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Laboratory and in situ evaluations of using bio-based co-product for pavement geo-materials stabilization

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Laboratory and in situ evaluations of using bio-based co-product for pavement geo-materials stabilization

by

Yizhou Li

A thesis submitted to the graduate faculty

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Geotechnical Engineering)

Program of Study Committee:
Halil Ceylan, Major Professor
Sunghwan Kim
Bora Cetin
Charles T. Jahren

Iowa State University

Ames, Iowa

2019

DEDICATION

I dedicate this thesis to my family, my girlfriend, and my friends who have helped me at both personal and professional levels during the course of this two-year graduate program.

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ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Halil Ceylan, and my committee members, Dr. Sunghwan Kim, Dr. Bora Cetin, and Dr. Charles T. Jahren, for serving on my Program of Study and Committee (POSC) and providing guidance for my research.

I want to thank Dr. Halil Ceylan for his financial support during my graduate study and his valuable advice regarding job interviews. Without his financial support, I would not have completed my graduate program without having to worry about the tuition. I want to thank Dr. Yang Zhang for his dedication, enthusiasm, and patience in answering every question I had, and always encouraging me to do my best in my research project. I also want to thank Dr. Bo Yang, who completed the previous phase of this study, for providing me with much information and knowledge in my research.

A graduate program is much different than an undergraduate program. During the multitasking of research and study, you improve upon your problem-solving, time management, and aplomb skills. This graduate program has provided me with the opportunities to not only take advanced courses in geotechnical and material engineering but also to participate in various research projects and to interact with research fellows, faculty members, and industry representatives. All of these valuable experiences have served as the application and extension of my undergraduate study, prepared me to be a knowledgeable and experienced geotechnical engineer, improved my interpersonal skills, and shaped my personality.

Last but not least, I want to thank everyone who has helped me complete my research, no matter how large or small the contribution. I have always been grateful for your help and assistance.

ABSTRACT

Lignosulfonate, a co-product of paper pulp production, has traditionally been used for dust suppression purpose. Although lignosulfonate has been reported as an alternative soil stabilizer because of its natural properties, its use has not been adequately investigated for soil stabilization purposes. Correspondingly, very limited field practice has been conducted in applying these laboratory attempts.

For this study, homogeneously diluted lignosulfonate was mixed with two types of silty soils in the laboratory with the goals of improving their strength and durability. Measurements and observations were obtained from six laboratory tests on untreated and lignosulfonate stabilized soils, including: (1) Proctor compaction test, (2) unconfined compressive strength (UCS) test, (3) freeze-thaw durability test, (4) wet-dry durability test, (5) scanning electron microscope (SEM) analysis, and (6) set time test. The unconfined compressive strength test results demonstrated that only a low dosage of lignosulfonate and water was required to improve the strength of sandy silt with gravel. Based on the outcomes of the durability tests, lignosulfonate improved the wet-dry resistance of both types of silty soils, and a significant improvement was noticed in freeze-thaw durability for sandy silt with clay with the addition of lignosulfonate. The SEM analysis indicated that lignosulfonate was capable of physically bonding soil particles. The set time test conveyed the strength increment of lignosulfonate itself and its mechanisms, indicating that the hardening process also contributed to increasing the stabilized soil strength.

In the field demonstration, five soil stabilizers (cement, ammonium-based lignosulfonate, chlorides, Claycrete, and Base One) were sprayed on a gravel road subgrade. Seasonal in situ tests and documentations were conducted both before and one week after the construction to

monitor the performance of the stabilized section and to draw the lessons learned from the practice. Light weight deflectometer (LWD) test and dynamic cone penetration (DCP) test were performed. The construction process was documented both visually and in written form. Some critical lessons were learned, which provide recommendations for future studies and benefit relevant practitioners.

This study provides guidance for subgrade stabilization with lignosulfonate on the basis of its laboratory and field investigations.

CHAPTER 1. INTRODUCTION

Background and Motivation

While the Midwest region in the U.S. is “one of the most intense areas of agricultural production in the world and consistently affects the global economy” (U.S. Department of Agriculture Climate Hubs 2017) due to its fertile soils with high agricultural capacity (Montgomery 2012), these soils do not benefit roadway construction and maintenance in the same way they benefit agriculture. The low bearing capacity of natural subgrade composed of such these weak soils costs highway agencies billions of dollars each year to construct and rehabilitate roads (Cetin et al. 2018).

There is a huge number of gravel roads in a Midwestern state like Iowa. According to the Federal Highway Administration (FHWA), by 2012, there were 1.4 million miles of unpaved roads in the U.S., accounting for approximately 35% of the total mileage of roads that constitute the nation’s transportation system (Federal Highway Administration’s Office of Highway policy Information 2014). According to Des Moines Register (2015), nearly 60% of Iowa’s public roads are gravel roads (Munson 2015). The quality and serviceability of gravel roads affect not only local residents’ daily activities but also farm work efficiency.

Statewide Urban Design and specification (SUDAS) (2013) stated that 37.5% of natural soils in Iowa are silts (SUDAS 2013). Whereas silty soils are good for agriculture due to their abundant fertility (National Geographic 2019), they do not provide a stable roadway foundation because of their poor compaction characteristics and virtually nonexistent dry strength (Saint Michael’s College 1984). As a matter of fact, silty soils make a fair to poor subgrade in accordance with the American Association of State Highway and Transportation Officials (AASHTO) soil classification system (AASHTO 2017). Hence, it is necessary to have these silty soils reinforced so that their bearing capacity and durability can be improved to ensure the safety of transportation infrastructures.

In addition to compaction and traditional soil stabilization methods (i.e., cement and lime), there are various nontraditional soil stabilizers that are generally classified into seven categories: ionic, enzymes, lignosulfonate, salts, petroleum resins, polymers, and tree resins (Tingle et al. 2007). Among these, lignosulfonate is one of the derivatives of lignin, which is a natural polymer extracted from plants through organic solvent extraction, alkaline extraction, and anthraquinone extraction; and lignosulfonate is specifically extracted from sulfite lignin (GreenAgrochem 2013).

Over the past three decades, because of the increasingly serious pollution problem caused by the overuse of fossil-based energy resources, there has been a desire to promote the use of renewable energy products in roadway infrastructure construction (Yang et al. 2015). Biomass, waste material from plant production, food processing, animal farming, or human waste (U.S. Energy Information Administration 2018), can be transformed into biofuel products that contain a significant amount of lignin. The typical representatives of biomass products include corn stover, switchgrass, and wood waste (Tumuluru et al. 2011).

Lignosulfonate has mainly been used for gravel road dust control, and its performance as an alternative soil stabilizer has not been widely investigated, so very few field demonstrations of soil stabilization with lignosulfonate have been reported. This study is comprised of two portions, laboratory investigation and field demonstration, with the goal of reducing knowledge and experience gaps with respect to soil stabilization with lignosulfonate.

Research Goals and Objectives

The primary goal of this study was to continue Yang (2015)'s investigation of soil stabilization with biofuel co-products (Yang 2015) by extending laboratory tests using lignosulfonate. The second goal of this study was to perform a field demonstration in Buchanan County, IA, and evaluate the performance of the field demonstration. This study's objectives include:

- Conducting the Proctor compaction test to reveal the correlation between lignosulfonate dosage and both optimum moisture content and maximum dry unit weight;
- Conducting the unconfined compressive strength test to determine the preferable lignosulfonate dosage, the optimum mix proportion, and the maximum increase in compressive strength for each soil;
- Conducting the wet-dry durability test and freeze-thaw durability test to investigate the optimum mix proportion specimens' susceptibility to repeated wet-dry and freeze-thaw damage;
- Conducting a field demonstration project to verify laboratory results and identify lessons learned; and
- Comparing five different soil stabilizers with respect to their strength and durability performance by conducting light weight deflectometer (LWD) test and dynamic cone penetration (DCP) test.

Research Approach

As it is shown in Figure 1.1, the desk study began with gradation and Atterberg limit results from previous research outcomes (Yang 2015), followed by a search of lignin-based products, followed by the literature review related to lignin-based soil stabilization practices, silty soil properties, in situ tests, compaction equipment and methods, and lessons learned from the field practice of two soil stabilizers (Claycrete, Base One). After purchasing the lignosulfonate, the laboratory investigation began with the Proctor compaction test to determine the maximum dry density and optimum moisture content of different lignosulfonate dosages, followed by the unconfined compressive strength (UCS) test to determine the optimum lignosulfonate and water mixture proportions. The difference of two silty soils' strength improvement was justified by scanning electron microscope (SEM) analysis and set time test. Then, the specimens with the optimum lignosulfonate and water proportions were tested with respect to their susceptibility to repeated wet-dry and freeze-thaw damage. Based on the above laboratory test results, a field demonstration project was conducted at which Soil 1 was collected, and a total of five soil stabilizers were applied on gravel road subgrade. Light weight deflectometer (LWD) test and dynamic cone penetration (DCP) test were conducted to compare the strength and durability performance of these five stabilizers. The construction process and the critical lessons learned from this construction have been documented both visually and in written form.

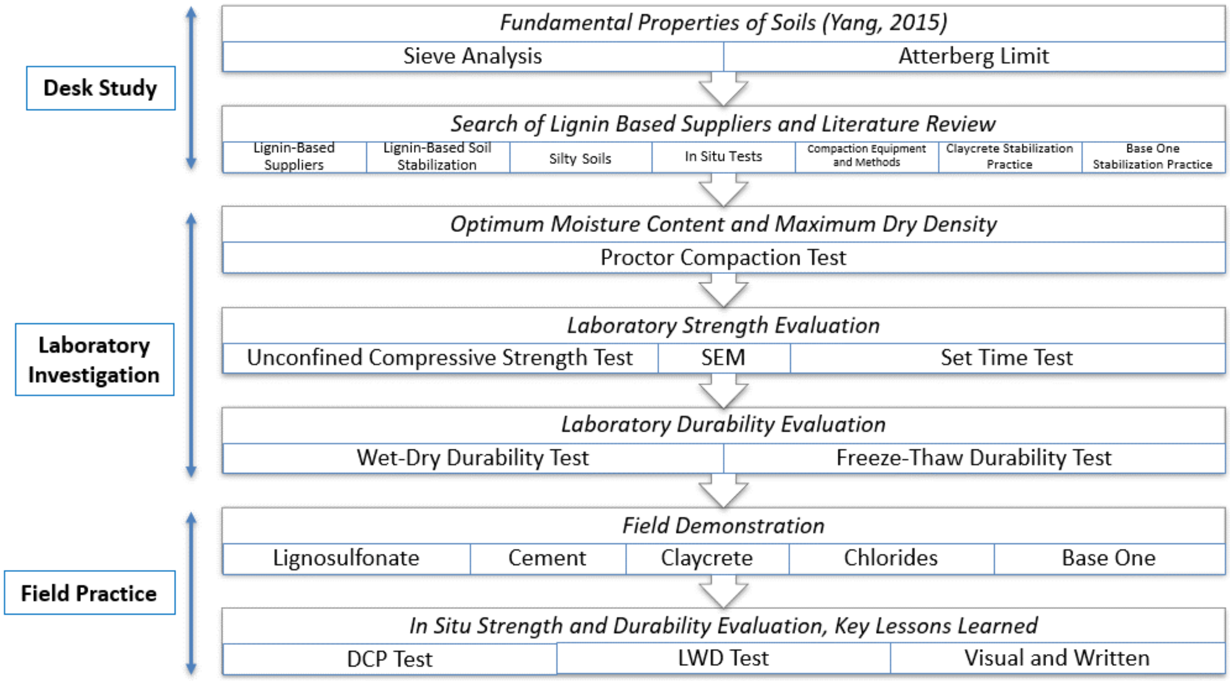


Figure 1.1 *Research Approach*

Organization

Following Chapter 1, this thesis is organized into 4 chapters. Chapter 2 summarizes the background information and literature review. Chapter 3 describes the materials used, and laboratory and in situ testing methods in this study, followed by the results that are illustrated and discussed in Chapter 4. Chapter 5 concludes the findings of this study, and provides suggestions for future research on this topic.

CHAPTER 2. SEARCH OF LIGNIN-BASED PRODUCT SUPPLIERS AND LITERATURE REVIEW SUMMARY

Search of Lignin-based Product Suppliers

Unlike the previous 2 phases, this project phase was focused on the field demonstration. Therefore, first and foremost, finding a bio-based co-product supplier became an essential task to initiate this phrase of the project. A search for lignin-based suppliers in and/or around Iowa was performed, followed by contacting them for important information such as product categories, product availability, and price, then asking about opportunities for their potential collaboration.

There were three major considerations in looking for bio-based co-product suppliers: (1) price, (2) location of the bio-based co-product plant, and (3) ecotoxicity.

Because the principal purpose of this phase of the project was to apply the laboratory investigative outcomes in the field, it was vital to find a bio-based co-product that was financially feasible for both researchers and pavement administrative agencies. Besides, the biggest difference between bio-based co-product soil stabilization and traditional soil stabilization (fly ash, lime, etc.) is the production of soil stabilizer. Since a co-product is not a specifically-produced product but rather one that naturally accompanies the production of other products, if the price of a bio-based co-product is more than that of traditional soil stabilizers, the product would not be practical for use in the field.

For the convenience of making bio-based co-product plant visits and performing sample collection, lignin suppliers in and/or around Iowa were preferable options. Besides, a shorter distance between the construction site and the plant would contribute to completing field demonstration in a timely manner. In this task, we made sure to convey the long-term benefits of bio-based co-product's use for pavement geomaterials stabilization purposes to lignin suppliers.

The ecotoxicity of bio-based co-product was another important consideration, because the bio-based co-product will stay within the pavement system once compaction has occurred. If there is an ecotoxicity of bio-based co-product, the soils and the plants along the road could be polluted.

With details information of company names, location, product categories, and the highlight information of the companies, Table 2.1 contains the literature review for a number of selective and representative lignin-based suppliers that were searched and contacted.

Table 2.1 *Lignin-based Co-Product Suppliers*

Company Names	Locations	Product Categories	Highlighting Information
Absolute Energy, L.L.C.	St. Ansgar, IA, Lyle, MN	Located on the Iowa-Minnesota border, Absolute Energy buys local corn and produces ethanol products, such as E85 (an ethanol furl blend of 85% denatured ethanol fuel and 15% gasoline or other hydrocarbon by volume).	Absolute Energy produced the first grind on February 12, 2008. With the belief that the production of E15 can contribute to the drive growth of American's rural communities, Absolute Energy focuses its interest on Iowa and Minnesota's local corn availability, renewable fuel and clean air coming from vehicles.
Archer Daniels Midland	Decatur, IL	Archer Daniels Midland purchases raw farm products like wheat, corn, and soy, followed by transforming them into ingredient in bulk and selling them to other food manufacturing, processing, and packaging companies.	Archer Daniels Midland is a global food processing commodity and provides a large variety of products including organic food, nutritional supplements, animal nutrition, fuel, along with farmer and financial services. We were only interested at Archer Daniels Midland's plant located in Decatur, Illinois. In addition, Archer Daniels Midland produces ethanol and lysine (widely used as animal food supplement).

Table 2.1 *(continued)*

Big River Resources, LLC	West Burlington, IA Monmouth, IL Taylor Ridge, IL Galva, IL Dyersville, IA Grinnell, IA Boyceville, WI	Located and targeting the market in Midwest, Big River Resources produces a significant amount of corn based ethanol and provides it as the renewable fuel.	The initial start of Big River Resources began in 1992 with fuel and feed production objectives. Up to date, Big River Resources owns an investment of a 100 mgy ethanol facility in St. Ansgar, IA. Big River Resources is also a majority shareholder and managing company of Big River United Energy, LLC located in Dyersville, IA. Big River Resources takes the responsibility of improving and stabilizing the agricultural economic resources by producing corn based ethanol as the primary renewable fuel within the multiple states in Midwest.
Corn, LP	Goldfield, IA	Located and targeting the market in Iowa, CORN processes Iowa's corn bushels into ethanol.	By producing ethanol, CORN has the goal of keeping the air cleaner and reducing the America's dependence on foreign oil. CORN takes the responsibility to add value to locally grown grains in Iowa, which profits the investor owners, local communities, the economy, and the nation.
Golden Grain Energy, LLC	Mason City, IA	Located and targeting the market in Iowa, Golden Grain Energy produces clean-burning ethanol from locally-grown corn.	Golden Grain Energy takes the responsibility of enhancing the local corn value by turning locally-grown corn into clean-burning ethanol. Golden Grain Energy produces approximately 120 million gallons of ethanol annually. The majority of shareholders of Golden Grain Energy are Iowa farmers. Golden Grain Energy strives to help meet the national demand for domestic biofuels, which contributes to reducing reliance on foreign oil and improving air quality.

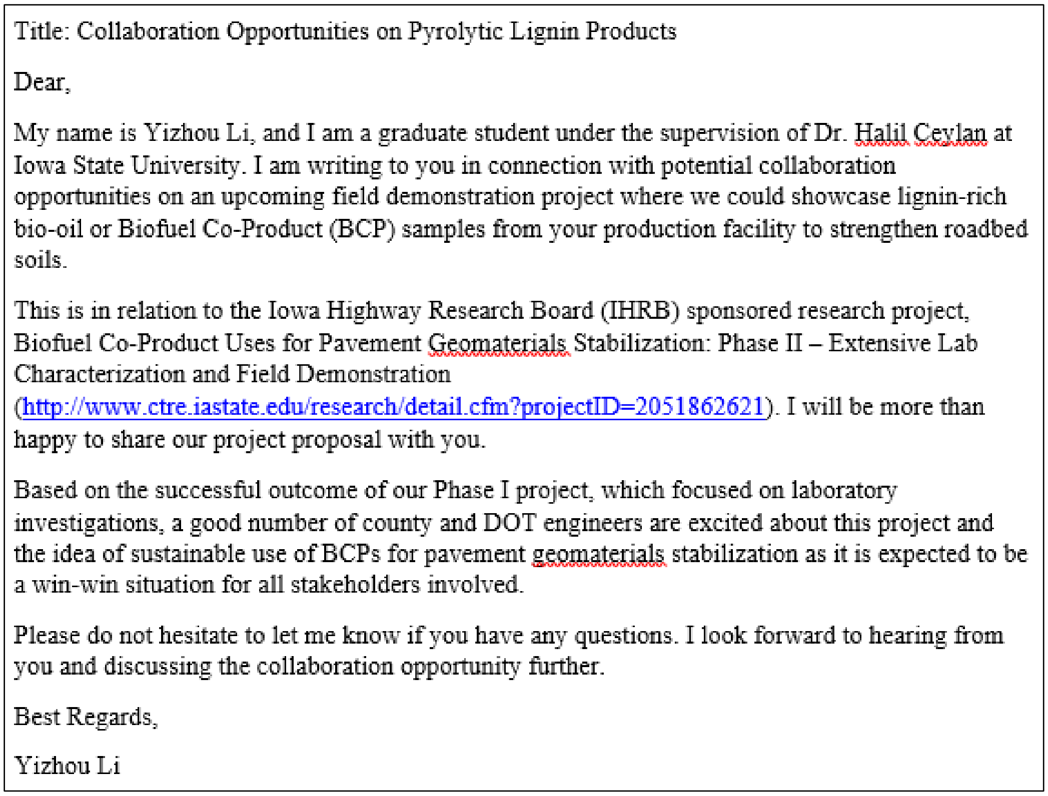
Table 2.1 *(continued)*

Homeland Energy Solutions, LLC	Lawler, IA	Homeland Energy Solutions produces ethanol and its co-product. In addition, it also produces significant distillers' grains.	Homeland Energy Solutions began to develop and plan the Ethanol Processing Facility in 2005. The Ethanol Processing Facility has the capabilities to produce 100,000,000 gallon of ethanol annually. The facility serves agriculture producers of corn from 11 counties in Iowa. Homeland Energy Solutions takes the responsibility to provide homeland energy independence for the US.
Plymouth Energy, LLC	Merrill, IA	Operating from its location in western Iowa, Plymouth Energy developed a nameplate 50 million gallons of undernatured ethanol per year ethanol plant with the capability to expand. Plymouth Energy also adopts a Vomitoxin (DON) sampling and testing policy to provide confidence to its clients in the co-products it produces.	Plymouth Energy, LLC was founded in 2005 with the target of design, build, own, and operate an ethanol plant in Plymouth County. Plymouth Energy participated in researching ethanol industry, acquiring land option, engaging project a management company, completing preliminary layout, completing air permit application, receiving an EPC contract for design and construction, preordering stainless steel, interviewing marketing companies, and discussing marketing agreement with other producers.
LincolnWay Energy, LLC	Navada, IA	LincolnWay Energy processes corn into fuel grade ethanol and distillers' gains.	LincolnWay Energy was founded in 2004 with the goal of building a name plate 50 million gallon per year dry mill ethanol plant.

Table 2.1 *(continued)*

Little Sioux Corn Processors	Marcus, IA	Little Sioux Corn Processors produces DDG, alcohol, and ethanol from corn. In addition, Little Sioux Corn Processors offers two types of co-porducts: Dried Distillers Grains with Solubles product, and “Modified” Wet Distillers Grains with Solubles product.	Up to 2015, Little Sioux Corn Processors has the corn processing capacity of 135 mmgy.
Blue Flame Propane	Letts, IA	Blue Flame Propane mainly provides propane and service. Blue Flame Propane also provides dust control services in May and August in a year.	Blue Flame Propane mainly provides propane and service for home by providing rental tanks, filling cylinders, maintaining your tanks, connecting hardware, and providing 24 hour emergency service. Blue Flame Propane also provide dust control and other unpaved surfaces using all natural tree sap.

We reached out to many lignin-based suppliers with the hope of getting key information about the lignin-based product. The email sample sent to the suppliers is shown in Figure 2.1, and the suppliers’ contact information is summarized in Table 2.2.



Title: Collaboration Opportunities on Pyrolytic Lignin Products

Dear,

My name is Yizhou Li, and I am a graduate student under the supervision of Dr. Halil Ceylan at Iowa State University. I am writing to you in connection with potential collaboration opportunities on an upcoming field demonstration project where we could showcase lignin-rich bio-oil or Biofuel Co-Product (BCP) samples from your production facility to strengthen roadbed soils.

This is in relation to the Iowa Highway Research Board (IHRB) sponsored research project, Biofuel Co-Product Uses for Pavement Geomaterials Stabilization: Phase II – Extensive Lab Characterization and Field Demonstration (http://www.ctre.iastate.edu/research/detail.cfm?projectID=2051862621). I will be more than happy to share our project proposal with you.

Based on the successful outcome of our Phase I project, which focused on laboratory investigations, a good number of county and DOT engineers are excited about this project and the idea of sustainable use of BCPs for pavement geomaterials stabilization as it is expected to be a win-win situation for all stakeholders involved.

Please do not hesitate to let me know if you have any questions. I look forward to hearing from you and discussing the collaboration opportunity further.

Best Regards,

Yizhou Li

Figure 2.1 *Email Sample Sent to Lignin-based Suppliers*

Table 2.2 *Lignin-based Suppliers Contact List*

Plant	Location	Contact Name	Email/Phone
Absolute Energy	St. Ansgar, IA	Rick Schwarck	rick.schwarck@absenergy.org
Archer Daniels Midland	Decatur, IL	Product Finder: https://www.adm.com/products-services/products Need to choose specific oils	
Big River Resources	West Burlington, IA	No contact info but Facebook: https://www.facebook.com/Big-River-Resources-LLC-181368415222259/	
Cargill	N/A	Contacted as a role of customer https://www.cargill.com/page/cargill-contact-us	
Corn LP	Goldfield, IA	Jim Glawe	jglawe@cornlp.com
DuPont	N/A	Contacted as a role of customer Product finder: http://duponttools.force.com/ppf?lang=en_US&country=USA	
Flint Hills	N/A	Product Finder: https://www.fhr.com/about-fhr/locations#2.75/49.39/-106.09	

Table 2.2 *(continued)*

Golden Grain Energy	Mason City, IA	Contacted as a role of customer http://www.ggecorn.com/contact/	
Homeland Energy Solutions	Lawler, IA	Contacted as a role of customer http://www.homelandenergysolutions.com/contact/	
Plymouth Energy LLC	Merrill, IA	Contacted as a role of customer http://www.plymouth-energy.com/index.cfm?show=30&mid=14	
Grain Processing Corporation	Muscatine, IA	N/A	sales@grainprocessing.com
Green Plains, Inc.	Omaha, NE	Contacted as a role of customer http://www.gpreinc.com/contact	
Lincolnway Energy	Nevada, IA	N/A	info@lincolnwayenergy.com
Little Sioux Corn Processors	Mascus, IA	Contacted as a role of customer http://www.littlesiouxcornprocessors.com/pages/contact.php	
Quad County Corn Processors	Glava, IA	Delayne Johnson	N/A
Siouxland Energy Cooperative	Sioux Center, IA	N/A	(712) 722-3263
Blue Flame Propane	Letts, IA	Jennifer Dahnke	(319) 726-3103
Eastern Iowa Propane	Clinton, IA	N/A	(800) 397-2921

Lignosulfonate

Lignosulfonate is derived from lignin, which is a naturally occurring polymer that exists in wood and holds the cellulose fibers of pulp together (Pacific Dust Control Inc. 2019). Traditionally being used as a dust suppression agent, lignosulfonate binds the gravel road particles together and traps the dust particles. During this process, lignosulfonate can function far beyond its ordinary dust control purpose and improve some road engineering properties, such as strength and resistance to washout by heavy rains and flooding (Pacific Dust Control Inc. 2019). Lignosulfonate is usually a waste product from paper pulp industries and stored in tanks, and therefore, finding a way to reuse lignosulfonate in construction leads to the reduction in landfill requirements, waste disposal costs, waste of natural resources, and risk to the environment, as well as the improvement and sustainability of civil engineering infrastructures (Cetin et al. 2010; Zhang et al. 2017). In soil stabilization practice, lignosulfonate acts as a water agent (Blackmon et al. 2010) and provides an attraction force (van der Waals force or secondary bonding force) to draw soil particles closer among each other and form a flocculate structure, which then improves the soil's strength (Lambe et al. 2008).

Silt Soils

Silt soils make up 37.5% of natural subgrade soils in Iowa (SUDAS 2013). A-4 soils, classified in accordance with the AASHTO Soil Classification system, are predominantly silts with different amounts of granular or clay. Not only are A-4 soils very susceptible to frost heaving, but also their strength changes with water content (Casagrande 1948). Due to silt soils' natural properties, it is important to improve their bearing capacity and durability in roadway infrastructures through stabilization (Zhang et al. 2016; Li et al. 2018; Yang et al. 2018).

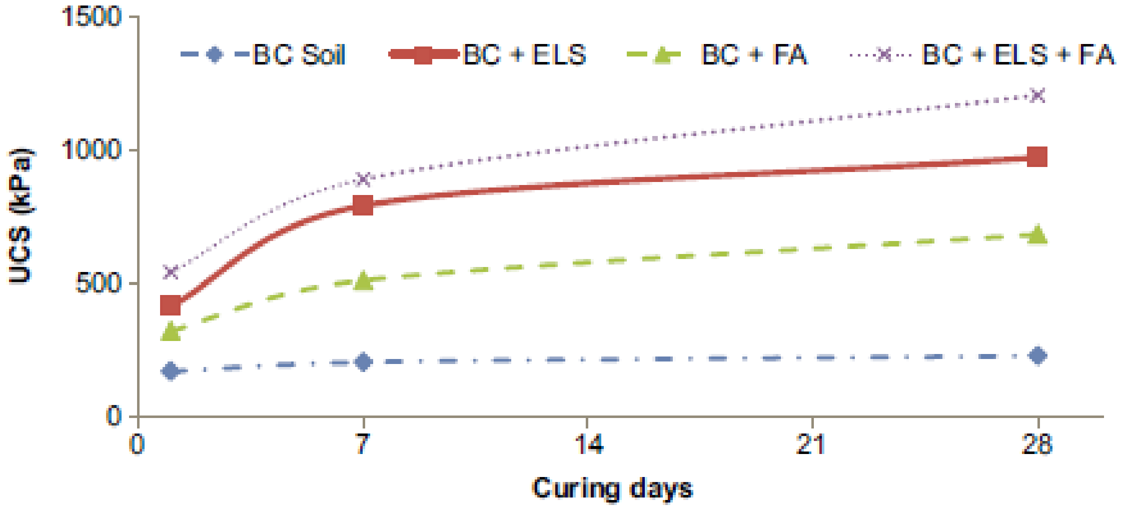
Lignin-based Soil Stabilization

A successful lignin-based co-product soil stabilization test performed in China demonstrated that the unconfined compressive strength increased as the content of lignin-based soil stabilizer increased, and that the optimum amount of lignin-based soil stabilizer was 12% in all cases (Zhang et al. 2014).

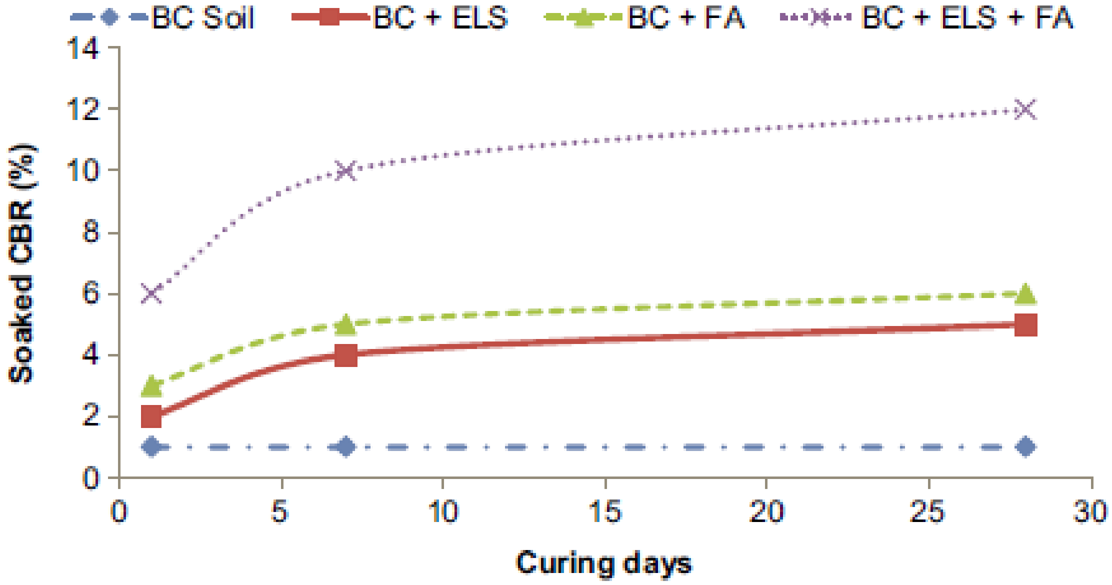
US Patent 7,758,280 states that lignin sulfonate is a metallic sulfonate salt made from the lignin of sulfite pulp-mill liquors [Blackmon et al. 2010]. Lignin sulfonate usually takes approximately from 20% to 60% by weight of the whole composition [Blackmon et al. 2010].

Lignin sulfonate can act as a water agent and the combination of lignin sulfonate and petroleum resin can be used as a soil stabilizer to create the bond among various types of soils and fly ash particles, which generate a waterproof surface and prevent fly ash from dispersing overtime [Blackmon et al. 2010]. Ammonium lignin sulfonate is one type of suitable lignin sulfonate material, along with calcium lignin sulfonate and sodium lignin sulfonate [Blackmon et al. 2010].

A research focused on the effect of electrolyte lignin and fly ash in stabilizing black cotton soil in India, in which a commercial electrolyte lignin stabilizer (ELS), fly ash (FA), and a combination of both were applied to black cotton (BC) soil from the North Karnataka region in India [Lekha et al. 2015]. It was concluded that consistency limits, dry density, unconfined compressive strength, and California bearing ratio were improved for treated soil [Lekha et al. 2015]. The stabilized soil was also proved to be more durable after 12 cycles in freeze-thaw test [Lekha et al. 2015]. The researchers concluded that the combination of the commercial electrolyte lignin stabilizer and fly ash was an optimum stabilizer for black cotton soil with respect to enhancing the subgrade strength (Figure 2.2) [Lekha et al. 2015].



(a)



(b)

Figure 2.2 *Variation of (a) UCS and (b) soaked CBR values at OMC (Lekha et al. 2015)*

A recent study tested the efficiency of casein and sodium caseinate salt biopolymers as soil stabilizers, with the motivation of looking for a soil stabilizer with little or no harmful effects on the environment [Fatehi et al. 2018]. It was concluded that the compressive strength of biopolymer treated sand increased as curing time and biopolymer content increased (Figure 2.4 and Figure 2.5) [Fatehi et al. 2018]. Curing temperature was also found to be one of the key factors affecting compressive strength, and the optimum curing temperature was found to be 60°C (Figure 2.3) [Fatehi et al. 2018]. The researchers found that this protein-based biopolymers had a higher potential as soil stabilizer than cement or other chemical polymers [Fatehi et al. 2018].

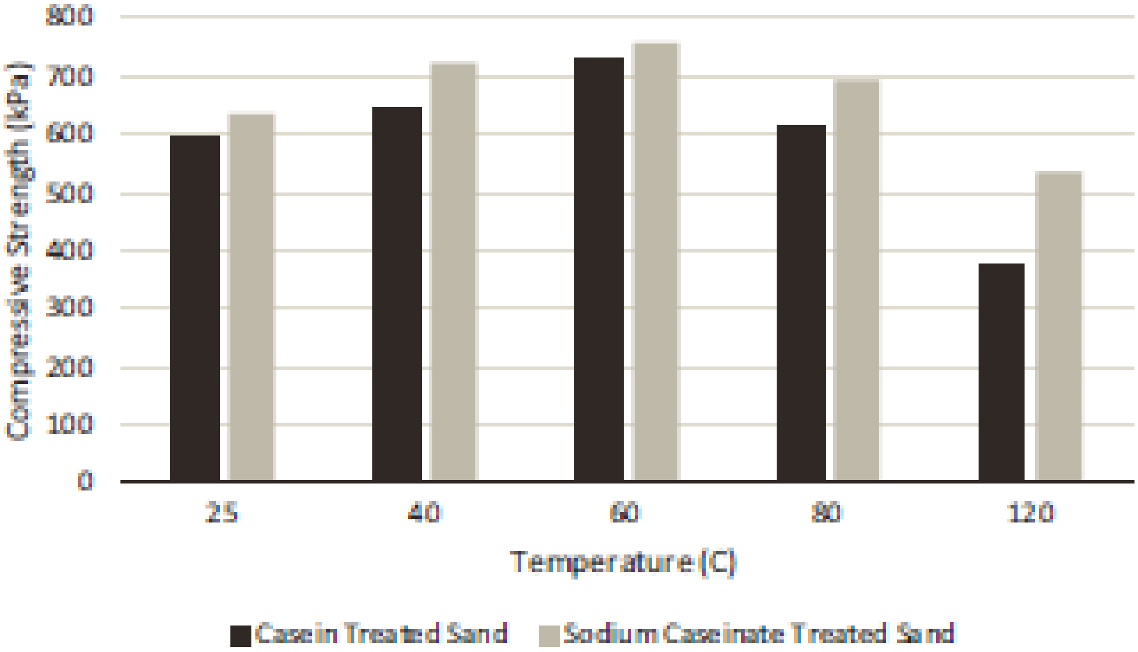


Figure 2.3 *Compressive strength of casein and sodium caseinate treated soil with respect to different curing temperatures (Fatehi et al. 2018)*

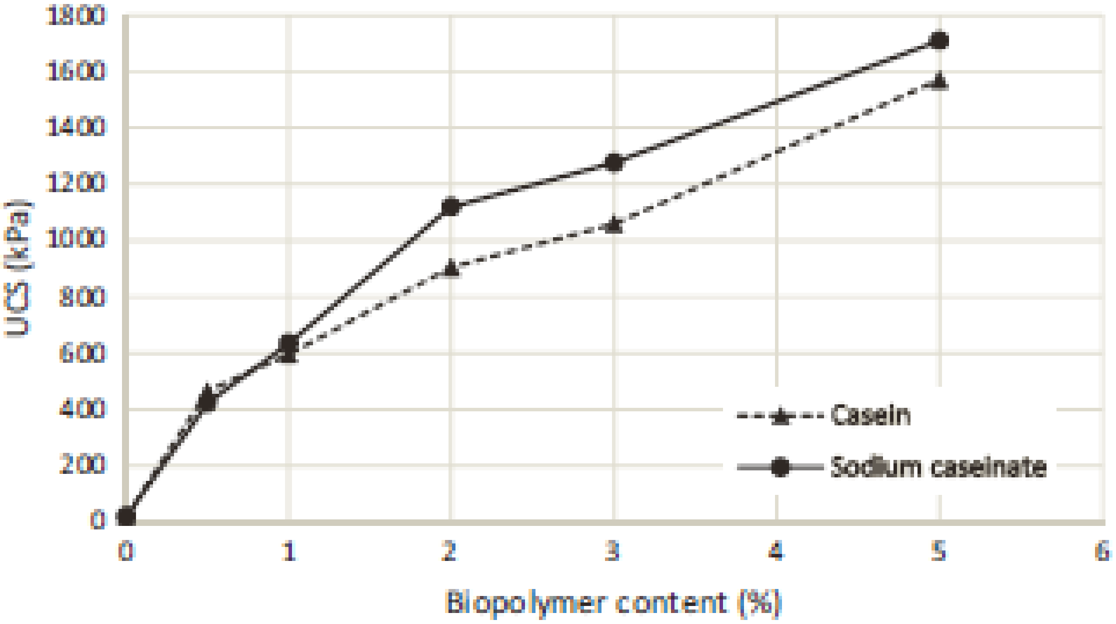


Figure 2.4 *Compressive strength of casein and sodium caseinate treated soil with respect to biopolymer content (Fatehi et al. 2018)*

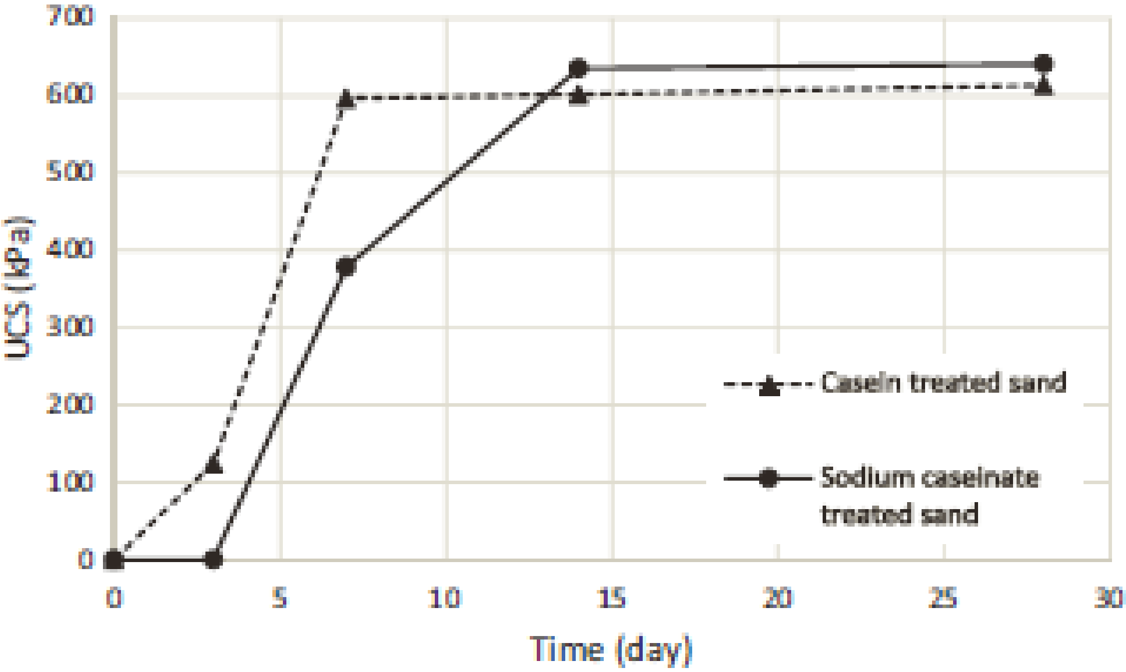


Figure 2.5 *Compressive strength of casein and sodium caseinate treated soil with respect to curing times (Fatehi et al. 2018)*

In a study in China, the strength of silt was believed to be improved by a lignin-based bioenergy coproduct filling pores and linking soil particles so that a more compact and stable soil structure is formed [Zhang et al. 2014]. As it is shown in Figure 2.6, the highest improved strength occurred with 12% of bioenergy coproducts A and B. The researchers believed the optimum dosage of the tested bioenergy coproducts ranged from 10 to 12% [Zhang et al. 2014]. It is also observed from Figure 5 that the improved strength after 28-day curing was higher than those after 1-day and 7-day curing [Zhang et al. 2014]. In this research, specimens underwent air-dried process, and therefore, specimens cured for 1 day contained more moisture than those cured for 7 and 28 days. Based on this, the researchers believed that bioenergy coproduct B is more effective to improve strength for silt under “wet” condition, and Coproduct A is more effective to improve strength for silt under “dry” condition [Zhang et al. 2014].

The researchers further investigated the reasons why the strength improvement with respect to morphology, and found the bioenergy coproduct treated sample was bonded with precipitated cementing materials. As it is shown in Figure 2.7, the silt particles became coated by the coproduct which formed a stronger and more stable soil-coproduct structure [Zhang et al. 2014]. It was concluded that lignin-based bioenergy coproducts function as cementing material, which act completely different than traditional soil stabilizers [Zhang et al. 2014].

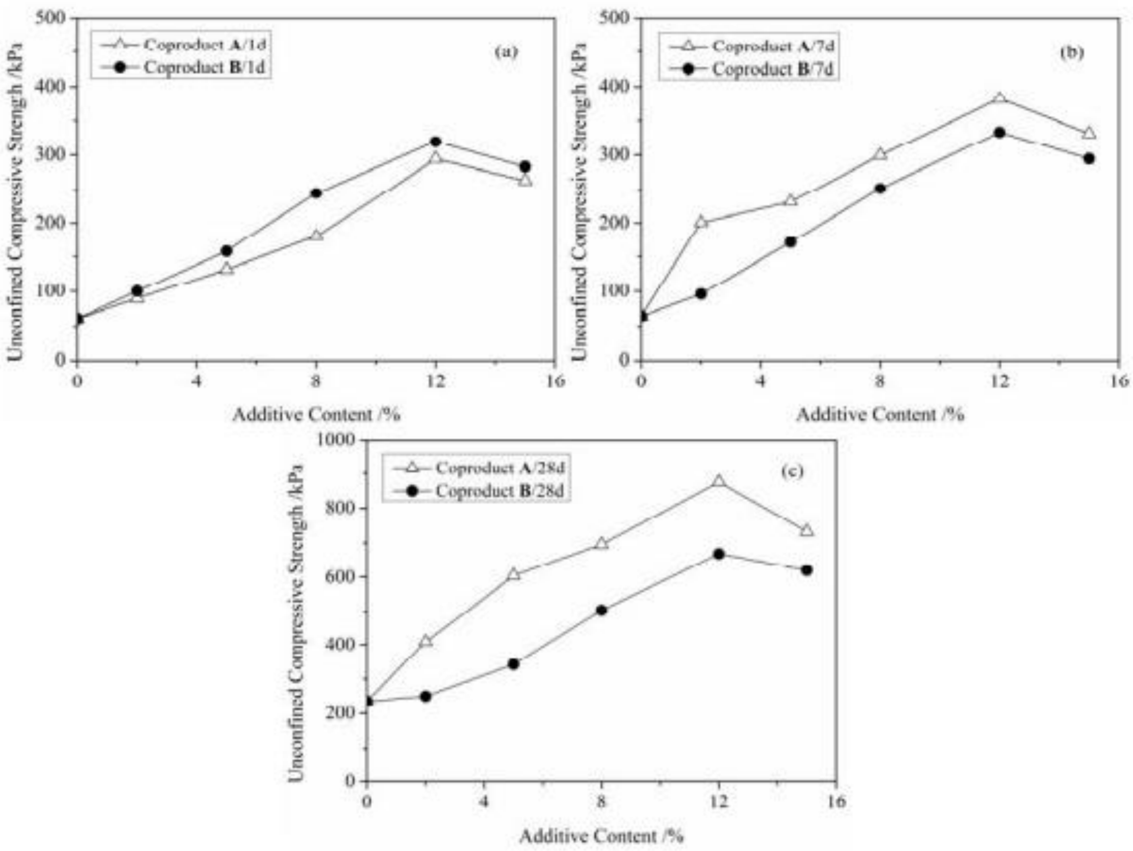


Figure 2.6 *UCS Results of 1d, 7d, and 28d curing (Zhang et al. 2014)*

In a recent study, the efficiency of casein and sodium caseinate salt biopolymers being soil stabilizer was tested, where the researchers investigated the reasons for the improvement of strength by conducting SEM analysis. Through comparing Figure 2.8 (a) and Figure 2.8 (c), one can observe that the casein biopolymer interacted with soil particles. The researchers believed that the adhesion occurred in 4 stages - wetting, adsorption, curing, and mechanical locking [Fatehi et al. 2018].

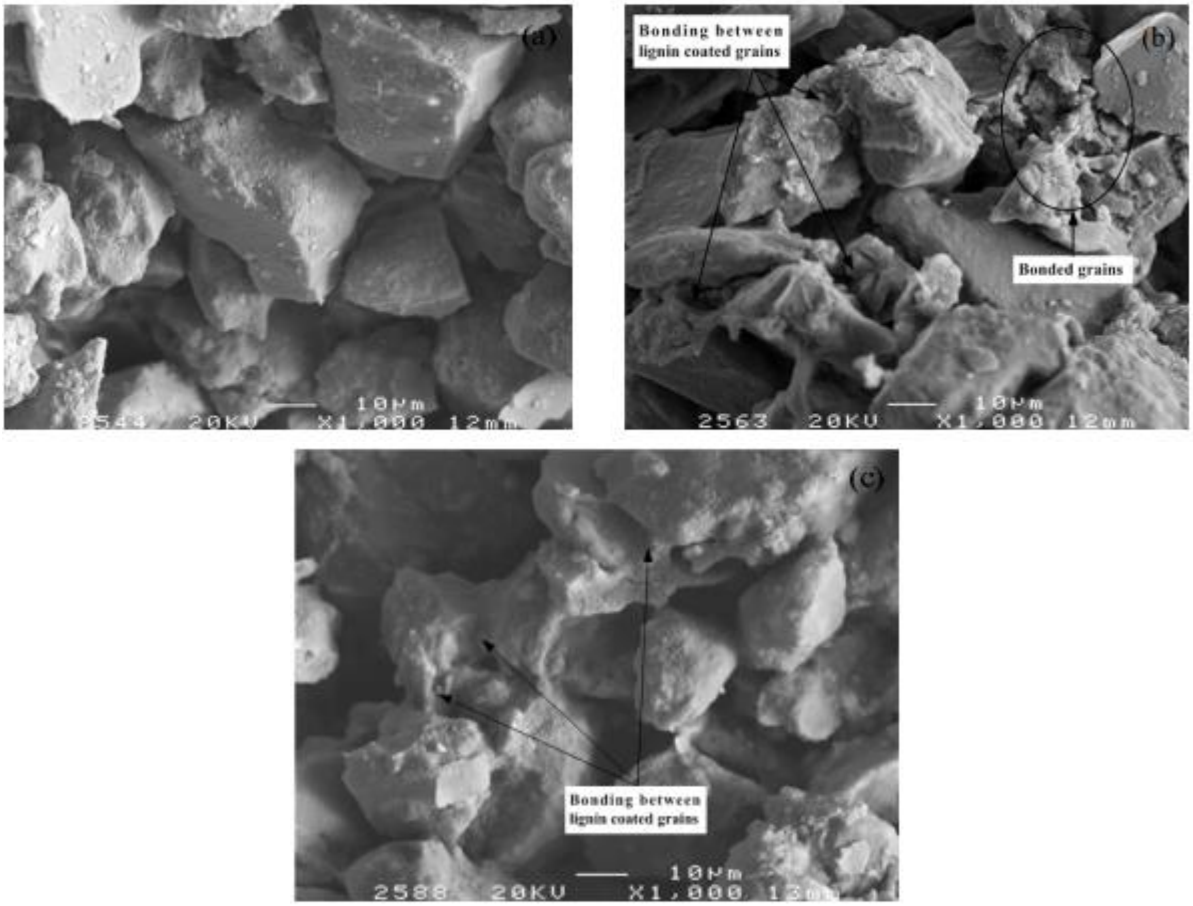


Figure 2.7 *SEM Results of untreated and 12% bioenergy coproduct A-treated soil (Zhang et al. 2014)*

Another recent study investigated the efficiency of enhancing the properties of expansive clay with lignosulfonate. It was found that lignosulfonate improved the clay strength, and strength improvement increased with decrease in compaction water content [Noorzad et al. 2018]. In addition, the reduce of swell percent, swell pressure, and plasticity index of clay soil also related to the lignosulfonate addition [Noorzad et al. 2018]. Through SEM, it was concluded that these improvements occurred because of soil aggregation that related to the electrostatic reaction between lignosulfonate-water mixture and clay particles [Noorzad et al. 2018].

A similar study focused on clayey soil, and the results showed that plastic index (PI) reduced with the treatment of lignosulfonate [Ta'negonbadi et al 2017]. It was also found that the stabilization increased the stiffness and unconfined compressive strength without causing considerate brittle behavior [Ta'negonbadi et al 2017].

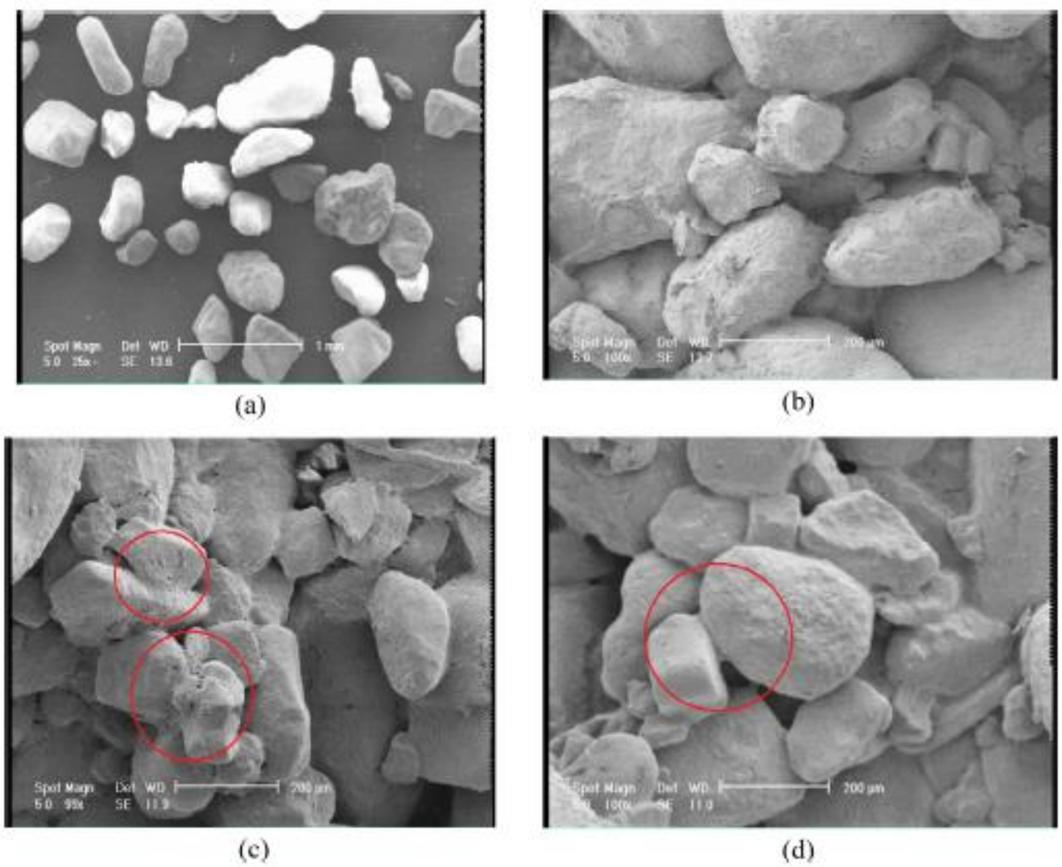


Figure 2.8 *SEM images of a) natural state of dune sand, b) compacted untreated sand, c) casein treated sand, and d) sodium caseinate treated sand (Fatehi et al. 2018)*

The mechanism of expansive soil stabilization with lignosulfonate has recently been identified, and the result indicated that the swelling property was intimately related to the amount of water absorbed by the clay minerals, which was significantly influenced by the small addition of lignosulfonate (Alazigha et al. 2017).

During the previous decade, several researchers reported the improvement of soils' strength with the treatment of lignosulfonate, yet very few field demonstration has been carried out to verify the feasibility of field scale application using the laboratory result. A field performance test was conducted in which lignin and quicklime were used for stabilizing silty soils in highway subgrade (Zhang et al. 2017). The in situ test results indicated that, with 96% degree of compaction, and after 15 days of curing, the silt treated with 12% lignin showed outstanding mechanical performances (higher values of California Bearing Ratio and resilient modulus, lower values of resilient deflection and dynamic cone penetration index) than the one treated with 8% quicklime. Under the same percentage of additive (8%), the lignin stabilized silt illustrated a slightly lower bearing capacity compared to the quicklime stabilized silt (Zhang et al. 2017). Consequently, Zhang et al. (2017) concluded that lignin can be an alternative stabilizer for subgrade soil because of its insignificant environmental influences and affordable construction costs (Zhang et al. 2017).

In Situ Tests

Table 2.3 summarizes a series of in situ tests for measuring the stiffness/strength of compacted unbounded materials (Nazzal 2014). The testing devices can be divided in 4 groups: Group I consists of impact devices, Group II's methods apply static, vibratory, or impact load to the ground, then receive the load and displacement measurements for stiffness estimation; Group III's devices generate surface waves and thus determine the modulus based on geophysical techniques; Group IV consists of sensors buried in the group. In addition, there is another type stiffness/strength technology (Group V) that is used to provide continuous assessment of compaction.

Table 2.3 *Summary of in situ tests*

Group	Test	Device	Influence Depth	Standard	Cost
I	Dynamic Cone Penetrometer (DCP)	Dynamic Cone Penetrometer	As deep as 1.2 m	ASTM D6951 or ASTM D7380	About $1,500

Table 2.3 *(continued)*

I	Clegg Hammer (CH)	Clegg Hammer	Maximum 250 mm for 10 and 20-kg hammers; Maximum 300 mm for 10 and 20-kg hammers Maximum 203 mm	ASTM D5874	Basic CH system costs $3,000. The complete system costs up to $20,000
II	Briaud Compaction Device (BCD)	Briaud Compaction Device	Ranged between 121 mm to 311 mm for an acceptable modulus range	N/A	N/A (new device)
	GroGauge	GeoGauge (soil stiffness gauge)	190 mm to 203 mm); 127 mm to 254 mm	ASTM D6758	Ranges between $5,000 and $5,500
	Light Weight Deflectometer (LWD)	Light Weight Deflectometer	Between 270 and 280 mm, or 1.5 times the diameter of the loading plate; 0.9 to 1.1 times times the diameter of the loading plate	ASTM E2583-07	It varies with producers.
III	Portable Seismic Property Analyzer (PSPA)	Portable Seismic Property Analyzer	N/A	N/A	Ranges from $20,000 to $30,000
IV	Soil Compaction Supervisor (SCS), or Soil Compaction Meter	Soil compaction supervisor (SCS) sensor with a control unit	Approximately 7662 mm	N/A	$1,650

Table 2.3 *(continued)*

Table 2.3 *(continued)* V	Continuous Compaction Control (CCC)	Rollers equipped with a real-time kinematic system (RTK), GPS, and roller-integrated measurement system	It varies with type of ICMV measurement used.	N/A	Expensive
	Intelligent Compaction (IC)	IC Roller, or Bomag VarioControl System	It varies with type of ICMV measurement used.	N/A	Expensive

Cetin (2017) stated six stiffness measurement methods, including: 1) nuclear methods, 2) sand cone method, 3) Shelby tube or thin drive sampler, 4) dynamic cone penetration, 5) falling weight deflectometer (FWD), and 6) plate load test (Cetin 2017). Among all of these compaction measurement methods, falling weight deflectometer (FWD) is the most commonly used one. Generally speaking, a falling weight deflectometer (FWD) is used to measure if a pavement system is overload by traffic and if a pavement layer is well compacted. The data obtained from falling weight deflectometer (FWD), such as the elastic moduli of an individual layer within a pavement system, is usually used to calculate the stiffness-related parameters of the pavement system. A light weight deflectometer (LWD) is a lighter version of falling weight deflectometer (FWD), which is often used to conduct rapid road test.

Compaction Equipment and Methods

In general, there are several types of compaction equipment that are commonly used in the U.S., including rubber tired rollers, smooth steel drums, sheep foot rollers, and pad foot rollers. In general, the choice of compaction equipment and methods depends on soil type, moisture condition, and intended function of the compacted fill (Cetin 2017).

It has been determined that the degree of soil compaction is depended more on the number of roller passes than the weight of a roller (Cetin 2017). Demonstrated in Figure 2.9, it is recommended to use varied types of rollers based on soil types (Cetin 2017). Sheep foot rollers provide mixing and kneading that help create uniformity in a given cohesive soil life. Consequently, as it is shown in Figure 2.9, sheep foot rollers are more desirable when there is a large amount of clay existing, whereas smooth drum are more preferable when sand content is more than 50%. It is also noticed that pneumatic, pad foot drum, and tamping are more flexible to use when sand/clay ratio is unknown or complicated. It is obvious that, to use this method to determine compaction equipment, the most priority work is to detect the sand/clay ratio of the field. However, in almost all circumstances, the sand/clay ratio is not in an even manner within the construction field. Thus, a conclusion can be drawn that the roller types that cover a large range, such as smooth drum rollers, tamping rollers, and patfoot drum rollers, are more practical in field construction. Rubber tired rollers are more efficient than sheep foot rollers because rubber tired rollers require fewer numbers of passes for the same degree of compaction (Cetin 2017). Rubber tired rollers are also more likely to increase the degree of saturation and induce pore pressure for water and air (Cetin 2017). Therefore, rubber tired rollers are more desirable when the existing soil is dense.

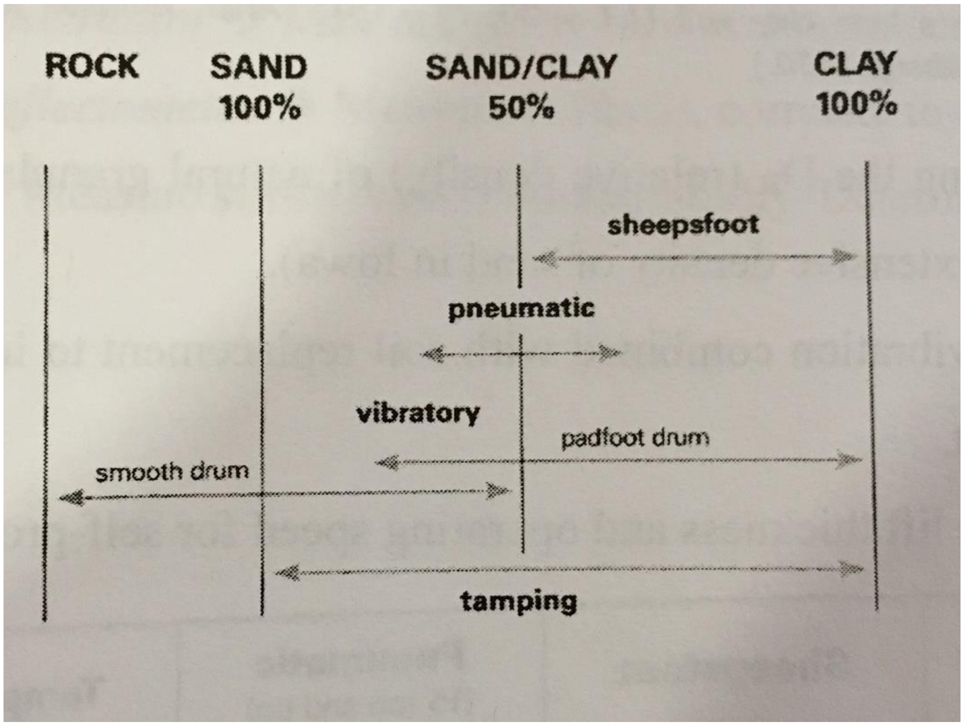


Figure 2.9 *BuRec's recommendation of using different roller types based on soil types (Cetin 2017)*

Cetin (2017) illustrated the unique characteristics for three types of compaction rollers in a detailed manner (Cetin 2017). Table 2.4 summaries a selection made for the greatest contribution to the field demonstration project.

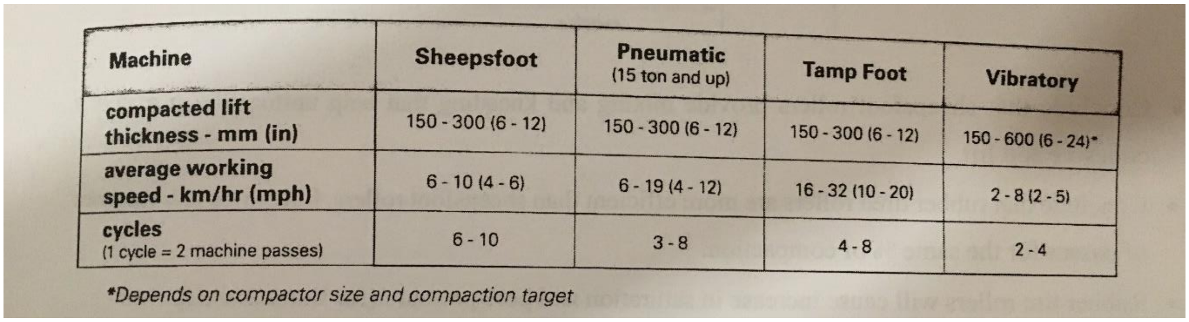
Table 2.4 *Characteristics of three types of compaction rollers*

Compaction Rollers	**Highlighted Characteristics**
Sheep foot (tamping) Rollers	Some standards for rollers (tamping) include roller drums, tamping feet, and roller weight. A good construction requires the excavation and placement obtains as much mixing as practicable.

Table 2.4 *(continued)*

Rubber-Tired Rollers	Rubber tired rollers can usually compact in a more speedy manner and comes with a lower cost compared to a sheep foot roller. Rubber-tired rollers leave a smooth compacted surface. However, it is not in the consideration if the subbase layer is being compacted. The moisture content of soil becomes a sensitive consideration if rubber-tired roller is used for compaction. Heavy rubber tired rollers are not recommended for soils with high initial clay contents but are effective and economical to apply for soils with a large range from clean sand to silty clay. The unit pressure applied to any depth of soil is positively proportional to wheel load and tire inflation pressure. In order to produce higher density of compacted soil, it is more effective to increase tire pressure than wheel load.
Vibratory Rollers	There are 4 factors that influence vibratory compaction: static pressure, manipulation, impact, and vibration. Thickness of compacted lifts is controlled by weight and vibration frequency, which must be matched to the material being compacted. In order to achieve the biggest practicable efficiency, the operation frequency should be at least as large as the resonant frequency The feet of a vibratory roller should penetrate the entire life thickness so that the bond between lifts can be secured.

Figure 2.10 contains a list of suggested values of compacted lift thickness, moving speed, and the required compaction cycles for 4 different self-propelled compaction rollers (Cetin, 2017). The compacted lift thickness for four listed types of compaction rollers are all ranged from 150 to 300 mm; difference lie on operating speed and number of passes. It should be noted that the exact choice to compacted lift, average working speed, and cycles are depended on compactor size and compaction target. Consequently, the suggested values in Figure 2.10 cannot apply to field demonstration without knowing the details of compactor and compaction field.



Machine	**Sheepsfoot**	**Pneumatic** (15 ton and up)	**Tamp Foot**	**Vibratory**
compacted lift thickness - mm (in)	150 - 300 (6 - 12)	150 - 300 (6 - 12)	150 - 300 (6 - 12)	150 - 600 (6 - 24)*
average working speed - km/hr (mph)	6 - 10 (4 - 6)	6 - 19 (4 - 12)	16 - 32 (10 - 20)	2 - 8 (2 - 5)
cycles (1 cycle = 2 machine passes)	6 - 10	3 - 8	4 - 8	2 - 4

**Depends on compactor size and compaction target*

Figure 2.10 *Lift thickness and operating speed for self-propelled compaction equipment (Cetin 2017)*

Claycrete Stabilization at Ringgold County

A field visit was carried out on July 20th, 2018 when PROSPER team headed to Ringgold County, IA to document the application of base layer stabilization using Claycrete. Claycrete is a liquid type soil stabilizer which was introduced from Australia. Claycrete™ claims that Claycrete is an environmentally friendly ionic stabilization product. The author had a great opportunity to talk with Rod Shields, the road superintendent of Ringgold County Engineer's Office, regarding the application of base layer stabilization using liquid type stabilizer.

Shields mentioned that County Highway P68 underwent Chip Seals treatment multiple times over the past several decades. The most recent time was in 1994. The base layer stabilization started with the removal of 7'' of gravel and multiple Chip Seals layer. Based on the width and spraying rate of the Claycrete spraying,3-4 passes were required for the whole site.

The author has also visited the field which had been applied Claycrete a day before. Too much water had been applied to the field so the base layer was still wet even after 1 day of compaction. The ¾ ton truck was hard to control when driving on this base layer due to the high moisture content of the base layer. It also delayed the date of traffic opening because it required more days for the water evaporation. The solution for this issue would be applying less water and having the rollers passing several more trips.

Base One Stabilization at Louisa County

A field visit was carried out on July 17th 2018 when the PROSPER team headed to Louisa County, IA to document the application of base layer stabilization using Base One. Base One is a liquid type soil stabilizer which was originally used for dust control purpose. The author had a great opportunity to talk to Adam Shutt, the assistant Louisa County engineer, regarding the application of base layer stabilization using liquid type stabilizer.

Shutt shared the procedure of base layer stabilization: 1) the water tank truck sprays water on soil, 2) the Base One spraying truck applies the soil stabilizer, 3) the road grader blends the soils, and 4) the roller compacts the soil. Theoretically, Steps 1 through 4 counted one trip, and 10 trip was required for base stabilization. The purpose of Step 1 was to moisten the base layer soil so as the stabilizer would be applied in an even manner. Road graders are capable to cut ditches to a depth of 3 feet, however, in this application, the depth of road grader was set to be around 1 foot due to financial reasons. In Step 4, the base layer required approximately 3 roller passes.

Shutt also mentioned the proportion of Base One and water with respective to field demonstration. The spraying amount of Base One and the speed of Base One sprayer was calculated based on the suggestion from the company producing Base One. The amount of water used for dilution did not make a significant effect. The informed rule of thumb to test the optimum moisture content (OMC) is to grab the mixed soil in palm. If the mixed soil turns into a solid shape under some palm strength, the optimum moisture content (OMC) is achieved. Due to the uneven distribution of water and Base One, it was suggested that the field engineer performed this simple test at different locations of the field.

As for the field equipment coordination, Louisa County owns the road grader. Shutt borrowed the other field equipment from for-profit companies (Blue Flame Propane) and city/county facilities. The biggest challenge for the project was the water tank truck. It was not easy to find a water tank truck with spraying device in the middle of summer, and the closest location where Shutt could find one was 100 miles away. Shutt borrowed a water tank truck from a neighboring county.

CHAPTER 3. MATERIALS AND METHODOLOGY

Materials

Lignosulfonate

The concentrated ammonium-based lignosulfonate (Figure 3.1), identified as Lignin LS-50, is a co-product from paper pulp production that appears as a black, viscous, and homogeneous liquid with a botanical smell. According to the safety data sheet, this lignosulfonate is not classified as environmental hazardous with respect to the ecotoxicity. This lignosulfonate is not known as a "hazardous chemical" in accordance with the OSHA Hazard Communication Standard, 29 CFR 1910.1200. Besides, all of the components are on the U.S. EPA TSCA Inventory List. Good ventilation (i.e. 10 air changes per hour) is required for the storage of this lignosulfonate. The information regarding the lignosulfonate's melting/freezing point or boiling point was unknown from the safety data sheet. Although the safety data sheet stated the lignosulfonate has a concentration of 90 – 100%, the purchased lignosulfonate was treated as a pure product in this study.

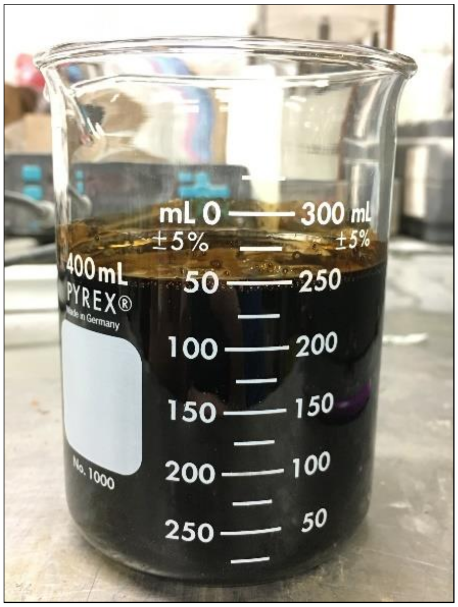


Figure 3.1 *Ammonium-based lignosulfonate*

Purchase of Lignosulfonate

The ammonium-based lignosulfonate was purchased from Blue Flame Propane, an industry located in Letts, IA providing propane and services for home, farm, and business, and rental truck service. In addition, Blue Flame Propane provides dust control service for unpaved roads (Blue Flame Propane 2018). With the unit price of $30 for 19.0 liters, 37.9 liters of ammonium-based lignosulfonate was purchased from Blue Flame Propane for laboratory investigation. The lignosulfonate from Blue Flame Propane was manufactured by Prince Minerals LLC. in New Johnsonville, TN (Figure 3.2).

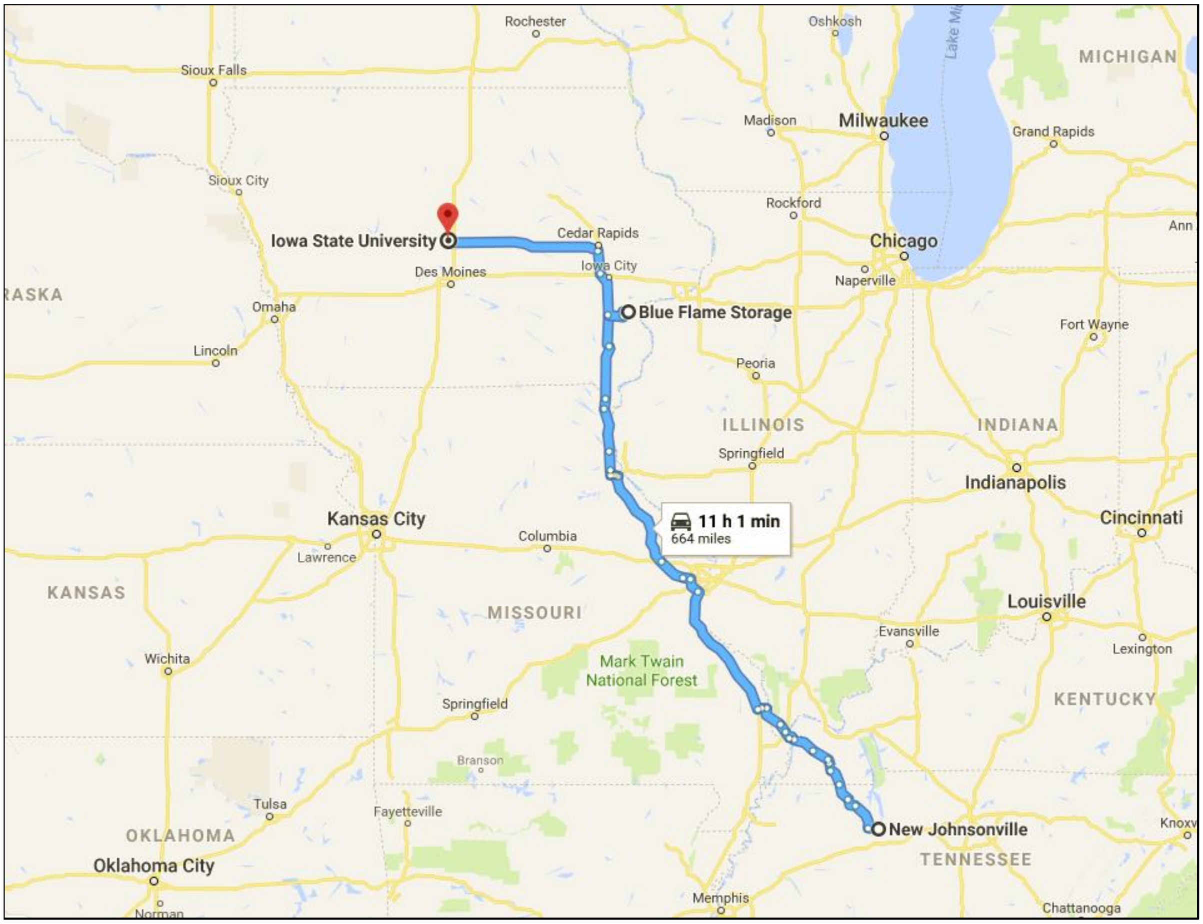
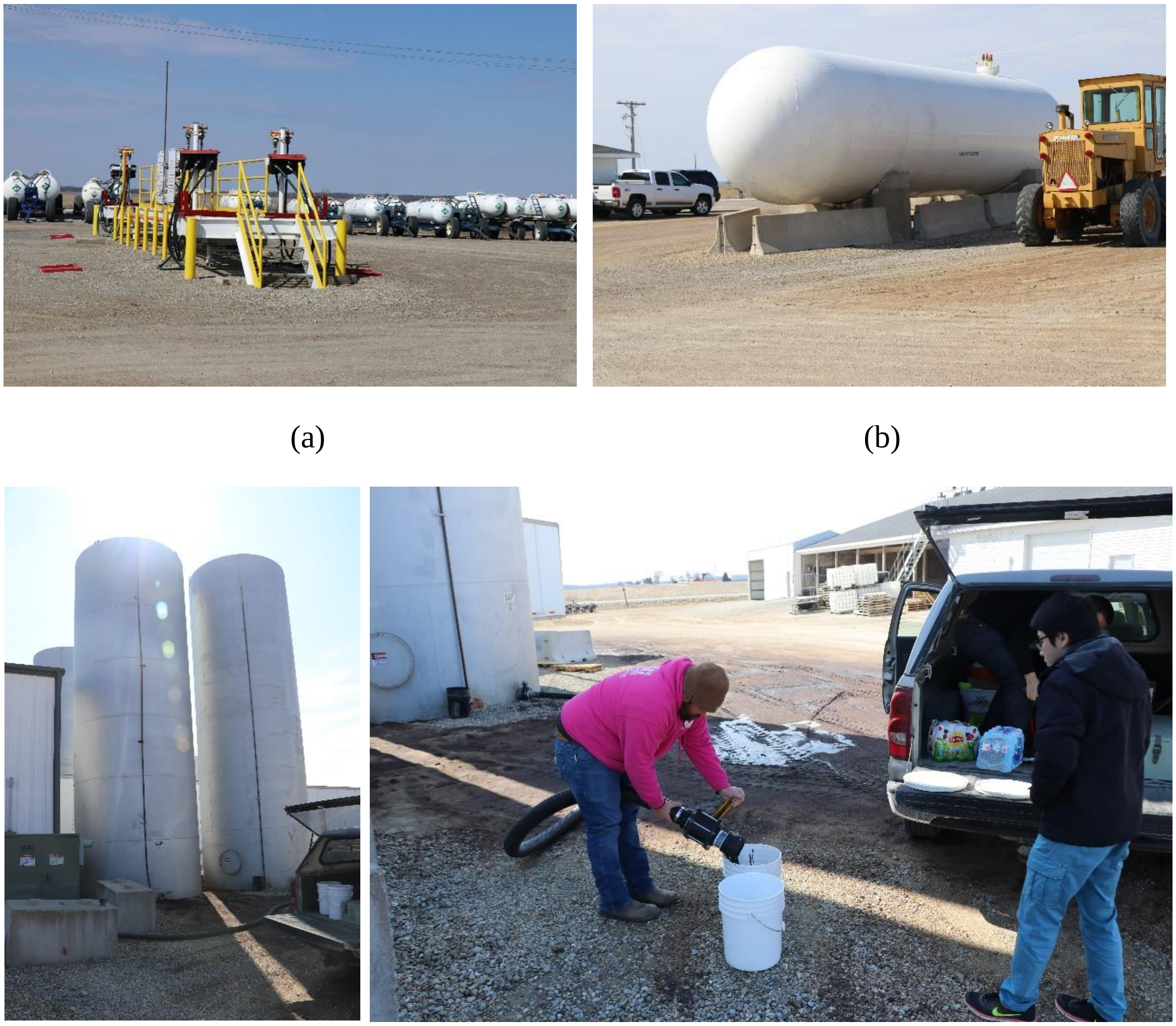


Figure 3.2 *Locations of manufacturer and distributer of lignosulfonate*

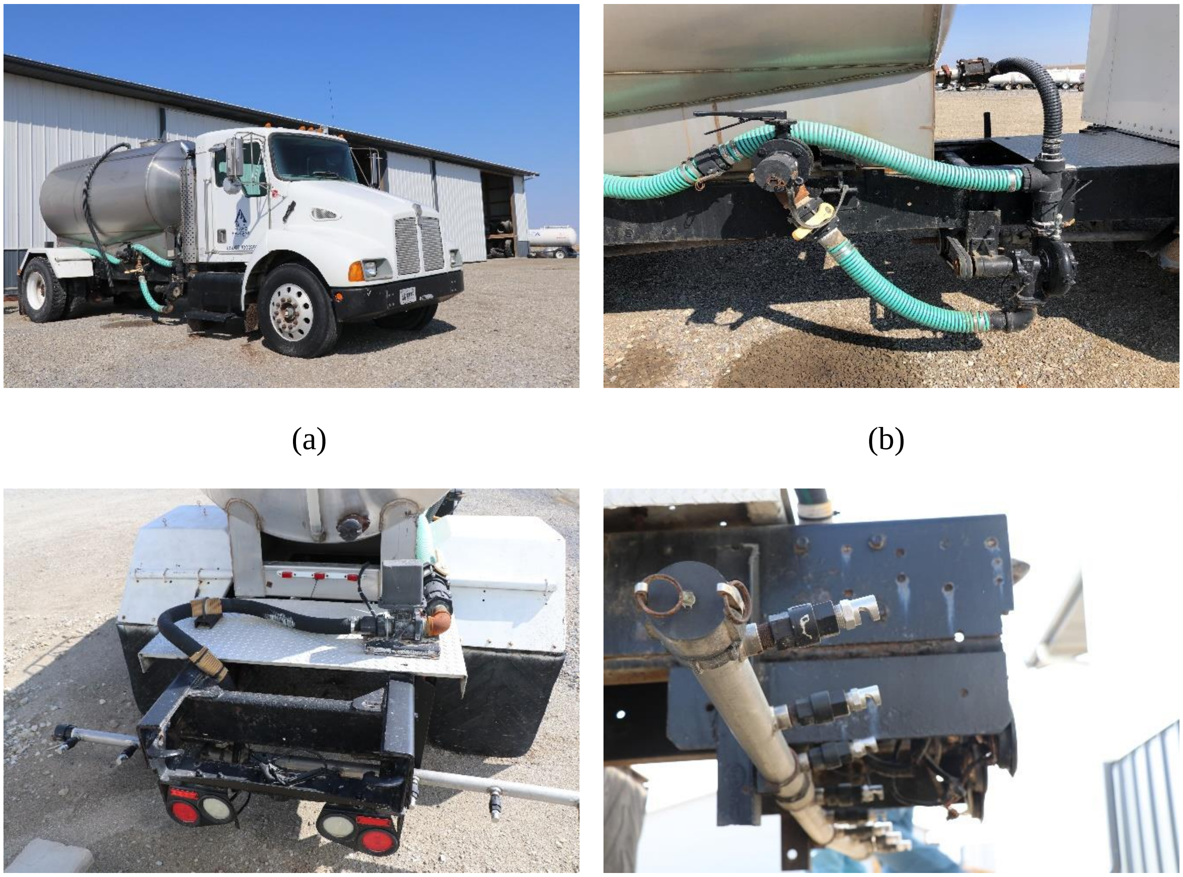
PROSPER team visited the lignosulfonate plant on March 23, 2018. The visual documentation showed the lignosulfonate storage facility (Figure 3.3), and the spraying truck (Figure 3.4).



(a) (b)

(c) (d)

Figure 3.3 *Lignosulfonate storage facility (Blue Flame Propane)*



(a) (b)

(c) (d)

Figure 3.4 *Lignosulfonate spraying truck (Blue Flame Propane)*

Silty soil

Two types of silty soils from Buchanan County, IA (Figure 3.5) were collected and tested for laboratory. The soil classifications and Atterberg limits were obtained with results summarized in Table 3.1, and their particle size distributions in accordance with the ASTM standards are shown in Figure 3.6 (Yang 2015).

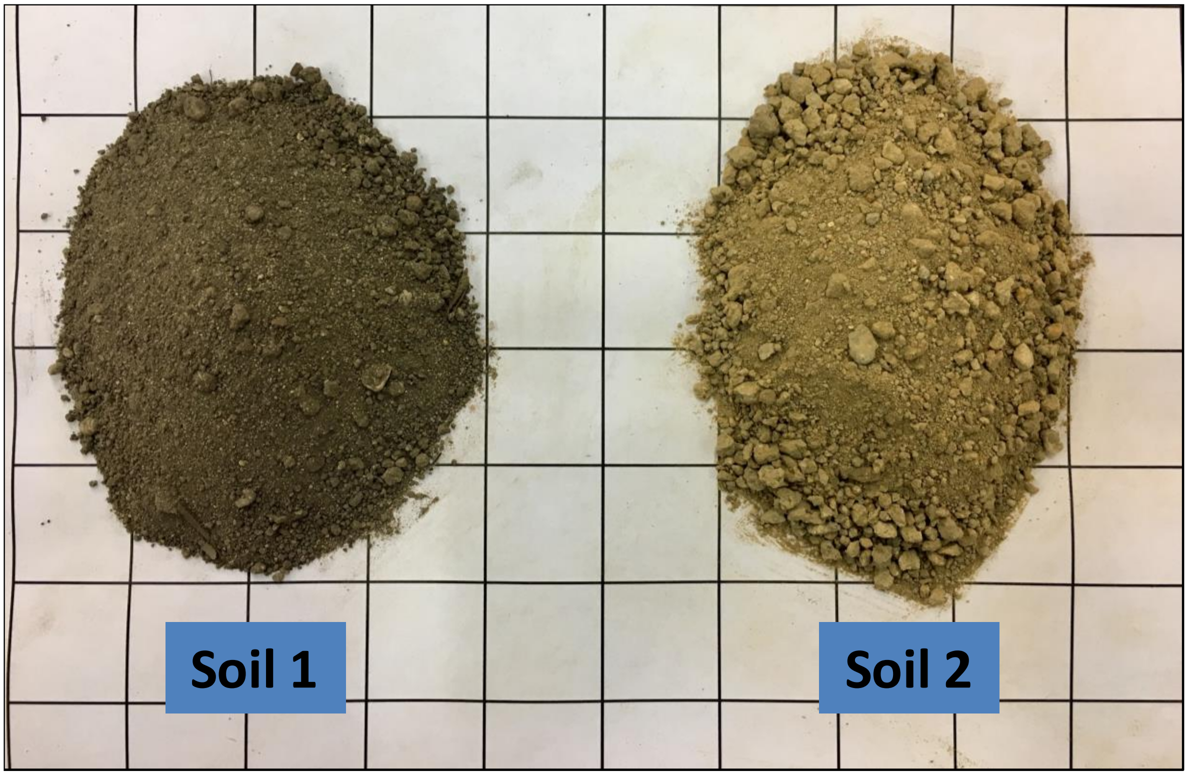
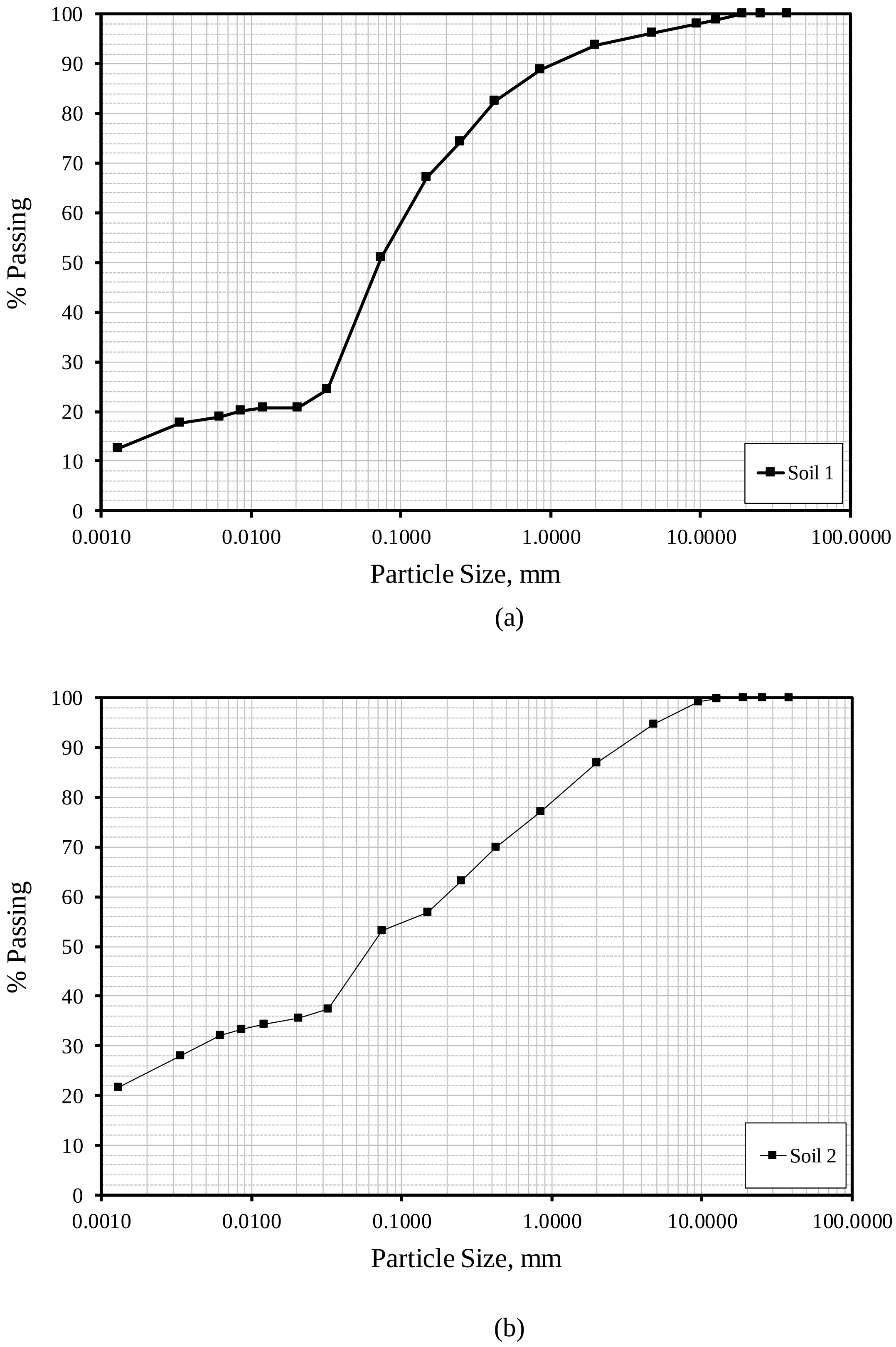


Figure 3.5 *Two types of silty soils*

Table 3.1 *Summary of index properties of soils in this study*

	Soil 1	**Soil 2**
Classification		
AASHTO (group index)	A-4(0)	A-4(1)
USCS (group symbol)	ML	CL-ML
USCS (group name)	Sandy Silt with Gravel	Sandy Silt with Clay
Grain Size Distribution in accordance with ASTM Standard, %		
Gravel (> 4.75 mm)	3.8	5.2
Sand (0.075–4.75 mm)	45.3	41.7
Silt and clay (< 0.075 mm)	50.9	53.1
Atterberg Limits, %		
Liquid limit (LL)	17.2	27.5
Plasticity limit (PL)	15.1	22.2
Plasticity Index (PI)	2.1	5.3



(a)

(b)

Figure 3.6 *Particle size distribution curves for (a) Soil 1, and (b) Soil 2 (Yang 2015)*

Laboratory Test Programs

Table 3.2 summarizes the laboratory tests conducted for evaluating the performance of lignosulfonate-stabilized silty soils. Because of the specific properties of lignosulfonate used as an alternative soil stabilizer, standard specifications listed as references in Table 3.2 were not strictly followed but modified and used.

Table 3.2 *Summary of laboratory test programs*

Test	Measurement	Reference
Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort	Optimum Moisture Content and Maximum Dry Unit Weight	ASTM D698
Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures, and Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders	Unconfined Compressive Strength	ASTM D5102 ASTM D1633
Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures	Volume Change	ASTM D560
Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures	Volume Change	ASTM D559
Set Time Test	Surface Strength and Evaporable Content	N/A

Proctor compaction tests (Figure 3.7) were conducted for both unmodified soils and soil-lignosulfonate mixtures. For unstabilized soils, the purpose of the Proctor compaction test was to determine the optimum moisture content (OMC) and the maximum dry unit weight. For the soil-lignosulfonate mixtures, Proctor compaction tests were carried out to determine the optimum moisture content (OMC) and the maximum dry unit weight at each dosage level of lignosulfonate. Dry silty soils passed through a No. 4 sieve were mixed with 5, 10, and 15 percent levels of diluted lignosulfonate and varying percentages of water in a homogenous manner, then rammed into a 6.0-inch (15.24-cm) cylindrical mold. Because there was less than 25% by weight of cumulative retained soils on the No. 4 sieve based during sieve analysis, the Method A in ASTM D698 was employed.

Figure 3.7 *Proctor compaction test*

The specimens were sealed with plastic wrap and aluminum foil to prevent moisture loss and heat transfer. Because the curing process of specimens was deemed to involve physical reaction only (i.e., binding between lignosulfonate and soil particle), a curing period of 7 days at room temperature was implemented. Figure 3.8 shows a specimen after curing.

Figure 3.8 *A specimen after curing*

An unconfined compressive strength test using the versa loader from ELE International with a strain rate of 2% per minute was conducted to determine the compressive strength of the Proctor compaction test specimens (Figure 3.9), and specimens with the highest compressive strength would reflect the optimum lignosulfonate dosage and moisture content. The actual moisture content of each specimen was tested after the compaction of each specimen.

Figure 3.9 *Unconfined compressive strength test*

A freeze-thaw durability test (Figure 3.10) and a wet-dry durability test (Figure 3.11) were performed to determine specimens' volume change and mass loss caused by repeated freezing and thawing cycles, and specimens' volume change caused by repeated wetting and drying cycles. For testing each soil type, two groups of specimens were prepared: (1) soil specimens with the optimum mix proportion (the optimum mix proportion was revealed in the unconfined compressive strength test), and (2) lignosulfonate-stabilized specimens with the optimum mix proportion. The specimens used for durability tests were prepared and cured in the same way as for the unconfined compressive strength (UCS) tests. The Method A was utilized in both tests based on the particle size distributions. The diameter and height of each specimen were measured every half cycle (i.e., each time after freezing, thawing, wetting, and drying) so that specimen volume could be consistently determined and monitored. Moreover, the mass of each specimen in the freeze-thaw durability test was also measured at the same frequency.

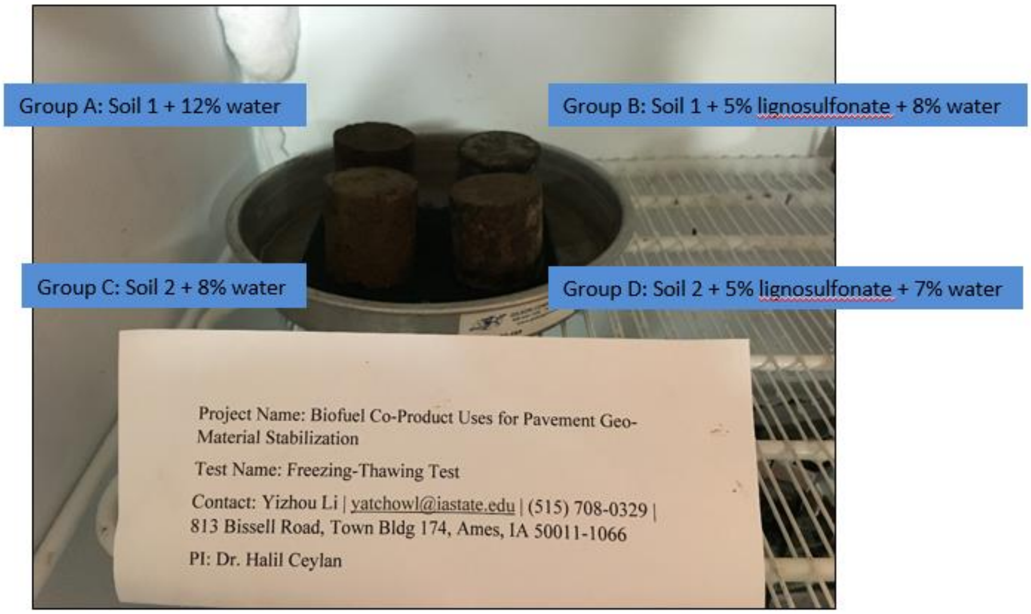


Figure 3.10 *Freeze-thaw durability test*

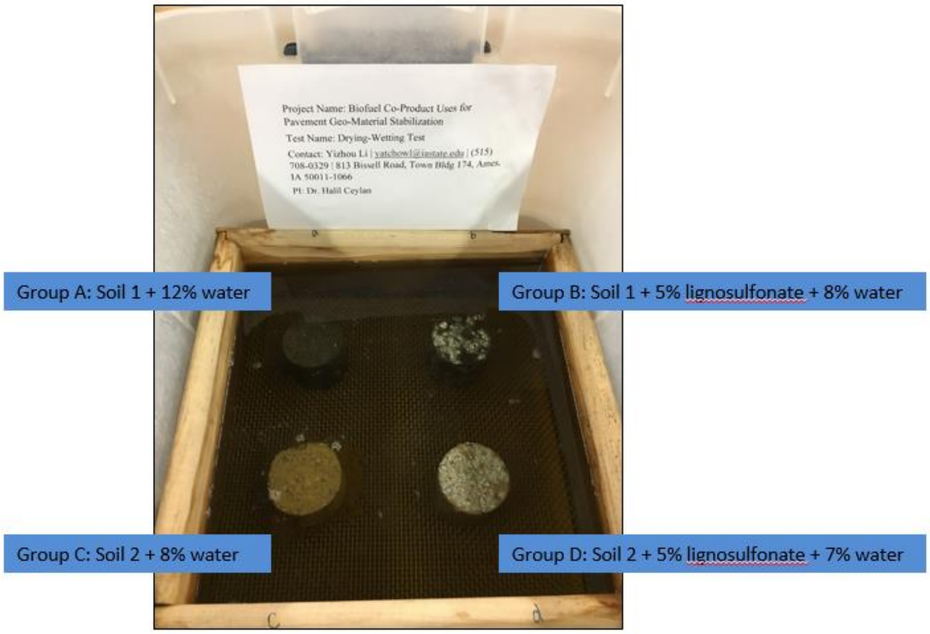


Figure 3.11 *Wet-dry durability test*

During repeated freezing and thawing cycles, specimens did not show a tendency to collapse as expected. Instead, the shape of specimens had been changed in an uneven manner along with soil shedded off from the specimens, which caused mass loss of specimens (Figure 3.12), and therefore, the accumulated volume change was defined (Equation Equation 1) to measure this change.

Figure 3.12 *Specimens after 6 (left), 7 (middle), and 8 (right) cycles of freezing and thawing*

$$Accumulated\ Volume\ Change \qquad \text{(Equation 1)}$$

$$= \sum_{n=1}^{N} |the\ ith\ Measured\ Volume\ (\%) - Original\ Volume\ (\%)|$$

where: $Measured\ Volume\ (\%) = \frac{Specimen\ Volume}{Original\ Volume}$

$Original\ Volume\ (\%) = 100$

$N = Times\ of\ Volume\ Measurement$

The scanning electron microscope (SEM) analysis was performed to justify Soil 1's significant improvement of strength and durability. Two groups of specimens were prepared: (1) Soil 1 specimens with the optimum mix proportion, and (2) lignosulfonate-Soil 1 specimens with the optimum mix proportion. The specimens used for scanning electron microscope were prepared and cured in the same way as for the unconfined compressive strength (UCS) tests and durability tests. During the SEM analysis, cured specimens from both groups were carefully crushed with finger pressure, and small amount of Soil 1 (Group 1) and Soil 1-lignosulfonate (Group 2) fragments were randomly collected for coating prior to taking micrographs.

With the goal of studying the lignosulfonate treated soil's strength improvement with another method, a set time test was conducted to investigate the speed of lignosulfonate becoming hard at different temperatures and their mechanism. 10 grams of lignosulfonate was placed in a 5 cm-wide and 2.2 cm-deep pan to create a thin and smooth surface (Figure 3.13). These pans were then placed in 40°C, 20°C, 0°C, and -18°C conditions to represent the in situ temperatures in summer, spring/fall, winter, and severe winter. A pocket penetrometer was used to check the unconfined compressive strength of these samples' surface every 6 hours. These samples' percentage of evaporable component was also tested using the method for the determination of water content in soil (American Society for Testing and Materials 2019).

(a) (b)

Figure 3.13 *Set time test*

Construction and In Situ Test Programs

Construction Overview, Construction Sections, and Soil Conditions

The construction started at 7:30 am on October 11th, 2018. The temperature of the construction site was detected to be around 3°C. The construction section (Figure 3.14) was selected based on Soil 1's strength and durability test outcomes in the laboratory. With the dimension of 701-meter long and 7.9-meter wide gravel road, the construction road section is located on the 240th Street in Independence, IA. Bowers Best Discount Factory is located at the east end of the 240th Street, and there is no infrastructure along the road but cornfield. The annual average daily traffic (AADT) counts of the 240th Street in 2017 was reported as 240 (Iowa Department of Transportation 2018). There was no major preservation and rehabilitation on the tested road section over the past decade. Heavily-loaded farming machines use this road section frequently during corn's cultivating and harvest seasons, which applies excess load to the gravel road surface and the subgrade layer. Soils from the test section had been collected and tested in laboratory with respect to soil classifications and related soil index properties (Soil 1 in Table 3.1). Note that, a subgrade at which the soils are classified as A-4 in accordance with the AASHTO standard is rated as fair to poor (AASHTO 2017).

Figure 3.14 *Construction sections*

Cement Section

The cement section was a 152.4-meter long and 7.9-meter wide gravel road. Donated by LafargeHolcim Ltd., the amount of cement needed for the construction was estimated to be 17.2 tons. The target cement dosage was 5% based on the stabilization depth (0.15 meter). The utilized equipment included a rear ripper, a cement transport truck with spreader, a reclaimer, a water tank truck equipped with a hose, and the pad foot rollers. The construction stated with the resurfacing of approximately 0.15 meter of road surface with a rear ripper (Figure 3.15), followed by the cement sprayed on the subgrade (Figure 3.16). The soil and cement were then blended along with the water spraying (Figure 3.17), and finally, the pad foot rollers were used for compaction (Figure 3.18).

(a) (b)

Figure 3.15 *Rear ripper resurfaced road surface*

(a) (b)

Figure 3.16 *Cement spraying (cement)*

(a) (b)

Figure 3.17 *Blending with reclaimer (cement)*

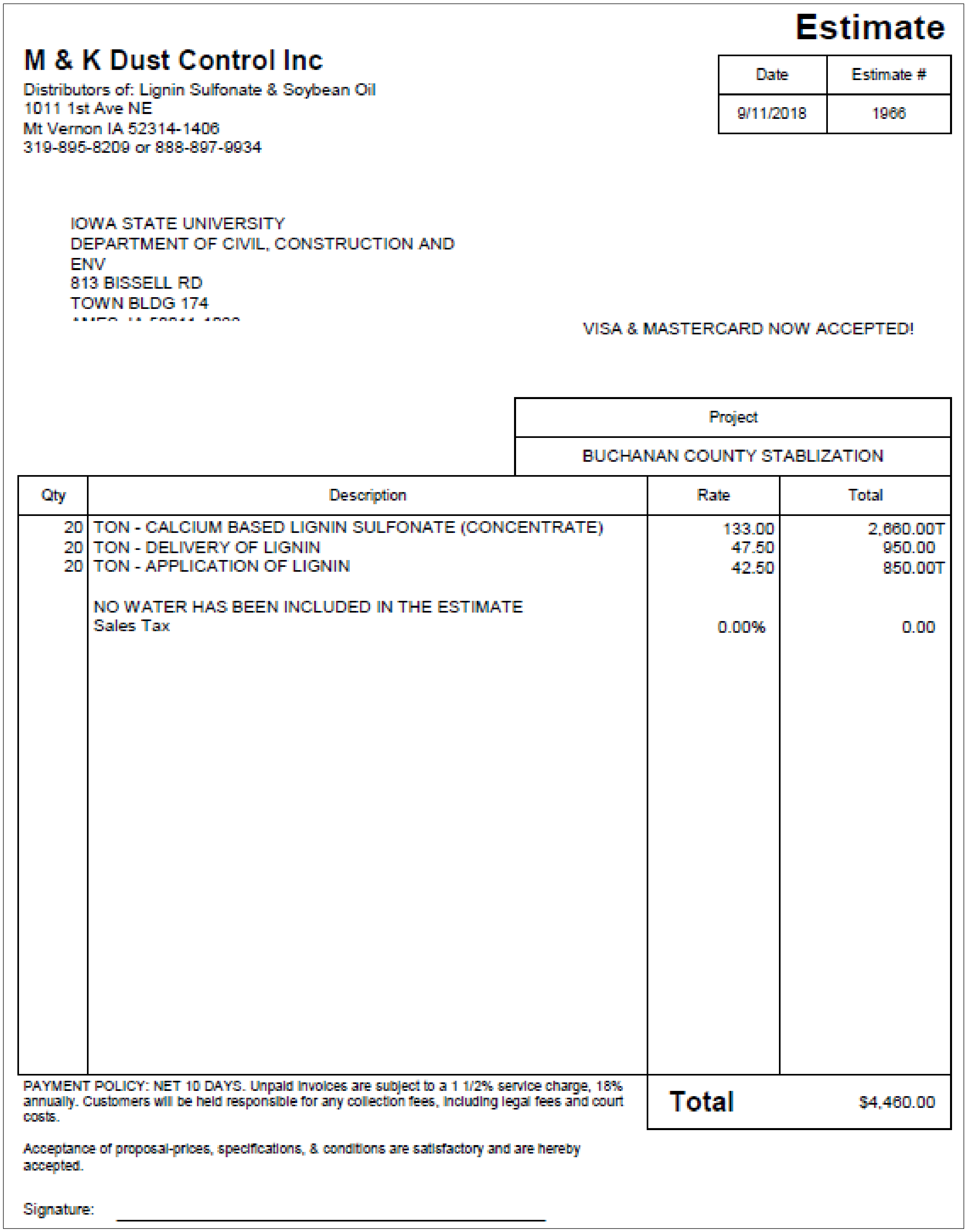
(a) (b)

Figure 3.18 *Compaction with pad foot rollers (cement)*

Lignosulfonate Section

The ammonium-based lignosulfonate was purchased from M & K Dust Control Inc., an industry located in Mount Vernon, IA specializing in dust control, snow removal, and hauling services. M & K Dust Control Inc. also provided the spraying service in the field construction. The quotes of the lignosulfonate and application service are illustrated in Figure 3.19.

The lignosulfonate section was a 91.4-meter long and 7.9-meter wide gravel road. The laboratory investigation reported 5% as the optimum dosage of lignosulfonate used to stabilize sandy silt with gravel, and it led to a 225% increase in unconfined compressive strength. Based on the laboratory investigation, approximately 11.8 tons of concentrated ammonium-based lignosulfonate was planned to be diluted with tap water based on a 1:1 ratio concentration. The utilized equipment included rear rippers, a 3-axle truck carrying four spraying nozzles and a cylindrical tanker filled with diluted lignosulfonate, a motor grader, and pneumatic rollers (Figure 3.20).



Estimate

M & K Dust Control Inc
Distributors of: Lignin Sulfonate & Soybean Oil
1011 1st Ave NE
Mt Vernon IA 52314-1406
319-895-8209 or 888-897-9934

Date	Estimate #
9/11/2018	1966

IOWA STATE UNIVERSITY
DEPARTMENT OF CIVIL, CONSTRUCTION AND
ENV
813 BISSELL RD
TOWN BLDG 174

VISA & MASTERCARD NOW ACCEPTED!

Project
BUCHANAN COUNTY STABLIZATION

Qty	Description	Rate	Total
20	TON - CALCIUM BASED LIGNIN SULFONATE (CONCENTRATE)	133.00	2,660.00T
20	TON - DELIVERY OF LIGNIN	47.50	950.00
20	TON - APPLICATION OF LIGNIN	42.50	850.00T
	NO WATER HAS BEEN INCLUDED IN THE ESTIMATE		
	Sales Tax	0.00%	0.00

PAYMENT POLICY: NET 10 DAYS. Unpaid invoices are subject to a 1 1/2% service charge, 18% annually. Customers will be held responsible for any collection fees, including legal fees and court costs.

Total $4,460.00

Acceptance of proposal-prices, specifications, & conditions are satisfactory and are hereby accepted.

Signature: ______________________

Figure 3.19 *Quotes for lignosulfonate and application service from M & K Dust Control Inc.*

The construction started by resurfacing approximately 6 inches of gravel surface with rear rippers to expose the subgrade layer. Then the diluted lignosulfonate was sprayed on the subgrade as the truck slowly moved forward. A motor grader was used to blend “wet” soil with “dry” soil using its long moldboard, and finally, the pneumatic rollers were used for compaction. Because the lignosulfonate treated soil was still too “wet” 12 hours after construction, a small amount of limestone was then placed on the stabilized soil to absorb the excessive moisture, and pneumatic rollers were used again for compaction, after which the tested road section was closed for 7 days.

(a) (b)

(c) (d)

Figure 3.20 *Rear rippers (a), truck equipped with spraying nozzles and tank (b), motor grader (c), and pneumatic rollers (d) (lignosulfonate)*

Chlorides Section

The chlorides section was a 152.4-meter long and 7.9-meter wide gravel road. Donated by Heffron Services, the target dosage and the amount of chlorides needed for the construction was determined based on the user manual and field dimensions (length = 152.4 meters, width = 7.9 meters, and depth = 0.15 meter) by the company representative on site. The utilized equipment included a truck with chemical liquid container and sprayers, a reclaimer, and the pad foot rollers. The construction started with the resurfacing of approximately 0.15 meter of road surface with a rear ripper (Figure 3.15), followed by the liquid chlorides sprayed on the subgrade (Figure 3.21a). A reclaimer was then used to blend the soils (Figure 3.21b), and finally, the pad foot rollers were used for compaction (Figure 3.21c).

(a) (b)

(c)

Figure 3.21 *Chlorides spraying (a), soil blending with reclaimer, and (c) compaction with pad foot roller (chlorides)*

Claycrete Section

Claycrete is a liquid soil stabilizer that is efficient for soils containing clay. Claycrete reduces the shrink and swell characteristics by changing the ionic charge of the clay portion of the soil. The Claycrete treated soils have sufficient bonding strength among clay particles within their microstructure, and thus can resist expansion of the clay (Road Pavement Products PTY Ltd. 2017).

The Claycrete section was a 152.4-meter long and 7.9-meter wide gravel road. Donated by Claycrete Noth America, the amount of Claycrete needed for the construction was estimated to be 37.8 liters. The target dosage was calculated based on the user manual and the field dimensions (length = 152.4 meters, width = 7.9 meters, and depth = 0.15 meter). The utilized equipment included a truck with chemical liquid container and sprayers, a grader, and a pneumatic rubber tire roller. The construction started with the resurfacing of approximately 0.15 meter of road surface with a rear ripper (Figure 3.15), followed by Claycrete sprayed on the subgrade (Figure 3.22). A motor grader was used to blend “wet” soil with “dry” soil using its long moldboard (Figure 3.23a), and finally, the pneumatic rubber tire rollers (Figure 3.23b) were used for compaction.

(a) (b)

Figure 3.22 *Claycrete spraying and the subgrade condition (Claycrete)*

(a) (b)

Figure 3.23 *Soils blending with motor grader (a) and compaction with the pneumatic rubber tire roller (b) (Claycrete)*

Base One Section

Base One is a liquid soil stabilizer produced by Team Laboratory Chemical Corporation. Base One is utilized by being diluted with water to bring the in situ soils to the required moisture content for compaction (Stabilized Reclamation Using Base One 2018).

The Base One section was a 152.4-meter long and 7.9-meter wide gravel road. The amount of Base One needed for the construction was estimated to be 163.9 liters based on the design requirements (0.005 gallons per square yard per inch of stabilized reclamation depth) and road section dimensions (length = 152.4 meters, width = 7.9 meter, and depth = 0.15 meter). The utilized equipment included a truck with chemical liquid container and sprayers, a reclaimer, a grader, a pneumatic roller, and the pad foot rollers. The construction started with the resurfacing of approximately 0.15 meter of road surface with a rear ripper (Figure 3.15), followed by the Base One dilution and spraying on the subgrade (Figure 3.24). A reclaimer was then used to blend the soils with the Base One (Figure 3.25), and the pad foot rollers were used for the preliminary compaction (Figure 3.26). Then, a motor grader was used to further blend soils using its long moldboard (Figure 3.27), and finally, the pneumatic roller was used for the final compaction (Figure 3.28).

(a) (b)

Figure 3.24 *Base One dilution and spraying (Base One)*

(a) (b)

Figure 3.25 *Blending with reclaimer (Base One)*

(a) (b)

Figure 3.26 *Pad foot roller for preliminary compaction (Base One)*

(a) (b)

Figure 3.27 *Blending with motor grader (Base One)*

(a) (b)

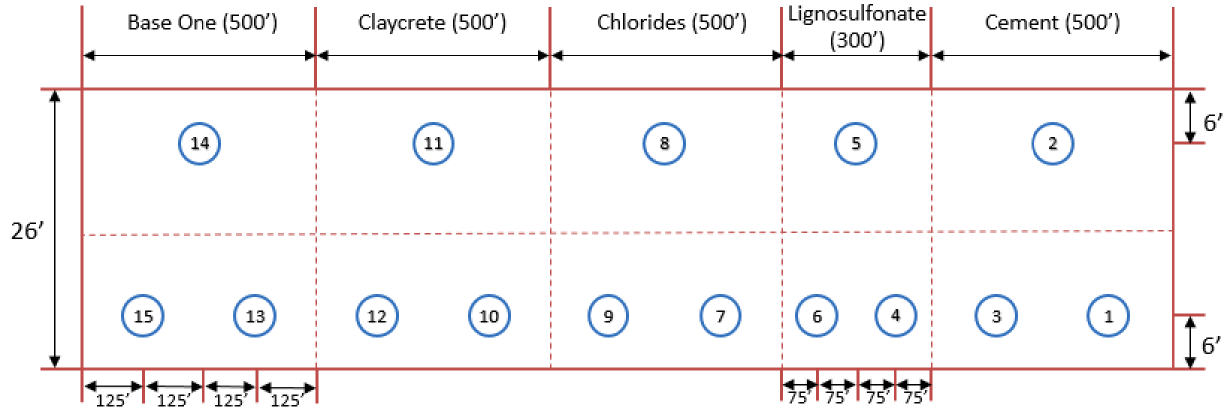
Figure 3.28 *Pneumatic roller for final compaction (Base One)*

In Situ Test Sections

Two in situ tests were performed before and one week after the construction to monitor the strength and durability of the lignosulfonate stabilized soil. The light weight deflectometer (LWD) test was used to spot check the in situ elastic modulus to predict the subgrade stiffness, whereas the dynamic cone penetration (DCP) test was used to measure the subgrade soil's resistance to penetration and correlate to California Bearing Ratio (CBR). In consideration of the two-way traffic, three test points were selected for each test section (Figure 3.14). Table 3.3 (matrix unit) summarizes the locations of in situ test points, which are also visualized in Figure 3.29 (English units).

Table 3.3 *In situ test point locations*

Section	Test Point	Longitudinal distance from the origin of the corresponding test section (meter)	Transverse distance from the north edge of the roadway (meter)
Cement	1	38.1	6.1
	2	76.2	1.8
	3	114.3	6.1
Lignosulfonate	4	22.9	6.1
	5	45.7	1.8
	6	68.6	6.1
Chlorides	7	38.1	6.1
	8	76.2	1.8
	9	114.3	6.1
Claycrete	10	38.1	6.1
	11	76.2	1.8
	12	114.3	6.1
Base One	13	38.1	6.1
	14	76.2	1.8
	15	114.3	6.1



(In situ tests points)

(Not to scale)

Figure 3.29 *In situ test point locations*

CHAPTER 4. RESULTS AND DISCUSSIONS

Laboratory Tests

Proctor Compaction Test

The Proctor compaction test revealed correlation between lignosulfonate dosage and both optimum moisture content and maximum dry unit weight (Table 4.1). Soil 1 exhibited an optimum moisture content of 14.5%, and this remained approximately the same with less than 10% of lignosulfonate added, and was negatively correlated with lignosulfonate dosage. The maximum dry unit weight decreased when 5% of lignosulfonate was added and increased as more lignosulfonate was added. Soil 2 exhibited an optimum moisture content of 13.0% that had a negative correlation with lignosulfonate dosage. The maximum dry unit weight decreased with the use of lignosulfonate, and displayed little change with lignosulfonate dosage.

Table 4.1 *Proctor test result*

	Optimum Moisture Content (%)	**Maximum Dry Unit Weight (kPa)**
Soil 1	14.5	0.176
Soil 1 + 5% Lignosulfonate	15.0	0.169
Soil 1 + 10% Lignosulfonate	13.6	0.175
Soil 1 + 15% Lignosulfonate	9.3	0.188
Soil 2	13.0	0.181
Soil 2 + 5% Lignosulfonate	11.9	0.176
Soil 2 + 10% Lignosulfonate	11.2	0.178
Soil 2 + 15% Lignosulfonate	10.5	0.178

Unconfined Compressive Strength (UCS) Test

14 and 16 unconfined compressive strength tests were performed for Soil 1 and Soil 2, respectively. These tests revealed the preferable lignosulfonate dosage, the optimum mix proportion, and the maximum increase of compressive strength for each soil. As shown in Figure 4.1, low and medium dosages (i.e. 5% and 10%) of lignosulfonate strengthened Soil 1 to some

degree, while higher dosage (i.e. 15%) of lignosulfonate displayed no significant impact on soil strength. The optimum mix proportion was determined to be 5% of lignosulfonate with 11.85% of actual water content, resulting in a 225% increase in compressive strength. As shown in Figure 4.2, only a low lignosulfonate dosage (i.e. 5%) strengthened Soil 2. Medium and high dosages (10% and 15%) had a negative impact on soil strength. The optimum mix proportion was determined to be 5% of lignosulfonate with 8.04% of actual water content, resulting in a 9.3% increase in compressive strength.

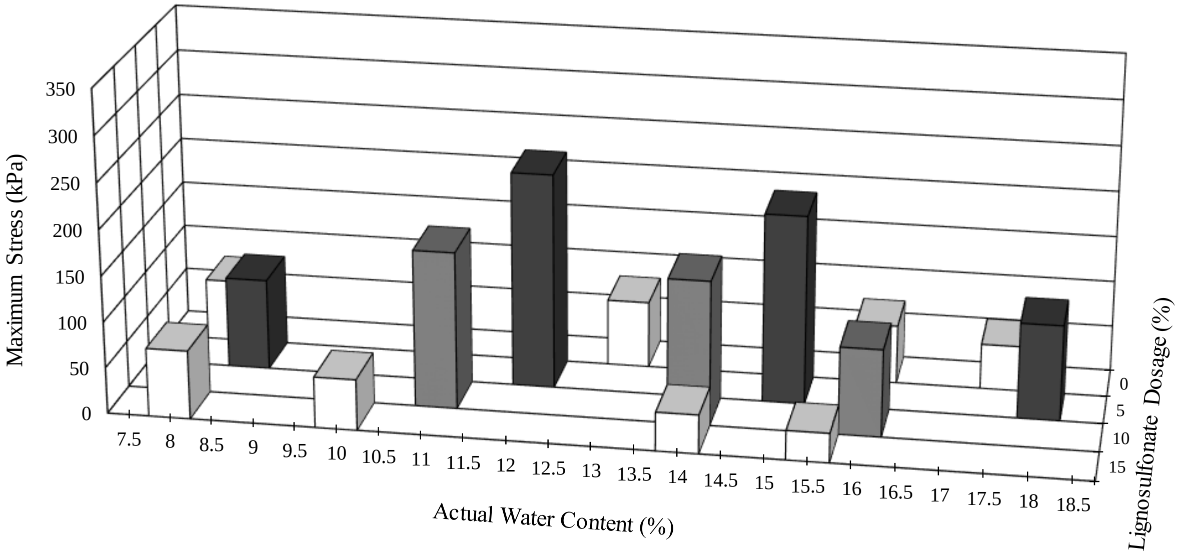


Figure 4.1 *Unconfined compressive strength (UCS) test result for Soil 1*

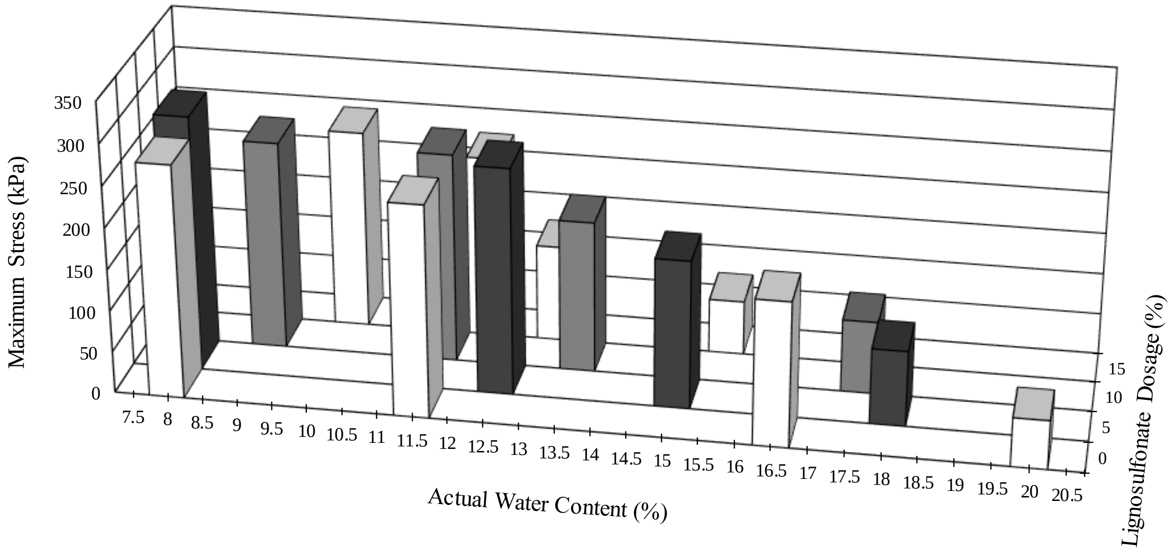


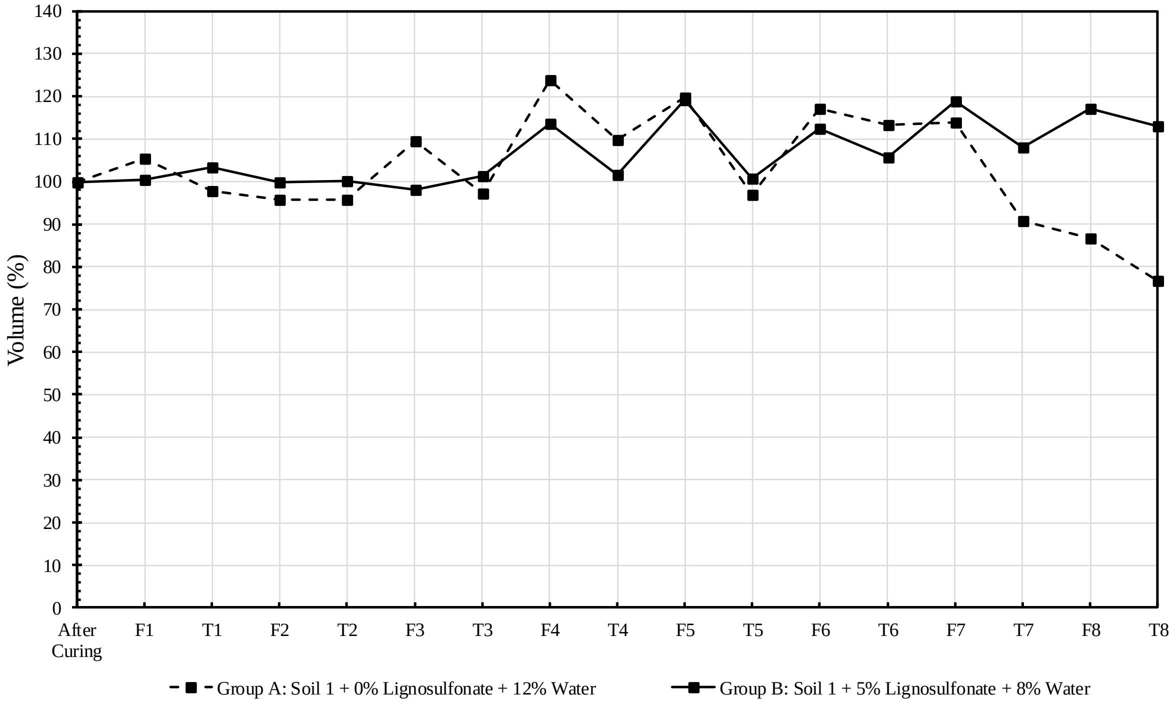
Figure 4.2 *Unconfined compressive strength (UCS) test result for Soil 2*

Freeze-Thaw and Wet-Dry Durability Tests

Eight freeze-thaw cycles were performed in the freeze-thaw durability tests. Specimens expanded and contracted during repeated freeze-thaw cycles with resulting changes in volume, but specimens showed no tendency to collapse as had been expected. The specimen shapes instead changed in an uneven manner, accompanied by soil shedded from the specimens. It can be observed from Figure 4.3 that, for Soil 1, the lignosulfonate began to show a positive impact on performance related to freeze-thaw resistance after 6 cycles of repeated freezing and thawing. For Soil 2, since the lignosulfonate exhibited the same impact after only 2 cycles of repeated freezing and thawing, the lignosulfonate affected Soil 2’s susceptibility to freeze-thaw damage more significantly. From Figure 4.4, it is more obvious that Soil 1 was more susceptible to freeze-thaw damage, and Soil 2’s susceptibility to repeated freeze-thaw cycles was improved more by lignosulfonate.

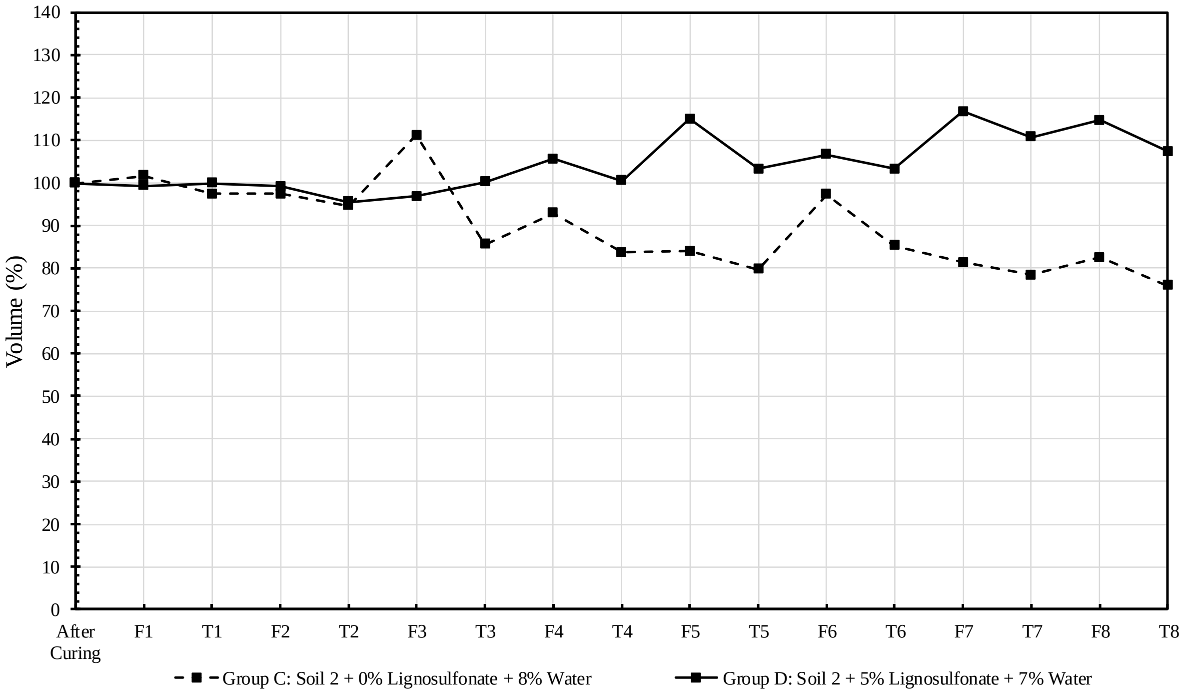
Similarly, eight wet-dry cycles were performed to test wet-dry durability (Figure 4.5 and Figure 4.6), and while both Group A and Group C specimens collapsed after 4 cycles of repeated wet-dry cycles, more rapid deformation and dimension change of Group C specimens was observed at early stages. Both Group B and Group D specimens deformed similarly and completely collapsed after 7 cycles. These tests therefore demonstrated that lignosulfonate had an equal and positive impact on performance of both soils with respect to wet-dry resistance.

Figures were taken every half cycle of the wet-dry and freeze-thaw durability tests to visualize the change of the specimens (Figure 4.7 and Figure 4.8).

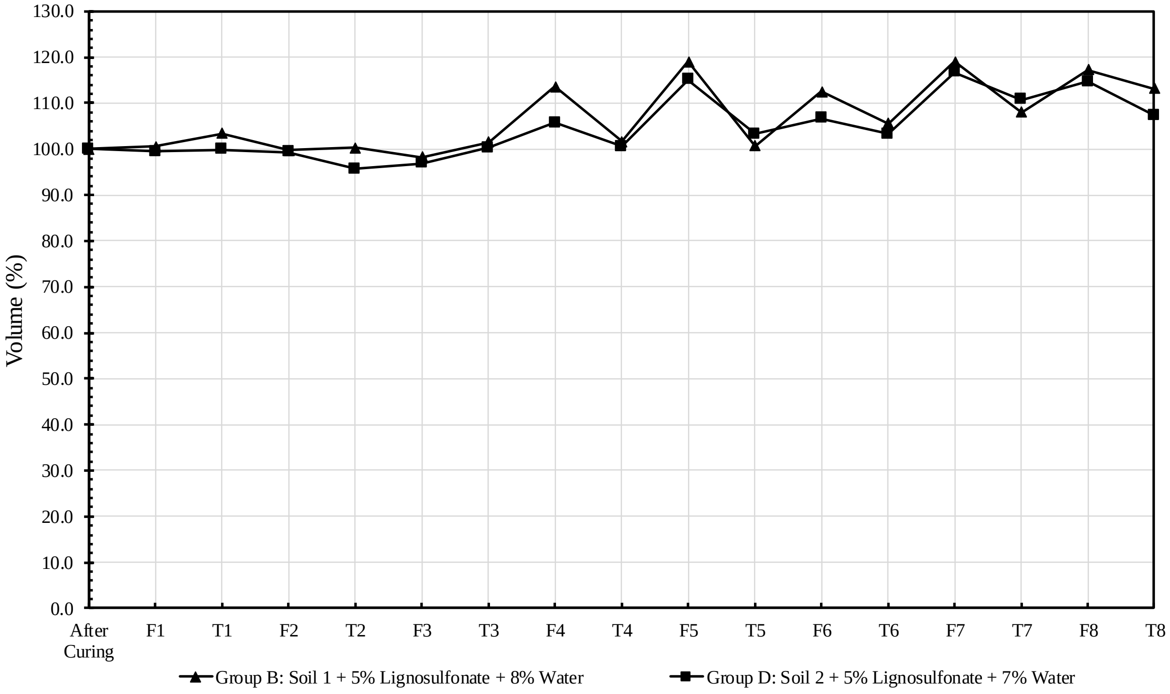


(a)

Figure 4.3 *Volume change for freeze-thaw durability test*

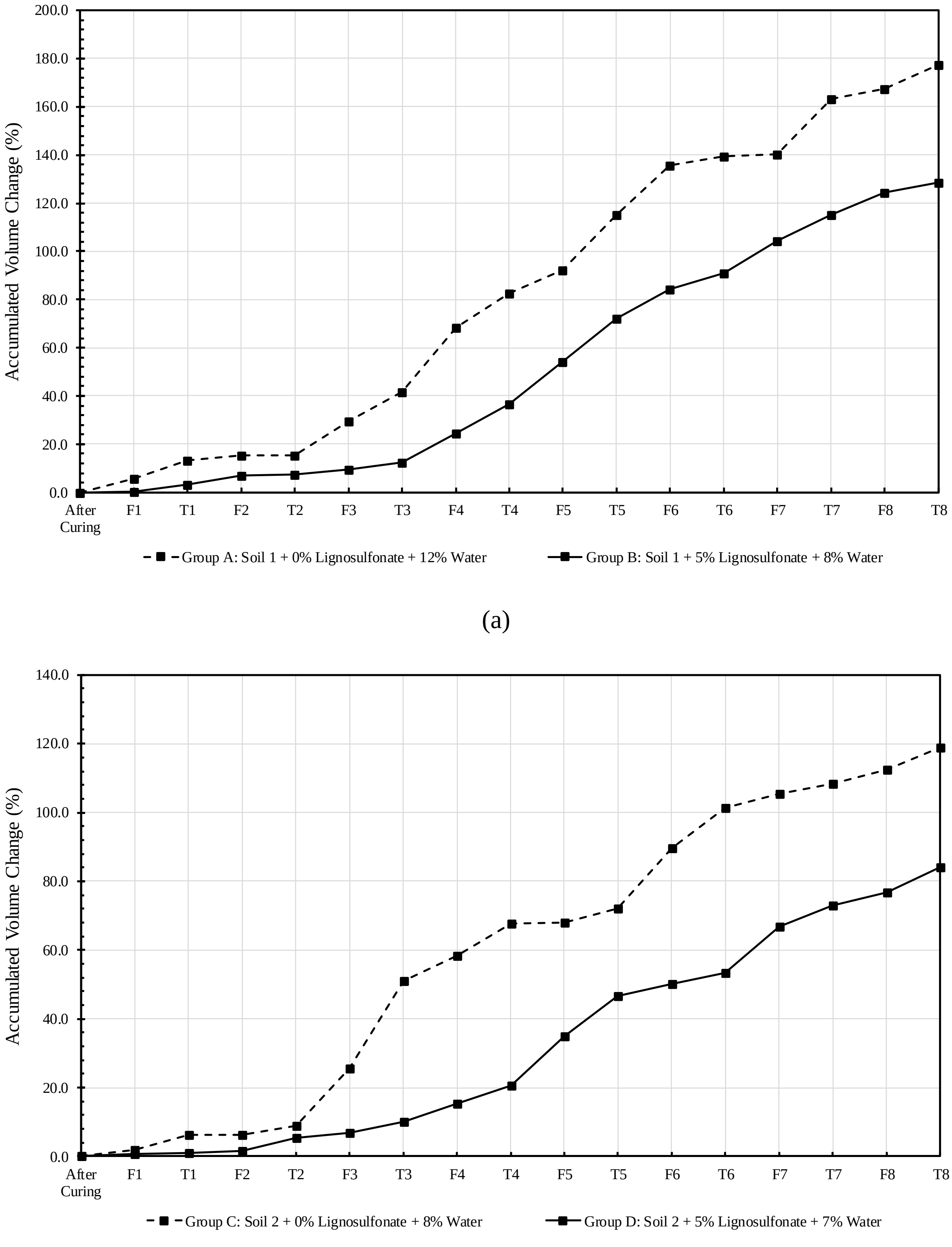


(b)



(c)

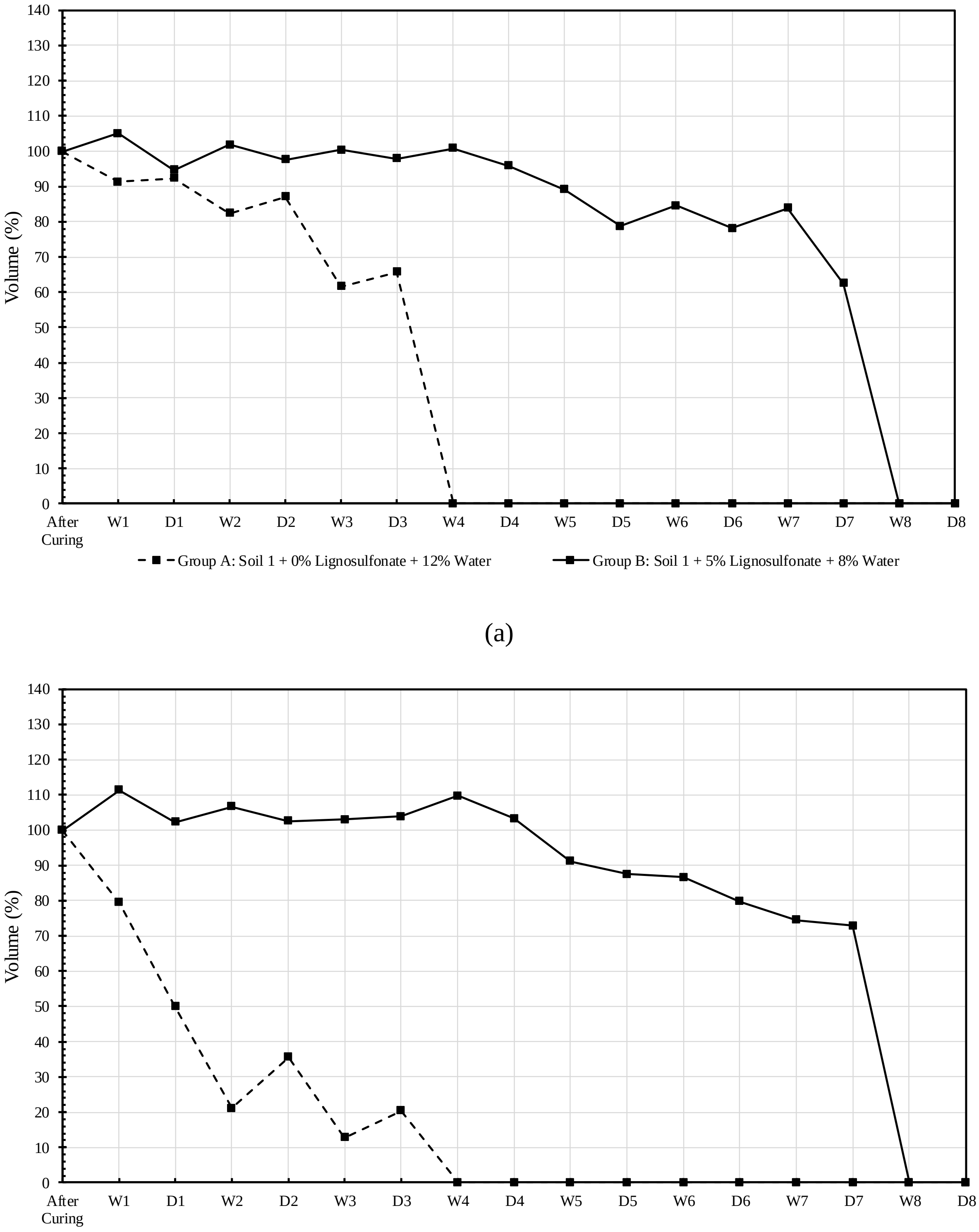
Figure 4.3 *(continued)*



(a)

(b)

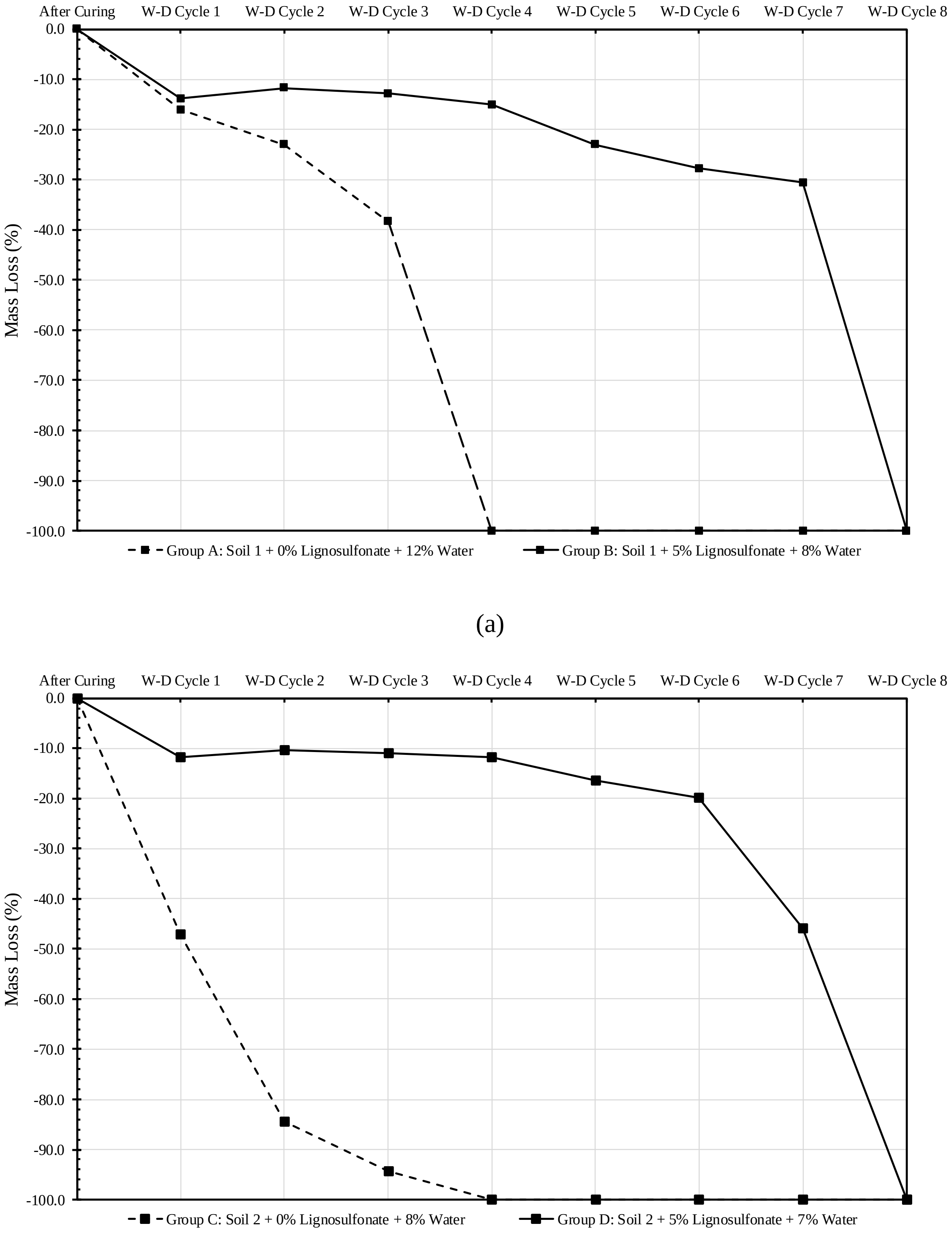
Figure 4.4 *Accumulated volume change for freeze-thaw durability test*



(a)

(b)

Figure 4.5 *Volume change for wet-dry durability test*



(a)

(b)

Figure 4.6 *Mass loss for wet-dry durability test*

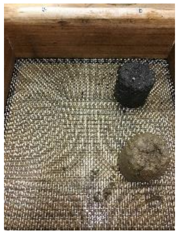
After Curing	W1	D1	W2	D2	W3	D3	W4	D4
								
W5	**D5**	**W6**	**D6**	**W7**	**D7**	**W8**	**D8**	
							**N/A**	

Figure 4.7 *Overall visualization of wet-dry durability test*

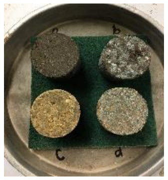
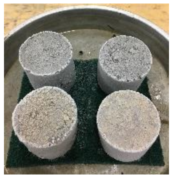
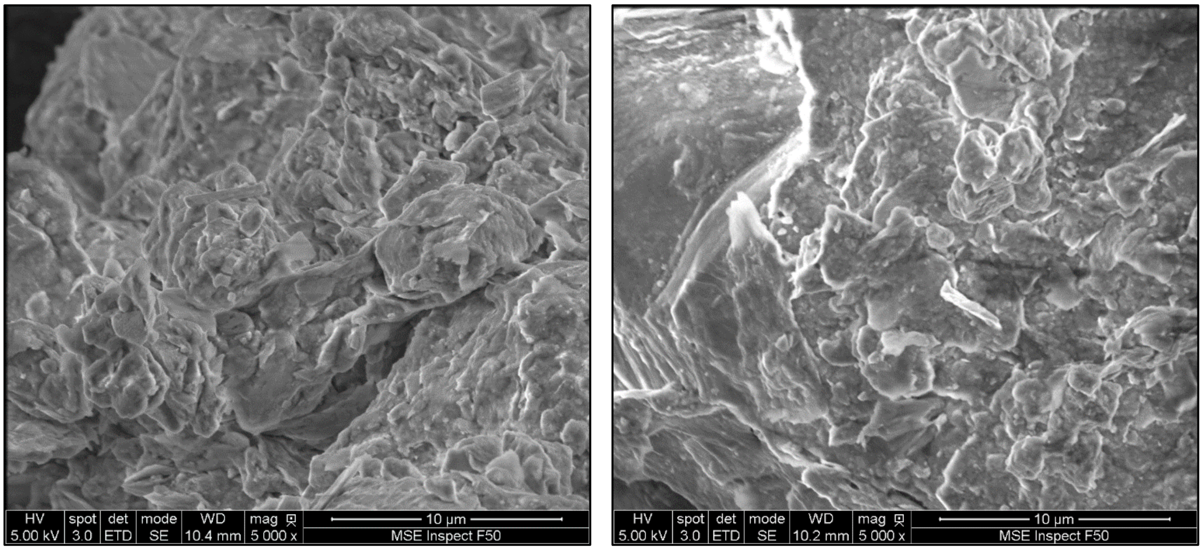
After Curing	**F1**	**T1**	**F2**	**T2**	**F3**	**T3**	**F4**	**T4**
								
F5	**T5**	**F6**	**T6**	**F7**	**T7**	**F8**	**T8**	
								

Figure 4.8 *Overall visualization of freeze-thaw durability test*

Scanning Electron Microscope (SEM)

Both micrographs were taken at 5000 magnification level, from which the lignosulfonate treatment in Soil 1 can be recognized morphologically (Figure 4.9). The silt particles had sharper edges, and its structure contained a good amount of small voids. With the treatment, some of the silt particles were coated with lignosulfonate (lighter part in Figure 4.9b), and larger but fewer voids were observed. Compared to Soil 1's "loose" microstructure, the lignosulfonate-Soil 1's "compact" microstructure had more capability to restrict the movement of water and air, which then created a stronger and more stable environment. Alazigha et al. (2017) pointed out that, due to the hydrophobic property of lignosulfonate and the flocculation induced by cationic exchange occurring between lignosulfonate and soil particles, the bonding lignosulfonate provides waterproof effect and leads to a decrease in swelling (Alazigha et al. 2017), which accounts for the improvement of strength in Soil 1.



(a) (b)

Figure 4.9 *Micrographs of (a) untreated soil 1, and (b) lignosulfonate treated soil 1*

Set Time Test

As it is shown in Figure 4.10, the concentrated lignosulfonate contained approximately 50% evaporative component. When the temperature was above 0°C, the lignosulfonate became hard as evaporation occurred, and therefore, it took less time to gain strength at the higher temperature. When the temperature was 0°C, evaporation gradually occurred and the lignosulfonate achieved a low strength. In the contrary, the lignosulfonate gained strength by freezing when the temperature was below 0°C. The recorded field temperature at which the one-week-after-construction test was performed was around -5°C, thus the increase of lignosulfonate's strength was believed to contribute to the improvement of the lignosulfonate treated soil's strength. With the same theory, it was predicted that the lignosulfonate treated soil can achieve higher strength in summer.

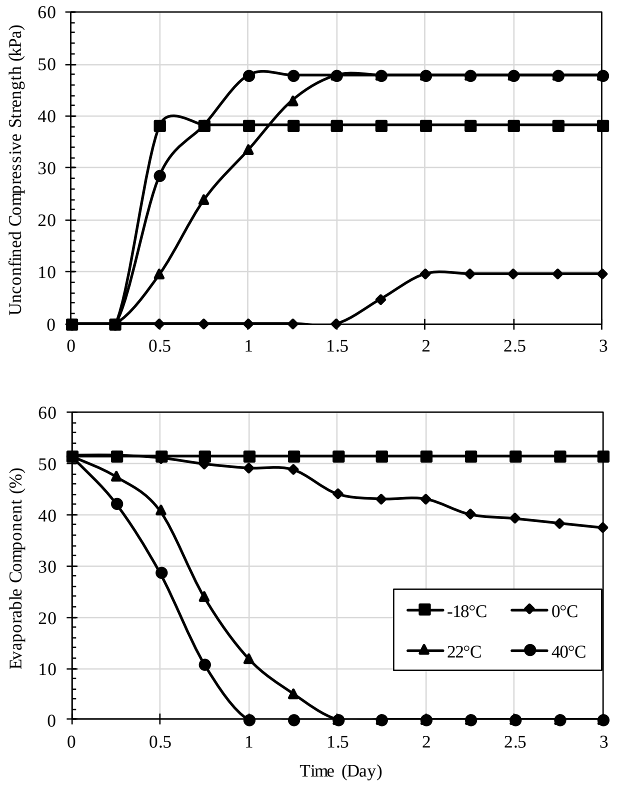


Figure 4.10 *Set time test results*

Construction and In Situ Tests

Construction Lessons Learned

Resurfacing of Gravel Road Surface

The resurfacing of the gravel road surface was performed by a rear ripper, after which different soil stabilization constructions were carried out on this surface (Figure 4.11). From the author’s perspective, a subgrade stabilization construction should be carried out on a subgrade layer, which means the fragments of the destroyed gravel road surface should be removed. However, due to the shortage of budget and coordinated field equipment, this subgrade stabilization was conducted on the destroyed gravel road surface. As it is shown in Figure 4.11, big gravel pieces were left on the surface after the resurfacing of gravel road, and they would reduce and slow down the reactions among different soil stabilizers and the soils. This phenomena could have been mitigated if the reclaimer was used for each section, yet it was only used in three out of five sections. There is no other equipment that can blend soils and stabilizers as thoroughly as a reclaimer does.

In comparison, in the Claycrete stabilization project in Ringgold County (described in Chapter 2), the gravel surface and multiple Chip Seals layers were ripped by a rear ripper, then a motor grader was used to move the destroyed gravel pieces to the edge of the roadway. After the Base One application, these gravel pieces were moved back the roadway by the motor grader, followed by compaction. In this case, the Base One stabilizer was able to react with the base layer soil thoroughly.

(a) (b)

Figure 4.11 *Resurfaced gravel road surface*

Cement Stabilization

A total of 27.6 tons of cement has been applied, so the actual cement dosage rate was 7.2%. Figure 4.12 shows the cement section after one week of construction. The County Engineer chose the first section for cement stabilization because Bowers Best Discount Store is located at the intersection between Old IA-150 Highway and 240th St., a crossing where semi-trucks are engaged in frequent load and unload activities. Considering cement is one of the most promising and experienced stabilization products, it was selected to stabilize the first section so that Bowers Best Discount Store would have a more stable roadway right in front of their loading area. Moreover, Bowers Best Discount Store did not want the roadway to be closed for too long because they need it for transportation purposes and maintaining daily operation.

(a) (b)

Figure 4.12 *Cement section after one week of construction*

Lignosulfonate Stabilization

Figure 4.13a describes the spraying nozzles and process, and Figure 4.13b illustrates the subgrade condition soon after the diluted lignosulfonate was sprayed. Figure 4.13c shows the motor grader was blending “wet” soil with “dry soil”, and Figure 4.13d shows the “over wet” condition of the subgrade after the soil blending. Figure 4.13e exhibits the compaction with pneumatic rollers. Figure 4.13f and Figure 4.13g show the subgrade conditions after one week of construction.

A continuous precipitation was detected prior to the construction date, and therefore, it was predicted that a large amount of water stayed in the subgrade layer before the construction started. The construction took place in the second week of October in 2018, during which the temperature of the construction site was detected to be around 0°C. Thus, it was predicted that the evaporation of moisture in the subgrade went slowly during and after the construction. Both of these climate factors led to the over “wet” condition.

Empirical experience mattered in the field construction. Initially, the lignosulfonate was planned to be diluted with water based on a 1:1 ratio concentration. The lignosulfonate spray rate was calculated as 10.4 L/m^2 based on the stabilized depth (0.15 meter), the soil dry unit weight

(1790.9 kg/m^3), and the lignosulfonate optimum dosage (5%). However, the truck driver diluted the lignosulfonate with water based on a 1:2.3 ratio concentration to meet the spraying nozzles' working requirements. A larger spray rate was used in the field application also because the truck driver was more confident in this value based on his past work experience. Consequently, the tested section was over "wet" only after half of the diluted lignosulfonate was sprayed, and therefore, the actual dosage of lignosulfonate was only 2.5%. The change of lignosulfonate dilution and spray rate also led to the over "wet" condition.

Project budget and safety were two extremely important considerations in the field construction. A common method to solve the "over-wet" situation was that the rear rippers were used to dig several more centimeters in the subgrade layer so that more soil can blend with the diluted lignosulfonate. Another common method was to increase the roller passes in the compaction. However, both methods would lead to an increase in fuel cost, the concern of field workers' safety of working in a dark environment, and the increase in project budget due to the overtime work shift.

The pneumatic rollers, which refer to small sized rubber-tired rollers, were used for the compaction. The pneumatic rollers are often used for the final compaction of the upper 0.15 meter of a subgrade, and can obtain a high degree of compaction if the subgrade contains sufficient granular soils (Department of the Army 1997). The pneumatic rollers are also recommended to compact softer materials that many break down or degrade under the pressure of a steel roller (Department of the Army 1997). Therefore, the pneumatic rollers were believed to be the optimal choice as the compaction equipment. It should also be noted that, for an adequate compaction of granular soils that contain fine silt and clay, effective control of moisture is required (Department of the Army 1997). This also explained the over "wet" condition.

Incidents happened frequently in the field construction and caused delays in the completion of project. The observed incidents included the maintenance of a tiny screw, the miscommunication of water tank location, and the wrong estimate of working hours. All of these uncontrollable activities resulted in the changes of project schedule.

As it is shown in Figure 4.13f and Figure 4.13g, some sections contained more lignosulfonate, and some sections contained less. This problem could have been avoided if the motor grader blended lignosulfonate and soils in a more thorough manner, or if the reclaimer was used for the blending process.

Bleeding (Figure 4.13h) was observed after one month of construction. Bleeding occurred when the lignosulfonate filled in the limestone and soil voids and expanded onto the road surface, thus it was estimated that excessive lignosulfonate was sprayed. One way to solve the bleeding problem was to further reduce the lignosulfonate dosage; another way was to increase the stabilized depth by digging several more centimeters in the subgrade layer with the rear rippers.

(a) (b)

Figure 4.13 *Lignosulfonate section construction: (a) spraying nozzles, (b) subgrade condition soon after spraying, (c) motor grader blended soils, (d) over "wet" subgrade condition, (e) compaction with pneumatic rollers, (f) & (g) conditions after one week of construction, and (h) bleeding after a month of construction*

(c) (d)

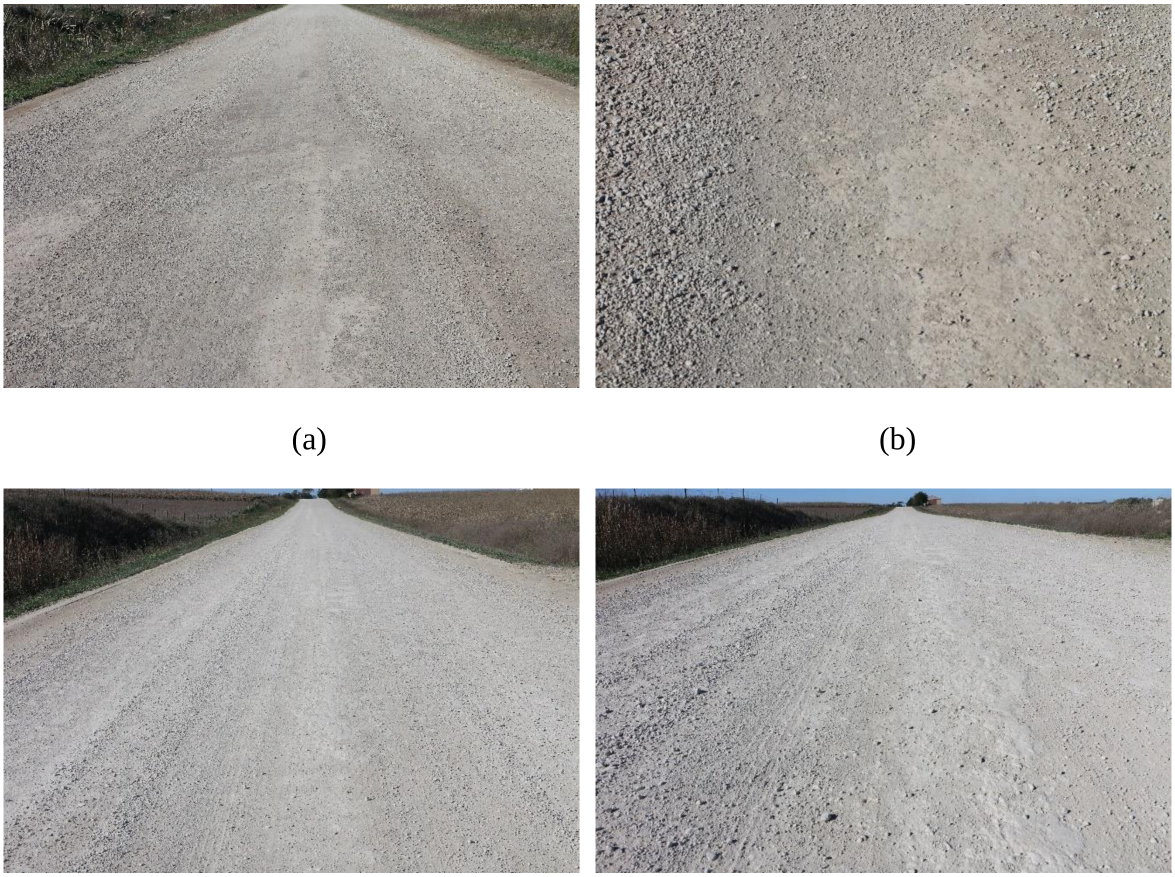
(e) (f)

(g) (h)

Figure 4.13 *(continued)*

Chlorides, Claycrete, and Base One Stabilization

The chlorides section and the Claycrete section were switched due to the miscommunication among the County Engineer and contractors (Note: Figure 3.14 reflects the correct construction orders). All of the three chemical stabilizers are commercial products that had successful field experience in the past. Their company/factory representatives on site were able to explain, coordinate, and execute the construction, so the construction of these three sections went fast and professionally. It is observed from Figure 4.14 that all of the three sections had a smooth surface after one week of construction.



(a) (b)

(c) (d)

Figure 4.14 *Chlorides section (a) & (b), Claycrete section (c) & (d), and Base One section (e) & (f) after one week of construction*

(e) (f)

Figure 4.14 *(continued)*

Light Weight Deflectometer (LWD) Test

The light weight deflectometer (LWD) test revealed the subgrade stiffness by measuring in situ elastic modulus. The determination of in situ modulus was based on the Boussinesq Half Space Equation (Equation Equation 2), where the plate radius (R) was 0.15 m, the applied stress (ρ) was approximately 0.1 MPa, and the Poisson ratio (μ) was estimated to be 0.35 due to the soil classification.

$$E_{LWD} = \frac{2(1-\mu^2)\rho R}{s} \qquad \text{(Equation 2)}$$

As demonstrated in Figure 4.15, the subgrade did not have a consistent stiffness before the construction. After a week of construction, the cement and Base One sections had larger in situ modulus, which indicated these two sections had higher stiffness. The stiffness of the lignosulfonate section decreased greatly. It was predicted that this subgrade section was fully saturated due to the excessive amount of water used in the lignosulfonate dilution. In spite of the sufficiency of compaction effort, the fully saturated subgrade did not contain enough pores for the moisture to run off, and thus, caused the decrease of stiffness. This decrease of stiffness may potentially lead to an increase in future settlement of the subgrade layer. The chlorides and Claycrete sections also had a decrease in stiffness after one week of construction. Nevertheless the company/factory representatives of these two products did not reveal any information regarding the liquid stabilizer proportion or compaction requirements, it was estimated that the continuous precipitation before the construction caused excessive amount of water in the subgrade, which decreased the stiffness. Another reasonable and scientific estimation was the lack of compaction.

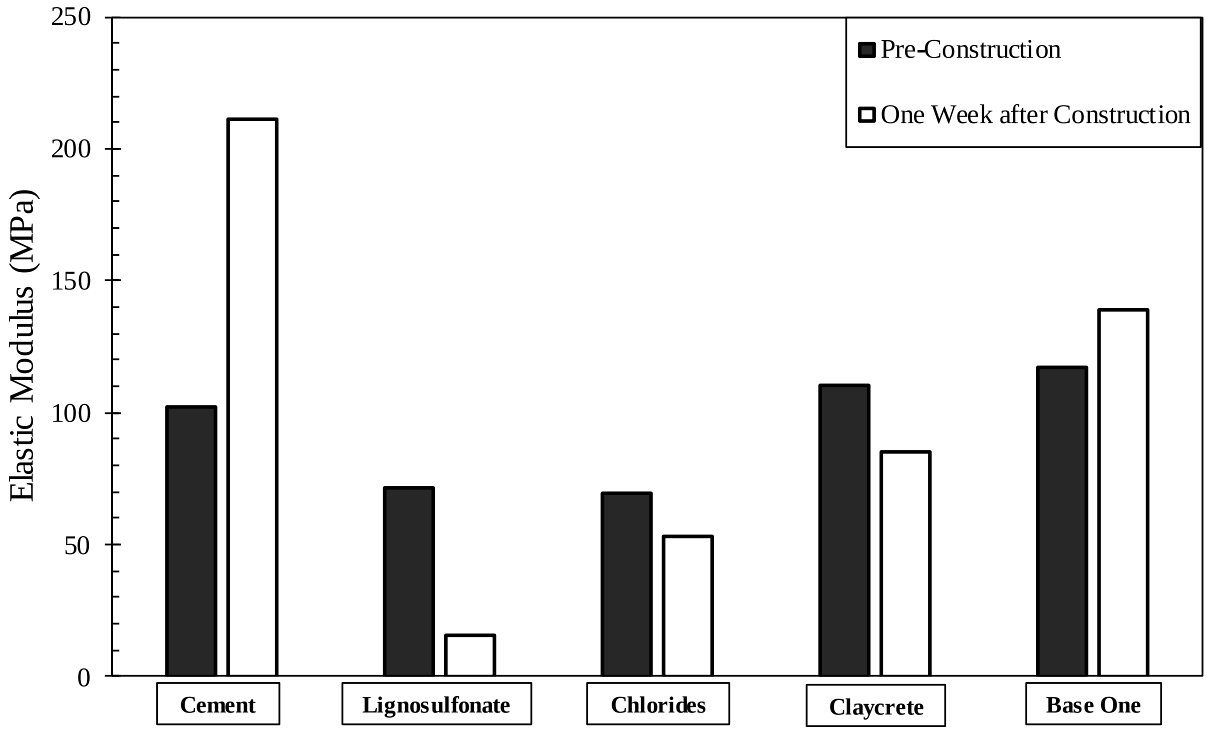


Figure 4.15 *Elastic modulus measured from light weight deflectometer (LWD) test*

Dynamic Cone Penetration (DCP) Test

The dynamic cone penetration (DCP) test revealed the subgrade strength by measuring the DCP index, and from which the California Bearing Ratio (CBR) can be correlated. In the calculation of the DCP index, a hammer factor of 1 was used because the device was equipped with an 8-kg hammer (American Society of Civil Engineers 2018). In the correlation between the DCP index and California Bearing Ratio (CBR), the equation recommended by the U.S. Army Corps of Engineers (Equation 3) was utilized (American Society of Civil Engineers 2018). In the data analysis, a smaller DCP index meant the DCP device’s lower shaft obtained less penetration for each blow, which indicated the subgrade had a stronger shear resistance. Besides, a larger CBR value indicated higher bearing capacity of the test point.

$$CBR = \frac{292}{DCP^{1.12}} \qquad \text{(Equation 3)}$$

Figure 4.16 to Figure 4.24 demonstrate the DCP index and the DCP – CBR correlation of each sections before and one week after the construction. Note that, after one week of construction, the dynamic cone penetration test hit refusal around 300 mm below the cement treated surface, and therefore the corresponding graphs are not shown in this report. Cohesive soils in Iowa have been investigated, and it was concluded that their shear resistance measured by the dynamic cone penetration (DCP) test improved with an increase in compaction effort and a reduce in moisture content (Nazzal 2014). For the lignosulfonate, chlorides, and Claycrete sections, the low stiffness after one week of construction concluded from the light weight deflectometer (LWD) test suggested that excessive amount of moisture existed in the subgrade after construction. Thus, it was predicted that these three sections’ improvement of subgrade’s resistance to shear failure resulted from the sufficient compaction effort. For the lignosulfonate section, as explained in the set time test result, it was predicted that the increased strength of lignosulfonate also contributed to the improvement of lignosulfonate treated soil’s strength. For the cement section, a great increase in subgrade strength was predicted although there was no statistic result supporting this conclusion. It proved the cement was the most promising and experience soil stabilizer among the five products. The Base One section was also predicted to have a higher strength after one week of construction based on the lower DCP index. A higher in situ CBR value after one week of construction was observed for all of the sections, which indicated that these subgrade sections had higher load bearing capacity. To summary, all of these five soil stabilizers strengthened the subgrade to some extent after one week of construction. Among them, cement and Base One were more promising stabilizer products than the others.

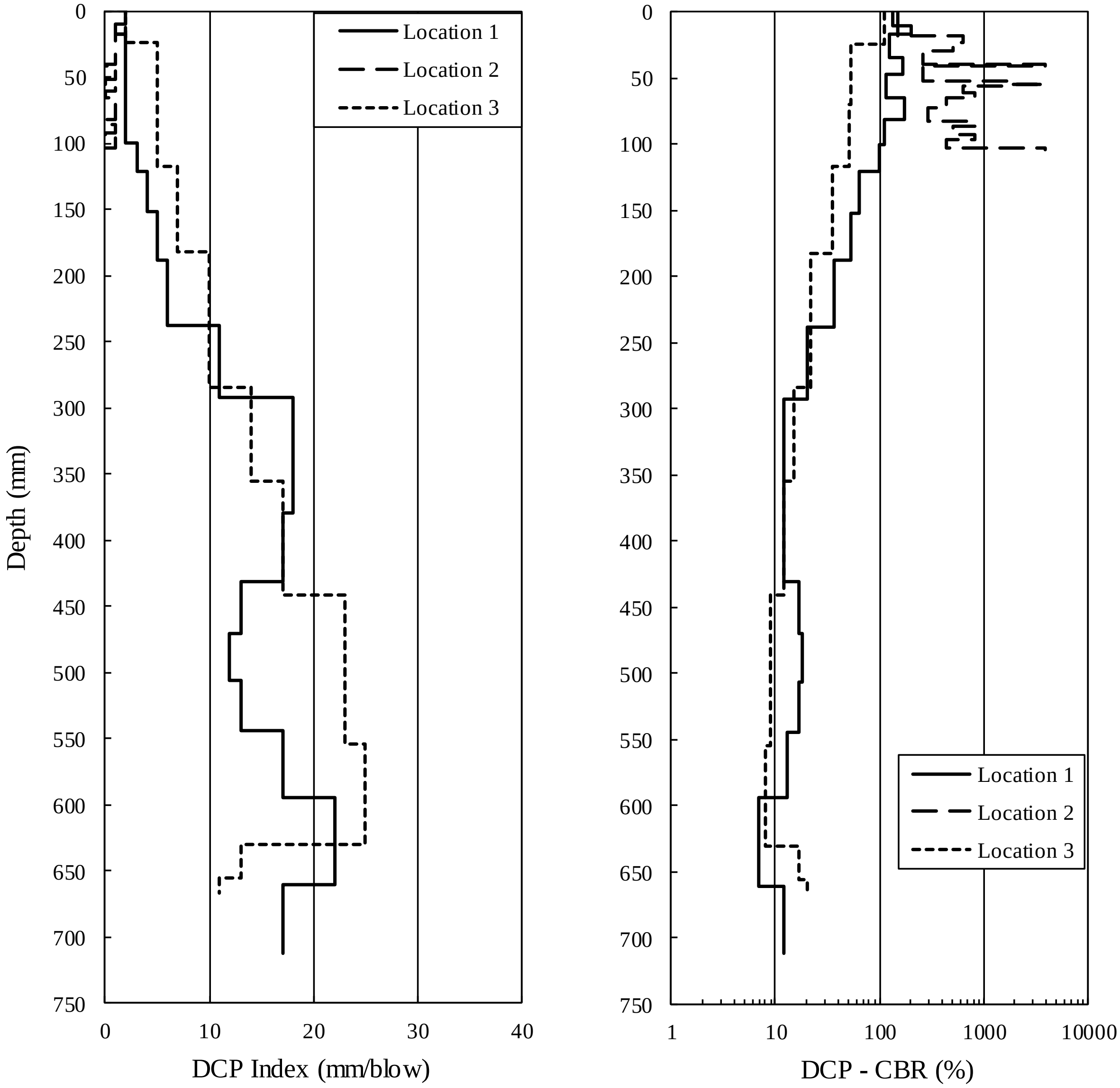


Figure 4.16 *Pre-construction DCP test result (cement)*

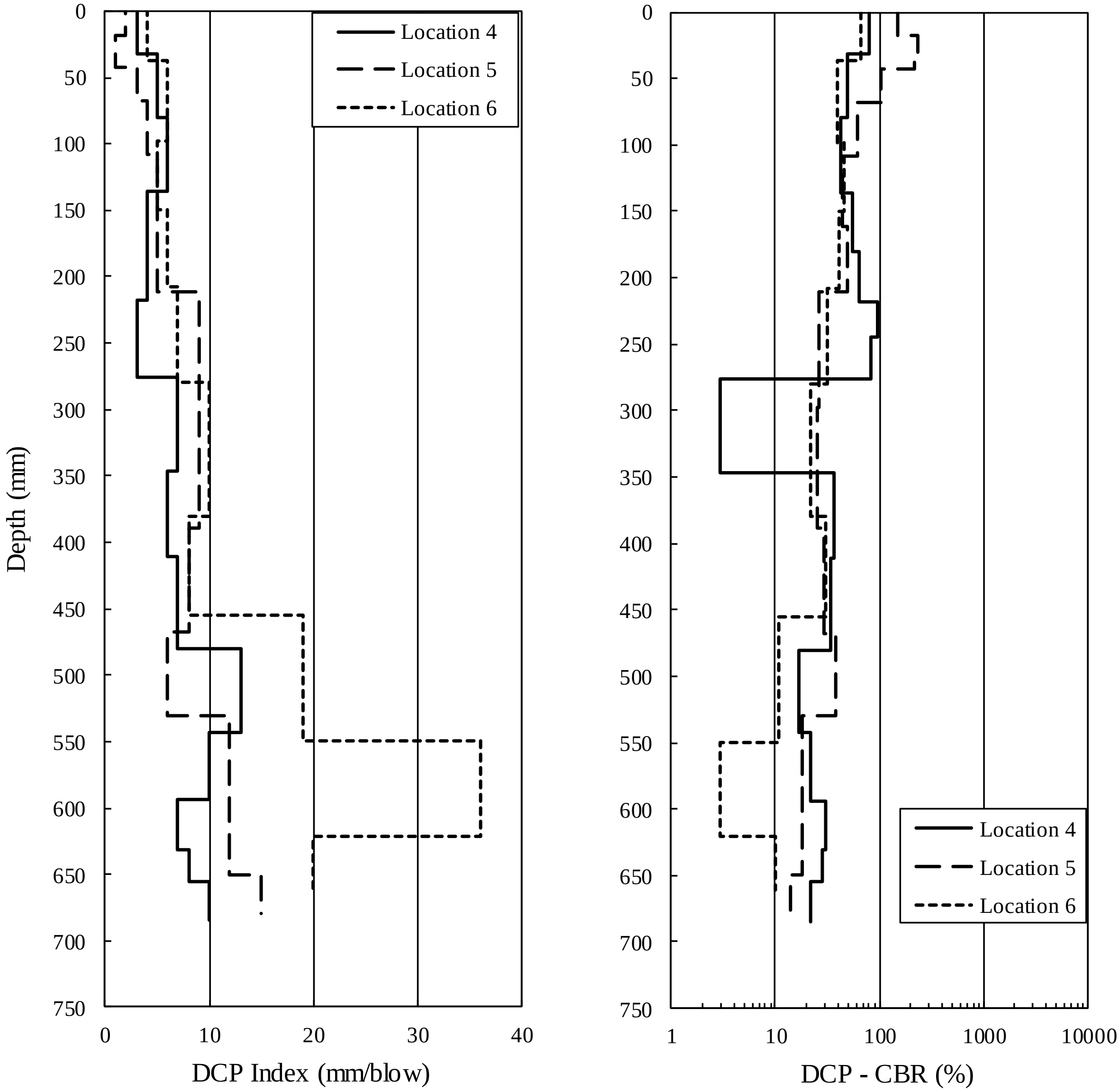


Figure 4.17 *Pre-construction DCP test result (lignosulfonate)*

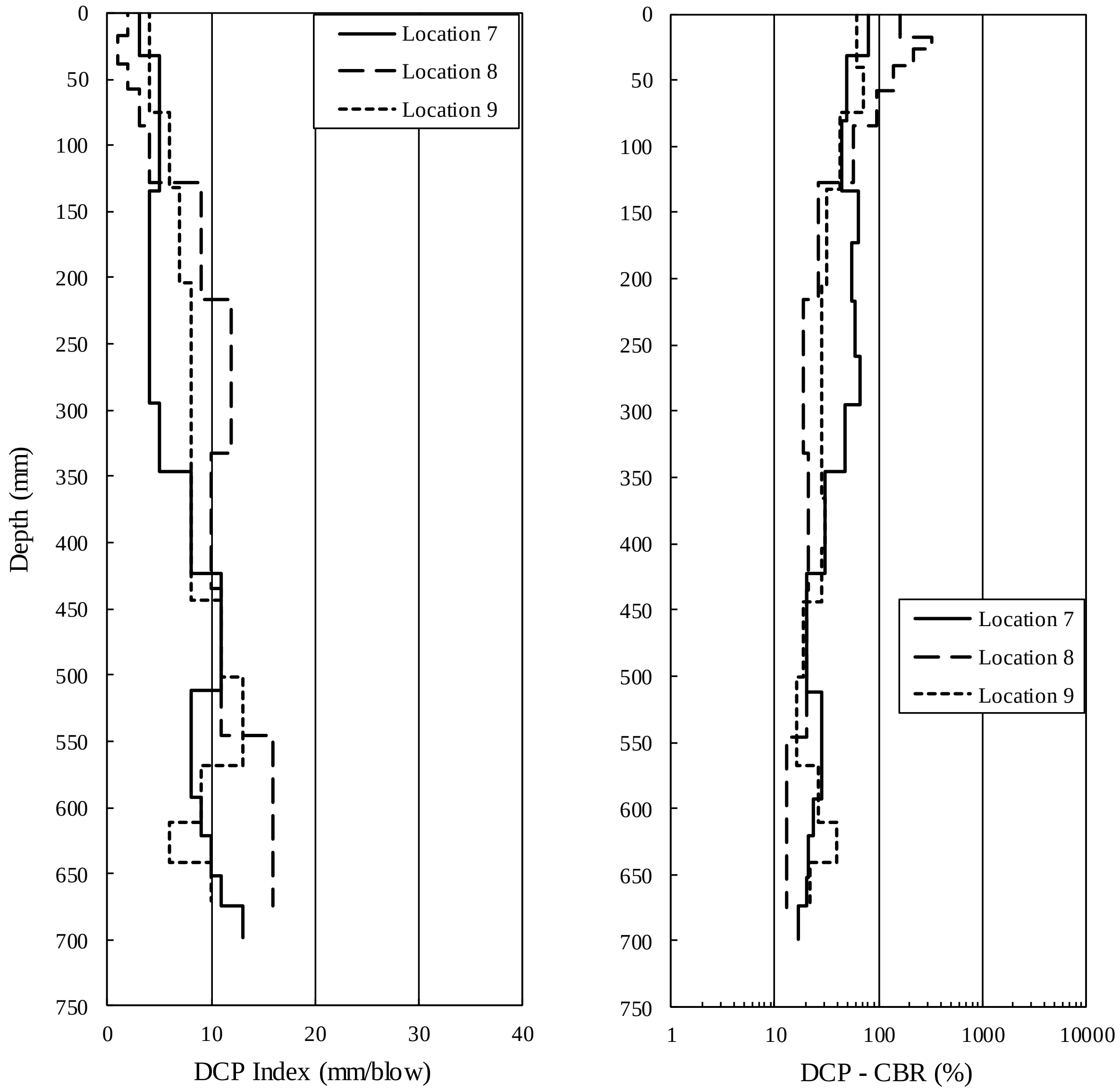


Figure 4.18 *Pre-construction DCP test result (chlorides)*

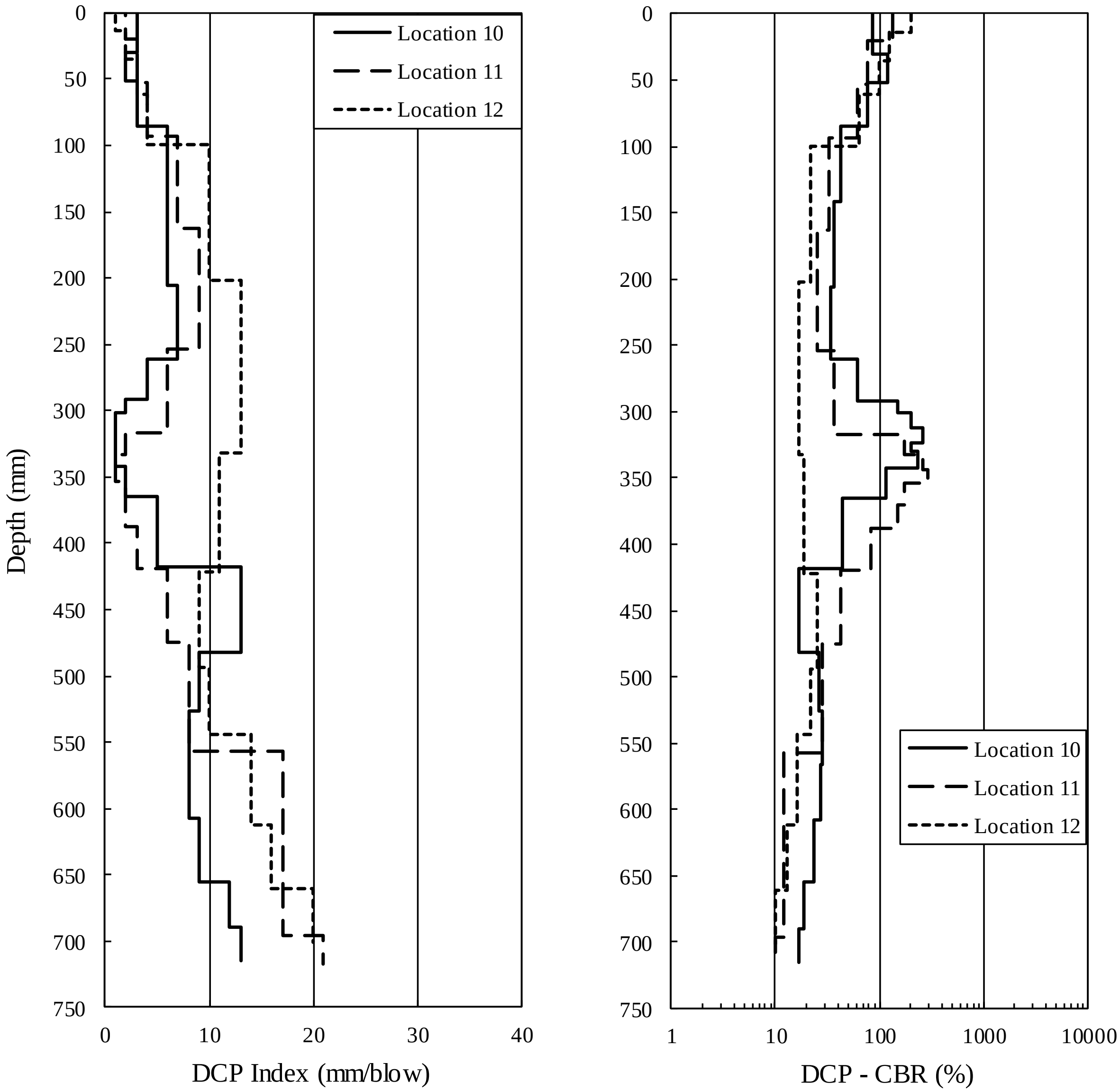


Figure 4.19 *Pre-construction DCP test result (Claycrete)*

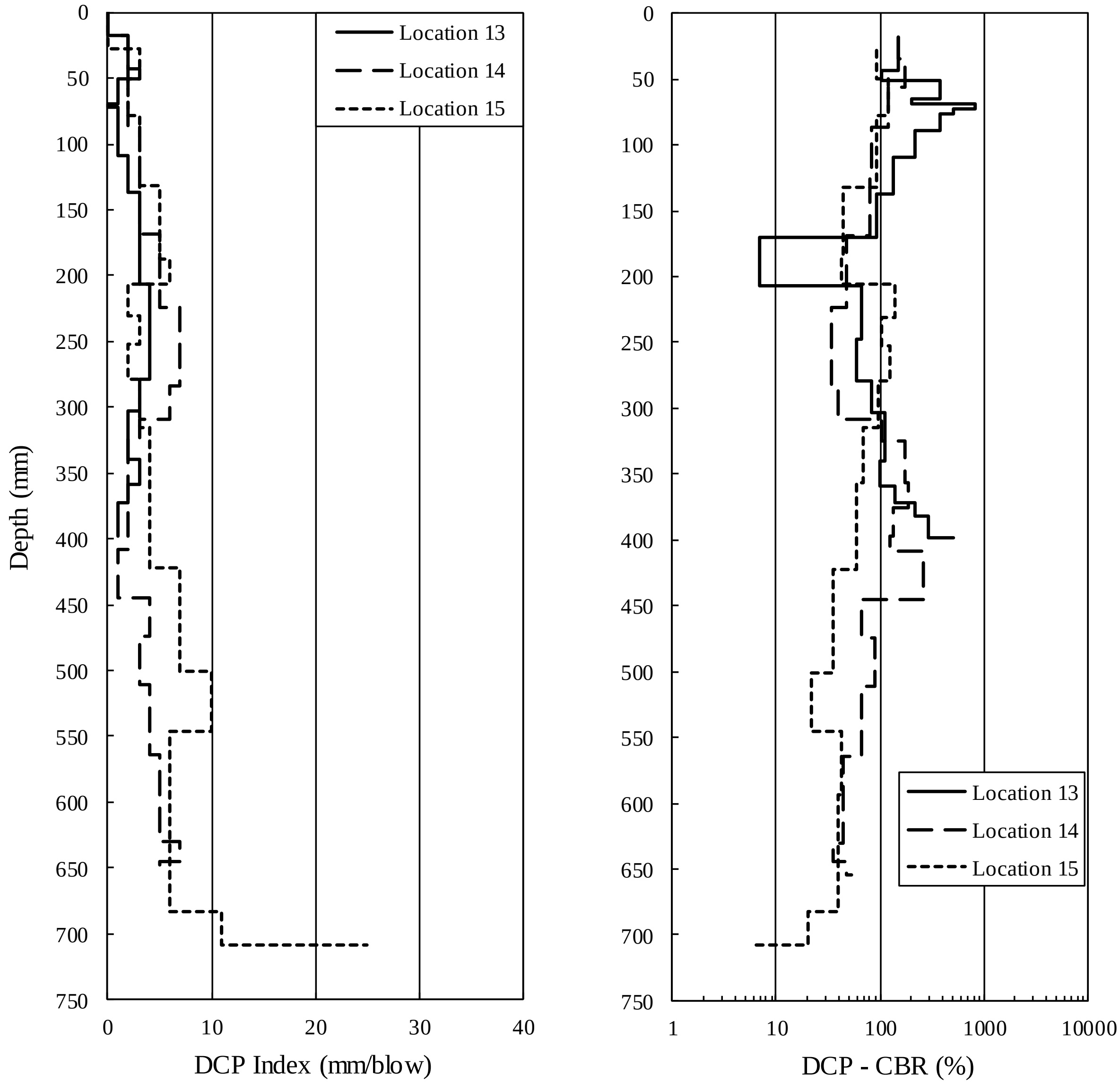


Figure 4.20 *Pre-construction DCP test result (Base One)*

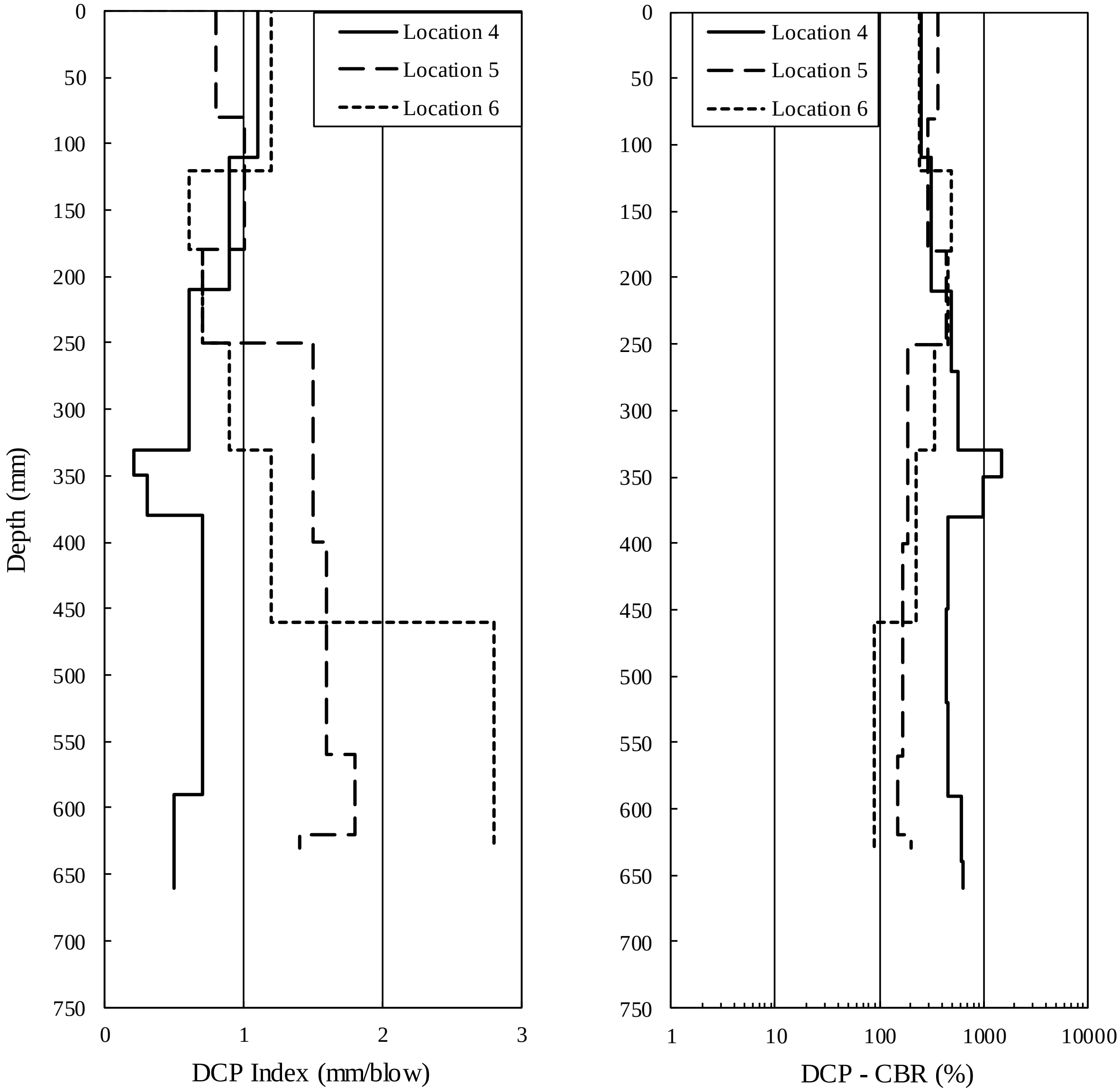


Figure 4.21 *One week after construction DCP test result (lignosulfonate)*

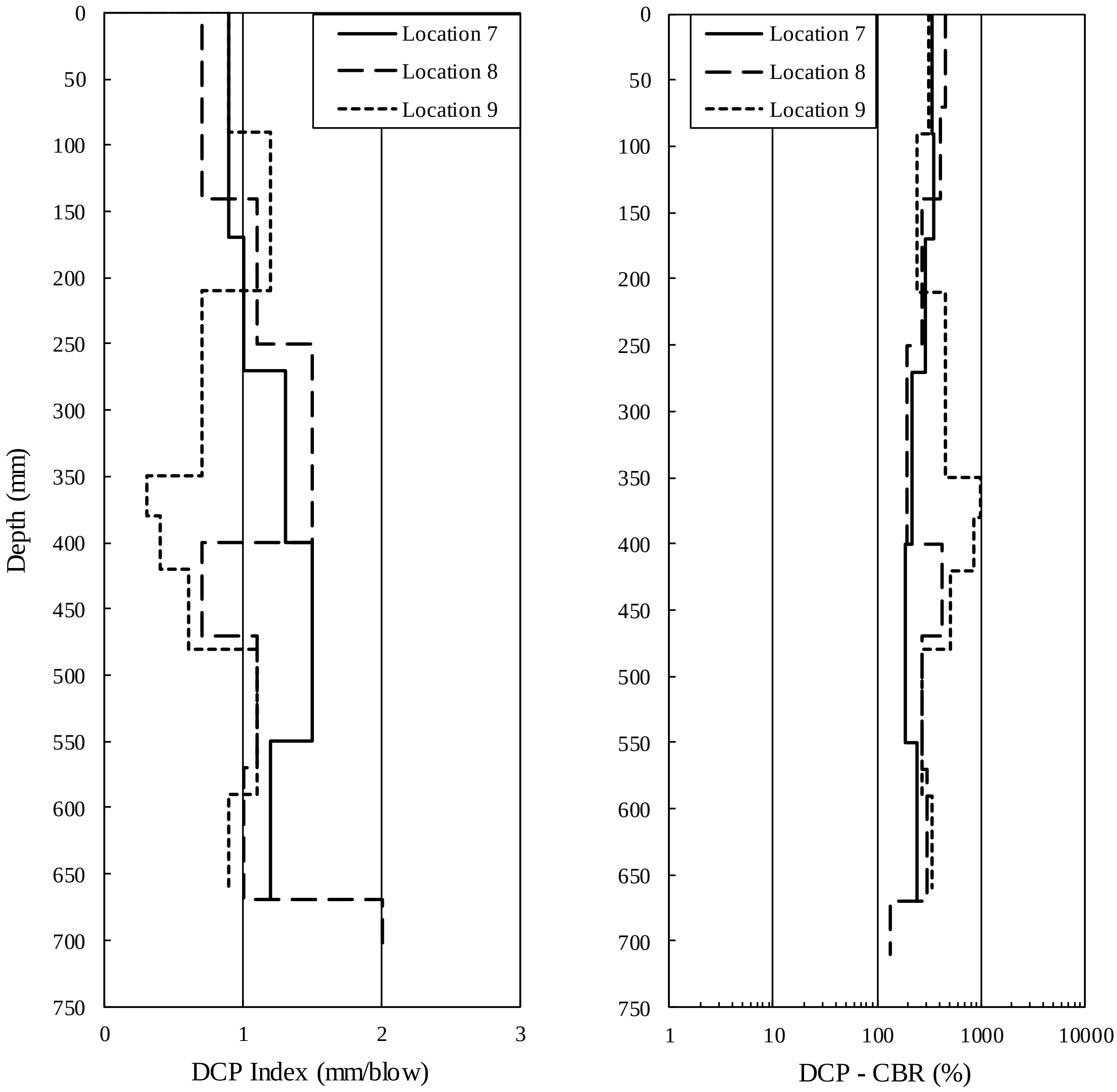


Figure 4.22 *One week after construction DCP test result (chlorides)*

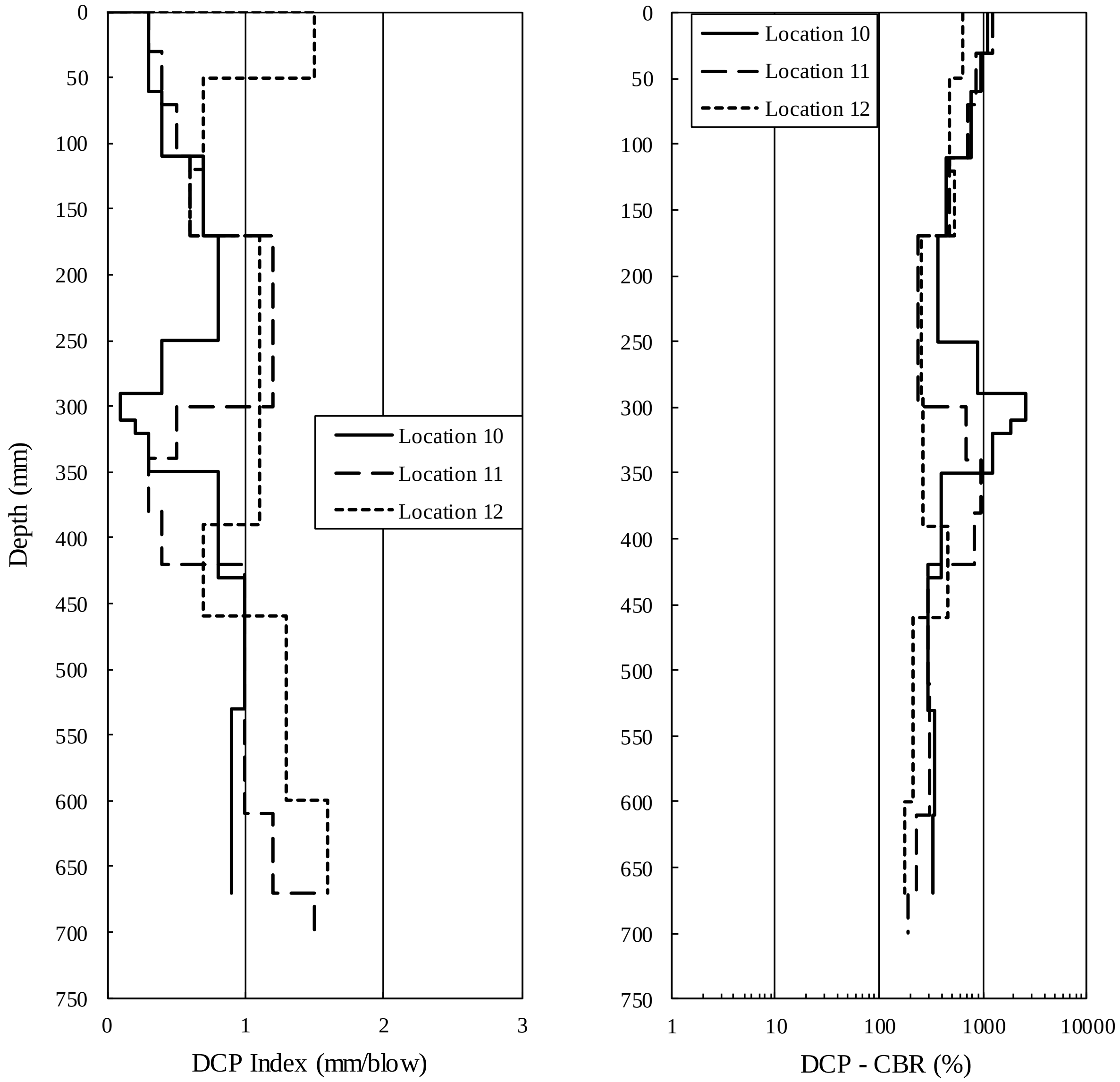


Figure 4.23 *One week after construction DCP test result (Claycrete)*

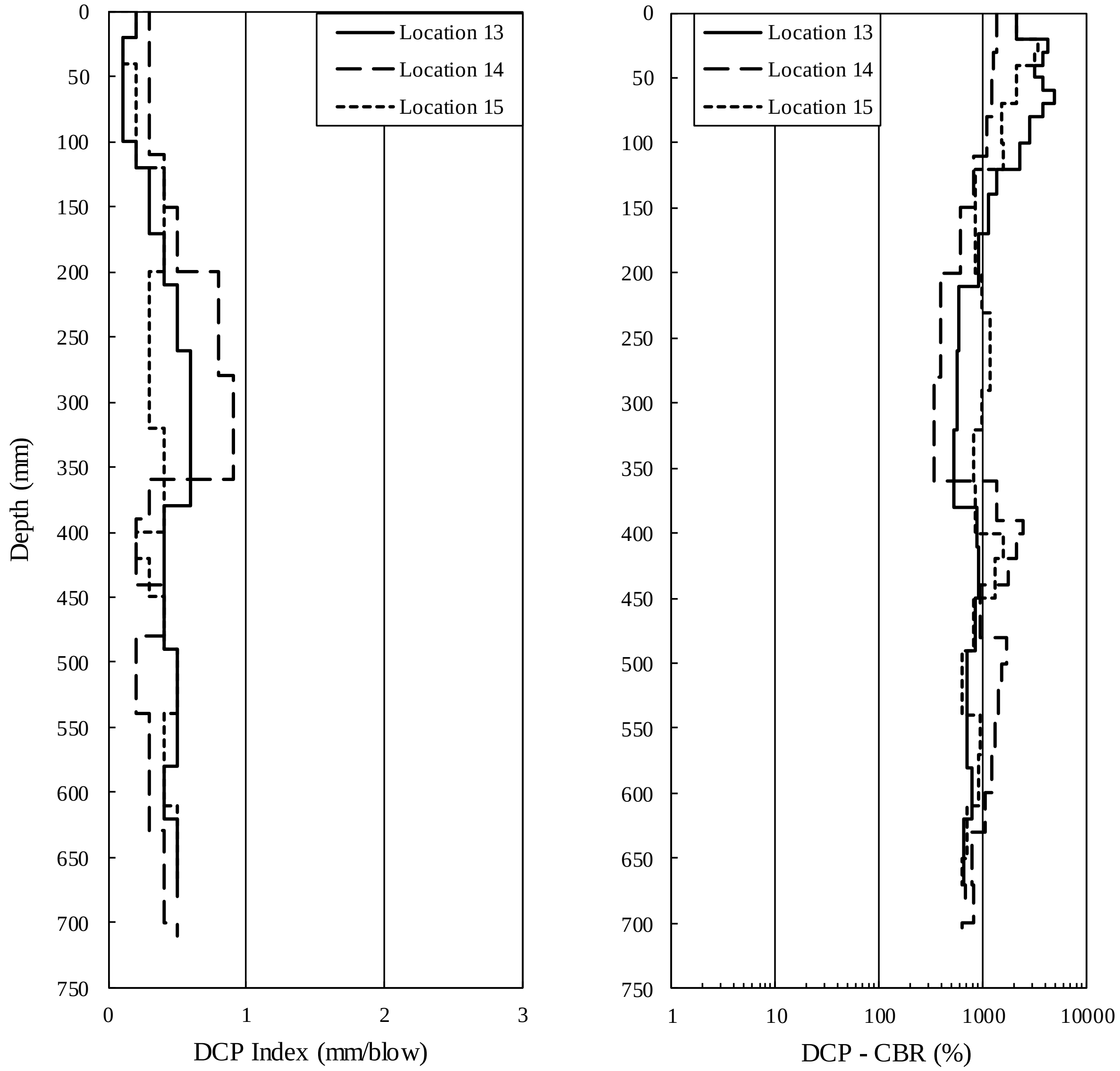


Figure 4.24 *One week after construction DCP test result (Base One)*

CHAPTER 5. CONCLUSIONS

In this section, the key findings from laboratory and in situ tests and the critical lessons learned from the construction are summarized. The significance of this study and the suggestions for future studies on this topic are also provided.

Laboratory Tests

With the objective of evaluating lignosulfonate as an alternative soil stabilizer for improving the strength and durability of silty soils, six laboratory tests were performed to serve as the guideline for the field demonstration. The Proctor compaction tests were focused on correlation between lignosulfonate dosage, optimum moisture content, and maximum dry unit weight. The results from unconfined compressive strength tests determined the optimum mix proportion for each soil and the corresponding increase in compressive strength. The durability tests were performed to determine whether an optimum mix proportion of lignosulfonate can achieve resistance to weathering. The scanning electron microscope (SEM) analysis revealed the reason why lignosulfonate's addition to Soil 1 had an improvement on its strength, whereas the set time test justified the improvement of lignosulfonate treated soil's strength with another method. The key conclusions drawn from the laboratory investigation can be summarized as follows.

- The Proctor compaction test results revealed that both types of silty soils showed various behavior with regard to optimum moisture contents and maximum dry unit weight resulting from specific lignosulfonate dosages.
- The unconfined compressive strength test results determined that only a low dosage of lignosulfonate is required to improve soil strength. Soil 1's (sandy silt with gravel)

optimum mix proportion was 5% of lignosulfonate with 11.85% of actual water content, leading to a 225% increase in unstabilized soil compressive strength.

- The durability test results demonstrated that lignosulfonate equally improved wet-dry durability for both silty soils, and use of lignosulfonate also produced a significant improvement in freeze-thaw durability for soil classified as sandy silt with clay.
- The scanning electron microscope (SEM) analysis suggested that the stronger and more stable microstructure in the lignosulfonate-Soil 1 mixture resulted in a decrease in soil swelling and an improvement of strength.
- The set time test revealed that the increase of lignosulfonate's strength also contributed to the improvement of the lignosulfonate treated soil's strength.

Construction and In Situ Tests

In the field demonstration, diluted ammonium-based lignosulfonate was sprayed on a gravel road subgrade with the goal of improving the strength and durability. Four other soil stabilizers were also applied on the subgrade, so comparison and contrast could be performed among various stabilizers with respect to in situ performance. In situ tests and documentation were conducted at different periods of the construction to monitor the seasonal performance of the stabilized section and draw the lessons learned from the practice. The light weight deflectometer (LWD) test and the dynamic cone penetration (DCP) test were performed before and one week after the construction. The construction process was documented visually and in written forms. Some critical lessons learned from this demonstration were obtained, which provide recommendations for future studies and benefit relevant practitioners.

- This field construction should be conducted on a subgrade layer, yet the stabilization construction was conducted on the destroyed gravel road surface due to the shortage of budget and coordinated field equipment. The big gravel pieces left on the gravel road surface reduced and slowed down the reactions among soil stabilizers and soils.

- In the cement section, the actual dosage was adjusted to 7.2%. Cement was selected to be the stabilizer for the first section because Bowers Best Discount Store needed to use this section for transportation purposes and maintained their daily operation. Cement was believed to be the most promising stabilizing product in this construction.
- In the lignosulfonate section, the actual dosage was adjusted to 7.2%. The subgrade's "over-wet" condition was caused by both climate factor and human factor. Excessive amount of water stayed in the subgrade due to the continuous precipitation prior to the construction date. The lignosulfonate was diluted with too much water and applied in a larger spray rate. Moreover, the low temperature slowed down the evaporation of these excessive amount of moisture in the subgrade. The "over-wet" condition could have been avoided if the construction was executing in late summer (i.e., July and August) because of the high air temperature and the relatively small amount and low frequency of rainfall (U.S. Climate Data 2019). Besides, empirical experience should be weighed in conjunction with engineering design so that the lignosulfonate dilution and spray rate could have been more reasonable. The pneumatic rollers were believed to be the optimal choice as the compaction equipment due to the stabilized depth, the subgrade soil classification, and the hardness of the lignosulfonate treated soil.
- The biggest gap between laboratory investigation and field practice is the unpredictable and uncontrollable factors that may lead to the temporary change of

construction plan, budget overspending, overtime shifts for the involved parties, and the potential danger from working in a dark environment. A good example of this gap was to avoid the “over-wet” condition and the bleeding phenomena by increasing the stabilized depth. This change would have led to various unpredictable and uncontrollable factors that are described above.

- The chlorides, Claycrete, and Base One sections were stabilized by commercial soil stabilizers. The technical problems on site were coordinated by the field representatives from these companies.
- After one week of construction, the cement and Base One sections displayed higher stiffness. The lignosulfonate section showed a lower stiffness due to the excessive amount of water used in the lignosulfonate dilution. The chlorides and Claycrete sections also displayed a lower stiffness, and the reasons could be the excessive amount of precipitation water accumulated in the subgrade and/or the lack of compaction.
- All of the five sections displayed higher strength after one week of construction. Cement and Base One were more promising stabilization products than the others. For the lignosulfonate, chlorides, and Claycrete sections, the improvement of the subgrade resistance resulted from the sufficient compaction. Moreover, the increased strength of lignosulfonate itself also contributed to the improvement of the lignosulfonate treated soil’s strength besides the lignosulfonate’s bonding effect. The higher CBR values also proved that all of the five sections had higher bearing capacity after one week of construction.

Significance of Research

Each year, roadway agencies in Midwest spend a huge amount of funds on roadway maintenance in consideration of the poor soil conditions in the pavement layers. It is important to develop a financially and environmentally beneficial and performance efficient method to stabilize the subgrade soils to meet the transportation infrastructure needs. Lignosulfonate has been widely used as a dust suppression agent, during which it can function far beyond that and strengthen the soil. This research focused on the laboratory and in situ evaluations with respect to lignosulfonate’s strength and durability. The findings from this research provide the guideline regarding laboratory tests and field construction for future studies on this topic.

Suggestions for Future Research

A future research on soil stabilization with lignosulfonate should:

- Study more soil types to further determine lignosulfonate’s efficiency as a soil stabilizer;
- Perform other triaxial tests in the laboratory to determine more shear strength parameters;
- Perform a field demonstration when the weather is hot and dry; and
- Establish a better coordination between mechanistic calculation and empirical experience in the field construction.

REFERENCES

AASHTO (American Association of State Highway and Transportation Officials). (2017). *AASHTO M 145-91 Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes*.

Agriculture in the Midwest. (2017). U.S. Department of Agriculture Climate Hubs. https://www.climatehubs.oce.usda.gov/hubs/midwest/topic/agriculture-midwest.

Alazigha, D., Indraratna, B., Vinod, J.S., and Heitor, A. (2018). "Mechanisms of stabilization of expansive soil with lignosulfonate admixture." Transportation Geotechnics, Vol. 14, pp. 81-92. https://doi.org/10.1016/j.trgeo.2017.11.001.

ASTM Standard. (2009). "Standard Test Methods for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures." ASTM International, West Conshohocken, PA, 2009, DOI: 10.1520/D5102-09, www.astm.org.

ASTM Standard. (2015). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort/" ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/D0698-12E01, www.astm.org.

ASTM Standard. (2015). "Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures." ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/D0559_D0559M-15, www.astm.org.

ASTM Standard. (2016). "Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures." ASTM International, West Conshohocken, PA, 2016, DOI: 10.1520/D0560_D0560M-16, www.astm.org.

ASTM Standard. (2017). "Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders." ASTM International, West Conshohocken, PA, 2017, DOI: 10.1520/D1633-17, www.astm.org.

ASTM Standard. (2019). "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass." ASTM International, West Conshohocken, PA, 2017, DOI: 10.1520/D2216-19, www.astm.org.

Blackmon, D., Shealy, G., and Jones, B.K., inventor; EnviRoad LLC, Assignee. (2010). Composition and Method for Stabilizing Road Base. United States patent US 7,758,280 B2.

Blue Flame Propane. (2018). http://blueflamepropanellc.com/.

Casagrande, A. (1948). Classification and Identification of Soils. Transaction, ASCE, vol. 113, 901-930.

Cetin, B. (2017). CE 567 Geomaterial Stabilization.

Cetin, B., Aydilek, A.H., and Guney, Y. (2010). “Stabilization of recycled base materials with high carbon fly ash.” Resources, Conservation and Recycling, Vol. 54, pp. 878-892. https://doi.org/10.1016/j.resconrec.2010.01.007.

Cetin, B., Ceylan, H., and Ashlock, J.C. (2018). “Evaluation of the Mechanical and Environmental Performance of Biofuel Co-Product Stabilized Unpaved Roads.” Midwest Transportation Center at Institute of Transportation, Iowa State University, Ames, IA.

Department of the Army. (1997). *Soil Compaction*. Military Soils Engineering. Washington, DC.

Fatehi, H., Abtahi, S.M., Hashemolhosseini, H., Hejazi, S.M. (2018). “A novel study on using protein based biopolymers in soil strengthening.” Construction and Building Materials, Vol. 167, pp. 813-821. https://doi.org/10.1016/j.conbuildmat.2018.02.028.

Federal Highway Administration’s Office of Highway policy Information. (2014). “Public Road Length - 2012 (1) Miles by Type of Surface and Ownership/Functional System National Summary.” https://www.fhwa.dot.gov/policyinformation/statistics/2012/hm12.cfm.

GreenAgrochem. (2013). Different between lignin and lignosulfonate. https://www.greenagrochem.com/difference-between-lignin-and-lignosulfonate/.

Iowa Department of Transportation. (2018). Traffic Flow Map of Buchanan County, IA, https://iowadot.gov/maps/msp/traffic/2017/Counties/BUCHANAN.pdf.

Lambe, T.W. and Whitman, R.V. (2008). *Soil Mechanics*. Wiley, New York.

Lekha, B.M., Sarang, G., and Ravi Shankar, A.U. (2015). “Effect of electrolyte lignin and fly ash in stabilizing black cotton soil.” Transportation Infrastructure Geotechnology, Vol. 2 (2), pp. 87-101.

Li, C., Ashlock, J.C., Cetin, B., Jahren, C.T., and Goetz, V. (2018). “Performance-based design method for gradation and plasticity of granular road surface materials.” Transportation Research Record, Transport Res Board, https://doi.org/10.1177/0361198118787372.

Li, Y., Zhang, Y., Ceylan, H., and Kim, S. (2019). “Laboratory Evaluation of Silty Soils Stabilized with Lignosulfonate.” International Airfield and Highway Pavements Conference, ASCE, Chicago, IL.

Montgomery, D. (2012). “Soil wealth | Why North America Feed the World.” Farm Progress, Corn + Soybean Digest. https://www.farmprogress.com/issues/soil-wealth-why-north-america-feeds-world.

Munson, K. (2015). “You’re not an Iowan until you have...” Des Moines Register. https://www.desmoinesregister.com/story/life/2015/04/08/iowan-gravel-roads/25485175/.

National Geographic. (2019). Silt. https://www.nationalgeographic.org/encyclopedia/silt/.

Nazzal, M. (2014). “Methods for measuring the in situ stiffness/strength of unbound materials.”

Non-Nuclear Methods for Compaction Control of Unbound Materials, pp. 47-89.

Noorzad, R., Ta'negonbadi, B. (2018). "Mechanical properties of expansive clay stabilized with lignosulphonate." Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 51, pp. 483-492. https://doi.org/10.1144/qjegh2017-050.

Pacific Dust Control. (2019). Lignin Sulfonate, http://www.pacificdustcontrol.com/lignin-sulfonate/.

Pacific Dust Control. (2019). Soil Stabilization, http://www.pacificdustcontrol.com/soil-stabilization/.

Road Pavement Products PTY Ltd. (2017). Claycrete Application and Road Construction Manual 2017.

Statewide Urban Design and Specifications (SUDAS). (2013). Design Manual Chapter 6 – Geotechnical, Ames, Iowa.

Team Laboratory Chemical Corporation. (2018). Stabilized Reclamation Using Base One.

The Vermont Local Roads Program (1984). "Soils For Road Work." Transpiration Information Exchange at Saint Michael's College. https://t2.unh.edu/sites/t2.unh.edu/files/documents/publications/soils_for_road_work.pdf.

Tingle, J.S., Newman, J.K., Larson, S.L., Weiss, C.A., and Rushing, J.F. (2007). "Stabilization mechanisms of nontraditional additives." Transportation Research Record, No. 1989, Vol. 2, pp. 59-67.

Tumuluru, J.S., Sokhansanj, S., Wright, C.T., Boardman, R.D., and Yancey, N.A. (2011). "A Review on Biomass Classification and Composition, Co-Firing Issues and Pretreatment Methods." 2011 ASABE Annual International Meeting, ASABE, Louisville, KY.

U.S. Climate Data. (2019). Climate Independence – Iowa, https://www.usclimatedata.com/climate/independence/iowa/united-states/usia0410.

U.S. Energy Information Administration. (2018). Biomass Explained. https://www.eia.gov/energyexplained/?page=biomass_home.

Yang, B. (2015). Performance of bio-based soil stabilizers in transportation earthworks-laboratory investigations. Iowa State University. Ames, IA.

Yang, B., Zhang, Y., Ceylan, H., Kim, S., and Gopalakrishnan, K. (2018). "Assessment of soils stabilized with lignin-based byproducts." Transportation Geotechnics, Vol. 17, Part 1, pp. 122–132. https://doi.org/10.1016/j.trgeo.2018.10.005.

Zhang, T., Cai, G., and Liu, S. (2017). "Application of lignin-based by-product stabilized silty soil in highway subgrade: A field investigation." Journal of Cleaner Production, Vol. 142, pp. 4243-4257. http://dx.doi.org/10.1016/j.jclepro.2016.12.002.

Zhang, T., Cai, G., Liu, S., and Puppala, A.J. (2014). “Stabilization of silt using a lignin-based bioenergy coproduct.” the proceedings of Transportation Research Board 93rd Annual Meeting, Washington D.C.

Zhang, T., Liu, S., Cai, G., Puppala, A.J. (2014). “Study on Strength Characteristics and Microcosmic Mechanism of Silt Improved by Lignin-Based Bio-Energy Coproducts.” Ground Improvement and Geosynthetics, Vol. 238, pp. 220-230. https://doi.org/10.1061/9780784413401.022.

Zhang, Y., Johnson, A.E., and White, D.J. (2016). “Laboratory freeze–thaw assessment of cement, fly ash, and fiber stabilized pavement foundation materials.” Cold Regions Science and Technology, Vol. 122, pp. 50–57. http://dx.doi.org/10.1016/j.coldregions.2015.11.005.