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Use of Vegetation Enhanced by Green Soil Stabilization to Protect Kansas Roadsides from Erosion

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16 **Abstract**

The primary objective of this study was to investigate the feasibility of using lignin, an environmentally friendly biopolymer, for sustainable protection of Kansas roadsides against wind and rainfall erosion during the critical stage of construction that occurs prior to the emergence of a vegetative cover. Results from laboratory-scale experiments showed that spraying lignin over the surface of dry silty soil provided very good to excellent protection against erosion. A crust formed on the surface of the soil upon spraying, thus inducing increased bonding among the particles and increased compressive strength, resulting in a decreased amount of wind erosion with increased spraying rate. Although the lignin used in this study is water-soluble, its presence in the soil increased viscosity of the pore fluid, thus decreasing hydraulic conductivity and decreasing the amount of rain erosion. Lignin concentration of 1% at 0.0325 gal/ft^2 was sufficient to suppress wind erosion, while 15% at 0.123 gal/ft^2 was required to decrease the amount of rainfall erosion tenfold and sixfold for sloped and horizontal soil configurations, respectively. Additionally, lignin concentrations up to 4% and spraying rate of 0.0866 gal/ft^2 did not affect monocot and dicot counts or vegetative cover size in field trials. Lower zinc and iron levels were found in soil treated with 1% and 2% lignin, but no difference was observed at 4% lignin compared to the untreated soil.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

The primary objective of this study was to investigate the feasibility of using lignin, an environmentally friendly biopolymer, for sustainable protection of Kansas roadsides against wind and rainfall erosion during the critical stage of construction that occurs prior to the emergence of a vegetative cover. Results from laboratory-scale experiments showed that spraying lignin over the surface of dry, silty soil provided very good to excellent protection against erosion. A crust formed on the surface of the soil upon spraying, thus inducing increased bonding among the particles and increased compressive strength, resulting in a decreased amount of wind erosion with increased spraying rate. Although the lignin used in this study is water-soluble, its presence in the soil increased viscosity of the pore fluid, thus decreasing hydraulic conductivity and decreasing the amount of rain erosion. Lignin concentration of 1% at 0.0325 gal/ft^2 was sufficient to suppress wind erosion, while 15% at 0.123 gal/ft^2 was required to decrease the amount of rainfall erosion tenfold and sixfold for sloped and horizontal soil configurations, respectively. Additionally, lignin concentrations up to 4% and spraying rate of 0.0866 gal/ft^2 did not affect monocot and dicot counts or vegetative cover size in field trials. Lower zinc and iron levels were found in soil treated with 1% and 2% lignin, but no difference was observed at 4% lignin compared to the untreated soil.

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Chapter 1: Introduction

1.1 Overview and Background

Soil erosion refers to the dislodging and transport of soil particles primarily caused by wind and water. In 2017, 126.82 million tons of soil were eroded in Kansas, making it one of eight states with the highest rates of erosion (Schilling, 2022). In addition to cropland, erosion occurs on unpaved roads and roadsides during road construction. The United States contains nearly 1.6 million miles of unpaved roads, with approximately 98,000 miles of unpaved roads in Kansas, of which approximately 78,000 miles are gravel roads (Dissanayake & Liu, 2009). Wind erosion can also cause impaired visibility for air and ground transportation. For example, in 1991, a series of collisions involving 164 vehicles occurred on Interstate 5 in San Joaquin Valley in California during a dust storm that reduced visibility to nearly zero (Pauley et al., 1996).

Uncontrolled erosion accelerates over time, thus requiring erosion control via rapid revegetation, planting of quick-growing grasses, manual placement of harvested straw and erosion control blankets, and the use of compost on embankments (Barkley, 2004). Vegetative stabilization, which is used on Kansas roadsides, prevents wind and rain erosion while improving wildlife habitat and aesthetics.

1.2 Problem Statement

Construction sites are traditionally cleared from vegetation prior to construction, thus exposing unprotected soil to erosion prior to the establishment of new vegetation. Therefore, this study addresses the need for protection against wind and rainfall erosion during the critical construction phase that occurs prior to the germination of new vegetation using a sustainable, environmentally friendly approach that utilizes lignin, a biopolymer that is a by-product of paper mill and bio-fuel industries. Lignin, which is natural phenolic polymer with high molecular weight and complex composition and structure, is the main component of the plant cell wall, enhancing its rigidity, while its hydrophobic properties promote transport through the vascular bundles in a plant (Schuetz et al., 2014). With cellulose and hemicellulose, lignin forms plant skeleton. Lignin isolated from lignocellulosic biomass is the second most abundant natural polymer after cellulose (Ganewatta et al., 2019). Furthermore, lignin can regenerate in natural conditions via photosynthesis, resulting in approximately 50 billion tons per year (Shen et al., 2015). Lignosulfonates, which are produced from lignin from sulfite pulping of wood, are renewable, inherently biodegradable, and non-toxic. These plant-friendly materials offer a sustainable alternative to synthetic polymers, making them ideally suited to protect against wind and rain erosion prior to grass germination.

1.3 Objectives and Scope

The primary objective of this investigation study was to demonstrate the effectiveness of the lignin product for protecting Kansas roadsides against wind and rain erosion during the critical construction phase that occurs prior to vegetation germination. Another research objective included the evaluation of lignin effects on soil nutrients and the percentage of vegetative cover. Consequently, the investigation was comprised of laboratory-scale erosion tests and field trial, as well as hand penetrometer tests in laboratory and field settings to reveal underlying erosion and strength mechanisms.

Chapter 2: Literature Review

Lignin has been applied to soils to enhance their mechanical properties including strength, erosion resistance, dust suppression and other applications. Surdahl et al. (2005) and Woll et al. (2008) found that the lignosulfonate was effective for soil stabilization and as a dust palliative material on unpaved roads. Similarly, Nikoosefat et al. (2023) studied the efficiency of Dubb humic acid (DHA)/lignin and DHA/lignosulfonate-stabilized sandy soil for protection against wind erosion using lignin obtained from the paper industry and lignosulfonate, which is a by-product of wood. Results showed that the soil sample stabilized with a DHA/lignin weight ratio of 1:2 and concentration of 9 weight/volume percentage was optimal because it resulted in the lowest amount of erosion and the least number of fractures on the soil surface. Indraratna et al. (2009) found that silty sand stabilized by lignin offered superior resistance to water erosion compared to portland cement-treated soil. Comparatively, Wang et al. (2005) and Wang et al. (2009) investigated the sand stabilization potential of lignin extracted from straw pulp black liquor waste. Their field experiment showed that a lignin solution concentration of 2% applied at a spraying rate of 0.0614 gal/ft^2 effectively stabilized fugitive sand dunes in an arid climate. Two years after seeding, the araceous plants survived and soil nutrients, including organic matter, available phosphorus, and total nitrogen, increased compared to the control, while changes in phosphorus and potassium content were negligible.

Previous research has also shown that spraying a soil surface with lignin results in a crust formation that increases erosion resistance and increases strength. By conducting mercury intrusion porosimetry Zhang et al. (2016) determined that cumulative pore volume of a soil stabilized with lignin decreased compared to untreated soil. Furthermore, the lignin-based cementing materials generated in a soil matrix after curing coated and bonded the solid particles and filled the pores, resulting in effective cementation that increased erosion resistance and strength.

Stress-strain behavior of soil stabilized with lignin was investigated by conducting uniaxial compression and tension tests, direct shear tests, and conventional triaxial tests. Santoni et al. (2002) and Tingle and Santoni (2003) found that unconfined compressive strength (UCS) of silty sand and clay stabilized with lignin increased, with highest strength values obtained at a lignin content of 5%. Similarly, Ceylan et al. (2010) observed an increase in uniaxial strength of low plasticity clay stabilized with two types of lignin and a decrease in strength for lignin concentrations larger than 12%. Perić et al. (2016) conducted direct shear tests on sand stabilized with lignosulfonate, and although the experiments were performed before the sand samples were completely dried, cohesion of stabilized sand increased up to a gravimetric lignin content of 6% and decreased thereafter. Internal lubrication provided by the gel-like structure of lignosulfonate potentially decreased the friction of the stabilized sand. The observed shear stress versus horizontal displacement responses of the stabilized sand were ductile. Conversely, Chen et al. (2014) and Zhang et al. (2016) found that the brittleness of a post-peak axial stress versus axial strain response increased with increasing lignin content for samples tested after 7 and 28 days of curing, respectively. Based on undrained conventional triaxial compression tests, Bagheri et al. (2023) found that adding lignin to soil caused a significant increase in cohesion and a slight reduction of a friction angle.

Chapter 3: Methodology

In a previous study, Xiao et al. (2010) identified uncontrollable test conditions (e.g., rainfall, wind intensity, and duration), wind interference, collection difficulty of eroded soils, and high costs as challenges associated with field erosion experiments. Therefore, this research conducted laboratory-scale experiments under controlled conditions to assess the effects of lignin on the susceptibility of treated soil to wind and rainfall erosion. Lignin effects on the vegetative cover and soil nutrients were evaluated through a field trial, and soil classification tests, including grain size distribution and Atterberg limits, were conducted prior to all other tests. Soil strength was evaluated via hand penetrometer tests in the laboratory and the field. Reference experiments were conducted on untreated soil, and other experiments were performed on different soil lignin mixes. All soil classification tests, wind erosion tests, and hand penetrometer laboratory tests were performed on the campus of Kansas State University (K-State) in Manhattan, Kansas, while rainfall erosion and field trial were conducted on the campus in Olathe, Kansas.

The initial experimental program to evaluate lignin effects on soil erosion was modified slightly during actual experimentation. Because the planned spraying rates offered outstanding protection against wind erosion and the planned lignin solution concentrations did not sufficiently protect against rainfall erosion, the spraying rates were decreased for wind erosion tests and lignin solution concentrations were increased for rainfall erosion tests. Summaries of the final experimental programs for the laboratory penetrometer tests, wind erosion tests, rainfall erosion tests, and field trial are provided in Tables 3.1, 3.2, 3.3, and 3.4, respectively. Further details of the tests and results are provided in Chapter 4.

Table 3.1: Experimental Program for Laboratory Hand Penetrometer Tests

Lignin Solution Concentration (%)	**Spraying Rate (gal/ft^2)**			
	0.0162	**0.0325**	**0.0492**	**0.0866**
0	1	1	1	1
1	1	1	1	1
2	1	1	1	1
4	0	1	0	1
Sum	3	4	3	4

Table 3.1 summarizes results for the laboratory hand penetrometer tests. Each test was repeated two times, totaling 42 tests, and measurements, which were taken prior to spraying the soil with the lignin solution, were reported under zero concentration for different spraying rates.

Table 3.2: Experimental Program for Wind Erosion Tests

Lignin Solution Concentration (%)	Spraying Rate (gal/ft^2)				
	0	**0.0162**	**0.0246**	**0.0325**	**0.0866**
0	H & S*	N/A	N/A	N/A	N/A
1	N/A	H & S	H & S	H & S	H & S
2	N/A	H & S	H & S	H & S	none
Sum	2	4	4	4	2

Each configuration in Table 3.2 was tested at three wind speeds for a total of 48 tests, with each test repeated once, resulting in 96 wind erosion tests. H denotes tests on horizontally positioned soil, while S denotes tests on sloped soil. The inclination angle with horizontal direction was 18.4°, which is representative of roadside embankments in Kansas. All configurations in Table 3.3 were tested at the same intensity of the rainfall. Each test was repeated once for a total of 28 tests.

Table 3.3: Experimental Program for Rainfall Erosion Tests

Lignin Solution Concentration (%)	Spraying Rate (gal/ft^2)		
	0	**0.0861**	**0.123**
0	H & S	N/A	N/A
4	N/A	H & S	H & S
10	N/A	H & S	H & S
15	N/A	H & S	H & S
Sum	2	6	6

Table 3.4: Experimental Program for Field Trial

Lignin Solution Concentration (%)	**Spraying Rate (gal/ft^2)**		
	0	**0.033**	**0.086**
0	1	N/A	N/A
1	N/A	1	1
2	N/A	1	1
4	N/A	1	1
Sum	1	3	3

Plots measuring 5 ft by 5 ft were laid out in a randomized complete block design with four replicates for the field trial to evaluate the effects of lignin on soil nutrients and vegetative cover. Table 3.4 highlights seven treatments with four replicates, for a total of 28 tests. Additionally, three hand penetrometer tests were performed at each plot, and the average of each test was reported for each plot. Further details of the field trial are provided in Section 4.5.

Chapter 4: Results

4.1 Grain Size Distribution and Atterberg Limits

Sieve analysis and hydrometer tests were performed in accordance with ASTM D422-63 (2007) on soil obtained from the K-State Olathe Horticulture Research & Extension Center in Olathe, Kansas. Based on the United States Department of Agriculture (USDA) soil classification system, clay particles (D < 0.002 mm) constituted 6% of the soil, silt particles (0.05 mm > D > 0.002 mm) constituted 44% of the soil, and sand particles (< 0.05 mm < D < 2 mm) constituted the remaining 48% of the soil, creating a sandy loam soil. Figure 4.1 depicts the corresponding grain size distribution for this soil. In addition, 60% of the soil particles were smaller than 0.075 mm, requiring the determination of Atterberg limits according to the Unified Soil Classification System (USCS). Atterberg limits were determined in accordance with ASTM D4318-00 (2000), resulting in liquid limit (LL) of 32 and plastic limit (PL) of 24, with a final soil classification as a silt of low plasticity (ML).

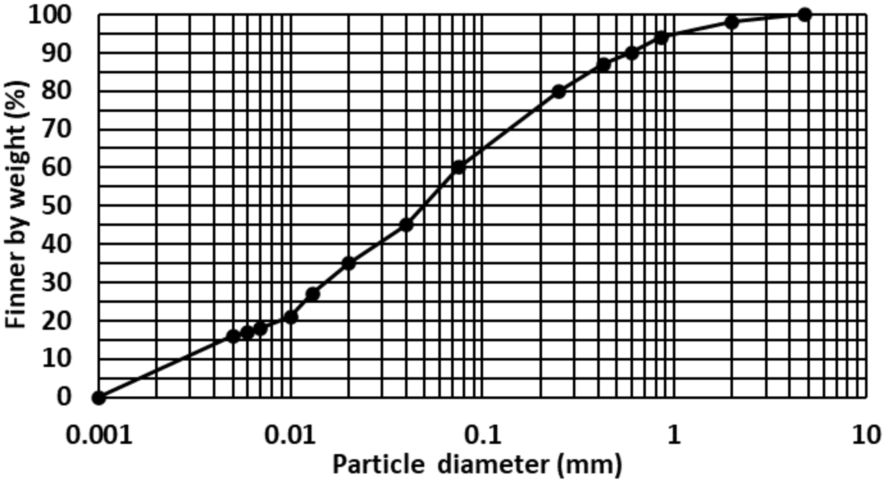


Figure 4.1: Particle Size Distribution of the Selected Soil

This study also determined Atterberg limits for soil and lignin mixes using Borregaard LignoTech Norlig G (Borregaard, 2008), or lignin. Norlig G is a neutral pH, purified calcium/sodium lignosulfonate solution in water that contains 58% of solids. It has a high molecular weight, making it highly viscous and resistant to flow. For this research, the concentration was further decreased by adding water. Lignosulfonates are water-soluble, sulfonated derivatives of lignin produced during the sulfite pulping process of wood. Lignin extracted from wood chips is subsequently sulfonated using hydrogen sulfite, introducing sulfonic and acid groups onto the lignin structure and resulting in a water-soluble polymer (Borregaard, n.d.).

To evaluate the effects of lignin on Atterberg limits, the selected soil was treated with lignin so that the resulting gravimetric lignin content (χ_l) was 2%, 4%, and 6%, whereby χ_l is defined as:

$$\chi_l = \frac{M_l}{M_s}$$

Equation 4.1

Where:

M_l = mass olignin solids,

Ms = mass of soil solids, and

X_l = gravimetric lignin content

Figures 4.2 and 4.3 show the effects of lignin on LL, PL, and plasticity index (PI) of the treated soil. As shown, the LL and PL decreased with increasing lignin content, but PL had a higher rate of decrease, resulting in the overall increase of plasticity index (Figure 4.3), leading to a change in soil type.

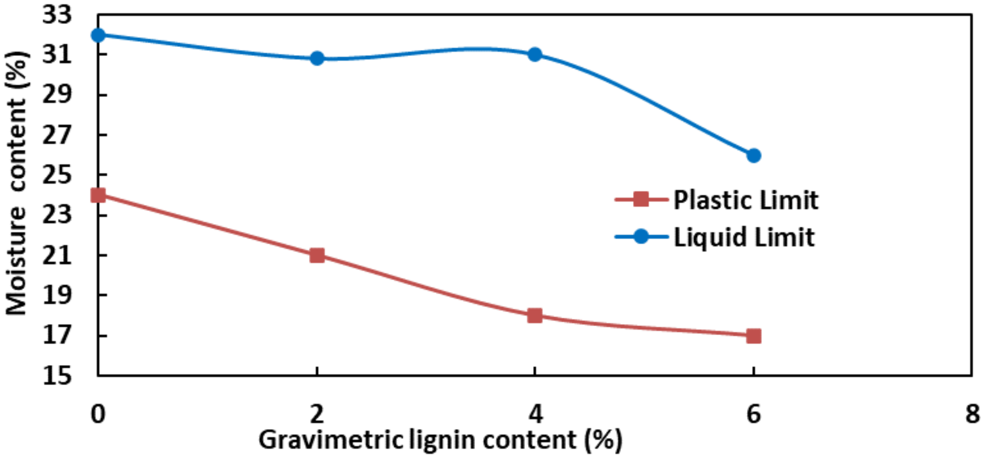


Figure 4.2: Effect of Lignin on Atterberg Limits of Treated Soil

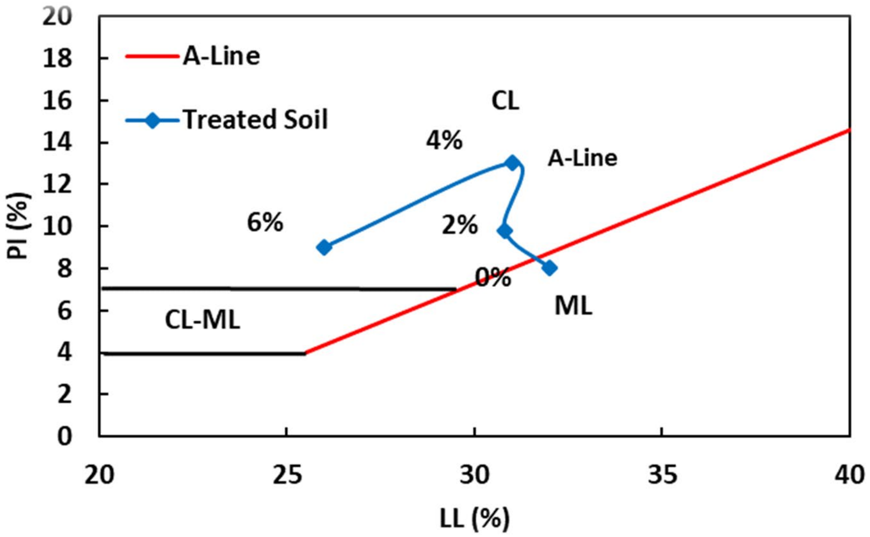


Figure 4.3: Effects of Lignin on USCS of Treated Soil

Soils containing 2%, 4%, and 6% lignin are classified as clays of low plasticity (CL), as shown in Figure 4.3. Moisture content (*w*) is defined as:

$$\boldsymbol{w = \frac{M_w}{M_S + M_l}}$$

Equation 4.2

Where:

M_w = mass of water,

M_s = mass of soil solids,

M_l = mass of lignin solids, and

w = gravimetric moisture content

4.2 Laboratory Hand Penetrometer Tests

This study sprayed lignin solutions directly onto the surface of soil prior to all erosion tests and immediately after seeding during the field trial. To simulate extreme field conditions, the soil for laboratory tests was oven dried, grinded, and placed loosely in 2-in. deep trays. A Gilson Soil Pocket Penetrometer HM-500, or hand penetrometer, was used to measure the UCS of the soil. Measurements were taken during the 24-hour period after spraying in the laboratory and on the same day the soil was sprayed during the field trial, by pushing a penetration piston measuring 0.25 in. in diameter into the soil to a groove machined on the piston at 0.25 inches. Penetration resistance from the calibrated spring was registered on an integrated scale engraved on the penetrometer barrel. Scale units were shown, and a sliding indicator ring retained the reading until reset. An optional adapter foot attachment, available for testing very soft soils, had an increased piston diameter of 1.0 in., which increased the contact surface area by 16. Three measurements were averaged to obtain the final reading and minimize reading errors. Using the experimental configurations presented in Table 3.1, Figures 4.4–4.6 depict changes in measured UCS over time for lignin solution concentrations of 1%, 2%, and 4%, respectively.

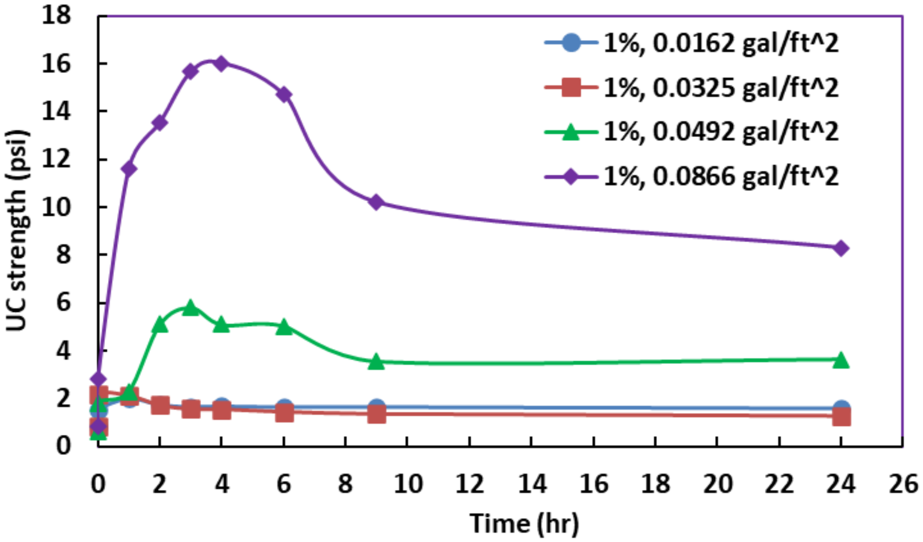


Figure 4.4: Effect of Lignin Spraying Rate on UCS of Treated Soil for χ_l = 1%

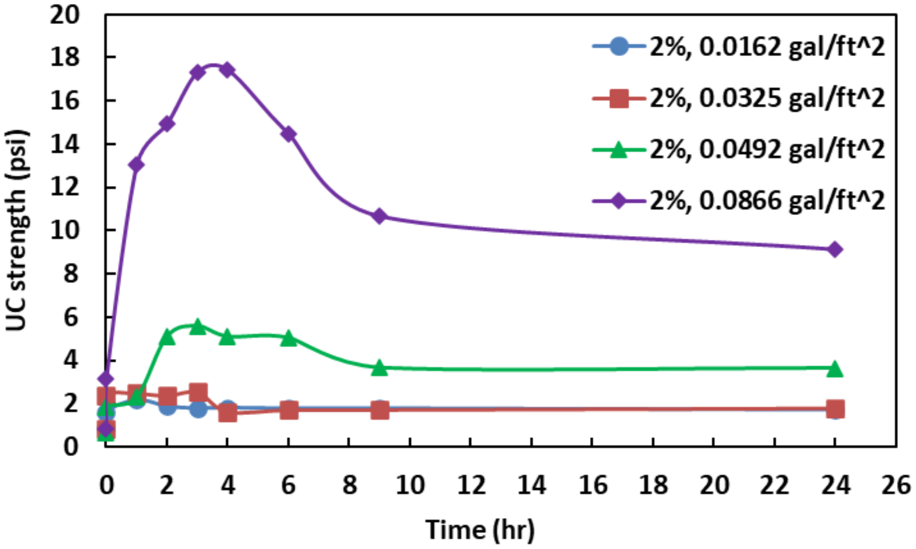


Figure 4.5: Effect of Lignin Spraying Rate on UCS of Treated Soil for χ_l = 2%

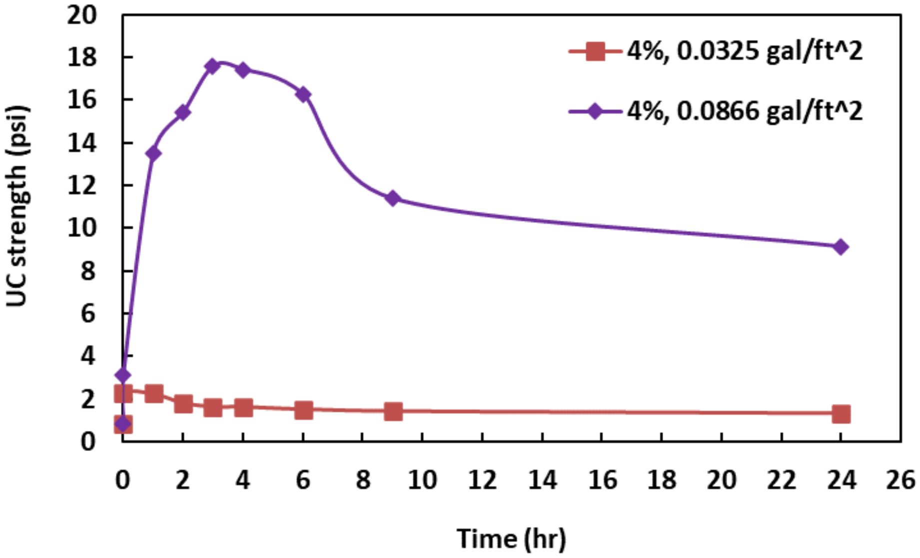


Figure 4.6: Effect of Lignin Spraying Rate on UCS of Treated Soil for χ_l = 4%

The low values of UCS at time zero in the figures represent untreated soil. These measurements were taken for each lignin concentration and each spraying rate immediately prior to spraying, resulting in 10 measurements, eight of which were 0.854 psi and two of which were 0.630 psi, averaging 0.810 psi. Figures 4.4–4.6 also demonstrate a spike in UCS after the application of lignin solution; the higher the spraying rate, the more time required to reach the spike. As shown, the strength decreased with increased elapsed time until it plateaued. According to the figures, spraying rate was the main factor controlling the UCS, while the lignin solution concentration had less effect on the strength.

Figure 4.7 illustrates the dependence of UCS on the spraying rate for peak strength, early post-peak strength, and 24-hour strength, whereby peak and post-peak refer to a change in strength over time. All three strengths exhibited exponential increase with increasing spraying rate, with the peak strength showing the largest rate of increase and the 24-hour strength showing the smallest rate of increase. Chapter 5 details the underlying strength mechanism.

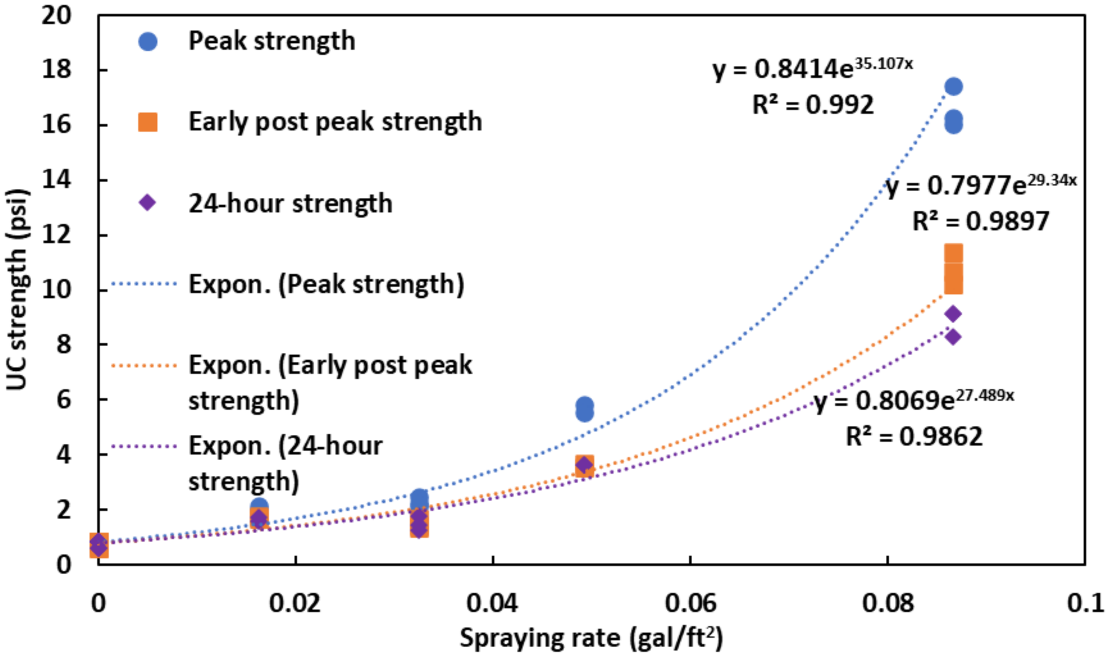


Figure 4.7: Laboratory UCS of Sprayed Near-Surface Soil versus Spraying Rate

4.3 Wind Erosion Tests

Using the experimental configurations of wind erosion tests in Table 3.2, for each test, the soil was oven dried, grinded, and deposited loosely, flush with the edge of the steel container using a funnel bottom near the soil surface. This method of preparation represented the extreme conditions associated with erosion susceptibility. All wind erosion test configurations reached post-peak strength 4 hours after the soil was sprayed with a lignin solution.

During the wind erosion tests, a container measuring 48 in. long, 8 in. wide, and 1 in. deep was placed within a wind tunnel constructed from a PVC frame and transparent polyvinyl fabric measuring 30 in. wide and 35 in. high (Figure 4.8). Wind was generated by placing a blower in front of the wind tunnel. The duration of all tests was 15 minutes. The container was placed horizontally on the floor and inclined at 18.4° for the sloped configurations. Three anemometers were placed near the container at the soil surface, and wind speed was obtained by averaging their measurements. Test results showing the percentage of eroded material mass versus average wind speed are depicted in Figures 4.9 and 4.10 for horizontal and sloped test configurations, respectively. For the horizontally placed soil, the amount of eroded soil increased exponentially with increased wind speed, while the amount of eroded soil displayed logarithmic growth with increased wind speed for the sloped configurations.

Figure 4.8: Photo of a Wind Erosion Test for a Sloped Configuration

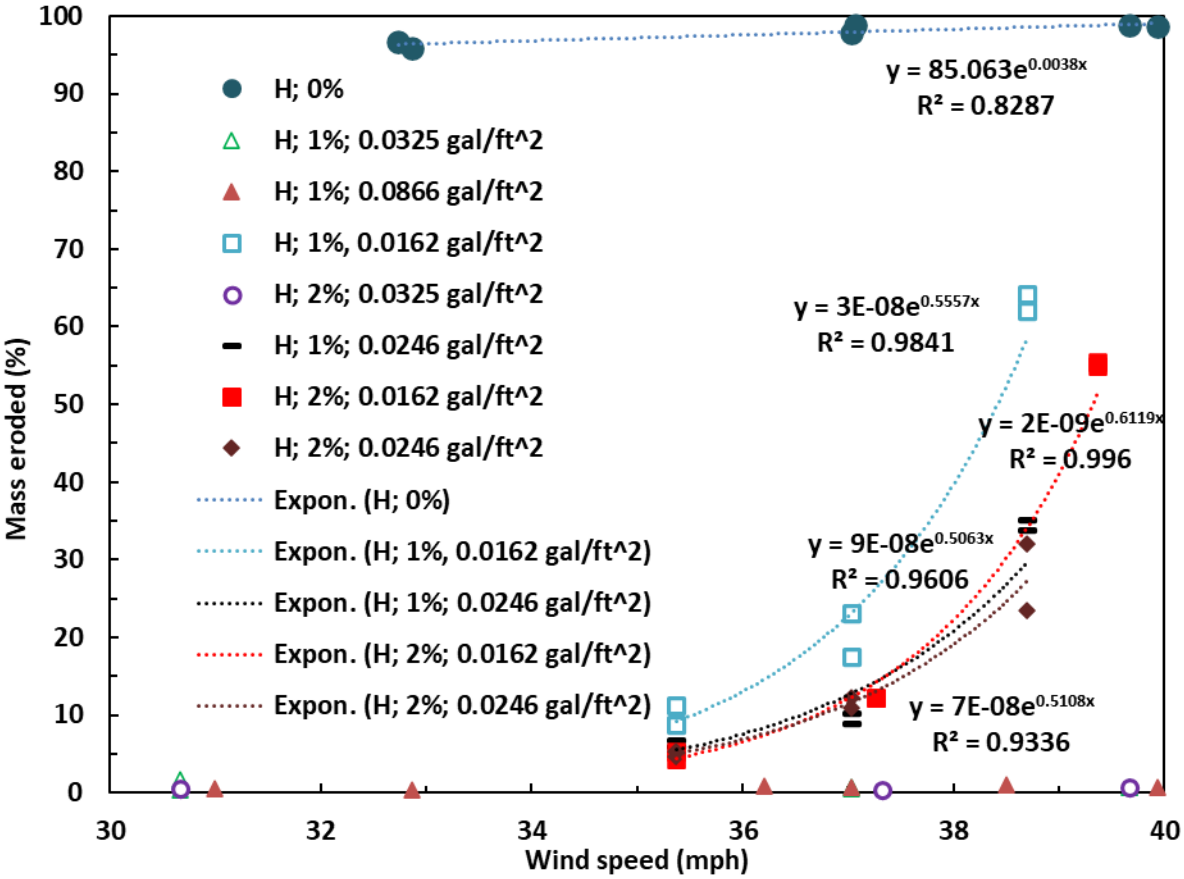


Figure 4.9: Percentage of Eroded Soil Mass versus Wind Speed for Horizontal Soil Configuration

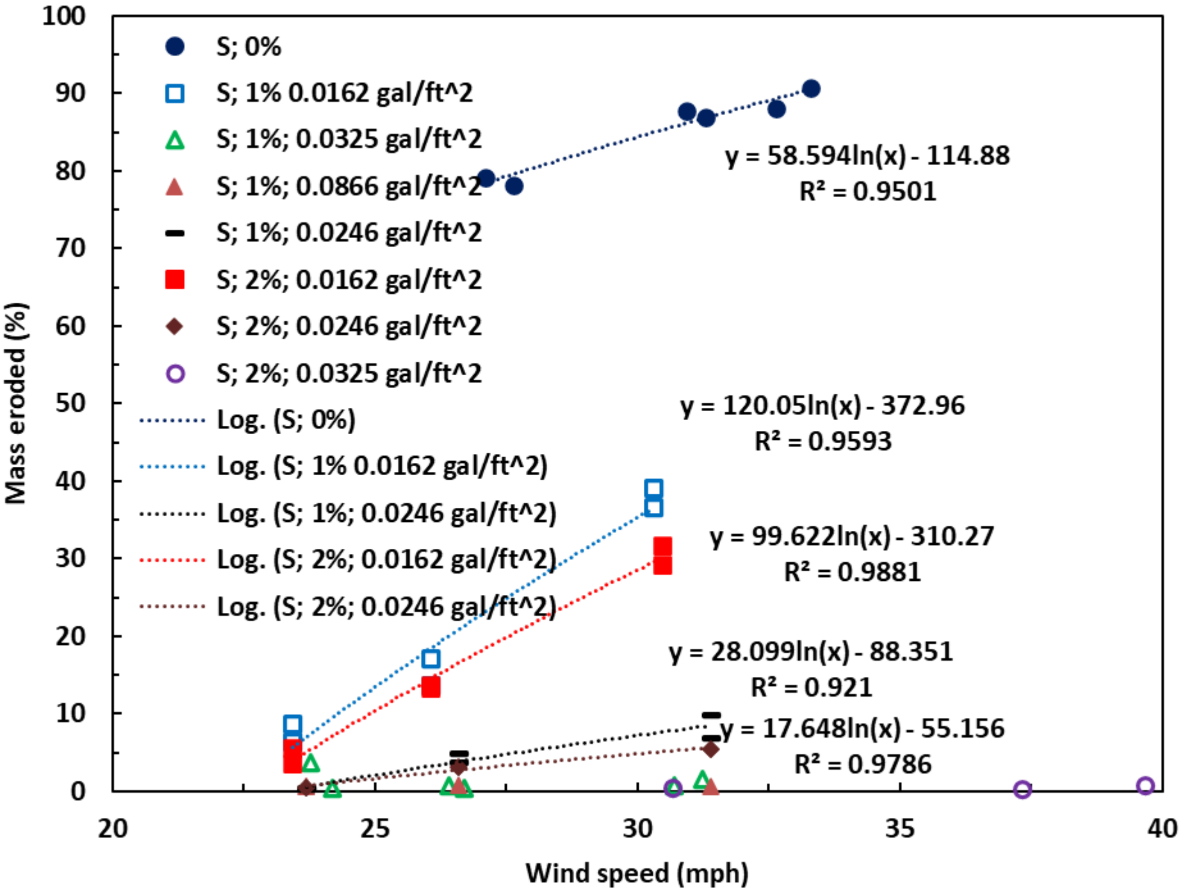


Figure 4.10: Percentage of Eroded Soil Mass versus Wind Speed for Sloped Soil Configuration

Equal patterns were observed for horizontal and inclined configurations whereby erosion was completely prevented with a spraying rate of 0.0325 gal/ft^2 using 2% and 1% lignin solutions and 0.0866 gal/ft^2 for 1% lignin solution. The threshold for initiating erosion was a spraying rate of 0.0246 gal/ft^2 at 2% solution concentration, closely followed by a spraying rate of 0.0246 gal/ft^2 at 1% solution concentration and then a spraying rate of 0.0162 gal/ft^2 at 2% and 1%, culminating with extremely high erosion rates of the unprotected soil. All tested configurations were ranked according to erosion susceptibility, with susceptibility rankings increasing with decreasing susceptibility to wind erosion (Table 4.1).

Table 4.1: Summary of Susceptibility to Wind Erosion

Spraying Rate (gal/ft^2)	Lignin Solution Concentration (%)	Susceptibility Ranking
0	0	1
0.0162	1	2
0.0162	2	3
0.0246	1	4
0.0246	2	5
0.00325	1	6
0.0325	2	6
0.0866	0	6

Although the amount of erosion expectedly increased with increasing wind speed, erosion was primarily governed by the spraying rate with minimal effect of lignin solution concentration. Figure 4.11, which depicts the mass of eroded soil versus spraying rate, shows that the best fit with the experimental data was obtained by quadratic functions that were valid strictly over spraying rates ranging from zero to 0.0325 gal/ft^2. Data for the spraying rate of 0.0866 gal/ft^2 were omitted because erosion practically stopped at the lower spraying rate of 0.0325 gal/ft^2. Figure 4.11 also shows that, as expected, the amount of erosion was larger in sloped configurations. Except for spraying rates less than approximately 0.005 gal/ft^2, eroded mass was greater at a wind speed of 31 mph for the sloped configuration than at 37.1 mph for the horizontal configuration.

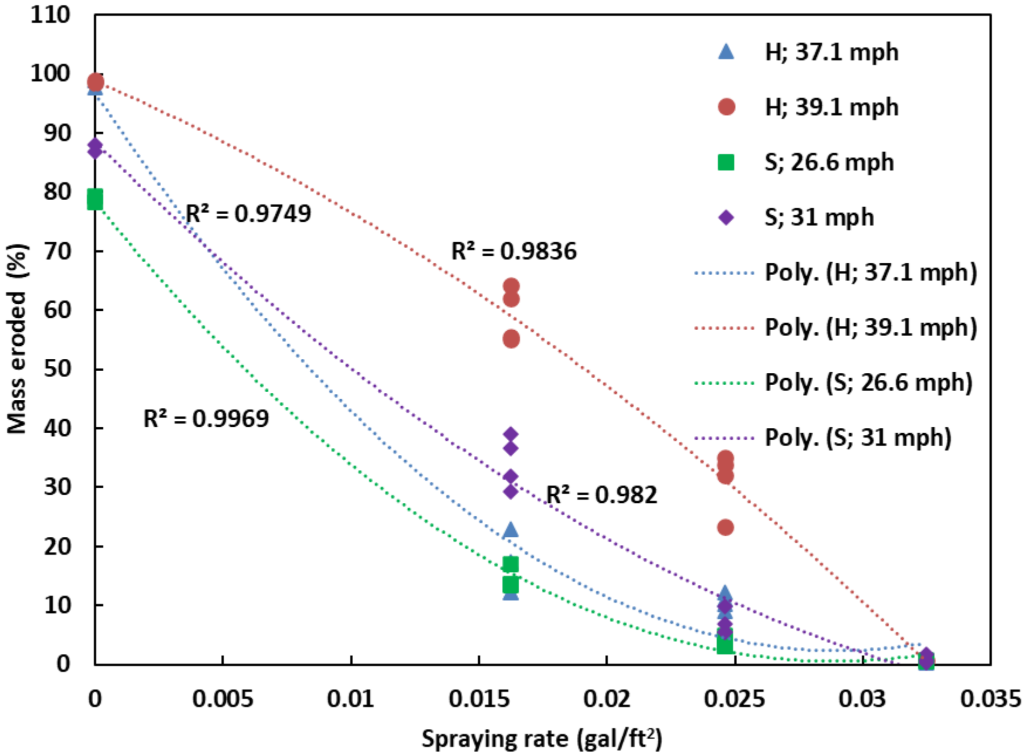


Figure 4.11: Percentage of Eroded Soil Mass versus Spraying Rate

The equation of the quadratic curve that fits the experimental data for the horizontal configuration at a wind speed of 39.1 mph is given by:

$$\boldsymbol{E = -35732 s_r^2 - 1867.6 s_r + 98.791}$$

Equation 4.3

Where:

s_r = spraying rate (gal/ft^2), and

E = eroded material mass (%).

The equation of the quadratic curve that fits the experimental data for the horizontal configuration at a wind speed of 37.1 mph is given by:

$$\boldsymbol{E = -112226 s_r^2 - 6513.1 s_r + 96.828}$$

Equation 4.4

Where:

s_r = spraying rate (gal/ft^2), and

E = eroded material mass (%).

The equation of the quadratic curve that fits the experimental data for the inclined configuration at a wind speed of 31 mph is given by:

$$\boldsymbol{E = -47697s_r^2 - 4317.6s_r + 88.543}$$

Equation 4.5

Where:

s_r = spraying rate (gal/ft^2), and

E = eroded material mass (%).

The equation of the quadratic curve that fits the experimental data for the inclined configuration at a wind speed of 26.6 mph is given by:

$$\boldsymbol{E = -93085s_r^2 - 5383.2s_r + 78.368}$$

Equation 4.6

Where:

s_r = spraying rate (gal/ft^2), and

E = eroded material mass (%).

In summary, wind erosion exhibited quadratic decay with increasing spraying rates for four different wind speeds, and it practically diminished at 0.0325 gal/ft^2 for all horizontal and sloped configurations and all wind speeds tested. Furthermore, only the curve describing erosion at a wind speed of 39.1 mph for the horizontal configuration was convex, and all remaining curves were concave. Chapter 5 details the mechanism of wind erosion.

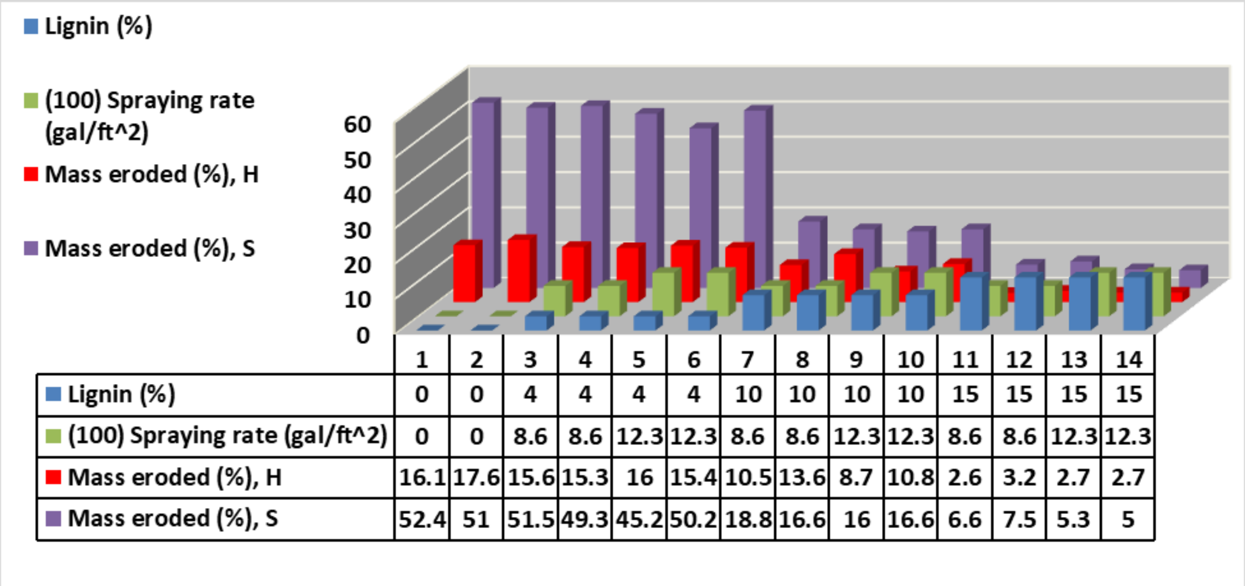
4.4 Rainfall Erosion Tests

Using the experimental configurations of rainfall erosion tests in Table 3.3, the soil was oven dried, grinded, and deposited loosely using a funnel bottom near the soil surface. The soil was deposited to a depth of 1 in. into a steel container measuring 35.5 in. long, 12 in. wide, and 5 in. deep, with Plexiglas® vertical walls and a steel mesh at one end to allow passage of soil and water into a smaller compartment measuring 5 in. in length and 12 in. wide. Plastic tubing connected to this compartment collected a drained liquid that was then oven dried with the eroded soil to provide a mass of eroded material and a percentage of eroded material. Testing commenced 4 and 6 hours after spraying at spraying rates of 0.0861 gal/ft^2 and 0.123 gal/ft^2, respectively.

A rainfall simulator was constructed by attaching a full cone nozzle 50 (WSQ Spraying Systems Co., Wheaton, IL) to a PVC frame (Figure 4.12). The single-spray nozzle was placed approximately 9.8 feet above the soil surface, and the water pressure was adjusted to produce a rainfall intensity of approximately 2.5 in./hr uniformly over the soil container. Humphry et al. (2002) used the same nozzle at the same height to show that the simulated rainfall was similar to natural rainfall in terms of drop size distribution, impact energy, intensity, and uniformity. According to Hershfield (1961), a previous report indicating that the rainfall intensity of 2.5 in./hr corresponded to a 10- to 25-year event of a 1-hour rainfall in various regions of Kansas, the duration of all rainfall erosion tests was 1 hr.

Figure 4.13 shows summary results and a magnified (100 times) spraying rate for all rainfall erosion tests, including horizontal soil configuration (H) and sloped soil configuration (S) with soil inclined at 18.4° towards horizontal direction. Unlike the wind erosion results, the concentration of lignin solution significantly affected the amount of rainfall erosion, meaning erosion decreased as the lignin concentration increased. Similarly, Figure 4.14 shows the percentage of eroded soil mass versus lignin concentration including various spraying rates. Overall, the amount of erosion was larger for the sloped configuration, but the erosion difference between sloped and horizontal configurations decreased with increasing lignin concentration. In both configurations, the amount of eroded soil mass versus lignin solution concentration exhibited a more pronounced quadratic decay for the inclined soil configuration. At a lignin concentration of 15%, erosion decreased to an average of 3.9% for horizontal and sloped configurations. Chapter 5 details the underlying mechanism of rainfall erosion.

Figure 4.12: Photo of a Rainfall Erosion Test



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
🟦 Lignin (%)	0	0	4	4	4	4	10	10	10	10	15	15	15	15
🟩 (100) Spraying rate (gal/ft^2)	0	0	8.6	8.6	12.3	12.3	8.6	8.6	12.3	12.3	8.6	8.6	12.3	12.3
🟥 Mass eroded (%), H	16.1	17.6	15.6	15.3	16	15.4	10.5	13.6	8.7	10.8	2.6	3.2	2.7	2.7
🟪 Mass eroded (%), S	52.4	51	51.5	49.3	45.2	50.2	18.8	16.6	16	16.6	6.6	7.5	5.3	5

Figure 4.13: Summary of Rainfall Erosion Tests

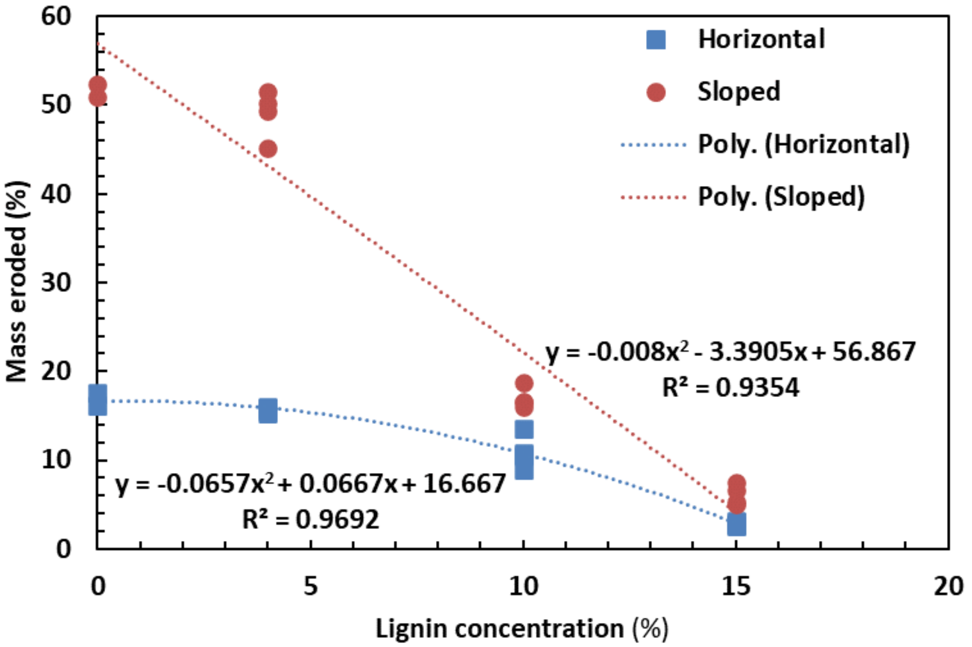


Figure 4.14: Eroded Soil Mass versus Lignin Solution Concentration for all Rainfall Erosion Tests

4.5 Field Trial

Research trials were conducted at the K-State Olathe Horticulture Research & Extension Center to confirm the use of lignin as a soil stabilizer during the establishment of turf grass. To evaluate the effects of lignin on the vegetative cover and soil nutrients, plots measuring 5 ft by 5 ft were laid out in a randomized complete block design with four replicates (Table 4.2 and Figure 4.15). A native grass mixture with wildflowers was seeded on June 4, 2021, at 45 lbs pure live seed per acre based on KDOT recommendations. Contents of the mixture from Sharp Brothers Seed Company (Healy, KS) included quickguard (22.4%), Sharps Improved Buffalo (18.8%), El Reno sideoats gram (15.9%), Barton western wheatgrass (8%), Aldous little bluestem (4.2%), Kaw big bluestem (4.2%), Cheyenne yellow indiangrass (4.1%), Illinois bundleflower (2.9%), blanket flower (2.1%), switchgrass blackwell (2.1%), Lovington blue grama (2%), pitcher sage (0.84%), purple prairie clover (0.81%), leadplant (0.76%), blackeyed susan (0.67%), butterfly milkweed (0.65%), lemon mint (0.63%), white prairie clover (0.6%), plains coreopsis (0.46%), maximilian sunflower (0.43%), western yarrow (0.42%), and prairie coneflower (0.41%). At the time of seeding, a 24-25-4 Scotts fertilizer was applied to the equivalent of 45 lbs N/acre, 49 lbs P_2O_5/acre, and 33 lbs K_2O/acre.

A total of seven treatments included lignin concentrations of 1%, 2%, and 4% and were applied at the low spraying rate (0.0332 gal/25 ft^2) and the high spraying rate (0.086 gal/ft^2) with the untreated control (Table 4.2 and Figure 4.15). Treatments were applied the same day as seeding, and irrigation was applied the following day. Additional irrigation was applied as needed to keep the soil surface moist the first few weeks after planting. The applied treatments (Table 4.2) were:

1. Low volume (0.0332 gal/ft^2), 1% lignin
2. High volume (0.086 gal/ft^2), 1% lignin
3. Low volume (0.0332 gal/ft^2), 2% lignin
4. High volume (0.086 gal/ft^2), 2% lignin
5. Low volume (0.0332 gal/ft^2), 4% lignin
6. High volume (0.086 gal/ft^2), 4% lignin
7. No lignin

Table 4.2: Experimental Program for Wind Erosion Tests (Left Arrow Points North)

⬆

5	1	4	2	3	7	6
1	2	3	4	5	6	7
6	2	4	3	7	1	5
4	7	1	5	2	6	3

Figure 4.15: Photo of Field Trial Plots

Table 4.3 lists the data collected for hand penetrometer resistance, number of emerged monocots, number of emerged dicots, total monocots and dicots, and percentage of green vegetative cover, monocot and dicot emergence and vegetative cover included desired species and weeds. All measured values in the table are averages of the four measurements. Soil was sampled from plots that received a high volume of water treatment and each lignin concentration, along with untreated soil. Soil analysis included pH, electrical conductivity (EC), and nutrient levels of phosphorus (P), magnesium (Mg), sodium (Na), calcium (Ca), manganese (Mn), copper (Cu), zinc (Zn), and iron (Fe). The emergence of monocots and dicots generally indicated that lignin had no effect on the numbers of monocots or dicots or vegetative green cover. Soil test results indicated that the soil that received lignin at a concentration of 1% had lower Zn levels, while the soil receiving 2% lignin had lower Fe and Zn levels compared to non-treated plots. No statistically significant difference was observed for Fe and Zn levels of untreated soil and soil receiving 4% lignin solution. In spring 2022, a pre-emergence herbicide was applied to suppress annual grassy weeds, and the presence of grasses and broadleaves, including broadleaf weeds, across the plots was uniform. As shown in Table 4.3, means followed by the same letter are not significantly different according to Tukey's honestly significant difference (HSD) test ($P < 0.05$). Columns with no letters indicate no significant differences among treatments. Similar to the laboratory tests, penetrometer resistance in field increased with increased spraying rate.

Table 4.3: Influence of Lignin Treatments

Treatment*	Penetrometer Res. (psi)	Monocots Emerged (per ft^2)	Dicots Emerged (per ft^2)	Vegetative Green Cover (%)	Soil Fe Level (ppm)	Soil Zn Level (ppm)
1% (low vol.)	14.6 e	50	59	41		
1% (high vol.)	21.3 d	20	33	41	115 a	1.8 b
2 % (low vol.)	24.2 cd	22	8	24		
2% (high vol.)	27.0 bc	56	22	43	98 b	1.5 b
4% (low vol.)	31.3 ab	33	32	34		
4% (high vol.)	35.6 a	23	10	24	122 a	1.9 a
Untreated	12.8 e	47	33	33	125 a	2.0 a

*low vol. = 0.0332 gal/ft^2; high vol. = 0.086 gal/ft^2

Chapter 5: Discussion

5.1 UCS and Wind Erosion

The spraying rate of lignin solution was shown to affect both the UCS obtained from hand penetrometer tests and the amount of soil eroded in wind erosion tests. The strength increased exponentially with increased spraying rate, while erosion exhibited a quadratic decay with increased spraying rate. Erosion was practically suppressed at the spraying rate of 0.0325 gal/ft^2. The exponential growth of UCS shown in Figure 4.7 can be expressed as:

$$\boldsymbol{q_u = \alpha\, exp\,(\beta s_r)}$$

Equation 5.1

Where:

q_u = unconfined compression strength from hand penetrometer (psi),

α = fitting parameter,

β = fitting parameter, and

s_r = spraying rate (gal/ft^2).

The quadratic decay of eroded soil mass depicted in Figure 4.11 can be expressed as:

$$\boldsymbol{E}\,(\%) = \boldsymbol{a s_r^2 + b s_r + c}$$

Equation 5.2

Where:

E = eroded material mass (%),

α = fitting parameter,

β = fitting parameter, and

s_r = spraying rate (gal/ft^2).

Combining Equations 5.1 and 5.2 results in the following expression that relates the amount of wind erosion and UCS:

$$\boldsymbol{E}(\%) = \boldsymbol{a_1 \overline{q}_u^2 + a_2 \overline{q}_u + a_3}$$

Equation 5.3

Where:

E = eroded material mass (%),

a_1 = fitting parameter,

a_2 = fitting parameter,

a_3 = fitting parameter, and

q_u = unconfined compressive strength from hand penetrometer (psi).

and:

$$\bar{q}_u = \ln q_u$$

Equation 5.4

Where:

q_u = unconfined compressive strength from hand penetrometer (psi).

Fitting parameters are expressed as previously defined parameters α, β, a, b, and c as:

$$a_1 = \frac{a}{\beta^2}$$

Equation 5.5

$$a_2 = \frac{1}{\beta}\left(b - \frac{2a}{\beta}\ln \alpha\right)$$

Equation 5.6

$$a_3 = \frac{1}{\beta}\left(\frac{a}{\beta}\ln \alpha - b\right)\ln \alpha + c$$

Equation 5.7

Figure 5.1, which does not contain experimental data, depicts Equation 5.3, and Table 5.1 provides parameters of Equation 5.3, for various testing configurations and wind speeds. The experimental data shown in Figure 4.7 indicated that early post-peak strength at the spraying rate of 0.0325 gal/ft^2 ranged from 1.36 to 1.7 psi, while the fitted trend line yielded 2.07 psi at the same spraying rate. However, the derived relationship shown in Figure 5.1 required a UCS of 2.24 psi to prevent erosion for the horizontal configuration and a wind speed of 39.1 mph, thus overestimating the required strength, but the derived relationship for the sloped configuration at a wind speed of 31 mph required UCS of 1.54 psi, which fits the above experimental data well. The two remaining cases, horizontal configuration at 37.1 mph and sloped configuration at 26.6 mph, required a UCS of 1.1 psi, according to Figure 5.1, while the minimum UCS from the hand penetrometer tests at 0.0325 gal/ft^2 was 1.36 psi. This underestimation of required strength was due to the corresponding quadratic trend lines depicted in Figure 4.11. Although these lines overall fit the experimental data well, they showed a slight mismatch at the spraying rate of 0.0325 gal/ft^2, resulting in a discrepancy in the required UCS.

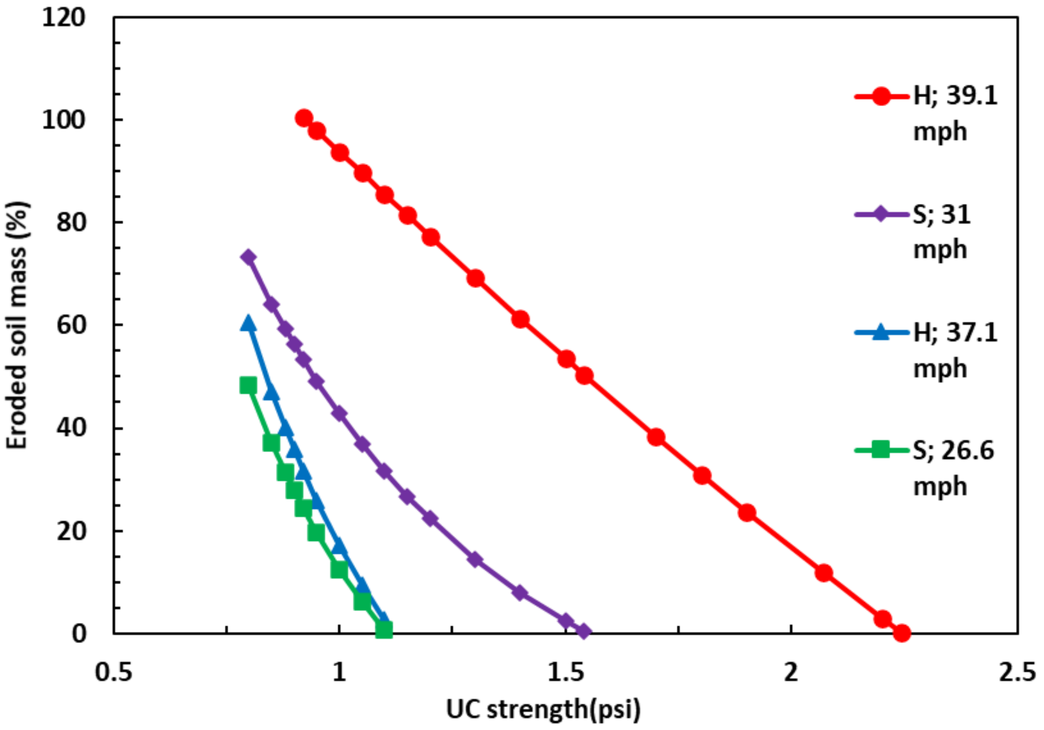


Figure 5.1: Eroded Soil Mass as a Function of UCS for Testing Configurations

Table 5.1: Parameters of Equation 5.3 for Wind Erosion Testing Configurations

Parameter	**Testing Configuration**			
	H; 39.1 mph	H; 37.1 mph	S; 31 mph	S; 26.6 mph
a_1	-41.509	130.369	55.408	108.133
a_2	-82.417	-163.050	-122.11	-134.600
a_3	93.7857	17.188	42.759	12.458

Overall, UCS can be used to predict the suppression of wind erosion after introducing a safety factor of 1.4. The minimum required UCS of 1.1 psi from Figure 5.1 multiplied by 1.55 was 1.70 psi, which corresponded to the highest measured UCS at the spraying rate of 0.0325 psi. UCS can be used to predict the amount of erosion because strength and erosion are controlled by cohesion that develops due to solidified lignin solution that sticks to soil particles and produces cementation. The lignin solution began to penetrate the soil upon spraying, penetrating deeper for higher spraying rates, resulting in the formation of a thick crust (Figure 5.2) that provided significant resistance during hand penetrometer tests; the resistance increased with increased thickness. Resistance to erosion increased with increased spraying rate due to stronger bonding between the particles and increased crust thickness.

Figure 5.2: Crust Formation During Hand Penetrometer Tests for Spraying Rate of 0.0863 gal/ft^2

Figures 4.4–4.6 show the development of peak UCS over time, followed by a decreased post-peak value that changed slightly at 24 hours. Because soil was oven dried prior to spraying with lignin solution, no suction occurred until spraying with lignin solution began. Two mechanisms were likely activated after spraying: development of suction due to partial saturation and development of particle bonding induced by the presence of lignin. However, drying that evolved with elapsed time caused the lignin solution to change into a gel-like consistency, consequently eliminating suction and producing decreased strength over time.

5.2 Rainfall Erosion

Results of the rainfall erosion tests indicated that lignin solution concentration is the primary factor affecting rainfall erosion (Figures 4.13 and 4.14). Although spraying rates applied in rainfall erosion tests were higher than those in wind erosion tests (Tables 3.3 and 3.2, respectively), lignin concentration had to be increased significantly to reduce erosion to 5%. The largest lignin concentration in wind erosion tests was 2%, but the largest concentration in rainfall erosion tests was 15% because the lignin solution had very high viscosity. The 58% lignin solution had a viscosity of 6.27×10^{-3} lb-s/ft^2 at 77 °F, while the viscosity of water at 77 °F is only 1.86×10^{-5} lb-s/ft^2. Consequently, as lignin concentration increased from 0% to 15%, the viscosity of pore fluid increased and hydraulic conductivity of pore fluid decreased since the latter is inversely proportional to the viscosity, thereby increasing the difficulty for soil to be washed out during a rainfall erosion event. Finally, because soil remains dry during wind erosion events, the viscosity of pore fluid had no relevance and the lignin concentration did not have a significant effect on wind erosion.

The effectiveness of lignin solution against rainfall erosion in field conditions was evaluated using the following Universal Soil Loss Equation (USLE), which considers rainfall pattern, soil type, crop system, and management practices and is applicable only to sloping configurations (Wischmeier & Smith, 1978):

$$\boldsymbol{A = RKLSCP}$$

Equation 5.8

Where:

A = average annual soil loss (tons/acre/yr),

R = rainfall and runoff factor ([hundreds of ft-tonf-in.]/[acre-hour-yr]),

K = soil erodibility factor ([ton-acre-hour]/[hundreds of acre-ft-tonf-in.]),

L = slope length factor (dimensionless),

S = slope steepness factor (dimensionless),

C = cover and management factor (dimensionless), and

P = support practice factor (dimensionless).

The rainfall and runoff factor (R) for a given location depends on rainfall intensity and duration. Therefore, this study utilized the chart containing average annual values of rainfall erosion index from Wischmeier and Smith (1978). Because rainfall intensity changes significantly throughout Kansas, two extreme values were used: *R* = 250 ([hundreds of ft-tonf-in.]/[acre-hour-yr]) for southeastern Kansas with a rainfall intensity of 40.9 in./yr, and *R* = 100 ([hundreds of ft-tonf-in.]/[acre-hour-yr]) for western Kansas with a rainfall intensity of 15 in./year.

The soil erodibility factor (*K*), which represents soil resistance to erosion, is based on soil texture, soil structure, organic content, and soil permeability. This factor equals the average soil loss per unit of factor *R* from a 9% slope measuring 72.59 ft long in a clean-tilled continuous fallow (Wischmeier, 1976). This study utilized a *K* value of 0.25 ([ton-acre-hour]/[hundreds of acre-ft-tonf-in.]) for sandy loam from Wischmeier et al. (1971). McCool et al. (1982) provided the following expression for the lumped slope length and steepness factor (*LS*):

$$\boldsymbol{LS = \left(\frac{\lambda}{72.59}\right)^{0.3}\left(\frac{s}{9}\right)^{1.3}}$$

Equation 5.9

Where:
λ = slope length (ft), and
s = slope gradient (%).

The slope angle of 18.44° that was selected in this study corresponded to an *s* value of 33%, and λ = 72.59 ft was assumed in field, resulting in an *LS* value of 5.41. The cover and management factor (*C*) is the ratio of soil loss in an area with specified cover and management and the corresponding soil loss in a clean-tilled and continuously fallow condition. Therefore, this study used *C* = 1 for bare ground. For construction sites such as roadside embankment, *P* was not used in Equation 5.8, which predicted *A* = 338.12 (ton/[acre-yr]) for eastern Kansas and *A* = 135.25 (ton/[acre-yr]) for western Kansas (Balousek et al., 2000). However, both values exceed the tolerable soil loss of 5 (ton/[acre-year]) given by the Natural Resources Conservation Service (NRCS, 1999).

Xiao et al. (2010) proposed an equation to describe the relationship between erosion measured in field and in a laboratory-scale experiment. This study modified their equation to:

$$A_{field} = Z_{lab}N$$

Equation 5.10

Where:

A_{field} = annual soil loss in the field (ton/[acre-year]),

Z_{lab} = soil loss in laboratory-scale test (ton/[acre-hour]), and

N = annual equivalent number of 1-hour rainfall events with identical simulated rainfall intensity.

Because N depends on the annual precipitation for a given region, Equations 5.8 and 5.10 can be combined to yield N value as:

$$N = \frac{RKLSCP}{Z_{lab}}$$

Equation 5.11

Where:

Z_{lab} = soil loss in laboratory-scale test (ton/[acre-hour]),

N = annual equivalent number of 1-hour rainfall events with identical simulated rainfall intensity,

R = rainfall and runoff factor ([hundreds of ft-tonf-in.]/[acre-hour-yr]),

K = soil erodibility factor ([ton-acre-hour]/[hundreds of acre-ft-tonf-in.]),

L = slope length factor (dimensionless),

S = slope steepness factor (dimensionless),

C = cover and management factor (dimensionless), and

P = support practice factor (dimensionless).

Once the scaling factor (N) was determined from Equation 5.11 for unprotected soil, the equation was used to determine the soil erodibility factor (K) for soil protected with lignin solution. Table 5.2 provides the up-scaled soil loss per area based on the amount from experiments in this study, predicted average annual soil loss (A_1 and A_2) obtained from Equation 5.8, corresponding N values, and subsequent K values. The decreasing K value with increasing lignin concentration showed that the presence of lignin reduces erosion. At lignin concentration of 15%, $K = 0.029$, which is 8.62 times smaller than K of unprotected soil. This decreased value of K demonstrates the effects of lignin on soil texture, structure, and permeability.

Table 5.2: Effect of Lignin Concentration on the Soil Erodibility Factor

Lignin Concentration (%)	Soil Loss per Area (ton/acre)	A_1 (ton/acre-year)	A_2 (ton/acre-year)	N_1*	N_2	K_1	K_2
0	59.945	135.25	338.125	2.26	5.64	0.25	0.25
4	56.854	N/A	N/A	N/A	N/A	0.237	0.237
10	19.739	N/A	N/A	N/A	N/A	0.082	0.082
15	7.04	N/A	N/A	N/A	N/A	0.029	0.029

*subscript 1 denotes rainfall intensity of western Kansas; subscript 2 denotes rainfall intensity of southeastern Kansas

The soil in these experiments was extremely loose due to the selected preparation method, and A_1 and A_2 could be calculated using Equation 5.8 after the new K values for various lignin concentrations were determined (Table 5.2), providing the same values of N_1 and N_2 as listed in Table 5.2. Determination process for K values that reflect the presence of lignin is outlined in Table 5.2.

Chapter 6: Applications and Suggestions for Implementation

6.1 Applications

Results of this study are useful for protecting Kansas roadsides from wind and rainfall erosion during the critical construction period preceding the establishment of a vegetative cover. Optimum application was determined to be spraying selected lignin water solutions on the soil surface shortly after seeding of a native grass and wildflower mixture. The effect of lignin on vegetative cover and soil nutrients was evaluated for lignin concentrations of 1%, 2%, and 4% at a low spraying rate (0.0322 gal/ft^2) and a high spraying rate (0.0866 gal/ft^2). Results showed that the presence of lignin in the soil did not affect the size of vegetative cover and only minimally affected soil nutrients at lignin solution concentrations less than 4%.

6.2 Suggestions for Implementation

6.2.1 Wind Erosion

Experiments conducted in this study determined that the threshold spraying rate of 0.0325 gal/ft^2 completely prevents wind erosion at lignin concentrations of 1% and 2% for both horizontal and sloped soil configurations and all tested wind speeds. Therefore, this spraying rate at the minimum lignin solution concentration of 1% should completely prevent wind erosion based on wind duration of 15 min. For horizontal configurations, spraying rates lower than 0.0325 gal/ft^2 resulted in eroded soil mass of 5% at a wind speed of 35.4 mph to 66% at a wind speed of 38.7 mph. Specifically, at a spraying rate of 0.0162 gal/ft^2, the secant erosion rates were 16.8%/mph and 10.1%/mph at lignin solution concentrations of 1% and 2%, respectively, meaning that the amount of eroded soil increased by 16.8% per unit increase in wind speed at 1% lignin concentration and by 10.1% per unit increase in wind speed at 2% lignin concentration. At the spraying rate of 0.0246 gal/ft^2, the secant erosion rates were 7.15%/mph and 6.3%/mph at lignin concentrations of 1% and 2%, respectively. These increased erosion rates were obtained by fitting a straight line to the curves shown in Figure 4.9 over the wind speeds ranging from 35.4 to 38.7 mph. Comparatively, the erosion amounts for unprotected soil were 97.3% and 98.5% at wind speeds of 35.4 and 38.7 mph, respectively.

For sloped configurations, spraying rates lower than 0.0325 gal/ft^2 resulted in a range of eroded soil mass from 0% at a wind speed of 23.2 mph to 36.9% at a wind speed of 30.4 mph. At the spraying rate of 0.0162 gal/ft^2, secant erosion rates were 4.5%/mph and 3.7%/mph at lignin solution concentrations of 1% and 2%, respectively, meaning that the amount of eroded soil increased by 4.5% per unit increase in wind speed at 1% lignin concentration and by 3.7% per unit increase in wind speed at 2% lignin concentration. At the spraying rate of 0.0246 gal/ft^2, the secant erosion rates were 1.05%/mph and 0.67%/mph at lignin concentrations of 1% and 2%, respectively. The quoted rates of erosion were very similar to the measured rates over the entire wind speed interval because corresponding curves in Figure 4.10 were similar to linear functions. Comparatively, the erosion amounts of unprotected slopes were 78.7% and 90.8% at wind speeds of 27.2 and 33.5 mph, respectively.

The relationship between the UCS from hand penetrometer tests and erosion amounts from wind erosion tests (Figure 5.1) provides a succinct assessment of erosion protection, proving that hand penetrometer tests can be used to assess the corresponding amount of protection against wind erosion. According to Figure 5.1, UCS of at least 2.25 and 1.12 psi are required to completely suppress wind erosion at wind speeds of 39.1 and 37.1 mph, respectively, for horizontal soil configurations, and UCS of at least 1.55 and 1.11 psi are required to completely suppress wind erosion at wind speeds of 31 and 26.6. mph for sloped soil configurations. Additional information that could be useful for implementation is in Figures 4.9, 4.10, 4.11, and 5.1.

6.2.2 Rain Erosion

Results of rainfall erosion tests indicated that a significant increase in lignin solution concentration is required to suppress rainfall erosion. The minimum amount of erosion was obtained for 15% lignin solution, resulting in mass of eroded soil of 4.2% and 2.9% for sloped and horizontal configurations, respectively. Only a slight extrapolation of the curves fitting the experimental data (Figure 4.14) was required to determine that spraying rates of 16.1% and 16.4% are required to suppress rainfall erosion in sloped and horizonal soil configurations, respectively. Results showed that lignin solution concentration is the decisive factor controlling rainfall erosion, while spraying rate has only minimal effects. In fact, the rate of decrease of soil erosion increased with increasing lignin concentration for horizonal soil configuration at a rate of 0.192%/%, 0.85%/%, and 1.58%/% for lignin concentration intervals of 0–4%, 4%–10%, and 10%–15%, respectively. For example, the rate of erosion decreased by 1.58% per each additional percentage of increase in lignin concentration for concentrations of 10%–15%.

For sloped soil configuration, the rate of decrease of eroded soil mass was approximately constant throughout the entire range of tested lignin concentrations (0–15%). The corresponding average rate was 3.5%/%, so the erosion decreased at a higher rate for sloping soil configurations than horizontal soil configurations. Additional useful information is included in Figures 4.13 and 4.14.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

The primary goal of this research was to assess the feasibility of using lignin (calcium/sodium lignosulfonate) to decrease and prevent rainfall and wind erosion on Kansas roadsides prior to the emergence of a vegetative cover. Experimental research was devised and divided into two experimental groups. The objective of the first group was to assess the effectiveness of lignin solution to prevent rainfall and wind erosion using laboratory-scale hand penetrometer tests, wind erosion tests, and rainfall erosion tests on horizontal and sloped soil configurations. The objective of the second group of tests was to investigate the effects of lignin on the emergence of vegetative cover and the level of soil nutrients via a field trial involving 5 ft by 5 ft plots laid out in a randomized complete block design.

Findings of this study are limited to the silty soil used in the study that classified as a silt of low plasticity (ML) according to USCS and as a sandy loam according to USDA classification system, as well as use of calcium/sodium lignosulfonate, specifically Norlig G. Findings are based on use of the described native grass and wildflower mixture recommended by KDOT. Findings are also based on 15-min durations of wind erosion tests with wind speeds of 32.9–40 mph for horizontal soil configurations and 23–33.5 mph for sloped configurations with a slope of 18.44^{o} towards the horizontal direction. Wind speeds were measured near the soil surface, and findings related to rainfall erosion tests were based on 1-hr test durations with rainfall intensity of 2.5 in./hr.

- Hand penetrometer tests showed that the UCS of soil sprayed with a lignin solution increased exponentially with increased spraying rates of 0–0.086 gal/ft^2 and lignin solution concentrations of 0–2%. The spraying rate significantly impacted the strength increase, while the percentage of lignin only minimally affected the strength.
- The duration of wind erosion experiments was 15 min, and they were conducted at spraying rates of 0–0.0866 gal/ft^2 and lignin concentrations of 0–2%. Mass of eroded material expressed as a percentage of total mass prior to testing increased exponentially with increased wind speed for horizontal configurations while it exhibited logarithmic growth with

increasing wind speed for sloped configurations. The average wind speed near the soil surface ranged from 31 to 40 mph for horizontal configurations and from 23 to 33 mph for sloped configurations. Wind erosion was practically suppressed at the spraying rate of 0.0325 gal/ft^2 and lignin concentration of 1% for both configurations. Furthermore, the percentage of eroded soil mass showed a quadratic decay with increasing spraying rate at wind speeds of 37.1 and 39.1 mph for horizontal configurations and 26.6 and 31 mph for sloped configurations. The spraying rate was shown to significantly impact wind erosion, while the lignin concentration only minimally affected wind erosion.

- Increased spraying rate provided coating and improved bonding of soil particles within the soil crust that formed after spraying. Consequently, increased spraying rate increased soil cohesion and subsequently decreased the amount of erosion. Based on experimental data collected from the hand penetrometer and wind erosion tests, the relationship between the UCS and percentage of eroded material mass showed a quadratic decay of erosion with increasing natural logarithm of UCS. This relationship can be used to quickly estimate the effectiveness of lignin protection against wind erosion based on the UCS obtained from hand penetrometer tests.
- The duration of rainfall erosion tests was 1 hr with rainfall intensity of approximately 2.5 in./hr. Lignin spraying rates in these tests ranged from zero to 0.123 gal/ft^2 with lignin concentration of 0–15%. A percentage of eroded material mass showed quadratic decay with increasing lignin concentration, while spraying rate only minimally affected erosion. Because lignin is soluble in water, the intact crust could not be maintained during rainfall. Nevertheless, the lignin increased viscosity of the pore fluid, thereby decreasing the soil

permeability and significantly slowing the erosion process. Tenfold and six-fold decreases in rainfall erosion compared to untreated soil were measured at a lignin concentration of 15% and spraying rate of 0.123 gal/ft^2 for sloped and horizontal configurations, respectively.

- Results of the field trial showed that lignin reduced the Zn level at 1% lignin and reduced Zn and Fe levels at 2% lignin but did not affect Zn and Fe levels at 4% lignin compared to untreated soil. Furthermore, the presence of lignin did not affect monocot and dicot counts or percentage of vegetative cover. The field trial was conducted for spraying rates of 0.0325–0.0866 gal/ft^2 and lignin solution concentrations of 0–2%.

In summary, spraying lignin solution onto the surface of silty soil is an effective, environmentally friendly, and sustainable solution to significantly decrease the amount of wind and rainfall erosion. Lower spraying rate and significantly lower lignin concentration were required to suppress wind erosion than to decrease rainfall erosion from 16.8% to 2.7% for the horizontal configuration and from 51.7% to 5.3% for the sloped configuration.

7.2 Recommendations

Detailed suggestions for implementing the findings of this report are provided in Section 6.2. Additional guidance for protecting against wind erosion is provided in Figures 4.9–4.11, Figures 4.13 and 4.14 for rain erosion, Figure 5.1 for the relationship between wind erosion and UCS, and Table 4.3 for the effects of lignin on vegetative cover and soil nutrition.

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