57 a	7.5	1.3
3	0.33 b	7.6	1.2
4	0.34 b	7.5	1.4
Average:	0.41	7.55	1.3

Table A4: Greenhouse plot layout for treatments and blocks.

Greenhouse Plot Layout										
Row/ Column	1	2	3	4	5	6	7	8	9	10
10	PAM Cent	BF Cent	CHM Tf	WF Berm	WF Tf	TT Berm	CHM Cent			
9	NT Cent	Plan Tf (x2)	WF Cent	TT Cent	ST Berm	Em Berm				
8	NT Tf	Plan Cent (x2)	ST Cent (x2)	PAM Tf	BF Berm	NT Berm	Plan Berm (x2)			
7	BF Tf	CHM Berm	Em Tf	ST Tf	PAM Berm	Em Cent	TT Tf			
6	NT Cent	WF Tf	TT Berm	ST Cent (x2)	BF Tf	NT Tf	ST Tf	Em Cent		
5	BF Berm	PAM Berm	CHM Cent	NT Berm	PAM TF	ST Berm	WF Berm	WF Cent	Plan Berm (x2)	
4	PAM Cent	BF Tf	WF Tf	Em Berm	TT Tf	ST Berm	NT Cent	Em TF	TT Cent	
3	WF Berm	WF Cent	ST Tf	Em Cent	TT Berm	Plan TF (x2)	Plan Tf (x2)	CHM Berm	Em Berm	
2	CHM Cent	Plan Cent (x2)	Em Tf	BF Berm	CHM Berm	PAM TF	Plan Berm (x2)	TT Tf	Plan Cent (x2)	
1	ST Cent	BF Cent	TT Cent	NT Tf	NT Berm	CHM Tf	PAM Berm	BF Cent	PAM Cent	CHM Tf

Key: PAM = polyacrylamide, NT = no tack, BF = bonded fiber FGM, WF = wood fiber HM, CH = cellulose HM, ST = Soiltac, Plan = Plantago, Em = emulsified asphalt, TT = Tornado Tack HM, Cent = centipedegrass , Tf = tall fescue, Berm = Bermudagrass, (x2) = double tackifier application

Green – Block 1

Blue – Block 2

Purple – Block 3

Table A5: Weights of 200 seeds from each grass species to be used in the greenhouse trial.

Trial (200 Seed Count)	Tall Fescue	Bermudagrass (hauled)	Centepede
1st Weight (g)	0.44	0.048	0.208
2nd Weight (g)	0.44	0.050	0.214
3rd Weight (g)	0.44	0.050	0.206
Average Weight (g)	0.44	0.049	0.209

Table A6: Grass emergence for tall fescue for all evaluation times, with averaged values for each treatment day and tackifier. Values within a column which do not have a common letter are significantly different ($p<0.05$).
Key: No Tack = No Tackifier, CHM = Cellulose HM, EMA = Emulsified Asphalt, PAM = Polyacrylamide, TT = Tornado Tack, BF = Bonded Fiber HM and WF = Wood Fiber HM

Tackifier	Day 9	Day 11	Day 14	Day 16	Day 18	Day 20	Day 22
	------------------------ Grass Emergence (%) -------------------------						
No Tack Average	18 ab	53 a	67 a	72 ab	74 ab	77 ab	81 a
CHM Average	30 ab	62 a	64 a	67 b	68 b	69 b	73 a
EMA Average	0.2 b	7 b	61 a	69 b	71 ab	73 ab	76 a
PAM Average	33 a	65 a	70 a	73 ab	75 ab	75 ab	78 a
TT Average	35 a	70 a	69 a	77 a	78 a	79 a	82 a
Soiltac Average	13 ab	46 a	60 a	73 ab	73 ab	73 ab	76 a
Plantago Average	25 ab	62 a	69 a	74 ab	75 ab	76 ab	80 a
BF Average	27 ab	59 a	65 a	67 b	69 b	70 b	75 a
WF Average	26 ab	61 a	66 a	68 b	70 b	71 ab	75 a