Biofuel Co-Product Use for Pavement Geo-Materials Stabilization Phase II: Extensive Lab Characterization and Field Demonstration

Final Report
December 2019

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16. Abstract

Rapid advancements in bioenergy-based industry have not only reduced our dependency on fossil resources but also brought about sustainable development for human society. The production of biofuel derived from biomass also produces co-products containing lignin. Biofuel co-products (BCPs) containing sulfur-free lignin were investigated in this research study to gain further insight into their benefits in stabilizing pavement subgrade soil. Four different types of co-products were tested: (1) an oily liquid type with medium lignin content (BCP A), (2) a powder type with low lignin content (BCP B), (3) another oily liquid type with high lignin content (BCP C), and (4) an oily liquid type of lignin derived from paper pulp production (lignosulfonate). The laboratory tests focused on engineering properties, including unconfined compressive strength (UCS), shear strength, freeze-thaw durability, and moisture sustainability of BCPs-treated soils. Four types of Iowa soil were mixed with BCPs and lignosulfonate for testing, and the results indicated that BCPs are more promising additives for soil stabilization in Iowa because of their beneficial effects in improving soil engineering properties, strength properties, durability, and resistance to moisture degradation. Scanning electron microscope (SEM) and x-ray diffraction (XRD) analyses were also performed to identify mechanisms of lignin-based soil stabilization. A microstructural analysis showed that lignin materials could coat and bind soil grains and thereby form a strong soil structure.

Five soil stabilizers (cement, lignosulfonate, chlorides, Claycrete, and Base One) were sprayed on a gravel road subgrade for the field demonstration. In situ tests including light weight deflectometer (LWD) and dynamic cone penetration (DCP) were performed before, one week after, and one year after the construction to monitor the performance of the stabilized sections and to draw the lessons learned from the practice. 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. Based on this study's findings, the application of BCPs in soil stabilization appears to benefit both the bioenergy industry and the pavement construction industry.

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BIOFUEL CO-PRODUCT USE FOR PAVEMENT GEO-MATERIALS STABILIZATION PHASE II: EXTENSIVE LAB CHARACTERIZATION AND FIELD DEMONSTRATION

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December 2019

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

Biofuel derived from biomass is a renewable energy product and has attracted great attention in past decades. As an effective alternative for sustainable development, the use of biofuel can decrease the fossil energy crisis and environmental impacts. The production of biofuel has increased dramatically in recent years, and this process also produces various co-products, which contain lignin. To seek further benefits from the biofuel industry, engineers are investigating many utilizations of these co-products, and pavement subgrade soil stabilization is the one of them. Although traditional lignin containing sulfite (lignosulfonate) from the paper industry has been studied for many years, newer lignin that is sulfur-free and derived from biofuel production has not been studied much. The primary objective of this research was to investigate the laboratory performance of biofuel co-products (BCPs) containing sulfur-free lignin in pavement subgrade soil stabilization, and the secondary objective was to evaluate the laboratory and field performance of lignosulfonate and four other commercial soil stabilizers (cement, chlorides, Claycrete, and Base One) for comparison purposes.

The laboratory test programs were separated into two parts: BCPs and lignosulfonate. For BCPs, several laboratory tests including Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), direct shear, freeze-thaw durability, moisture susceptibility, and micro-structural characterization consisting of scanning electron microscope (SEM) and x-ray diffraction (XRD) analyses were conducted in this study to evaluate the performance of three BCPs: (1) an oily liquid type with medium lignin content (BCP A), (2) a powder type with lower lignin content (BCP B), and (3) another oily liquid type with high lignin content (BCP C). Four types of soil were collected from different locations in Iowa for this study, and they were (1) an A-6 or clayey sand (SC) soil (Soil 1) collected in Calhoun County, (2) an A-4 or sandy silt with clay (CL-ML) soil (Soil 2) in Sioux County, (3) an A-4 or CL-ML soil (Soil 3) collected from Buchanan County, and (4) an A-4 or sandy silt (ML) soil (Soil 4) also collected from Buchanan County. In addition, the additive content was selected as 12% due to the Phase I study conducted by Ceylan et al. (2010). This study was restricted by the insufficient quantity of BCP materials, and some test programs were unbalanced. For lignosulfonate, similar laboratory tests including compaction characteristics, UCS, freeze-thaw durability, wet-dry durability, lignin set time, and SEM were performed for Soil 3 and Soil 4. The dosages of lignosulfonate investigated in this study were 5%, 10%, and 15%.

In the strength test programs, moisture levels and curing periods were considered as variables that could affect the strength capacity of specimens. Freeze-thaw durability and wet-dry durability tests only considered the effect of the curing period, and the durability of the specimens was evaluated based on visual images, mass loss, and volume expansion. In the moisture susceptibility tests, the specimens were soaked in water for observation of the damages from moisture. Set time tests were performed to investigate the speed at which lignosulfonate became hard at different temperatures and its mechanism. SEM and XRD were used to identify the interactions between lignin and soil grains.

The laboratory test performance to date indicated that BCPs and lignosulfonate can improve strength and durability effectively for Iowa soils. They also were useful to increase moisture

resistance based on experimental observation. The microstructural analysis concluded that BCPs can coat soil grains and bind them together through an adhesive film to form strong soil structures, and lignosulfonate can bond soil grains through flocculation caused by its hydrophobic property and cation-exchange activity.

To evaluate the performance of using lignin product as a soil stabilizer under field conditions, a gravel road in Independence, Iowa, was selected to apply five soil stabilizers (cement, lignosulfonate, chlorides, Claycrete, and Base One) in the second week of October in 2018. In situ tests consisting of light weight deflectometer (LWD) and dynamic cone penetration (DCP) tests were performed and documentations were collected before, one week after, and one year after the construction to monitor the performance of the stabilized section and to draw the lessons learned from the practice. 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.

The use of BCPs containing lignin as a soil stabilizer for pavement construction appears to be an effective approach to provide a desired work platform, and the field demonstration of lignosulfonate treatment performed in this study provides guidance for subgrade stabilization with lignin on the basis of its laboratory and field investigations. Natural soil foundation has a low bearing capacity and is susceptible to moisture, and the laboratory performance of the BCPs demonstrated excellent potential to improve the quality of subgrade materials. A strengthened soil foundation system is essential to pavement life and performance, because it significantly reduces pavement distress. In consideration of the economic profit, the renewable energy industry has more utilizations to improve its added value, and reduce the dependence on fossil energy products for human society. The production cost of BCPs also may benefit from this study and become lower. In addition, as a "green" material, BCPs cause less contamination in both soil and underground water compared to traditional stabilizers such as cement.

This research also proposed future areas of study. First, the entire laboratory test program should be balanced to obtain more comparable results when additional quantities of the oily liquid BCPs are available; second, a field pavement section should be constructed with BCPs-treated soil foundation for field demonstration. Although laboratory data showed improvements from BCP stabilization, the field condition under actual traffic loads should be evaluated for pavement infrastructure systems. Moreover, the application of lignosulfonate in the field demonstrated in this study can be a good lesson for future construction. Considering traditional lignin products already have a wide range of applications in concrete and asphalt admixtures, as a dust control agent, and as a pavement geo-material stabilizer, the utilization of the new type BCPs containing sulfur-free lignin also can be investigated in these applications. As a green construction material, the use of BCPs has the potential to replace traditional additives and contribute to the establishment of a green road infrastructure.

1. INTRODUCTION

Background and Motivation

During the 20th century, a growing demand for fossil resources not only caused a fossil energy crisis but also serious pollution of the global environment (IPCC 1990, IPCC 1996). The use of fossil energy-based products (petroleum, natural gas, coal, etc.) has been found to be a primary cause of carbon dioxide emission and the so-called greenhouse effect (IPCC 2014). The issue of a fossil energy shortage and the voices in support of environment protection have, therefore, motivated significant development of biofuel production (ethanol) derived from biomass to fulfill transportation needs.

Corn is a very common agricultural crop in the US. The residual parts of corn after harvesting such as stalk and leaves are termed corn stover. Corn stover is a representative biomass resource containing a sufficient mass of lignin to produce ethanol. Johnson et al. (2004) concluded that byproducts from corn stover processing such as fermentation can also produce economic and environmental benefits, including production of electrical energy and soil improvement. The byproducts from biofuel production using corn stover as a raw material contain as much as 60% to 70% lignin. Other biomass materials, such as agricultural and forest residues, also can be used to produce biofuel and lignin, and the estimated worldwide annual yield of lignin is about 50 million tons (Demuner et al. 2019). Many lignin products have been commercialized and marketed over a wide range of applications including concrete admixture, asphalt modifier, batteries, pavement-surface sealing, dispersants, animal nutrition, and agriculture (ILI n.d., Sundstrom et al. 1983). In pavement construction particularly, traditional lignin derived from the paper industry, termed lignosulfonate, has been proven to have positive effects with respect to road dust control, service life, and antioxidation in binder (Khandal 1992, Rummer et al. 2001, Guffey et al. 2005). However, the total amount of lignin derived from paper and biofuel industries still exceeds the capability of its absorption by the current market. To enhance the economic value added by the biofuel industry, new applications for its lignin-based byproducts are needed.

Much natural soil doesn't provide a desired platform for pavement construction due to its poor engineering properties, so the addition of agents in soil, a practice termed soil stabilization, is necessary to make the soil strong enough to support a road. Soil stabilization is a common practice for road construction defined as the alteration of soils through the addition of chemicals to enhance their engineering properties. In general, the effect of additives on soil stabilization is determined by the measurement of strength improvement of the soil-additive mixture. The performance of soil stabilization is influenced by many factors, the most remarkable being the physical and chemical properties of the natural soil and the additive used.

Over the last couple decades, lignin products have been studied with respect to their soil stabilization properties and are believed to benefit soil mechanical properties (Nicholls and Davidson 1958, Kozan 1955, Johnson et al. 2003). As a class of complex organic polymers, lignin contributes to formation of physical bonds and humic acid in soil and thereby increases soil stability (Landon and Williamson 1983, Ingles and Metcalf 1973, Woods 1960).

Biofuel co-products (BCPs) may be effective in soil stabilization because of their high lignin content, and an initial study by Johnson et al. (2004) investigated the influence of corn stover-derived BCP on chemical and physical properties of soil. Lignosulfonates are the traditional lignin products studied for use in industry, but another category of lignin, sulfur-free lignin, has gained some attention. Ceylan et al. (2010) proposed an innovative approach to the use of BCP containing sulfur-free lignin in pavement subgrade soil stabilization and hypothesized that such a BCP could be a promising soil-strengthening additive. A BCP containing sulfur-free lignin could, therefore, be a potential alternative for pavement subgrade soil stabilization and should be studied further to determine its other specific benefits. Utilization of lignin-based BCPs in pavement geo-material stabilization should be investigated, because it is hypothesized that stronger geo-material stabilization may be thereby achieved, possibly reducing the geo-material need through this innovative approach.

Research Objective

The primary purpose of this research was to continue the laboratory investigation of the utilization of BCPs containing sulfur-free lignin as an effective soil stabilizer for pavement earthworks under Iowa conditions. This research is a follow-up to a previous study by Ceylan et al. (2010), and seeks to gain further insight into BCP soil stabilization mechanisms and effects on more types of soil. In particular, an oily liquid-type BCP produced at the Iowa State University (ISU) Bioeconomy Institute was evaluated. The second goal of this research was to perform a laboratory investigation and field demonstration for lignosulfonate-treated soil. The specific objectives of the study were:

- Evaluate the performance of BCPs in different soils with respect to engineering properties and strength properties
- Evaluate the performance of BCPs in different soils with respect to freeze-thaw durability and moisture susceptibility
- Identify the mechanisms of BCP soil stabilization through using microstructural analysis
- Identify the performance and mechanism of lignosulfonate soil stabilization
- Conduct a field demonstration project to verify laboratory results and identify lessons learned
- Compare five different soil stabilizers with respect to their strength and durability performance by conducting light weight deflectometer (LWD) and dynamic cone penetration (DCP) tests

Research Approach

In the laboratory investigation, this research focused on investigating soil-BCPs and soil-lignosulfonate mixtures through laboratory testing. Three types of BCPs were mixed with four types of Iowa soils collected from Calhoun County, Sioux County, and Buchanan County, and one type of lignosulfonate was mixed with two soils from Buchanan County only. Type I portland cement also was used as a traditional stabilizer for comparison purposes. The natural soil or soil-additive mixtures were compacted into cylinder or plate specimens for strength and durability testing. The laboratory results were expected to provide information about how much improvement with respect to the engineering properties of soil can be achieved by lignin

stabilization. X-ray diffraction (XRD) and scanning electron microscope (SEM) studies were also conducted to analyze the microstructure of the soil-BCPs mixtures and identify potential mechanisms of BCP and lignosulfonate soil stabilization. An oily liquid type BCP with medium lignin content (BCP A) and another with high lignin content (BCP C) had not been previously available in sufficient quantities, so their performance with respect to unconfined compressive strength (UCS) and freeze-thaw durability were considered high-priority activities.

Based on the laboratory test results of lignosulfonate, a field demonstration project was conducted at the site where Soil 4 had been collected (Buchanan County), and a total of five soil stabilizers were applied on gravel road subgrade. LWD tests and DCP tests were conducted to compare the strength and durability performance of these five stabilizers. The construction process and the critical lessons learned from this construction were documented both visually and in written form.

Report Organization

This report is organized into seven sections (Figure 1).
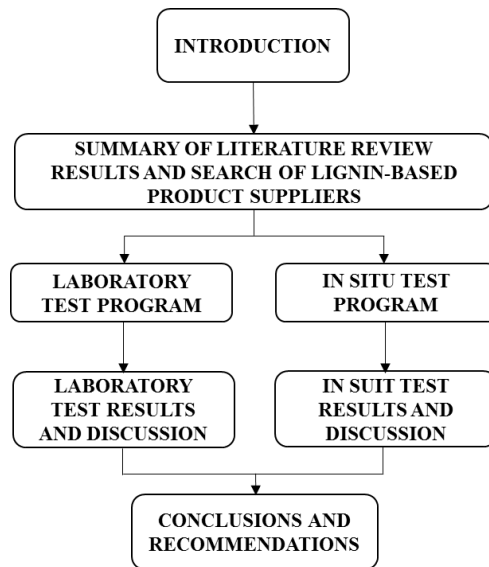
Figure 1. Report organization flow chart

Chapter 1 presents the background, motivation, objectives, and general approach of this study. A literature review of traditional stabilizers, nontraditional stabilizers, and lignin-based products is summarized in Chapter 2. In Chapters 3 and 4, the soils and additives used, specimen preparation methods, and various laboratory and in situ testing methods are described in detail. Chapters 5 and 6 discuss the results from the laboratory and in situ test program, respectively. Finally, Chapter 7 concludes the report and provides recommendations for future laboratory testing and field performance studies.

The seven appendices at the end of this report include a list of lignin-based suppliers and/or around Iowa (Appendix A), laboratory specimen mix design data sheets (Appendix B), draft mix design and test procedures for BCP stabilized soil (Appendix C), raw data of UCS test results (Appendix D), visual images of durability test results (Appendix E), raw data of freeze-thaw durability test results (Appendix F), and images and data of XRD patterns (Appendix G).

2. LITERATURE REVIEW AND LIGNIN-BASED PRODUCT SUPPLIERS SEARCH

Overview of Traditional Soil Stabilizers

A high-quality subgrade soil foundation can provide the desired long-term pavement performance. Soil stabilization is a process for strengthening the engineering properties of soil through physical, chemical, or combined methods. Portland cement, lime, and fly ash have been widely used all over the world to stabilize soil, and they are, therefore, known as traditional stabilizers. Extensive research over many years has investigated the use of traditional stabilizers in terms of their operating mechanisms, mix design procedures, advantages, and limitations.

Portland Cement

Portland cement is a gray, fine powder comprised of calcium silicates, aluminum and iron compounds, and other compounds (ASTM C150). Table 1 shows the chemical composition of portland cement that includes tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) as major compounds and their respective abbreviations.

Table 1. Chemical composition of portland cement

Oxides	Amount, %	Abbreviation
Calcium oxide (CaO)	60–65	C
Magnesium oxide (MgO)	0–5	M
Aluminum oxide (Al_2O_3)	4–8	A
Ferric oxide (Fe_2O_3)	2–5	F
Silicon dioxide (SiO_2)	20–24	S
Sulfur trioxide (SO_3)	1–3	S
Loss of ignition	0.5–3	

Source: Winterkorn and Pamukcu 1991

Water can react with these chemical compounds to form calcium hydroxide ($Ca(OH)_2$) and hydrated structures such as hydrated silicate and aluminum. In these hydrated products, a calcium silicate gel expressed as CSH ($3CaO \cdot SiO_2 \cdot 3H_2O$) can resemble tobermorite mineral in forming a stable tobermorite gel. Calcium hydroxide also generates some secondary reactions with silicates and aluminates in soil to form more stable gels such as tobermorite gel (Herzon and Mitchell 1963). The hydration process in cement produces strong and stable products to improve strength, durability, and frost resistance of the mixture, so a soil-cement mixture is widely used in pavement geo-material stabilization.

The cement content recommended for soil depends on the soil type. The Portland Cement Association (PCA) suggests that soil classified from A-1 to A-7 groups by the American Association of State Highway and Transportation Officials (AASHTO) soil classification system (AASHTO M 145-91) can use cement as a stabilizer, and the recommended amount of cement varies from 3% to 16% (PCA 1995). To simplify the mix design procedures for soil-cement

stabilization, PCA, after analyzing experimental databases from thousands of cement-treated soil specimens, has developed a short-cut method. This short-cut method can't be applied to organic soil or soil containing more than 50% by weight of particles smaller than 0.002 in. and/or less than 20% by weight of particles smaller than 0.0002 in. (clay). If the soil materials don't satisfy these criteria, the short-cut method cannot be used. For soil containing no particles retained on a No. 4 sieve, short-cut method A can be used to estimate the cement amount. Figure 2 through Figure 4 give the general design steps for method A.
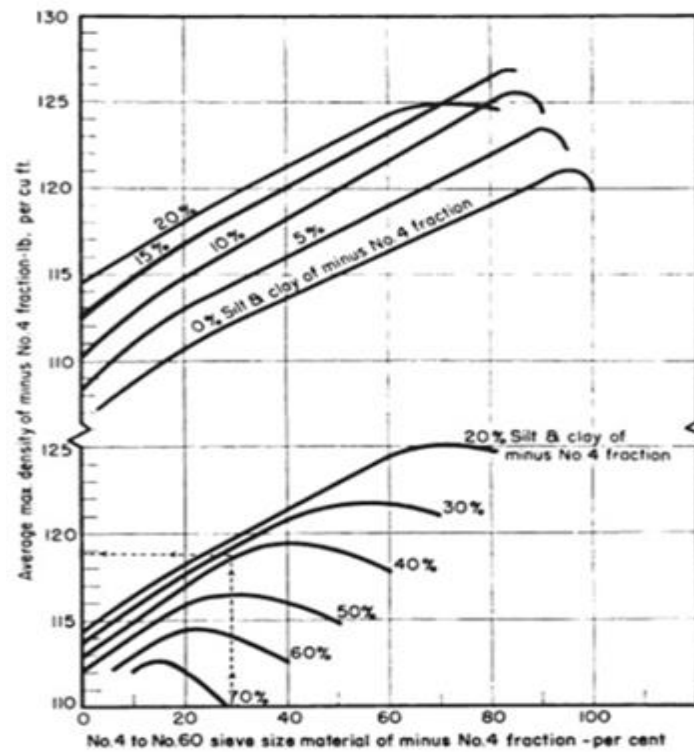
PCA 1956

Figure 2. Estimated average maximum densities of soil-cement mixtures without materials retained on a No. 4 sieve
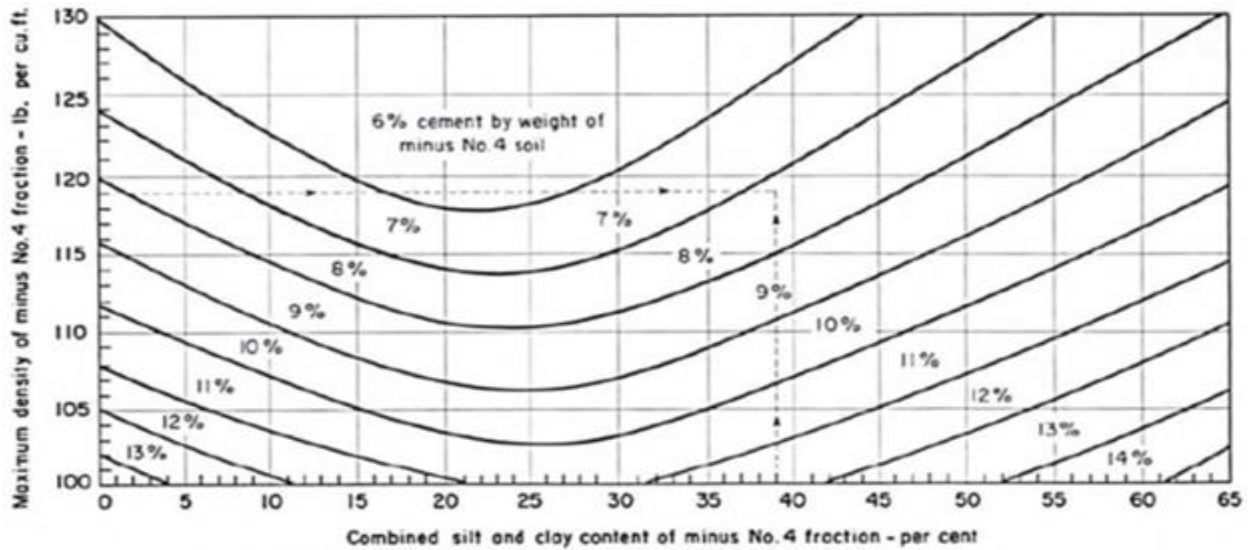
6

Figure 3. Required cement content for soil-cement mixtures without materials retained on a No. 4 sieve
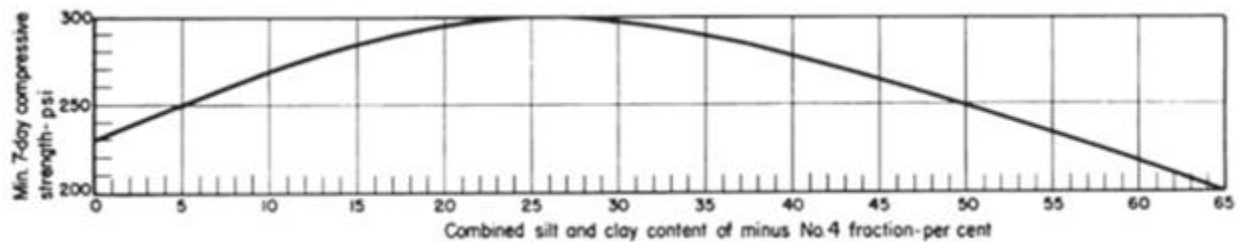
Figure 4. Required minimum 7-day compressive strength for soil-cement mixtures without materials retained on a No. 4 sieve

The first step is to perform a sieve analysis to determine soil particle-size distribution (gradation), and then the maximum density of the soil-cement specimen can be selected, as shown in Figure 2. Second, combine the maximum density obtained from Figure 2 and the percentage of material passing through a No. 4 sieve to select a recommended cement amount, as shown in Figure 3. Next, the soil-cement mixture can be compacted and molded at the optimum moisture content (OMC) for strength measurement. After a seven-day moist-curing process, the average measured compressive strength values shown in Figure 4 should be close to the specimen strength. Moisture content plays an important role in strength improvement of soil-cement mixture, and ASTM D558 specifies a method for obtaining the moisture-density relationship of a soil-cement mixture, and the optimum moisture content can be determined following this method.

The application of cement to pavement subgrade soil stabilization has been practiced for many years. Rapid strength improvement and moisture resistance are major advantages for cement treatment, but there are some shortcomings such as high cost, high-alkalinity, and potential

shrinkage cracking that have restricted the use of cement treatment for soil (Winterkorn and Pamukcu 1991).

Lime

Lime is a white calcium-compound material. Generally, there are two types of lime, quicklime (CaO) and hydrated lime (Ca(OH)$_2$). Lime has commonly been used as an important traditional soil stabilizer and has a long history of application. The underlying mechanism of lime stabilization is pozzolanic reaction. Similarly to the portland cement hydration process, lime provides calcium for a chemical reaction with the clay (silica rich) component of soil to produce stable calcium silicate hydrates (CSH). In addition, cation exchange, flocculation-agglomeration, and carbonation can occur in the presence of water, and these chemical reactions improve soil workability and strength capacity (Winterkorn and Pamukcu 1991).

Lime-stabilized mixture design procedures are based on statistical analysis of laboratory tests. After much data analysis and validation activity, AASHTO T 220-66 presents an approach for estimating proper lime application rates in soil stabilization, as shown in Figure 5.
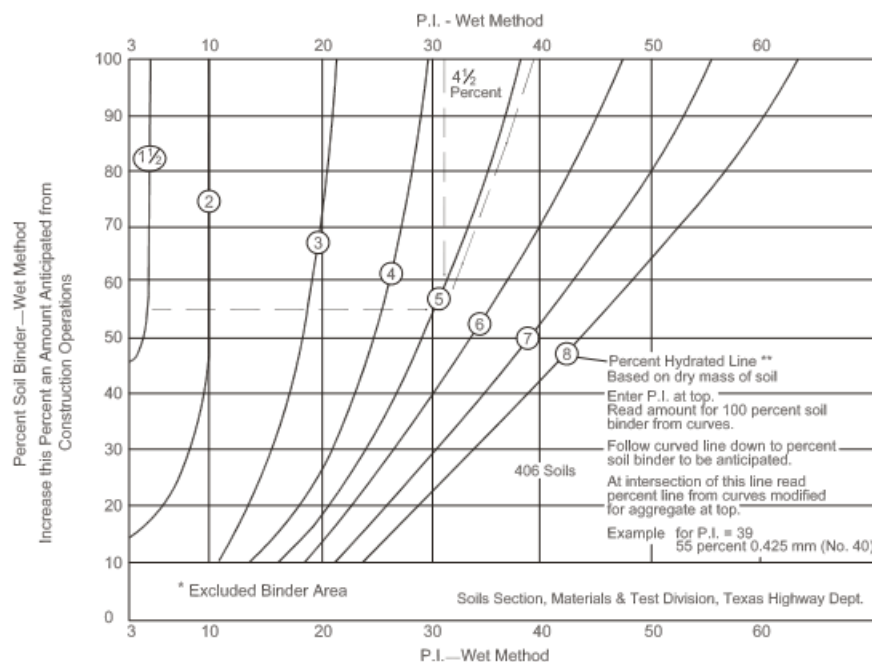
AASHTO T 220-66

Figure 5. Recommended amounts of lime for stabilization of subgrades and bases

8

As shown, this chart doesn't work for soil with less than 10% passing through a No. 40 sieve and a plasticity index (PI) less than 3 (cohesionless soil). To estimate the proper percentage of lime, the first step is to perform a soil sieve analysis and an Atterberg limits test (to determine plasticity, PI). The obtained value of plasticity is then identified along the top horizontal axis. Next, follow along the curved line to find the intersection with the percentage of soil binder. Finally, read the required percentage of lime from the curves modified for aggregate soils.

Lime is most effective for clayey soils and soils with high plasticity indices and can have many benefits in soil stabilization. For example, it is a rapid drying agent, and strength increase may require waiting a period of days or even months to avoid long-term strength loss. On the other hand, problems related to slow strength gain and lime's caustic properties must be considered.

Fly Ash

Fly ash is also widely used in the US as a traditional stabilization agent. It is a byproduct produced by coal combustion at power plants. The chemical composition of fly ash is shown in Table 2.

Table 2. Weight percentage of various components of fly ash

Component	Bituminous	Subbituminous	Lignite
Calcium oxide (CaO)	1–12	5–30	15–40
Aluminum oxide (Al_2O_3)	5–35	20–30	20–25
Ferric oxide (Fe_2O_3)	10–40	4–10	4–15
Silicon dioxide (SiO_2)	20–60	40–60	15–45
Sulfur oxide (SO_3)	0.5–5	1–8	1–8
Loss of ignition	0–15	0–3	0–5

Source: Styron 1980

Generally, the primary components of fly ash are calcium oxide, aluminum oxide, ferric oxide, and silicon dioxide. Fly ash is similar to soils in that there is a wide range of physical and chemical properties of ashes produced by different power plants. Fly ash from lignite or subbituminous contains a higher percentage of calcium and sulfates, and is defined as Class C by ASTM C618. The burning of younger lignite or subbituminous coal typically produces Class F fly ash containing less calcium oxide (ASTM C618). These two different types of fly ash exhibit different mechanisms due to their different compositions.

Class C fly ash has both cementitious and pozzolanic properties, meaning that it can cause both hydraulic and pozzolanic reactions. The mechanism of Class C fly ash is very similar to that of cement and produces a stable gel with the presence of water but not nearly as effectively as portland cement. Class F fly ash is pure pozzolan and not a hydraulic stabilizer. One notable characteristic of this ash is that it must be used with lime to be effective (Winterkorn and Pamukcu 1991); the addition of lime can generate ash setting, a hardening process. Pozzolanic reactions among soil, lime, and fly ash produce stable structures that lead to gains in soil strength and durability and a decrease in shrink-swell potential (TRB 1976).

Fly ash mix design is based on trial-mix data. The great variability among fly ash impels engineers to develop several approaches to selecting fly ash content for soil stabilization. Using a combination of lime and fly ash design is one of the common methods for strengthening soil. Davidson (1961) proposed a lime-to fly-ash ratio chart (Figure 6) that satisfies the strength requirement.
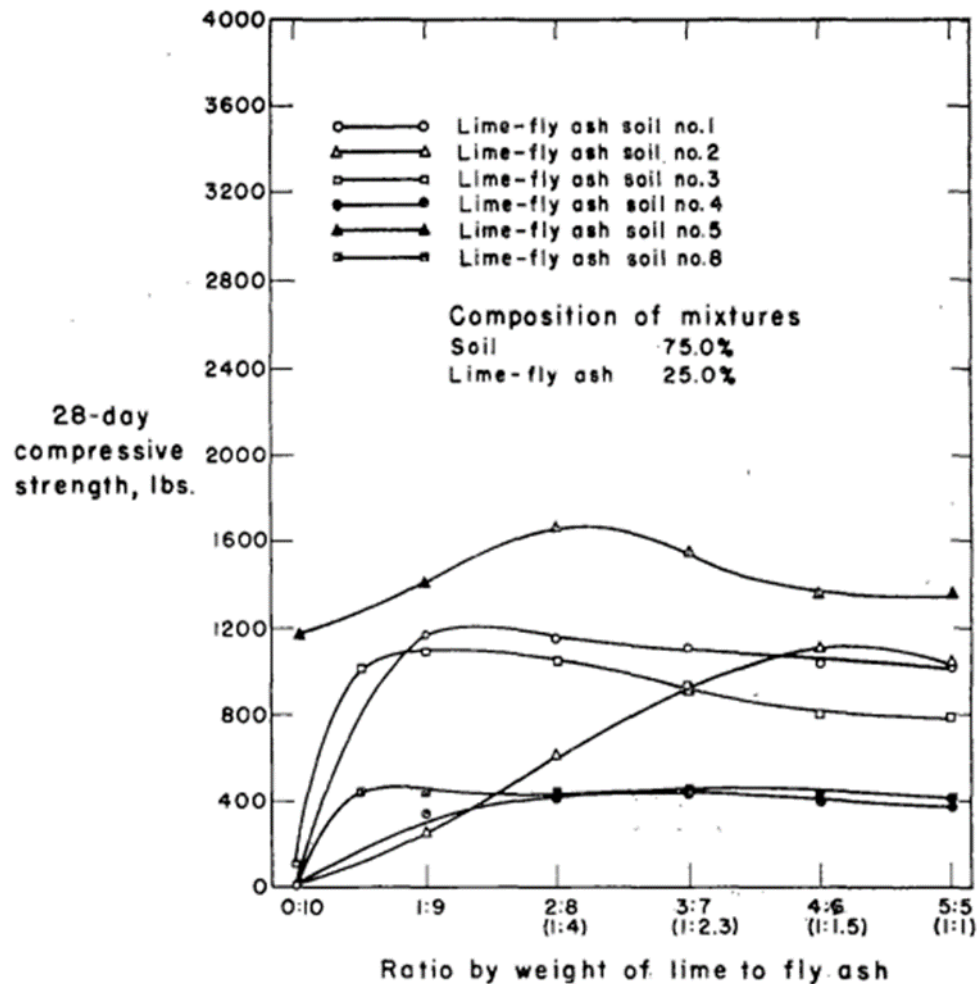
Davidson and Associates 1961, Iowa State University

Figure 6. Effect of variations in the ratio of lime to fly ash on the compressive strengths of lime and fly ash-stabilized fine-grained soil

In this chart, the required strength curve can be used to identify the appropriate lime and fly ash content in the total mixture. The typical accepted range of lime-to-fly-ash ratio is 1:2 to 1:7, and ratios of 1:3 and 1:4 are common due to economic and quality considerations (Winterkorn and Pamukcu 1991). To perform the UCS test (ASTM C39) and thereby verify the trial mix lime-to-fly-ash selection, ASTM C593 should be used for guidance and provide criteria for specimen preparation.

The use of fly ash in soil stabilization is effective for both granular and fine soils. It contributes to long-term strength and freeze-thaw durability improvement, to reducing shrink-swell potential of clay soil, and to saving construction cost compared to that of cement. However, the high sulfate (SO_3) sources from fly ash may cause sulfate attack, a chemical reaction that causes pavement to expand. A fly ash sulfur content below 5% is generally acceptable.

Traditional stabilizers depend on chemical reactions to form stable products and thereby strengthen soil structure. While thousands of applications have proven that these chemical agents can create good working platforms, their limitations, such as relatively high cost and non-environmentally friendly properties, have become concerns over the past several decades. Nontraditional stabilizers have, therefore, received increasing global attention.

Review of Nontraditional Soil Stabilizers

The disadvantages of traditional materials for soil stabilization can't be ignored, and these issues have forced engineers to seek alternatives. In recent years, rapid development of nontraditional stabilizers has created hundreds of new products for soil stabilization. A large number of independent research efforts pertaining to the effects of using nontraditional stabilizers in soil have been documented. Nontraditional stabilizers have generally been grouped into seven categories based on their primary chemical components: ionic, enzymes, lignosulfonates, salts, petroleum resins, polymers, and tree resins (Tingle et al. 2007). Although laboratory and field performance studies of nontraditional stabilizers generally have been more highly valued than understanding their interactions with geo-materials, much effort has been expended toward determining the mechanisms of nontraditional stabilizers.

Ionic Stabilizers

In recent years, acids and alkaline have been common ionic additives studied for stabilizing soil. The hypothesized mechanism of ionic stabilizers is producing cation-exchange flocculation of clay minerals by altering electrolyte concentration in fluid (Scholen 1992). The presence of flocculation can improve strength capacity in soil. The cation-exchange capacity of soil is a very significant property with respect to soil structure stability, pH value, and other properties. Ionic stabilizers can provide ions and react with soil to reduce the surface charge of soil particles. Once soil surface charge is decreased, the double-layer water will also be reduced, and soil structures will then become more closely packed and produce more flocculation, thereby improving soil strength. Most previous studies have already reported the benefits of the addition of ionic agents to improve strength, stabilize volume, and resist moisture in soil. Katz et al. (2001) and Rauch et al. (2002) conducted a series of laboratory tests to investigate soil microstructure with ionic stabilization. They reported that minimal changes in soil structure, such as d-spacing, XRD, and specific surface areas, were observed with the use of ionic additives. Their laboratory results supported Scholen's viewpoint regarding the underlying mechanism of ionic stabilizers. The hypothesized mechanism also suggests that these stabilizers are suitable for fine soil or clay because the behavior of fine soil is more easily influenced by electrical charges.

In Texas, two ionic stabilizers and one polymer stabilizer were used in highway construction to investigate their field performance (Harris et al. 2006). The field performance of these additives differed from the engineers' expectations based on laboratory results. Undesirable field performance due to the lack of studies and guidelines has inhibited the application of ionic stabilizers (Campbell and Jones 2010).

Enzyme Stabilizers

Enzymes are biological molecules that catalyze chemical reactions. Enzymes, unlike traditional stabilizers, don't consume themselves in reactions, so the enzyme dosage is generally small. The challenge of enzyme soil stabilization is how to let an enzyme reach and remain at a working site to catalyze reactions; enzyme choice is soil-specific due to a mobility requirement. The hypothesized mechanism suggests that enzymes build bonding between organic molecules and cause them to be attracted by the surface charge of clay minerals (Scholen 1992). The clay minerals surrounded by organic molecules have, therefore, a neutralized charge to reduce affinity for moisture. Similar to laboratory testing results of ionic stabilizers, Rauch et al. (2002) found no significant changes in XRD and specific surface area with the use of enzymes; these findings support the mechanism hypothesized by Scholen (1992). The laboratory results from enzyme studies also demonstrated good strength improvement in highly plastic clay with some organic content; their laboratory performance for granular soil is, however, poor.

Some roads in Asia have used enzyme stabilization as an approach for enhancing pavement performance. Some successful studies in India and Malaysia have reported that several advantages of enzyme stabilization had been achieved, including an increase in pavement strength and durability and a reduction of containment and cost (Marasteanu et al. 2005). However, use of enzymes as stabilizers is critically dependent on soil environment conditions. Some failed pavement performance cases resulting from enzyme stabilization are good examples for study (Marasteanu et al. 2005).

Lignosulfonate Stabilizers

Lignosulfonate products are derived from cellulose fibers such as grass and wood used in the paper industry. The exact composition of lignosulfonates will differ because different plants are used for production. The proposed mechanism of lignosulfonate stabilization is coating soil particles and binding them together with an adhesive-like film (Tingle et al. 2007). Lignosulfonates are regarded as cementing agents that form physical bonds between soil particles through minor chemical reactions (Landon and Williamson 1983, Ingles and Metcalf 1973, Woods 1960). They are also similar to ionic stabilizers in being water soluble with an ion-exchange capacity for reacting with soil. Traditionally 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 a 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 and Whitman 2008).

To investigate the effects of lignosulfonate stabilization, Tingle and Santoni (2003) cooperated to conduct laboratory testing on a lean clay (CL) soil. A significant increase in strength was obtained after 28 days under both dry- and wet-cure conditioning. Santoni et al. (2002) also conducted some strength tests for silty sand (SM) with lignosulfonate treatment, and they reported moderate improvement in strength compared to that of untreated soil. Peric et al. (2014) evaluated the effects of lignosulfonate on early-age shear behavior of sand. They reported an increase in cohesion of sand after lignin-treatment, indicating that improvement of slope stability of sand was achieved. These results are in accord with the proposed mechanism of coating and binding soil particles by film. Under this theory, the ability to coat soil particles is an important effect produced by lignosulfonates. This indicates that lignosulfonates should be more effective for granular soil because this soil exhibits greater specific surface area for bonding formation.

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 7758280 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 a bond among various types of soils and fly ash particles, which generates a waterproof surface and prevents fly ash from dispersing over time (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).

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 (CBR) were improved for treated soil (Lekha et al. 2015). The stabilized soil also proved to be more durable after 12 cycles in a 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 7) (Lekha et al. 2015).
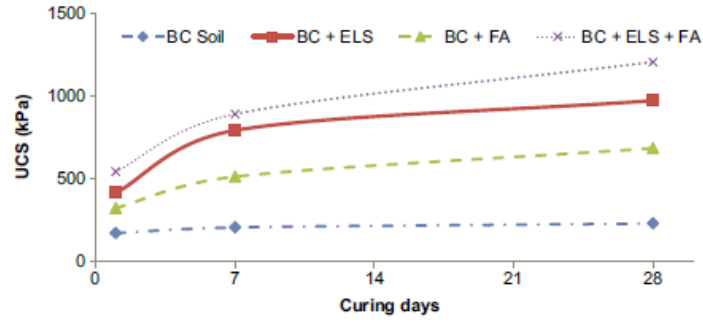
(a)
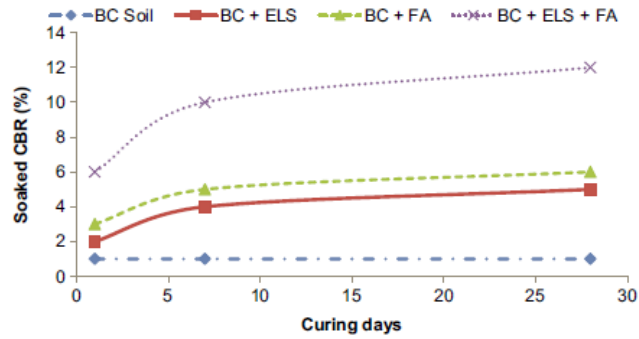
(b)

Lekha et al. 2015

Figure 7. Variation of (a) UCS and (b) soaked CBR values at OMC

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 8 and Figure 9) (Fatehi et al. 2018).
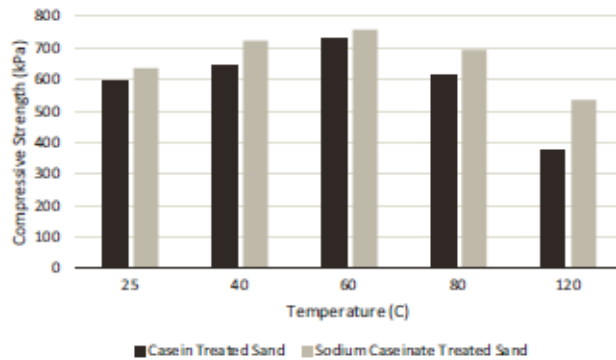
Fatehi et al. 2018

Figure 8. Compressive strength of casein and sodium caseinate treated soil with respect to different curing temperatures

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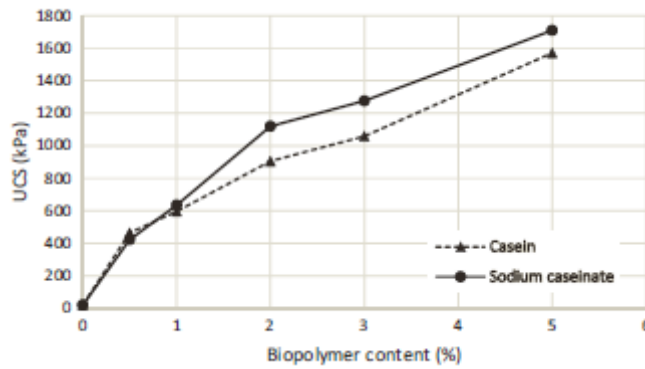
Fatehi et al. 2018

Figure 9. Compressive strength of casein and sodium caseinate treated soil with respect to biopolymer content

The curing temperature also was found to be one of the key factors affecting compressive strength, and the optimum curing temperature was found to be 140°F (Figure 10) (Fatehi et al. 2018).
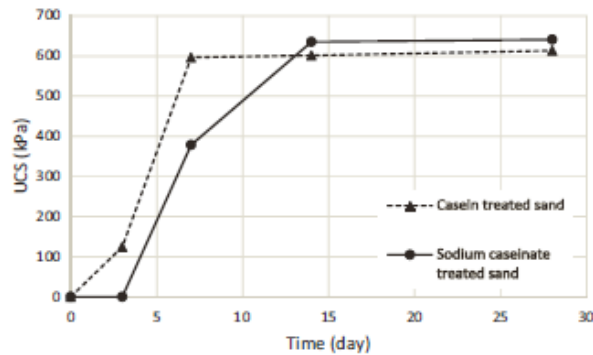
Fatehi et al. 2018

Figure 10. Compressive strength of casein and sodium caseinate treated soil with respect to curing times

The researchers found that these protein-based biopolymers had higher potential as a soil stabilizer than cement or other chemical polymers (Fatehi et al. 2018).

In a study in China, the strength of silt was believed to be improved by a lignin-based bioenergy co-product filling pores and linking soil particles so that a more compact and stable soil structure is formed (Zhang et al. 2014). As shown in Figure 11, the highest improved strength occurred with 12% of bioenergy co-products A and B.

15
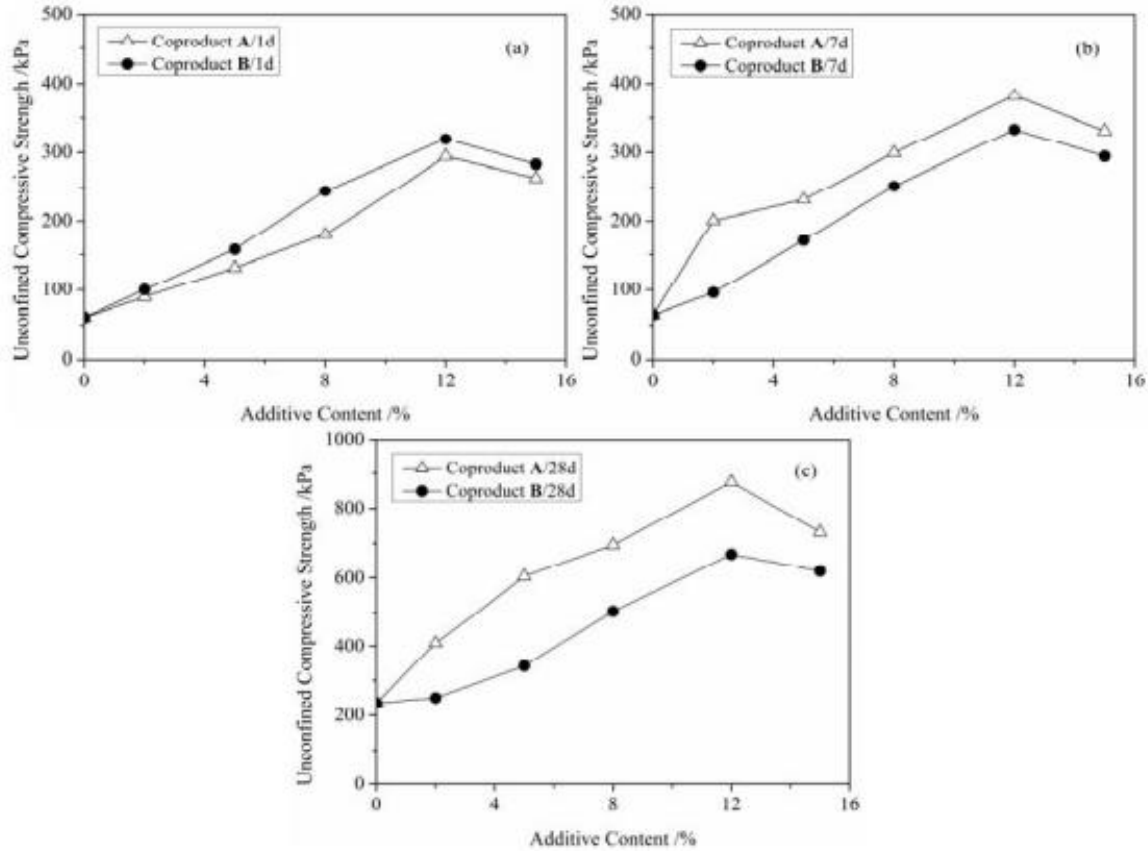
Zhang et al. 2014

Figure 11. UCS results of (a) 1-day, (b) 7-day, and (c) 28-day curing

The researchers believed the optimum dosage of the tested bioenergy co-products ranged from 10 to 12% (Zhang et al. 2014). It is also observed from Figure 11 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 an 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 co-product B is more effective to improve strength for silt under the wet condition, and co-product A is more effective to improve strength for silt under the dry condition (Zhang et al. 2014). The researchers further investigated why strength improved with respect to morphology and found the bioenergy co-product treated sample was bonded with precipitated cementing materials. As shown in Figure 12, the silt particles became coated by the co-product, which formed a stronger and more stable soil co-product structure (Zhang et al. 2014).
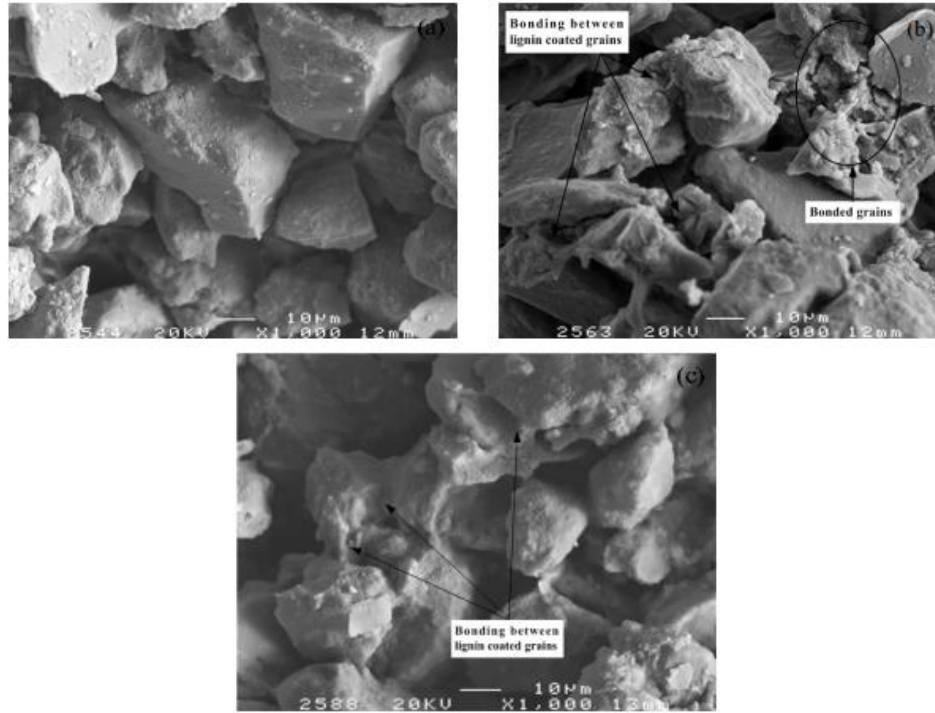
Zhang et al. 2014

Figure 12. SEM results of untreated and 12% bioenergy co-product A-treated soil

It was concluded that lignin-based bioenergy co-products function as cementing material, which act completely different than traditional soil stabilizers (Zhang et al. 2014).

In a recent study conducted by Fatehi et al. (2018), the efficiency of casein and sodium caseinate salt biopolymers as soil stabilizers was tested, where the researchers investigated the reasons for the improvement of strength by conducting SEM analysis. Through comparing Figure 13a and Figure 13c, one can observe that the casein biopolymer interacted with soil particles.
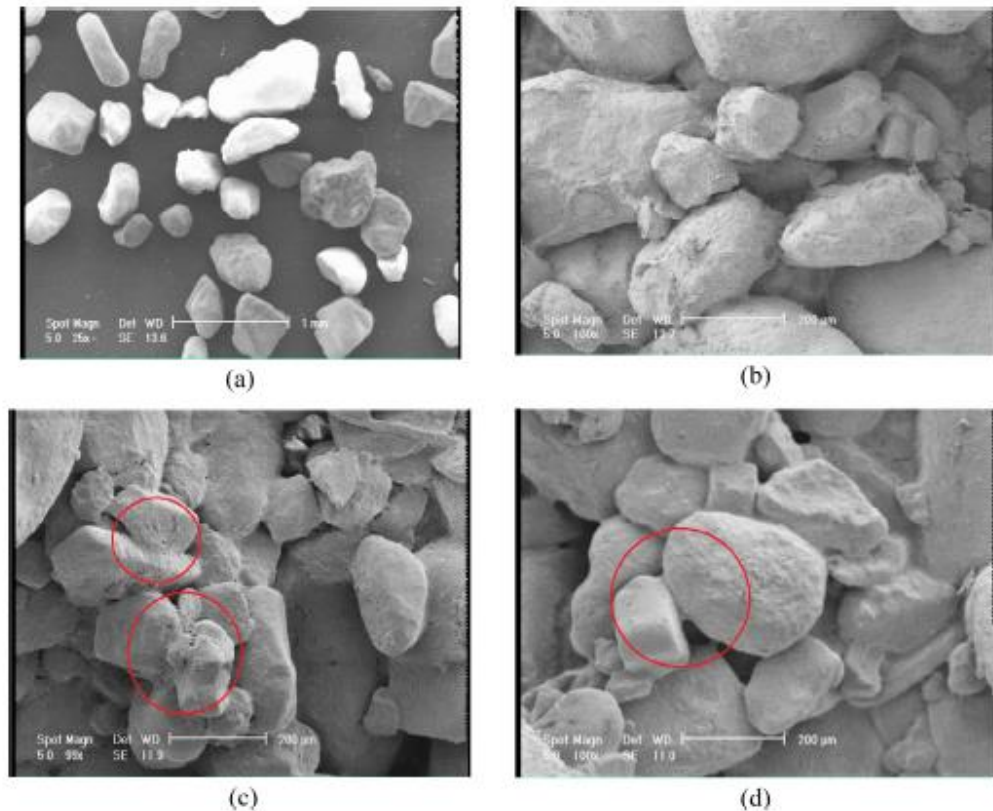
Fatehi et al. 2018

Figure 13. SEM images of (a) natural state of dune sand, (b) compacted untreated sand, (c) casein-treated sand, and (d) sodium caseinate-treated sand

The researchers believed that the adhesion occurred in four stages: wetting, adsorption, curing, and mechanical locking (Fatehi et al. 2018).

Another recent study investigated the efficiency of enhancing the properties of expansive clay with lignosulfonate (Noorzad and Ta'negonbadi 2018). It was found that lignosulfonate improved the clay strength, and strength improvement increased with a decrease in compaction water content. In addition, the reduction of swell percent, swell pressure, and plasticity index of clay soil also related to the lignosulfonate addition (Noorzad and Ta'negonbadi 2018). Through SEM analysis, 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 and Ta'negonbadi 2018).

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

The mechanism of expansive soil stabilization with lignosulfonate recently has been identified, and the results 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. 2018).

During the previous decade, several researchers reported the improvement of soils' strength with the treatment of lignosulfonate, yet very few field demonstrations have been carried out to verify the feasibility of field scale application using the laboratory results. 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 CBR and resilient modulus, lower values of resilient deflection and DCP 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 Alabama, a lignin-based stabilizer was added for testing low-volume road subgrade soil (Rummer et al. 2001). Compared to untreated road sections, a lignosulfonate-treated section showed a higher CBR, as defined in a penetration test guided by ASTM D4429 and ASTM D1883 for mechanical strength evaluation of pavement base and subgrade layer (Rummer et al. 2001). This field performance showed results similar to those of Santoni's laboratory testing that described lignosulfonate stabilization as an economic method for treating subgrade soil. However, some long-term reduction in moisture susceptibility and strength in clay was also observed. The hypothesized explanation for this phenomena is that the negative surface charge of lignosulfonates causes deflocculating of clay particles. Lignosulfonate may also cause leaching under moist conditions due to its water solubility, so fine-grained soil or clay is not suitable for lignosulfonate products.

Salt Stabilizers

The common composition of salt stabilizers is calcium and magnesium chloride. Salt has a moisture absorption capability and can maintain moisture in soil. In soil-salt mixtures, cation exchange can occur between monovalent cations in the soil and divalent cations in the salt. This process of exchange makes soil particles more stable and reduces their double-layer water. More flocculated structures can be formed because of smaller spacing between soil particles, and the benefit of strength improvement can be achieved. Moreover, salt additives have two secondary mechanisms for strengthening soil; they not only produce recrystallized structures in pore spaces to make soil more dense but also improve the surface tension of pore water and soil cohesion to increase soil strength (Tingle et al. 2007). The hypothesized underlying mechanisms of salt stabilizers, therefore, indicate that both granular and fine soil can be treated with these additives.

As a suitable alternative, salt stabilizers have been used in road construction for many years. In many cases, salts successfully stabilized soil and improved road performance, but salts are water-

soluble agents susceptible to leaching, and the potential resulting metal corrosion can damage the reinforced pavement.

Petroleum Resins

An asphalt emulsion consisting of asphalt and surfactant is the most commonly used petroleum resin for geo-material pavement stabilization. The primary mechanism of bituminous stabilization is to coat soil particles and physically bind them together (Tingle et al. 2007). The surfactant agents added by asphalt play an important role in stabilization; they can change soil surface charge to enhance the adhesion of asphalt to soil particles (Winterkorn and Reich 1962). The most suitable soil for asphalt-emulsion stabilization is granular soil that has a lower specific surface area. Particles in fine-grained soil with high specific surface area are more difficult to adequately bond with asphalt emulsion than those in granular soil.

Santoni et al. (2002) evaluated asphalt emulsion treatment for silty sand and found no significant improvement in strength. That study indicated that physical bonds contribute to moderate strength improvement. The remarkable benefit of asphalt-emulsion stabilization is its excellent waterproofing capability; the formed coating of soil particles reduces the susceptibility to moisture. These benefits have also been achieved in Minnesota for existing pavement treated with asphalt emulsion (Skok et al. 1983). A 10-year performance report shows that the pavement still has good serviceability with little deformation and distress.

Polymer Stabilizers

A polymer has large molecules consisting of repeated and small units. In general, they are converted into emulsion with the addition of surfactant agents. Tingle et al. (2007) summarized that the primary mechanism of polymer stabilization is to form physical bonds by coating soil particles when the evaporation of water in the emulsion leaves a residual strong soil-polymer matrix. This is very similar to asphalt emulsion stabilization, and both mechanisms can use surfactant to improve particle coating by surface charge modification. The similarity between polymer and asphalt stabilization, therefore, makes polymers also suitable for use in granular soil. As with asphalt cement, polymers provide very good waterproofing and moderate strength improvement. The hypothesized mechanism of physical bonds has been confirmed by SEM analysis (Rauch et al. 2003). Santoni et al. (2002) conducted strength tests for silty sand treated with different polymer emulsions and reported a significant increase in strength for silty sand stabilized by polymer emulsion after both dry and wet conditioning. Subsequently, Tingle and Santoni (2003) cooperated to treat clayed soil with four different polymers and reported that only one of these four polymers provided significant strength improvement under both dry and wet conditions. These laboratory results indicated that polymer emulsion performs better in granular soil than fine-grained soil.

In California, a polymer emulsion called Soil-Sement ® from Midwest Industrial Supply Inc. was used for soil stabilization. This agent successfully made the road more durable and cost-effective with less erosion (California Air Resources Board 2002). Significantly improved strength was achieved in field performance with the addition of polymer emulsion in granular

soil. Although polymer stabilization provides a strong subgrade layer for pavement, its potential toxicity could lead to environmental problems.

Tree Resin Stabilizers

Resin derived from the timber and paper industries is a highly viscous substance. To prevent premature coalescence, resin is generally added into an emulsifying agent. As with petroleum resins and polymer emulsions, tree resin can coat individual soil particles to form a film that binds particles together, so tree resin is a cementing stabilizer only suitable for granular soil (Tingle et al. 2007). Santoni et al. (2002) also tested silty sand stabilized by tree resins and observed an increase in strength under wet conditions after 7-day and 28-day periods. However, the same silty sand treated with polymer emulsion showed greater strength improvement than tree resin stabilization. Tingle and Santoni (2003) used one type of tree resin to treat a CL soil and found that this treatment provided no remarkable improvement in soil strength, supporting the idea that the mechanism is physical bonding between soil particles. The other advantage of tree resin is its lesser susceptibility to leaching because it is a natural material. The most common use of tree resin in soil stabilization is to control dust.

Summary of Nontraditional Stabilizers

The mechanisms underlying different stabilizers are summarized in Table 3.

Table 3. Categories, laboratory performance, and hypothesized mechanisms of nontraditional stabilizers

Type	Primary stabilization mechanism	Strength improvement	Volume stability	Moisture resistance	Suggested suitable soil
Ionic	Cationic exchange and flocculation	Low–medium	Low–medium	Low–medium	Fine-grained soil, silt, clay
Enzymes	Organic molecule encapsulation	Low	Low–medium	Low	High plastic clay with organic content
Ligno-sulfonates	Physical bonding/cementation	Medium	Low–medium	Low–medium	Granular soil
Salts (sodium chloride)	cation exchange, flocculation and cementation	Low–medium	Low	Low	Granular soil Fine-grained soil
Petroleum resins	Physical bonding/cementation	Medium	Medium	High	Granular soil
Polymers	Physical bonding/cementation	Medium–high	Medium	Medium–high	Granular soil
Tree resins	Physical bonding/cementation	Medium–high	Medium	Medium–high	Granular soil

Stabilizers relying on physical bonds and cementations are suitable for granular soil due to high specific surface area in soil. Some generating cation exchange and flocculation in clay resulting from the surface charge of clay particles are more easily modified to flocculate together. Although several previous laboratory studies have investigated the performance of these nontraditional stabilizers, improvements in soil strength were not significant compared to traditional stabilization, and sometimes they even experienced a loss of strength capacity. Unfortunately, although the relatively low cost of nontraditional stabilizers is an important motivation in applying them to soil stabilization, their development has been restricted by many factors such as lack of guidance and standards, improper use of additives with specific soils, inadequate application or mixing of the products and soils, and misinformation distributed by vendors (Campbell and Jones 2010). For future development of nontraditional stabilizers, the stabilization additive industry should cooperate with research organizations to conduct laboratory and field testing for additive evaluation. Both industry and researchers also should embrace change and use databases to propose protocols for nontraditional stabilization mix design.

Biofuel Co-Products

The burning of fossil fuels (petroleum, coal, natural gas, etc.) has provided energy for the development of society, but it has also polluted the environment through the emission of greenhouse gases. Because of this background, sustainable energy resources have been proposed for industrial replacement of traditional fuels since the 1970s. Biomass, an economical and safe material from the natural environment, has attracted a great deal of interest along with alterative resources like wind, sunlight, water, and nuclear (Kamm and Kamm 2004). A biofuel is a fuel produced through processing of plant, agriculture, and food waste biomass. Its use has been strongly supported by the US government for industrial applications to reduce the use of fossil fuels (U.S. Congress 2000). The development of biofuel is also expected to provide up to 50% of future liquid-fuel needs (Kamm and Kamm 2004).

In recent years, the development of the bioenergy-based industry has greatly progressed with government support. Conventional biofuel manufacturing uses corn crops, sugar cane, and other agricultural residuals for alcoholic fermentation. However, in recent years other advanced technologies have been investigated for their potential in producing biofuel with higher energy density and lower cost (Koshel and McAllister 2010). Figure 14 depicts the process of biofuel and co-products production.
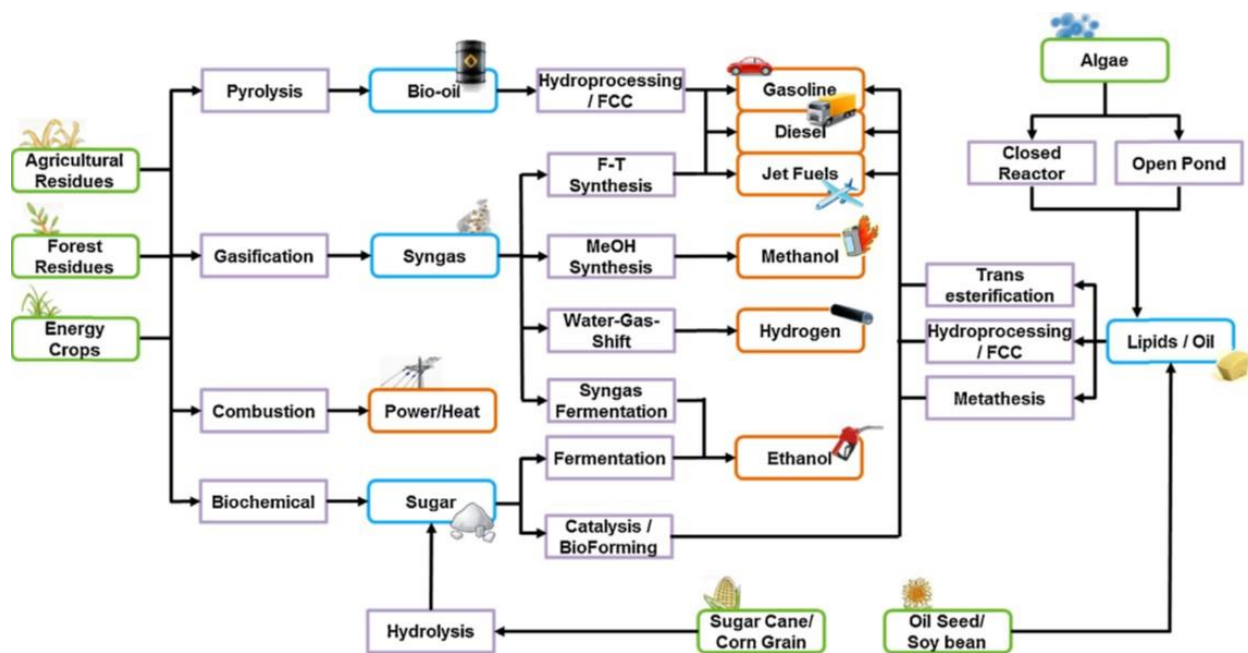
Yue et al. 2014

Figure 14. Generalized biomass to biofuel process diagram

Biomass processes of pyrolysis, gasification, combustion, biochemical, hydrolysis, transesterification, hydroprocessing, and metathesis can produce ethanol, electricity, hydrogen, methanol, and transportation oils (Yue et al. 2014). In addition, a next-generation biofuel supply chain that maximizes biofuel industry profitability has been proposed. Hence, rapid biofuel industry development can be foreseen and related to the current context of energy (Koshel and McAllister 2010).

Residual biomass used for biofuel production also produces a large quantity of byproducts, with lignin products composed of complex organic polymers being one example (Hamelinck et al. 2005). As a byproduct derived from biomass, lignin exhibits a variety of structures depending on the choice of raw materials and methods of processing; various lignin products, therefore, have different chemical and physical properties. For example, they can be produced in different phases, including oily liquid and solid, and also with different colors such as brown, black, and yellow. Some lignin products not only have water solubility because of their special backbone structures (SO_3H, etc.) but also have aliphatic thiol groups that may generate nasty smells, especially during heating (Lora and Glasser 2002).

Lignin products derived from industry as byproducts or co-products can be categorized into two different types according to their composition: lignosulfonates and sulfur-free lignin. The former, derived from the paper industry, has a wide variety of applications such as in binder modification and concrete plasticizing (Lora and Glasser 2002), and its utilization in soil stabilization and improvement of engineering properties has been recognized in several research studies over the past decades (Kozan 1955, Nicholls and Davidson 1958, Lane et al. 1984, Palmer et al. 1995, Puppala and Hanchanloet 1999, Tingle and Santoni 2003). Sulfur-free lignin derived from biofuel production has been known about for many years; it has not, however, been as

23

commercialized as that from other industries, but it has been researched to explore its potential application (Lora and Glasser 2002).

Considering that lignin widely exists as a large fraction of plant biomass, use of sulfur-free lignin in soil stabilization has been previously proposed by researchers at ISU for deriving potential new economic benefits from lignocellulosic biorefineries (Ceylan et al. 2010, Gopalakrishnan et al. 2010). Celyan et al. (2010) treated sandy lean clay (CL) soil with two different BCPs containing sulfur-free lignin, a black oily liquid type and a yellow powder type. They added each of these two BCPs to soil with up to 15% dry unit weight at three different moisture levels: dry side (OMC-4%), optimum moisture content (OMC), and wet side (OMC+4%). After one-day and seven-day curing, they reported that maximum strength improvement (UCS) was achieved on both specimens containing 12% of the two BCPs (Figure 15).
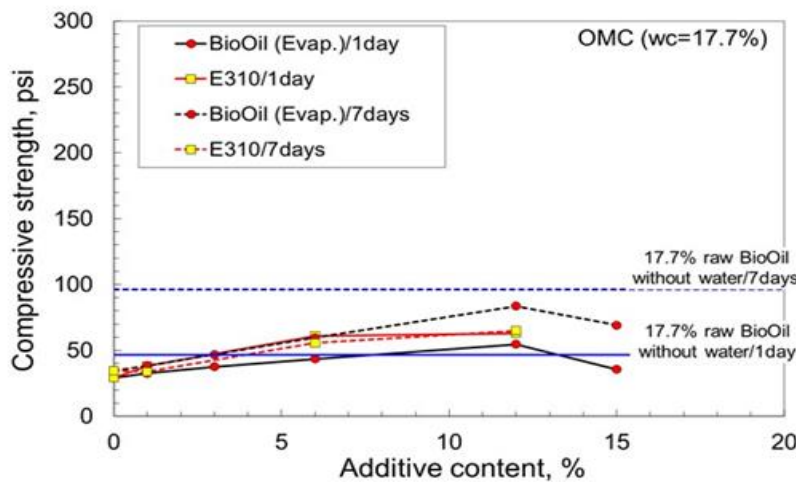
Ceylan et al. 2010

Figure 15. UCS for soil treated with various contents of BCPs at optimum moisture content

They also conducted UCS tests for specimens under both saturation and half-saturation and reported significant strength improvement with these two BCP treatments, especially with the oily liquid-type treatment. Zhang et al. (2014) and Zhang et al. (2015) used two other BCPs containing sulfur-free lignin containing up to 15% by dry soil weight to treat silt soil. They also reported that a 12% application rate for both these BCPs could achieve the highest strength improvement after 1-day, 7-day, and 28-day curing. They also carried out XRD and SEM analyses to verify physical bonds as the mechanism of sulfur-free lignin for soil stabilization. These results indicated that sulfur-free lignin can play a positive role in soil stabilization at a recommended application rate of 12% by dry soil weight. However, more studies are needed to evaluate such effects as freeze-thaw durability of sulfur-free lignin for soil stabilization.

Summary of Literature Review

Natural granular and fine-grained soils have poor intrinsic engineering properties with respect to supporting pavement but have been treated successfully using traditional stabilizers (cement,

lime, and fly ash) for many decades. Hydration and pozzolanic reactions in traditional stabilization of soil can produce a very strong gel to improve soil strength. Although traditional stabilization in soil has improved pavement performance for many years, nontraditional stabilization methods have more recently been proposed, studied, and applied in pavement construction because of their relatively low cost and lesser environment pollution. Common nontraditional stabilizers fall into several types based on their chemical composition. Most of them, such as lignosulfonates, polymers, petroleum resins, and tree resins can generate cation exchange and flocculation and are effective for both granular and fine soils. Enzymes are different because they use organic molecule encapsulation to stabilize. Suitable soil for them should be fine-grained with organic content. Even though several laboratory studies and field demonstrations provide reliable evidence and prove the benefits of current nontraditional stabilizers in pavement construction, engineers continue to propose new additives for soil stabilization, and BCP containing sulfur-free lignin is one in which the promise is aligned with the massive 21st century development of the biofuel industry.

Ceylan et al. (2010), Zhang et al. (2014) and Zhang et al. (2015) conducted UCS tests for sulfur-free lignin-treated silt and clay soils. In addition, Zhang et al. (2014) and Zhang et al. (2015) also conducted microstructural analysis for BCPs. Their results revealed a maximum increase in strength in soil with 12% of co-products by dry soil weight and a hypothesized mechanism of physical bonds for sulfur-free lignin. Therefore, BCP seems to have potential for stabilizing pavement subgrade soil, even though more research is needed for verification.

This research is an extension of the study of Ceylan et al. (2010); they developed this laboratory test program and the same BCPs were used. In this follow-up study, more laboratory tests have been carried out to evaluate the performance of three different types of biomass-derived BCPs for stabilizing soil in different Iowa counties. These laboratory results can be used as a reference in evaluation of future field practices.

Search of Lignin-Based Product Suppliers

This project phase included a field demonstration, and therefore, finding a bio-based co-product supplier for the field construction became an essential task. 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, and then asking about opportunities for their potential collaboration. The contact information of lignin-based suppliers are listed in Appendix A.

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. 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. In addition, a shorter distance between the construction site and the plant would contribute to completing the field demonstration in a timely manner. In this task, the research team made sure to convey to lignin suppliers the long-term benefits of the bio-based co-product's use for pavement geo-materials stabilization purposes.

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 the bio-based co-product, the soils and the plants along the road could be polluted.

Table 4 contains the details of company name, location(s), product categories, and general information of a number of selective and representative lignin-based suppliers that were searched and contacted.

Table 4. Lignin-based co-product suppliers

Company name	Location(s)	Product categories	General information
Absolute Energy, L.L.C.	St. Ansgar, IA; Lyle, MN	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).	Located on the Iowa-Minnesota border, Absolute Energy produced the first grind on February 12, 2008. With the belief that the production of E15 can contribute to the growth of America's rural communities. Absolute Energy focuses its interest on Iowa and Minnesota's local corn availability, renewable fuel, and clean air coming from vehicles.

Company name	Location(s)	Product categories	General information
Archer Daniels Midland	Decatur, IL	Archer Daniels Midland purchases raw farm products like wheat, corn, and soy, and transforms into bulk ingredients to sell to other food manufacturing, processing, and packaging companies.	Archer Daniels Midland is a global food processing company that provides a large variety of products, including organic food, nutritional supplements, animal nutrition, fuel, along with farmer and financial services. The researchers were only interested in Archer Daniels Midland's plant located in Decatur, Illinois.
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.	Big River Resources began in 1992 with fuel and feed production objectives. 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 improves and stabilizes the agricultural economic resources by producing corn-based ethanol as the primary renewable fuel within multiple states in the 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 America's dependence on foreign oil. CORN adds value to locally grown grains in Iowa, which profits the investor owners, local communities, the economy, and the nation.

Company name	Location(s)	Product categories	General information
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 enhances 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.
Homeland Energy Solutions, LLC	Lawler, IA	Homeland Energy Solutions produces ethanol and its co-products. In addition, it also produces significant distillers grains.	Homeland Energy Solutions began to develop and plan its ethanol processing facility in 2005. The ethanol processing facility has the capabilities to produce 100,000,000 gallons of ethanol annually. The facility serves agriculture producers of corn from 11 counties in Iowa. Homeland Energy Solutions provides homeland energy independence for the US.
Plymouth Energy, LLC	Merrill, IA	Operating from western Iowa, Plymouth Energy developed a nameplate 50 million gallons of undenatured ethanol per year 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 goal of designing, building, owning, and operating an ethanol plant in Plymouth County.

Company name	Location(s)	Product categories	General information
Lincolnway Energy, LLC	Nevada, IA	Lincolnway Energy processes corn into fuel-grade ethanol and distillers grains.	Lincolnway Energy was founded in 2004 with the goal of building a nameplate 50 million gallon per year dry mill ethanol plant.
Little Sioux Corn Processors	Marcus, IA	Little Sioux Corn Processors produces dried distillers grains (DDG), alcohol, and ethanol from corn. In addition, Little Sioux Corn Processors offers two types of co-products: DDG with solubles, and "modified" wet distillers grains with solubles.	Up to 2015, Little Sioux Corn Processors had the corn processing capacity of 135 mmgy.
Blue Flame Propane	Letts, IA	Blue Flame Propane mainly provides propane and services. Blue Flame Propane also provides dust control services in May and August each year.	Blue Flame Propane mainly provides propane and services for home by providing rental tanks, filling cylinders, maintaining tanks, connecting hardware, and providing 24-hour emergency services. Blue Flame Propane also provides dust control services for unpaved surfaces using all natural tree sap.

3. LABORATORY TEST PROGRAM

Experimental Materials

Natural Soil

There are various soils produced from different geological origins (loess, glacial till, alluvium, etc.) in Iowa, and each of them possesses different properties (Figure 16).
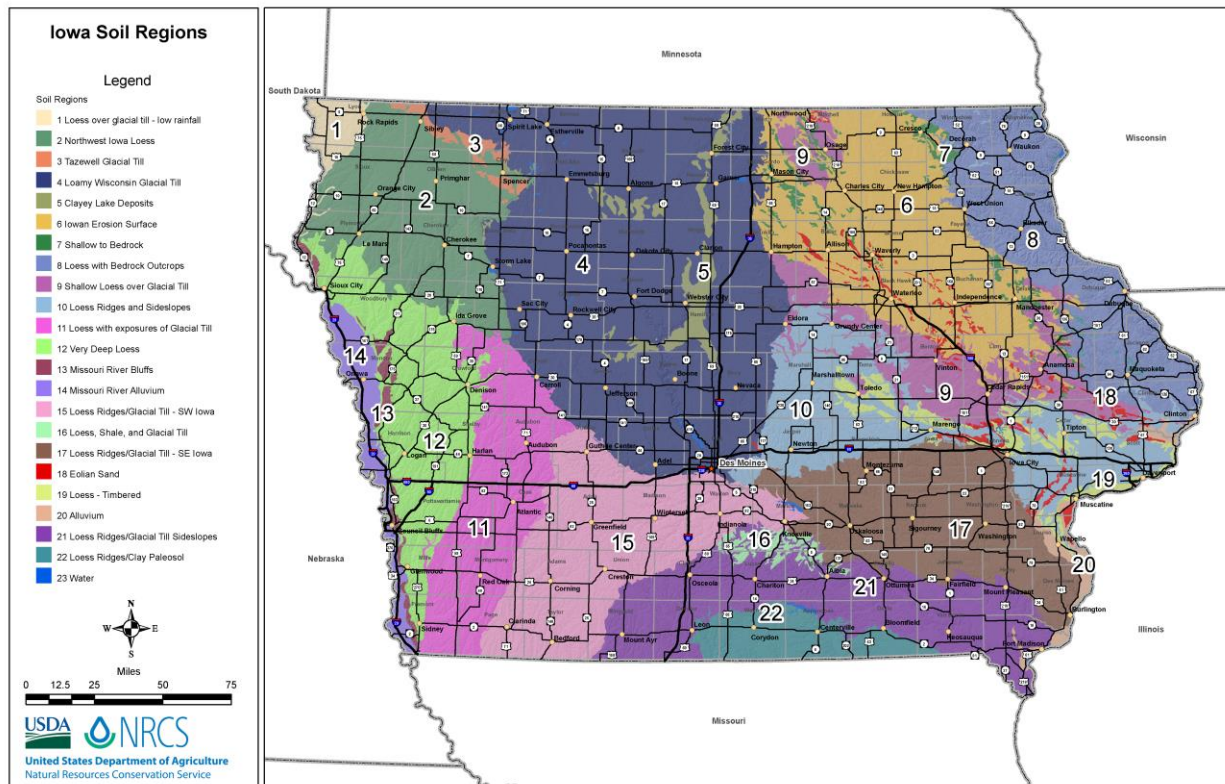
Natural Resource Conservation Service

Figure 16. Iowa soil map

In this research, four types of soil were collected from different counties; their characteristics and pictures are given in Table 5 and Figure 17, respectively.

Table 5. Engineering properties of four different soils investigated

Property	Soil 1	Soil 2	Soil 3	Soil 4
Classification				
AASHTO (group index)	A-6(2)	A-4(2)	A-4(1)	A-4(0)
USCS group symbol	SC	CL-ML	CL-ML	ML
USCS group name	Clayed sand	Sandy silty with clay	Sandy silty with clay	Sandy silty
Grain size distribution				
Gravel (> 0.187 in.), %	7.1	0.1	5.2	3.8
Sand (0.003–0.187 in.), %	54.9	37.2	41.7	45.3
Silt and clay (< 0.003 in.), %	38.0	62.7	53.1	50.9
Atterberg limits				
Liquid limit (LL) , %	32.8	29.1	27.5	17.2
Plasticity limit (PL), %	17.4	22.9	22.2	15.1
Plasticity index (PI), %	15.4	6.2	5.3	2.1
Proctor test				
Optimum moisture content (OMC), %	14.4	18.2	13.5	12.0
Maximum dry unit weight ($\gamma_{d\ max}$), pcf	107.9	101.8	113.5	114.8

Soil 1	Soil 2	Soil 3	Soil 4
A-6(2) or SC	A-4(2) or CL-ML	A-4(1) or CL-ML	A-4(0) or ML

Figure 17. Four types of soil collected in Iowa for research

The AASHTO soil classification system and Unified Soil Classification System (USCS) are the two primary approaches used in classifying these soils by their gradation. The particle-size distribution of the soils used in this study are shown in Figure 18 through Figure 21.
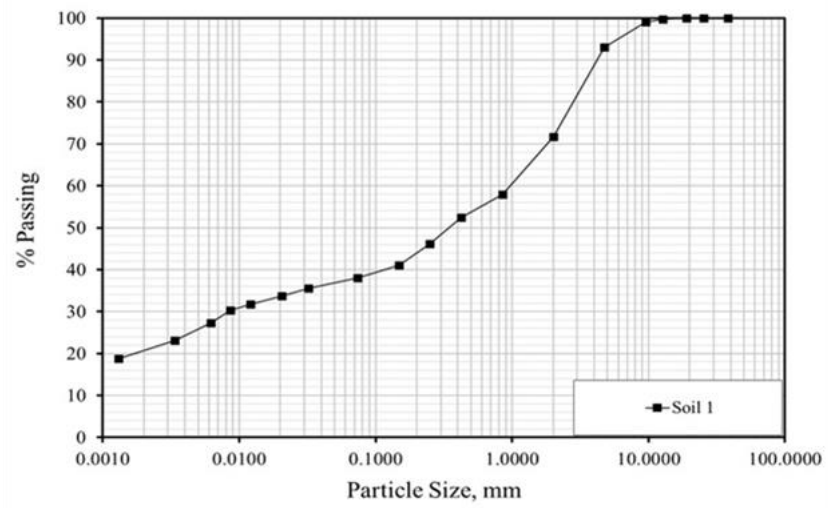
Figure 18. Particle-size distribution curve of Soil 1 classified as A-6(2) and SC
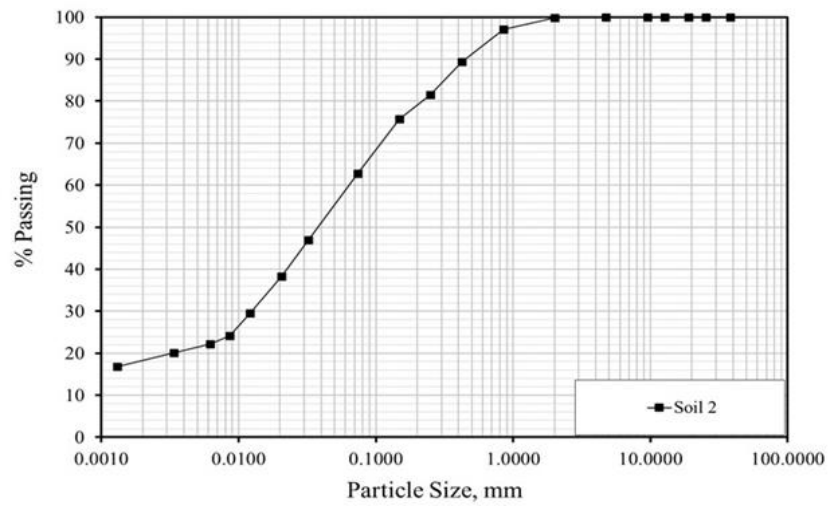
Figure 19. Particle-size distribution curve of Soil 2 classified as A-4(2) and CL-ML
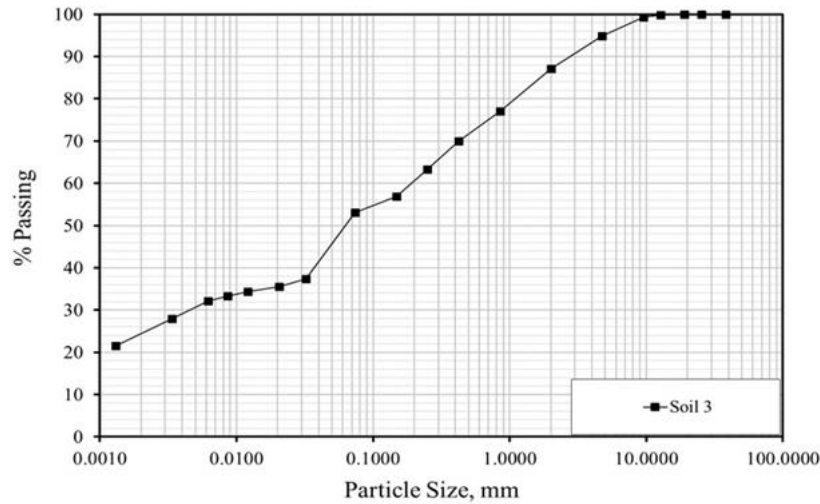
Figure 20. Particle-size distribution curve of Soil 3 classified as A-4(1) and ML
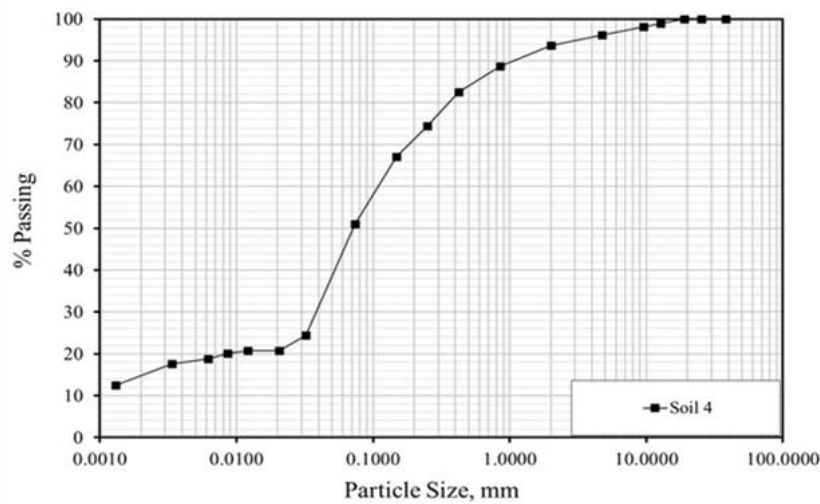
Figure 21. Particle-size distribution curve of Soil 4 classified as A-4(0) and ML

Soil 1 was collected in Calhoun County and classified as an A-6(2) soil or SC in accordance with the AASHTO and USCS, respectively. Soil 2, generally called "loess," was obtained in Sioux County and classified as an A-4(2) or CL-ML soil. Soils 3 and 4 were excavated from the same place, Buchanan County, and classified as A-4(1) or CL-ML and A-4(0) or ML, respectively. Soil 1 is a relatively "coarser" soil than the others, and Soil 2 is the finest soil with the highest clay content, 63%.

Additives

This study investigated four different types of BCPs and one type of lignosulfonate as additives for soil stabilization; the BCPs were designated as BCP A, BCP B, and BCP C, respectively (Figure 22).

33

Figure 22. Three types of biofuel co-products used in this research

In addition, Type I portland cement, a traditional stabilizer, was also used for comparison purposes.

BCP A is a dark brown oily liquid obtained from Dynamotive Energy Systems Corporation, which develops and commercializes energy solutions in Canada for conversion of biomass-to-liquid fuel based on its fast pyrolysis technology. This oily liquid is produced from fast pyrolysis of biomass, a process that heats forest and agricultural residues at temperatures ranging from 752°F to 932°F in an oxygen-free environment (Green Car Congress 2007). This oily liquid has a pungent smell, especially during heating. The primary component materials of BCP A are shown in Table 6.

Table 6. Component materials in BCP A

Components	% by weight
Gases	5 to10%
Water	Up to 25%
Lignin	25%
Char	4%
Aldehydes	35% to 41%

Its lignin content is about 25% and water content is up to 25%; it also contains 5% to 10% gases, 4% char, and 35% to 41% aldehydes. This oily liquid can be heated to remove some portion of moisture after which its behavior becomes more like asphalt binder. At high temperatures, it behaves as an oily liquid, while at low temperatures, it behaves as a solid, so this material is obviously sensitive to temperature. In this research, BCP A was not available in sufficient quantity because the company stopped the production of BCP A for marketing reasons, and standard Proctor compaction tests and direct shear strength (DS) tests were not conducted.

BCP B is produced by a corn-based ethanol plant operated by the Grain Processing Corporation (GPC) of Muscatine, Iowa. This corporation uses alkaline-washed corn hull obtained as a byproduct of ethanol production to produce this yellow powder BCP. The components of BCP B shown in Table 7 are 50% hemicellulose, 20% cellulose, 5% lignin, and assorted others.

Table 7. Component materials in BCP B

Components	% by weight
Hemicellulose	50%
Cellulose	20%
Lignin	5%
Others	25%

This BCP is more like corn ash, and its unit weight is low due to its light molecular weight.

BCP C is also a dark brown oily liquid produced by the ISU Bioeconomy Institute and is similar to BCP A. Rover et al. (2014) developed the alternative technology that combined condensing and water washing gaseous products to produce clean sugar from lignocellulosic biomass for biorenewable fuel production. This approach can separate bio-oil derived from lignocellulosic biomass by fast pyrolysis into clean sugar and lignin-derived phenolic oligomers (BCP C). BCP C contains about 40% lignin-derived phenolic oligomers, 20% water, and 40% assorted other components. As with BCP A, this co-product also gives off a smoky odor during heating. BCP C has a higher lignin content than BCP B, but unfortunately, the amount of this co-product produced is less than the other BCP types since it is a prototype material from ISU Bioeconomy Institute research activities and only in development for large-scale production, so it was not subjected to the full array of laboratory testing.

As with other oily liquid types of BCP containing water, the addition of BCP A and BCP C in soil should consider the influence of moisture content on the mixtures. This means that the required amount of water in the soil-BCP A or soil-BCP C mixtures should be adjusted by water content in BCP A or BCP C. The mixing of oily liquid BCPs with soil also requires good liquid flowability; however, these oily liquid co-products are viscous and difficult to mix. To achieve uniform mixing, it is recommended that these oily liquid BCPs be heated for about 12 hours at 212°F before use, reducing their moisture content to approximately 18%.

The ammonium-based lignosulfonate, identified as Lignin LS-50, shown in Figure 23, is a co-product from paper pulp production that appears as a black, viscous, and homogeneous liquid with a botanical smell.
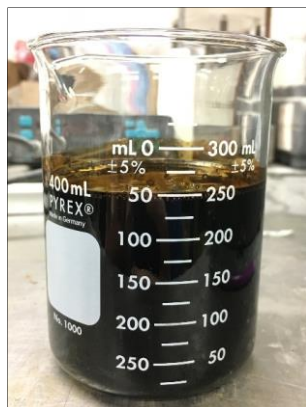
Figure 23. Ammonium-based lignosulfonate used in this research

According to the safety data sheet, this lignosulfonate is not classified as environmentally hazardous with respect to the ecotoxicity. This lignosulfonate is not known as a "hazardous chemical" in accordance with the Occupational Safety and Health Administration (OSHA) Hazard Communication Standard, 29 CFR 1910.1200. In addition, all of the components are on the U.S. Environmental Protection Agency (EPA) Toxic Substances Control Act (TSCA) Inventory List. A 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.

The ammonium-based lignosulfonate in this study was purchased from Blue Flame Propane, an industry located in Letts, Iowa, providing propane and services for home, farm, and business, and rental truck service. In addition, Blue Flame Propane provides dust control services for unpaved roads (Blue Flame Propane 2018). With a unit price of $30 for 642.5 oz, a total of 1281.5 oz 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, Tennessee. The research team visited the lignosulfonate plant on March 23, 2018, and several figures were documented from the plant, which showed the lignosulfonate storage facility and the spraying truck (Figure 24).
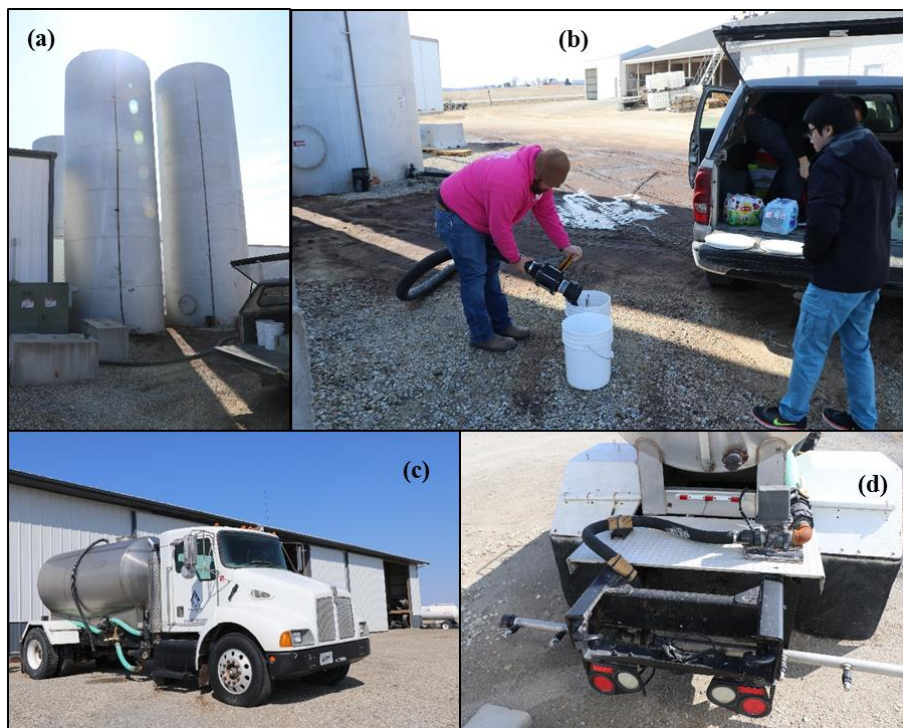
Figure 24. Lignosulfonate storage facility and spraying truck from Blue Flame Propane

Type I portland cement is a general-purpose cement containing 55% C_3S, 19% C_2S, 10% C_3A, and other components as shown in Table 8.

Table 8. Components of Type I portland cement (ASTM C150)

Components	% by weight
C_3S	55%
C_2S	19%
C_3A	10%
C_4AF	7%
MgO	2.8%
SO_3	2.9%
CaO	1.0%
Ignition loss	1.0%

In this study, Type I portland cement was selected for comparison with three co-products' relative performance.

Experimental Plan

The experimental plan for this research was divided into five categories:

- Engineering properties characterization, consisting of Atterberg limits and standard Proctor compaction tests
- Strength-property tests, consisting of the UCS and DS tests
- Moisture susceptibility tests
- Freeze-thaw durability tests
- Microstructural characterization, consisting of XRD and SEM

For the purposes of comparison, there were six different soil treatments in this experiment plan:

- Pure soil without any treatment (control)
- BCP A-treated soil specimen
- BCP B-treated soil specimen
- BCP C-treated soil specimen
- Type I portland cement-treated soil specimen
- Lignosulfonate-treated soil specimen

Ceylan et al. (2010) reported that 12% of BCP content by dry soil weight would produce the best strength improvement for the A-6(8) or CL type of Iowa soil. Zhang et al. (2014) and Zhang et al. (2015) demonstrated strength improvement for soil classified as A-4 or ML through use of 12% of BCP content by dry soil weight. Based on these results, 12% of BCP content was selected for the four soil types investigated in this study. A BCP content of 12% may not be the optimum additive content for each soil type but seems close enough to provide strength improvement in practical use. The optimum rate of lignosulfonate was determined through a trial test.

However, the lack of BCP A and BCP C materials meant that some laboratory tests couldn't be performed for these two BCP treatments. Atterberg limits tests evaluated pure soils and soils mixed with 12% of BCP A, 12% of BCP B, and 12% of cement by dry soil weight. Standard Proctor compaction tests only evaluated pure soils and soils mixed with 12% of BCP B and 12% of cement by dry soil weight. These two tests don't require curing, conditioning, and specific moisture content for materials. The treatment group combinations evaluated for UCS and DS are listed in Table 9.

Table 9. Treatment group combinations for strength property tests

| Soil Types | Moisture content level | Curing period | Additives[a], % | | | | | Direct shear strength |
| | | | Unconfined compressive strength | | | | | |
			BCP A	BCP B	BCP C	Cement	lignosulfonate[b]	BCP B
Soil 1	OMC-4%	1 day	12	12	-	3, 6, 12	-	12
		7 days	12	12	-	3, 6, 12	-	12
		28 days	12	12	-	3, 6, 12	-	12
	OMC	1 day	12	12	-	3, 6, 12	-	12
		7 days	12	12	-	3, 6, 12	-	12
		28 days	12	12	-	3, 6, 12	-	12
	OMC+4%	1 day	12	12	-	3, 6, 12	-	12
		7 days	12	12	-	3, 6, 12	-	12
		28 days	12	12	-	3, 6, 12	-	12
Soil 2	OMC-4%	1 day	12	12	12	3, 6, 12	-	12
		7 days	12	12	12	3, 6, 12	-	12
		28 days	12	12	12	3, 6, 12	-	12
	OMC	1 day	12	12	12	3, 6, 12	-	12
		7 days	12	12	12	3, 6, 12	-	12
		28 days	12	12	12	3, 6, 12	-	12
	OMC+4%	1 day	12	12	12	3, 6, 12	-	12
		7 days	12	12	12	3, 6, 12	-	12
		28 days	12	12	12	3, 6, 12	-	12
Soil 3	OMC-4%	1 day	12	12	-	3, 6, 12	5, 10, 15	12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12
	OMC	1 day	12	12	-	3, 6, 12		12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12
	OMC+4%	1 day	12	12	-	3, 6, 12		12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12
Soil 4	OMC-4%	1 day	12	12	-	3, 6, 12		12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12
	OMC	1 day	12	12	-	3, 6, 12		12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12
	OMC+4%	1 day	12	12	-	3, 6, 12		12
		7 days	12	12	-	3, 6, 12		12
		28 days	12	12	-	3, 6, 12		12

a. Numbers indicate percent additive added by dry soil weight. b. Lignosulfonate-treated specimens are fabricated at different moisture level due to the water content of lignin, not OMC-4%, OMC, and OMC+4%.

In the UCS tests, the application rate of BCPs added to soil was 12% by dry soil weight, and the application rates of cement were variable, with values of 3%, 6%, and 12% by dry soil weight. In consideration of the insufficient quantity of BCP C, the UCS and durability tests were taken as highest priority for evaluation. Soil 2 was selected for evaluation for BCP C since it had the weakest strength and was widely present in western counties in Iowa. In the DS test, only BCP B was mixed with soil because of insufficient quantities of other material. Cement-treated specimens were not allowed because their specimens after curing became a little bit larger and very hard so that they couldn't be placed in the shear box that had a fixed 2.5 in. diameter space.

Even though these specimens could be placed in the shear box after specimen trimming, their peak strengths might exceed the test machine's capacity (500 lbf) and cause equipment damage. The pure soils without any additive treatment were also evaluated through UCS and DS tests. The moisture content level and curing periods were two significant variables in this research. Three moisture content levels were evaluated: optimum moisture content (OMC), OMC+4%, and OMC-4% of pure soil. Curing periods were 1 day, 7 days, and 28 days after sample preparation. The lignosulfonate-treated specimens used a different test plan and all specimens were cured for seven days. Because lignosulfonate has a large fraction of water, trial tests with different moisture contents were conducted.

The treatment group combinations for freeze-thaw durability evaluation are listed in Table 10.

Table 10. Treatment group combinations for freeze-thaw durability tests

Soil types	Moisture content level	Curing period	Additives[a], %				
			BCP A	BCP B	BCP C	lignosulfonate	Cement
Soil 1	OMC	1 day	12	12	-	-	3, 6, 12
		7 days	12	12	-	-	3, 6, 12
Soil 2	OMC	1 day	12	12	12	-	3, 6, 12
		7 days	12	12	12	-	3, 6, 12
Soil 3	OMC	1 day	12	12	-	-	3, 6, 12
		7 days	12	12	-	5	3, 6, 12
Soil 4	OMC	1 day	12	12	-	-	3, 6, 12
		7 days	12	12	-	5	3, 6, 12

a. Numbers indicate percent of additive added by dry soil weight.

Similar to the strength property test plan, 12% of BCP A and 12% of BCP B by dry soil weight were added to all soils, 3%, 6%, and 12% of cement by dry soil weight were also added for comparison purposes, and 12% of BCP C by dry soil weight was added only to Soil 2 due to insufficient material. The untreated soils were also evaluated in this test. For freeze-thaw durability tests, the moisture content level was not considered to be an important factor and all specimens were fabricated under OMC; one-day and seven-day curing periods were investigated. For lignosulfonate, only 5% rate with seven-day curing was evaluated.

Table 11 lists the treatment group combinations for moisture susceptibility, XRD, and SEM tests.

Table 11. Treatment group combinations for moisture susceptibility, XRD and SEM tests

Soil types	Moisture content level	Curing period	Additives[a], %		
			BCP A	BCP B	lignosulfonate[b]
Soil 1	OMC	7 days	12	12	-
Soil 2	OMC	7 days	12	12	-
Soil 3	OMC	7 days	12	12	5
Soil 4	OMC	7 days	12	12	5

a. Numbers indicate percent additive added by dry soil weight. b. Lignosulfonate-treated specimens were tested with SEM only, no moisture susceptibility or XRD tests.

The number of combinations for these tests was fewer than the amount used in the strength properties and freeze-thaw durability tests. The BCP A and BCP B contents were evaluated for 12% by dry soil weight. The quantity of BCP C was fully depleted after the UCS test and the freeze-thaw test for Soil 2; hence, its performance on moisture susceptibility, XRD, and SEM was not evaluated. Cement was not investigated in these three tests because there were already many studies in the literature that evaluated the related properties. Previous studies (Nontananandh et al. 2005a, 2005b) had already conducted XRD and SEM for cement and reported that its primary mechanism of hydration resulted in cement-treated soil-strength gains. In addition, the mixture containing cement in forms like paste, mortar, and concrete are generally cured by soaking in water baths and can't result in degradation; the performance of cement in soaking tests can be predicted. The moisture contents and curing periods of all specimens used for these three tests were OMC and seven-day, respectively. Untreated soil specimens were also fabricated for comparison purposes.

Specimen Preparation

Different laboratory tests had different specimen requirements. Atterberg limits tests, standard Proctor compaction tests, XRD, and SEM need only loose soil-water-additive mixtures, but the other tests required compacted and cured specimens. In this study, three types of compacted specimens with different geometries were fabricated. The first was a compacted cylinder specimen 2 in. in diameter and 2 in. in height, used for the UCS tests, the freeze-thaw durability tests, and the moisture susceptibility tests; the second type was a compacted plate specimen 2.5 in. in diameter and 1 in. in height and used only for the DS tests. The acceptable dimensional differences between fabricated and standard specimens were less than 0.05 in.; the third type is a 4 in. by 6 in. cylinder prepared by following the ASTM D698 and used for UCS measurements of lignosulfonate-treated specimens only.

To fabricate the two different types (2 in. × 2 in. and 2.5 in. × 1 in.) of specimens, mixing designs and procedures, compaction methods, and curing methods should be considered. Test specimen preparation required five steps as follows:

1. First, the collected soil was dried at a temperature between 212°F and 230°F for about 24 hours and at constant weight for removal of initial moisture. After drying, the soil is broken down into smaller particles. The fraction of soil passing through a No. 4 sieve was used for specimen preparation. BCP A and BCP C were also heated to 212°F for about 12 hours to reduce their water content to about 18%. BCP B was heated at a temperature below 140°F to reduce its water content to nearly 0%.
2. Second, after materials preparation, the soil was mixed with stabilizers and water uniformly to achieve target water and stabilizer values.
3. Then, a quantity of loose mixture materials was measured to achieve the maximum dry unit weight of soil obtained from standard Proctor compaction tests (shown in Table 5) for each 2 in. by 2 in. and 2.5 in. by 1 in. specimen. The parts of specific molds were assembled and then the measured material was placed in it. Two types of mold were used to produce different sizes of specimens. The mixing proportions are listed in Appendix B.
4. The next step was to compact the specific mold with a loose mixture to fabricate a specimen

with the required geometry. In this research, a static load was applied to the mold to produce a specimen with uniform mixture and maximum dry unit soil weight.

5. Finally, the produced specimens were wrapped in plastic film and cured using air-dried conditions at a 77°F room temperature to avoid loss of moisture. The curing time was determined by the specific test plan.

2 in. by 2 in. Specimen Preparation

This 2 in. by 2 in. sampling method was developed by O'Flaherty et al. (1963) at Iowa State University. They dropped a 5 lbf hammer from a 12 in. height, striking five blows on the end of the material to produce dynamic loading for 2 in. by 2 in. specimen compaction. Compared to traditional sampling methods introduced in the standard Proctor compaction method (ASTM D698), the 2 in. by 2 in. ISU sampling method requires less labor to produce more specimens. However, this sampling method made it difficult to produce specimens with uniform density, and the density differences among specimens interfered with the comparisons. In this research, static loading replaced dynamic loading for specimen preparation with uniform density.

The mold apparatus for the ISU 2 in. by 2 in. sampling method is shown in Figure 25.

Figure 25. Mold apparatus for 2 in. by 2 in. specimen compaction

It has four parts: a 1 in. tall spacer plug, a 4 in. long spacer plug, a mold, and a removable collar. After adding the mold to the removable collar at the top and inserting the 1 in. tall spacer plug, the measured amount of loose mixture was placed in the mold and a 4 in. long spacer plug was placed on the mixture in the mold. Static loading was then applied on the end of 4 in. long spacer plug until the plug end was parallel with the end of the removable collar. After compaction, the mold was disassembled by removal of the collar and the two spacer plugs, and an extruder was used to remove the compacted specimen from the mold. The compacted specimens shown in Figure 26 were then wrapped in plastic film for curing.

Figure 26. Prepared 2 in. by 2 in. samples

2.5 in. by 1 in. Specimen Preparation

This special specimen was used only for the DS test due to test apparatus requirements. The shear specimen should be placed in the shear box for shearing, and the principle was the same as for the 2 in. by 2 in. sampling method with static loading. This mold had four parts, two 1 in. tall metal rings of 2.5 in. inside diameter, a 1 in. tall spacer plug of 2.5 in. diameter, and a 4 in. metal plate. Two 1 in. tall metal rings were stacked up and assembled into a 2 in. tall mold and placed on the metal plate. A measured amount of loose mixture was placed in this mold and a 1 in. tall spacer plug was inserted. A static load was also applied on the end of the plug until its end was parallel to the end of the mold ring. After removal of the upper metal ring with a 1 in. tall spacer plug, the compacted specimen could be extracted with an extruder, as shown in Figure 27.

Figure 27. Mold apparatus for 2.5 in. by 1 in. specimen compaction

These 2.5 in. by 1 in. specimens shown in Figure 28 have the same density as a 2 in. by 2 in. specimen.
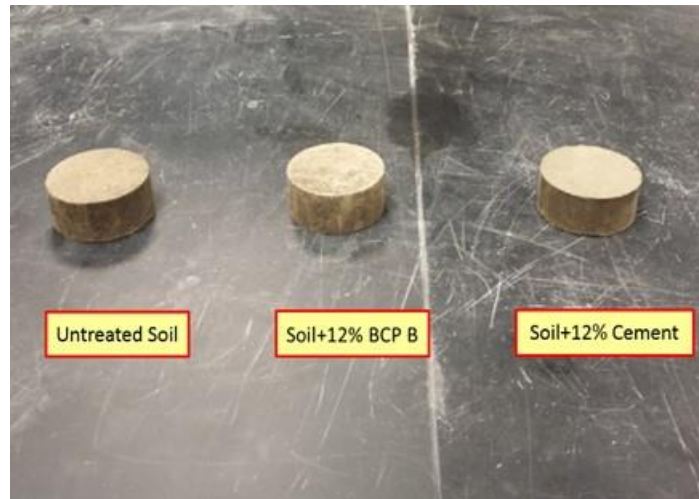
Figure 28. Prepared 2.5 in. by 1 in. samples

Compared to traditional DS sampling methods introduced in ASTM D3080, this represents a more convenient method for producing a large quantity of specimens with consistent properties. Moreover, use of a static load could make the specimen surface smoother compared to one produced by a dynamic load; this might be important in reducing error due to contact surface fraction.

Atterberg Limits Testing

Fine-grained soil undergoes distinct changes in behavior and consistency with an increase in water content, from solid to semi-solid to plastic to liquid. The boundary between these different stages is termed its limit. Absorption of water in soil can cause soil volume expansion, a potential risk for construction, because it causes soil layer deformation that may damage pavement. Pure soil and soil with additives were subjected to Atterberg limits tests, basic measures of critical water contents of soil and their mixtures for finding the plastic limit (PL) and the liquid limit (LL). The results were expressed as the water content for PL and LL.

The plastic limit is defined as the water content at which the soil behavior becomes plastic. Plastic behavior was determined by rolling out a thread of a fine portion of soil passing through a No. 40 sieve until it reaches a 1/8 in. diameter. The liquid limit is defined as the water content at which the soil behavior becomes liquid. The test apparatus for liquid limit measurements is shown in Figure 29; it consists of a metal bowl that can be struck.
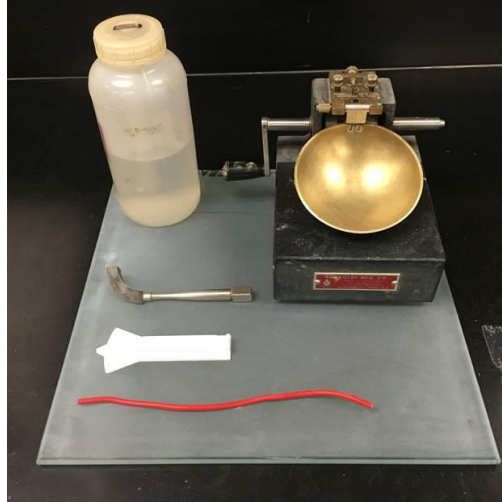
Figure 29. Atterberg limits test apparatus

In this test, a portion of wet soil was placed in this metal bowl and a groove made down its center. This groove would gradually close up when the bowl was repeatedly dropped from a 0.394 in. height. The different moisture content in soil corresponds to the variable number of blows required to close the groove. The liquid limit was defined as the water content at which the groove closed after 25 drops. The procedures for the Atterberg limits test were performed in accordance with ASTM D4318 Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. The PI is the range of water content over which soil exhibits plastic behavior and is defined as the difference between the plastic limit and liquid limit, as shown in equation (1):

$$PI = LL - PL \tag{1}$$

where, *PI* is the plastic index (plasticity) of soil and *LL* and *PL* are liquid limit and plastic limit of soil, respectively.

The primary purpose of the Atterberg limits test is to identify soil plasticity (PI), an important factor that should be considered before construction. Generally, low PI soil is promising for construction because of its low volume-expansion risk, so additives added to soil are expected to lower the soil plasticity.

Moisture-Density Relationship Testing

Soil structure consists of soil particles, air voids, and water. The density of soil is a significant factor in influencing soil behavior. Soil at a construction site is always compacted to produce a higher density and thereby become stronger in providing a desired work platform. During compaction processes, soil becomes denser because the air pores between soil particles are expelled. The density of soil is affected by four primary variables: compaction effort, moisture content, air voids, and dry soil density. The moisture-density relationship or compaction

characteristic of soil is generally defined as the curve obtained by plotting soil moisture content and dry soil density. Figure 30 shows moisture-density relationships for a cohesive soil with various compaction efforts.
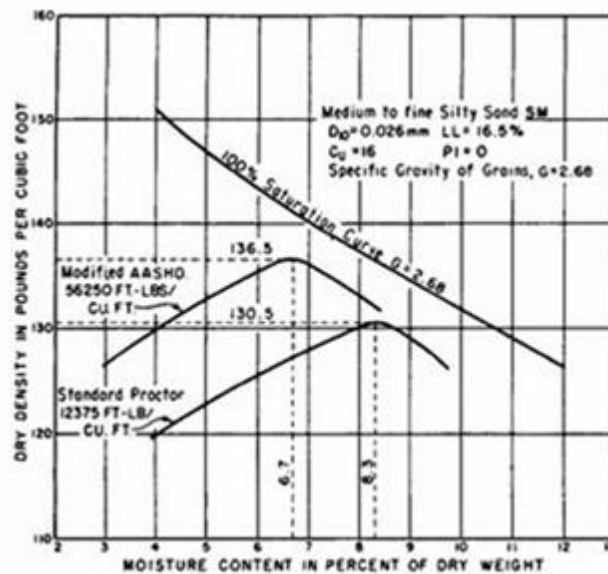
Hilf 1956

Figure 30. Moisture-density relationships of a soil for two compactions

This figure indicates that a higher compaction effort produces a higher soil density, and dry soil density increases with an increase in moisture content until it reaches some specific moisture content. Its density at that point diminishes with further increase in moisture content. The moisture content corresponding to the peak dry soil density, also termed maximum dry unit weight (Υd max), is referred to as the optimum moisture content (OMC).

The curve shapes can be explained by the influence of capillary pressure and pore air pressure (Hilf 1956). The high-frictional force of dry soil resists compactive effort, while an increase in soil water content reduces the soil particle frictional force and makes soil easier to compact. When dry soil density reaches its maximum point, an increase in soil water traps air and reduces compactive effectiveness by increases in pore pressure.

The moisture-density relationship of a cohesive soil is generally obtained by a standard Proctor compaction test in accordance with ASTM D698 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3). In this study, Method A introduced in ASTM D698 was adopted due to a retaining of 20% or less mass of soil by the No. 4 sieve. The collected loose soils or soil-additive mixtures with different water content were inserted into a 4 in. diameter mold in three layers, with each layer rodded 25 times from a 12 in. height by a 5.5 lbf compaction rammer. The compacted specimen was then extracted to measure weight and moisture content. After trial tests, the moisture-density relationships of soils or soil-additive mixtures were plotted to identify their maximum dry unit weights and optimum moisture contents. The test apparatus is shown in Figure 31.

46

Figure 31. Standard Proctor compaction apparatus

Unconfined Compressive Strength Testing

UCS is defined as the peak strength of a soil specimen when crushed in a uniaxial direction without lateral restraint. It is an important characteristic of additive treatment for soil stabilization performance. In this research, the test followed the guide of ASTM D2166 Standard Test Method for UCS of Cohesive Soil. Figure 32 depicts the automated computer control system used in this study for determining soil UCS.
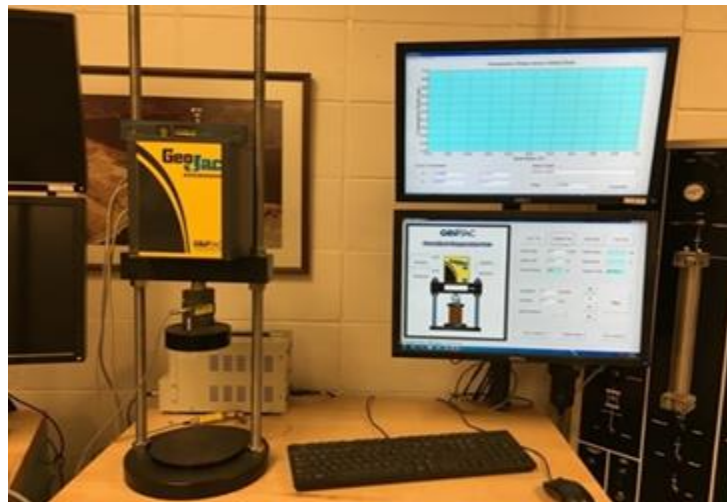
Figure 32. Automated Geotac system for unconfined compressive strength testing

The load rate of this automated equipment is strain-controlled, meaning that it exerts force on a specimen with a constant axial strain rate. Strain rate in this test was defined as the relative deformation of specimen height per minute. ASTM D2166 regulates that the strain rate varies from 0.5 to 2%/min with a strain limit is 15%. In this study, the default settings were 2%/min strain rate and 15% strain limit to meet the requirements of ASTM D2166.

The prepared 2 in. by 2 in. specimens and the 4 in. by 6 in. lignosulfonate-treated specimens were loaded into the frame after curing and endured a sustained force until it was crushed. The load cell indicator and strain gage recorded stress and strain during the entire process of specimen failure. Generally, the stress applied on the specimen increased with an increase in strain change until it reached a peak, then the stress decreased due to the sample being crushed. The computer could plot the specimen's strain-stress relationship and display the peak stress. Once the specimen had reached the 15% strain limit without crush, the stress at 15% strain change would be the peak stress of the specimen.

In this test, over 600 specimens were broken using this automated procedure. The crushed specimens were put into an oven for drying to check their actual moisture content. Each treatment group combination was repeated three times to calculate average peak stress. Since ASTM D2166 didn't provide an accepted reference value, the precision and bias for results depended on engineering judgement.

Direct Shear Strength Testing

The shear strength is the strength capacity of a material resisting structure failure resulting from shear. It is another important property for materials used in construction and equipment fabrication. During a shearing process, the force produces a sliding failure along a plane parallel to the shear force direction. The DS test used in this study is a test used for measurement of consolidated-drained (CD) shear strength of soil properties in accordance with ASTM D3080 Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions. The CD shear test allowed the specimen under pore pressure to consolidate and adjust to the surrounding stresses. Figure 33 shows the automated computer control system used for the DS test.
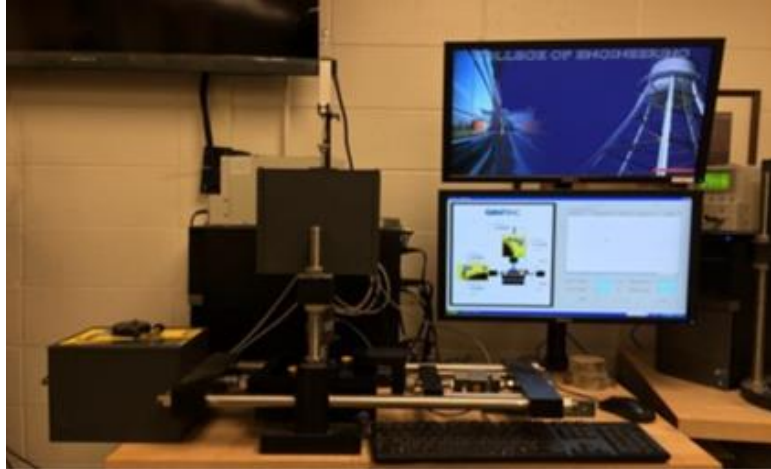
Figure 33. Automated Geotac system for direct shear strength testing

In this test, a prepared 2.5 in. by 1 in. specimen was placed in a shear box consisting of two stacked 2.5 in. diameter rings; the contact between these two rings was at the midpoint of the specimen height. Two porous stones were placed on the specimen top and bottom surfaces for draining. Figure 34 depicts a shearing demonstration for a specimen in the shear box.
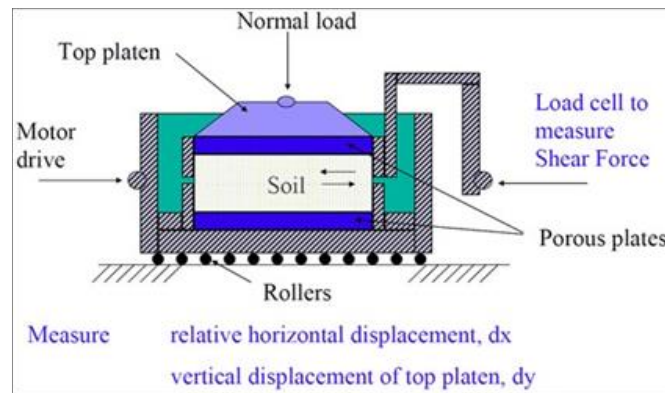
Figure 34. Demonstration of direct shear test

Once the specimen had been properly held by the shear box and placed in the load frame, the vertical load cell applied a normal stress (σ) and the upper ring was pulled horizontally to shear the specimen until it either failed or reached its maximum relative displacement. The computer could automatically plot the relationship between specimen stress and displacement, and the shear capacity (τ) of the specimen under specific vertical confining stress was thereby obtained. In this study, the DS test was strain controlled, and the shear rate and maximum relative horizontal displacement were set to 0.01 in./min and 0.25 in., respectively.

The other purpose of the DS test is to determine shear strength parameters consisting of soil cohesion (c), resistance force per unit area, and friction angle (ϕ), the inclination angle of the plane. Shear parameters can be determined using a Mohr–Coulomb plot. The linear function of normal stress (σ) versus shear stress (τ) is shown in Figure 35 and expressed in equation (2).

49
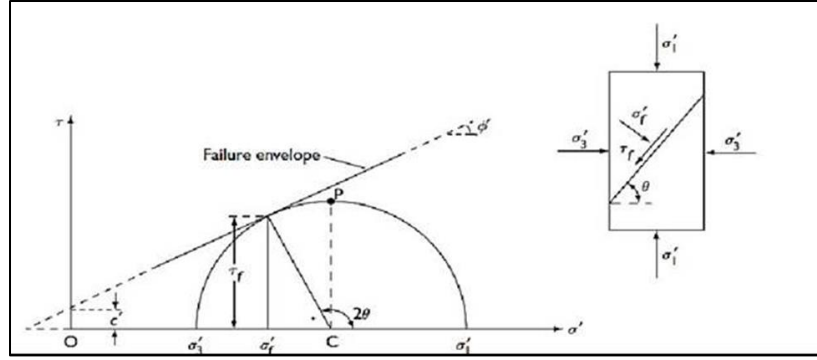
Craig 2005, © R. F. Craig 1974–2004, used with permission

Figure 35. Mohr–Coulomb plot for determination of shear parameters

$$\tau = c + \sigma \tan \phi \qquad\qquad (2)$$

where, τ is shear capacity, c is cohesion, ϕ is friction angle, and σ is the normal stress.

Soil cohesion is defined as the intercept of the linear function, i.e., the shear value at 0 psi normal stress. The friction angle is defined as the slope angle of the linear function. In this study, three normal stress levels: 10, 20, and 30 psi, were selected for investigating the shear parameters of each soil and soil-additive mixture. The shear parameters of materials can be used to estimate their shear capacities under different confining stresses.

Freeze-Thaw Durability Test

Durability is basically the ability to endure and is a significant soil property. Considering that the hundreds of repeated cycles of freeze-thaw due to annual changes of season cause a great deal of soil damage, the durability of soil with respect to freeze-thaw damage should be evaluated for stabilization purposes. Freeze-thaw durability tests were conducted in this study by imitating natural freeze-thaw cycles to evaluate the durability improvement for additive-modified soils in accordance with ASTM D560 Standard Test Methods for Freeze-Thaw Compacted Soil-Cement Mixtures.

To conduct freeze-thaw durability tests, the cured specimens were placed on a saturated filter pad in an uncovered metal container and subjected to 12 freeze-thaw cycles. Each cycle was scheduled as 24 hours in a freezing cabinet at -9.4°F, followed by another 23 hours in a moist room at 70°F and relative 100% humidity. During each thawing period, the specimen absorbed water from the moisture environment and increased in size; then, in the subsequent cycle, the water in the specimen was frozen and expanded, causing damage to the internal structure of specimen; and finally, in the following thawing period, the ice melting resulted in specimen mass loss. After several such cycles, specimens could be disintegrated or partially disintegrated.

The test required two identical specimens in compliance with ASTM D560. The first specimen was used only to determine the average diameter and height for volume change evaluation at the

end of each cycle, and the second was used to determine the oven-dried weight for mass loss evaluation after only 12 cycles. Equation (3) shows the calculation of mass loss. Three repetitions were conducted to improve test reliability. All specimens were initially regular cylinders and their shapes changed after several cycles. Once the shapes had changed considerably and became non-cylindrical based on visual examination, volume measurements were terminated. Therefore, for one treatment group combination with OMC level with either 1-day or 7-day curing, 6 specimens were processed over 12 freeze-thaw cycles. At the end of each thawing period, all specimens were photographed for visual examination with three of them measured three times each to determine average diameters and heights while they were still cylindrical. After the entire set of 12 cycles, the other 3 specimens were oven-dried at 230°F to measure the mass loss percentage.

$$\text{Mass loss of specimen}, \% = (A/B) \times 100 \tag{3}$$

where, *A* is the original calculated oven-dry mass minus the final oven-dry mass, and *B* is the original calculated oven-dry mass.

During freeze-thaw durability tests, visual evidence, volume change, and mass loss of specimen were used to evaluate the effects of soil additive treatment.

Moisture Susceptibility Test

Moisture susceptibility is a significant factor that can influence performance of pavement subgrade soils. A rising water table can "soak" soil and cause loss of mechanical properties, so the moisture susceptibility of soil should be evaluated when considering long-term performance. The U.S. Army Engineer Research and Development Center (ERDC) has developed a simple method for evaluating the moisture susceptibility of soil treated with stabilizers (Santoni et al. 2002). They tested the UCS of specimens partially soaked in water. In this study, a similar method was used to evaluate specimens treated with BCPs.

The moisture susceptibility test in this research included full saturation of both untreated and BCP-treated specimens with seven-day curing. Full saturation was achieved by specimen immersion in a water bath for a period of seven days. Visual inspection was used as the criteria instead of a UCS test. All specimens were photographed at five minutes, four hours, one day, and seven days.

Set Time Test

With the goal of studying the lignosulfonate-treated soil's strength improvement, a set time test was conducted to investigate the speed at which lignosulfonate became hard at different temperatures and its mechanism. A total of 0.35 oz of lignosulfonate was placed in a 2 in. wide and 0.9 in. deep pan to create a thin and smooth surface (Figure 36).

Figure 36. Set time test

These pans were then placed in 104°F, 68°F, 32°F, and -0.4°F 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 six hours. These samples' percentage of evaporable component was also tested using the method for the determination of water content in soil (ASTM D2216-19).

Microstructural Characterization

Microstructural characterization of a stabilizer-treated soil can be used to understand the stabilization mechanism. SEM (Figure 37) and XRD (Figure 38) are two available approaches for identifying how a stabilizer improves soil mechanical properties, and both these tests were carried out on BCP-treated specimens to analyze lignin-related mechanisms at the particle level.
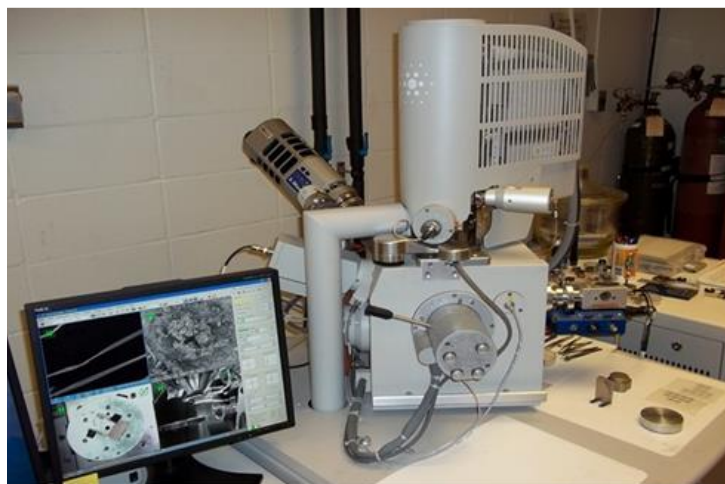
Figure 37. Scanning electron microscope equipment at Iowa State University

Figure 38. X-ray diffraction equipment at Iowa State University

SEM is an electron microscope procedure using a focused beam of electrons to produce solid-surface images. During such testing, interactions between electrons and the specimen can generate signals representing the specimen's external morphology and chemical composition, and these signals can be detected and used to produce an image reflecting soil-additive interactions at the particle level. XRD is an analytical technique used for the identification of compound formation and crystalline size in clay minerals. In XRD testing, x-rays are generated by heating a filament to produce electrons that can be accelerated at a specific voltage to bombard the target specimen. This process produces x-ray spectra signals with different wavelengths and intensities that can be used to identify unknown materials. In this research, untreated and BCP-treated specimens with seven-day curing were subjected to SEM and XRD tests to identify underlying mechanisms in sulfur-free lignin. The cured specimens were broken into small, loose pieces for testing.

Summary of Laboratory Test Program

The primary purpose of this laboratory program was to identify the benefits of sulfur-free lignin treatment on soil engineering properties, mechanical properties, durability, and moisture susceptibility based on results from Ceylan et al. (2010). Microstructural analysis was also conducted to identify how these BCPs work in soil stabilization. However, the developed test program was limited because of insufficient BCP materials with the result that some tests didn't cover all treatments of BCPs. It is suggested that the remaining tests be performed after sufficient amounts of BCP have been obtained. Table 12 summarizes the laboratory tests conducted for evaluating the performance of lignosulfonate-stabilized silty soils.

Table 12. 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
SEM and XRD	Microstructure	N/A

Because of the specific properties of lignosulfonate used as an alternative soil stabilizer, standard specifications listed as references in Table 12 were not strictly followed but modified and used.

4. IN SITU TEST PROGRAMS

Information of Construction Site

To evaluate the performance of different stabilizers, a field site treated with five stabilizers including cement, lignosulfonate, and three other commercial stabilizers was set up on October 11, 2018. The demonstration site is a 2,300 ft long and 26 ft wide gravel road on 240th Street in Independence, Iowa. Soils from the demonstration site had been collected and tested in the laboratory with respect to soil classifications and related soil index properties (similar to Soil 4 in Table 5), indicating it is an A-4 soil rated as fair to poor (AASHTO M 145-91). The road has annual average daily traffic (AADT) of 240 (Iowa DOT 2018), and 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. The construction site shown in Figure 39 consisted of five treated sections: 500 ft cement-treated, 300 ft lignosulfonate-treated, 500 ft chlorides-treated, 500 ft Claycrete-treated, and 500 ft Base One-treated. Appendix C provides the detailed guidance that was used for BCP mix design, pre-laboratory testing, and field application.
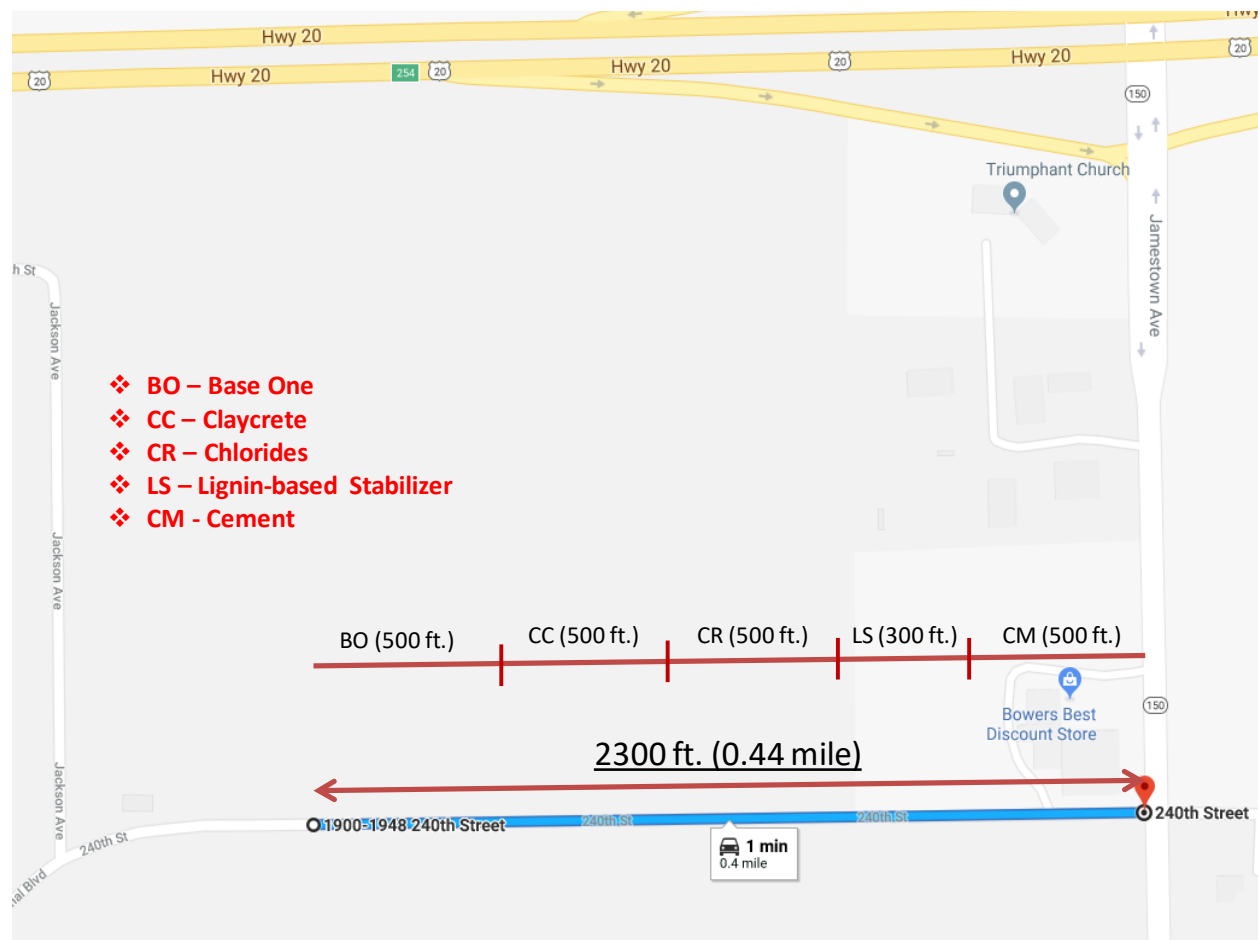
Figure 39. Construction sections in Independence, Iowa

In this field demonstration, two in situ tests were performed before, one week after, and one year after the construction to monitor the strength and durability of the lignosulfonate-stabilized soil and the other four additives-stabilized soils. LWD tests were used to spot check the in situ elastic modulus to predict the subgrade stiffness, whereas DCP tests were used to measure the subgrade soil's resistance to penetration and correlate to the CBR. In consideration of the two-way traffic, three test points were selected for each test section. Table 13 summarizes the location of each of the 15 in situ test points.

Table 13. In situ test point locations

Section	Test point	Longitudinal distance from the origin of the corresponding test section (ft)	Transverse distance from the north edge of the roadway (ft)
Cement	1	410	20
	2	820	6
	3	1,230	20
Lignosulfonate	4	246	20
	5	492	6
	6	738	20
Chlorides	7	410	20
	8	820	6
	9	1,230	20
Claycrete	10	410	20
	11	820	6
	12	1,230	20
Base One	13	410	20
	14	820	6
	15	1,230	20

Cement Section

The cement section was a 500 ft long and 26 ft 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 (6 in.). 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 started with the resurfacing of approximately 6 in. of road surface with a rear ripper (Figure 40a), followed by the cement sprayed on the subgrade (Figure 40b). The soil and cement were then blended along with the water spraying (Figure 40c), and finally, the pad foot rollers were used for compaction (Figure 40d).

Figure 40. Cement-treated section construction: (a) rear ripper resurfaced road surface, (b) cement spraying, (c) blending with reclaimer, and (d) compaction with pad foot rollers

Lignosulfonate Section

The ammonium-based lignosulfonate was purchased from M & K Dust Control Inc., an industry located in Mount Vernon, Iowa specializing in dust control, snow removal, and hauling services. M & K Dust Control Inc. also provided the spraying services in the field construction. The quoted rates for the lignosulfonate and application services are illustrated in Figure 41.

Figure 41. Quotes for lignosulfonate and application services from M & K Dust Control Inc.

The lignosulfonate section was 300 ft long. 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 three-axle truck carrying four spraying nozzles and a cylindrical tanker filled with diluted lignosulfonate, a motor grader, and pneumatic rollers (Figure 42).

Figure 42. Lignosulfonate-treated section construction: (a) rear rippers, (b) truck equipped with spraying nozzles and tank, (c) motor grader, and (d) pneumatic rollers

The construction started by resurfacing approximately 6 in. 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 the wet soil (lignosulfonate-treated) with the dry soil (untreated) 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.

Chlorides Section

The chlorides section was 500 ft long. Donated by Heffron Services Inc., the target dosage and the amount of chlorides needed for the construction was determined based on the user manual, field dimensions, and the company representative on site. The utilized equipment included a truck with chemical liquid container and sprayers, a reclaimer, and pad foot rollers. The construction started with resurfacing approximately 6 in. of road surface with a rear ripper followed by the liquid chlorides sprayed on the subgrade (Figure 43a). A reclaimer was then used to blend the soils (Figure 43b), and finally, the pad foot rollers were used for compaction (Figure 43c).

(a)   (b)

(c)
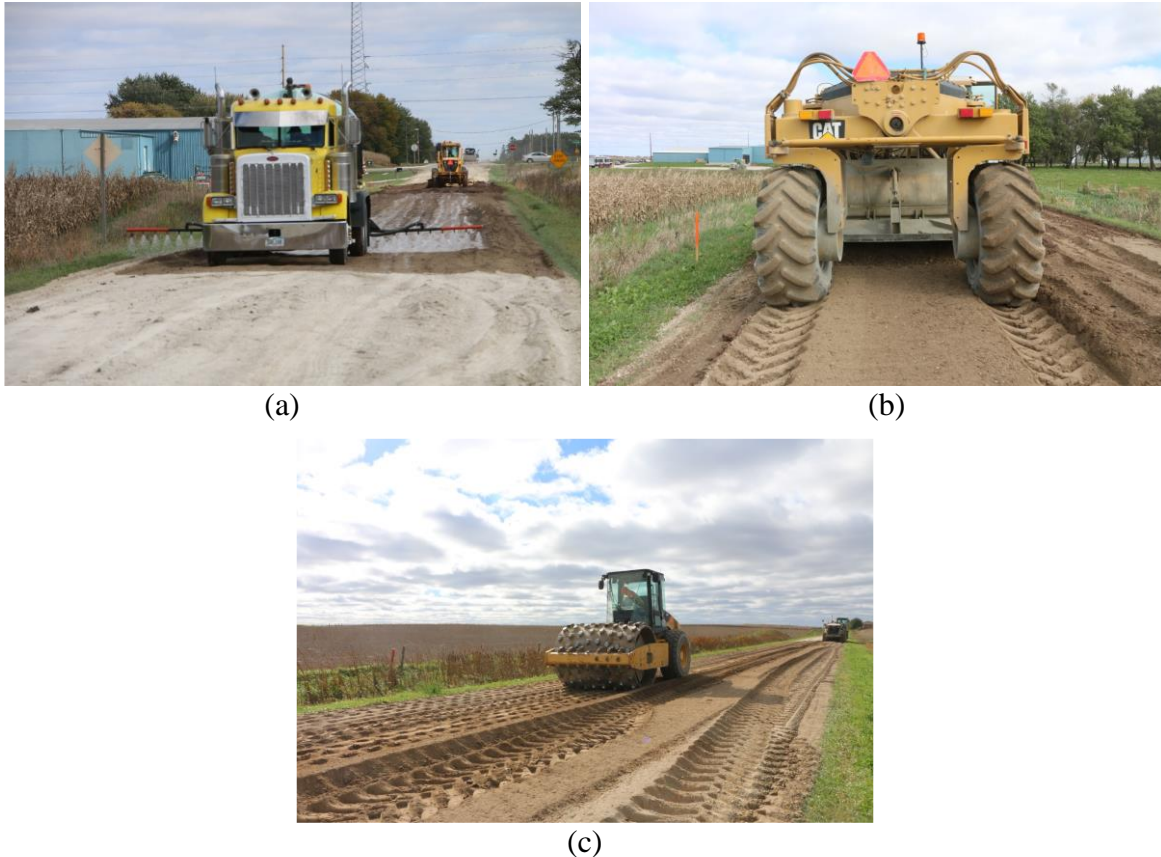
Figure 43. Chlorides-treated section construction: (a) Chlorides spraying, (b) soil blending with reclaimer, and (c) compaction with pad foot roller

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., 2016). The Claycrete section was a 500 ft long gravel road. Donated by Claycrete North America, the amount of Claycrete needed for the construction was estimated to be 10 gal. The target dosage was calculated based on the user manual and the field dimension. The utilized equipment included a truck with chemical liquid container and sprayers, a grader, and a pneumatic rubber tire roller. The construction started with resurfacing approximately 6 in. of road surface with a rear ripper (Figure 44a), followed by Claycrete sprayed on the subgrade (Figure 44b). A motor grader was used to blend the wet soil (Claycrete-treated) with the dry soil (untreated) using its long moldboard (Figure 44c), and finally, the pneumatic rubber tire rollers (Figure 44d) were used for compaction.

Figure 44. Claycrete-treated section construction: (a) Claycrete spraying, (b) subgrade condition, (c) soils blending with motor grader, and (d) compaction with the pneumatic rubber tire roller

Base One Section

Base One is a liquid soil stabilizer produced by TeamLab Chemical Corporation. Base One is utilized by being diluted with water to bring the in situ soils to the required moisture content for compaction (TeamLab n.d.).

The Base One section was 500 ft long as well. The amount of Base One needed for the construction was estimated to be 43 gal based on the design requirements (0.005 gal/yd^2/in. of stabilized reclamation depth) and road section dimensions. The utilized equipment included a truck with chemical liquid container and sprayers, a reclaimer, a grader, a pneumatic roller, and pad foot rollers. The construction started with resurfacing approximately 6 in. of road surface with a rear ripper (Figure 45), followed by the Base One dilution and spraying on the subgrade (Figure 45). A reclaimer was then used to blend the soils with the Base One (Figure 45), and the pad foot rollers were used for the preliminary compaction (Figure 45). Then, a motor grader was used to further blend soils using its long moldboard (Figure 45), and finally, the pneumatic roller was used for the final compaction (Figure 45).

(a)

(b)

(c)

(d)

(e)

Figure 45. Base One-treated section construction: (a) Base One spraying, (b) blending with reclaimer, (c) preliminary compaction with pad foot roller, (d) blending with motor grader, and (e) final compaction with pneumatic roller

Light Weight Deflectometer Test

The LWD tests 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 (4)), where the plate radius (R) was 6 in., the applied stress (ρ) was approximately 14.5 psi, and Poisson's ratio (μ) was estimated to be 0.35 due to the soil classification.

$$E_{LWD} = \frac{2(1-\mu^2)\rho R}{s} \tag{4}$$

Dynamic Cone Penetration Test

The DCP tests revealed the subgrade strength by measuring the DCP index, and from which the CBR can be correlated. In the calculation of the DCP index, a hammer factor of 1 was used because the device was equipped with a 17.6 lb hammer (ASTM D6951M-19). In the correlation between the DCP index and CBR, equation (5) in in./blow was recommended in ASTM D6951M-18. 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. In addition, a larger CBR value indicated higher bearing capacity of the test point.

$$CBR = \frac{292}{(DCP \times 25.4)^{1.12}} \tag{5}$$

5. LABORATORY TEST RESULTS AND DISCUSSION

Atterberg Limits Results

The effects of co-products and cement on Atterberg limits of different soils are shown in Figure 46 and Table 14.
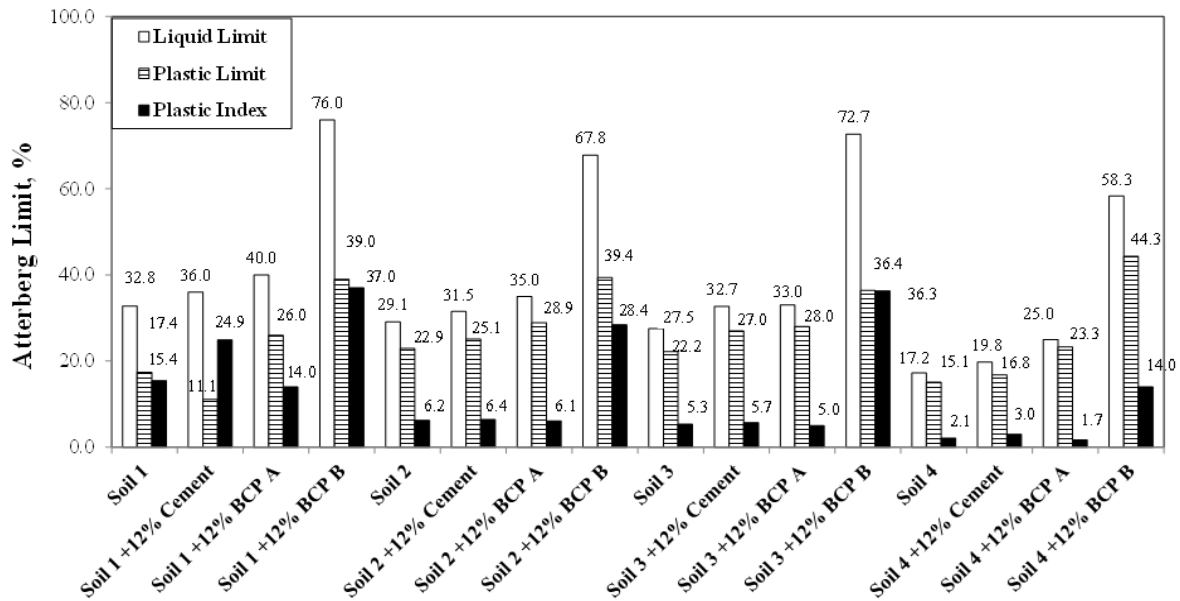
Figure 46. Effect of additives on consistency limits of soil

Table 14. Effect of additives on consistency limits of soil

Mixture	Value of increase			Percentage of increase*		
	LL	PL	PI	LL	PL	PI
Soil 1	0.0	0.0	0.0	0%	0%	0%
Soil 1 +12% Cement	3.2	-6.3	9.5	10%	-36%	62%
Soil 1 +12% BCP A	7.2	8.6	-1.4	22%	49%	-9%
Soil 1 +12% BCP B	43.2	21.6	21.6	132%	124%	140%
Soil 2	0.0	0.0	0.0	0%	0%	0%
Soil 2 +12% Cement	2.4	2.2	0.2	8%	10%	3%
Soil 2 +12% BCP A	5.9	6.0	-0.1	20%	26%	-2%
Soil 2 +12% BCP B	38.7	16.5	22.2	133%	72%	358%
Soil 3	0.0	0.0	0.0	0%	0%	0%
Soil 3 +12% Cement	5.2	4.8	0.4	19%	22%	8%
Soil 3 +12% BCP A	5.5	5.8	-0.3	20%	26%	-6%
Soil 3 +12% BCP B	45.2	14.2	31.0	164%	64%	585%
Soil 4	0.0	0.0	0.0	0%	0%	0%
Soil 4 +12% Cement	2.6	1.7	0.9	15%	11%	43%
Soil 4 +12% BCP A	7.8	8.2	-0.4	45%	54%	-19%
Soil 4 +12% BCP B	41.1	29.2	11.9	239%	193%	567%

* The improvement in limits of treated soil over limits of untreated soil. Negative value indicates the decrease.

The selected application rate of additives was 12%, because the highest increases of UCS were reported at that rate of co-products in the final report of Ceylan et al. (2010). As shown in Figure 46, the four types of soil investigated in this research have different consistency limits.

Soil 1 had the highest values of 32.8 for the liquid limit and 15.4 for plasticity. Soils 2 and 3 had very similar consistency values, 29.1 and 27.5 for liquid limits, 22.9 and 22.2 for plastic limits, and 6.2 and 5.3 for plastic index, respectively. In contrast to Soil 1, Soil 4 had the lowest liquid limit of 17.2, plastic limit of 15.1, and plastic index of only 2.1. A traditional stabilizer, cement, increased the plasticity of Soil 1 by 62% with an increase in liquid limit and a decrease in plastic limit. It also increased the plasticity of the other three soils due to increases in both liquid limit and plastic limit values. For cement-treated Soils 2 and 3, the increases in liquid limits were slight and lower than 0.4, or 8%, when compared to untreated soil. However, the plasticity of Soil 4 increased from 2.1 to 3.0 after the addition of cement, a 43% increase. The oily liquid-type BCP A decreased the plasticity for all soils. The 9%, 2%, and 6% decreases in plasticity of Soils 1, 2, and 3, respectively, were obtained with the addition of BCP A. Plasticity of Soil 4 was reduced by 19% with BCP A, a difference of 0.4. The powder type, BCP B, showed the greatest influence on consistency limits for all soils. The liquid limits of soils treated with BCP B were increased by up to 240%, and their plastic limits were also increased by up to 200%. As a result, all four types of treated soil had much higher plasticity, and increases in Soil 1 and 2 were relatively lower, by 140% and 358%, respectively. For Soils 3 and 4, plasticity increased by about 600% with BCP B. All three additives changed the consistency limits of natural soil. Cement showed a medium increase in plasticity of Soils 1 and 4 and a slight increase in plasticity of Soils 2 and 3.

In summary, BCP A slightly decreased the plasticity of all soils, but BCP B greatly increased the plasticity of all soils. Obviously, BCP B significantly influenced consistency limits of soil, and even increased the limits by several times. However, as a field indicator, high plasticity of soil is related to lower slope stability and higher volume expansion, so the Atterberg limits results indicate that BCP A is a more promising additive in terms of reduction in soil plasticity.

Moisture-Density Relationship Results

Figure 47 presents the effects of additives on compaction characteristics of soil.
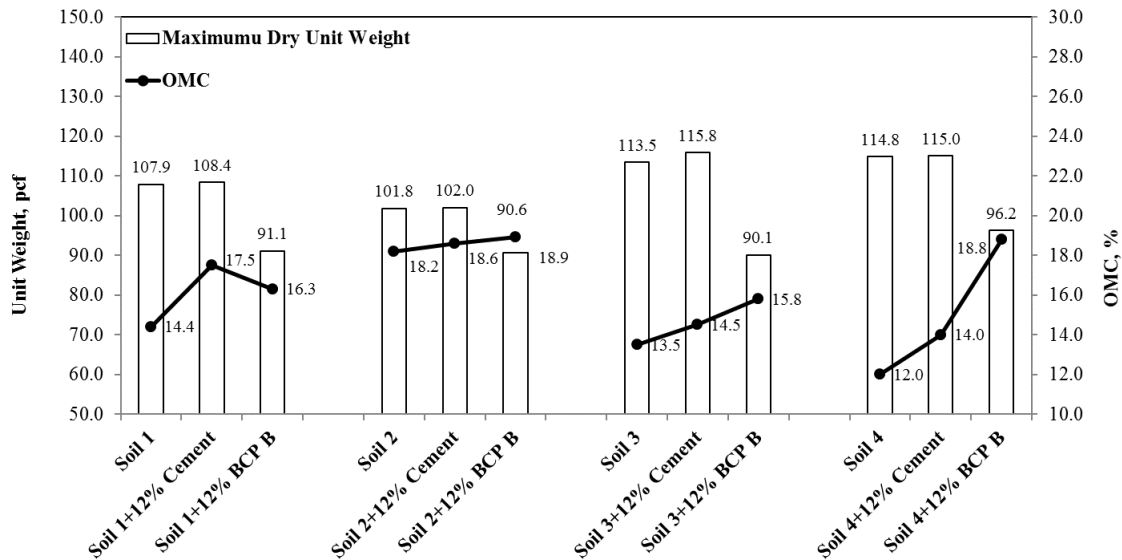
Figure 47. Effect of additives on compaction properties of soil

The maximum dry density and OMC for different soils with 12% cement and 12% BCP B were evaluated in this study. For these four types of soil without additives, Soil 1 had a maximum dry density of 107 with 14.4% of OMC. The maximum dry density and OMC for Soil 3 were 113.5 pcf and 13.5%, respectively. Soil 2 had the lowest maximum dry density and the highest OMC, 101.8 pcf and 18.2%, respectively. In contrast to the compaction properties of Soil 2, Soil 4 had the highest maximum dry density, 114.8 pcf, with the lowest OMC of 12%.

Cement caused a slight increase in maximum dry density and OMC for all soils. The typical specific gravity values for natural sand, silt, and clay changed from 2.6 to 2.9; the specific gravity of cement is 3.15, slightly higher than that of natural soil. As a result, cement, with a relatively high specific gravity, when added to soil increased the maximum dry density of the mixture by up to 2.3 pcf. The powder type co-product, BCP B, produced a significant decrease in maximum dry density of soil, between 11.2 and 18.6 pcf, due to a low specific gravity of 2.0, much lower than the value for natural soils. BCP B also increased OMC for all soils.

The additives could change the moisture-density relationships of the soil. Cement increased but BCP B decreased the maximum dry density of soil. The maximum dry density of each mixture

was affected by the additive specific gravity. Both cement and BCP B increased the OMC of soil. Factors that might affect OMC of mixtures included soil structure, air void distribution, and an electrical double layer of solid particles. For stabilization purposes, a promising additive should increase maximum dry density and decrease the OMC of soil, so BCP B didn't demonstrate better performance than cement with respect to compaction properties.

The standard Proctor compaction tests revealed correlation between lignosulfonate dosage and both OMC and maximum dry unit weight (Table 15).

Table 15. Standard Proctor test results for Soil 3 and Soil 4 with lignosulfonate

Soil type	OMC (%)	Maximum dry unit weight (pcf)
Soil 3	13.5	113.5
Soil 3 + 5% Lignosulfonate	11.9	112.0
Soil 3 + 10% Lignosulfonate	11.2	113.1
Soil 3 + 15% Lignosulfonate	10.5	113.1
Soil 4	12.0	114.8
Soil 4 + 5% Lignosulfonate	15.0	107.9
Soil 4 + 10% Lignosulfonate	13.6	111.2
Soil 4 + 15% Lignosulfonate	9.3	119.6

Soil 3 exhibited an OMC of 13.5% 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. Soil 4 exhibited an OMC of 12.0%; however, the addition of 5% of lignosulfonate caused the highest OMC and the lowest maximum dry unit weight.

Unconfined Compressive Strength Results and Analysis

The effects of additives on compressive capacity of soil are shown in Figure 48 through Figure 52. Note that raw data of UCS test results are presented in Appendix D.
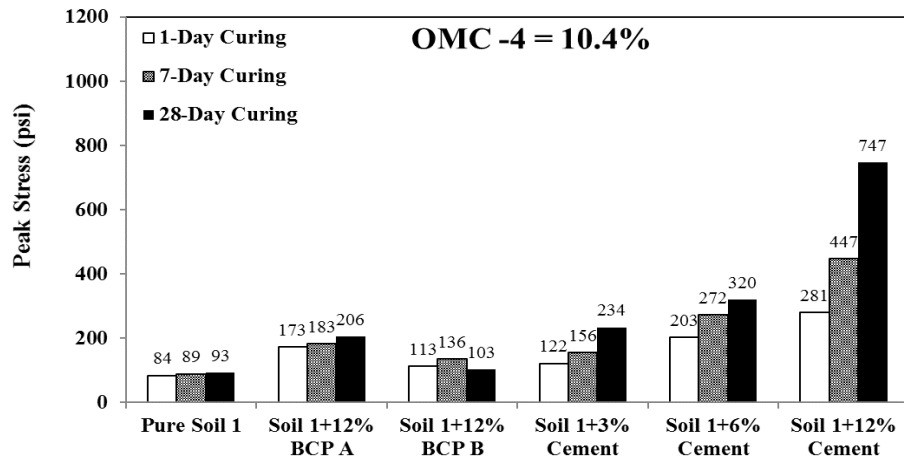
(a)
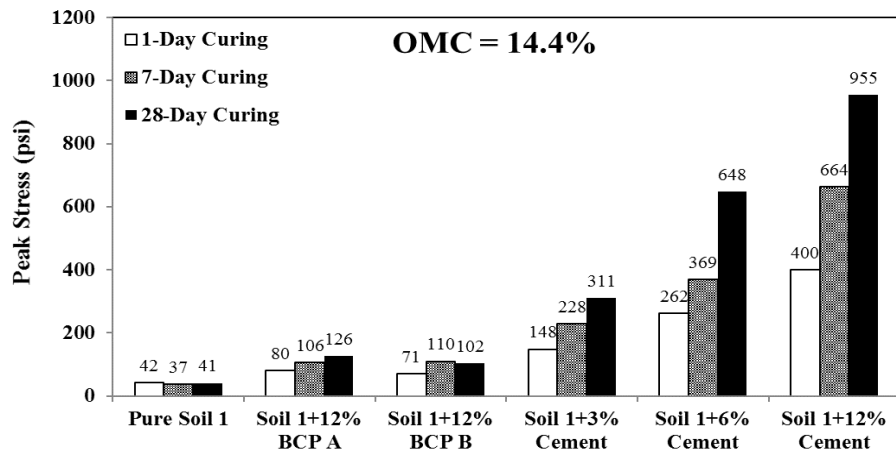
(b)
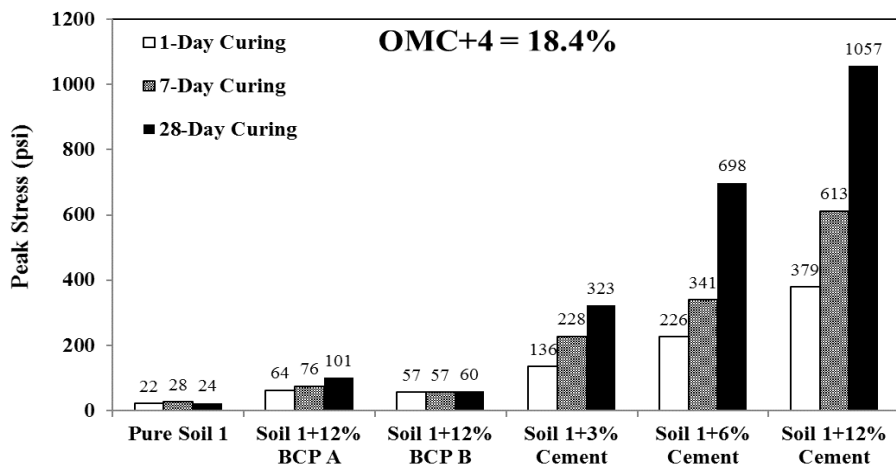
(c)

Figure 48. UCS test results for Soil 1 under (a) OMC-4%, (b) OMC, and (c) OMC+4%
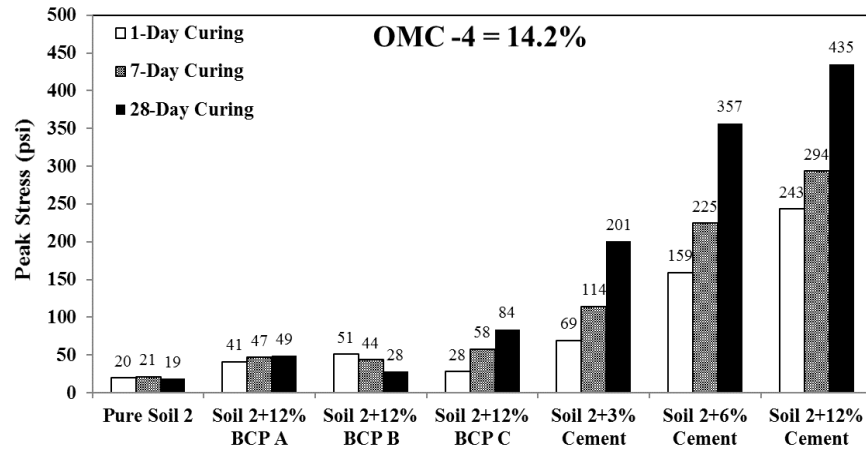
(a)
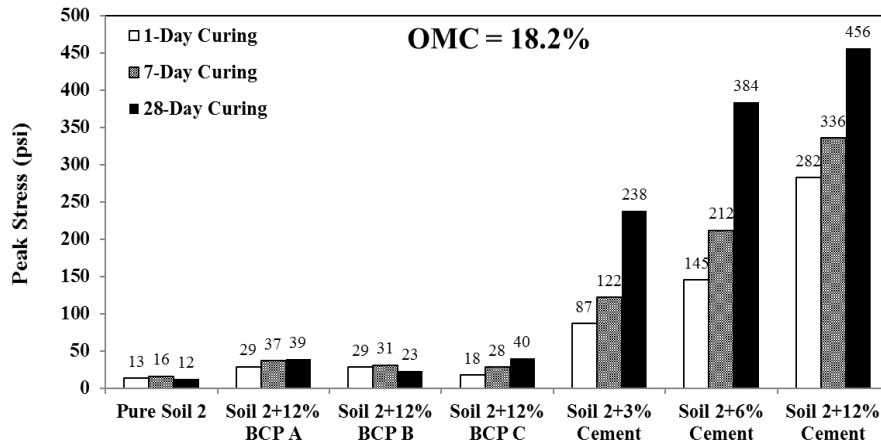
(b)
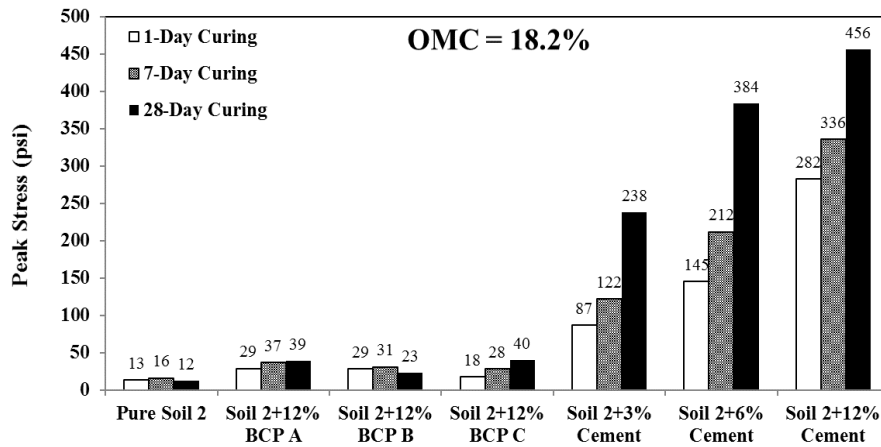
(c)

Figure 49. UCS test results for Soil 2 under (a) OMC-4%, (b) OMC, and (c) OMC+4%
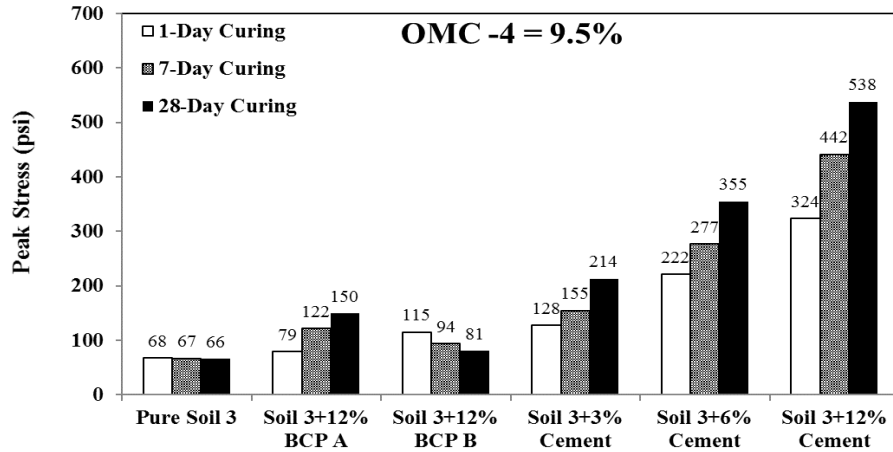
(a)
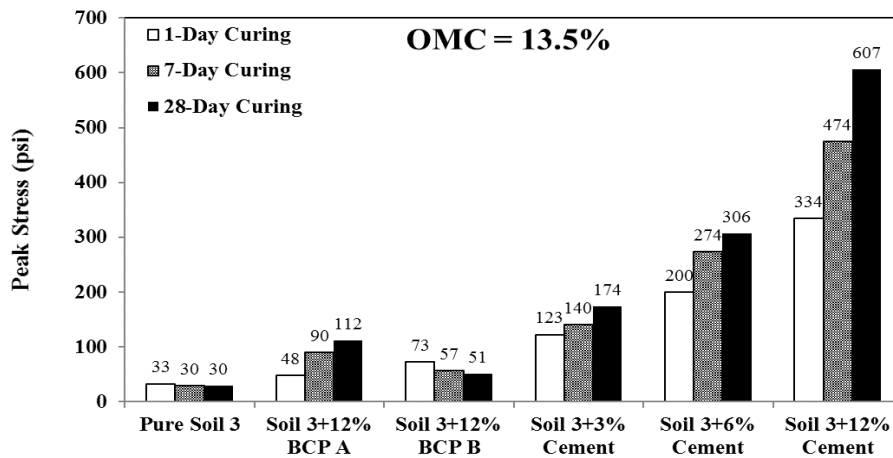
(b)
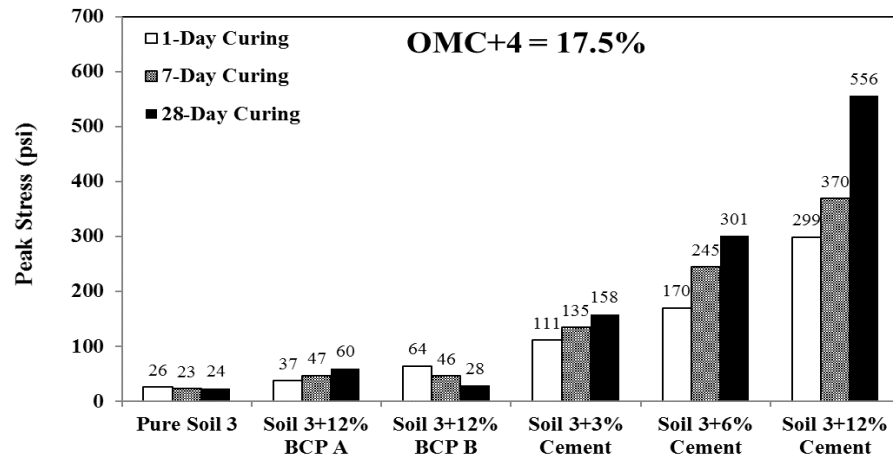
(c)

Figure 50. UCS test results for Soil 3 under (a) OMC-4%, (b) OMC, and (c) OMC+4%
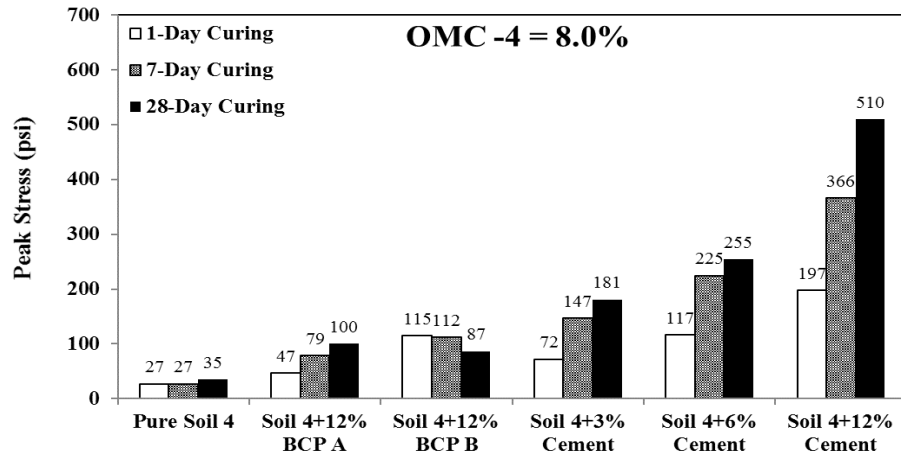
(a)
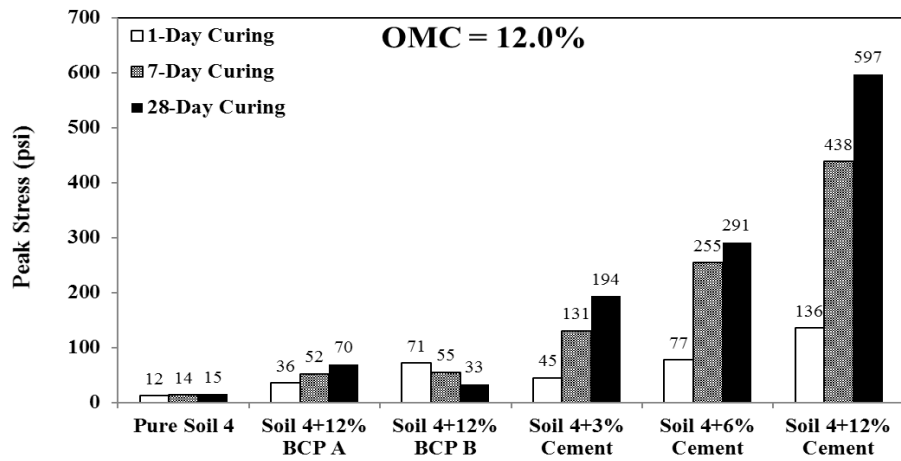
(b)
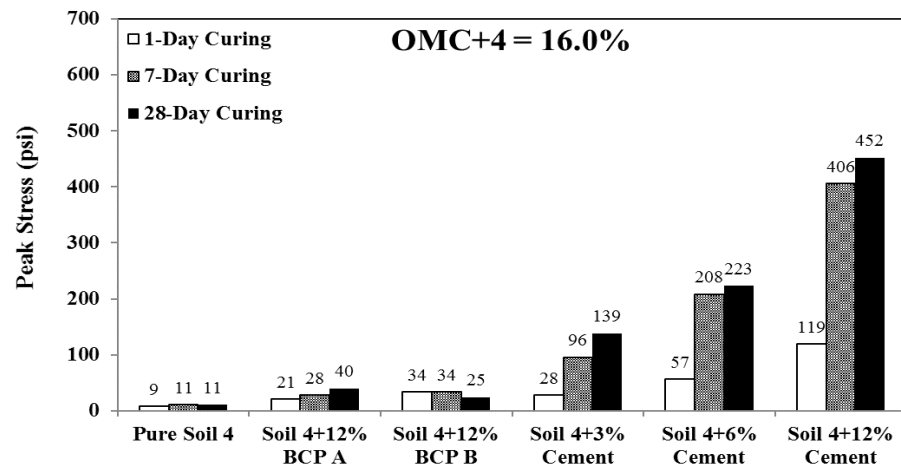
(c)

Figure 51. UCS test results for Soil 4 under (a) OMC-4%, (b) OMC, and (c) OMC+4%
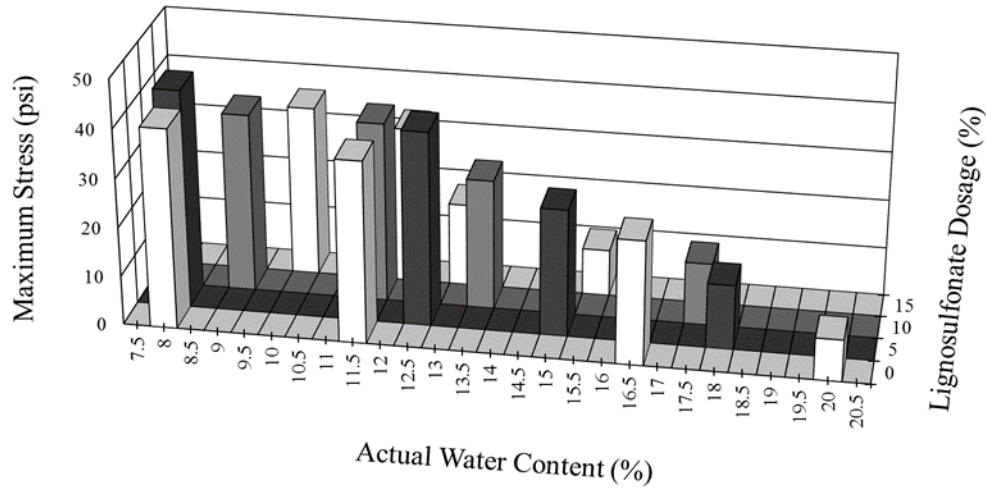
(a)
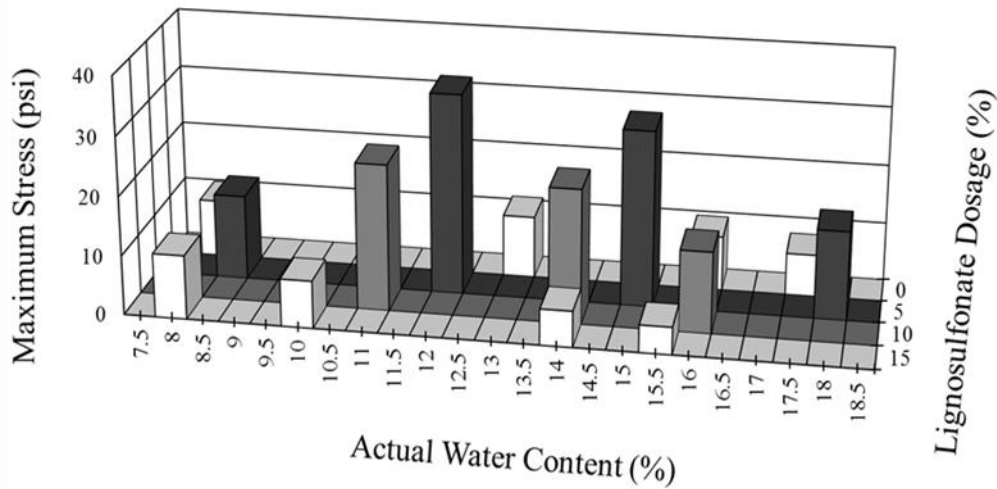
(b)

Figure 52. UCS test results for (a) Soil 3 and (b) Soil 4 with lignosulfonate

In this test, 12% of BCP A, 12% of BCP B, and 3%, 6%, and 12% of cement treatments were evaluated for all types of soil. Soil 2 had an extra evaluation for UCS with 12% of BCP C-treatment. Specimens with different moisture contents (OMC-4%, OMC, and OMC+4%) and different curing periods (1-day, 7-day, and 28-day) were measured for peak stresses when specimens failed under a load. UCS results could be affected by many variables, and in this study the following variables were evaluated: (1) type of soil, (2) type of additive, (3) moisture level, (4) curing periods, and (5) additive content. The contents of co-products were 12%, and the content of cement varied from 3% to 12% only for comparison purposes.

Effects of Soil Types

Soil type (classification) based on fines content affects the compressive strength capacity of soil. Soil 1 classified as A-6(2) and SC with the lowest fines content achieved the highest strength in

all types of specimens. Soil 2 had the highest silt and clay content and was classified as A-4(2) and CL-ML, and it achieved the weakest strength for all types of specimens. Although Soil 3 had the same A-4(1) and CL-ML classifications as Soil 2, its fines content was close to that of Soil 4, resulting in the second highest strength in most specimens except those treated with 12% of BCP under OMC-4%. The silt and clay content in Soil 4, classified as A-4(0) and ML, was a little bit lower than the fines content of Soil 3, but most Soil 4 specimens demonstrated strength higher only than that of Soil 2, so the overall strength results indicate that Soil 1 is the strongest soil, Soil 2 the weakest soil, Soil 3 the second strongest soil, and Soil 4 stronger only than Soil 2.

Soil classification is primarily determined by fines content of soil, i.e., the fines content of soil contributes significantly to different soil strength capacities. High clay content in soil can present problems for loaded structures because of volumetric changes and degraded mechanical properties due to seasonal moisture variation (Petry and Little 2002). Clay particles are inherently very fine and sensitive to moisture, and this can cause negative effects on a soil skeleton, reducing its bearing capacity. Other involved factors such as grain size, clay type, and exchange of base can also affect UCS of soil, as summarized by Trask and Close (1957).

In these tests, the results agree in showing that high clay content corresponds to lower strength. Soils 3 and 4 had similar fines content, but Soil 3 exhibited greater strength resulting from other factors such as clay type, soil particle texture, surface area, soil structure, and organic content. In conclusion, a soil type with relatively high fines content generally has relatively low strength capacity.

Effects of Additive Types

Different additives produce different effects with respect to compressive strength of soil. In these tests, both co-product and cement-treated specimens exhibited higher strength capacity than untreated specimens. As shown in Table 16, the percentage strength improvement (SI) obtained by equation (6) and used for quantitative assessments of soil, UCS was increased by use of additives.

Table 16. Percent strength improvement of additive-treated soils compared to pure soil

Soil types	Sample type	OMC-4			OMC			OMC+4		
		1d	7d	28d	1d	7d	28d	1d	7d	28d
Soil 1	Pure Soil 1	0	0	0	0	0	0	0	0	0
	Soil 1+12% BCP A	104	105	121	91	184	208	189	173	318
	Soil 1+12% BCP B	34	52	11	70	193	150	157	104	146
	Soil 1+3% Cement	44	75	151	256	509	660	517	724	1235
	Soil 1+6% Cement	141	205	244	531	886	1482	930	1129	2787
	Soil 1+12% Cement	233	401	703	863	1672	2234	1624	2111	4268
Soil 2	Pure Soil 2	0	0	0	0	0	0	0	0	0
	Soil 2+12% BCP A	111	118	164	118	130	217	123	143	202
	Soil 2+12% BCP B	161	105	53	115	92	87	73	92	59
	Soil 2+12% BCP C	46	170	352	33	74	227	-18	64	287
	Soil 2+3% Cement	256	434	978	552	655	1847	423	865	1849
	Soil 2+6% Cement	717	948	1819	990	1211	3036	1071	1522	2457
	Soil 2+12% Cement	1148	1270	2241	2017	1978	3628	1748	2267	3032
Soil 3	Pure Soil 3	0	0	0	0	0	0	0	0	0
	Soil 3+12% BCP A	18	81	127	45	203	280	45	100	152
	Soil 3+12% BCP B	71	40	22	121	92	71	151	97	20
	Soil 3+3% Cement	90	131	224	272	372	488	335	474	569
	Soil 3+6% Cement	229	314	439	507	823	939	566	944	1170
	Soil 3+12% Cement	380	559	716	914	1499	1956	1072	1475	2248
Soil 4	Pure Soil 4	0	0	0	0	0	0	0	0	0
	Soil 4+12% BCP A	71	187	188	193	278	369	149	149	261
	Soil 4+12% BCP B	323	309	148	486	299	125	297	206	120
	Soil 4+3% Cement	164	436	418	268	842	1207	229	758	1145
	Soil 4+6% Cement	328	722	629	534	1737	1863	572	1766	1904
	Soil 4+12% Cement	624	1239	1361	1016	3058	3926	1304	3535	3962

The table header "UCS improvement (SI), %" spans all nine data columns.

$$SI, \% = (SAD - SCD)/SCD \times 100 \qquad (6)$$

where, *SI* represents the percentage strength improvement of additive-treated soil over untreated soil. *SAD* represents the average UCS of additive-treated soil specimens, and *SCD* represents average UCS of the control soil specimen (untreated soil).

For BCP A-treated specimens, SI values generally ranged from about 20% to 370%, and BCP A was more effective in Soil 1 because it exhibited higher strength than 3% of cement-treated samples under OMC-4% as shown in Figure 48. For BCP B-treated specimens, the SI values ranged from about 10% to 490%. The specimens of Soil 4 treated with BCP B showed the highest improvement in UCS when compared to other soils with BCP B, and the strength of Soil 4 was improved by over 300% for one-day curing. However, the UCS improvement of the other three soils using BCP B were generally lower than 200%. BCP C was only added into Soil 2, and it produced up to 450% increase in UCS when compared to untreated specimen. Cement is obviously the most effective stabilizer for improving soil UCS. The specimens treated with only 3% of cement could produce strengths between 40% and 1,900% as high as untreated specimens. The cement hydration process requiring water and time produces significant strength improvement in soil specimens with higher moisture content and longer curing periods.

Although all additives could improve natural soil strength, their effects were different because of their different underlying mechanisms. Cement produced the most dramatic improvement in strength for all soils. In general, the strengths of cement-treated specimens increased due to hydration with an increase in cement content, moisture level, and length of curing periods.

Co-products containing sulfur-free lignin presented a medium increase of about 20% to 500% in the strength of untreated soil because of the presence of lignin. BCP A was more suitable for Soils 1 and 4, which are relatively coarse soils. BCP B was very effective in strength improvement of Soil 4, but its performance with respect to UCS was lower than that of the other three types of soil treated with BCP A. As the other oily liquid co-product, BCP C was difficult to identify with its most suitable soil, because only Soil 2 was evaluated using this additive. However, the UCS results for BCP C indicated that it is a more promising additive than BCP A or BCP B for Soil 2, which is Iowa loess, due to its highest lignin content.

In total, 16 and 14 unconfined compressive strength tests were performed for Soil 3 and Soil 4 treated with lignosulfonate, 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 52a, only a low lignosulfonate dosage (i.e., 5%) strengthened Soil 3. 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. As shown in Figure 52b, low and medium dosages (i.e., 5% and 10%) of lignosulfonate strengthened Soil 4 to some degree, while a 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.

Effects of Moisture Content

The presence of moisture in soil can influence UCS. In these tests, three moisture levels were evaluated for each specimen type. OMC is the moisture content at which soil reaches its maximum dry density; OMC-4% represents the drier side of the optimum moisture level, and OMC+4% represents the wetter side of the optimum moisture level. Even though soil can obtain this maximum dry density under OMC, this doesn't necessarily mean that the highest strength can be obtained under OMC. Figure 48 through Figure 51 and Table 16 show the effects of moisture content on UCS of specimens.

All pure soils showed a reduction in UCS with an increase in moisture content, and their strengths were less than 50% of the strengths at the dry side. For oily liquid-type co-product treated specimens, UCS also decreased with rising moisture content, but SI values were increased under OMC and OMC+4% compared to OMC-4%. For example, the strength of Soil 1 on the dry side after 28-day curing could be increased by 121% with a 12% BCP A-treatment, but the strength of Soil 1 on the wet side after 28-day curing could be increased by over 300% with BCP A-treatment. Although BCP B-treated specimens exhibited about a 40% to 70% decrease in UCS on the wet side when compared to their strengths on the dry side, Soils 1 and 3 with BCP B had higher SIs on the wet side in contrast to Soils 2 and 4 with BCP B, which had

higher SIs on the dry side. The UCS results for both natural soil and co-products-treated soil can be summarized by stating that an increase in moisture content decreases strength. This phenomenon can be explained by considering diffuse double layers of solid particles (Lambe 1958).

Based on a theory proposed by Lambe (1958), many flocculated structures in soil require a high compressive load to overcome inter-frictional force that can produce failure at the dry side. Under OMC conditions, the diffuse double layers of particles expand and produce internal separation in flocculated structures to form dispersed structures. The presence of such structures decreases the inter-frictional and strength capacity of soil. As the moisture increases toward the wet side, the diffuse double layers continue to expand and enhance repulsion between solid particles to generate more dispersed structures, so the soil strength continues to decline. Co-products can't react with water to generate new compounds, as confirmed by XRD and SEM analysis. This indicated that co-products don't modify the diffuse double layer of solid particles to change the formation of dispersed structures with an increase in soil water content, so co-products-treated specimens also exhibited diminishing strength with rising moisture content.

Cement is different from other co-products in that it requires water to produce hydration, so soil treated with cement generally obtains its highest strength under OMC or OMC+4%. However, an excess of water in cement-treated specimens may produce pore spaces and thereby diminish strength, so a suitable water-cement ratio should be selected to avoid such loss of strength.

In summary, both pure soil and co-products-treated soil can lose up to 70% of strength with OMC+4% as explained by the diffuse double layer theory. However, the addition of co-products in soil can reduce the loss of strength on the wet side compared to that of pure soil. Cement-treated soil requires suitable water content, generally higher than OMC-4%, in consideration of hydration to achieve greatest strength.

Effects of Curing Periods

The strength capacity of specimens can be changed using different curing periods. In these tests, 1-day, 7-day, and 28-day specimen strengths are shown in Figure 48 through Figure 51. While the curing period length influences the strength capacity of additives-treated soil, it doesn't affect the strength capacity of pure soil. For cement-treated soil, a long curing time increased the strength because the hydration process requires time to harden soil.

Increasing the number of curing days using BCP A increased strength of all types of soil. For Soils 1 and 2 treated with BCP A, their strengths after 28-day curing showed about a 20% to 60% increase compared to their strengths after only 1-day curing. The influence of the curing period interval was more pronounced with respect to the strengths of Soils 3 and 4 treated with BCP A, about a 60% to 140% increase after 28-day curing. The BCP C added in Soil 2 presented similar results to BCP A as shown in Figure 49, but its short-term strength (1-day) was lower than that of BCP A-treated Soil 2, and the longer-term strength (28-day) was higher than that of BCP A-treated Soil 2.

For the powder co-product (BCP B) treated Soils 1 and 2, the increase in curing time didn't produce significant effects, and their highest strengths generally were achieved after seven-day curing. The strengths of Soils 3 and 4 treated with BCP B were decreased by up to 60% with an increase in curing time. Specimens treated with BCP B could achieve higher strength than specimens treated with BCP A and BCP C after 1-day curing, but after 28-day curing, their strengths were lower than the oily liquid-type co-product treated specimens. Although the UCS of BCP B-treated specimens decreased with an increase in curing time, their strengths were still higher than the UCS of pure soil.

The oily liquid type co-products, BCP A and BCP C, produced long-term benefits of soil strength improvement because these additives require time for setting. Their setting behaviors are similar to those of bitumen, and an increase in curing time can turn their liquid phase into a solid phase and form strong physical bonds between soil particles. The specific setting behaviors of oily liquid types of BCP depend on their constituents. It is hypothesized that bacterial-colony activity is the cause for decrease in UCS for BCP B-treated specimens with long-term curing. Figure 53 is an image of a failed specimen with BCP B-treatment after long-term curing.

Figure 53. Bacterial colony in BCP B-treated specimen

The fractured surface of the specimen has some dark green stains, and the outside surface also shows some white and dark green stains accompanied by a terrible odor. As a biologic material, co-product B has potential for feeding bacteria, and the growth of bacteria may negatively affect the soil strength after long-term curing.

In summary, the oily liquid-type co-products could provide an increase of up to 140% in UCS of treated soil after a 28-day curing when compared to 1-day curing. This indicates that oily liquid-type co-products can benefit the long-term UCS of soil through their setting behavior. Cement also dramatically increased the strength of soil with an increase in curing days; this phenomenon can be explained by cement hydration. Although BCP B exhibited an up to 60% decrease in UCS of treated soil after long-term curing, the specimens treated with BCP B were still stronger than

untreated specimens. It is hypothesized that bacterial growth can affect the strength of specimens. With respect to the effects of curing time, the oily liquid-type co-products (BCP A and BCP C) were more promising additives than BCP B.

Effects of Additive Contents

Suitable additive content of soil specimens is an important factor in obtaining the greatest strength, but an increase in additive content doesn't necessarily imply an increase in soil UCS. In these tests, a value of 12% based on a previous study was selected as the most suitable co-product content to be added to specimens. As already mentioned in the literature review section, BCP A and BCP B had been studied by Ceylan et al. (2010). They investigated the effects of co-product contents on soil strength to identify the most suitable additive content. Figure 15, Figure 54, and Figure 55 show the strength capacities of soil treated with various co-product contents under OMC, OMC-4%, and OMC+4%, respectively.
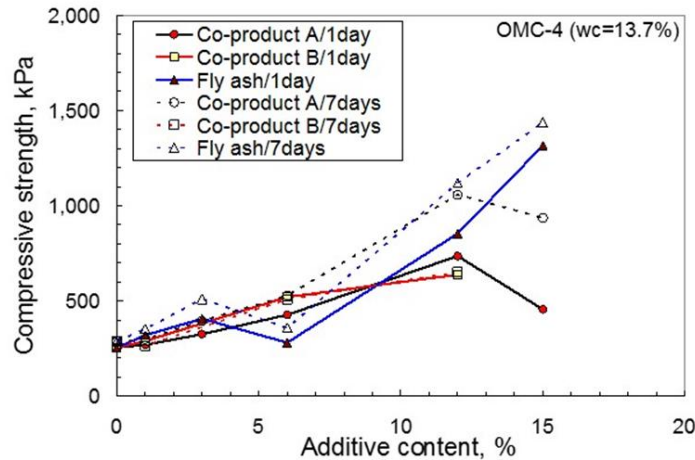
Ceylan et al. 2010

Figure 54. UCS for soil treated with various contents of BCPs under OMC-4%
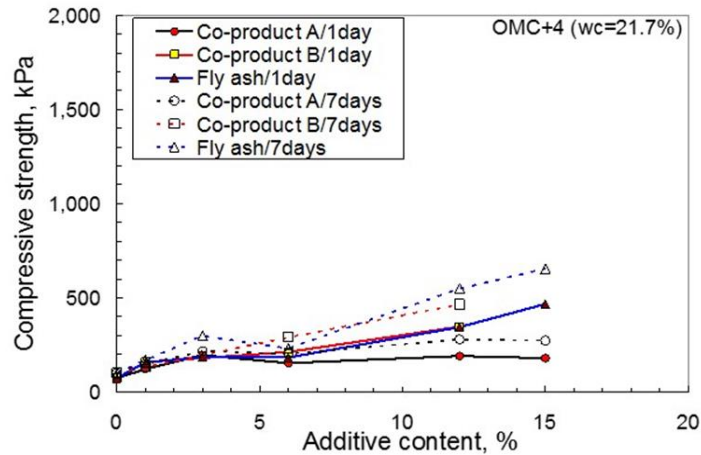
Ceylan et al. 2010

Figure 55. UCS for soil treated with various contents of BCPs under OMC+4%

Their results indicated that 12% was the best co-product content value for obtaining the highest strength. An excess of co-products in soil can decrease UCS, and cement content added to soil should be controlled for the same reason. PCA recommends that cement content should be lower than 16% and higher than 3% for soil stabilization purposes.

The UCS of untreated soil and additives-treated soil were evaluated, and the results indicate that pure soil is very weak and can be strengthened significantly by co-products. BCP A was effective for all types of soil, increasing strength by 20% to 370%, especially for specimens with higher moisture contents and longer curing periods. BCP B was more effective on Soil 4, for which the strength could be increased by about 120% to 490% over the strength of pure Soil 4. Although BCP B-stabilized soil generally achieved higher short-term strength than BCP A and BCP C stabilized soil, its long-term strength reflected a decrease and was less than that for oily liquid-type co-product treated soils. In addition, treatments using the two oily liquid-type co-products achieved a higher strength capacity than the powder-type BCP B treatment on the wet side. BCP C was added only to Soil 2, but it achieved higher 28-day strength than BCP A- and BCP B-treated Soil 2. Although the investigated co-products didn't exhibit much better UCS than cement, their UCS are much better than those of untreated soil. These UCS results indicate that the oily liquid-type co-products are more promising additives than powder-type BCP B.

Direct Shear Strength Results

Consolidated-drained (CD) triaxial compression tests were carried out to evaluate the shear properties of pure soil and soil treated with 12% of BCP B. Under normal stress levels of 10 psi (DS 10), 20 psi (DS 20), and 30 psi (DS 30), shear capacities of specimens with different moisture contents (OMC-4%, OMC, and OMC+4%) and different curing periods (1-day, 7-day, and 28-day) were measured by subjecting them to shear loads until they failed, with the results shown in Figure 56 through Figure 67.

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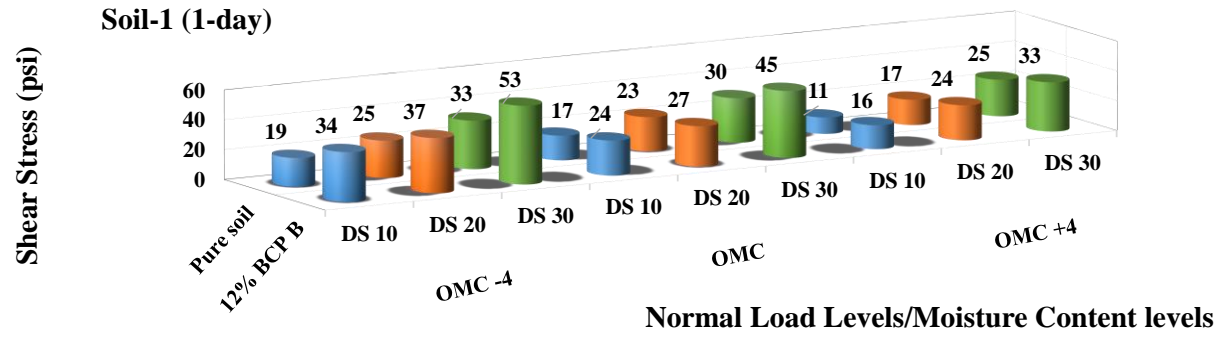
Figure 56. Shear strength for Soil 1 after 1-day curing
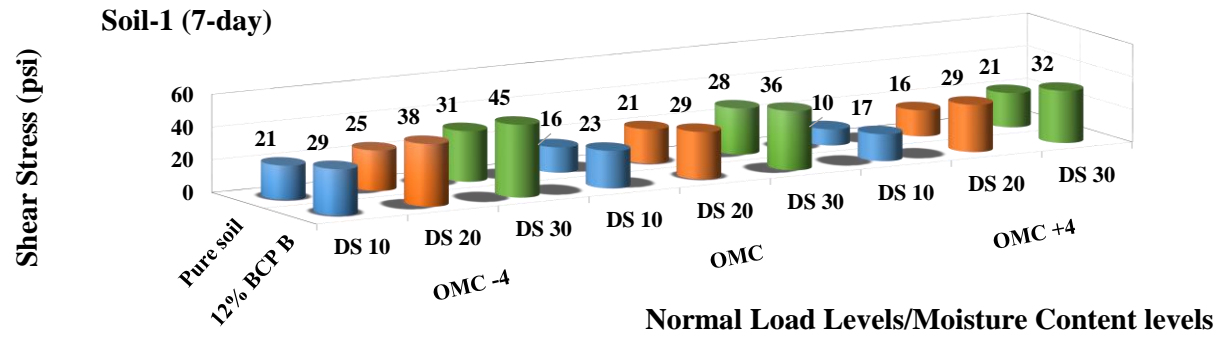
Figure 57. Shear strength for Soil 1 after 7-day curing
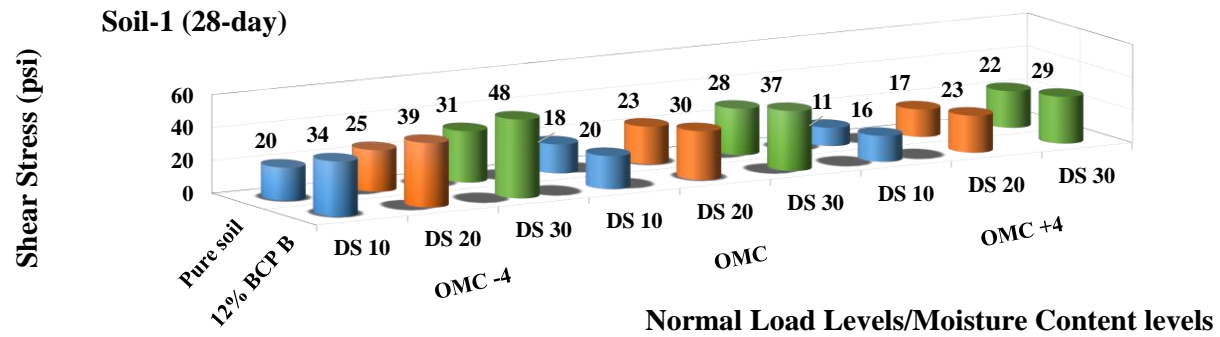
Figure 58. Shear strength for Soil 1 after 28-day curing
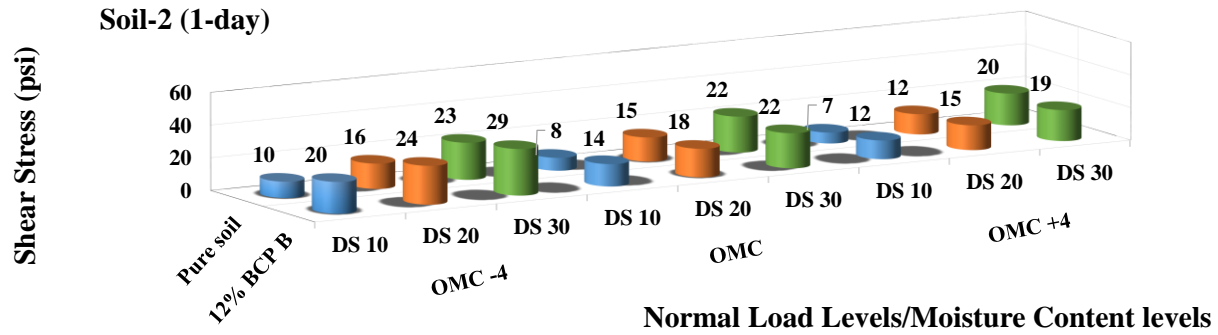
Figure 59. Shear strength for Soil 2 after 1-day curing
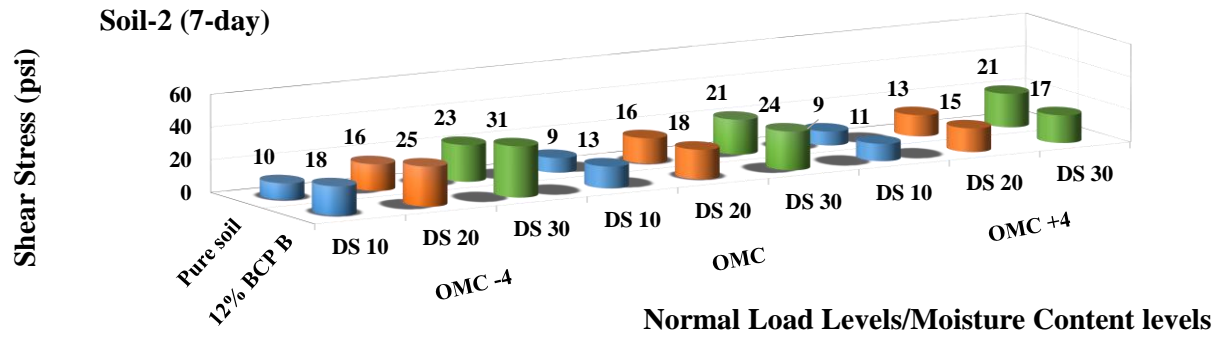
Figure 60. Shear strength for Soil 2 after 7-day curing
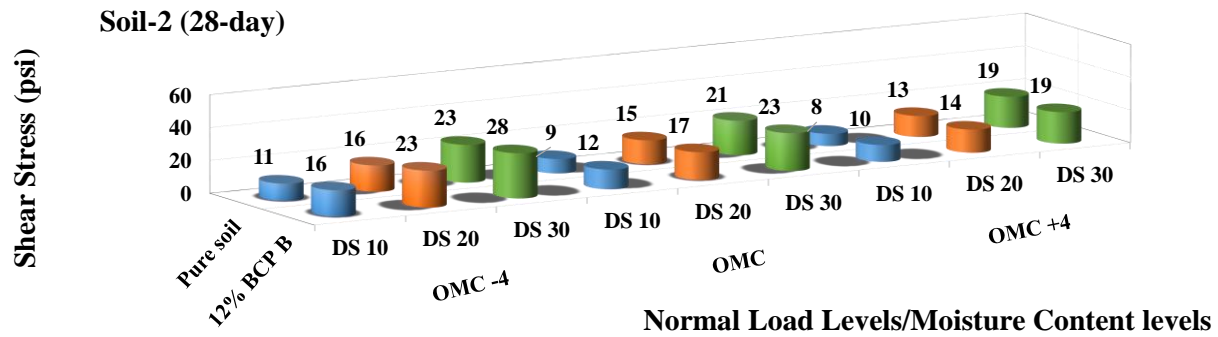
Figure 61. Shear strength for Soil 2 after 28-day curing

Soil-3 (1-day)
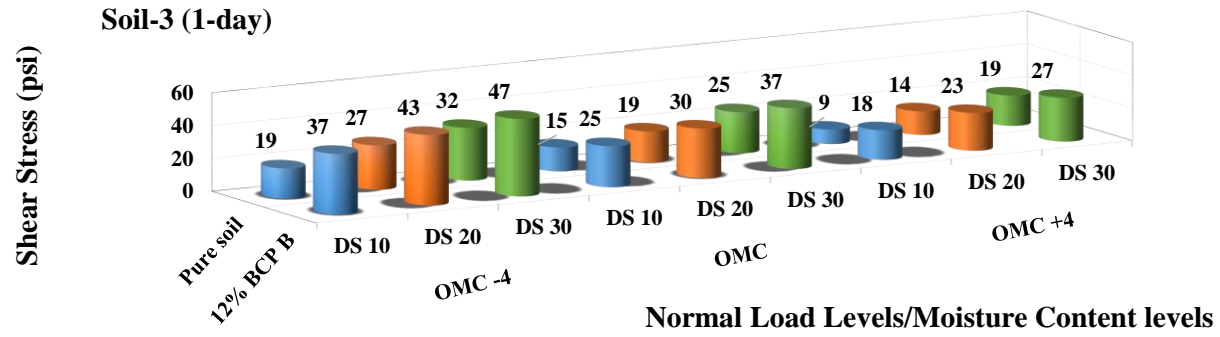
Figure 62. Shear strength for Soil 3 after 1-day curing

Soil-3 (7-day)
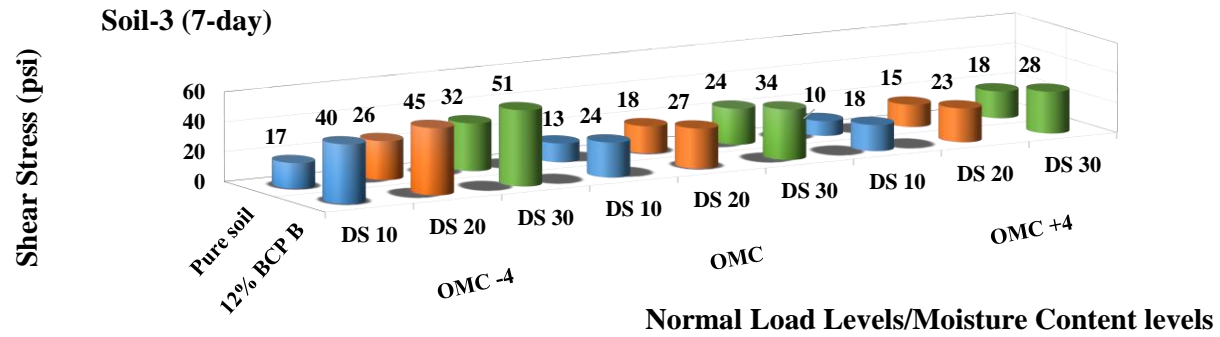
Figure 63. Shear strength for Soil 3 after 7-day curing

Soil-3 (28-day)
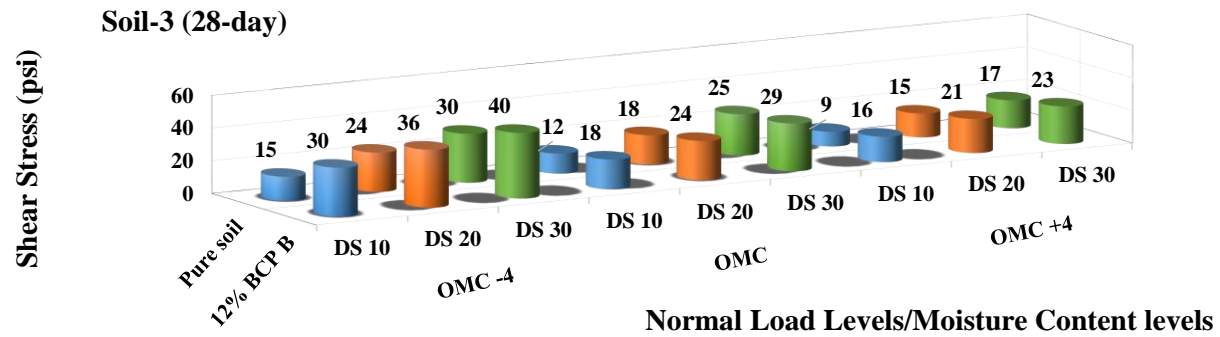
Figure 64. Shear strength for Soil 3 after 28-day curing

82

Soil-4 (1-day)
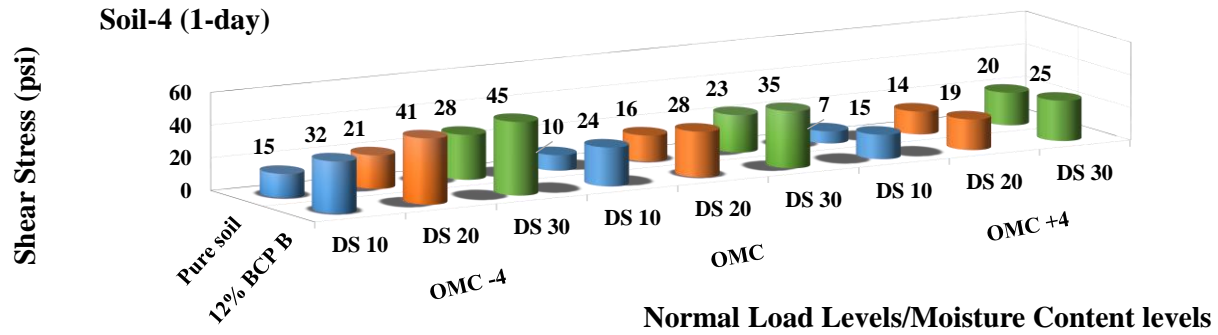
Figure 65. Shear strength for Soil 4 after 1-day curing

Soil-4 (7-day)
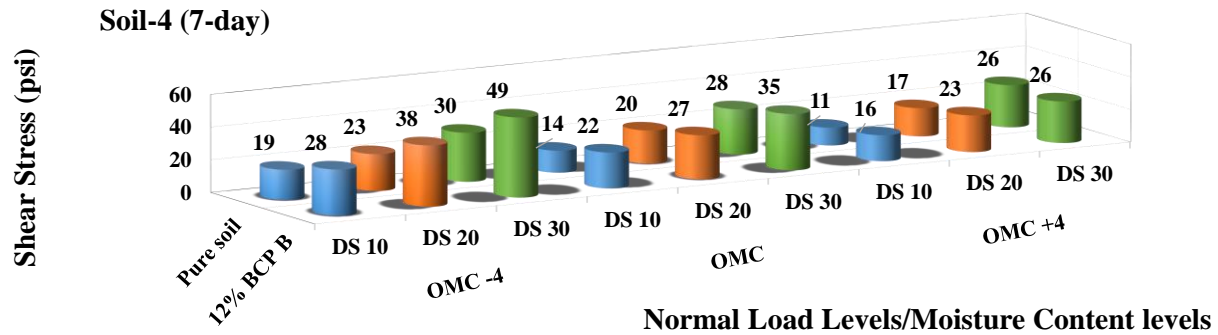
Figure 66. Shear strength for Soil 4 after 7-day curing

Soil-4 (28-day)
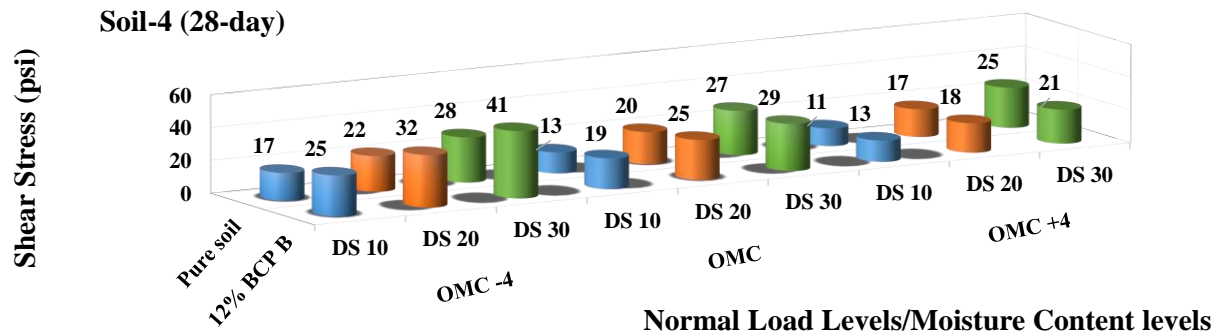
Figure 67. Shear strength for Soil 4 after 28-day curing

Shear strength envelopes for each untreated and treated soil were fit using the Mohr–Coulomb plot shown in Figure 35 to identify corresponding shear strength parameters, cohesion (c), and friction angle (ϕ), listed in Table 17.

Table 17. Shear strength parameters for untreated and treated soil

Specimen type		Curing periods	Friction angle (ϕ), degree			Cohesion (c), psi		
			OMC-4	OMC	OMC+4	OMC-4	OMC	OMC+4
Soil 1	Untreated	1 day	33.4	33.6	34.0	12.4	9.8	4.0
		7 day	26.6	32.4	29.0	15.6	8.9	4.5
		28 day	29.0	27.9	29.5	14.5	12.4	5.5
	12% BCP B treated	1 day	43.8	46.9	40.4	21.9	10.5	7.2
		7 day	38.7	33.6	37.8	21.1	16.1	10.3
		28 day	35.8	39.2	32.4	25.9	12.5	9.6
Soil 2	Untreated	1 day	32.4	35.2	32.6	3.4	0.8	0.1
		7 day	31.6	31.6	31.0	4.0	3.0	2.0
		28 day	32.0	31.4	29.9	4.0	2.6	1.6
	12% BCP B treated	1 day	24.2	21.3	20.6	14.9	9.8	7.7
		7 day	33.6	27.2	17.7	11.3	8.1	7.6
		28 day	29.7	28.8	24.0	10.6	6.3	5.6
Soil 3	Untreated	1 day	34.2	27.5	25.9	12.3	9.1	4.2
		7 day	36.5	29.9	22.0	10.3	6.8	6.2
		28 day	37.2	33.0	22.3	7.7	5.5	5.4
	12% BCP B treated	1 day	27.0	31.0	23.5	32.2	18.7	13.9
		7 day	28.8	27.2	27.7	34.3	17.8	12.2
		28day	27.0	28.6	20.3	25.0	13.0	12.4
Soil 4	Untreated	1 day	32.6	33.8	32.2	8.1	2.7	1.2
		7 day	29.9	35.4	36.9	12.2	6.3	3.0
		28 day	27.7	35.4	34.4	11.6	5.6	3.7
	12% BCP B treated	1 day	33.0	29.2	25.9	26.2	17.7	9.8
		7 day	46.0	32.0	25.6	17.6	15.3	11.7
		28 day	38.5	26.3	21.3	16.8	14.1	9.5

In these tests, different factors that affected shear strength of soil, such as type of soil, additive, moisture content, and curing period, were evaluated.

Effects of Soil Types

Different soils exhibited different shear strengths in these tests. Among the different untreated soils, Soil 1 presented the highest shear strength, up to 33.0 psi under OMC-4% at DS 30. Soil 2 was the weakest soil, exhibiting shear strength of only 23.0 psi under OMC-4% at DS 30. Soil 3 exhibited the second-highest shear strength, up to 32 psi, and the shear strength of Soil 4 was lower by between 0 psi to 6 psi than the shear strength of Soil 3. The friction angles of pure soils ranged from 22° to 37°, and the friction angles of Soil 3 exhibited the greatest difference, about 15° between OMC-4% and OMC+4% conditions. The cohesion of Soil 1 was still the highest and ranged between 4.0 psi and 12.4 psi; the cohesion of Soil 2 was much lower and ranged between 0.1 psi and 4.0. Soil 3 had higher cohesion than Soil 4, especially under OMC and OMC+4%.

The shear strength results presented in Figure 56 through Figure 67 and Table 17 indicate that Soil 1 exhibited the highest values of shear capacity and cohesion, Soil 2 exhibited the lowest,

and Soil 3 exhibited higher values than Soil 4, similar to UCS results. The friction angles of untreated soils ranged between 22° and 37° and didn't have a clear rank. The different shear strengths and shear parameters of soils are affected by gradation of soil and inherent properties of soil particles, and these factors can influence the effects of treatment using co-products.

Effects of Additive Types

The results of shear strength show that BCP B can improve shear properties of pure soils. Increases in shear strength for BCP B-treated soil samples ranged up to 23 psi compared to untreated soil samples. Soil 2 treated with BCP B exhibited a 0 psi to 10 psi increase in shear strength, and BCP B-treatment was more effective with respect to shear strength improvement on the other three soil types. Soils 1, 3, and 4 with BCP B-treatment increased shear strength by up to 20 psi, 23 psi, and 20 psi, respectively, compared to untreated soils. The shear parameters of soil were also changed by BCP B-treatment. For Soil 1, BCP B-treatment improved both friction angle and cohesion. For Soils 2 and 3, their friction angles were decreased and cohesions were increased with BCP B-treatment. Under OMC-4%, Soil 4 treated with BCP B presented a larger friction angle and greater cohesion than untreated Soil 4; its friction angle, however, was diminished and cohesion still increased under OMC and OMC+4%.

In general, higher values of shear parameters indicate higher soil shear strength, so Soil 1 is the most effective soil for BCP B-treatment in terms of its improvement in both shear capacity and shear parameters when compared to untreated soil. Although BCP B increased the shear strength and cohesion of the other three soils, the reduction in friction angle reflected a potential decrease in shear strength at high normal stress.

Effects of Moisture Content

Moisture content is an important factor affecting shear properties of soils. An increase in moisture content decreased both shear strengths and cohesions for all untreated and BCP B-treated soils. The specimens under OMC+4% lost up to 22 psi in both shear strength and cohesion when compared to specimens under OMC-4%, and the highest shear strength and cohesion values of treated soil under OMC-4% were 53 psi and 34.3 psi, respectively. The friction angles of treated soil specimens decreased with rising moisture content.

As with the results of UCS, a decrease in shear capacity with an increase in moisture content of soil can be explained by the theory proposed by Lambe (1958). An increase in water in soil can turn flocculated structures into dispersed structures by forming diffuse double layers of solid particles, and this change makes soil lose both compressive and shear strengths. Moisture content, therefore, plays a key role in influencing the effects of BCP B on improvement of soil properties.

Effects of Curing Periods

The pure soil samples were not significantly affected by curing periods because no chemical reaction occurs in them, but long-term curing can reduce the shear strength of soil stabilized with BCP B. The difference between 1-day shear strength and 28-day shear strength of BCP B-treated specimens was less than 9 psi, and some treated specimens exhibited the highest shear strengths after 7-day curing. For treated Soil 2, the decrease in shear strength between 1-day and 28-day curing was slight, less than 4 psi, and for the other three soils, the decrease was as much as 11 psi.

The lengths of curing periods also have different effects on shear parameters for differently treated soils. The friction angles of Soils 1, 3, and 4 were decreased by up to 16° after long-term curing in contrast to those of treated Soil 2. For cohesion of treated soil, only Soil 1 exhibited improvement after long-term curing; the other three soils reflected a decrease.

The degradation of shear properties of BCP B-treated soil with an increase in curing period may encounter the same problem described in the UCS results. The BCP B-treated shear samples with 28-day curing also exhibited some dark green and white stains indicating presence of a bacterial colony. However, BCP B treatment still improved shear capacity of natural soil.

In summary, BCP B-treatment is effective in increasing both shear capacity and cohesion of soil with short-term curing. Long-term performance degradation for BCP B was observed, although it was still better than natural soil. BCP A and BCP C were not subjected to DS tests due to the unavailability of necessary quantities. However, the lignin in BCP A and BCP C appears to have a potential benefit on shear strength based on the study of Peric et al. (2014) investigating the effects of lignin-based stabilizer on shear behavior of sand and finding that a cohesion gain could be obtained by using lignin in combination with other technologies to improve slope stability of pavement.

Freeze-Thaw Durability Test

The visual evidence results of soil loss and volume change in freeze-thaw and wet-dry tests are presented in Appendix E. The raw data of freeze-thaw test results are also presented in Appendix F. In this test, each set of treatment group combinations containing the same six specimens was recorded at the end of each cycle (the end of each thawing) until all 12 cycles had been completed.

Recorded Visual Images

Over 600 images were recorded to show visual changes in specimens during 12 freeze-thaw cycles. Appendix E shows that all four types of pure soil specimens have very poor durability and failed after 12 cycles. The untreated Soil 2 specimens showed the weakest performance in freeze-thaw testing and 50% disintegrated after only three cycles. The untreated Soil 4 specimens began to fail after two cycles, and they had totally failed after nine cycles. The untreated Soil 3

specimens exhibited relatively better performance than those of Soil 2 and Soil 4 with respect to freeze-thaw resistance cycles, some of them failing after nine cycles. Visual evidence also showed that untreated Soil 1 specimens exhibited the best performance, fully failing during the last three cycles. The different curing periods for untreated specimens showed no significant influence on resistance to freeze-thaw cycles.

BCP A-treated specimens improved in freeze-thaw resistance when compared to untreated soil specimens. For Soil 1, BCP A-treated samples still looked good after 12 cycles and exhibited only partial failure. Some BCP-A treated Soil 2 specimens failed only after eight cycles, and they exhibited great improvement with respect to durability. BCP A-treatment was also effective on Soil 3 and Soil 4, and neither fully failed after 12 cycles. The increased curing periods for BCP A-treated specimens also resulted in no significant reduction in specimen failure. The images of the BCP B-treated specimens portrayed good freeze-thaw resistance and had not fully failed after 12 cycles, indicating that BCP B treatment can significantly improve the resistance of soil to damage from freeze-thaw cycles. The BCP B-treated specimens with seven-day curing demonstrated better performance than specimens with one-day curing for Soils 2, 3, and 4; however, for Soil 1 treated with BCP B the curing periods didn't produce significant influence on performance. Volume expansions in BCP B-treated specimens were also noticed in the images. The other oily liquid-type co-product, BCP C, was used only for Soil 2. Both one-day cured and seven-day cured specimens treated with BCP C had not failed after completion of the entire freeze-thaw test. Comparing the freeze-thaw performance shown in the images, BCP C was better than BCP A for Soil 2 because the BCP A-treated Soil 2 specimens had failed after 12 cycles.

The soil specimens treated with 3%, 6%, and 12% cement were also evaluated using a freeze-thaw test. The recorded images showed that increased cement content and curing period time for all specimens could reduce the degree of specimen failure during freeze-thaw cycles. In fact, full failure occurred only at the end of the 10th cycle in the 1-day cured Soil 2 specimens treated with 3% cement. The cement-treated specimens showed the best performance in this test, especially when the cement content was up to 12%, and in that case, the specimens after 12 freeze-thaw cycles resembled the original specimens before testing.

Results of Mass Loss

The results of average mass loss in freeze-thaw tests are shown in Figure 68 through Figure 71.
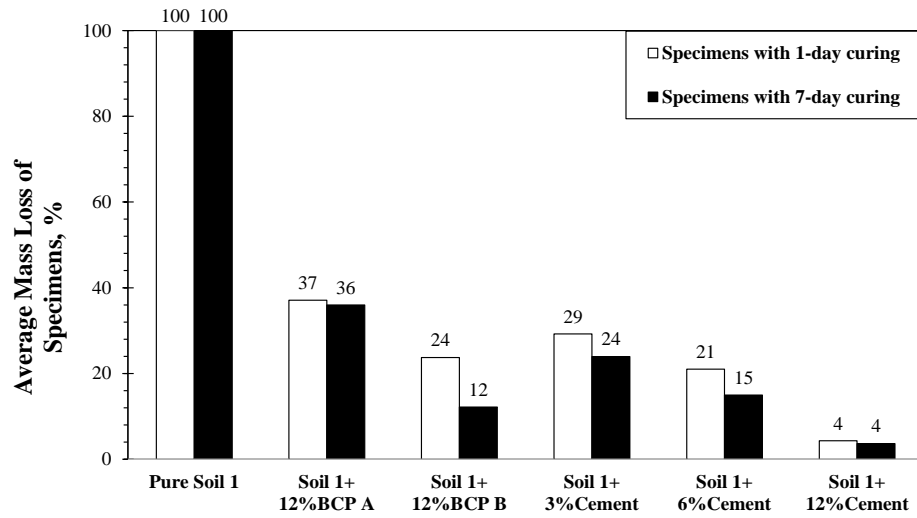
Figure 68. Average mass loss of specimens in Soil 1 sets
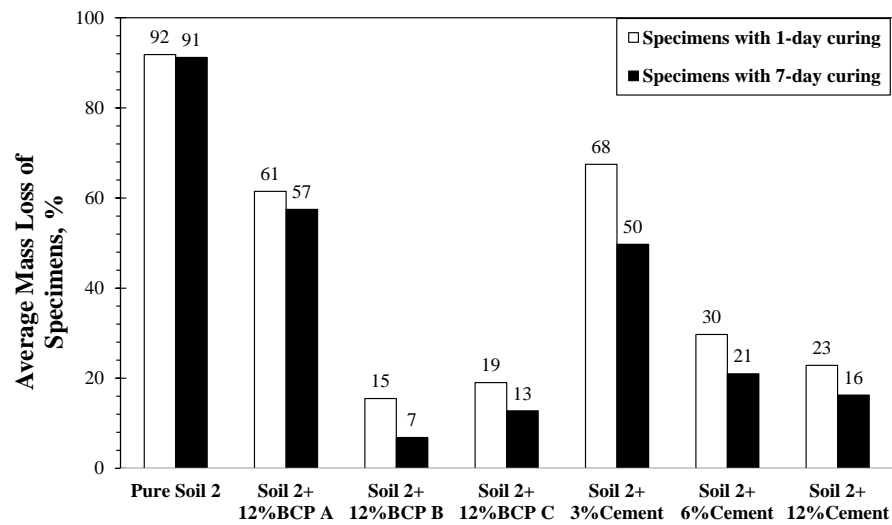
Figure 69. Average mass loss of specimens in Soil 2 sets
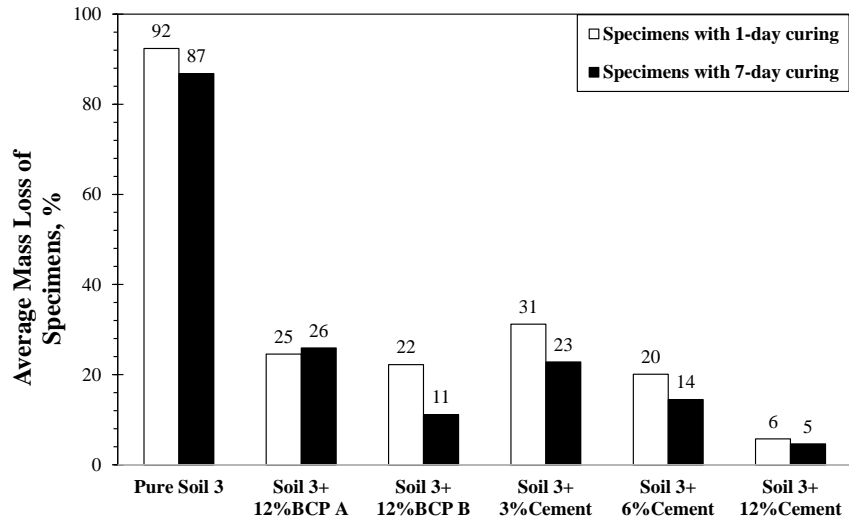
Figure 70. Average mass loss of specimens in Soil 3 sets
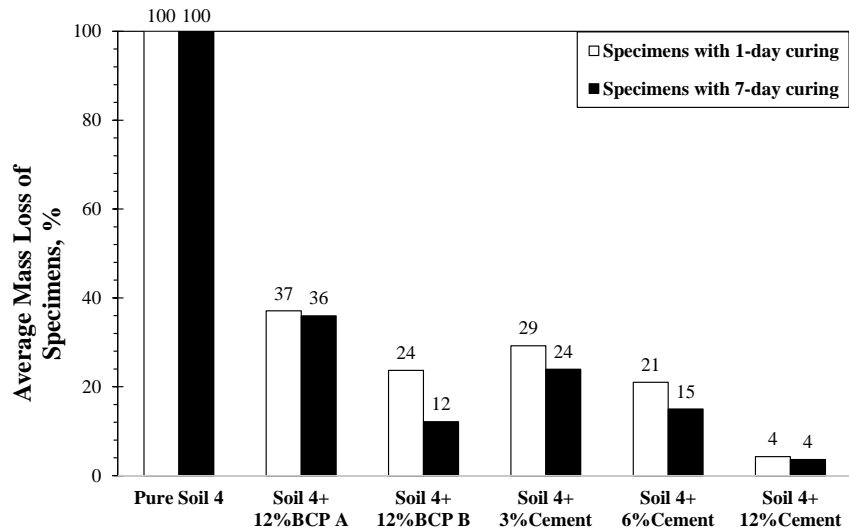
Figure 71. Average mass loss of specimens in Soil 4 sets

All pure soil specimens exhibited a maximum average mass loss greater than 80% compared to additive-treated specimens. The results show that pure soil loses nearly its total mass after 12 repeated freeze-thaw cycles.

The addition of any of the additives could reduce the mass loss of specimens to less than 68%. BCP A-treated specimens after 12 freeze-thaw cycles exhibited about 57% to 61% of mass loss for Soil 2 and about 25% to 37% of mass loss for the other three soils, indicating that BCP A was more effective in reducing mass loss with Soils 1, 3, and 4. BCP B performed best among the three co-products with respect to decrease in mass loss. It could reduce the mass loss to as little as 7% and not higher than 24%. BCP C also showed a significant reduction in mass loss ranging between 13% and 19% for Soil 2. Although the performance of BCP C was slightly worse than

BCP B for Soil 2, it was much better than BCP A in controlling mass loss. An increase in curing period also affected the reduction of mass loss for co-products-treated specimens. For BCP A- and BCP C-treatments, seven-day cured specimens slightly decreased mass loss, but the mass loss of BCP B-treated specimens with seven-day curing was only 50% that of BCP B-treated specimens with one-day curing.

The 3% cement treatment demonstrated no significant advantage with respect to reduction in mass loss compared to co-products treatments. The average mass loss for 3% cement-treated specimens was between 12% for BCP A- and 12% for BCP B-treated specimens of Soils 1 and 4 but greater than 12% for BCP A-treated specimens of Soils 2 and 3. When the cement content increased to 6%, the mass loss continued to decrease to near the values for the BCP B-treated specimens. The 12% for cement-treated specimens was lower than the 6% average mass loss for Soils 1, 3, and 4, and about 16% to 23% the average mass loss for Soil 2. The increase in curing period for cement-treated specimens also produced a decrease in mass loss.

Results of Volume Change

Figure 72 through Figure 79 show the average volume change of specimens during freeze-thaw cycles, and some specimens exhibiting partial or full failures after several cycles were not measured for volume change.
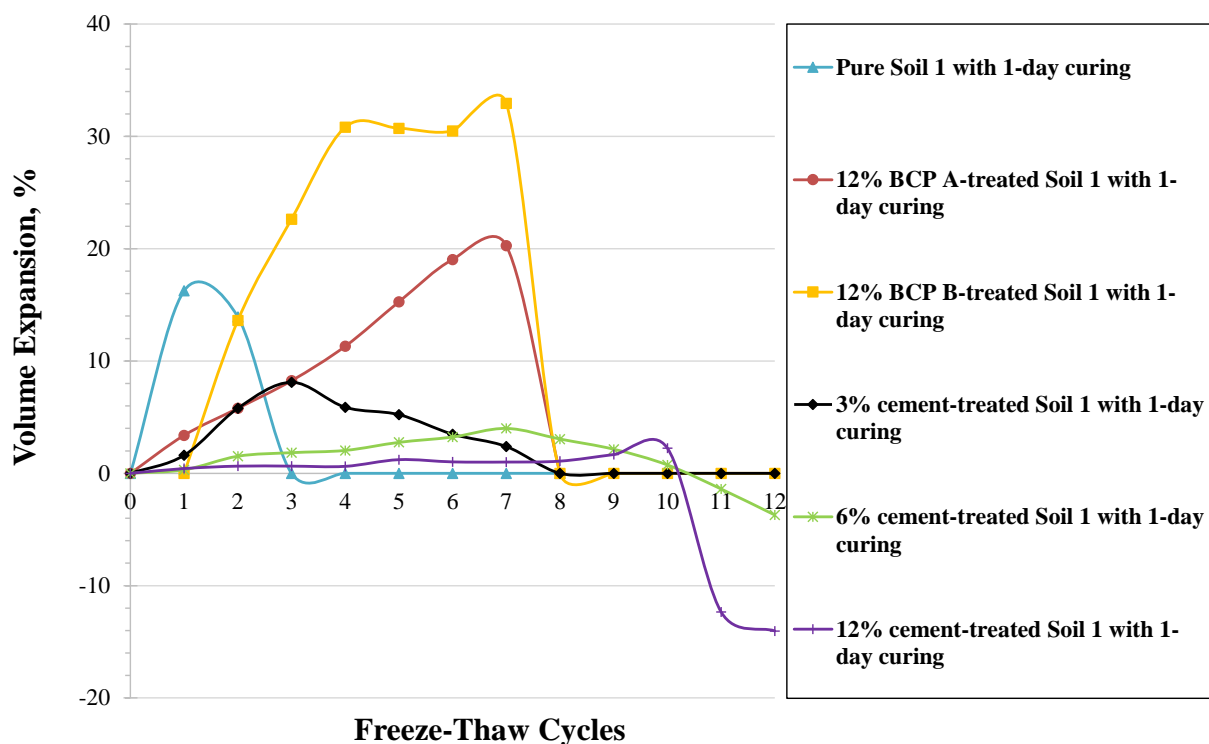
Figure 72. Average volume expansion of specimens in Soil 1 sets with 1-day curing
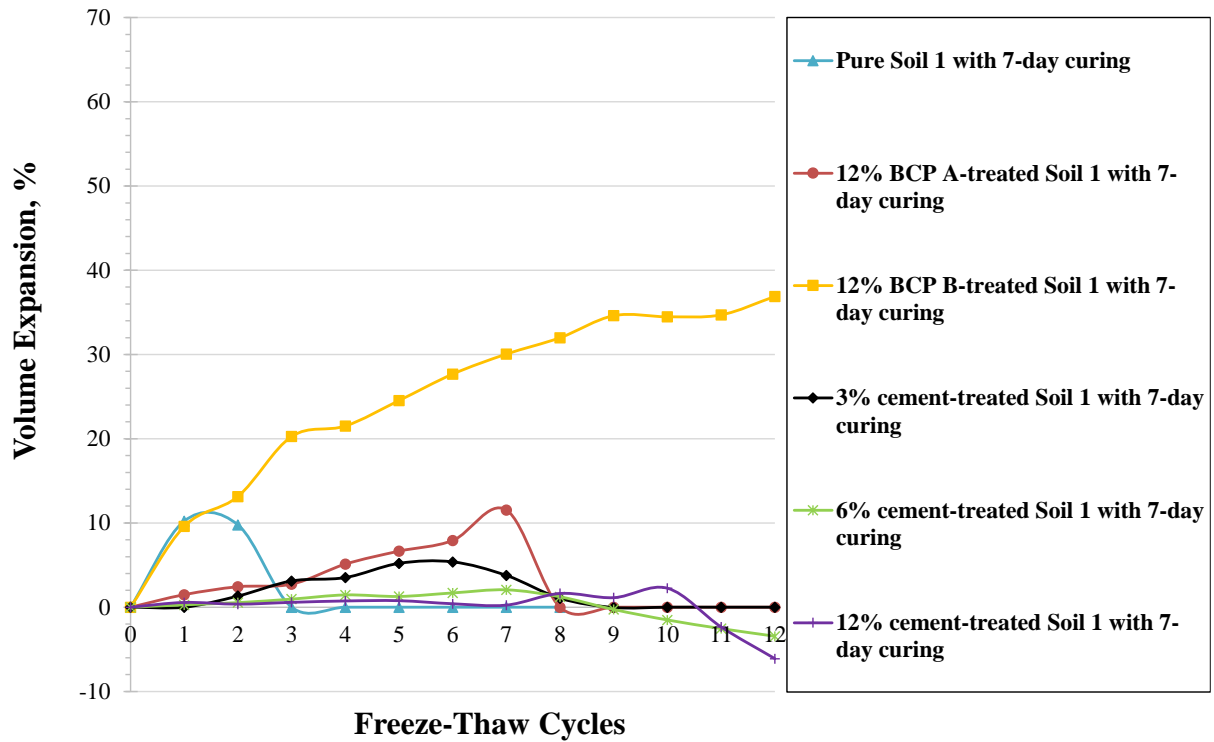
Figure 73. Average volume expansion of specimens in Soil 1 sets with 7-day curing
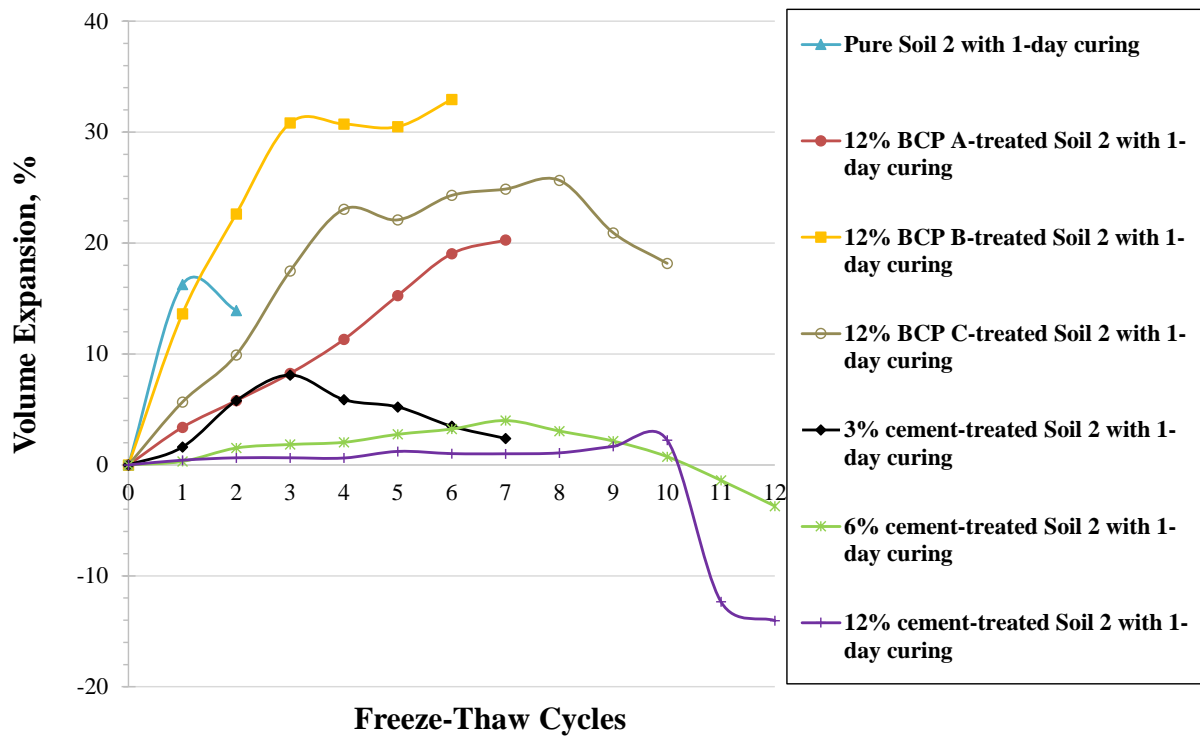
Figure 74. Average volume expansion of specimens in Soil 2 sets with 1-day curing
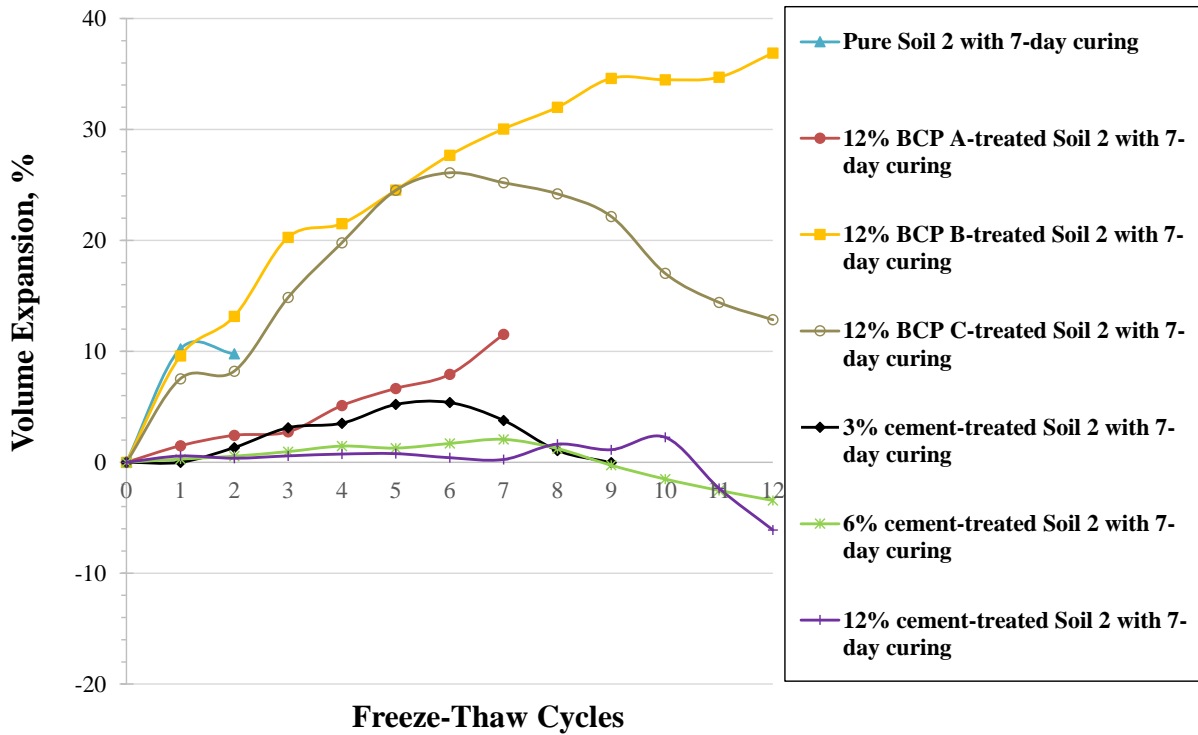
Figure 75. Average volume expansion of specimens in Soil 2 sets with 7-day curing
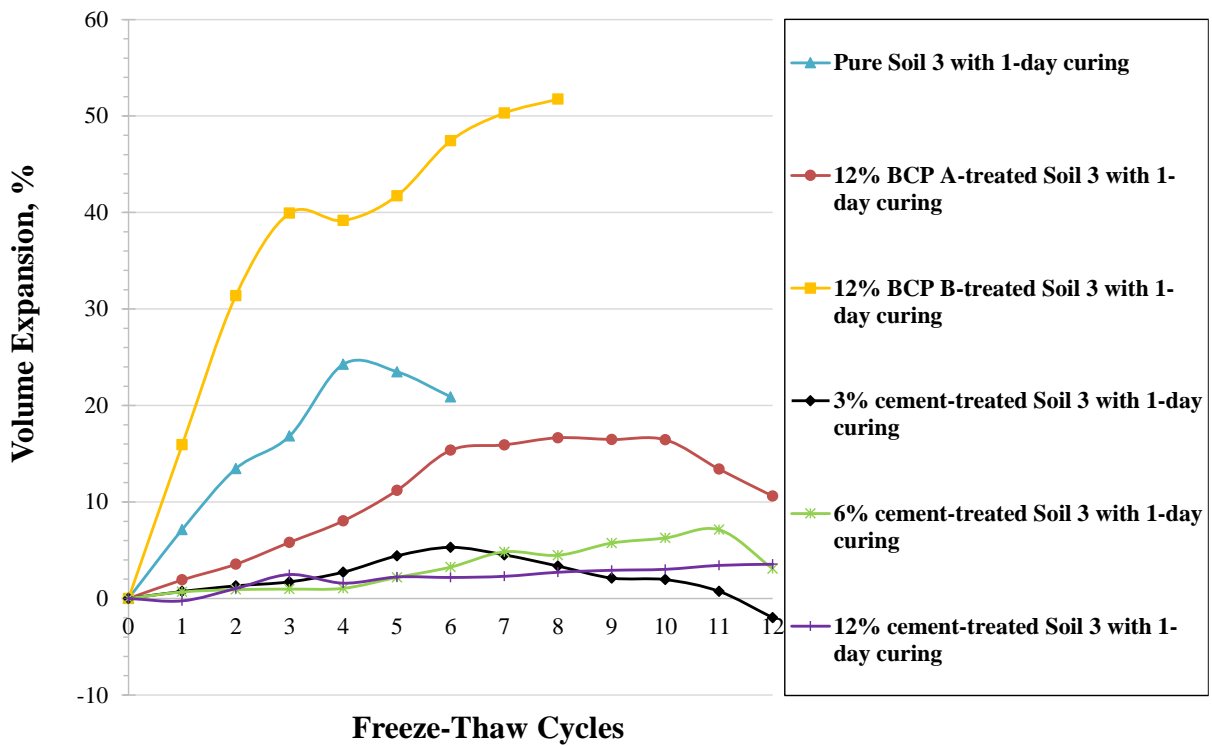
Figure 76. Average volume expansion of specimens in Soil 3 sets with 1-day curing
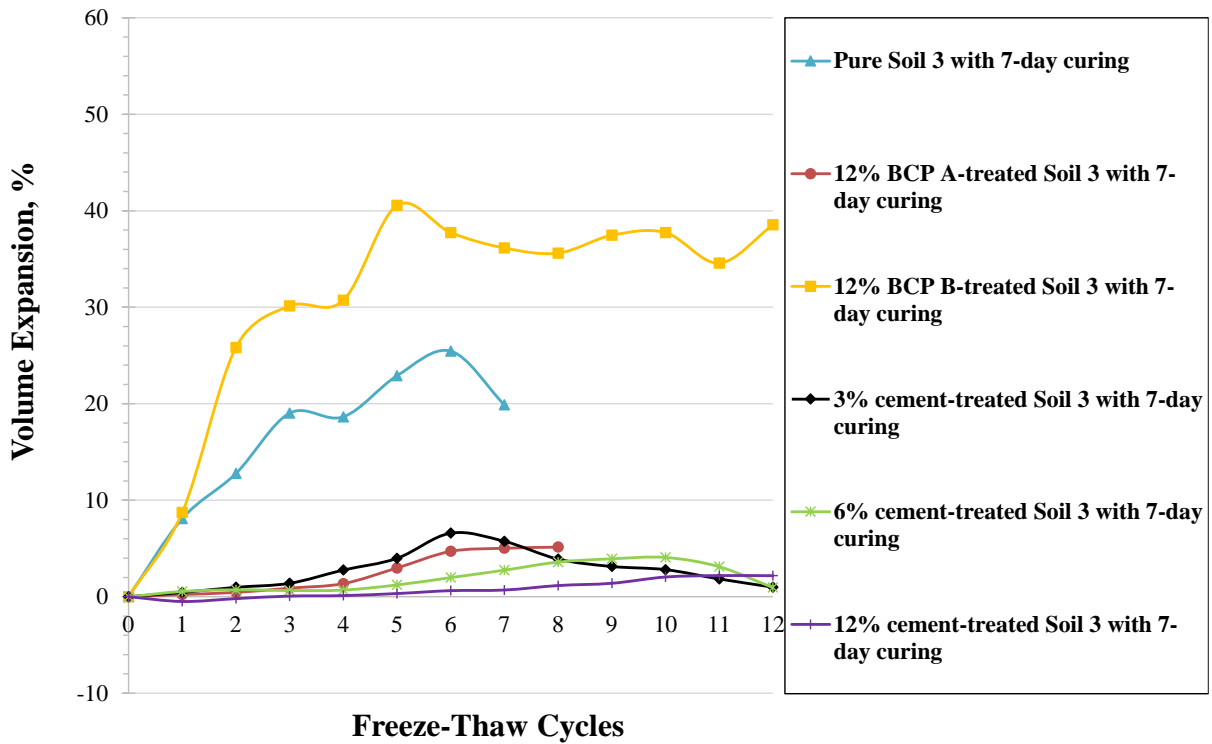
Figure 77. Average volume expansion of specimens in Soil 3 sets with 7-day curing
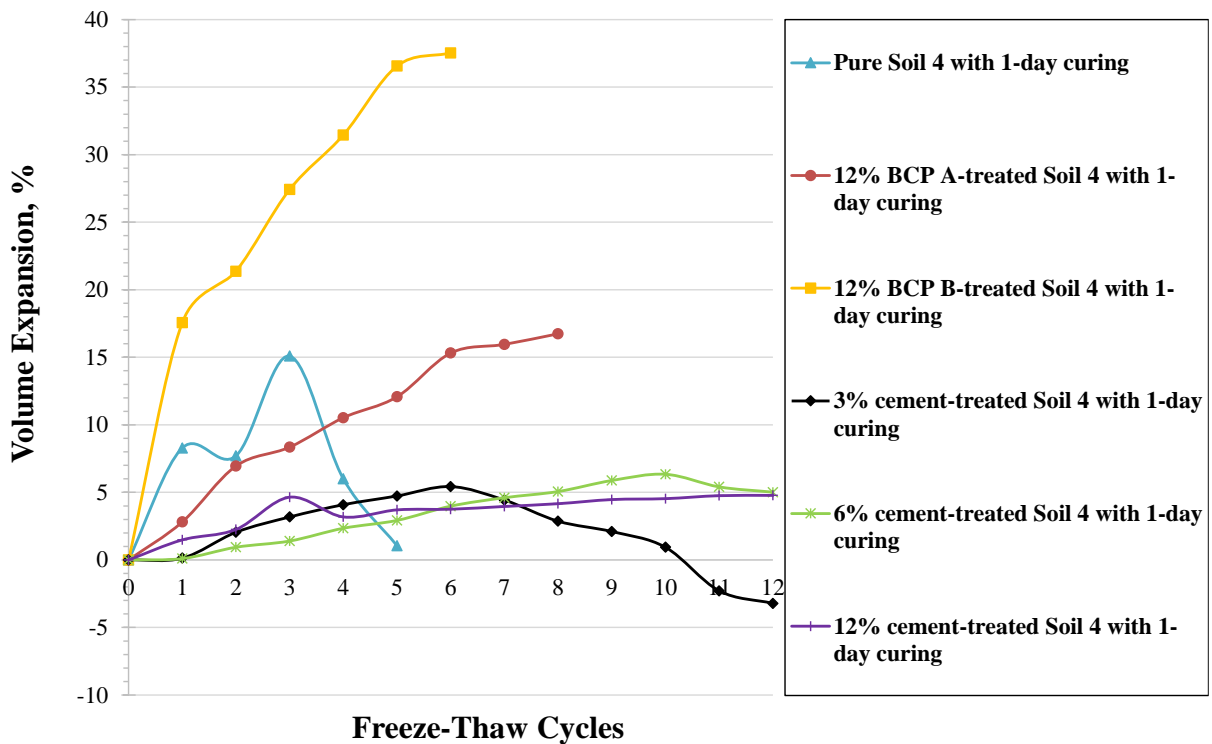
Figure 78. Average volume expansion of specimens in Soil 4 sets with 1-day curing
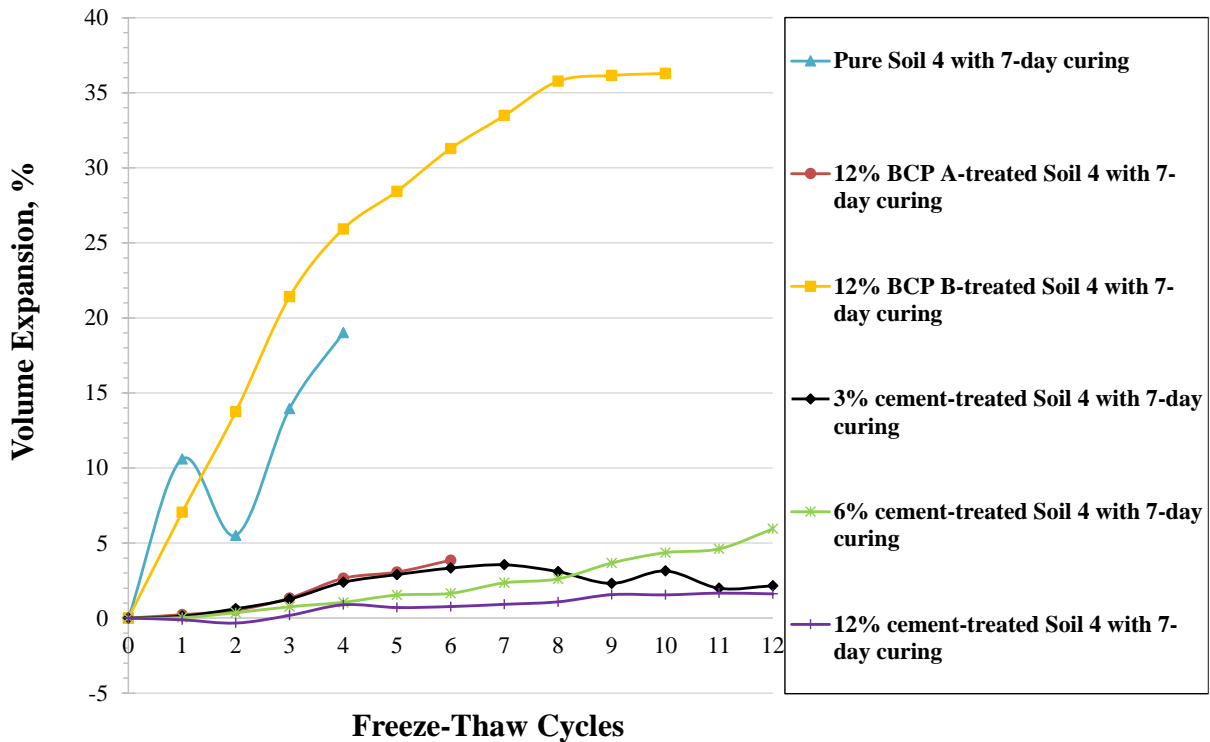
Figure 79. Average volume expansion of specimens in Soil 4 sets with 7-day curing

Pure specimens expanded by up to 125% of their original volumes with an increase in number of freeze-thaw cycles, and their volumes subsequently decreased due to mass loss until they fully failed.

All co-products-treated specimens also expanded with increased cycles, and some of them shrunk after peak expansion due to loss of mass. BCP A-treated specimens also showed a volume increase, but they exhibited less expansion than pure soil. The highest-volume expansion of BCP A-treated specimens, about 20%, occurred in Soil 2 with one-day curing. For all types of soils, BCP A-treated specimens with seven-day curing exhibited less than 10% volume expansion, much better than specimens with one-day curing. BCP B-treated specimens had the highest volume expansion, greater than 30%, among all treatment group combinations. The volume expansion of the BCP B-treatment is related to its high plasticity (PI). During the same cycles, one-day cured specimens treated with BCP B had 5% or more expansion than seven-day cured specimens treated with the same additive. The value of average volume expansion for BCP C-treated specimens was between the values for BCP A-treatment and BCP B-treatment. Differences were insignificant between one-day curing and seven-day curing in volume expansion of BCP C-treated specimens.

The cement-treated specimens showed the best stability with respect to volume control during freeze-thaw cycles. Only slight increases in volume by cement-treated specimens were observed as the number of cycles increased, indicating that an increase in both cement content and curing period could benefit specimen volume stability during freeze-thaw cycles.

94

To summarize freeze-thaw testing, pure soil was very weak and could be greatly damaged by freeze-thaw cycles. The addition of BCPs produced good results in resisting damage such as mass loss and volume expansion from freeze-thaw cycles. Specimens with 12% of BCP A had similar values of mass loss and higher volume expansion compared to specimens with 3% of cement. Among the co-products, BCP B-treatment for soil presented the best capability for reducing mass loss and was similar in that regard to the 6% cement-treatment. However, its significant volume expansion could be a concern. The performance of BCP C-treatment for Soil 2 was also similar to that of BCP B-treatment. In this test, co-products showed little performance improvement over that of the 12% cement, but they were better than the 3% cement. The co-products tested are promising additives for improving durability under freeze-thaw conditions, and each type has specific advantages.

Results of Lignosulfonate-Treated Specimens

Eight freeze-thaw cycles were performed in the freeze-thaw durability tests for lignosulfonate-treated Soil 3 and Soil 4. 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 shredded from the specimens. It can be observed from Figure 80a, the lignosulfonate affected Soil 3's susceptibility to freeze-thaw damage more significantly than that of Soil 4 since the lignosulfonate-treated Soil 3 specimen began to increase in volume after two cycles of repeated freezing and thawing.

(a)

95

(b)
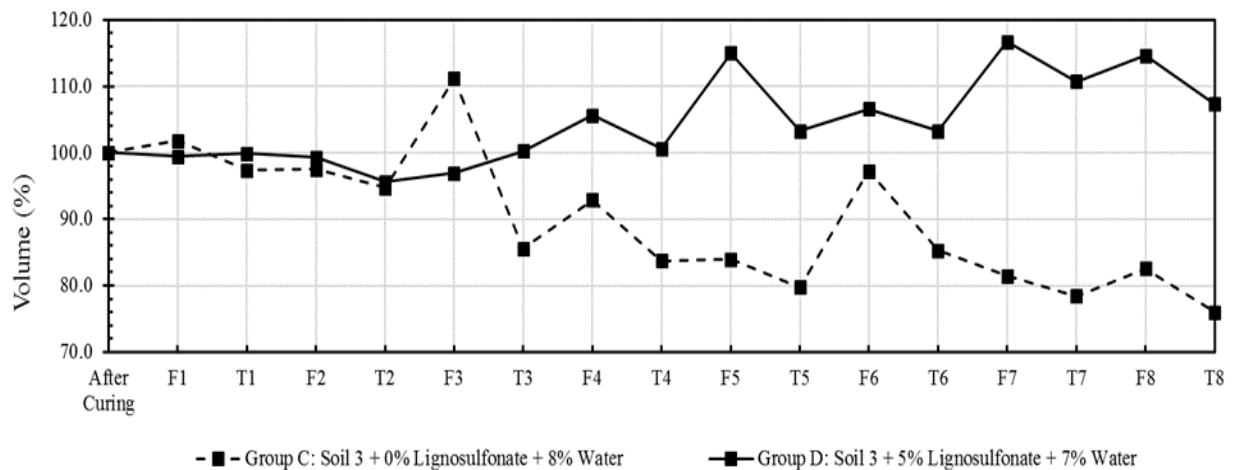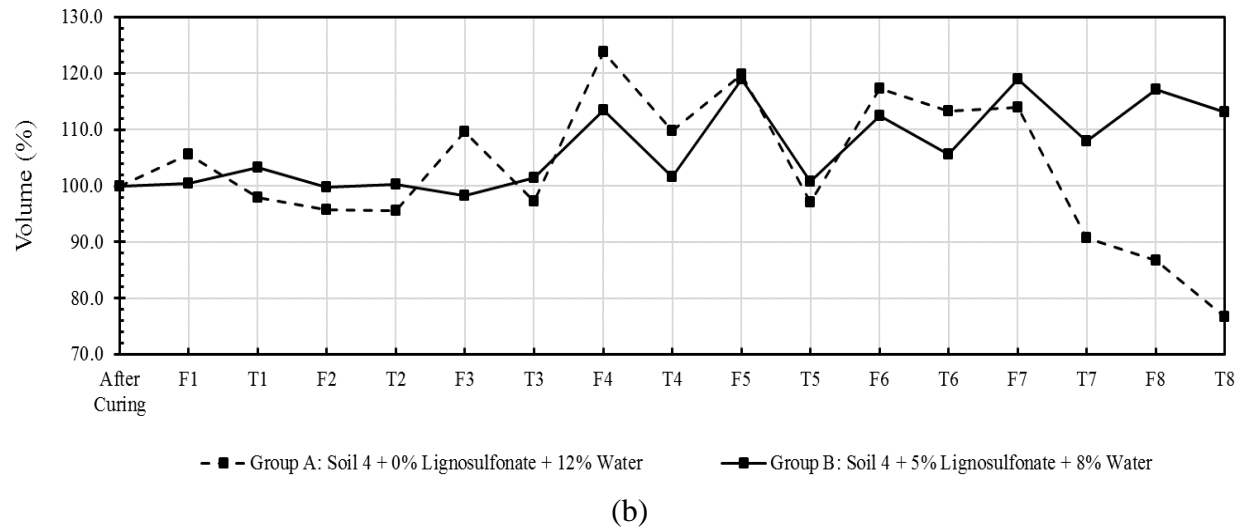
Figure 80. Volume change (a) Soil 3 and (b) Soil 4 in freeze-thaw test

For Soil 4, the lignosulfonate began to show a positive impact on the performance related to freeze-thaw resistance after six cycles of repeated freezing and thawing. From Figure 81, it is more obvious that Soil 3's susceptibility to repeated freeze-thaw cycles was improved more by lignosulfonate than that of Soil 4.

(a)
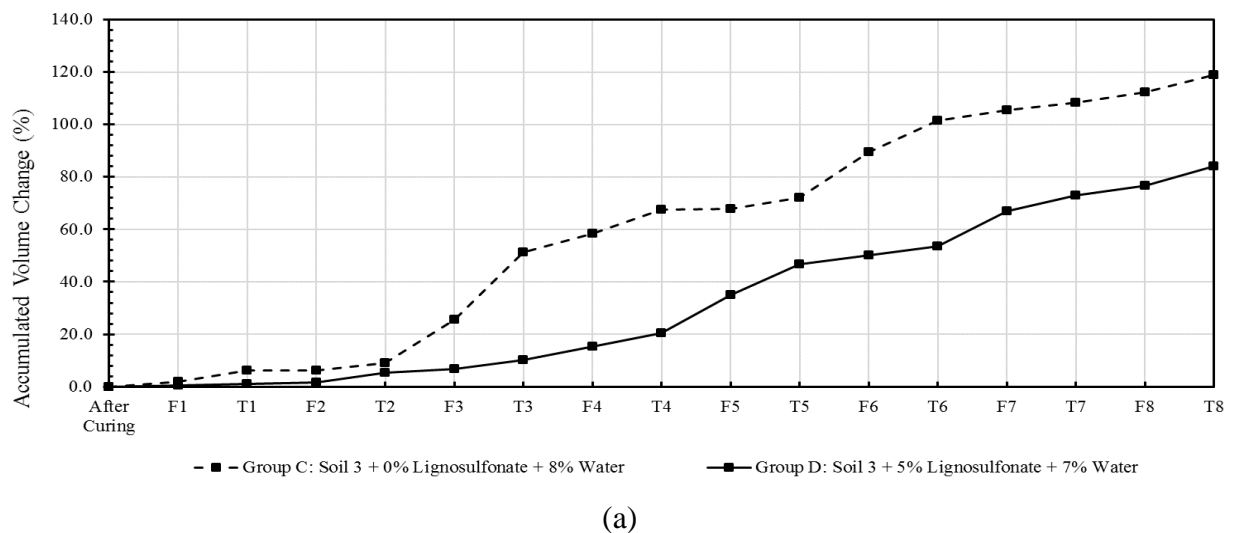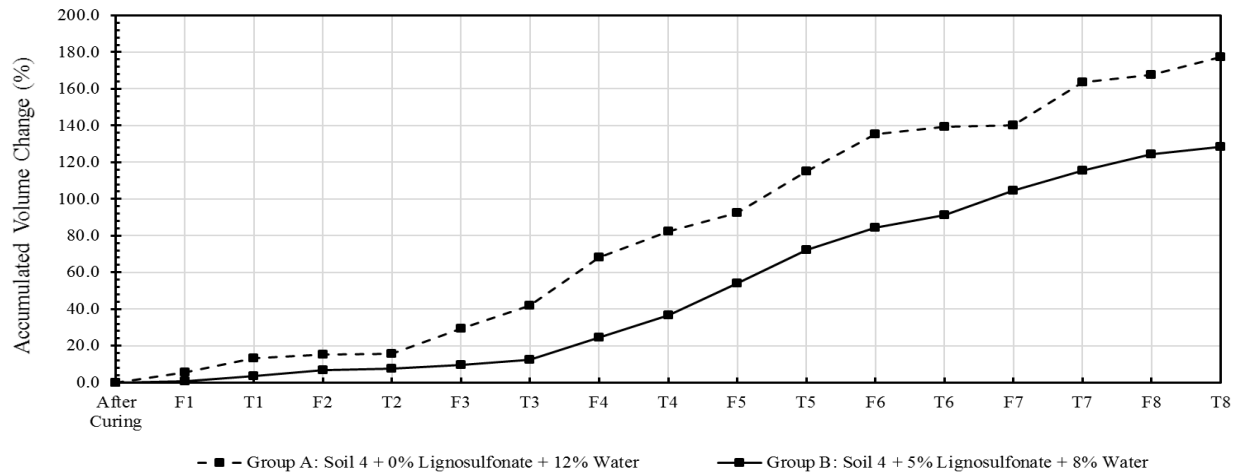
(b)

Figure 81. Accumulated volume change (a) Soil 3 and (b) Soil 4 in freeze-thaw test

Similarly, eight wet-dry cycles were performed to test wet-dry durability (Figure 82 and Figure 83).
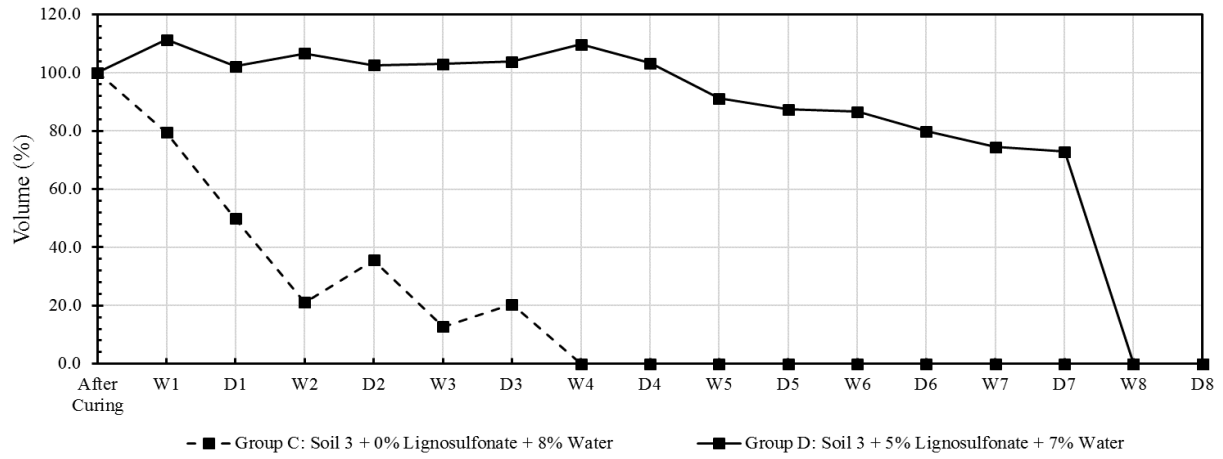
(a)
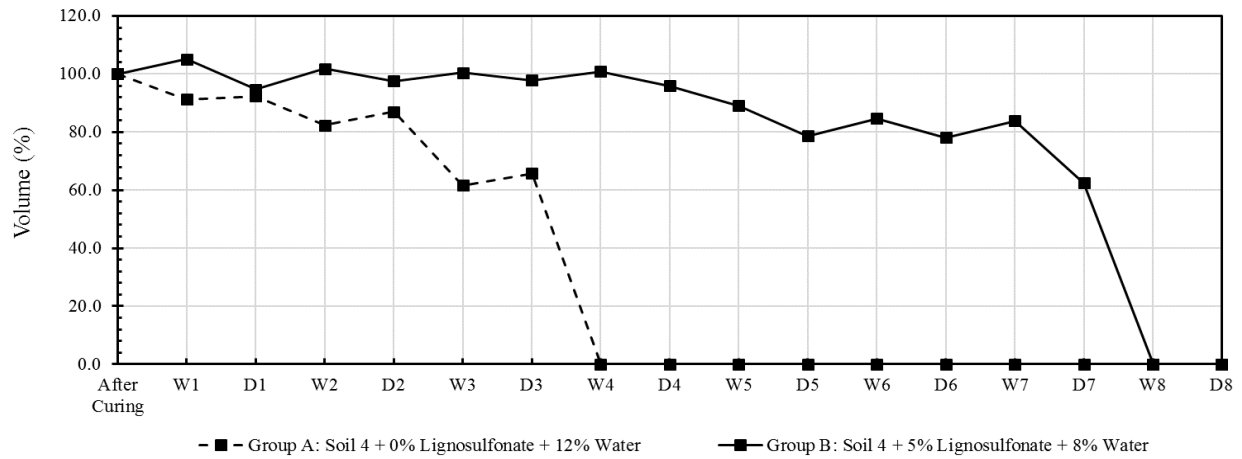
(b)

Figure 82. Volume change of (a) Soil 3 and (b) Soil 4 in wet-dry test
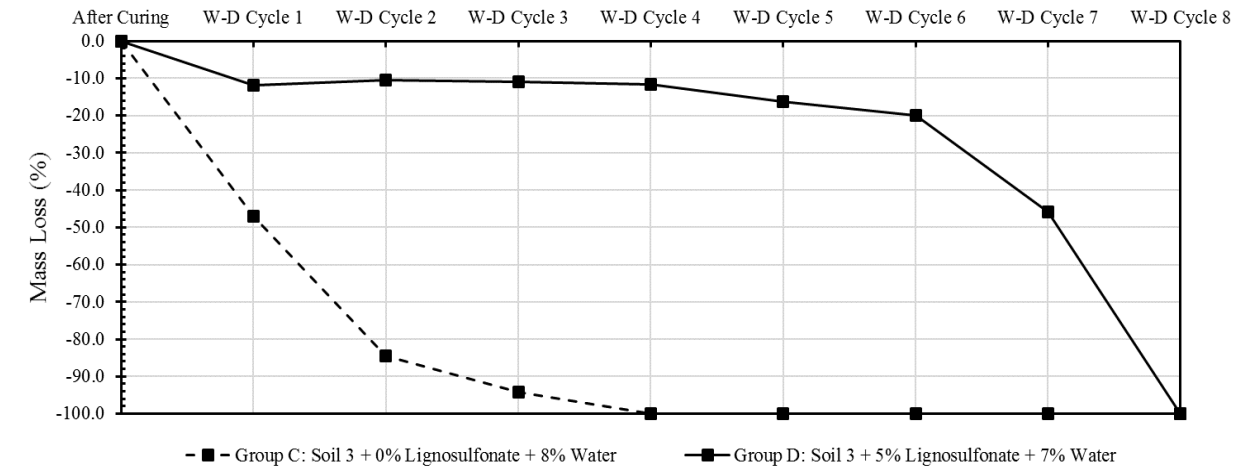
(a)
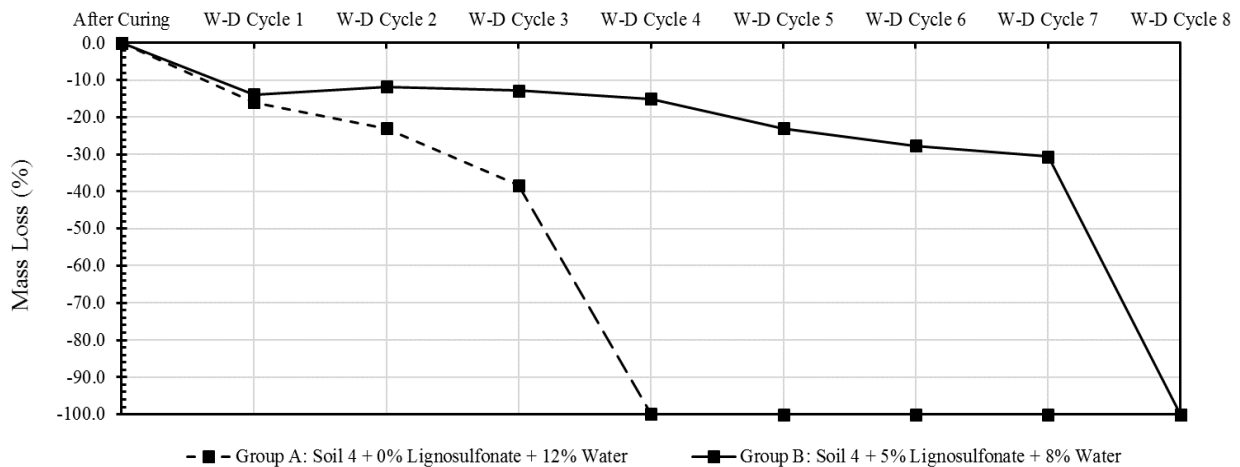
(b)

Figure 83. Mass loss of (a) Soil 3 and (b) Soil 4 in wet-dry test

While both Group A and Group C specimens (i.e., pure soil specimens without any treatment) collapsed after four 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 (i.e., lignosulfonate-treated specimens) deformed similarly and completely collapsed after seven 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 (Appendix E).

Set Time Test

As shown in Figure 84, the concentrated lignosulfonate contained approximately 50% evaporative component.
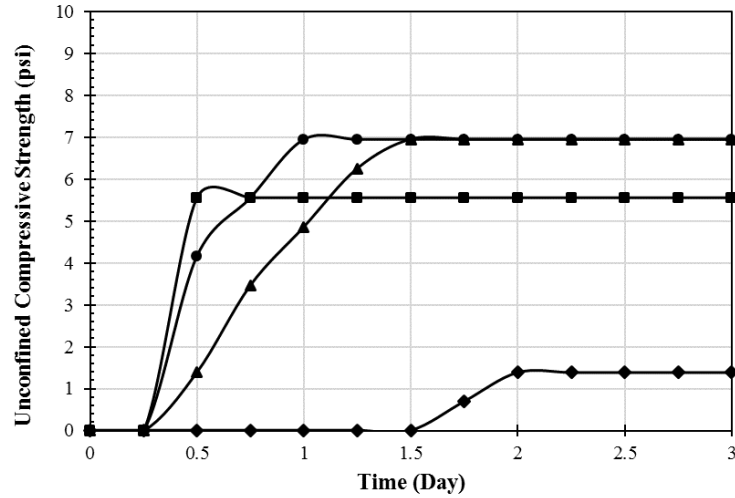
(a)
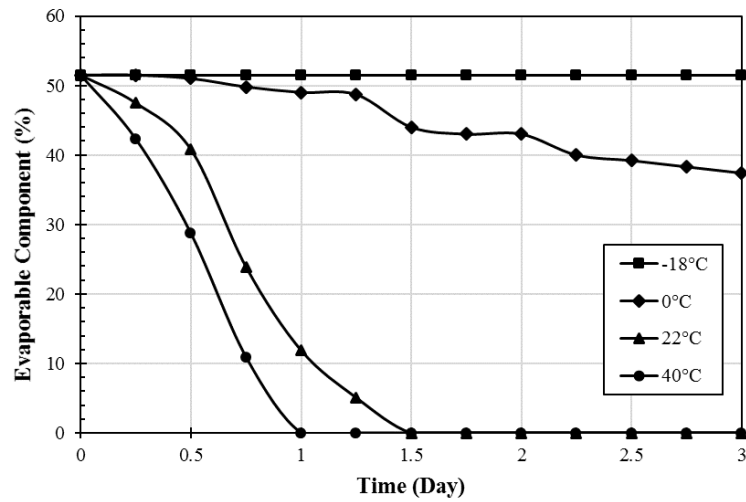
(b)

Figure 84. Set time test results

When the temperature was above 32°F, the lignosulfonate became hard as evaporation occurred, and therefore, it took less time to gain strength at the higher temperature. When the temperature was 32°F, evaporation gradually occurred and the lignosulfonate achieved a low strength. On the other hand, the lignosulfonate gained strength by freezing when the temperature was below 32°F. The recorded field temperature at which the one-week-after-construction test was performed was around 23°F; 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.

Moisture Susceptibility Test

The untreated, BCP A-treated, and BCP B-treated soil specimens with seven-day curing under OMC were soaked in water for seven days. The recorded images shown in Figure 85 through Figure 88 present visual evidence for evaluating the effects of BCPs on moisture susceptibility of soil.

(a)

(b)

(c)

(d)
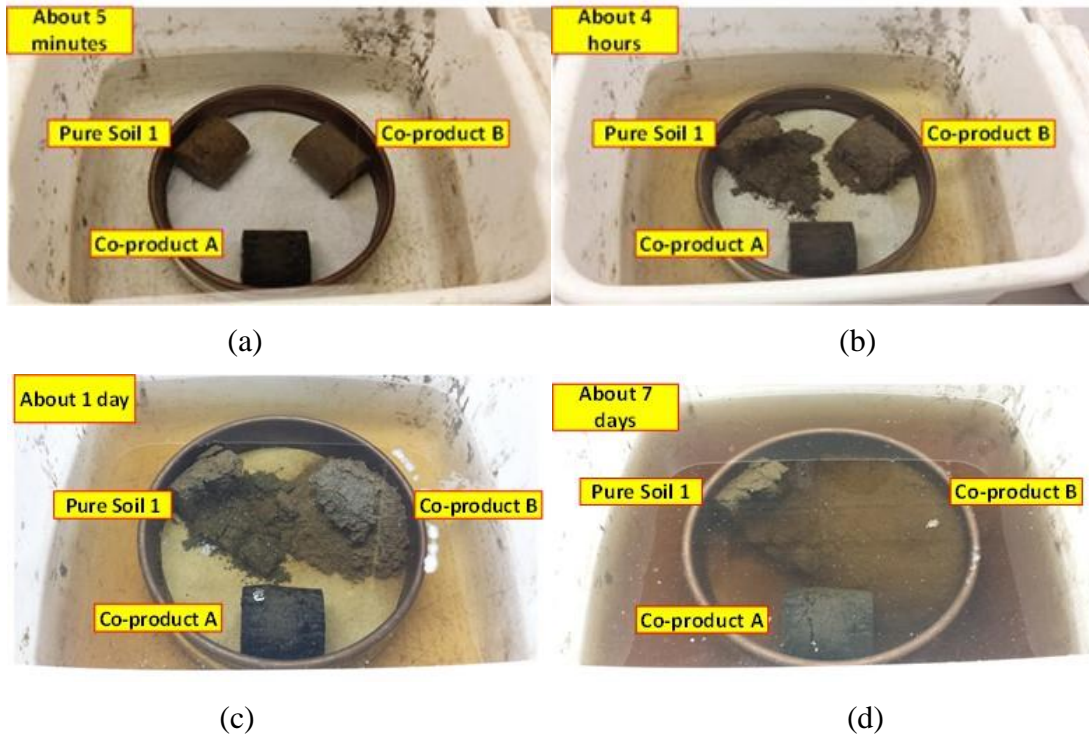
Figure 85. Soaking test results for specimens: (a) five minutes for Soil 1 set, (b) four hours for Soil 1 set (c) one day for Soil 1 set, and (d) seven days for Soil 1 set
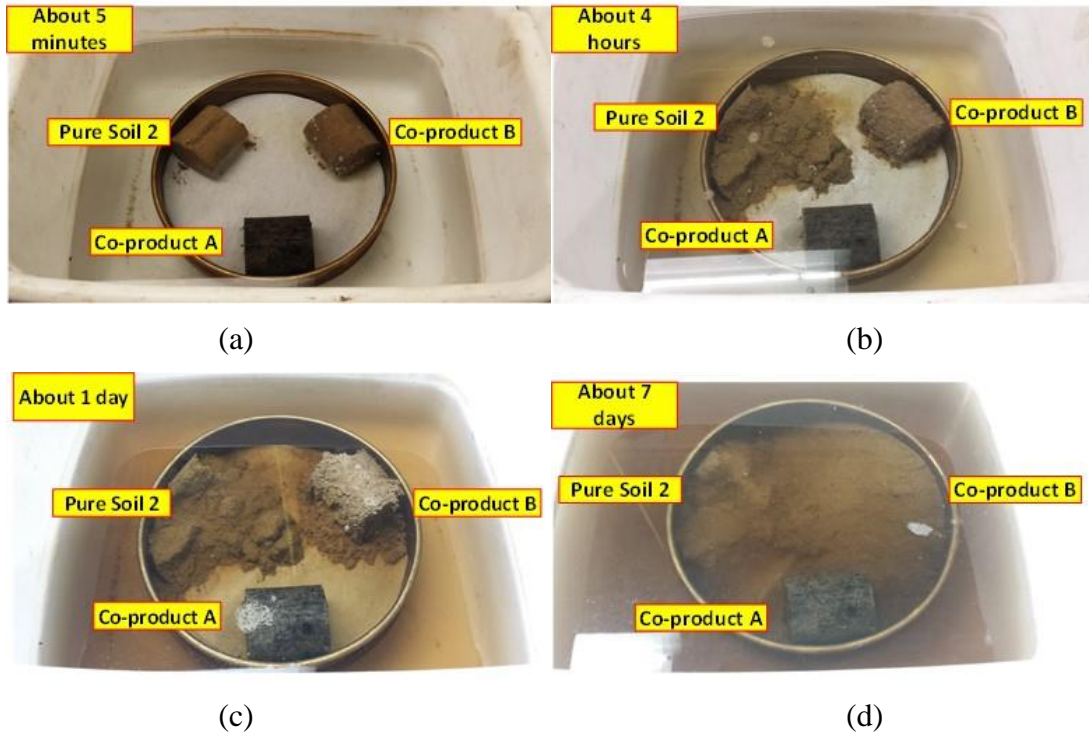
Figure 86. Soaking test results for specimens: (a) five minutes for Soil 2 set, (b) four hours for Soil 2 set. (c) one day for Soil 2 set, and (d) seven days for Soil 2 set
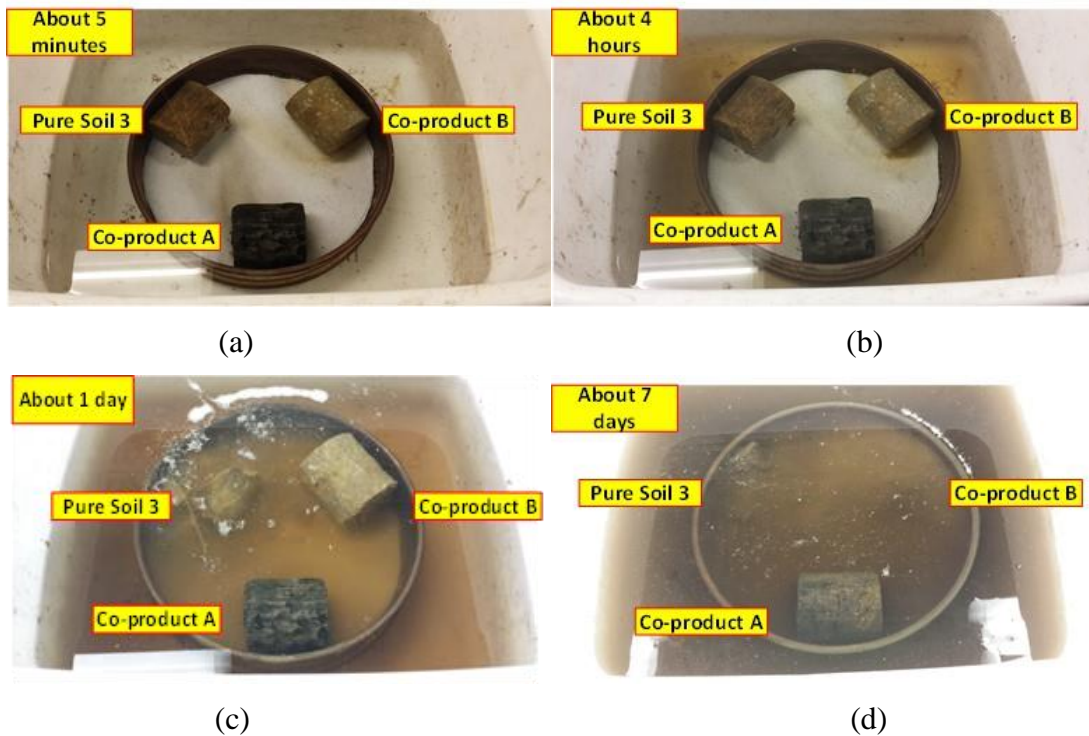
Figure 87. Soaking test results for specimens: (a) five minutes for Soil 3 set, (b) four hours for Soil 3 set, (c) one day for Soil 3 set, and (d) seven days for Soil 3 set
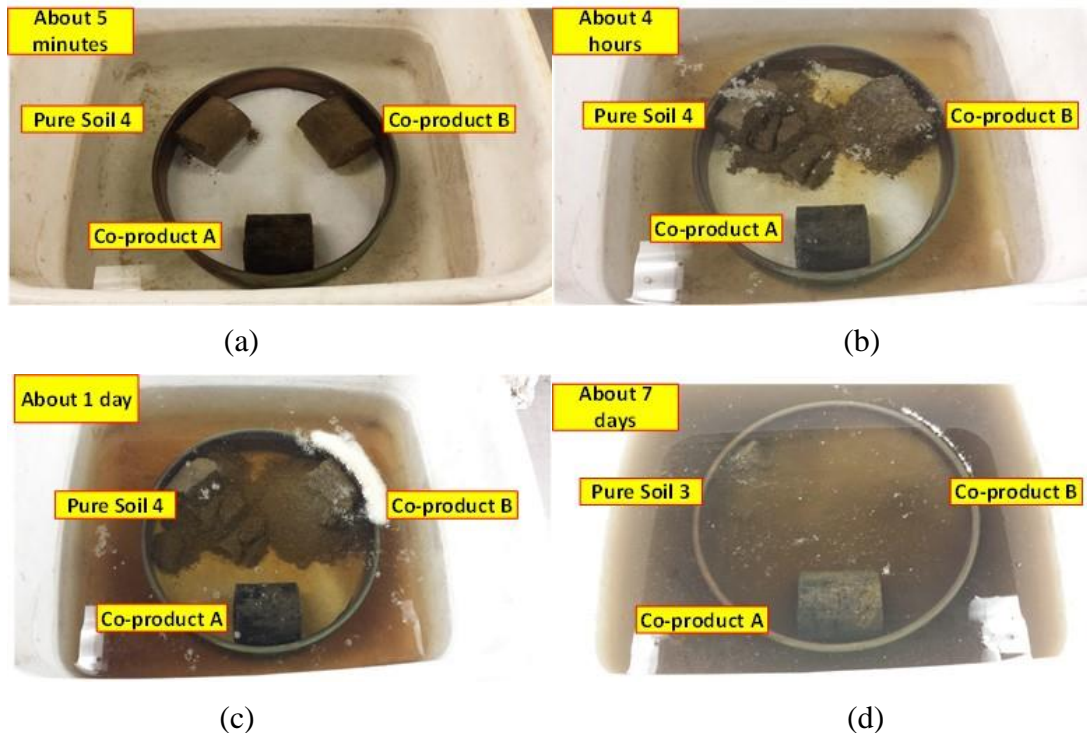
Figure 88. Soaking test results for specimens: (a) five minutes for Soil 4 set, (b) four hours for Soil 4 set, (c) one day for Soil 4 set, and (d) seven days for Soil 4 set

Figure 85 shows that the untreated and BCP B-treated specimens in Soil 1 set had disintegrated after one day of soaking. The untreated specimen had disintegrated about 50% after four hours of soaking, but the BCP B-treated specimen only showed slight disintegration after that same soaking time. For Soil 2 set, Figure 86 shows that the untreated Soil 2 specimen was fully disintegrated only after four hours of soaking and the Soil 2 BCP B-treated specimen became partially disintegrated after one day of soaking and fully disintegrated before seven days of soaking. Figure 87 shows the soaking performance of the Soil 3 set. The untreated Soil 3 specimen remained intact in the water bath until it had been soaked for about one day. The BCP B-treated specimen didn't show any disintegration after one day soaking, but it was fully disintegrated when the soaking time was increased to seven days. In Figure 88, although both untreated Soil 4 specimen and BCP B-treated Soil 4 specimen were disintegrated after soaking about one day, the BCP-treated specimen showed a lesser degree of disintegration than the untreated one after soaking for about four hours. The BCP A-treated specimens for all four types of soil exhibited the best improvement with respect to moisture susceptibility when compared to untreated soil specimens. Figure 85 through Figure 88 show that all BCP A-treated specimens remained intact after soaking for about seven days. This indicates that BCP A provides good waterproofing.

The performance of cement-treated samples in soaking tests can be predicted because their properties have been investigated over several decades. They are not damaged by a soaking bath because of cement hydration, as discussed in the literature review. BCP C was not subjected to soaking tests, but its physical properties and chemical composition are similar to BCP A, which would strongly suggest good waterproofing capability.

The soaking-test results demonstrated the benefits of using co-products to reduce moisture susceptibility of natural soil. Untreated soil specimens soaked in a water bath exhibited rapid disintegration and had completely failed after only one day of soaking. BCP A-treated specimens in this test performed much better with respect to waterproofing than others that generally had disintegrated after seven days of soaking. The BCP B-treated specimens showed limited improvement in moisture susceptibility of soil compared to that of untreated soil, so BCP A is a more promising additive than BCP B for improvement in soil moisture susceptibility.

Micro-Structural Characterization Results and Discussion

Scanning Electron Microscope (SEM)

An SEM can capture a large number of digital images for analyzing the mechanism of BCP stabilization at the particle level. Figure 89 through Figure 92 show the morphologies of the four types of soil sets, with each set containing untreated soil, 12% of BCP A-treated soil, and 12% of BCP B-treated soil specimens, all with seven-day curing under OMC.

(a)

BCP A-coated grains

(b)

BCP B-coated grains

(c)
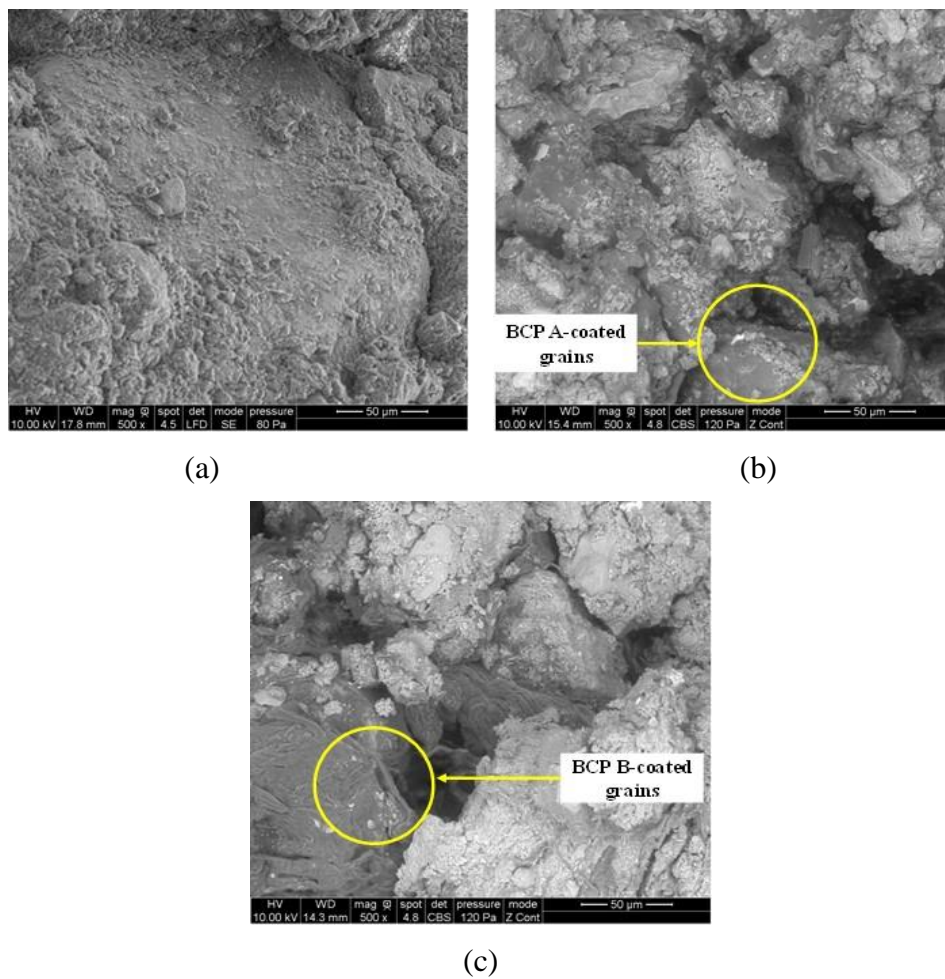
Figure 89. SEM images for Soil 1 set with 500x magnification: (a) untreated, (b) 12% of BCP A-treated, and (c) 12% of BCP B-treated
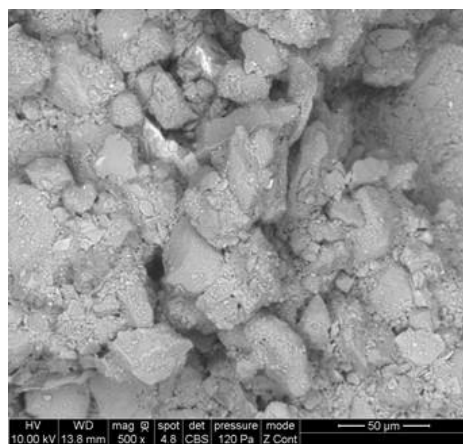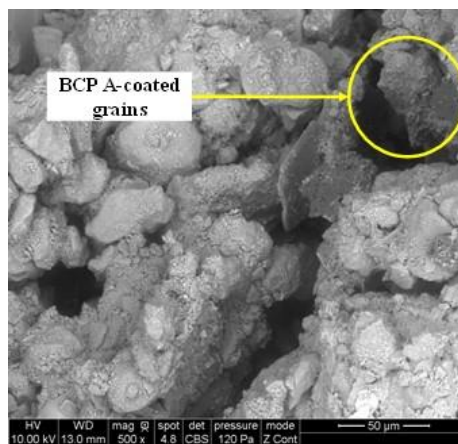
(a)   (b)
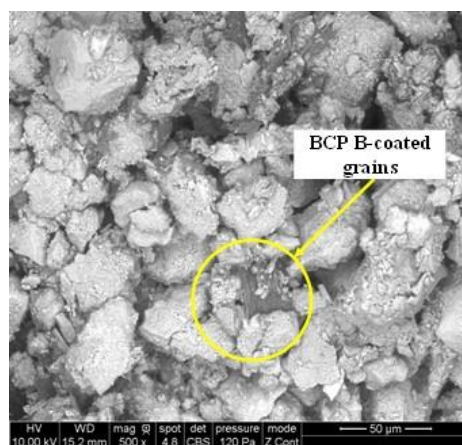
(c)

Figure 90. SEM images for Soil 2 set with 500x magnification: (a) untreated, (b) 12% of BCP A-treated, and (c) 12% of BCP B-treated

(a)

BCP A-coated grains

(b)

BCP B-coated grains
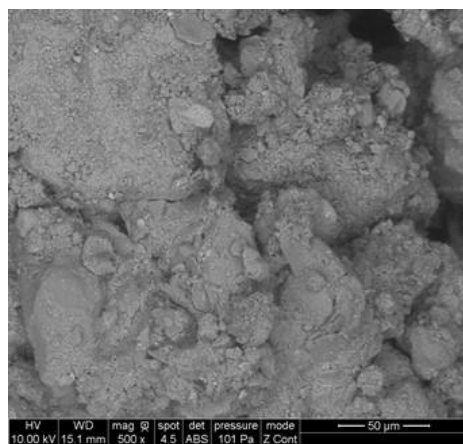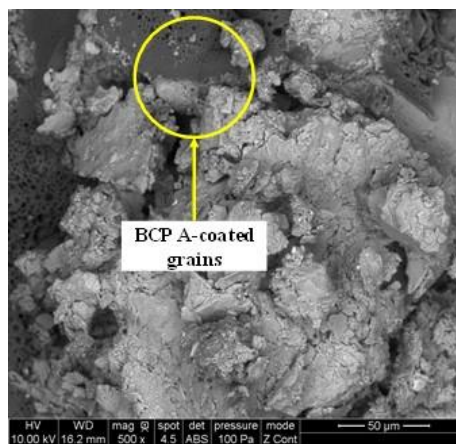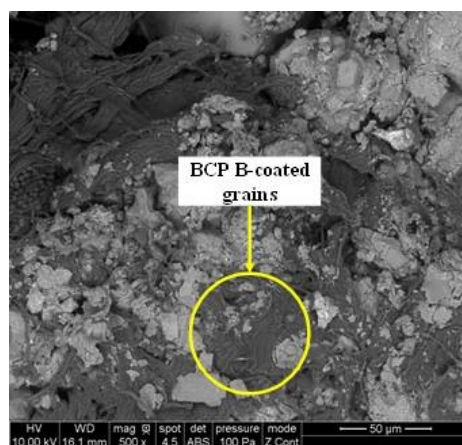
(c)

Figure 91. SEM images for Soil 3 set with 500x magnification: (a) untreated, (b) 12% of BCP A-treated, and (c) 12% of BCP B-treated

(a)

(b)

(c)
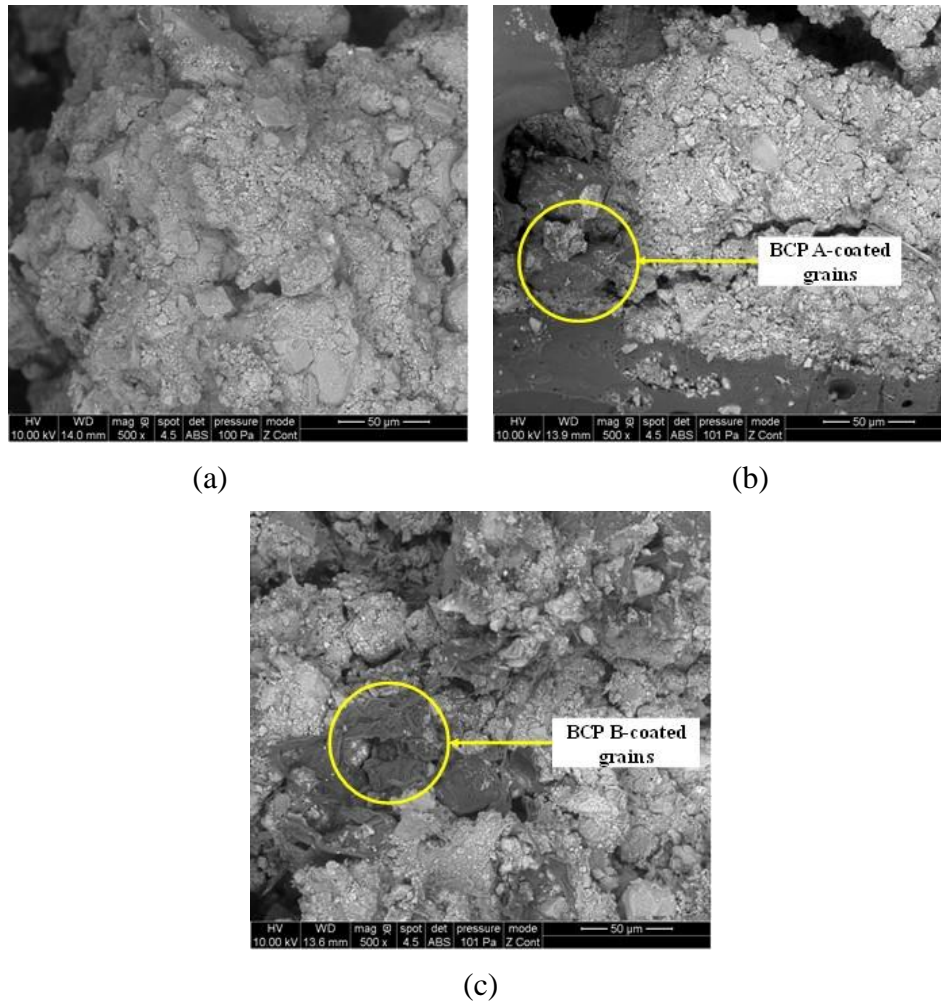
Figure 92. SEM images for Soil 4 set with 500x magnification: (a) untreated, (b) 12% of BCP A-treated, and (c) 12% of BCP B-treated

The untreated soil images show clear particle surfaces and boundaries and porous structures under 500x magnification. As seen in the images of the co-products-treated soil, the grains were coated by dark-colored materials, and these coated grains were bonded closely together with fewer pores to produce a stronger soil-additive structure. These images provide visual evidence that co-products performed the function of cementing bonded soil grains together. Use of an SEM on cement-treated samples has previously been extensively investigated (Nontananandh et al. 2005b), and CSH gel and other hydrated products were identified in cement-treated soils several years ago. To identify the interactions between soil grains and BCPs, XRD technology was used in this study.

The micrographs were taken at the 5,000x magnification level, from which the lignosulfonate treatment in Soil 4 can be recognized morphologically (Figure 93).

<div align="center">(a)   (b)</div>
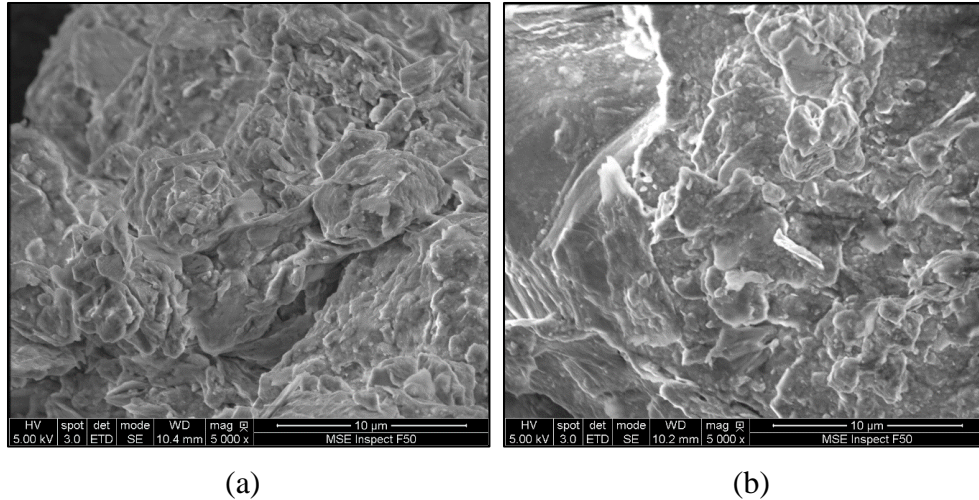
Figure 93. SEM images of (a) untreated Soil 4 and (b) lignosulfonate-treated Soil 4

The silt particles had sharper edges, and their structure contained a good amount of small voids. With the treatment, some of the silt particles were coated with lignosulfonate (lighter part in Figure 93b), and larger but fewer voids were observed. Compared to Soil 4's "loose" microstructure, the lignosulfonate-Soil 4'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. (2018) 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. 2018), which accounts for the improvement of strength in Soil 4.

X-Ray Diffraction (XRD)

XRD patterns for untreated, BCP A-treated, and BCP B-treated soils are shown in Figure 94 through Figure 97 and Appendix G.
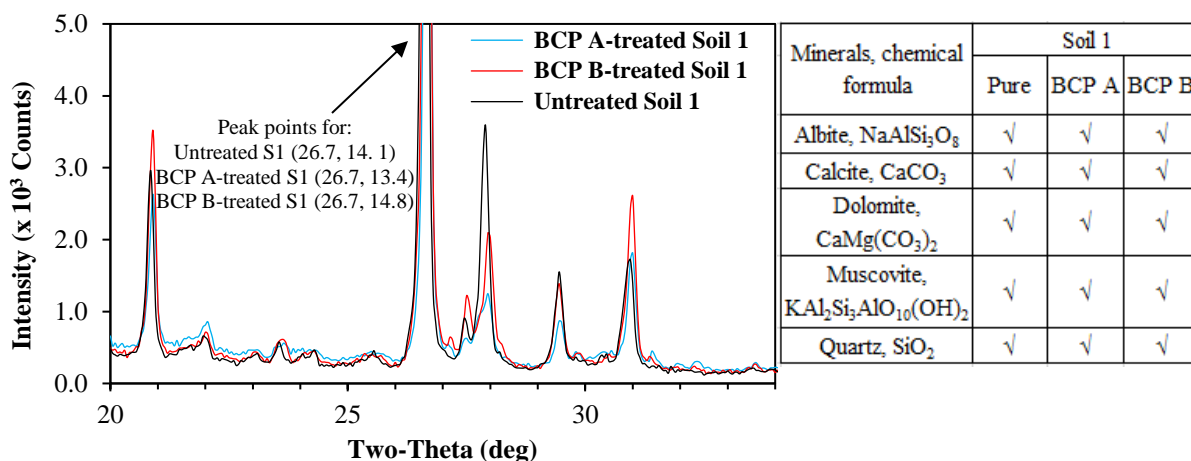
Figure 94. X-ray patterns for untreated, BCP A-treated, and BCP B-treated Soil 1

Peak points for:
Untreated S1 (26.7, 14. 1)
BCP A-treated S1 (26.7, 13.4)
BCP B-treated S1 (26.7, 14.8)

Minerals, chemical formula	Soil 1		
	Pure	BCP A	BCP B
Albite, NaAlSi$_3$O$_8$	√	√	√
Calcite, CaCO$_3$	√	√	√
Dolomite, CaMg(CO$_3$)$_2$	√	√	√
Muscovite, KAl$_2$Si$_3$AlO$_{10}$(OH)$_2$	√	√	√
Quartz, SiO$_2$	√	√	√
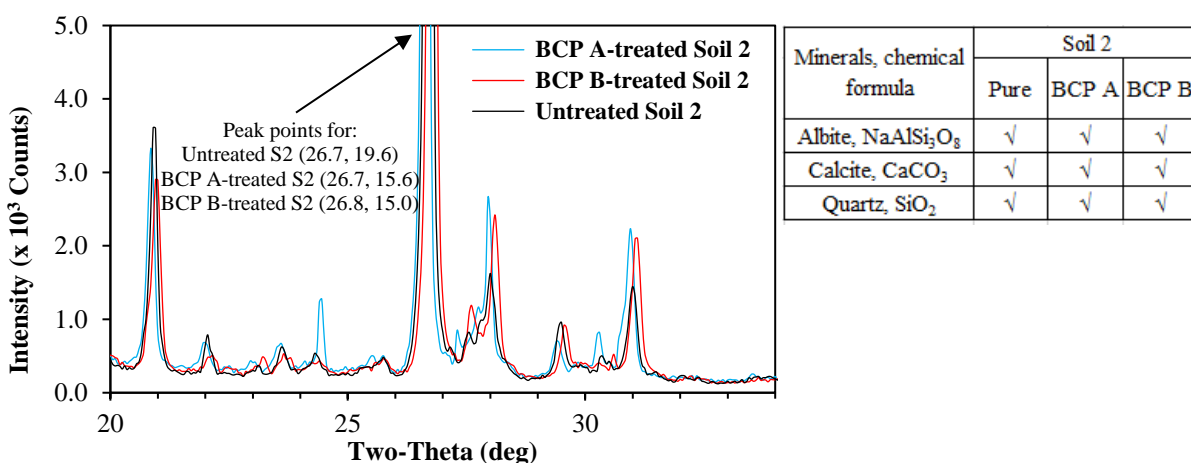
Figure 95. X-ray patterns for untreated, BCP A-treated, and BCP B-treated Soil 2

Peak points for:
Untreated S2 (26.7, 19.6)
BCP A-treated S2 (26.7, 15.6)
BCP B-treated S2 (26.8, 15.0)

Minerals, chemical formula	Soil 2		
	Pure	BCP A	BCP B
Albite, NaAlSi$_3$O$_8$	√	√	√
Calcite, CaCO$_3$	√	√	√
Quartz, SiO$_2$	√	√	√
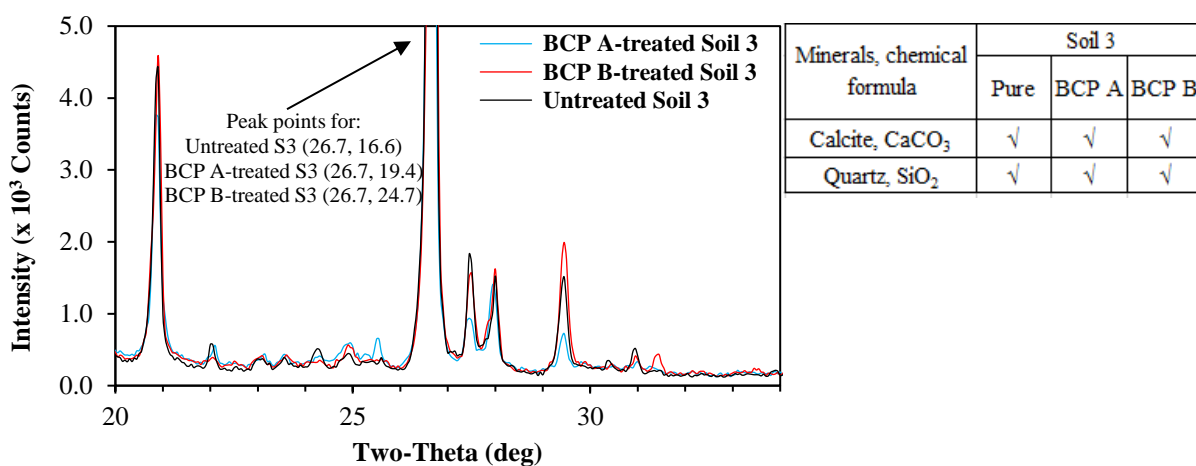
Figure 96. X-ray patterns for untreated, BCP A-treated, and BCP B-treated Soil 3

Peak points for:
Untreated S3 (26.7, 16.6)
BCP A-treated S3 (26.7, 19.4)
BCP B-treated S3 (26.7, 24.7)

Minerals, chemical formula	Soil 3		
	Pure	BCP A	BCP B
Calcite, CaCO$_3$	√	√	√
Quartz, SiO$_2$	√	√	√
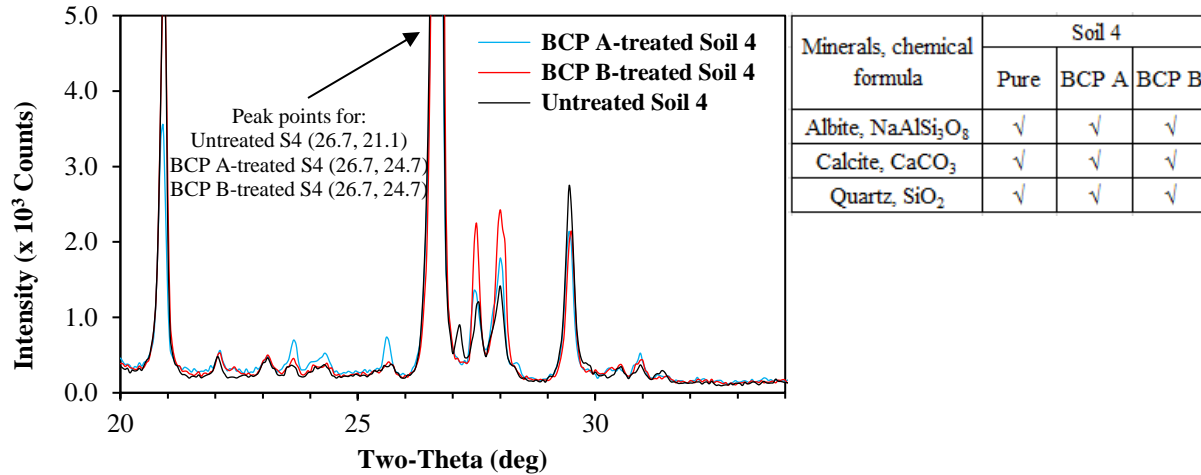
Figure 97. X-ray patterns for untreated, BCP A-treated, and BCP B-treated Soil 4

The inorganic materials identified in samples are listed in Appendix G as well. The untreated, BCP A-treated, and BCP B-treated soils showed similar patterns, and the same crystalline materials such as quartz and albite were identified. These XRD patterns indicated that there was no clear chemical reaction identified and no new compound produced during BCP soil stabilization. Therefore, BCP A and BCP B don't impact soil mineralogy, and they rely on physical bonds more than chemical reaction to improve soil properties. In addition, fewer chemical reactions in soil treatment generally indicated fewer environmental issues. XRD of cement-treated soil has already been described by extensive literature studies; new crystalline structures are produced during hydration of cement (Nontananandh et al. 2005a). It can be concluded that the underlying mechanism of cement is hydration reaction.

The combined SEM and XRD analyses can identify mechanisms of stabilization. In this test, the results of microstructural analysis indicated that the primary mechanisms of BCP A and BCP B for soil stabilization are coating and binding soil particles with adhesive film to form strong soil structures. Zhang et al. (2014) and Zhang et al. (2015) indicated that the underlying mechanism of BCPs was to bind soil grains together when they used other BCPs to stabilize silt. They reported that not only the BCPs-coated soil grains and filled-void space in SEM images but also no significant XRD pattern differences between untreated silt and BCPs-treated silt were observed. Co-products are similar to cementing materials, and the underlying mechanism of BCP C should be identifiable if it is available in sufficient quantity. The potential mechanisms may be similar to that of BCP A if their similar physical properties and chemical composition are considered.

111

6. IN SITU TEST RESULTS AND DISCUSSION

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 98).

(a)   (b)

Figure 98. Resurfaced gravel road surface

From the research team'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, the subgrade stabilization was conducted on a destroyed gravel road surface. As shown in Figure 98, 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 a reclaimer was used for each section, yet it was only used in three out of five sections. No other equipment can blend soils and stabilizers as thoroughly as a reclaimer does.

Cement Stabilization

A total of 27.6 tons of cement was applied, so the actual cement dosage rate was 7.2%. Figure 99 shows the cement section one week and one year after construction.

<center>(a)   (b)</center>

<center>**Figure 99. Cement section (a) one week after construction and (b) one year after construction**</center>

The county engineer chose the first section for cement stabilization because Bowers Best Discount Store is located at the intersection between Old IA 150 and 240th Street, a crossing where semi-trucks are engaged in frequent loading and unloading activities. Considering cement is one of the most promising and investigated stabilization products, it was selected to stabilize the first section so that Bowers Best Discount Store would have a more stable roadway directly 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.

Lignosulfonate Stabilization

Figure 100a shows the spraying nozzles and process, and Figure 100b illustrates the subgrade condition soon after the diluted lignosulfonate solution was sprayed.

<center>(a)   (b)</center>

(c)

(d)

(e)

(f)

(g)

(h)

Figure 100. 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) condition of road one week after construction, (g) condition of road one month after construction (areas with excess moisture are visible in dark color), and (h) condition of road one year after construction

Figure 100c shows the motor grader was blending wet soil with dry soil, and Figure 100d shows the over-wet condition of the subgrade after the soil blending. Figure 100e shows the compaction with pneumatic rollers. Figure 100f and Figure 100h show the subgrade conditions one week and one year after construction, respectively.

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 32°F. 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 solution was planned to be diluted with water based on a 1:1 ratio concentration. The diluted lignosulfonate solution spray rate was calculated as 0.26 gal/ft^2 based on the stabilized depth (6 in.), the soil dry unit weight (111.8 pcf), 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 also was used in the field application 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 extra water was added in the lignosulfonate solution, and therefore, the actual dosage of lignosulfonate solution was diluted to 2.5%.

Project budget and safety were two extremely important considerations in the field construction. A common method to solve the over-wet situation was to use the rear rippers to dig several more centimeters in the subgrade layer so that more soil could 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 an increase in project budget due to the overtime work shift.

Pneumatic rollers, which refer to small-sized rubber-tired rollers, were used for the compaction. Pneumatic rollers are often used for the final compaction of the upper 6 in. of a subgrade and can obtain a high degree of compaction if the subgrade contains sufficient granular soils (Department of the Army 1997). Pneumatic rollers are also recommended to compact softer materials that may break down or degrade under the pressure of a steel roller (Department of the Army 1997). Therefore, pneumatic rollers were believed to be the optimal choice as the compaction equipment. 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 the project. The observed incidents included the miscommunication of water tank location and the wrong estimate of working hours. All of these uncontrollable activities resulted in changes to the project schedule.

As shown in Figure 100f, some sections contained more diluted lignosulfonate solution, and some sections contained less. This problem could have been avoided if the motor grader blended the diluted lignosulfonate solution and soils in a more thorough manner, or if a reclaimer was used for the blending process.

Over-wetting (Figure 100g) was observed one month after construction. Over-wetting occurred when the lignosulfonate solution was over-diluted due to the addition of excessive water inside; thus, it was estimated that excessive water was sprayed. One solution to the over-wetting problem was to further reduce the dilution rate of lignosulfonate solution; another was to increase the stabilized depth by digging several more centimeters in the subgrade layer with the rear rippers.

Chlorides, Claycrete, and Base One Stabilization

The chlorides section and the Claycrete section were switched due to miscommunication between the county engineer and contractors. All 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 quickly and professionally. As shown in Figure 101, all three sections had a smooth surface one week and one year after construction.

(a)   (b)

(c)   (d)

<div align="center">(e)   (f)</div>

Figure 101. Commercially available stabilizers sections: chlorides (a) one week and (b) one year after construction, Claycrete (c) one week and (d) one year after construction, and Base One (e) one week and (f) one year after construction

Result Discussion

LWD Test

As shown in Figure 102, the subgrade did not have a consistent stiffness before construction.
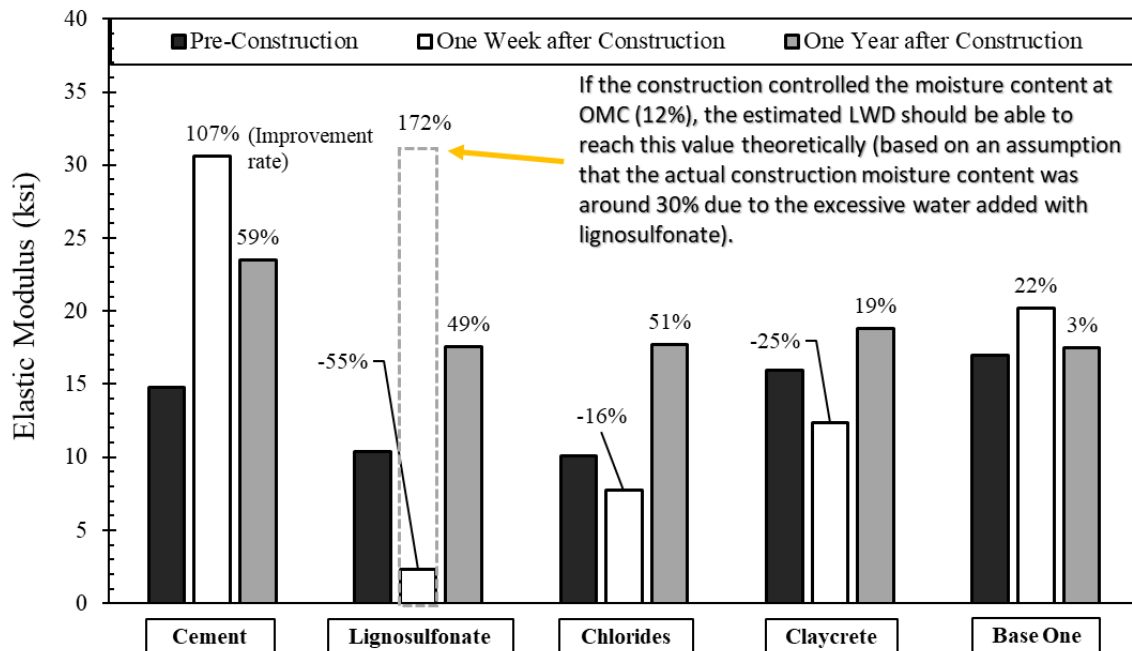
Figure 102. Elastic modulus measured from LWD tests

A week after construction, the cement and Base One sections had larger in situ moduli, which indicated these two sections had higher stiffness. The stiffness of the diluted lignosulfonate-treated 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 the compaction effort, the fully saturated subgrade did not contain enough pores for the moisture to run off, and thus, caused a decrease in stiffness. If the moisture could be controlled at the level of OMC in the field (12%), the theoretical value of elastic modulus would increase to 27.56 ksi based on the UCS test results presented in Figure 103. About one year after the treatment, the stiffness of the diluted lignosulfonate-, Chloride-, and Claycrete-treated sections was improved by 49%, 51%, and 19%, respectively, compared to their untreated stiffness values, indicating these stabilizers are capable of improving the engineering properties of these soils in the long term.

The equation shown on the chart: $y = 0.1615x^{-2.55}$
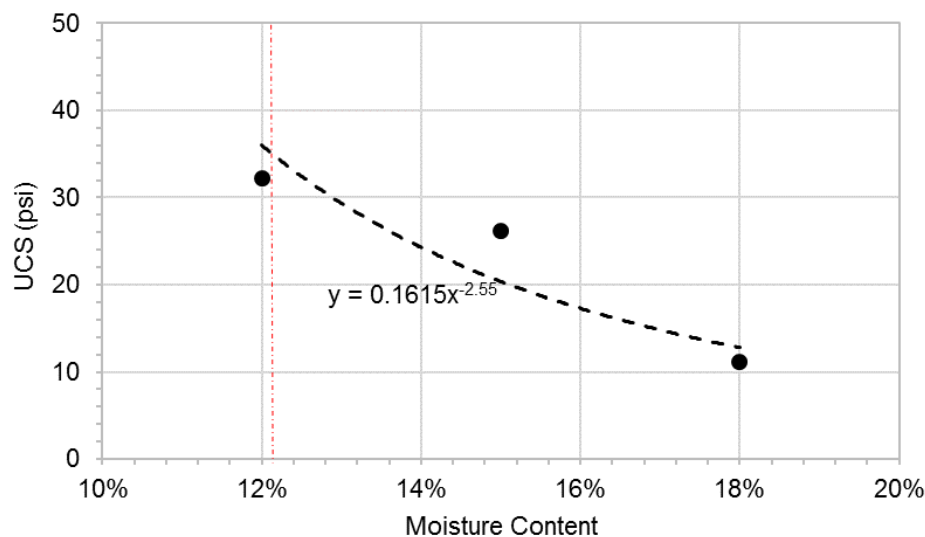
Figure 103. Strength decreases as moisture content increases based on laboratory test results on Soil 4 with 5% lignosulfonate

This decrease of stiffness may potentially lead to an increase in settlement of the base/subgrade layer within a short-term period. The chlorides and Claycrete sections also had a decrease in stiffness one week after construction. Nevertheless, the company/manufacturer representatives of these two products did not reveal any information regarding the liquid stabilizer proportion or compaction requirements. It was hypothesized that the continuous precipitation before the construction caused an excessive amount of water in the subgrade, which decreased the soil stiffness. Another reasonable and scientific hypothesis was the lack of compaction. The improved stiffness in the diluted lignosulfonate-, Chloride-, and Claycrete-treated sections was observed one year after construction, and the excess moisture that was present in the subgrade system during the construction of these tests sections had gradually left the subgrade system over this period.

DCP Test

Figure 104 to Figure 112 demonstrate the DCP index and the DCP – CBR correlation of each section before, one week after, and one year after the construction. Note that, one week after

118

construction, the dynamic cone penetration test hit refusal around 12 in. below the cement-treated surface, and therefore, the corresponding graphs are not shown in this report.
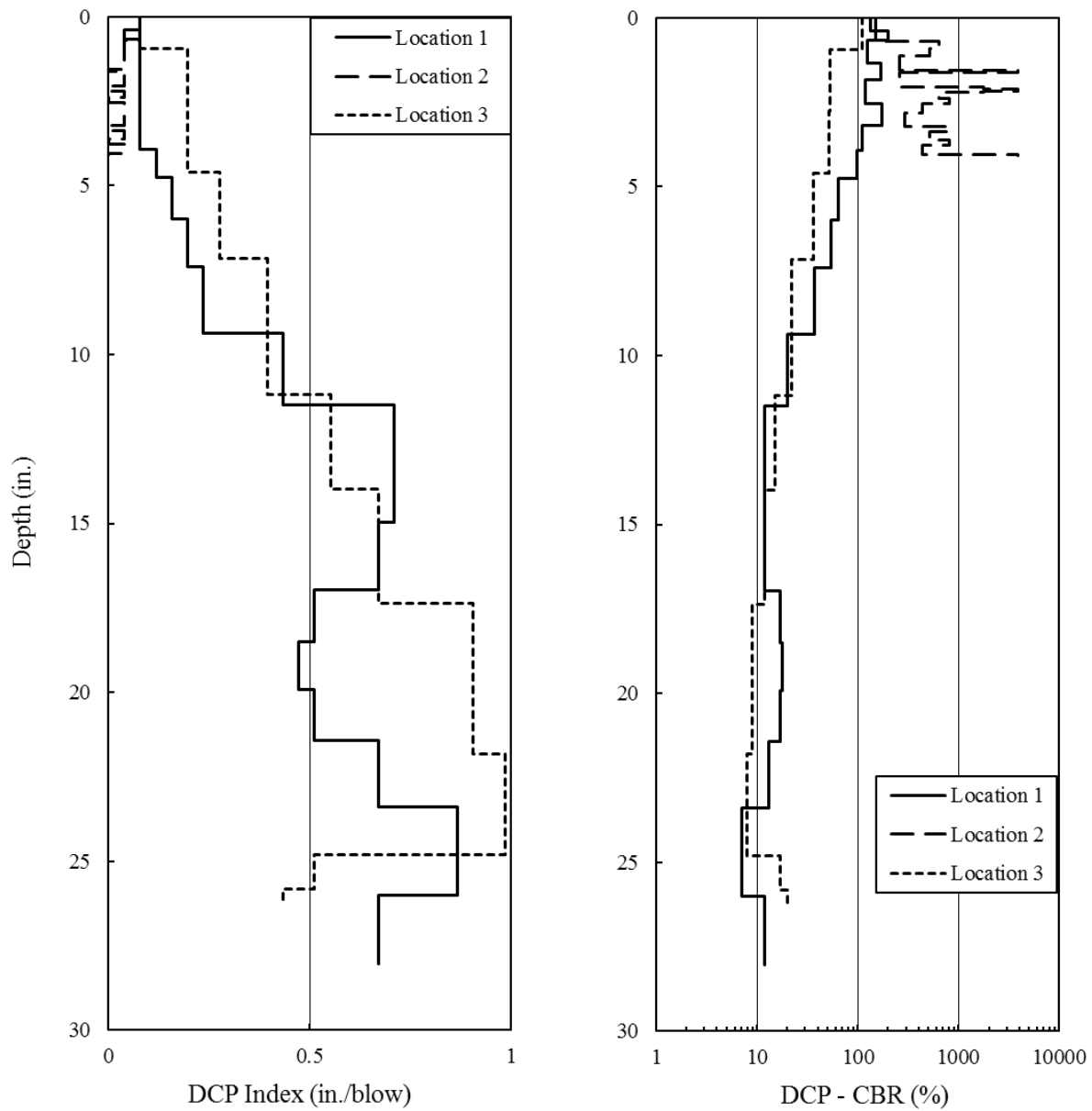
Figure 104. Pre-construction DCP test result (cement)
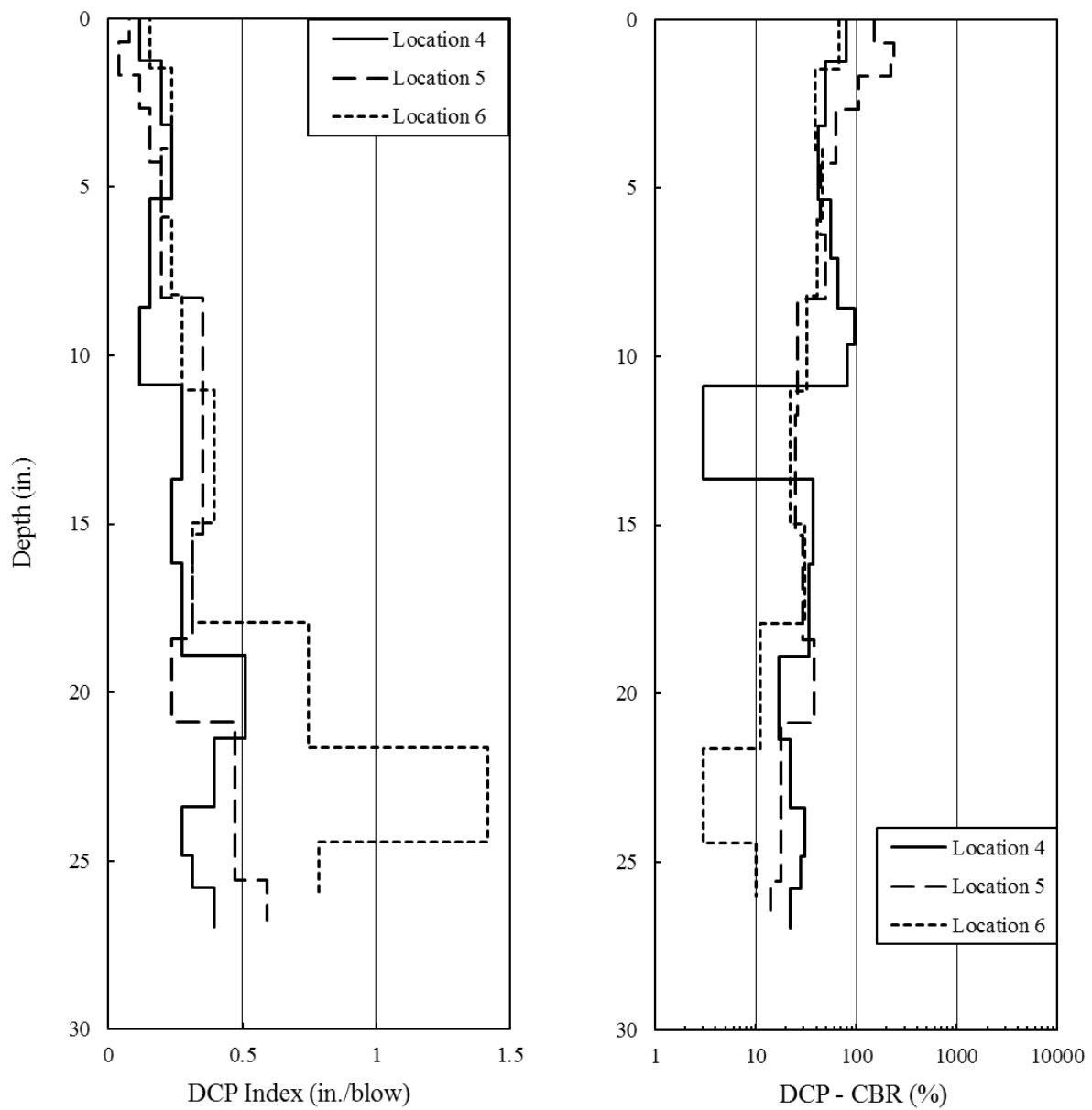
Figure 105. Pre-construction DCP test result (lignosulfonate)

120
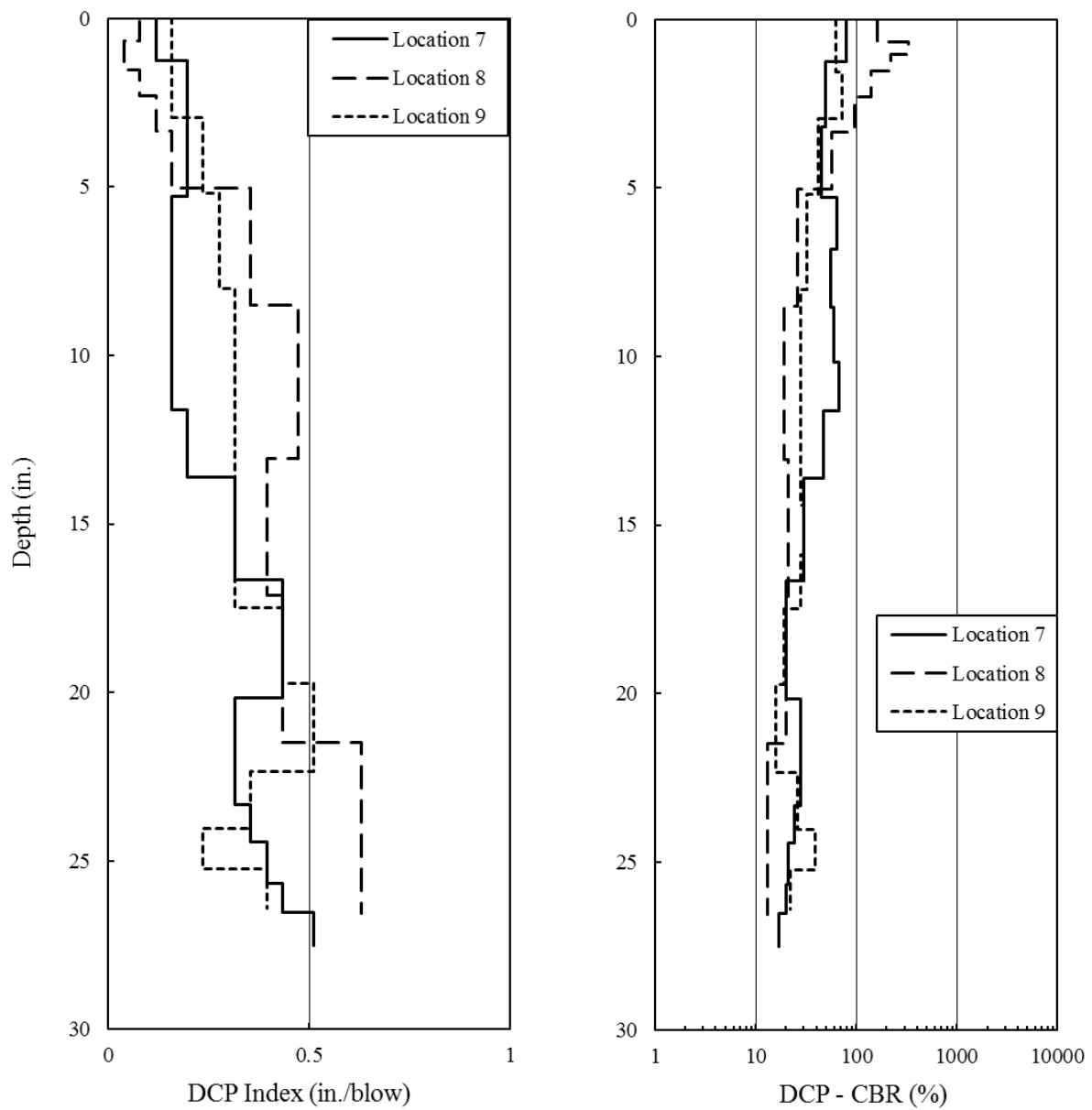
Figure 106. Pre-construction DCP test result (chlorides)
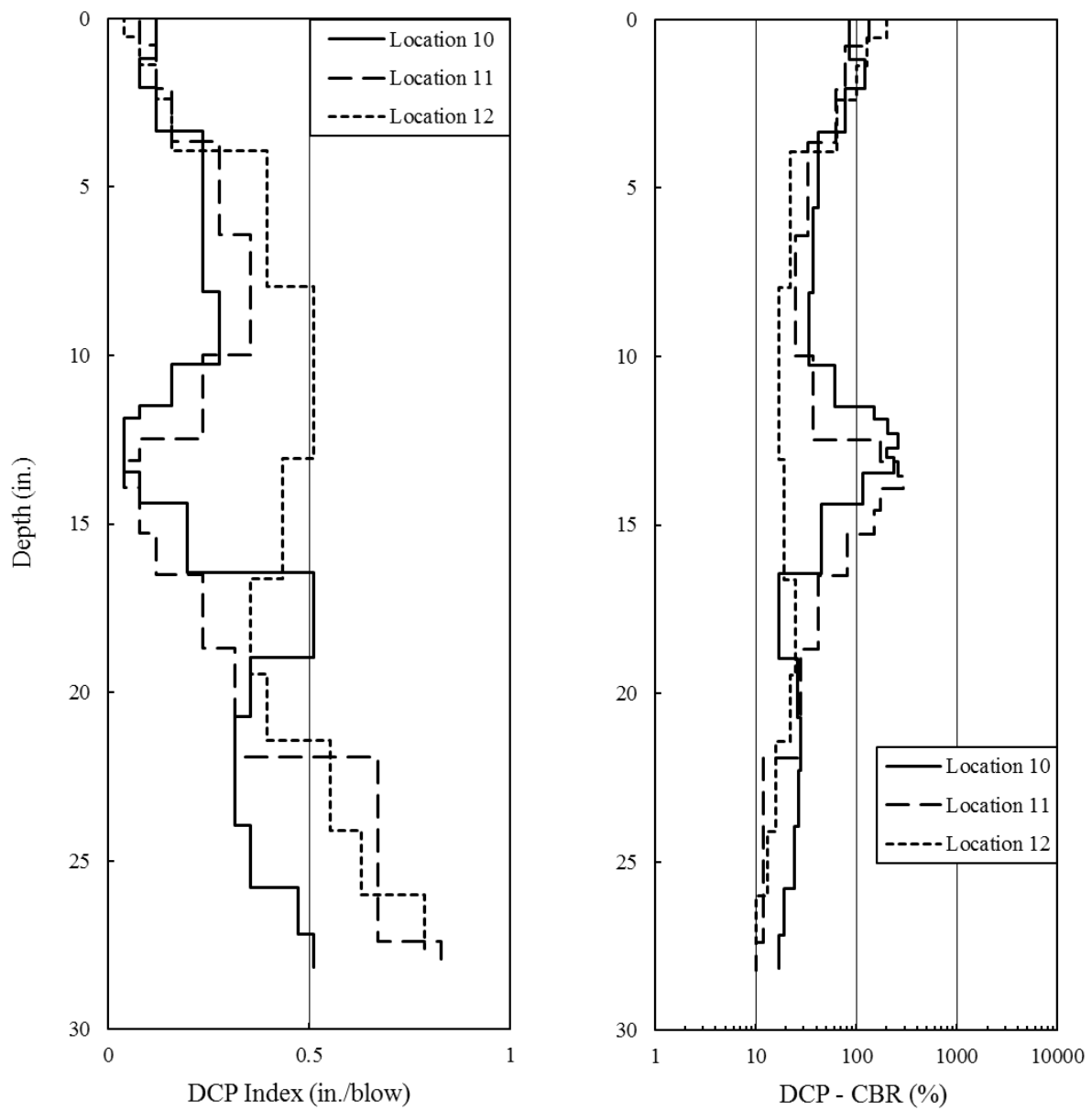
Figure 107. Pre-construction DCP test result (Claycrete)
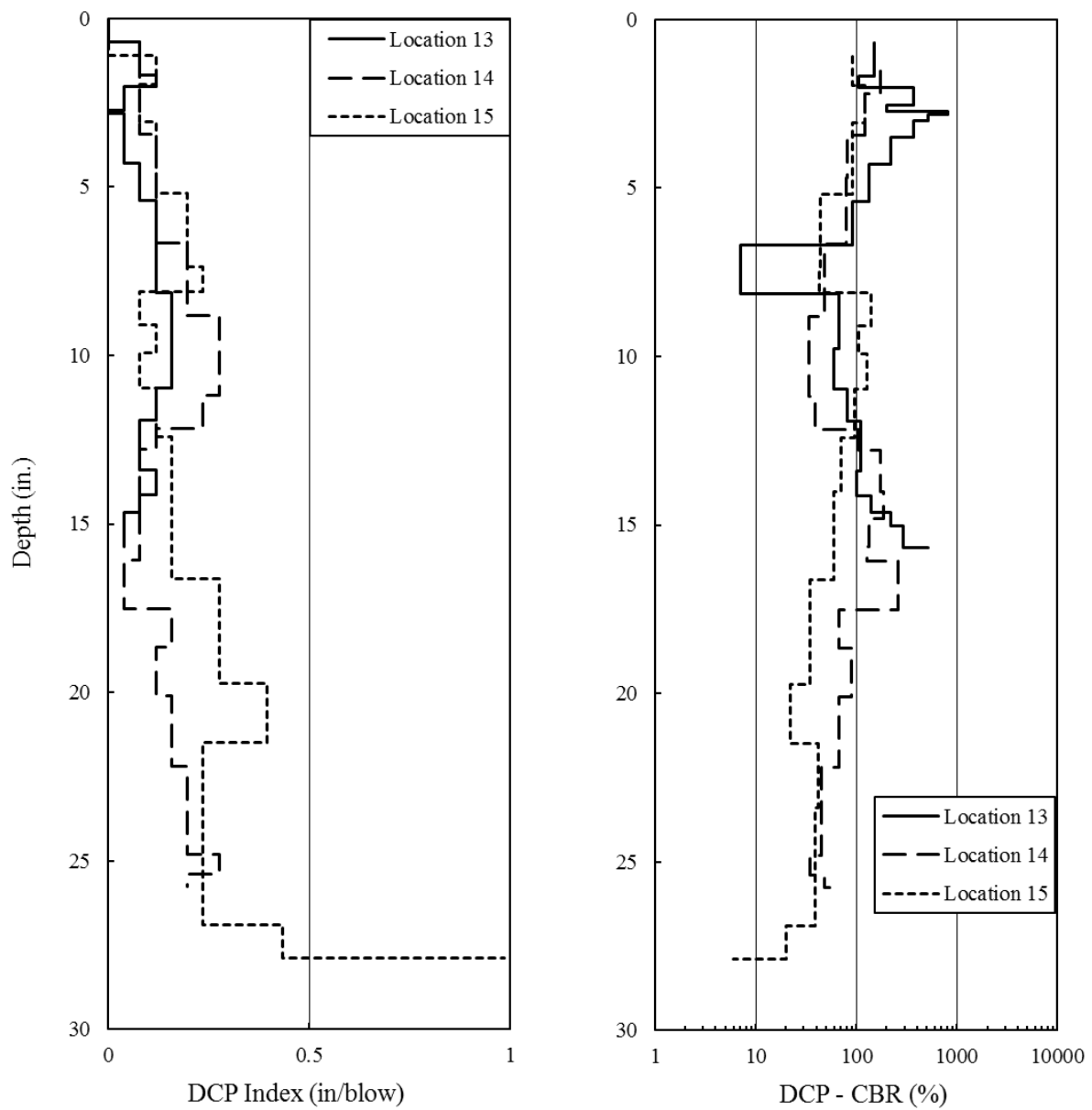
Figure 108. Pre-construction DCP test result (Base One)

123
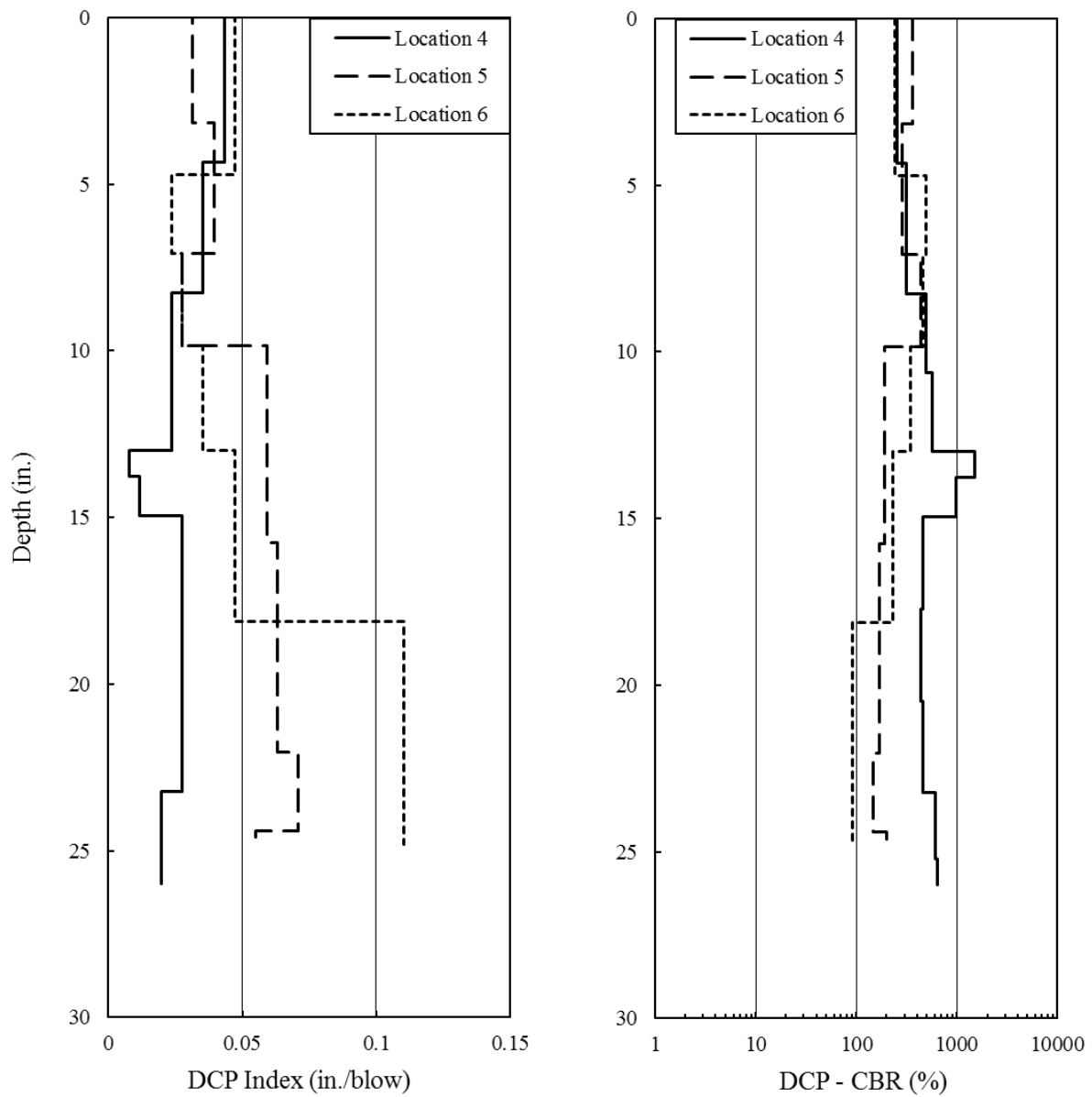
Figure 109. One week after construction DCP test result (lignosulfonate)
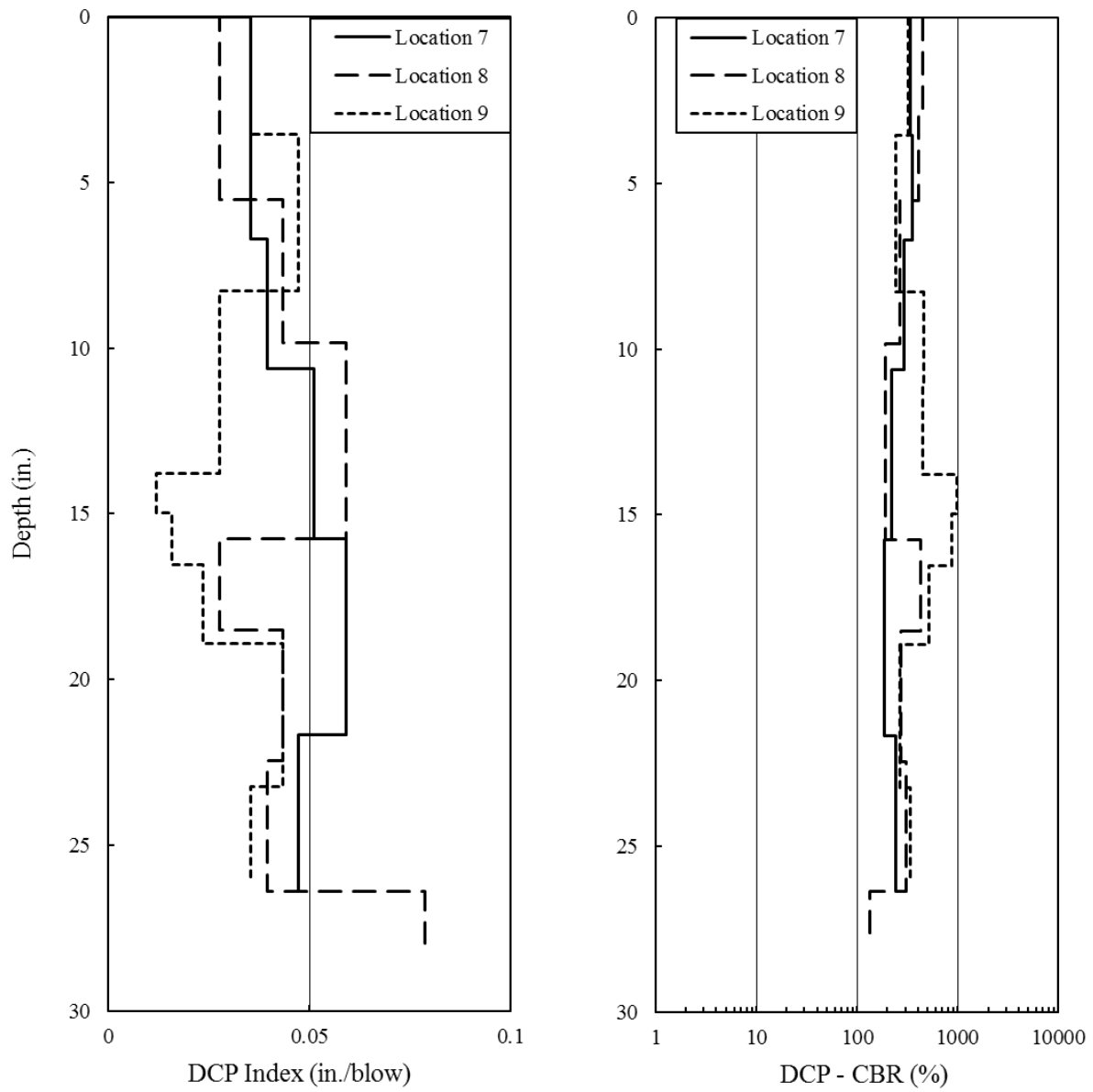
Figure 110. One week after construction DCP test result (chlorides)
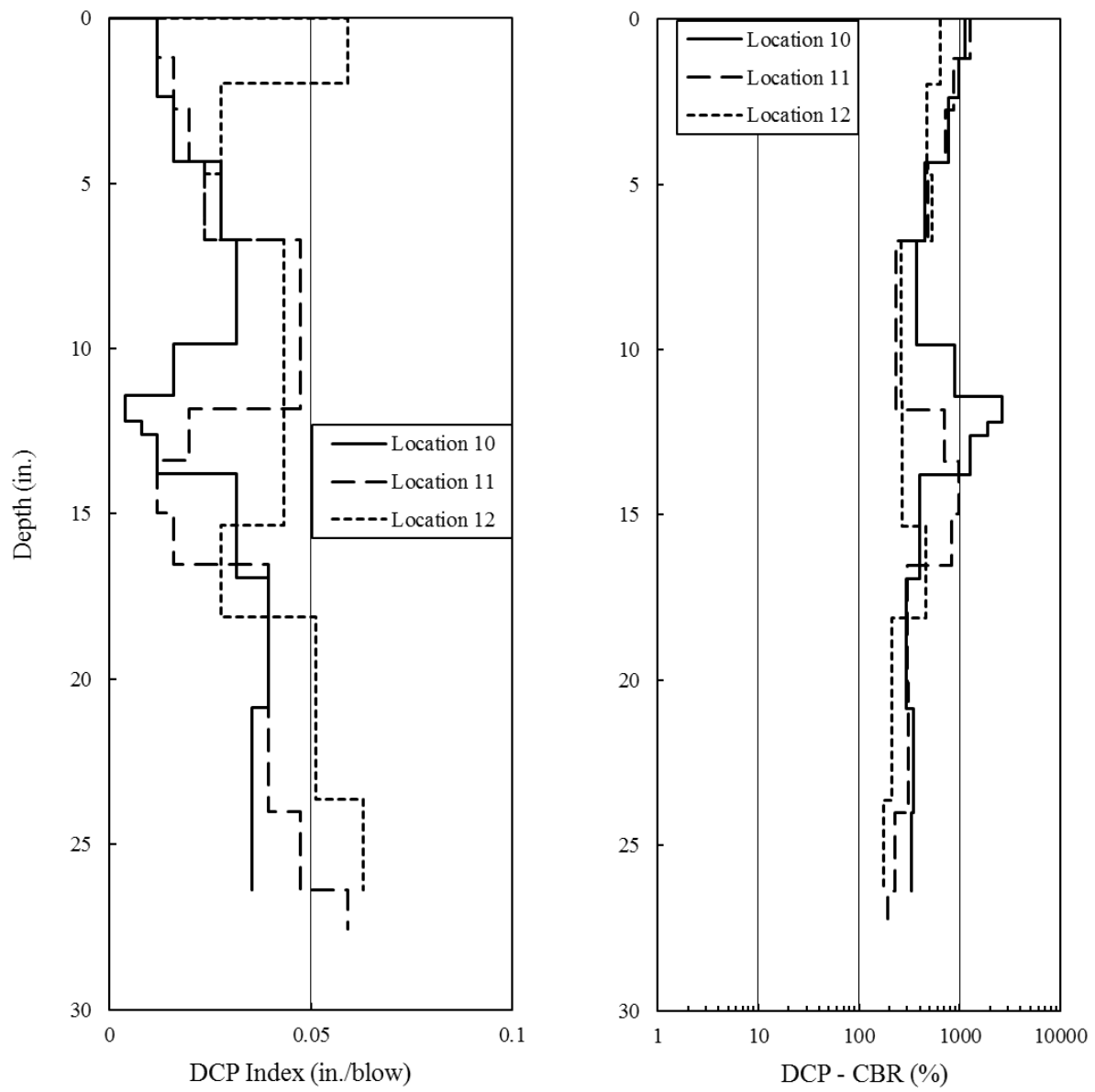
Figure 111. One week after construction DCP test result (Claycrete)
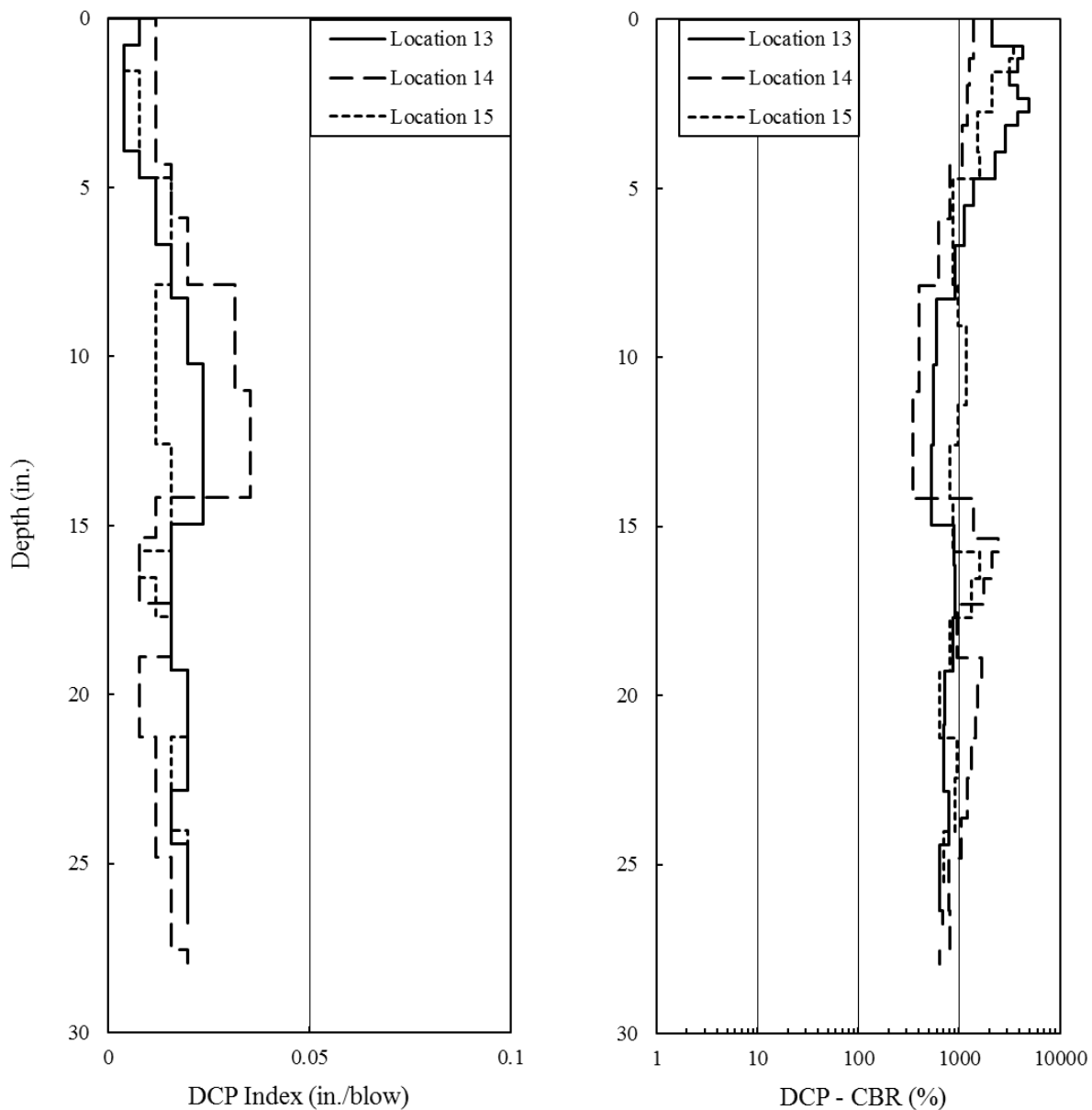
Figure 112. One week after construction DCP test result (Base One)

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 reduction in moisture content (Nazzal 2014). For the lignosulfonate, chlorides, and Claycrete sections, the low stiffness one week after construction concluded from the LWD tests suggested that an excessive amount of moisture existed in the subgrade after construction. Thus, it was predicted that these three sections' improvement of their subgrade's resistance to shear failure resulted from sufficient compaction effort. For the diluted lignosulfonate-treated section, as explained in the set time test results, it was predicted that the increased strength of

127

lignosulfonate also contributed to the improvement of the diluted 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. The field tests proved cement was the most promising soil stabilizer among the five products. The Base One section was also predicted to have a higher strength one week after construction based on the lower DCP index. A higher in situ CBR value one week after construction was observed for all of the sections, which indicated that these subgrade sections had higher load bearing capacity.

In summary, all five soil stabilizers strengthened the subgrade to some extent one week after construction. Among them, cement and Base One were more promising stabilizer products than the others.

7. CONCLUSIONS AND RECOMMENDATIONS

General Summary

The energy crisis and environmental pollution have driven efforts to develop an industry producing biofuel derived from biomass. Utilization of BCP has been explored in attempts to increase profitability of bioenergy-oriented businesses. This study investigated the use of BCPs containing sulfur-free lignin as nontraditional stabilizers for use in soil stabilization, a common practice for providing a soil platform with desirable engineering properties for pavement foundations. The potential advantages of using BCPs as stabilizing agents compared to traditional stabilizers (cement) are highlighted as follows:

- Lignin products are renewable and sustainable materials
- BCPs are derived from widely available source materials such as corn, trees, and other plants
- The utilization of BCPs in soil stabilization can improve the biofuel industry life cycle
- Lignin has lower alkalinity, causes less groundwater contamination, and causes fewer corrosion effects than traditional stabilizers and, therefore, has relatively negligible environmental impact
- Lignin is a nontoxic and safe material
- Sulfur-free lignin, while previously rarely commercialized, is potentially cost-effective if a large available quantity of inexpensive source material (food waste materials, corn residuals, etc.) is considered
- Cement as a soil stabilizer has some shortcomings such as high cost, high alkalinity, potential shrinkage cracking, and potential damage from sulfate attacks; all these issues negatively influence roadway service life (Winterkorn and Pamukcu 1991)
- In addition to the low-volume roads, BCPs could be utilized as a soil stabilizing agent for haul roads for local power plants, stockpiles, parking lots, road shoulders, military runways, etc.
- BCPs could be used for diverse purposes such as admixtures in concrete, antioxidants in asphalt, and dust control

Laboratory tests were carried out to evaluate the engineering properties, strength properties, durability, and moisture susceptibility of four types of Iowa soil specimens treated with three types of BCP, and to compare them to four types of untreated Iowa soil specimens and four types of soil specimens stabilized with cement. The BCPs investigated were (1) an oily liquid type of BCP with medium lignin content (BCP A), (2) a powder type of BCP with lower lignin content (BCP B), and (3) another type of oily liquid BCP with higher lignin content (BCP C). In this experimental program, moisture content and curing period were used as variables for evaluating the effects on performance of BCPs-treated specimens, especially with respect to UCS and DS strength. Freeze-thaw testing was carried out to investigate the benefits of BCPs in improving durability. Moisture susceptibility was studied to evaluate the waterproofing properties of BCPs. SEM and XRD studies were also conducted to identify the underlying mechanisms of BCPs. In this research, UCS tests and durability tests were given priority because quantities of BCP A and BCP C materials were insufficient. The experimental results verified the benefits of BCPs in soil

stabilization. Utilization of BCPs can improve a wide range of properties of natural soil with the potential of becoming a valuable nontraditional soil stabilizer.

To better understand the effects of lignin on stabilizing geo-materials, an alternative lignin product named lignosulfonate was investigated in this study, and its sufficient quantity supported different tests including a field demonstration. 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 standard Proctor compaction tests were focused on the 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 SEM analysis revealed the reason the addition of lignosulfonate to Soil 4 had an improvement on its strength, whereas the set time test justified the improvement of lignosulfonate-treated soil strength.

In the field demonstration, diluted ammonium-based lignosulfonate solution 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 were conducted and documentation were collected at different periods of the construction to monitor the seasonal performance of the stabilized section and draw the lessons learned from the practice. LWD tests and the DCP tests were performed before, one week after, and one year 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.

Specific Findings from Laboratory Investigations

The laboratory test results of utilization of BCPs and lignosulfonate in soil stabilization are summarized in the following specific findings:

- The investigated BCPs are promising additives for increasing compressive strength, shear strength, freeze-thaw durability, and resistance to moisture degradation for four types of Iowa soil: Soil 1 classified as SC or A-6(2) , Soil 2 classified as CL-ML or A-4(2), Soil 3 classified as CL-ML or A-4(1), and Soil 4 classified as ML or A-4(0). The investigated BCPs cannot, however, provide more strength improvement than cement.
- BCP A offered considerable advantages for soil stabilization, including reduction of soil plasticity, increase in UCS (especially for Soil 1), good waterproofing capability, and significant improvement of freeze-thaw durability.
- BCP B demonstrated benefits of improving compressive strength and shear strength for four types of soil. It also achieved a significant reduction in mass loss during freeze-thaw cycles and moderate improvement in soil resistance to moisture degradation. BCP A and BCP C were not conducted for subjected to DS tests due to the unavailability of necessary quantities.

- BCP C achieved the highest compressive strength for Soil 2 after a 28-day curing period. It also significantly reduced mass loss for Soil 2 during freeze-thaw cycles. It is a more promising additive for Soil 2 than the other BCPs with respect to compressive strength and durability.
- Generally, for pure soil and BCPs-treated soil, lower moisture content contributed to higher strength. The highest compressive strength value of cement-treated samples was observed at OMC.
- An increased curing time could increase the compressive strength of BCP A and BCP C-treated soils. In addition, BCP C could achieve higher strength than BCP A for Soil 2 after 28-day curing.
- An increase in curing time also increased performance with respect to durability and moisture susceptibility for BCP A- and BCP B-treated samples.
- SEM and XRD analyses revealed the primary underlying mechanisms of BCP A and BCP B to be coating and binding soil grains to form strong soil structures.
- The standard 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 4's 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 SEM analysis suggested that the stronger and more stable microstructure in the lignosulfonate-Soil 4 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 strength.

Although the results of laboratory tests in this research indicated that lignin products are promising materials for improving soil properties, there were still some limitations. An important limitation of the study was inadequate quantities of material for BCP A and BCP C. This lack of two oily liquid types of co-product resulted in an inability to conduct all desired tests, unbalancing the entire experimental plan. A second limitation was lack of data regarding utilization of BCPs in field soil stabilization practices because of differences between field and laboratory conditions.

Specific Findings from Field Demonstration

The field performances of lignosulfonate and the other four stabilizers are summarized in the following specific findings:

- This field construction should be conducted on a subgrade layer, yet the stabilization construction was conducted on a destroyed gravel road surface due to the shortage of budget

131

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 diluted lignosulfonate-treated section, the actual dosage was adjusted to 2.5%. The subgrade's over-wet condition was caused by both climate factor and human factor. Excessive amounts 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 at a larger spray rate. Moreover, the low temperature slowed down the evaporation of the excessive amount of moisture in the subgrade. If the site moisture can be well-controlled at the OMC level, the theoretical elastic modulus will increase dramatically compared to the measured actual data in the field. The over-wet condition could have been avoided if the construction was executed 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). In addition, empirical experience should be weighed in conjunction with engineering design so that the lignosulfonate dilution and spray rate could have been more reasonable. 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 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.
- One week after 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 accumulated in the subgrade and/or the lack of compaction. One year after construction, all five treated sections exhibited improved soil stiffness. The lignosulfonate-treated section showed 49% improvement with respect to its untreated stiffness. The improved stiffness is due to the excess moisture that was present in the soil system during the construction process leaving the base/subgrade system over time.
- All five sections displayed higher strength one week after 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 in addition to the lignosulfonate's bonding effect. The higher CBR values also proved that all five sections had higher bearing capacity one week after construction.

Recommendations and Future Research

Lignin products added to natural soil can provide benefits in soil stabilization. They not only improve strength capacity for such soil but also increase freeze-thaw durability and resistance to moisture degradation. Generally, co-products with higher lignin content (BCP A and BCP C) are more promising additives. Considering that lignin-based strength improvements are less effective than cement-based soil treatment, lignin products are primarily recommended for use in subgrade soil stabilization for unpaved, gravel paved, and low-volume roads, because their strength requirement is relatively less and durability is of greater concern.

While the addition of water to the oily liquid type BCPs can increase their flowability and make the BCP easily spreadable to produce a homogenous soil-additive mixture, the water in oily liquid co-products has a negative effect on soil binding. The recommendation for utilization of oily liquid products (BCPs and lignosulfonate) in field practice is, therefore, to adjust to optimum moisture content before using it as a soil stabilizer.

Future research is needed to evaluate the performance of BCP C on Soils 1, 3, and 4. BCP C was used only for the UCS and freeze-thaw durability testing of Soil 2, and its effects should be tested for the other three types of soil because it exhibited good performance on Soil 2. Standard Proctor compaction tests and DS tests of BCP A were not conducted in this study; hence, it is recommended to finish these tests if an appropriate quantity of material can be made available. Finally, more field demonstrations would be valuable for evaluating the benefits of lignin compared to traditional stabilizers. Field data should be collected and analyzed continuously to verify the effects of lignin based products in soil stabilization practices.

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AASHTO T 220-66: Standard Method of Test for Determination of the Strength of Soil-Lime Mixtures.

Standards from ASTM International, West Conshohocken, PA

ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C150: Standard Specification for Portland Cement.

ASTM C593: Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization.

ASTM C618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.

ASTM D95-13: Standard Test Method for Water in Petroleum Products and Bituminous Materials by Distillation.

ASTM D558: Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures.

ASTM D559: Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures.

ASTM D560: Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures.

ASTM D698: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3).

ASTM D1633: Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders.

ASTM D1883: Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils.

ASTM D2166: Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.

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APPENDIX A. CONTACT INFORMATION OF LIGNIN-BASED SUPPLIERS

Table A-1. 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	
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

APPENDIX B. LABORATORY MIX DESIGN DATA SHEETS

Table B-1. Mix design of Soil 1 for 2 in. by 2 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	18.5	178.0	196.5	0.0	196.5	9.4		0.0
Soil 1	OMC	14.4	25.6	178.0	203.6	0.0	203.6	12.6	No Addtives	0.0
	OMC +4%	18.4	32.7	178.0	210.7	0.0	210.7	15.5		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	13.8	178.0	191.8	26.0	217.8	6.3		12.0
Soil 1	OMC	14.4	20.9	178.0	198.9	26.0	224.9	9.3	BCP A	12.0
	OMC +4%	18.4	28.1	178.0	206.0	26.0	232.1	12.1		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	18.5	178.0	196.5	21.4	217.8	8.5		12.0
Soil 1	OMC	14.4	25.6	178.0	203.6	21.4	224.9	11.4	BCP B	12.0
	OMC +4%	18.4	32.7	178.0	210.7	21.4	232.1	14.1		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	18.5	178.0	196.5	21.4	217.8	8.5		12.0
Soil 1	OMC	14.4	25.6	178.0	203.6	21.4	224.9	11.4	Type I Portland Cement	12.0
	OMC +4%	18.4	32.7	178.0	210.7	21.4	232.1	14.1		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	18.5	178.0	196.5	5.3	201.8	9.2		3.0
Soil 1	OMC	14.4	25.6	178.0	203.6	5.3	208.9	12.3	Type I Portland Cement	3.0
	OMC +4%	18.4	32.7	178.0	210.7	5.3	216.0	15.2		3.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	18.5	178.0	196.5	10.7	207.1	8.9		6.0
Soil 1	OMC	14.4	25.6	178.0	203.6	10.7	214.3	12.0	Type I Portland Cement	6.0
	OMC +4%	18.4	32.7	178.0	210.7	10.7	221.4	14.8		6.0

Note: water content of BCP A is 18%.

Table B-2. Mix design of Soil 2 for 2 in. by 2 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	23.8	167.9	191.7	0.0	191.7	12.4		0.0
Soil 2	OMC	18.2	30.6	167.9	198.5	0.0	198.5	15.4	No Addtives	0.0
	OMC +4%	22.2	37.3	167.9	205.2	0.0	205.2	18.2		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	19.4	167.9	187.3	24.6	211.9	9.2		12.0
Soil 2	OMC	18.2	26.1	167.9	194.0	24.6	218.6	12.0	BCP A or BCP C	12.0
	OMC +4%	22.2	32.9	167.9	200.8	24.6	225.3	14.6		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	23.8	167.9	191.7	20.1	211.9	11.3		12.0
Soil 2	OMC	18.2	30.6	167.9	198.5	20.1	218.6	14.0	BCP B	12.0
	OMC +4%	22.2	37.3	167.9	205.2	20.1	225.3	16.5		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	23.8	167.9	191.7	5.0	196.8	12.1		3.0
Soil 2	OMC	18.2	30.6	167.9	198.5	5.0	203.5	15.0	Type I Portland Cement	3.0
	OMC +4%	22.2	37.3	167.9	205.2	5.0	210.2	17.7		3.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	23.8	167.9	191.7	10.1	201.8	11.8		6.0
Soil 2	OMC	18.2	30.6	167.9	198.5	10.1	208.5	14.7	Type I Portland Cement	6.0
	OMC +4%	22.2	37.3	167.9	205.2	10.1	215.2	17.3		6.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	23.8	167.9	191.7	20.1	211.9	11.3		12.0
Soil 2	OMC	18.2	30.6	167.9	198.5	20.1	218.6	14.0	Type I Portland Cement	12.0
	OMC +4%	22.2	37.3	167.9	205.2	20.1	225.3	16.5		12.0

Note: water contents of BCP A and BCP B are 18%.

Table B-3. Mix design of Soil 3 for 2 in. by 2 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	17.8	187.2	205.0	0.0	205.0	8.7		0.0
Soil 3	OMC	13.5	25.3	187.2	212.5	0.0	212.5	11.9	No Addtives	0.0
	OMC +4%	17.5	32.8	187.2	220.0	0.0	220.0	14.9		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	12.9	187.2	200.0	27.4	227.4	5.7		12.0
Soil 3	OMC	13.5	20.3	187.2	207.5	27.4	234.9	8.7	BCP A	12.0
	OMC +4%	17.5	27.8	187.2	215.0	27.4	242.4	11.5		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	17.8	187.2	205.0	22.5	227.4	7.8		12.0
Soil 3	OMC	13.5	25.3	187.2	212.5	22.5	234.9	10.8	BCP B	12.0
	OMC +4%	17.5	32.8	187.2	220.0	22.5	242.4	13.5		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	17.8	187.2	205.0	5.6	210.6	8.4		3.0
Soil 3	OMC	13.5	25.3	187.2	212.5	5.6	218.1	11.6	Type I Portland Cement	3.0
	OMC +4%	17.5	32.8	187.2	220.0	5.6	225.6	14.5		3.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	17.8	187.2	205.0	11.2	216.2	8.2		6.0
Soil 3	OMC	13.5	25.3	187.2	212.5	11.2	223.7	11.3	Type I Portland Cement	6.0
	OMC +4%	17.5	32.8	187.2	220.0	11.2	231.2	14.2		6.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	17.8	187.2	205.0	22.5	227.4	7.8		12.0
Soil 3	OMC	13.5	25.3	187.2	212.5	22.5	234.9	10.8	Type I Portland Cement	12.0
	OMC +4%	17.5	32.8	187.2	220.0	22.5	242.4	13.5		12.0

Note: water content of BCP A is 18%.

Table B-4. Mix design of Soil 4 for 2 in. by 2 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	15.1	189.3	204.5	0.0	204.5	7.4		0.0
Soil 4	OMC	12.0	22.7	189.3	212.1	0.0	212.1	10.7	No Addtives	0.0
	OMC +4%	16.0	30.3	189.3	219.6	0.0	219.6	13.8		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	10.2	189.3	199.5	27.7	227.2	4.5		12.0
Soil 4	OMC	12.0	17.7	189.3	207.1	27.7	234.8	7.6	BCP A	12.0
	OMC +4%	16.0	25.3	189.3	214.6	27.7	242.4	10.4		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	15.1	189.3	204.5	22.7	227.2	6.7		12.0
Soil 4	OMC	12.0	22.7	189.3	212.1	22.7	234.8	9.7	BCP B	12.0
	OMC +4%	16.0	30.3	189.3	219.6	22.7	242.4	12.5		12.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	15.1	189.3	204.5	5.7	210.2	7.2		3.0
Soil 4	OMC	12.0	22.7	189.3	212.1	5.7	217.7	10.4	Type I Portland Cement	3.0
	OMC +4%	16.0	30.3	189.3	219.6	5.7	225.3	13.4		3.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	15.1	189.3	204.5	11.4	215.8	7.0		6.0
Soil 4	OMC	12.0	22.7	189.3	212.1	11.4	223.4	10.2	Type I Portland Cement	6.0
	OMC +4%	16.0	30.3	189.3	219.6	11.4	231.0	13.1		6.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	15.1	189.3	204.5	22.7	227.2	6.7		12.0
Soil 4	OMC	12.0	22.7	189.3	212.1	22.7	234.8	9.7	Type I Portland Cement	12.0
	OMC +4%	16.0	30.3	189.3	219.6	22.7	242.4	12.5		12.0

Note: water content of BCP A is 18%.

Table B-5. Mix design of Soil 1 for 2.5 in. by 1 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	14.5	139.0	153.5	0.0	153.5	10.4		0.0
Soil 1	OMC	14.4	20.0	139.0	159.1	0.0	159.1	14.4	No Addtives	0.0
	OMC +4%	18.4	25.6	139.0	164.6	0.0	164.6	18.4		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	10.4	14.5	139.0	153.5	16.7	170.2	8.5		12.0
Soil 1	OMC	14.4	20.0	139.0	159.1	16.7	175.7	11.4	BCP B	12.0
	OMC +4%	18.4	25.6	139.0	164.6	16.7	181.3	14.1		12.0

Table B-6. Mix design of Soil 2 for 2.5 in. by 1 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	18.6	131.2	149.8	0.0	149.8	14.2		0.0
Soil 2	OMC	18.2	23.9	131.2	155.0	0.0	155.0	18.2	No Addtives	0.0
	OMC +4%	22.2	29.1	131.2	160.3	0.0	160.3	22.2		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	14.2	18.6	131.2	149.8	15.7	165.5	11.3		12.0
Soil 2	OMC	18.2	23.9	131.2	155.0	15.7	170.8	14.0	BCP B	12.0
	OMC +4%	22.2	29.1	131.2	160.3	15.7	176.0	16.5		12.0

Table B-7. Mix design of Soil 3 for 2.5 in. by 1 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	13.9	146.2	160.1	0.0	160.1	9.5		0.0
Soil 3	OMC	13.5	19.7	146.2	166.0	0.0	166.0	13.5	No Addtives	0.0
	OMC +4%	17.5	25.6	146.2	171.8	0.0	171.8	17.5		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	9.5	13.9	146.2	160.1	17.5	177.7	7.8		12.0
Soil 3	OMC	13.5	19.7	146.2	166.0	17.5	183.5	10.8	BCP B	12.0
	OMC +4%	17.5	25.6	146.2	171.8	17.5	189.4	13.5		12.0

Table B-8. Mix design of Soil 4 for 2.5 in. by 1 in. specimen

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	11.8	147.9	159.8	0.0	159.8	8.0		0.0
Soil 4	OMC	12.0	17.8	147.9	165.7	0.0	165.7	12.0	No Addtives	0.0
	OMC +4%	16.0	23.7	147.9	171.6	0.0	171.6	16.0		0.0

		Target Moisture Content (%)	Water Weight (g)	Soil Weight (g)	Soil + Water Weight (g)	Additive Weight (g)	Total Weight (g)	Actual Water Content (%)	Addtive Material	Additive Content (%)
	OMC -4%	8.0	11.8	147.9	159.8	17.8	177.5	6.7		12.0
Soil 4	OMC	12.0	17.8	147.9	165.7	17.8	183.4	9.7	BCP B	12.0
	OMC +4%	16.0	23.7	147.9	171.6	17.8	189.3	12.5		12.0

APPENDIX C. MIX DESIGN AND TEST PROCEDURES FOR BCP STABILIZED SOIL

Description

Biofuel co-products (BCPs) containing lignin derived from biomass can be used to stabilize roadbed soils and provide desired foundations for low-volume roads. There are two main types of BCP in terms of physical phases, a powder type, which is similar to fly ash, and an oily liquid type, which is similar to bitumen.

Materials

    A. Selection of BCP type: Depends on the climate and condition of the site. Two types of BCPs that can be used for soil stabilizations are:

        1. Powder type of BCP: It should follow the "Standard Guide for Evaluating Effectiveness of Admixtures for Soil Stabilization" (ASTM D4609-08).

        2. Oil type of BCP*: It should follow the "Standard Guide for Evaluating Effectiveness of Admixtures for Soil Stabilization" (ASTM D4609-08).

    B. The application rate of BCP should be determined by trial unconfined compressive strength (UCS) testing (see more details in the following section: Laboratory Evaluation before Construction).

* The water content of oily liquid-type BCP should be determined in accordance with the "Standard Test Method for Water in Petroleum Products and Bituminous Materials by Distillation" (ASTM D95-13).

Laboratory Evaluation before Construction

    A. The purpose of laboratory trial testing is to determine the optimum application rate of BCPs. Two tests are required:

        1. Moisture-density relationship test: It should follow the "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3))" (ASTM D698-12).

        2. Unconfined compressive strength test: It should follow the "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil" (ASTM D2166-16).

    B. BCP-treated soil specimen preparation and compaction testing:

        1. Soil sieving: Sieve the collected soil from the construction site in accordance with ASTM D698-12.

2. Moisture content of BCP materials:

    a. Powder-type of BCP: Air-dry BCP materials under a room temperature of 70°F.

    b. Oil-type BCP: Dry BCP materials in the oven at 150°F. Continuously monitor the moisture change of BCP until it reaches a moisture content of 25%.

3. Mix BCP and soil for the moisture-density relationship test (ASTM D698-12):

    a. Add 8% of pure BCP and the target water volume by dry soil weight into the sample soil.

    b. Mix soil, water, and BCP materials uniformly. For oily liquid-type BCP, the metal mixing pan and spatula should be preheated about 30 minutes in the oven at 70°F.

    c. Compact soil-BCP mixture in accordance with ASTM D698-12 at different moisture contents. Plot the moisture-relationship curve and determine the optimum moisture content (OMC) and maximum dry unit weight ($\gamma_{d, max}$).

    d. Repeat these procedures for 10%, 12%, 14%, and 16% of pure BCP by dry soil weight and record OMC and $\gamma_{d, max}$.

C. Unconfined compressive strength testing:

1. Prepare the compacted 8%, 10%, 12% 14%, and 16% of pure BCP-treated soil specimens with OMC in accordance with ASTM D698-12. For oily liquid-type BCP-treated soil specimens, the water in BCP materials should be considered as a part of the total moisture of specimens (OMC).

2. Wrap the soil specimens in plastic film and aluminum foil paper and cure all specimens for seven days at room temperature.

3. After seven-day curing, test the UCS of specimens in accordance with ASTM D2166-16.

4. Plot the BCP content versus UCS. Determine the optimum BCP content in terms of UCS improvement.

Construction Sequence

A. Scarification and initial pulverization:

1. Equipment: Grader-scarifier and/or disc harrow for scarification, rotary mixer for initial pulverization.

2. It is desirable to remove non-soil materials larger than 3 in., such as stumps, roots, turf, and aggregates.

B. BCP spreading:

1. Equipment: Distributor trucks with recirculation capabilities; pressure distributors are preferred.

2. In this application, the soil is generally scarified, and the distilled BCP is applied by distributor trucks.

C. Preliminary mixing and watering (if needed):

1. Equipment: Rotary mixers, water truck, and light sheepsfoot or pneumatic roller.

2. Preliminary mixing is required to distribute the BCP throughout the soil and to initially pulverize the soil to prepare for the addition of water to initiate the stabilization.

D. Final mixing and pulverization:

1. Equipment: Rotary mixers.

2. To accomplish complete stabilization, adequate final pulverization of the clay fraction and thorough distribution of the BCP throughout the soil are essential.

E. Compaction:

1. Equipment: Heavy pneumatic or vibratory padfoot rollers or a combination of the sheepsfoot and light pneumatic vibratory padfoot rollers or tamping foot rollers. Typically, the final surface compaction is completed using a steel wheel roller.

2. Compaction should begin immediately after final mixing.

F. Final Curing:

1. Before placing the next layer, the compacted subgrade (or subbase) should be allowed to harden until loaded dump trucks can operate without rutting the surface.

APPENDIX D. RAW DATA FOR UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS

Table D-1. Raw data of UCS for Soil 1 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress,	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
1	Natural Soil	OMC - 4	1	71	5.9	84	9.38	10.4	10.8	10.6
2		OMC - 4	1	93	6.1			10.4	9.9	
3		OMC - 4	1	89	4.5			10.4	11.1	
4	Natural Soil	OMC	1	41	6.5	42	0.86	14.4	14.6	14.6
5		OMC	1	41	7.3			14.4	14.3	
6		OMC	1	43	6.7			14.4	14.8	
7	Natural Soil	OMC + 4	1	22	12.2	22	0.52	18.4	18.0	18.4
8		OMC + 4	1	21	13.2			18.4	19.0	
9		OMC + 4	1	23	15.0			18.4	18.1	
10	Natural Soil	OMC - 4	7	80	3.9	89	8.62	10.4	9.8	10.4
11		OMC - 4	7	86	3.5			10.4	10.7	
12		OMC - 4	7	101	5.9			10.4	10.6	
13	Natural Soil	OMC	7	42	7.3	37	3.31	14.4	14.5	14.8
14		OMC	7	34	8.3			14.4	15.0	
15		OMC	7	36	7.1			14.4	14.7	
16	Natural Soil	OMC + 4	7	30	12.2	28	1.30	18.4	18.1	17.9
17		OMC + 4	7	27	12.7			18.4	18.1	
18		OMC + 4	7	26	11.7			18.4	17.7	
19	Natural Soil	OMC - 4	28	93	3.9	93	5.50	10.4	10.2	9.9
20		OMC - 4	28	100	3.7			10.4	9.7	
21		OMC - 4	28	86	3.8			10.4	9.6	
22	Natural Soil	OMC	28	40	2.4	41	1.01	14.4	13.8	13.8
23		OMC	28	40	2.0			14.4	14.0	
24		OMC	28	42	2.6			14.4	13.7	
25	Natural Soil	OMC + 4	28	23	4.7	24	2.48	18.4	17.9	17.7
26		OMC + 4	28	28	3.7			18.4	17.4	
27		OMC + 4	28	22	4.6			18.4	17.9	
28	Soil-12% BCP A	OMC - 4	1	174	5.2	173	3.74	10.4	9.0	10.3
29		OMC - 4	1	176	7.3			10.4	10.9	
30		OMC - 4	1	168	6.0			10.4	10.9	
31	Soil-12% BCP A	OMC - 4	7	185	6.7	183	6.56	10.4	9.7	10.1
32		OMC - 4	7	189	6.1			10.4	10.2	
33		OMC - 4	7	174	6.5			10.4	10.4	
34	Soil-12% BCP A	OMC - 4	28	200	5.8	206	4.58	10.4	10.5	10.2
35		OMC - 4	28	210	6.3			10.4	10.1	
36		OMC - 4	28	209	6.1			10.4	10.1	
37	Soil-12% BCP A	OMC	1	84	12.2	80	4.03	14.4	13.9	14.3
38		OMC	1	80	13.7			14.4	14.2	
39		OMC	1	74	12.0			14.4	14.7	
40	Soil-12% BCP A	OMC	7	109	7.1	106	5.12	14.4	13.8	14.3
41		OMC	7	111	7.1			14.4	14.3	
42		OMC	7	99	6.8			14.4	14.6	
43	Soil-12% BCP A	OMC	28	123	7.3	126	3.48	14.4	14.5	14.4
44		OMC	28	131	7.1			14.4	13.7	
45		OMC	28	124	6.8			14.4	14.9	
46	Soil-12% BCP A	OMC + 4	1	61	9.8	64	1.88	18.4	17.8	18.2
47		OMC + 4	1	66	10.8			18.4	18.3	
48		OMC + 4	1	63	6.5			18.4	18.6	
49	Soil-12% BCP A	OMC + 4	7	76	6.6	76	4.91	18.4	18.9	18.3
50		OMC + 4	7	81	7.3			18.4	17.6	
51		OMC + 4	7	69	7.1			18.4	18.5	
52	Soil-12% BCP A	OMC + 4	28	99	7.6	101	4.43	18.4	19.1	18.8
53		OMC + 4	28	107	7.9			18.4	18.5	
54		OMC + 4	28	97	7.7			18.4	18.9	

Table D-1 (Continued). Raw data of UCS for Soil 1 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress,	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
55		OMC - 4	1	126	10.7			10.4	10.8	
56	Soil-12% BCP B	OMC - 4	1	95	11.2	113	13.05	10.4	9.9	10.3
57		OMC - 4	1	119	10.7			10.4	10.1	
58		OMC - 4	7	122	10.7			10.4	10.5	
59	Soil-12% BCP B	OMC - 4	7	147	10.5	136	10.53	10.4	10.2	10.5
60		OMC - 4	7	138	10.7			10.4	10.8	
61		OMC - 4	28	110	9.5			10.4	9.6	
62	Soil-12% BCP B	OMC - 4	28	90	13.7	103	9.46	10.4	9.9	9.8
63		OMC - 4	28	110	11.3			10.4	9.8	
64		OMC	1	71	11.7			14.4	13.9	
65	Soil-12% BCP B	OMC	1	74	11.2	71	2.57	14.4	13.8	14.1
66		OMC	1	67	13.2			14.4	14.7	
67		OMC	7	113	11.7			14.4	13.4	
68	Soil-12% BCP B	OMC	7	114	13.7	110	5.42	14.4	13.5	13.9
69		OMC	7	102	10.1			14.4	14.7	
70		OMC	28	101	12.2			14.4	13.5	
71	Soil-12% BCP B	OMC	28	102	11.7	102	1.67	14.4	14.7	14.4
72		OMC	28	105	10.7			14.4	15.0	
73		OMC + 4	1	51	11.2			18.4	17.7	
74	Soil-12% BCP B	OMC + 4	1	68	15.0	57	8.11	18.4	17.7	17.7
75		OMC + 4	1	50	11.3			18.4	17.7	
76		OMC + 4	7	61	14.2			18.4	18.0	
77	Soil-12% BCP B	OMC + 4	7	48	14.2	57	5.90	18.4	17.9	17.9
78		OMC + 4	7	61	15.0			18.4	17.9	
79		OMC + 4	28	54	12.2			18.4	17.9	
80	Soil-12% BCP B	OMC + 4	28	66	15.0	60	4.73	18.4	18.6	18.1
81		OMC + 4	28	59	15.0			18.4	17.8	
82		OMC - 4	1	127	5.0			10.4	10.0	
83	Soil-3% Cement	OMC - 4	1	128	3.4	122	7.63	10.4	9.8	10.2
84		OMC - 4	1	111	4.3			10.4	10.7	
85		OMC - 4	7	170	2.7			10.4	9.5	
86	Soil-3% Cement	OMC - 4	7	154	2.6	156	10.26	10.4	10.3	10.0
87		OMC - 4	7	145	3.2			10.4	10.1	
88		OMC - 4	28	226	2.9			10.4	9.3	
89	Soil-3% Cement	OMC - 4	28	227	3.0	234	11.02	10.4	9.4	9.4
90		OMC - 4	28	250	3.5			10.4	9.5	
91		OMC	1	137	4.5			14.4	14.2	
92	Soil-3% Cement	OMC	1	154	3.9	148	7.97	14.4	14.2	14.4
93		OMC	1	153	3.6			14.4	14.8	
94		OMC	7	248	3.0			14.4	13.6	
95	Soil-3% Cement	OMC	7	214	3.5	228	14.61	14.4	14.1	13.7
96		OMC	7	223	3.7			14.4	13.5	
97		OMC	28	316	3.0			14.4	13.7	
98	Soil-3% Cement	OMC	28	289	4.1	311	16.50	14.4	13.1	13.4
99		OMC	28	329	4.3			14.4	13.6	
100		OMC + 4	1	135	3.1			18.4	18.6	
101	Soil-3% Cement	OMC + 4	1	133	3.1	136	1.88	18.4	18.7	18.4
102		OMC + 4	1	138	3.0			18.4	17.8	
103		OMC + 4	7	233	2.8			18.4	18.0	
104	Soil-3% Cement	OMC + 4	7	218	3.2	228	7.31	18.4	17.7	17.8
105		OMC + 4	7	235	3.2			18.4	17.7	
106		OMC + 4	28	339	3.5			18.4	17.3	
107	Soil-3% Cement	OMC + 4	28	310	3.1	323	12.11	18.4	17.2	17.2
108		OMC + 4	28	319	3.4			18.4	17.1	

Table D-1 (Continued). Raw data of UCS for Soil 1 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress,	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
109		OMC - 4	1	190	3.9			10.4	9.8	
110	Soil-6% Cement	OMC - 4	1	199	3.7	203	12.98	10.4	10.2	10.0
111		OMC - 4	1	221	3.2			10.4	9.9	
112		OMC - 4	7	292	3.9			10.4	10.8	
113	Soil-6% Cement	OMC - 4	7	265	3.5	272	13.96	10.4	10.2	10.3
114		OMC - 4	7	260	3.5			10.4	10.0	
115		OMC - 4	28	314	2.9			10.4	9.4	
116	Soil-6% Cement	OMC - 4	28	313	3.8	320	9.22	10.4	9.3	9.3
117		OMC - 4	28	333	3.5			10.4	9.3	
118		OMC	1	256	3.7			14.4	14.3	
119	Soil-6% Cement	OMC	1	259	4.0	262	6.78	14.4	13.7	13.7
120		OMC	1	272	2.9			14.4	13.2	
121		OMC	7	352	4.1			14.4	13.8	
122	Soil-6% Cement	OMC	7	380	3.6	369	12.52	14.4	14.5	13.9
123		OMC	7	376	3.7			14.4	13.6	
124		OMC	28	652	3.8			14.4	13.4	
125	Soil-6% Cement	OMC	28	666	3.9	648	17.02	14.4	13.5	13.3
126		OMC	28	625	4.2			14.4	12.9	
127		OMC + 4	1	230	3.2			18.4	17.9	
128	Soil-6% Cement	OMC + 4	1	218	4.6	226	5.79	18.4	17.9	18.0
129		OMC + 4	1	231	3.1			18.4	18.1	
130		OMC + 4	7	356	3.2			18.4	17.5	
131	Soil-6% Cement	OMC + 4	7	328	3.1	341	11.72	18.4	17.3	17.6
132		OMC + 4	7	337	3.1			18.4	18.0	
133		OMC + 4	28	670	3.6			18.4	17.2	
134	Soil-6% Cement	OMC + 4	28	720	3.5	698	20.95	18.4	17.4	17.4
135		OMC + 4	28	705	3.3			18.4	17.7	
136		OMC - 4	1	266	3.9			10.4	9.7	
137	Soil-12% Cement	OMC - 4	1	302	4.6	281	15.26	10.4	10.9	10.3
138		OMC - 4	1	276	5.5			10.4	10.4	
139		OMC - 4	7	451	4.4			10.4	9.8	
140	Soil-12% Cement	OMC - 4	7	431	5.0	447	12.00	10.4	10.1	10.0
141		OMC - 4	7	460	6.0			10.4	10.1	
142		OMC - 4	28	729	4.3			10.4	9.3	
143	Soil-12% Cement	OMC - 4	28	777	4.6	747	21.17	10.4	9.1	9.2
144		OMC - 4	28	736	4.7			10.4	9.0	
145		OMC	1	411	3.9			14.4	14.7	
146	Soil-12% Cement	OMC	1	396	4.4	400	7.39	14.4	14.5	14.4
147		OMC	1	394	3.8			14.4	14.1	
148		OMC	7	650	4.2			14.4	14.3	
149	Soil-12% Cement	OMC	7	667	4.5	664	9.90	14.4	13.5	13.9
150		OMC	7	674	4.6			14.4	13.8	
151		OMC	28	976	4.5			14.4	13.3	
152	Soil-12% Cement	OMC	28	915	4.6	955	28.52	14.4	13.1	13.2
153		OMC	28	975	4.6			14.4	13.1	
154		OMC + 4	1	392	4.2			18.4	18.8	
155	Soil-12% Cement	OMC + 4	1	381	4.5	379	11.11	18.4	17.6	18.2
156		OMC + 4	1	365	5.3			18.4	18.2	
157		OMC + 4	7	621	4.8			18.4	17.4	
158	Soil-12% Cement	OMC + 4	7	621	5.2	613	11.48	18.4	17.3	17.7
159		OMC + 4	7	597	4.8			18.4	18.2	
160		OMC + 4	28	1119	5.1			18.4	17.4	
161	Soil-12% Cement	OMC + 4	28	1016	4.9	1057	44.75	18.4	17.6	17.5
162		OMC + 4	28	1035	5.3			18.4	17.6	

Table D-2. Raw data of UCS for Soil 2 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
163	**Natural Soil**	OMC - 4	1	19	3.8	20	1.47	14.2	13.8	13.9
164		OMC - 4	1	18	3.2			14.2	13.8	
165		OMC - 4	1	22	3.0			14.2	14.0	
166	**Natural Soil**	OMC - 4	7	23	4.8	21	1.11	14.2	14.0	13.8
167		OMC - 4	7	22	4.5			14.2	13.9	
168		OMC - 4	7	20	3.5			14.2	13.5	
169	**Natural Soil**	OMC - 4	28	19	3.6	19	0.29	14.2	13.6	13.9
170		OMC - 4	28	18	3.3			14.2	13.9	
171		OMC - 4	28	19	2.9			14.2	14.1	
172	**Natural Soil**	OMC	1	13	2.9	13	1.25	18.2	18.0	18.3
173		OMC	1	12	3.3			18.2	18.4	
174		OMC	1	15	3.5			18.2	18.5	
175	**Natural Soil**	OMC	7	17	3.0	16	0.62	18.2	18.2	18.4
176		OMC	7	16	3.0			18.2	18.4	
177		OMC	7	16	3.2			18.2	18.5	
178	**Natural Soil**	OMC	28	14	3.6	12	0.95	18.2	17.8	17.7
179		OMC	28	11	3.7			18.2	17.5	
180		OMC	28	12	4.5			18.2	17.9	
181	**Natural Soil**	OMC + 4	1	11	4.2	11	0.31	22.2	22.0	22.0
182		OMC + 4	1	11	4.6			22.2	21.7	
183		OMC + 4	1	11	4.6			22.2	22.4	
184	**Natural Soil**	OMC + 4	7	10	6.3	12	1.41	22.2	22.0	22.3
185		OMC + 4	7	11	4.9			22.2	22.4	
186		OMC + 4	7	14	3.8			22.2	22.5	
187	**Natural Soil**	OMC + 4	28	9	4.3	10	0.73	22.2	21.5	21.6
188		OMC + 4	28	10	5.1			22.2	21.6	
189		OMC + 4	28	11	4.4			22.2	21.6	
190	**Soil-12% BCP A**	OMC - 4	1	40	6.2	41	0.82	14.2	15.0	14.9
191		OMC - 4	1	42	6.2			14.2	15.0	
192		OMC - 4	1	42	6.5			14.2	14.7	
193	**Soil-12% BCP A**	OMC - 4	7	47	5.4	47	1.07	14.2	15.2	15.1
194		OMC - 4	7	45	5.3			14.2	15.0	
195		OMC - 4	7	48	5.4			14.2	15.1	
196	**Soil-12% BCP A**	OMC - 4	28	46	8.2	49	2.77	14.2	14.7	14.1
197		OMC - 4	28	48	7.1			14.2	14.3	
198		OMC - 4	28	53	5.7			14.2	13.4	
199	**Soil-12% BCP A**	OMC	1	30	7.1	29	1.58	18.2	19.1	18.9
200		OMC	1	27	6.2			18.2	19.0	
201		OMC	1	31	7.2			18.2	18.7	
202	**Soil-12% BCP A**	OMC	7	36	5.2	37	0.76	18.2	18.8	18.9
203		OMC	7	38	5.3			18.2	19.1	
204		OMC	7	38	5.9			18.2	18.9	
205	**Soil-12% BCP A**	OMC	28	37	6.0	39	1.33	18.2	17.9	17.9
206		OMC	28	39	4.7			18.2	18.0	
207		OMC	28	40	5.8			18.2	17.9	
208	**Soil-12% BCP A**	OMC + 4	1	23	6.8	25	1.49	22.2	23.2	23.1
209		OMC + 4	1	26	6.0			22.2	22.9	
210		OMC + 4	1	26	6.2			22.2	23.3	
211	**Soil-12% BCP A**	OMC + 4	7	27	5.4	28	2.27	22.2	22.9	22.9
212		OMC + 4	7	26	5.8			22.2	22.8	
213		OMC + 4	7	31	5.6			22.2	23.1	
214	**Soil-12% BCP A**	OMC + 4	28	32	6.9	30	1.81	22.2	21.9	21.7
215		OMC + 4	28	28	5.7			22.2	21.4	
216		OMC + 4	28	31	5.1			22.2	21.8	

156

Table D-2 (Continued). Raw data of UCS for Soil 2 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
217	Soil-12% BCP B	OMC - 4	1	56	5.4	51	4.77	14.2	14.5	14.5
218		OMC - 4	1	45	5.4			14.2	14.6	
219		OMC - 4	1	52	5.6			14.2	14.4	
220	Soil-12% BCP B	OMC - 4	7	42	6.3	44	1.63	14.2	14.1	14.2
221		OMC - 4	7	46	6.3			14.2	14.4	
222		OMC - 4	7	44	5.6			14.2	14.0	
223	Soil-12% BCP B	OMC - 4	28	27	7.9	28	1.40	14.2	13.9	13.7
224		OMC - 4	28	30	8.4			14.2	13.6	
225		OMC - 4	28	29	7.3			14.2	13.5	
226	Soil-12% BCP B	OMC	1	26	8.4	29	2.49	18.2	18.8	18.3
227		OMC	1	28	6.0			18.2	18.4	
228		OMC	1	32	6.2			18.2	17.7	
229	Soil-12% BCP B	OMC	7	28	8.0	31	4.24	18.2	18.0	17.7
230		OMC	7	28	9.0			18.2	17.5	
231		OMC	7	37	8.0			18.2	17.5	
232	Soil-12% BCP B	OMC	28	23	9.6	23	1.25	18.2	17.7	17.8
233		OMC	28	22	9.8			18.2	17.9	
234		OMC	28	25	9.6			18.2	17.8	
235	Soil-12% BCP B	OMC + 4	1	17	4.9	19	1.51	22.2	21.3	21.6
236		OMC + 4	1	20	5.0			22.2	21.6	
237		OMC + 4	1	21	5.1			22.2	21.8	
238	Soil-12% BCP B	OMC + 4	7	27	10.0	22	4.09	22.2	22.0	21.7
239		OMC + 4	7	23	10.0			22.2	21.5	
240		OMC + 4	7	17	13.0			22.2	21.7	
241	Soil-12% BCP B	OMC + 4	28	17	13.4	16	1.23	22.2	22.2	21.8
242		OMC + 4	28	16	12.8			22.2	21.8	
243		OMC + 4	28	14	12.0			22.2	21.5	
244	Soil-12% BCP C	OMC - 4	1	25	5.4	28	2.39	14.2	14.4	14.3
245		OMC - 4	1	30	4.7			14.2	13.8	
246		OMC - 4	1	30	3.0			14.2	14.6	
247	Soil-12% BCP C	OMC - 4	7	55	3.3	58	3.87	14.2	14.1	13.9
248		OMC - 4	7	56	3.6			14.2	13.7	
249		OMC - 4	7	63	3.4			14.2	13.8	
250	Soil-12% BCP C	OMC - 4	28	85	2.8	84	8.22	14.2	14.9	14.4
251		OMC - 4	28	94	3.9			14.2	13.5	
252		OMC - 4	28	74	4.6			14.2	14.8	
253	Soil-12% BCP C	OMC	1	16	7.5	18	1.25	18.2	17.8	17.9
254		OMC	1	18	7.2			18.2	18.1	
255		OMC	1	19	7.3			18.2	18.0	
256	Soil-12% BCP C	OMC	7	29	4.9	28	0.85	18.2	17.4	17.7
257		OMC	7	28	4.8			18.2	17.7	
258		OMC	7	28	5.7			18.2	18.0	
259	Soil-12% BCP C	OMC	28	37	3.0	40	2.08	18.2	17.3	17.6
260		OMC	28	41	3.3			18.2	17.6	
261		OMC	28	42	5.3			18.2	18.0	
262	Soil-12% BCP C	OMC + 4	1	9	8.9	9	0.21	22.2	22.4	22.0
263		OMC + 4	1	9	9.2			22.2	21.6	
264		OMC + 4	1	9	9.0			22.2	21.9	
265	Soil-12% BCP C	OMC + 4	7	18	6.4	19	1.90	22.2	21.5	21.8
266		OMC + 4	7	17	6.5			22.2	22.1	
267		OMC + 4	7	22	7.0			22.2	21.6	
268	Soil-12% BCP C	OMC + 4	28	43	4.3	39	3.03	22.2	20.9	21.1
269		OMC + 4	28	38	4.1			22.2	21.2	
270		OMC + 4	28	35	4.5			22.2	21.4	
271	Soil-3% cement	OMC - 4	1	69	3.4	69	3.68	14.2	14.0	13.8
272		OMC - 4	1	65	3.4			14.2	13.5	
273		OMC - 4	1	74	3.0			14.2	13.8	
274	Soil-3% cement	OMC - 4	7	121	3.1	114	4.55	14.2	13.5	13.6
275		OMC - 4	7	111	5.6			14.2	14.2	
276		OMC - 4	7	112	3.9			14.2	13.1	
277	Soil-3% cement	OMC - 4	28	204	2.7	201	2.69	14.2	13.2	13.5
278		OMC - 4	28	197	2.6			14.2	13.5	
279		OMC - 4	28	201	3.6			14.2	13.9	
280	Soil-3% cement	OMC	1	82	3.8	87	6.75	18.2	17.9	18.0
281		OMC	1	82	3.4			18.2	18.3	
282		OMC	1	96	3.1			18.2	17.7	
283	Soil-3% cement	OMC	7	112	3.5	122	7.92	18.2	17.0	17.3
284		OMC	7	131	3.1			18.2	17.5	
285		OMC	7	123	3.7			18.2	17.2	

Table D-2 (Continued). Raw data of UCS for Soil 2 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
286		OMC	28	251	3.6			18.2	17.7	
287	Soil-3% cement	OMC	28	235	3.4	238	9.11	18.2	17.8	17.5
288		OMC	28	229	2.7			18.2	17.1	
289		OMC + 4	1	50	4.0			22.2	21.6	
290	Soil-3% cement	OMC + 4	1	62	3.5	58	5.44	22.2	21.4	21.5
291		OMC + 4	1	62	2.5			22.2	21.7	
292		OMC + 4	7	119	3.2			22.2	20.6	
293	Soil-3% cement	OMC + 4	7	108	3.8	112	5.08	22.2	20.8	20.7
294		OMC + 4	7	108	3.9			22.2	20.6	
295		OMC + 4	28	198	3.8			22.2	20.7	
296	Soil-3% cement	OMC + 4	28	188	2.9	195	5.28	22.2	21.1	20.9
297		OMC + 4	28	200	2.6			22.2	21.0	
298		OMC - 4	1	151	4.2			14.2	13.1	
299	Soil-6% cement	OMC - 4	1	166	4.0	159	6.15	14.2	13.6	13.4
300		OMC - 4	1	161	2.9			14.2	13.4	
301		OMC - 4	7	224	4.7			14.2	13.4	
302	Soil-6% cement	OMC - 4	7	200	4.5	225	20.42	14.2	13.4	13.8
303		OMC - 4	7	250	4.0			14.2	14.6	
304		OMC - 4	28	358	2.3			14.2	13.5	
305	Soil-6% cement	OMC - 4	28	345	3.5	357	9.60	14.2	13.7	13.5
306		OMC - 4	28	368	3.8			14.2	13.3	
307		OMC	1	137	4.6			18.2	17.6	
308	Soil-6% cement	OMC	1	149	4.1	145	5.75	18.2	17.8	17.8
309		OMC	1	150	4.8			18.2	18.0	
310		OMC	7	215	4.6			18.2	17.3	
311	Soil-6% cement	OMC	7	221	4.0	212	8.88	18.2	17.3	17.7
312		OMC	7	200	4.4			18.2	18.6	
313		OMC	28	352	3.0			18.2	17.8	
314	Soil-6% cement	OMC	28	387	3.7	384	24.53	18.2	17.7	17.6
315		OMC	28	412	3.1			18.2	17.2	
316		OMC + 4	1	130	3.4			22.2	21.4	
317	Soil-6% cement	OMC + 4	1	131	4.1	129	1.55	22.2	20.9	21.1
318		OMC + 4	1	127	3.5			22.2	21.0	
319		OMC + 4	7	191	4.0			22.2	20.9	
320	Soil-6% cement	OMC + 4	7	191	4.4	188	4.53	22.2	21.4	21.0
321		OMC + 4	7	181	5.2			22.2	20.8	
322		OMC + 4	28	270	3.7			22.2	21.7	
323	Soil-6% cement	OMC + 4	28	241	2.6	256	11.64	22.2	21.3	21.4
324		OMC + 4	28	256	3.0			22.2	21.2	
325		OMC - 4	1	251	5.4			14.2	14.8	
326	Soil-12 %Cement	OMC - 4	1	254	4.2	243	13.02	14.2	13.7	14.0
327		OMC - 4	1	225	5.8			14.2	13.4	
328		OMC - 4	7	283	3.9			14.2	13.9	
329	Soil-12 %Cement	OMC - 4	7	303	2.8	294	8.22	14.2	14.6	14.4
330		OMC - 4	7	295	3.3			14.2	14.7	
331		OMC - 4	28	429	4.1			14.2	13.8	
332	Soil-12 %Cement	OMC - 4	28	456	5.1	435	14.83	14.2	13.6	13.7
333		OMC - 4	28	421	3.5			14.2	13.6	
334		OMC	1	291	3.9			18.2	17.5	
335	Soil-12 %Cement	OMC	1	293	5.6	282	13.95	18.2	17.7	17.6
336		OMC	1	263	4.2			18.2	17.7	
337		OMC	7	340	3.8			18.2	18.5	
338	Soil-12 %Cement	OMC	7	353	3.2	336	15.77	18.2	18.4	18.2
339		OMC	7	315	4.2			18.2	17.8	
340		OMC	28	451	4.2			18.2	16.8	
341	Soil-12 %Cement	OMC	28	449	5.3	456	8.95	18.2	17.5	17.3
342		OMC	28	469	5.1			18.2	17.6	
343		OMC + 4	1	199	3.5			22.2	20.7	
344	Soil-12 %Cement	OMC + 4	1	216	3.7	204	8.61	22.2	22.3	21.4
345		OMC + 4	1	197	3.0			22.2	21.2	
346		OMC + 4	7	278	3.0			22.2	22.0	
347	Soil-12 %Cement	OMC + 4	7	265	3.8	274	6.53	22.2	21.4	21.7
348		OMC + 4	7	279	5.3			22.2	21.6	
349		OMC + 4	28	302	2.1			22.2	22.1	
350	Soil-12 %Cement	OMC + 4	28	312	5.4	313	9.55	22.2	20.8	21.5
351		OMC + 4	28	325	2.8			22.2	21.8	

158

Table D-3. Raw data of UCS for Soil 3 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
316		OMC - 4	1	73	3.6			9.5	9.7	
317	Natural Soil	OMC - 4	1	73	2.7	68	7.92	9.5	9.4	9.6
318		OMC - 4	1	56	4.4			9.5	9.6	
319		OMC - 4	7	63	4.5			9.5	9.7	
320	Natural Soil	OMC - 4	7	75	4.2	67	5.66	9.5	9.3	9.5
321		OMC - 4	7	63	3.5			9.5	9.6	
322		OMC - 4	28	74	3.2			9.5	9.2	
323	Natural Soil	OMC - 4	28	70	2.9	66	8.78	9.5	9.0	9.0
324		OMC - 4	28	54	1.8			9.5	8.9	
325		OMC	1	34	6.5			13.5	13.2	
326	Natural Soil	OMC	1	37	3.9	33	3.67	13.5	13.5	13.4
327		OMC	1	28	4.8			13.5	13.6	
328		OMC	7	34	5.5			13.5	13.7	
329	Natural Soil	OMC	7	27	6.5	30	3.09	13.5	13.1	13.4
330		OMC	7	28	6.0			13.5	13.5	
331		OMC	28	29	6.1			13.5	12.9	
332	Natural Soil	OMC	28	30	5.2	30	0.54	13.5	13.1	13.0
333		OMC	28	29	7.2			13.5	13.1	
334		OMC + 4	1	24	4.4			17.5	17.4	
335	Natural Soil	OMC + 4	1	23	4.0	26	2.86	17.5	17.7	17.6
336		OMC + 4	1	30	4.2			17.5	17.8	
337		OMC + 4	7	21	6.3			17.5	17.7	
338	Natural Soil	OMC + 4	7	28	5.4	23	3.01	17.5	17.9	17.7
339		OMC + 4	7	22	5.6			17.5	17.4	
340		OMC + 4	28	29	5.6			17.5	17.0	
341	Natural Soil	OMC + 4	28	28	5.6	24	6.65	17.5	16.8	17.0
342		OMC + 4	28	14	8.7			17.5	17.1	
343		OMC - 4	1	81	14.8			9.5	10.3	
344	Soil-12% BCP A	OMC - 4	1	80	13.4	79	1.87	9.5	10.4	10.2
345		OMC - 4	1	77	14.0			9.5	10.0	
346		OMC - 4	7	119	9.6			9.5	9.8	
347	Soil-12% BCP A	OMC - 4	7	112	9.9	122	9.11	9.5	10.1	9.8
348		OMC - 4	7	134	9.0			9.5	9.5	
349		OMC - 4	28	149	8.5			9.5	10.3	
350	Soil-12% BCP A	OMC - 4	28	152	7.9	150	2.17	9.5	9.9	10.1
351		OMC - 4	28	147	7.9			9.5	10.1	
352		OMC	1	45	15.0			13.5	13.9	
353	Soil-12% BCP A	OMC	1	53	14.4	48	3.61	13.5	13.8	14.0
354		OMC	1	45	17.7			13.5	14.2	
355		OMC	7	84	8.1			13.5	13.7	
356	Soil-12% BCP A	OMC	7	98	7.2	90	5.78	13.5	13.6	13.8
357		OMC	7	88	8.0			13.5	14.2	
358		OMC	28	111	7.8			13.5	13.2	
359	Soil-12% BCP A	OMC	28	108	7.9	112	3.42	13.5	13.8	13.5
360		OMC	28	117	7.6			13.5	13.4	
361		OMC + 4	1	39	10.9			17.5	17.6	
362	Soil-12% BCP A	OMC + 4	1	35	11.6	37	1.59	17.5	18.3	18.0
363		OMC + 4	1	37	11.8			17.5	18.1	
364		OMC + 4	7	46	11.4			17.5	17.3	
365	Soil-12% BCP A	OMC + 4	7	45	9.2	47	2.17	17.5	17.8	17.4
366		OMC + 4	7	50	9.0			17.5	17.2	
367		OMC + 4	28	60	8.8			17.5	17.2	
368	Soil-12% BCP A	OMC + 4	28	61	8.6	60	1.31	17.5	18.0	17.8
369		OMC + 4	28	58	8.7			17.5	18.1	

Table D-3 (Continued). Raw data of UCS for Soil 3 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
370		OMC - 4	1	116	5.3			9.5	9.3	
371	Soil-12% BCP B	OMC - 4	1	109	5.7	115	5.24	9.5	9.6	9.4
372		OMC - 4	1	121	6.7			9.5	9.4	
373		OMC - 4	7	95	8.4			9.5	9.2	
374	Soil-12% BCP B	OMC - 4	7	109	6.6	94	13.44	9.5	9.1	9.3
375		OMC - 4	7	77	7.8			9.5	9.5	
376		OMC - 4	28	75	9.5			9.5	8.8	
377	Soil-12% BCP B	OMC - 4	28	76	7.6	81	8.01	9.5	9.0	9.0
378		OMC - 4	28	92	8.0			9.5	9.1	
379		OMC	1	64	7.4			13.5	13.2	
380	Soil-12% BCP B	OMC	1	80	5.5	73	6.71	13.5	13.1	13.3
381		OMC	1	75	5.8			13.5	13.5	
382		OMC	7	72	9.6			13.5	13.6	
383	Soil-12% BCP B	OMC	7	48	8.5	57	10.85	13.5	13.4	13.4
384		OMC	7	50	7.9			13.5	13.3	
385		OMC	28	36	7.3			13.5	13.5	
386	Soil-12% BCP B	OMC	28	44	10.0	51	15.01	13.5	13.4	13.4
387		OMC	28	71	8.8			13.5	13.3	
388		OMC + 4	1	63	8.9			17.5	17.8	
389	Soil-12% BCP B	OMC + 4	1	63	6.1	64	1.85	17.5	17.7	17.6
390		OMC + 4	1	67	6.5			17.5	17.4	
391		OMC + 4	7	41	7.6			17.5	17.3	
392	Soil-12% BCP B	OMC + 4	7	52	7.2	46	4.40	17.5	17.6	17.5
393		OMC + 4	7	45	8.1			17.5	17.6	
394		OMC + 4	28	28	8.8			17.5	17.0	
395	Soil-12% BCP B	OMC + 4	28	34	9.2	28	3.97	17.5	17.1	17.1
396		OMC + 4	28	24	9.7			17.5	17.2	
397		OMC - 4	1	124	5.1			9.5	9.9	
398	Soil-3 %Cement	OMC - 4	1	132	3.4	128	3.43	9.5	9.5	9.5
399		OMC - 4	1	128	4.3			9.5	9.1	
400		OMC - 4	7	141	5.3			9.5	8.9	
401	Soil-3 %Cement	OMC - 4	7	170	3.5	155	11.99	9.5	8.7	8.7
402		OMC - 4	7	153	3.9			9.5	8.7	
403		OMC - 4	28	221	3.2			9.5	8.2	
404	Soil-3 %Cement	OMC - 4	28	199	3.0	214	10.26	9.5	8.0	8.2
405		OMC - 4	28	221	2.7			9.5	8.5	
406		OMC	1	123	4.2			13.5	12.9	
407	Soil-3 %Cement	OMC	1	122	3.7	123	0.33	13.5	13.0	13.0
408		OMC	1	123	3.6			13.5	13.0	
409		OMC	7	145	4.2			13.5	12.8	
410	Soil-3 %Cement	OMC	7	150	4.4	140	10.17	13.5	12.9	12.9
411		OMC	7	126	4.7			13.5	12.9	
412		OMC	28	169	3.0			13.5	12.9	
413	Soil-3 %Cement	OMC	28	182	3.0	174	5.99	13.5	12.4	12.6
414		OMC	28	169	3.6			13.5	12.4	
415		OMC + 4	1	107	4.5			17.5	17.4	
416	Soil-3 %Cement	OMC + 4	1	113	4.1	111	3.14	17.5	17.2	17.3
417		OMC + 4	1	113	4.0			17.5	17.3	
418		OMC + 4	7	130	4.7			17.5	17.0	
419	Soil-3 %Cement	OMC + 4	7	133	4.1	135	4.64	17.5	16.9	16.8
420		OMC + 4	7	141	3.4			17.5	16.6	
421		OMC + 4	28	154	3.3			17.5	16.9	
422	Soil-3 %Cement	OMC + 4	28	161	3.2	158	3.18	17.5	16.9	16.9
423		OMC + 4	28	160	3.6			17.5	17.0	

Table D-3 (Continued). Raw data of UCS for Soil 3 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
424		OMC - 4	1	213	4.6			9.5	9.2	
425	Soil-6 %Cement	OMC - 4	1	214	3.9	222	11.63	9.5	9.3	9.1
426		OMC - 4	1	238	3.5			9.5	8.9	
427		OMC - 4	7	270	4.0			9.5	9.0	
428	Soil-6 %Cement	OMC - 4	7	285	3.1	277	6.11	9.5	9.5	9.2
429		OMC - 4	7	276	3.5			9.5	9.2	
430		OMC - 4	28	348	3.5			9.5	8.9	
431	Soil-6 %Cement	OMC - 4	28	375	3.5	355	13.95	9.5	8.8	8.9
432		OMC - 4	28	344	4.6			9.5	9.0	
433		OMC	1	192	5.3			13.5	13.1	
434	Soil-6 %Cement	OMC	1	200	4.7	200	6.17	13.5	13.3	13.3
435		OMC	1	207	3.4			13.5	13.5	
436		OMC	7	288	3.7			13.5	12.6	
437	Soil-6 %Cement	OMC	7	261	5.2	274	11.06	13.5	12.8	12.8
438		OMC	7	272	4.7			13.5	12.9	
439		OMC	28	295	4.2			13.5	13.0	
440	Soil-6 %Cement	OMC	28	307	4.0	306	9.15	13.5	13.1	12.9
441		OMC	28	318	4.5			13.5	12.7	
442		OMC + 4	1	163	3.9			17.5	17.0	
443	Soil-6 %Cement	OMC + 4	1	170	4.3	170	5.47	17.5	17.3	17.3
444		OMC + 4	1	177	3.6			17.5	17.7	
445		OMC + 4	7	264	3.9			17.5	16.2	
446	Soil-6 %Cement	OMC + 4	7	224	5.2	245	16.45	17.5	16.3	16.2
447		OMC + 4	7	247	4.4			17.5	16.1	
448		OMC + 4	28	284	3.9			17.5	16.4	
449	Soil-6 %Cement	OMC + 4	28	307	4.1	301	11.99	17.5	16.3	16.3
450		OMC + 4	28	312	4.2			17.5	16.3	
451		OMC - 4	1	330	5.4			9.5	9.3	
452	Soil-12 %Cement	OMC - 4	1	315	3.7	324	6.39	9.5	9.4	9.5
453		OMC - 4	1	326	4.8			9.5	9.7	
454		OMC - 4	7	431	4.2			9.5	8.8	
455	Soil-12 %Cement	OMC - 4	7	483	4.2	442	30.56	9.5	8.0	8.5
456		OMC - 4	7	411	3.8			9.5	8.5	
457		OMC - 4	28	540	5.4			9.5	8.4	
458	Soil-12 %Cement	OMC - 4	28	553	5.2	538	12.55	9.5	8.2	8.3
459		OMC - 4	28	522	4.5			9.5	8.3	
460		OMC	1	313	4.4			13.5	13.1	
461	Soil-12 %Cement	OMC	1	333	4.9	334	17.33	13.5	13.5	13.3
462		OMC	1	356	4.1			13.5	13.2	
463		OMC	7	471	5.1			13.5	12.8	
464	Soil-12 %Cement	OMC	7	465	5.1	474	9.00	13.5	12.6	12.7
465		OMC	7	486	4.6			13.5	12.6	
466		OMC	28	589	5.6			13.5	12.4	
467	Soil-12 %Cement	OMC	28	610	4.8	607	12.95	13.5	12.6	12.5
468		OMC	28	621	4.7			13.5	12.4	
469		OMC + 4	1	279	3.7			17.5	17.1	
470	Soil-12 %Cement	OMC + 4	1	293	3.7	299	18.71	17.5	16.6	16.7
471		OMC + 4	1	324	4.1			17.5	16.4	
472		OMC + 4	7	359	4.7			17.5	16.5	
473	Soil-12 %Cement	OMC + 4	7	381	5.4	370	8.73	17.5	16.6	16.4
474		OMC + 4	7	369	5.1			17.5	16.2	
475		OMC + 4	28	520	3.5			17.5	15.8	
476	Soil-12 %Cement	OMC + 4	28	568	4.5	556	26.03	17.5	15.9	15.8
477		OMC + 4	28	580	3.8			17.5	15.7	

161

Table D-4. Raw data of UCS for Soil 4 set

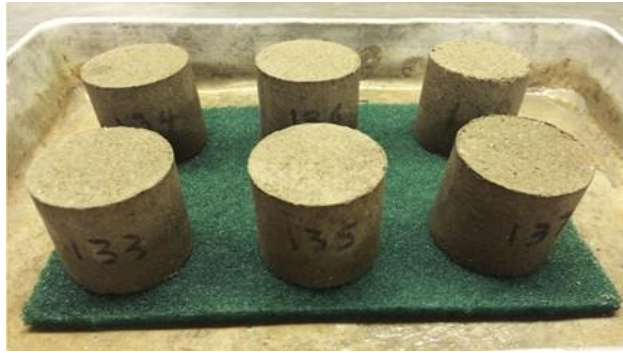| Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
478	Natural Soil	OMC - 4	1	26	4.0	27	1.65	8.0	8.2	8.3
479	Natural Soil	OMC - 4	1	30	4.3			8.0	8.3	
480		OMC - 4	1	27	3.5			8.0	8.4	
481	Natural Soil	OMC - 4	7	27	2.5	27	1.25	8.0	8.2	8.0
482	Natural Soil	OMC - 4	7	29	2.7			8.0	7.9	
483		OMC - 4	7	26	3.2			8.0	7.9	
484	Natural Soil	OMC - 4	28	30	2.4	35	3.60	8.0	7.5	7.7
485	Natural Soil	OMC - 4	28	36	2.9			8.0	7.8	
486		OMC - 4	28	39	2.3			8.0	7.7	
487	Natural Soil	OMC	1	11	4.8	12	1.53	12.0	11.6	11.9
488	Natural Soil	OMC	1	12	4.4			12.0	12.3	
489		OMC	1	14	4.5			12.0	11.9	
490	Natural Soil	OMC	7	14	3.6	14	0.98	12.0	12.0	12.1
491	Natural Soil	OMC	7	15	3.7			12.0	12.1	
492		OMC	7	13	3.5			12.0	12.1	
493	Natural Soil	OMC	28	14	3.6	15	1.11	12.0	11.5	11.6
494	Natural Soil	OMC	28	16	2.8			12.0	11.8	
495		OMC	28	15	3.4			12.0	11.4	
496	Natural Soil	OMC + 4	1	8	6.3	9	0.29	16.0	16.0	15.7
497	Natural Soil	OMC + 4	1	8	6.9			16.0	15.7	
498		OMC + 4	1	9	6.3			16.0	15.5	
499	Natural Soil	OMC + 4	7	10	5.0	11	0.85	16.0	15.6	15.8
500	Natural Soil	OMC + 4	7	12	4.9			16.0	15.8	
501		OMC + 4	7	12	5.0			16.0	15.9	
502	Natural Soil	OMC + 4	28	10	6.2	11	1.18	16.0	15.9	15.9
503	Natural Soil	OMC + 4	28	10	4.9			16.0	15.8	
504		OMC + 4	28	13	4.2			16.0	16.0	
505	Soil-12% BCP A	OMC - 4	1	44	12.0	47	3.00	8.0	9.3	9.5
506	Soil-12% BCP A	OMC - 4	1	45	12.8			8.0	9.4	
507		OMC - 4	1	51	12.7			8.0	9.7	
508	Soil-12% BCP A	OMC - 4	7	82	11.1	79	2.90	8.0	8.8	8.5
509	Soil-12% BCP A	OMC - 4	7	79	15.0			8.0	8.0	
510		OMC - 4	7	75	15.0			8.0	8.5	
511	Soil-12% BCP A	OMC - 4	28	99	10.8	100	3.49	8.0	8.4	8.3
512	Soil-12% BCP A	OMC - 4	28	105	11.0			8.0	8.2	
513		OMC - 4	28	97	11.3			8.0	8.3	
514	Soil-12% BCP A	OMC	1	36	11.2	36	0.96	12.0	13.1	13.3
515	Soil-12% BCP A	OMC	1	37	10.8			12.0	13.5	
516		OMC	1	34	10.2			12.0	13.2	
517	Soil-12% BCP A	OMC	7	55	7.0	52	2.01	12.0	12.8	12.7
518	Soil-12% BCP A	OMC	7	50	7.7			12.0	12.6	
519		OMC	7	52	7.9			12.0	12.6	
520	Soil-12% BCP A	OMC	28	69	6.8	70	1.08	12.0	12.4	12.5
521	Soil-12% BCP A	OMC	28	69	7.3			12.0	12.6	
522		OMC	28	71	7.2			12.0	12.4	
523	Soil-12% BCP A	OMC + 4	1	20	10.9	21	1.01	16.0	17.1	16.7
524	Soil-12% BCP A	OMC + 4	1	23	10.3			16.0	16.6	
525		OMC + 4	1	21	10.2			16.0	16.4	
526	Soil-12% BCP A	OMC + 4	7	26	7.6	28	1.61	16.0	16.5	16.4
527	Soil-12% BCP A	OMC + 4	7	29	7.9			16.0	16.6	
528		OMC + 4	7	28	6.9			16.0	16.2	
529	Soil-12% BCP A	OMC + 4	28	39	6.4	40	1.43	16.0	15.8	15.8
530	Soil-12% BCP A	OMC + 4	28	40	6.6			16.0	15.9	
531		OMC + 4	28	42	6.0			16.0	15.7	

Table D-4 (Continued). Raw data of UCS for Soil 4 set

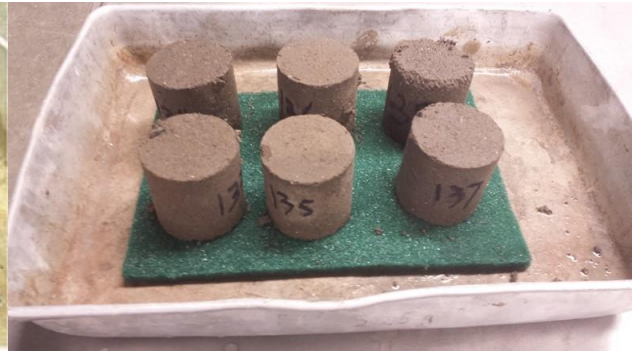| Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
532		OMC - 4	1	117	6.6			8.0	7.7	
533	Soil-12% BCP B	OMC - 4	1	121	6.9	115	5.59	8.0	7.8	7.8
534		OMC - 4	1	108	6.3			8.0	8.0	
535		OMC - 4	7	105	6.4			8.0	8.2	
536	Soil-12% BCP B	OMC - 4	7	108	7.2	112	7.41	8.0	8.0	8.0
537		OMC - 4	7	122	6.4			8.0	7.7	
538		OMC - 4	28	97	6.2			8.0	7.8	
539	Soil-12% BCP B	OMC - 4	28	83	7.3	87	7.41	8.0	7.7	7.7
540		OMC - 4	28	80	7.4			8.0	7.5	
541		OMC	1	76	8.4			12.0	11.9	
542	Soil-12% BCP B	OMC	1	68	7.0	71	3.40	12.0	12.3	12.0
543		OMC	1	70	7.2			12.0	11.9	
544		OMC	7	55	8.2			12.0	11.5	
545	Soil-12% BCP B	OMC	7	51	7.9	55	3.68	12.0	11.9	11.8
546		OMC	7	60	8.0			12.0	12.0	
547		OMC	28	32	8.5			12.0	11.6	
548	Soil-12% BCP B	OMC	28	37	8.0	33	2.25	12.0	11.4	11.7
549		OMC	28	32	8.6			12.0	12.2	
550		OMC + 4	1	39	7.7			16.0	16.6	
551	Soil-12% BCP B	OMC + 4	1	37	8.5	34	5.87	16.0	16.4	16.4
552		OMC + 4	1	26	7.9			16.0	16.1	
553		OMC + 4	7	39	8.9			16.0	15.9	
554	Soil-12% BCP B	OMC + 4	7	35	9.2	34	4.05	16.0	16.1	15.9
555		OMC + 4	7	29	7.5			16.0	15.7	
556		OMC + 4	28	23	9.6			16.0	15.4	
557	Soil-12% BCP B	OMC + 4	28	26	9.6	25	1.47	16.0	15.8	15.7
558		OMC + 4	28	25	9.4			16.0	16.0	
559		OMC - 4	1	77	3.7			8.0	9.9	
560	Soil-3 %Cement	OMC - 4	1	71	4.5	72	3.40	8.0	9.5	9.5
561		OMC - 4	1	69	3.9			8.0	9.1	
562		OMC - 4	7	146	3.3			8.0	8.9	
563	Soil-3 %Cement	OMC - 4	7	154	3.6	147	5.71	8.0	8.7	8.7
564		OMC - 4	7	140	4.4			8.0	8.7	
565		OMC - 4	28	176	2.8			8.0	8.2	
566	Soil-3 %Cement	OMC - 4	28	179	3.7	181	4.98	8.0	8.0	8.2
567		OMC - 4	28	188	3.7			8.0	8.5	
568		OMC	1	45	3.4			12.0	12.9	
569	Soil-3 %Cement	OMC	1	47	3.9	45	1.48	12.0	13.0	13.0
570		OMC	1	43	4.2			12.0	13.0	
571		OMC	7	128	2.7			12.0	12.8	
572	Soil-3 %Cement	OMC	7	132	2.9	131	2.04	12.0	12.9	12.9
573		OMC	7	132	3.3			12.0	12.9	
574		OMC	28	198	4.1			12.0	12.9	
575	Soil-3 %Cement	OMC	28	185	3.6	194	6.19	12.0	12.4	12.6
576		OMC	28	199	3.9			12.0	12.4	
577		OMC + 4	1	29	4.3			16.0	17.4	
578	Soil-3 %Cement	OMC + 4	1	28	3.9	28	0.62	16.0	17.2	17.3
579		OMC + 4	1	27	4.1			16.0	17.3	
580		OMC + 4	7	95	3.5			16.0	17.0	
581	Soil-3 %Cement	OMC + 4	7	92	4.4	96	3.64	16.0	16.9	16.8
582		OMC + 4	7	100	3.5			16.0	16.6	
583		OMC + 4	28	133	3.1			16.0	16.9	
584	Soil-3 %Cement	OMC + 4	28	143	4.0	139	4.05	16.0	16.9	16.9
585		OMC + 4	28	140	3.0			16.0	17.0	

Table D-4 (Continued). Raw data of UCS for Soil 4 set

Sample No.	Sample Type	Moisture Level	Curing Days	Peak Stress psi	Axial Strain %	Average Peak Stress, psi	Stress Standard Deviation	Target MC, %	Actual MC, %	Avg. Act, %
586		OMC - 4	1	116	4.7			8.0	9.2	
587	Soil-6 %Cement	OMC - 4	1	120	4.5	117	2.72	8.0	9.3	9.1
588		OMC - 4	1	114	4.4			8.0	8.9	
589		OMC - 4	7	234	4.3			8.0	9.0	
590	Soil-6 %Cement	OMC - 4	7	210	4.1	225	10.40	8.0	9.5	9.2
591		OMC - 4	7	229	4.4			8.0	9.2	
592		OMC - 4	28	260	3.3			8.0	8.9	
593	Soil-6 %Cement	OMC - 4	28	257	3.6	255	5.12	8.0	8.8	8.9
594		OMC - 4	28	248	4.2			8.0	9.0	
595		OMC	1	81	4.8			12.0	13.1	
596	Soil-6 %Cement	OMC	1	70	5.7	77	4.93	12.0	13.3	13.3
597		OMC	1	80	5.3			12.0	13.5	
598		OMC	7	238	3.8			12.0	12.6	
599	Soil-6 %Cement	OMC	7	277	3.3	255	16.49	12.0	12.8	12.8
600		OMC	7	248	3.5			12.0	12.9	
601		OMC	28	274	4.4			12.0	13.0	
602	Soil-6 %Cement	OMC	28	298	3.7	291	12.49	12.0	13.1	12.9
603		OMC	28	302	3.6			12.0	12.7	
604		OMC + 4	1	53	4.6			16.0	17.0	
605	Soil-6 %Cement	OMC + 4	1	61	6.3	57	2.96	16.0	17.3	17.3
606		OMC + 4	1	57	5.2			16.0	17.7	
607		OMC + 4	7	198	3.6			16.0	16.2	
608	Soil-6 %Cement	OMC + 4	7	201	4.0	208	12.60	16.0	16.3	16.2
609		OMC + 4	7	226	4.1			16.0	16.1	
610		OMC + 4	28	221	3.6			16.0	16.4	
611	Soil-6 %Cement	OMC + 4	28	216	2.8	223	7.02	16.0	16.3	16.3
612		OMC + 4	28	233	6.1			16.0	16.3	
613		OMC - 4	1	198	4.1			8.0	10.3	
614	Soil-12 %Cement	OMC - 4	1	204	3.7	197	5.57	8.0	10.4	10.2
615		OMC - 4	1	190	3.8			8.0	10.0	
616		OMC - 4	7	345	5.3			8.0	9.8	
617	Soil-12 %Cement	OMC - 4	7	389	4.5	366	17.97	8.0	10.1	9.8
618		OMC - 4	7	364	3.8			8.0	9.5	
619		OMC - 4	28	485	4.7			8.0	10.3	
620	Soil-12 %Cement	OMC - 4	28	507	4.6	510	22.20	8.0	9.9	10.1
621		OMC - 4	28	539	5.0			8.0	10.1	
622		OMC	1	136	4.4			12.0	13.9	
623	Soil-12 %Cement	OMC	1	135	3.9	136	1.03	12.0	13.8	14.0
624		OMC	1	137	4.6			12.0	14.2	
625		OMC	7	426	5.6			12.0	13.7	
626	Soil-12 %Cement	OMC	7	454	4.4	438	12.09	12.0	13.6	13.8
627		OMC	7	434	4.5			12.0	14.2	
628		OMC	28	600	4.5			12.0	13.2	
629	Soil-12 %Cement	OMC	28	610	4.5	597	11.72	12.0	13.8	13.5
630		OMC	28	582	3.7			12.0	13.4	
631		OMC + 4	1	124	4.5			16.0	17.6	
632	Soil-12 %Cement	OMC + 4	1	119	4.1	119	3.24	16.0	18.3	18.0
633		OMC + 4	1	116	3.7			16.0	18.1	
634		OMC + 4	7	420	5.2			16.0	17.3	
635	Soil-12 %Cement	OMC + 4	7	409	4.0	406	12.63	16.0	17.8	17.4
636		OMC + 4	7	389	4.8			16.0	17.2	
637		OMC + 4	28	451	5.1			16.0	17.2	
638	Soil-12 %Cement	OMC + 4	28	456	5.6	452	2.87	16.0	18.0	17.8
639		OMC + 4	28	450	5.3			16.0	18.1	

(a) 1st cycle

(b) 2nd cycle
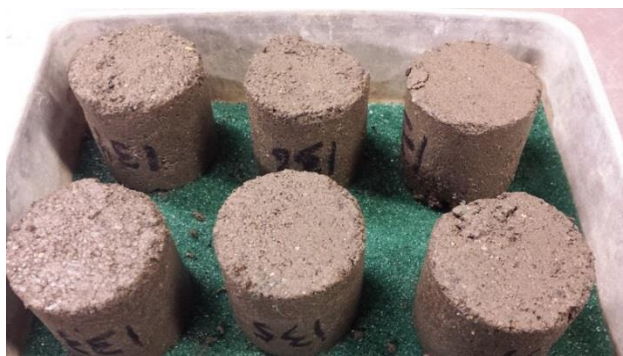
(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-1. Images of 1-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle
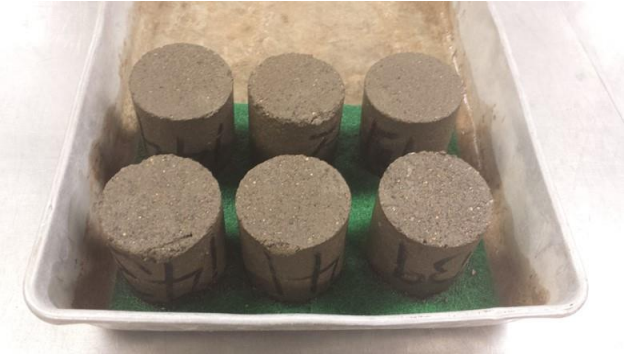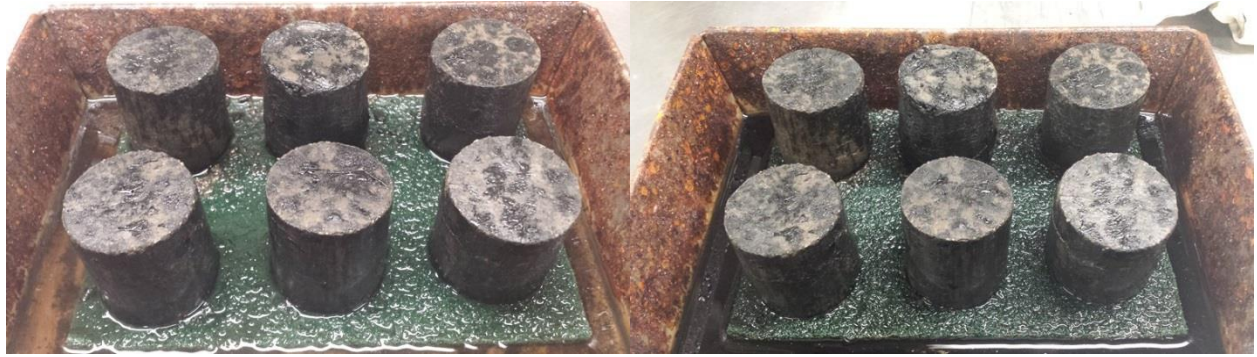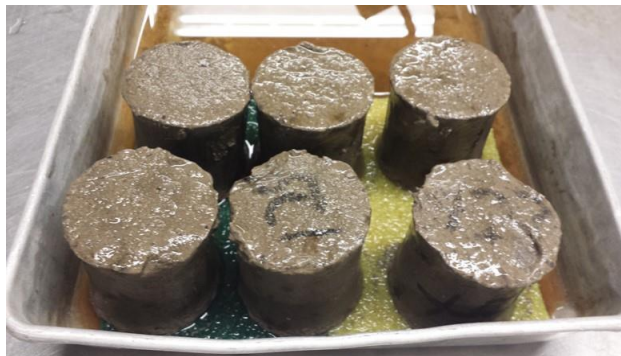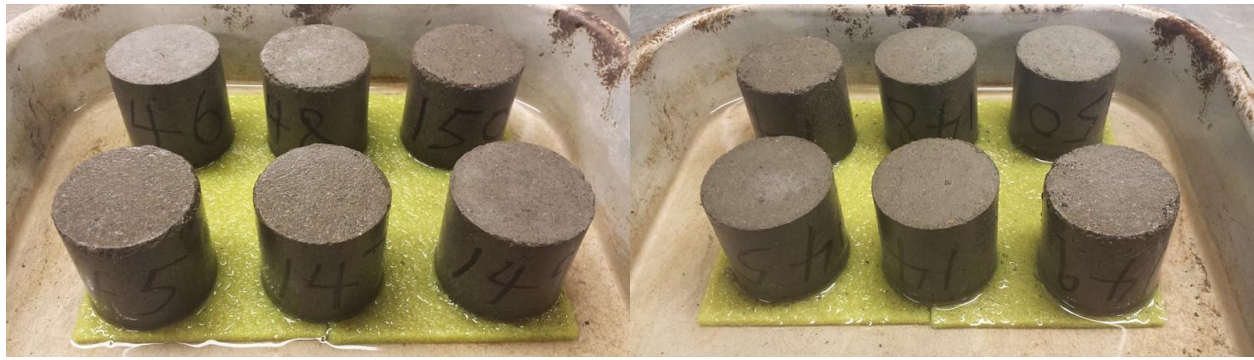

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-1 (Continued). Images of 1-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-2. Images of 7-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

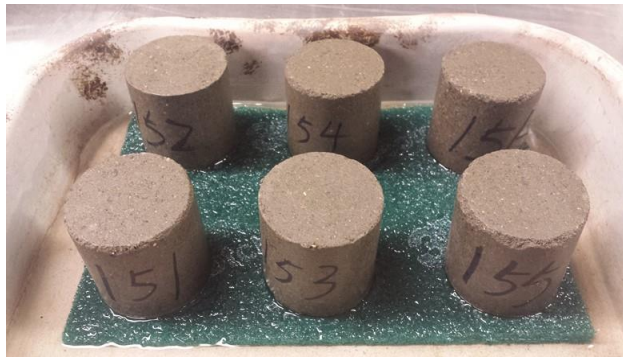(k) 11th cycle

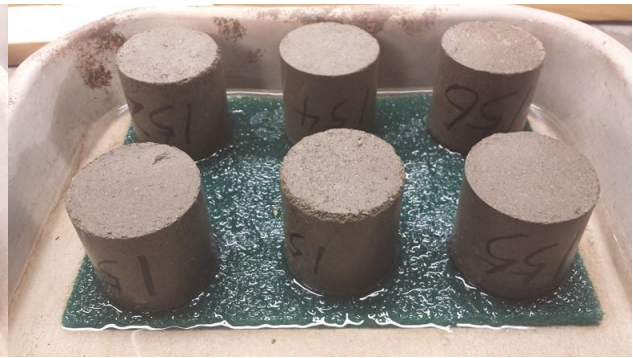(l) 12th cycle

Figure E-2 (Continued). Images of 7-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test
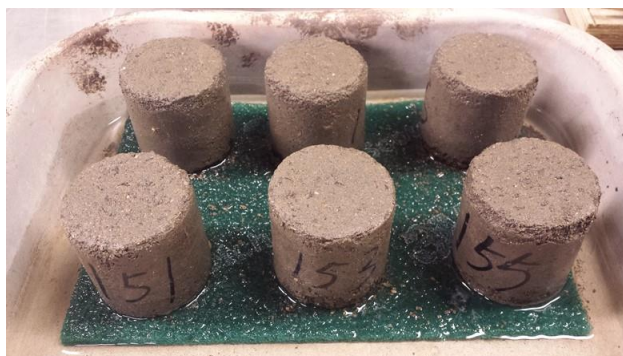
(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-3. Images of 1-day cured and 12% of BCP A-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-3 (Continued). Images of 1-day cured and 12% of BCP A-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle   (b) 2nd cycle

(c) 3rd cycle   (d) 4th cycle

(e) 5th cycle   (f) 6th cycle

Figure E-4. Images of 7-day cured and 12% of BCP A-treated Soil 1 for 12 cycles of freeze-thaw durability test
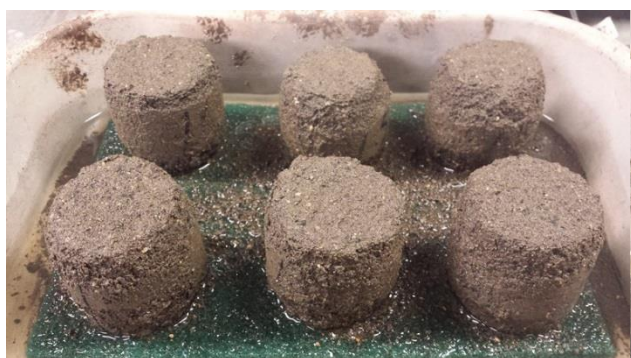
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-4 (Continued). Images of 7-day cured and 12% of BCP A-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-5. Images of 1-day cured and 12% of BCP B-treated Soil 1 for 12 cycles of freeze-thaw durability test
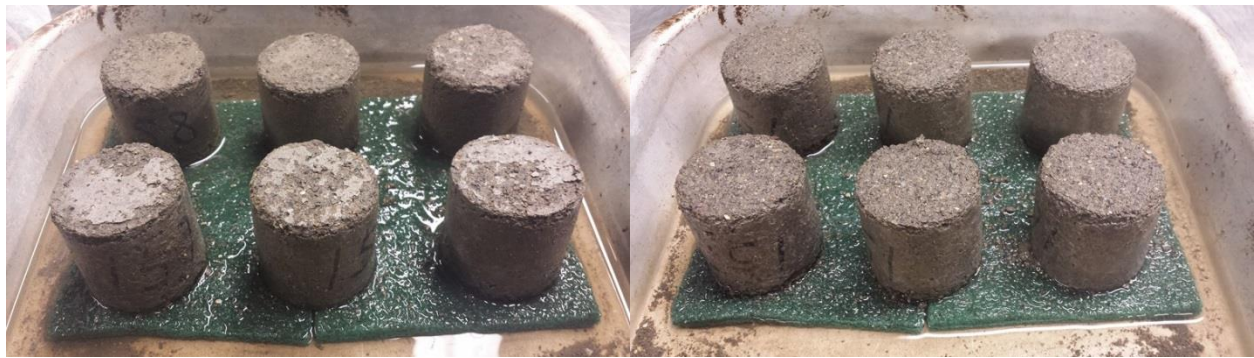
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-5 (Continued). Images of 1-day cured and 12% of BCP B-treated Soil 1 for 12 cycles of freeze-thaw durability test
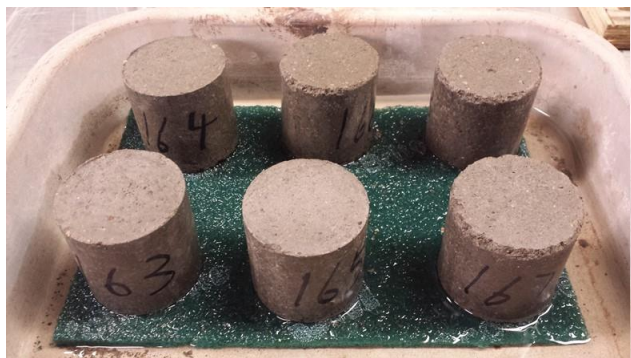
(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-6. Images of 7-day cured and 12% of BCP B-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-6 (Continued). Images of 7-day cured and 12% of BCP B-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle
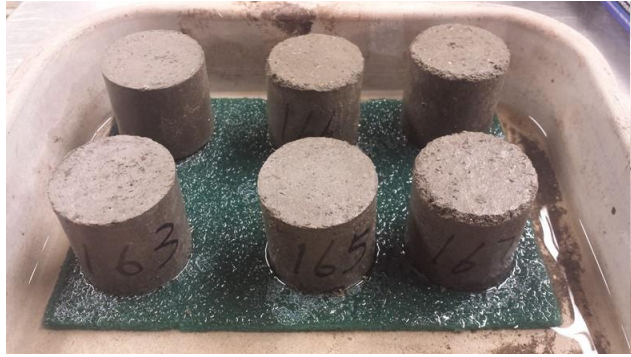
(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-7. Images of 1-day cured and 3% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test
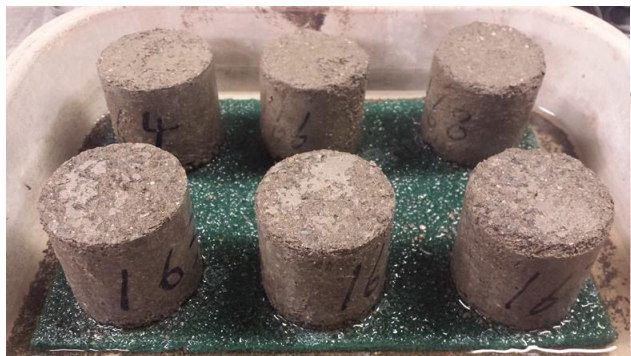
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-7 (Continued). Images of 1-day cured and 3% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-8. Images of 7-day cured and 3% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-8 (Continued). Images of 7-day cured and 3% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test
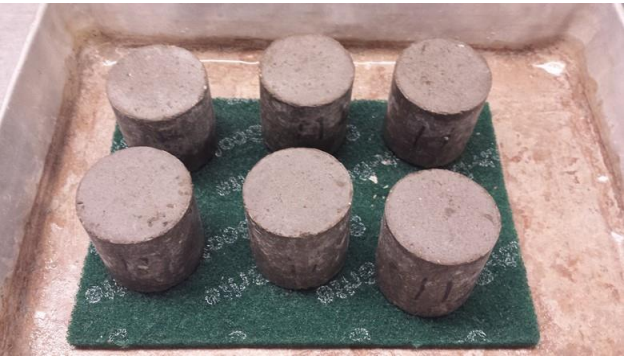
(a) 1st cycle   (b) 2nd cycle

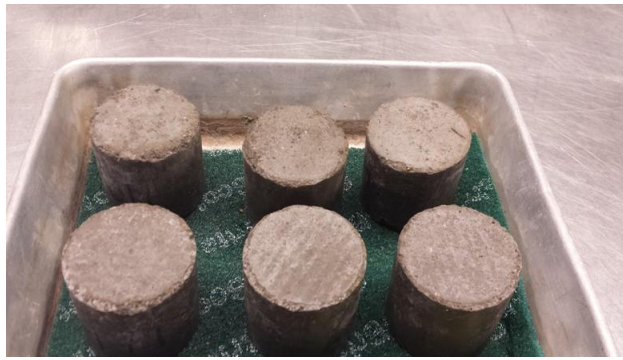(c) 3rd cycle   (d) 4th cycle

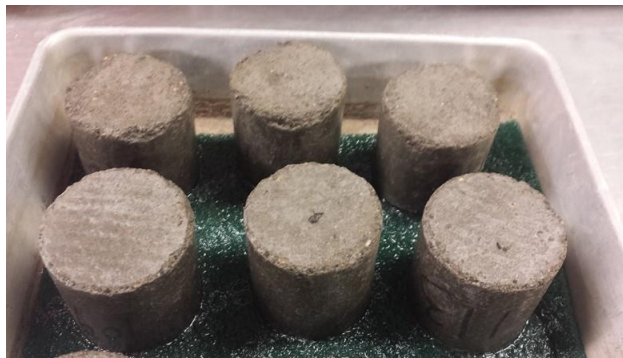(e) 5th cycle   (f) 6th cycle

Figure E-9. Images of 1-day cured and 6% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test
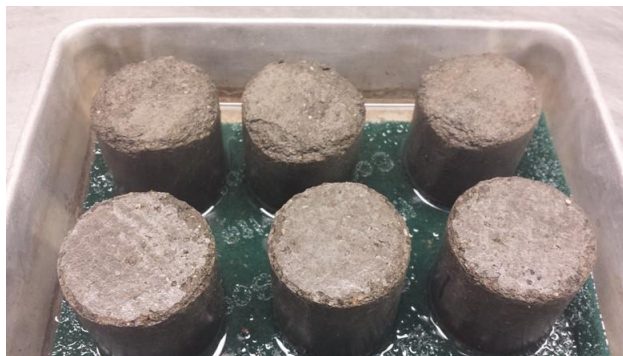
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-9 (Continued). Images of 1-day cured and 6% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-10. Images of 7-day cured and 6% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle
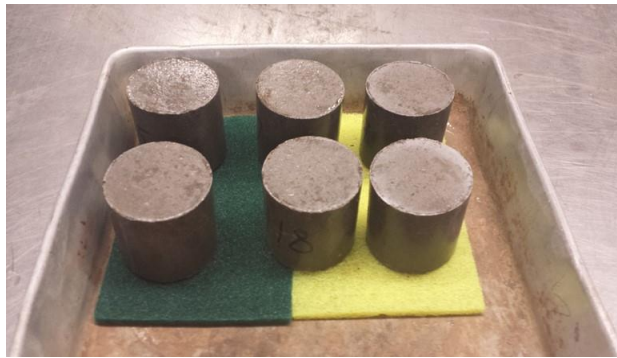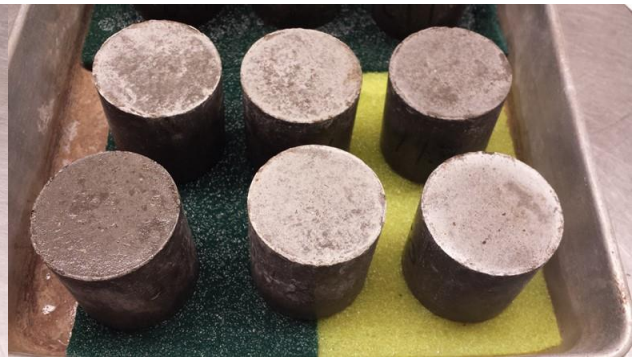
(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-10 (Continued). Images of 7-day cured and 6% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-11. Images of 1-day cured and 12% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-11 (Continued). Images of 1-day cured and 12% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(a) 1st cycle
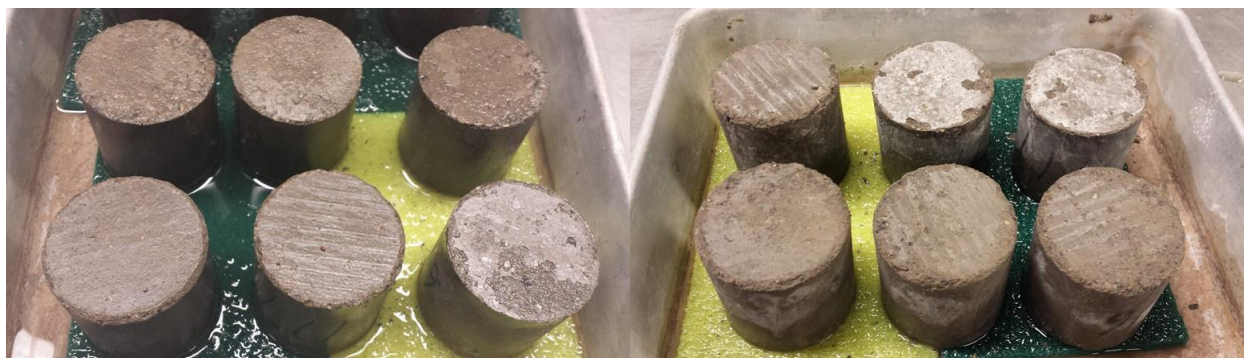
(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-12. Images of 7-day cured and 12% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-12 (Continued). Images of 7-day cured and 12% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test
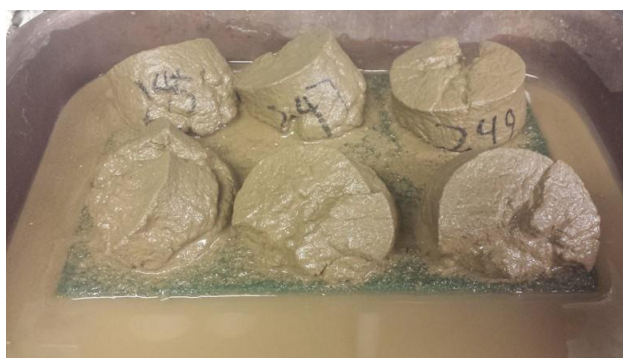
(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-13. Images of 1-day cured and untreated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-13 (Continued). Images of 1-day cured and untreated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-14. Images of 7-day cured and untreated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-14 (Continued). Images of 7-day cured and untreated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-15. Images of 1-day cured and 12% of BCP A-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-15 (Continued). Images of 1-day cured and 12% of BCP A-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-16. Images of 7-day cured and 12% of BCP A-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle
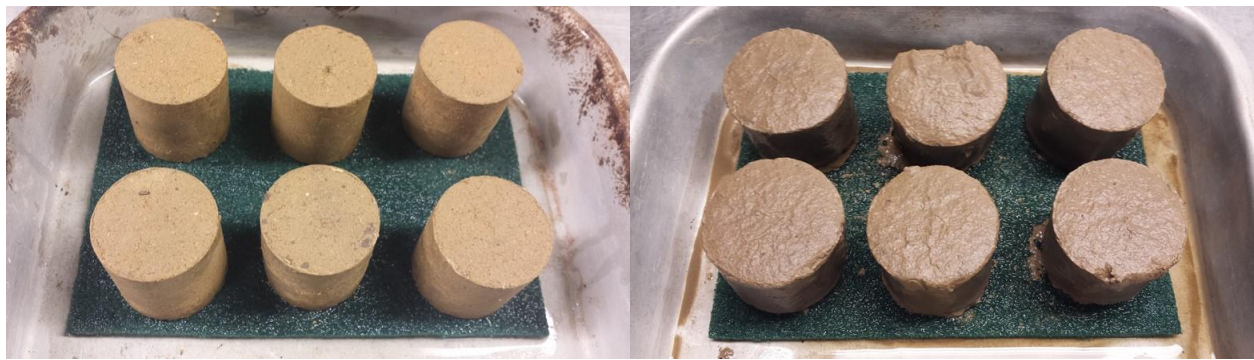

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-16 (Continued). Images of 7-day cured and 12% of BCP A-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-17. Images of 1-day cured and 12% of BCP B-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-17 (Continued). Images of 1-day cured and 12% of BCP B-treated Soil 2 for 12 cycles of freeze-thaw durability test

<table>
<tr><td>(a) 1st cycle</td><td>(b) 2nd cycle</td></tr>
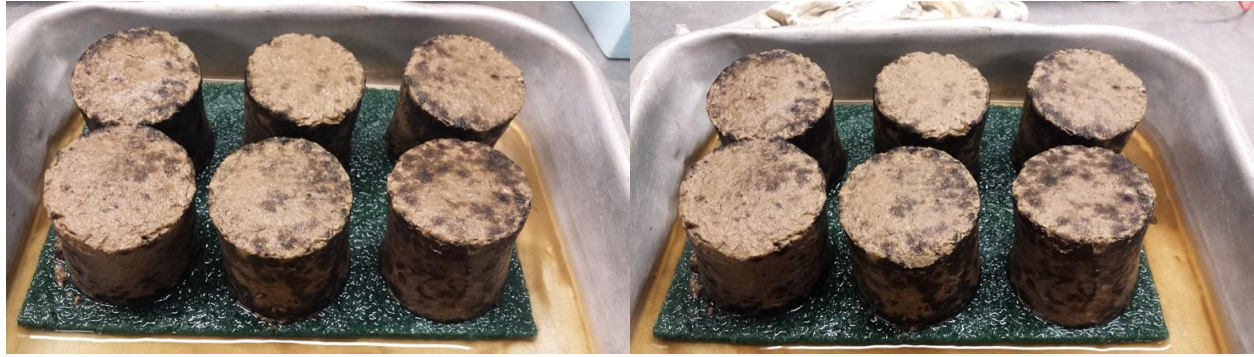<tr><td>(c) 3rd cycle</td><td>(d) 4th cycle</td></tr>
<tr><td>(e) 5th cycle</td><td>(f) 6th cycle</td></tr>
</table>

Figure E-18. Images of 7-day cured and 12% of BCP B-treated Soil 2 for 12 cycles of freeze-thaw durability test
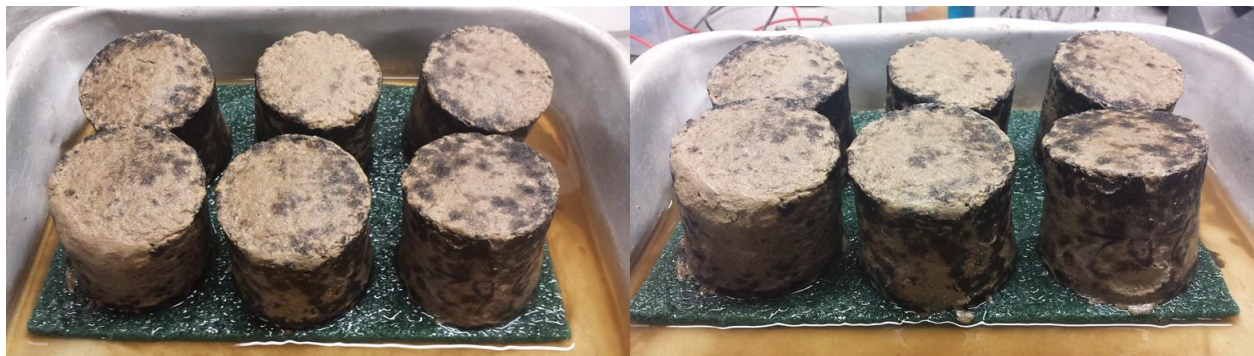
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-18 (Continued). Images of 7-day cured and 12% of BCP B-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-19. Images of 1-day cured and 12% of BCP C-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-19 (Continued). Images of 1-day cured and 12% of BCP C-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-20. Images of 7-day cured and 12% of BCP C-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle
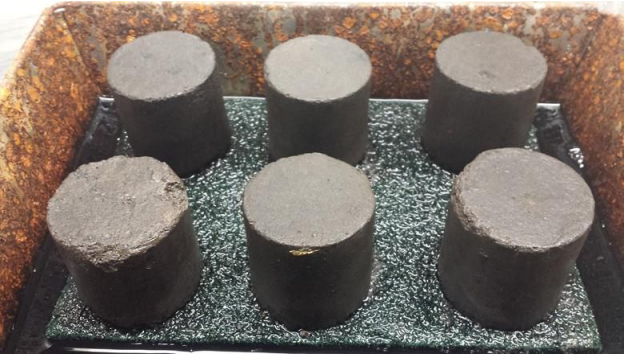
(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-20 (Continued). Images of 7-day cured and 12% of BCP C-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle
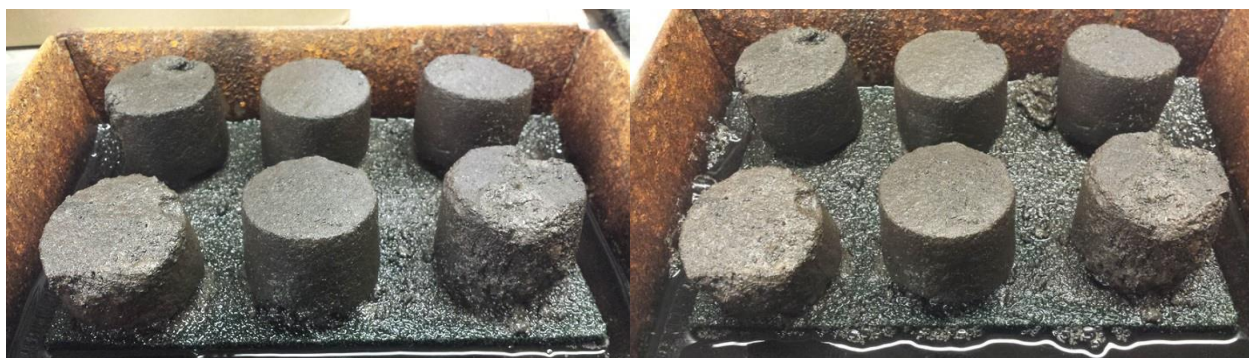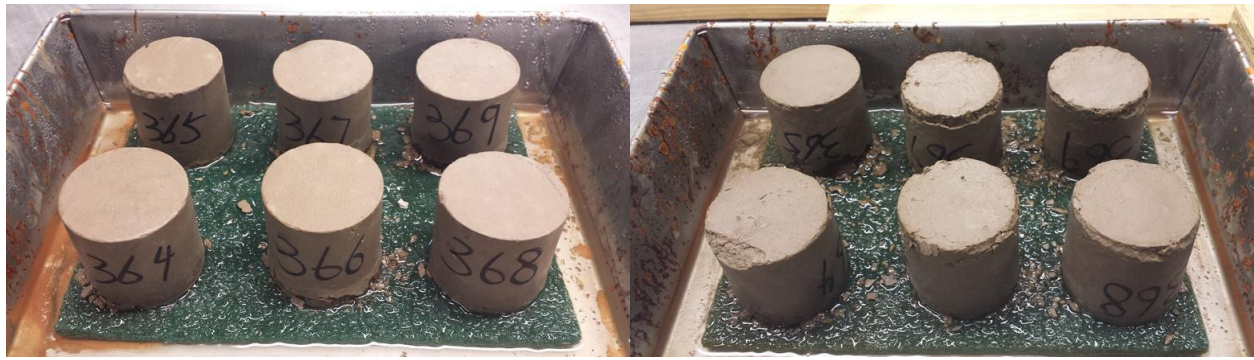
(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-21. Images of 1-day cured and 3% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-21 (Continued). Images of 1-day cured and 3% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-22. Images of 7-day cured and 3% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-22 (Continued). Images of 7-day cured and 3% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-23. Images of 1-day cured and 6% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

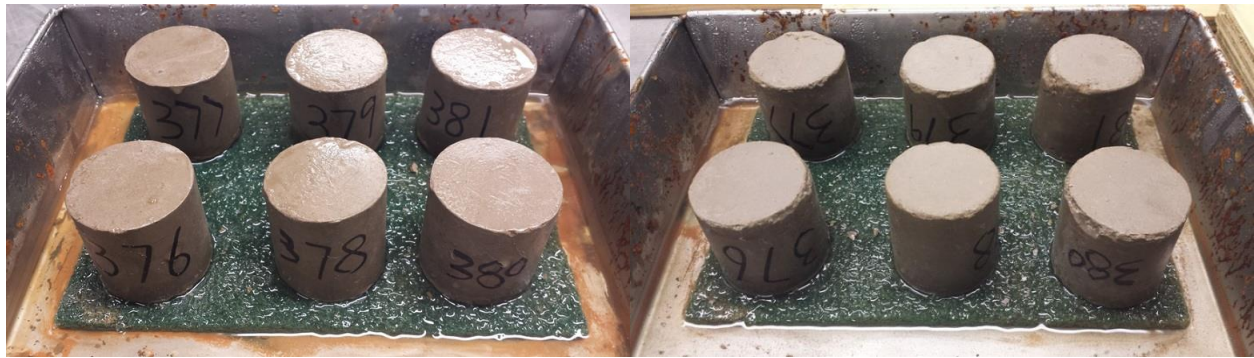(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-23 (Continued). Images of 1-day cured and 6% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-24. Images of 7-day cured and 6% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-24 (Continued). Images of 7-day cured and 6% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-25. Images of 1-day cured and 12% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-25 (Continued). Images of 1-day cured and 12% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-26. Images of 7-day cured and 12% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

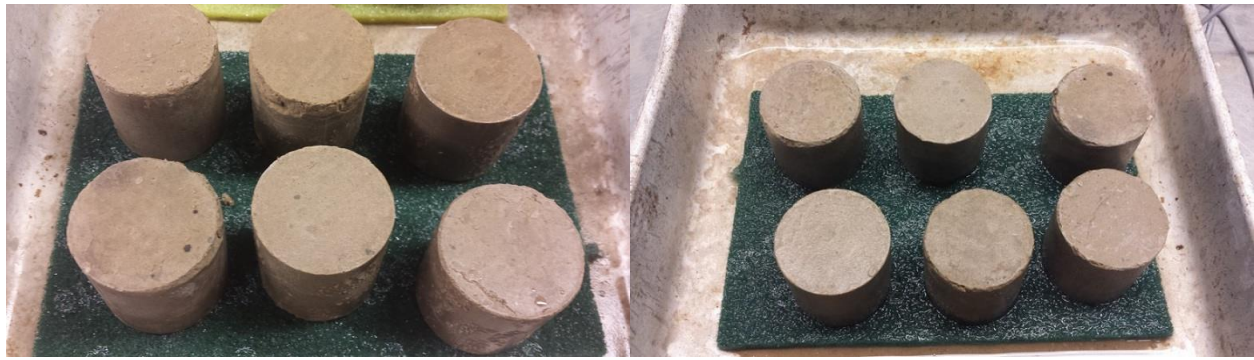(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-26 (Continued). Images of 7-day cured and 12% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-27. Images of 1-day cured and untreated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-27 (Continued). Images of 1-day cured and untreated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-28. Images of 7-day cured and untreated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

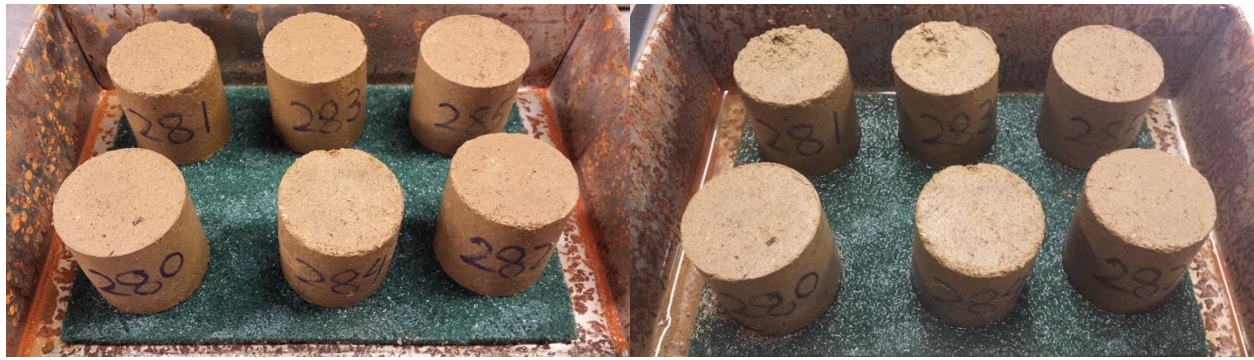(k) 11th cycle

(l) 12th cycle

Figure E-28 (Continued). Images of 7-day cured and untreated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-29. Images of 1-day cured and 12% of BCP A-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-29 (Continued). Images of 1-day cured and 12% of BCP A-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-30. Images of 7-day cured and 12% of BCP A-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-30 (Continued). Images of 7-day cured and 12% of BCP A-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle\

Figure E-31. Images of 1-day cured and 12% of BCP B-treated Soil 3 for 12 cycles of freeze-thaw durability test
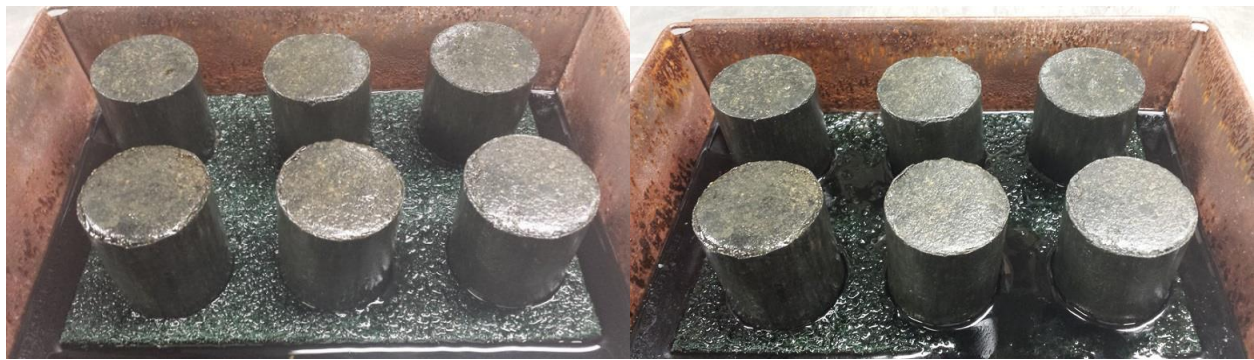
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-31 (Continued). Images of 1-day cured and 12% of BCP B-treated Soil 3 for 12 cycles of freeze-thaw durability test.

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle
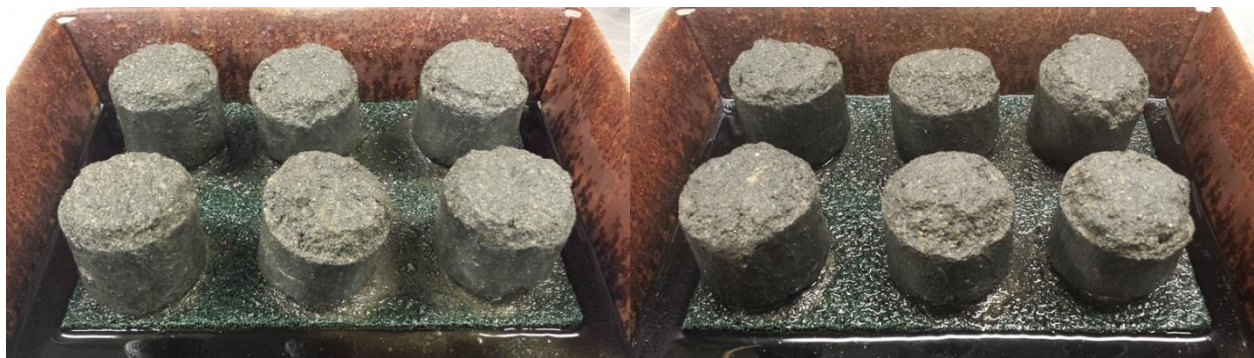
(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-32. Images of 7-day cured and 12% of BCP B-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

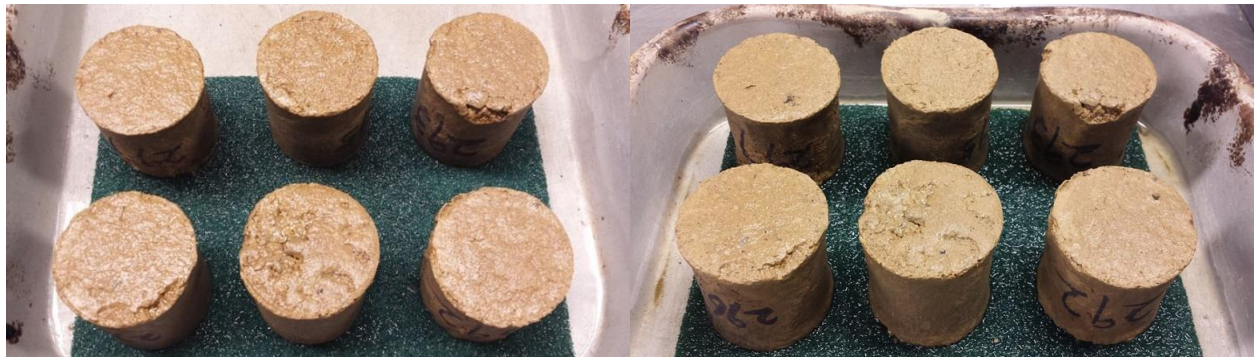(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-32 (Continued). Images of 7-day cured and 12% of BCP B-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-33. Images of 1-day cured and 3% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

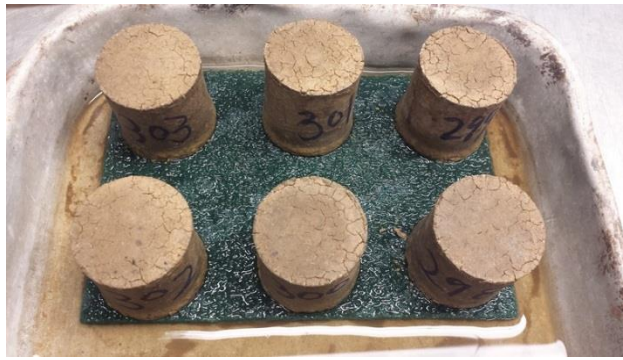(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-33 (Continued). Images of 1-day cured and 3% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-34. Images of 7-day cured and 3% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-34 (Continued). Images of 7-day cured and 3% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-35. Images of 1-day cured and 6% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-35 (Continued). Images of 1-day cured and 6% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-36. Images of 7-day cured and 6% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-36 (Continued). Images of 7-day cured and 6% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-37. Images of 1-day cured and 12% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

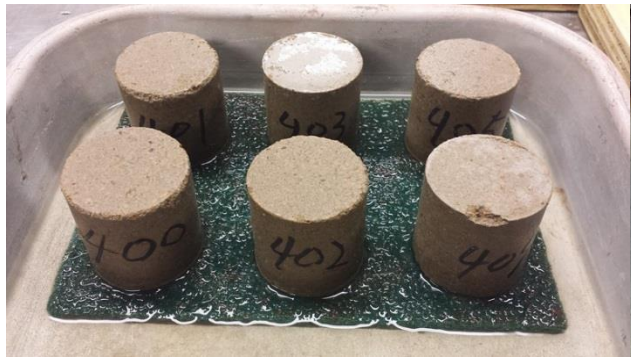(h) 8th cycle

(i) 9th cycle

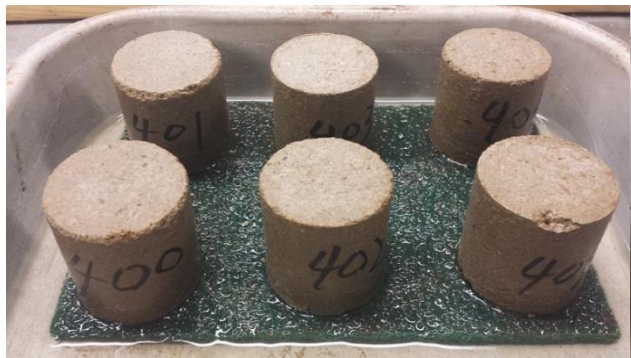(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-37 (Continued). Images of 1-day cured and 12% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-38. Images of 7-day cured and 12% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-38 (Continued). Images of 7-day cured and 12% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test

(a) 1st cycle   (b) 2nd cycle

(c) 3rd cycle   (d) 4th cycle

(e) 5th cycle   (f) 6th cycle

Figure E-39. Images of 1-day cured and untreated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-39 (Continued). Images of 1-day cured and untreated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle	(b) 2nd cycle
(c) 3rd cycle	(d) 4th cycle
(e) 5th cycle	(f) 6th cycle

Figure E-40. Images of 7-day cured and untreated Soil 4 for 12 cycles of freeze-thaw durability test
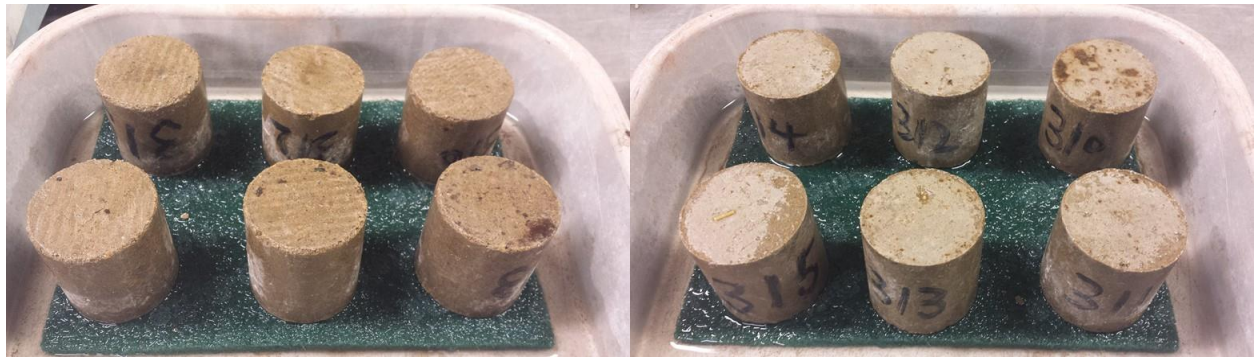
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-40 (Continued). Images of 7-day cured and untreated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

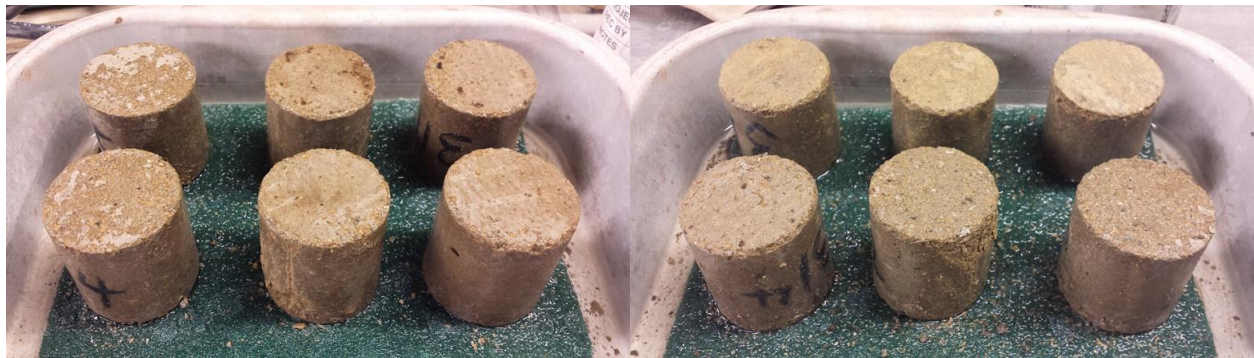(f) 6th cycle

Figure E-41. Images of 1-day cured and 12% of BCP A-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-41 (Continued). Images of 1-day cured and 12% of BCP A-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-42. Images of 7-day cured and 12% of BCP A-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-42 (Continued). Images of 7-day cured and 12% of BCP A-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-43. Images of 1-day cured and 12% of BCP B-treated Soil 4 for 12 cycles of freeze-thaw durability test
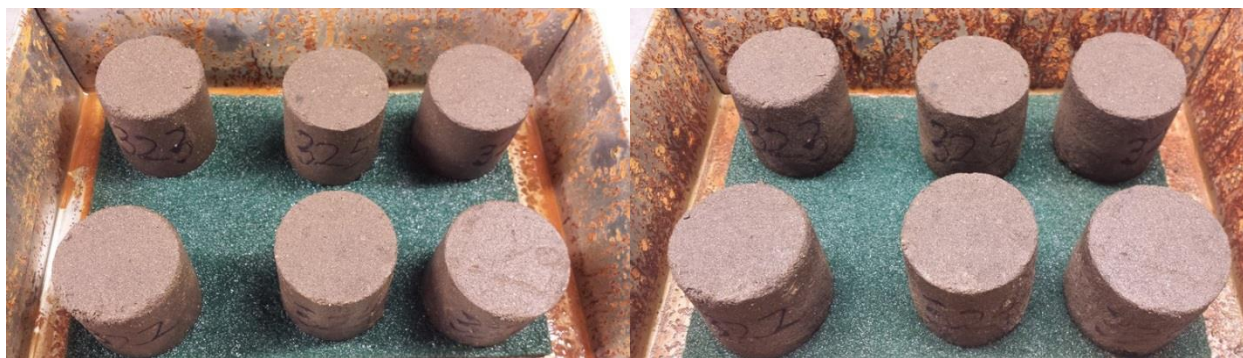
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-43 (Continued). Images of 1-day cured and 12% of BCP B-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-44. Images of 7-day cured and 12% of BCP B-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-44 (Continued). Images of 7-day cured and 12% of BCP B-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-45. Images of 1-day cured and 3% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-45 (Continued). Images of 1-day cured and 3% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle
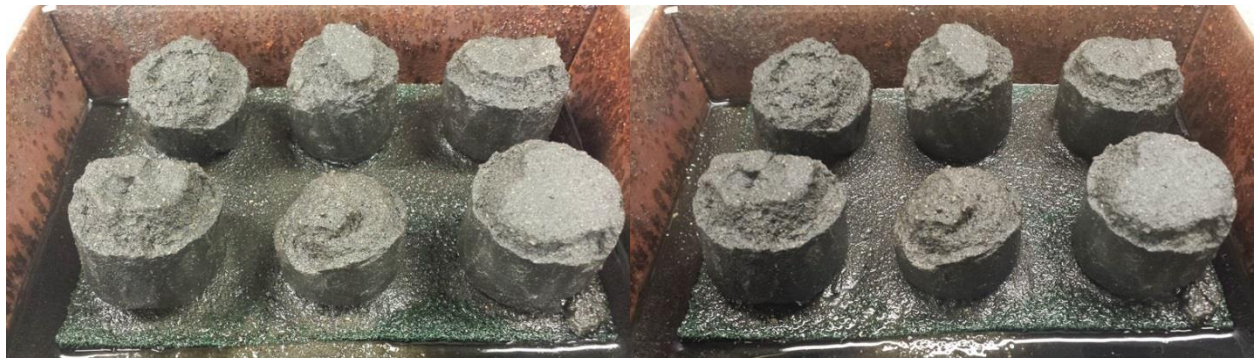
(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-46. Images of 7-day cured and 3% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle
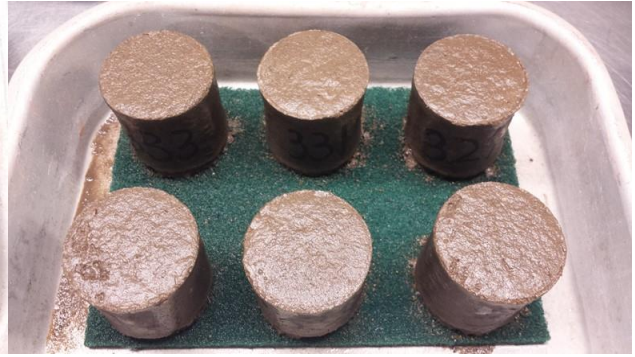

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-46 (Continued). Images of 7-day cured and 3% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test
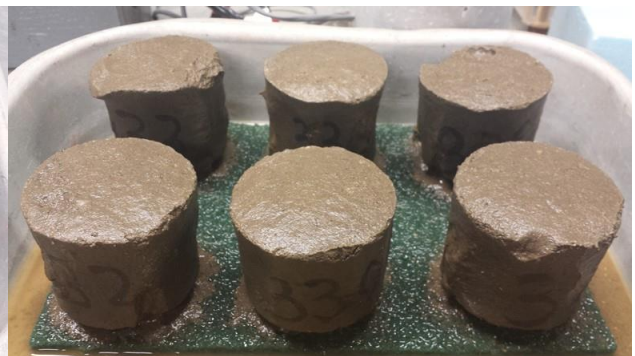
(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-47. Images of 1-day cured and 6% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-47 (Continued). Images of 1-day cured and 6% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-48. Images of 7-day cured and 6% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-48 (Continued). Images of 7-day cured and 6% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

<div align="center">

(a) 1st cycle   (b) 2nd cycle
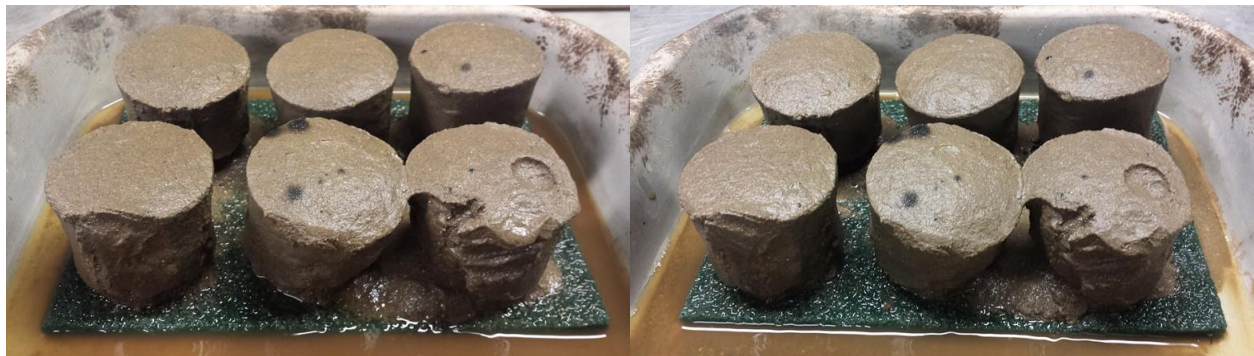
(c) 3rd cycle   (d) 4th cycle

(e) 5th cycle   (f) 6th cycle

Figure E-49. Images of 1-day cured and 12% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

</div>
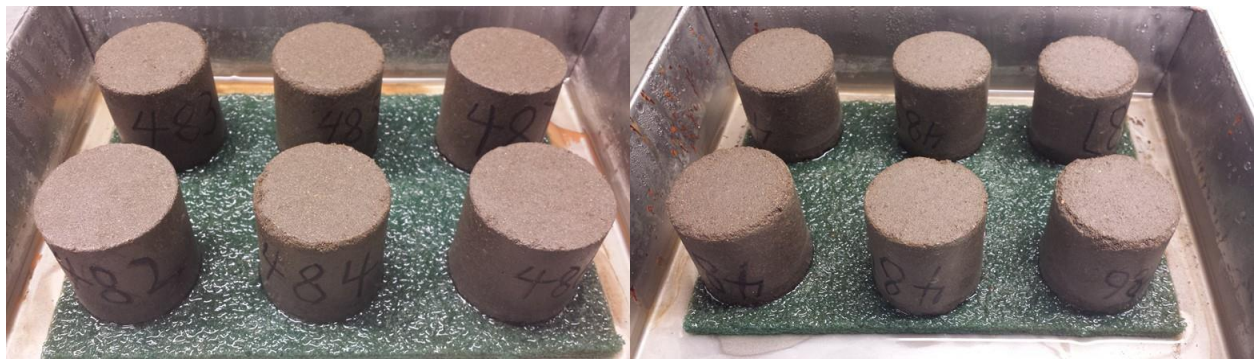
(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure E-49 (Continued). Images of 1-day cured and 12% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

Figure E-50. Images of 7-day cured and 12% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test

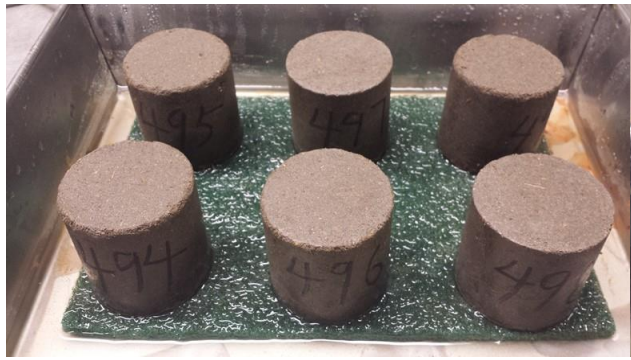(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

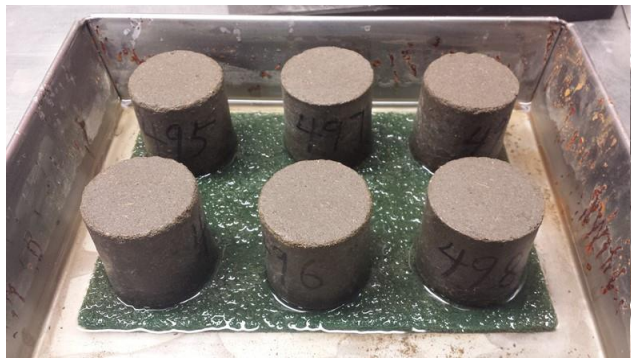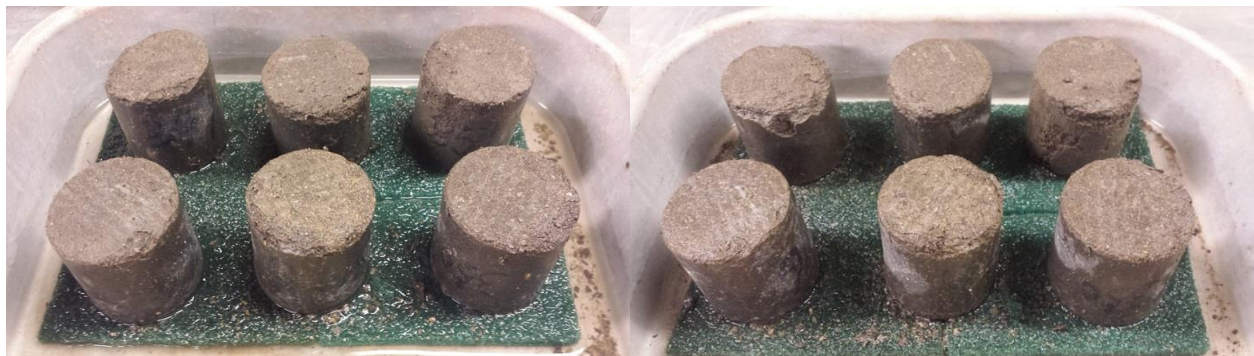**Figure E-50 (Continued). Images of 7-day cured and 12% of cement-treated Soil 4 for 12 cycles of freeze-thaw durability test**
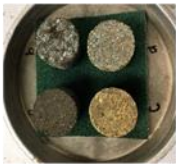
Figure E-51. Images of wet-dry durability test for lignosulfonate-treated Soil 3

Figure E-52. Images of freeze-thaw durability test for lignosulfonate-treated Soil 4

APPENDIX F. RAW DATA FOR FREEZE-THAW DURABILITY TEST RESULTS

Table F-1. Raw data of average volume expansion for Soil 1 set

Sample Type	Curing Day	After Curing (C0)	Average volume of specimens at the end of cycles, in.^3											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	6.38	6.65	6.68	7.22	7.31	7.30	7.33	6.94	6.94	N/A	N/A	N/A	N/A
	7	6.41	6.85	7.18	7.39	6.89	7.48	7.67	7.34	6.83	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	6.68	6.75	6.85	7.01	7.19	7.42	7.57	7.48	7.51	N/A	N/A	N/A	N/A
	7	6.52	6.53	6.54	6.61	6.69	6.70	6.71	6.72	6.73	6.68	6.64	6.65	6.67
Soil-12%BCP B	1	6.51	6.50	7.02	8.01	8.71	8.49	10.16	10.04	10.40	10.33	10.48	10.31	10.37
	7	6.64	7.08	7.64	8.57	8.24	9.20	9.11	8.68	8.79	9.08	9.29	9.36	9.33
Soil-3%Cement	1	6.46	6.47	6.58	6.64	6.73	6.76	6.81	6.89	6.94	6.97	6.95	6.91	6.82
	7	6.46	6.49	6.52	6.56	6.62	6.68	6.73	6.76	6.80	6.81	6.82	6.77	6.60
Soil-6%Cement	1	6.50	6.52	6.53	6.56	6.63	6.64	6.68	6.73	6.78	6.80	6.85	6.83	6.80
	7	6.45	6.48	6.48	6.48	6.52	6.55	6.58	6.61	6.64	6.65	6.67	6.70	6.74
Soil-12%Cement	1	6.53	6.58	6.56	6.62	6.64	6.65	6.65	6.63	6.60	6.62	6.89	6.85	7.08
	7	6.49	6.55	6.55	6.57	6.46	6.44	6.45	6.52	6.52	6.64	6.48	6.47	6.57
Sample Type	Curing Day	After Curing (C0)	Average volume expansion at the end of cycles											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	0%	4%	5%	13%	15%	14%	15%	9%	9%	N/A	N/A	N/A	N/A
	7	0%	7%	12%	15%	8%	17%	20%	15%	6%	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	0%	1%	3%	5%	8%	11%	13%	12%	13%	N/A	N/A	N/A	N/A
	7	0%	0%	0%	1%	3%	3%	3%	3%	3%	2%	2%	2%	2%
Soil-12%BCP B	1	0%	0%	8%	23%	34%	30%	56%	54%	60%	59%	61%	58%	59%
	7	0%	6%	15%	29%	24%	38%	37%	31%	32%	37%	40%	41%	40%
Soil-3%Cement	1	0%	0%	2%	3%	4%	5%	5%	7%	7%	8%	8%	7%	6%
	7	0%	0%	1%	2%	3%	3%	4%	5%	5%	5%	6%	5%	2%
Soil-6%Cement	1	0%	0%	0%	1%	2%	2%	3%	3%	4%	5%	5%	5%	5%
	7	0%	0%	0%	0%	1%	2%	2%	2%	3%	3%	3%	4%	4%
Soil-12%Cement	1	0%	1%	1%	1%	2%	2%	2%	2%	1%	1%	6%	5%	8%
	7	0%	1%	1%	1%	0%	-1%	-1%	0%	0%	2%	0%	0%	1%

Table F-2. Raw data of average volume expansion for Soil 2 set

Sample Type	Curing Day	After Curing (C0)	Average volume of specimens at the end of cycles, in.^3											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	6.45	7.49	7.34	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7	6.39	7.04	7.01	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	6.61	6.83	6.99	7.15	7.35	7.62	7.86	7.95	N/A	N/A	N/A	N/A	N/A
	7	6.57	6.67	6.73	6.75	6.91	7.01	7.09	7.33	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	6.61	7.51	8.10	8.65	8.64	8.62	8.79	N/A	N/A	N/A	N/A	N/A	N/A
	7	6.73	7.37	7.61	8.09	8.17	8.38	8.59	8.75	8.88	9.05	9.04	9.06	9.21
Soil-12%BCP C	1	6.37	6.73	7.00	7.48	7.84	7.78	7.92	7.96	8.01	7.70	7.53	N/A	N/A
	7	6.53	7.02	7.06	7.49	7.82	8.13	8.23	8.17	8.10	7.97	7.64	7.47	7.36
Soil-3%Cement	1	6.51	6.62	6.89	7.04	6.90	6.85	6.74	6.67	N/A	N/A	N/A	N/A	N/A
	7	6.49	6.49	6.58	6.69	6.72	6.83	6.84	6.73	6.56	6.49	N/A	N/A	N/A
Soil-6%Cement	1	6.47	6.49	6.57	6.59	6.60	6.65	6.68	6.73	6.67	6.61	6.52	6.38	6.23
	7	6.52	6.54	6.55	6.58	6.61	6.60	6.63	6.65	6.60	6.50	6.42	6.35	6.29
Soil-12%Cement	1	6.54	6.57	6.58	6.58	6.58	6.62	6.61	6.61	6.61	6.65	6.69	5.73	5.62
	7	6.55	6.59	6.57	6.59	6.60	6.60	6.58	6.57	6.66	6.62	6.70	6.40	6.15

Sample Type	Curing Day	After Curing (C0)	Average volume expansion at the end of cycles											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	0%	16%	14%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7	0%	10%	10%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	0%	3%	6%	8%	11%	15%	19%	20%	N/A	N/A	N/A	N/A	N/A
	7	0%	1%	2%	3%	5%	7%	8%	12%	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	0%	14%	23%	31%	31%	30%	33%	N/A	N/A	N/A	N/A	N/A	N/A
	7	0%	10%	13%	20%	22%	25%	28%	30%	32%	35%	34%	35%	37%
Soil-12%BCP C	1	0%	6%	10%	17%	23%	22%	24%	25%	26%	21%	18%	N/A	N/A
	7	0%	8%	8%	15%	20%	25%	26%	25%	24%	22%	17%	14%	13%
Soil-3%Cement	1	0%	2%	6%	8%	6%	5%	3%	2%	N/A	N/A	N/A	N/A	N/A
	7	0%	0%	1%	3%	4%	5%	5%	4%	1%	0%	N/A	N/A	N/A
Soil-6%Cement	1	0%	0%	2%	2%	2%	3%	3%	4%	3%	2%	1%	-1%	-4%
	7	0%	0%	1%	1%	1%	1%	2%	2%	1%	0%	-2%	-3%	-3%
Soil-12%Cement	1	0%	0%	1%	1%	1%	1%	1%	1%	1%	2%	2%	-12%	-14%
	7	0%	1%	0%	1%	1%	1%	0%	0%	2%	1%	2%	-2%	-6%

268

Table F-3. Raw data of average volume expansion for Soil 3 set

Sample Type	Curing Day	After Curing (C0)	Average volume of specimens at the end of cycles, in.^3											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	6.45	6.91	7.31	7.53	8.01	7.96	7.79	N/A	N/A	N/A	N/A	N/A	N/A
	7	6.41	6.92	7.22	7.63	7.60	7.87	8.04	7.68	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	6.69	6.82	6.93	7.08	7.23	7.44	7.72	7.76	7.81	7.80	7.79	7.59	7.40
	7	6.52	6.53	6.55	6.58	6.61	6.71	6.83	6.85	6.85	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	6.54	7.59	8.60	9.16	9.11	9.28	9.65	9.84	9.93	N/A	N/A	N/A	N/A
	7	6.58	7.15	8.28	8.56	8.60	9.24	9.06	8.95	8.92	9.04	9.06	8.85	9.11
Soil-3%Cement	1	6.48	6.53	6.57	6.59	6.66	6.77	6.83	6.78	6.70	6.62	6.61	6.53	6.35
	7	6.47	6.50	6.53	6.56	6.65	6.72	6.89	6.84	6.72	6.67	6.65	6.59	6.53
Soil-6%Cement	1	6.55	6.59	6.61	6.61	6.62	6.69	6.76	6.87	6.84	6.93	6.96	7.02	6.75
	7	6.53	6.56	6.57	6.57	6.57	6.61	6.66	6.71	6.76	6.78	6.79	6.73	6.59
Soil-12%Cement	1	6.34	6.33	6.41	6.50	6.44	6.48	6.48	6.49	6.51	6.53	6.53	6.56	6.57
	7	6.49	6.46	6.47	6.49	6.49	6.51	6.53	6.53	6.56	6.58	6.62	6.63	6.63

Sample Type	Curing Day	After Curing (C0)	Average volume expansion at the end of cycles											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	0%	7%	13%	17%	24%	23%	21%	N/A	N/A	N/A	N/A	N/A	N/A
	7	0%	8%	13%	19%	19%	23%	25%	20%	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	0%	2%	4%	6%	8%	11%	15%	16%	17%	16%	16%	13%	11%
	7	0%	0%	0%	1%	1%	3%	5%	5%	5%	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	0%	16%	31%	40%	39%	42%	47%	50%	52%	N/A	N/A	N/A	N/A
	7	0%	9%	26%	30%	31%	41%	38%	36%	36%	37%	38%	35%	39%
Soil-3%Cement	1	0%	1%	1%	2%	3%	4%	5%	5%	3%	2%	2%	1%	-2%
	7	0%	0%	1%	1%	3%	4%	7%	6%	4%	3%	3%	2%	1%
Soil-6%Cement	1	0%	1%	1%	1%	1%	2%	3%	5%	4%	6%	6%	7%	3%
	7	0%	1%	1%	1%	1%	1%	2%	3%	4%	4%	4%	3%	1%
Soil-12%Cement	1	0%	0%	1%	2%	2%	2%	2%	2%	3%	3%	3%	3%	4%
	7	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%

269

Table F-4. Raw data of average volume expansion for Soil 4 set

Sample Type	Curing Day	After Curing (C0)	Average volume of specimens at the end of cycles, in.^3											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	6.53	7.07	7.03	7.51	6.92	6.60	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7	6.50	7.19	6.86	7.41	7.74	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	6.62	6.81	7.08	7.17	7.32	7.42	7.63	7.68	7.73	N/A	N/A	N/A	N/A
	7	6.59	6.61	6.63	6.68	6.77	6.79	6.84	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	6.57	7.73	7.98	8.37	8.64	8.97	9.04	N/A	N/A	N/A	N/A	N/A	N/A
	7	6.66	7.13	7.57	8.08	8.38	8.55	8.74	8.89	9.04	9.06	9.07	N/A	N/A
Soil-3%Cement	1	6.58	6.59	6.71	6.79	6.85	6.89	6.93	6.87	6.77	6.72	6.64	6.43	6.37
	7	6.55	6.56	6.59	6.63	6.70	6.74	6.77	6.78	6.75	6.70	6.75	6.68	6.69
Soil-6%Cement	1	6.59	6.60	6.65	6.68	6.74	6.78	6.85	6.89	6.92	6.98	7.01	6.95	6.92
	7	6.56	6.56	6.58	6.61	6.63	6.66	6.67	6.71	6.73	6.80	6.84	6.86	6.95
Soil-12%Cement	1	6.45	6.55	6.60	6.75	6.66	6.69	6.69	6.71	6.72	6.74	6.75	6.76	6.76
	7	6.59	6.58	6.56	6.60	6.64	6.63	6.64	6.65	6.66	6.69	6.69	6.69	6.69
Sample Type	Curing Day	After Curing (C0)	Average volume expansion at the end of cycles											
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Untreated Soil	1	0%	8%	8%	15%	6%	1%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7	0%	11%	6%	14%	19%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP A	1	0%	3%	7%	8%	11%	12%	15%	16%	17%	N/A	N/A	N/A	N/A
	7	0%	0%	1%	1%	3%	3%	4%	N/A	N/A	N/A	N/A	N/A	N/A
Soil-12%BCP B	1	0%	18%	21%	27%	31%	37%	38%	N/A	N/A	N/A	N/A	N/A	N/A
	7	0%	7%	14%	21%	26%	28%	31%	33%	36%	36%	36%	N/A	N/A
Soil-3%Cement	1	0%	0%	2%	3%	4%	5%	5%	4%	3%	2%	1%	-2%	-3%
	7	0%	0%	1%	1%	2%	3%	3%	4%	3%	2%	3%	2%	2%
Soil-6%Cement	1	0%	0%	1%	1%	2%	3%	4%	5%	5%	6%	6%	5%	5%
	7	0%	0%	0%	1%	1%	2%	2%	2%	3%	4%	4%	5%	6%
Soil-12%Cement	1	0%	1%	2%	5%	3%	4%	4%	4%	4%	4%	5%	5%	5%
	7	0%	0%	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	2%

Table F-5. Raw data of average mass loss for Soil 1 set

Sample Type	Curing Days	Initial Dry Mass, g	Corrected Ovendry Mass, g	Mass Loss, %
Untreated Soil 1	1	177.11	37.18	79
	7	175.80	28.70	84
Soil 1+ 12%BCP A	1	196.48	129.64	34
	7	196.42	144.82	26
Soil 1+ 12%BCP B	1	196.61	165.05	16
	7	196.25	178.95	9
Soil 1+ 3%Cement	1	181.66	146.88	19
	7	181.47	150.85	17
Soil 1+ 6%Cement	1	187.08	168.49	10
	7	187.11	172.87	8
Soil 1+ 12%Cement	1	196.80	190.06	3
	7	197.54	194.54	2

Table F-6. Raw data of average mass loss for Soil 2 set

Sample Type	Curing Days	Initial Dry Mass, g	Corrected Ovendry Mass, g	Mass Loss, %
Untreated Soil 2	1	166.62	13.61	92
	7	166.22	14.64	91
Soil 2+ 12%BCP A	1	185.04	71.26	61
	7	184.88	78.64	57
Soil 2+ 12%BCP B	1	185.80	157.04	15
	7	186.00	173.24	7
Soil 2+ 12%BCP C	1	186.21	150.78	19
	7	185.89	162.14	13
Soil 2+ 3%Cement	1	172.26	55.98	68
	7	172.02	86.50	50
Soil 2+ 6%Cement	1	175.71	123.49	30
	7	174.62	137.94	21
Soil 2+ 12%Cement	1	187.96	144.95	23
	7	187.24	156.81	16

Table F-7. Raw data of average mass loss for Soil 3 set

Sample Type	Curing Days	Initial Dry Mass, g	Corrected Ovendry Mass, g	Mass Loss, %
Untreated Soil 3	1	187.22	14.24	92
	7	185.60	24.50	87
Soil 3+ 12%BCP A	1	204.76	154.49	25
	7	208.03	154.11	26
Soil 3+ 12%BCP B	1	207.28	161.20	22
	7	207.20	184.22	11
Soil 3+ 3%Cement	1	191.03	131.45	31
	7	191.07	147.47	23
Soil 3+ 6%Cement	1	196.62	157.13	20
	7	196.35	167.94	14
Soil 3+ 12%Cement	1	206.47	194.65	6
	7	210.01	200.28	5

Table F-8. Raw data of average mass loss for Soil 4 set

Sample Type	Curing Days	Initial Dry Mass, g	Corrected Ovendry Mass, g	Mass Loss, %
Untreated Soil 4	1	187.97	0	100
	7	188.03	0.00	100
Soil 4+ 12%BCP A	1	209.27	131.68	37
	7	208.75	133.66	36
Soil 4+ 12%BCP B	1	209.87	160.12	24
	7	208.45	183.09	12
Soil 4+ 3%Cement	1	194.06	137.34	29
	7	193.90	147.48	24
Soil 4+ 6%Cement	1	199.81	157.87	21
	7	199.44	169.57	15
Soil 4+ 12%Cement	1	210.72	201.68	4
	7	210.74	203.08	4

APPENDIX G. IMAGES AND DATA FOR XRD PATTERNS
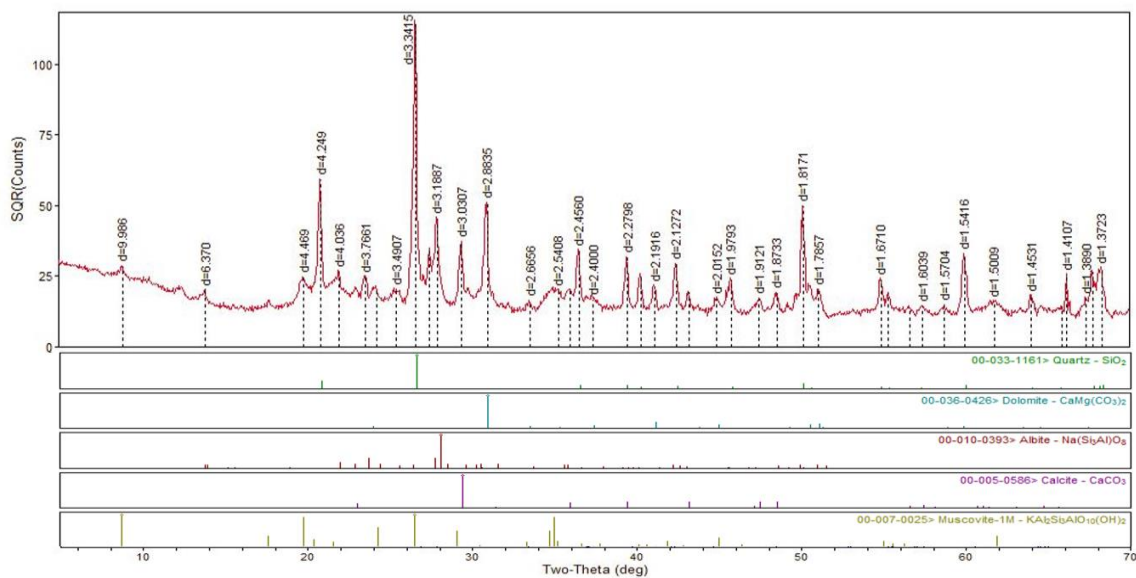
Figure G-1. XRD pattern for untreated Soil 1
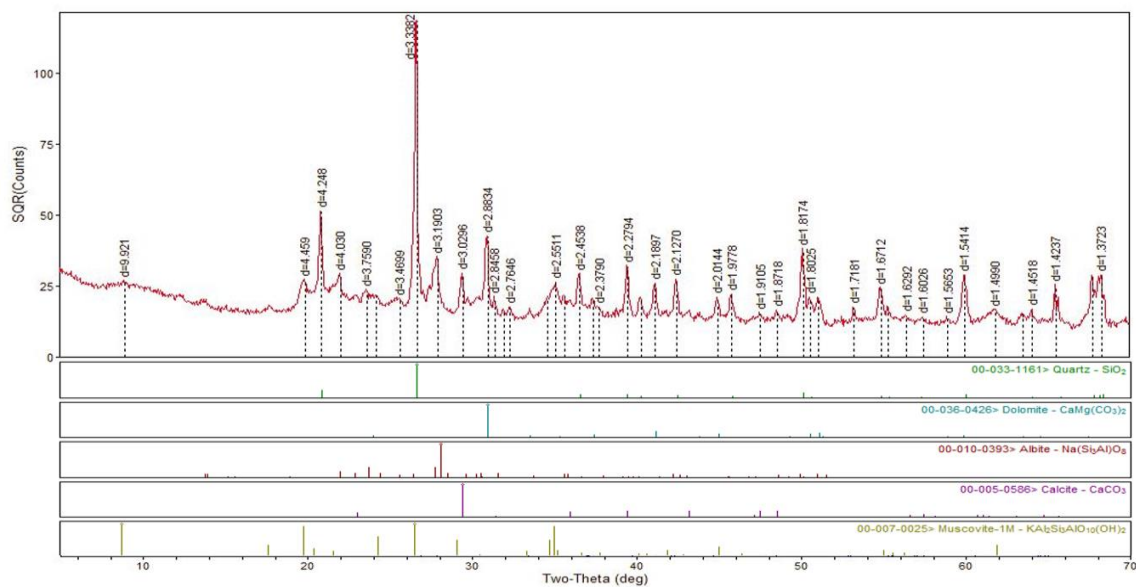
Figure G-2. XRD pattern for BCP A-treated Soil 1
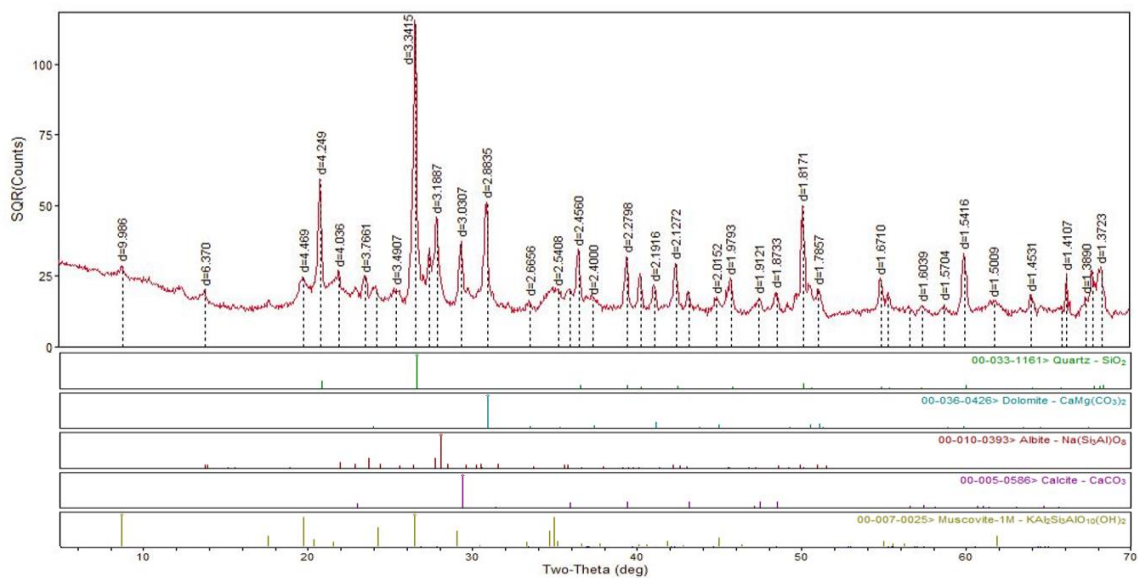
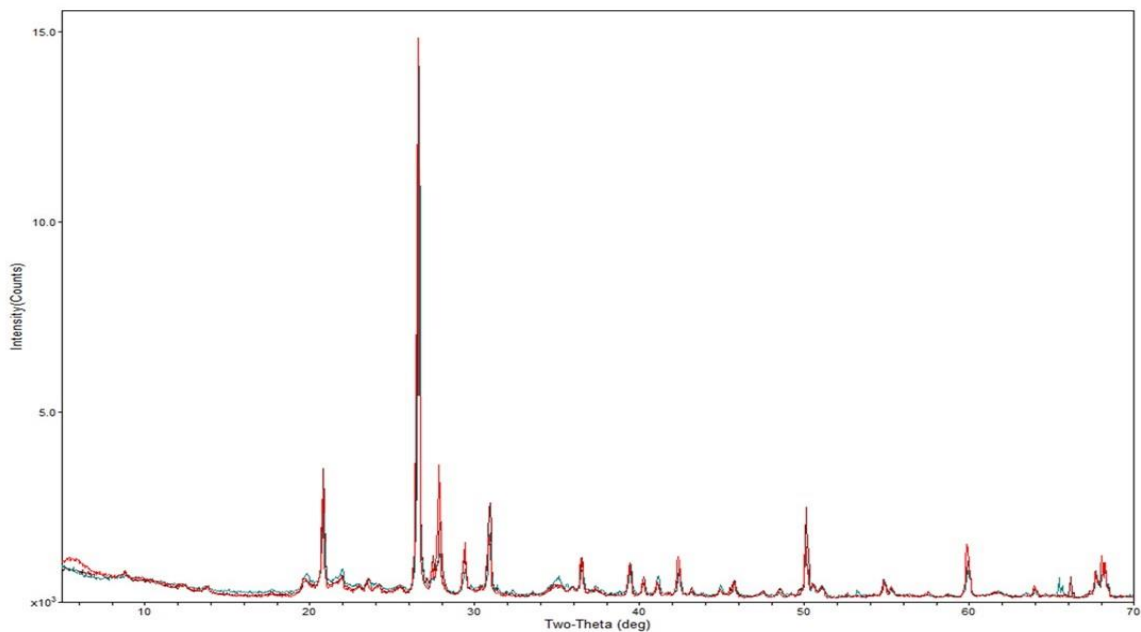**Figure G-3. XRD pattern for BCP B-treated Soil 1**

Iowa State

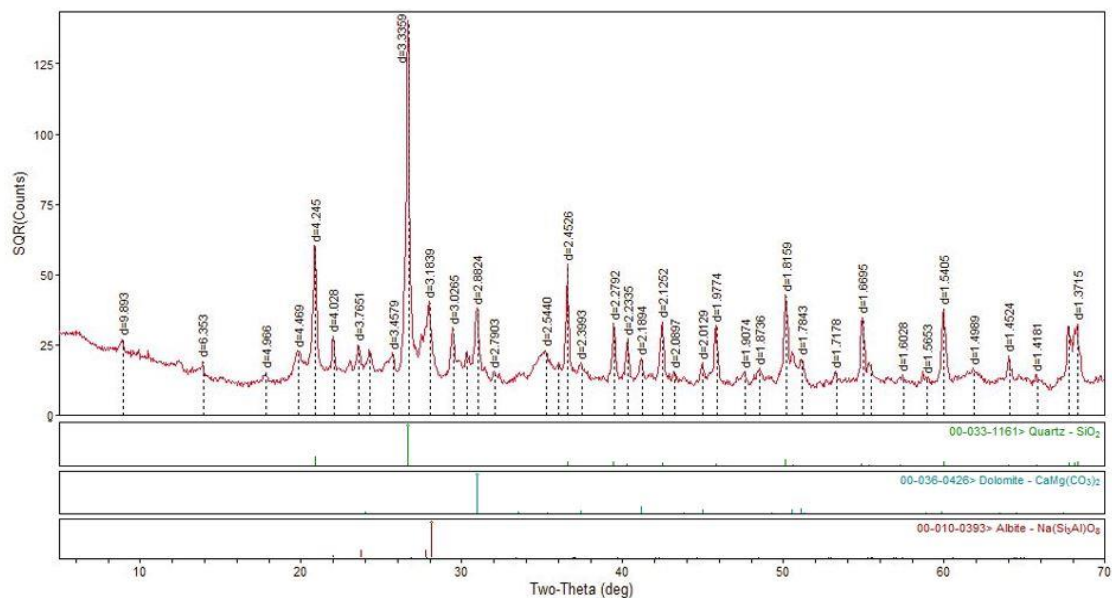**Figure G-4. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 1 samples**

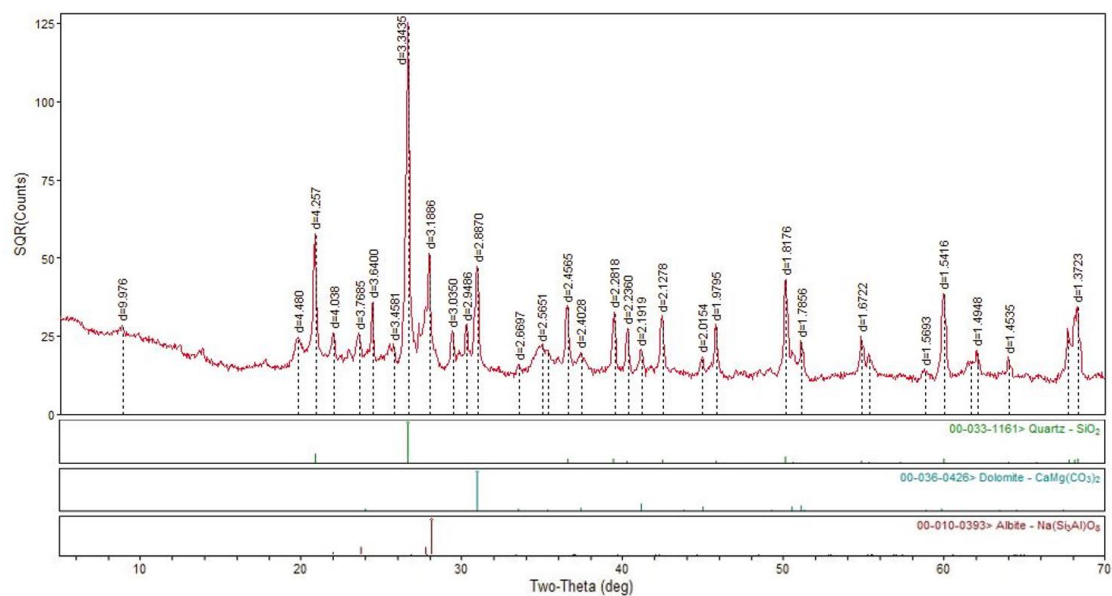**Figure G-5. XRD pattern for untreated Soil 2**

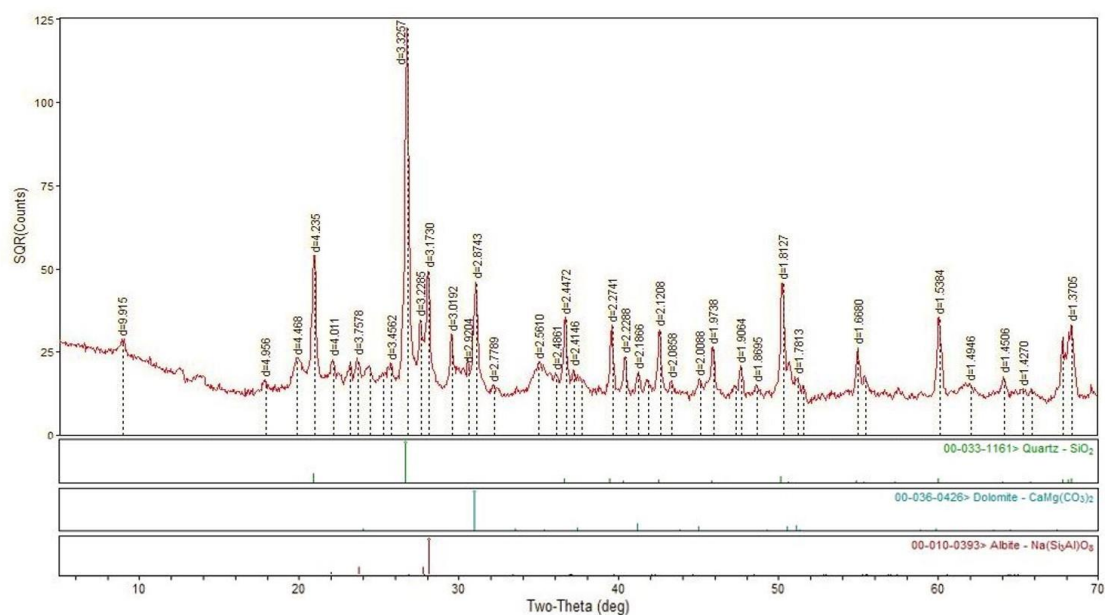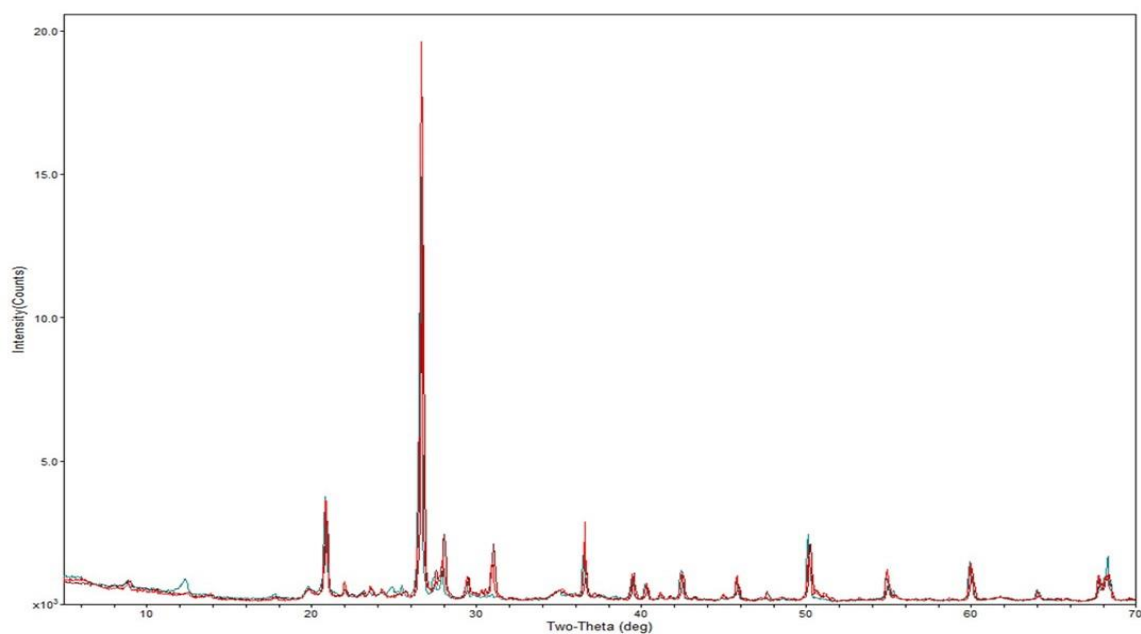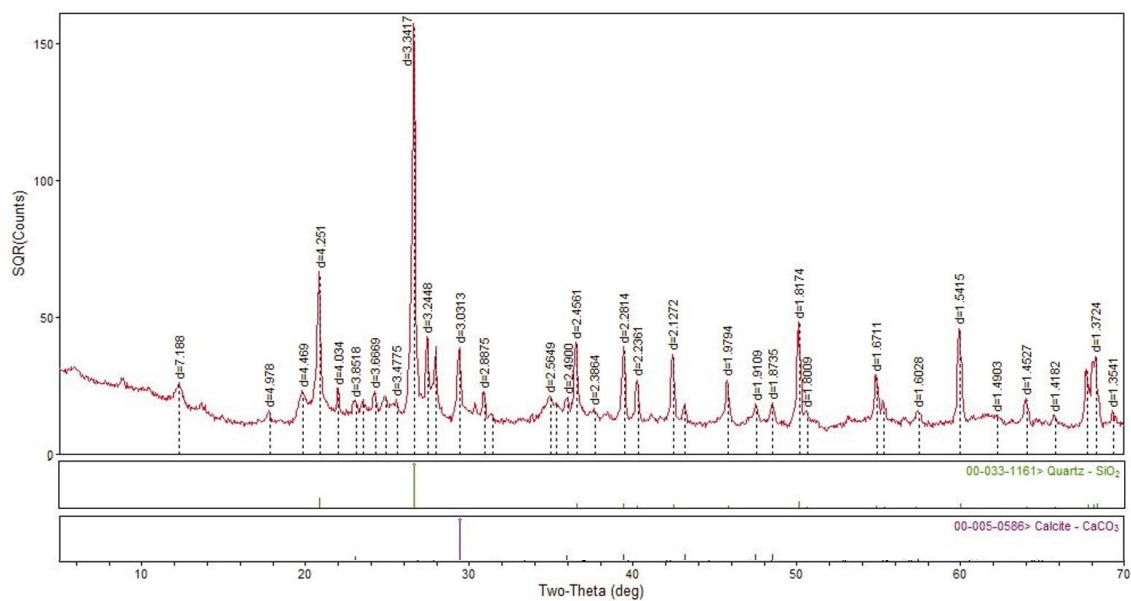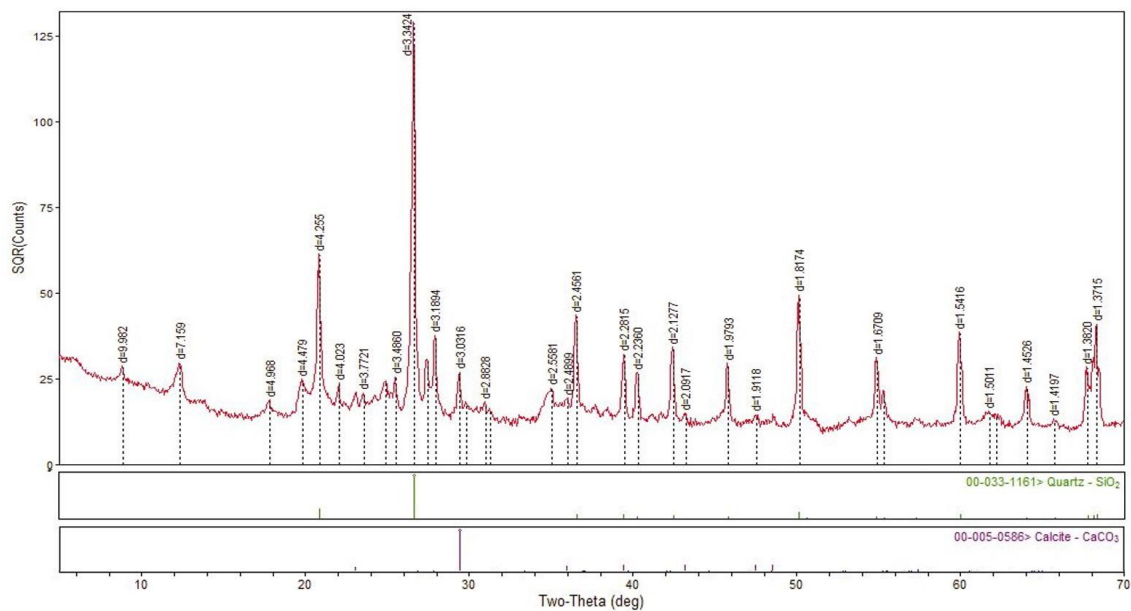**Figure G-6. XRD pattern for BCP A-treated Soil 2**

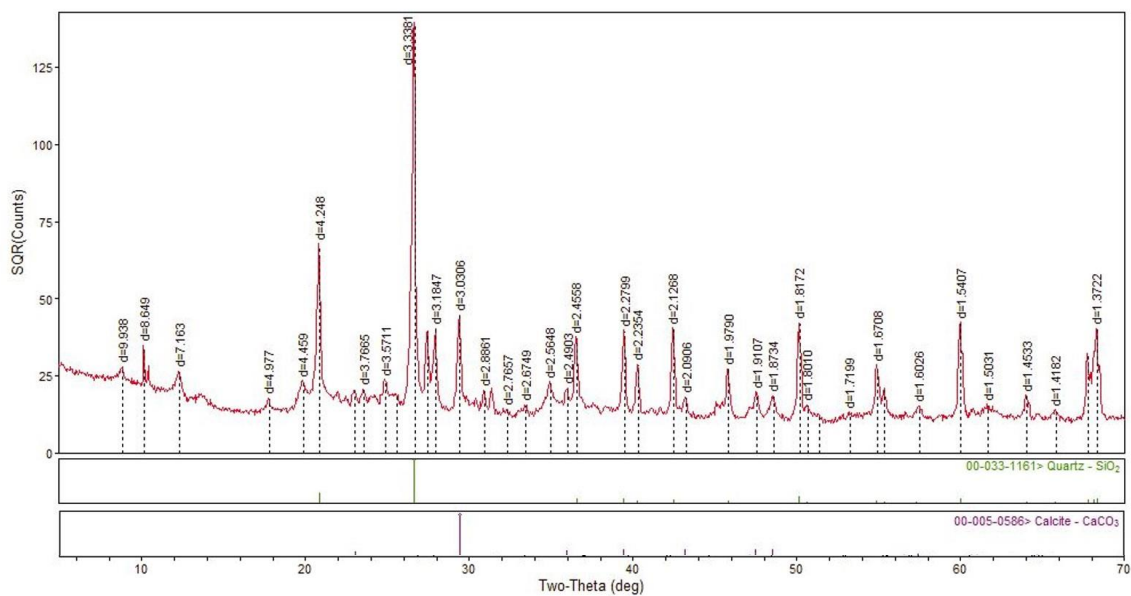**Figure G-7. XRD pattern for BCP B-treated Soil 2**

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Figure G-8. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 2 samples

Figure G-9. XRD pattern for untreated Soil 3
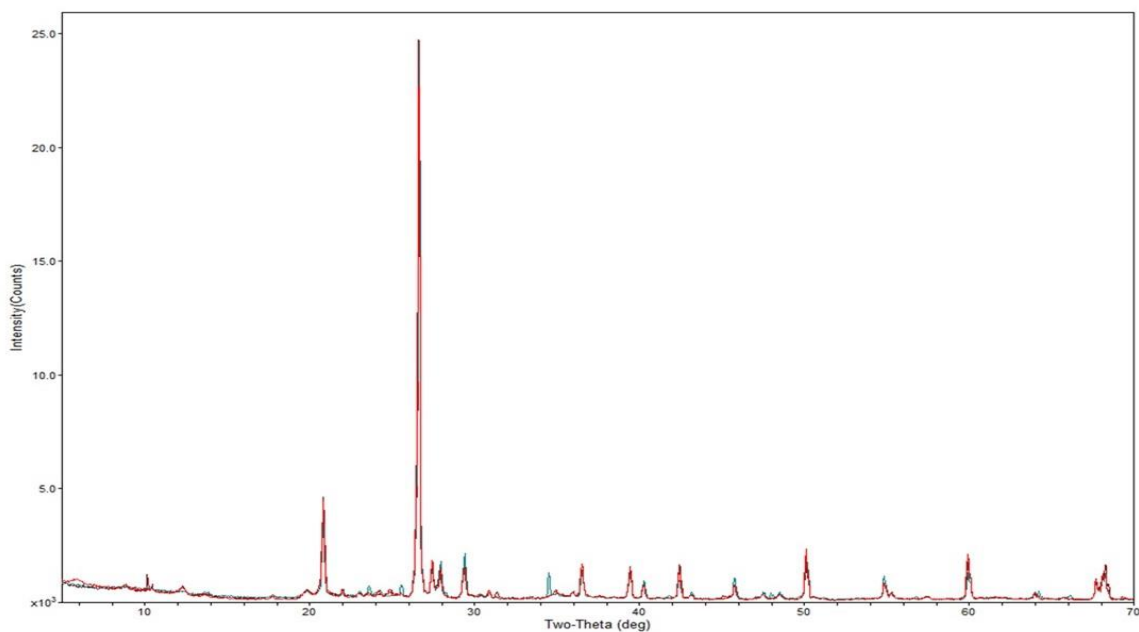

Figure G-10. XRD pattern for BCP A-treated Soil 3

Figure G-11. XRD pattern for BCP B-treated Soil 3

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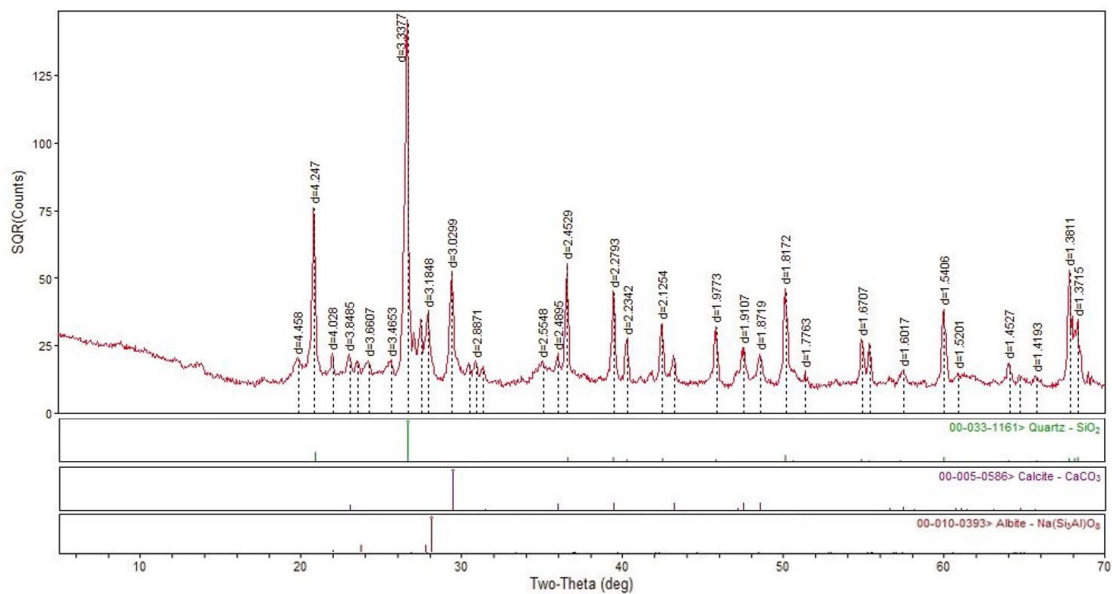**Figure G-12. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 3 samples**

Figure G-13. XRD pattern for untreated Soil 4
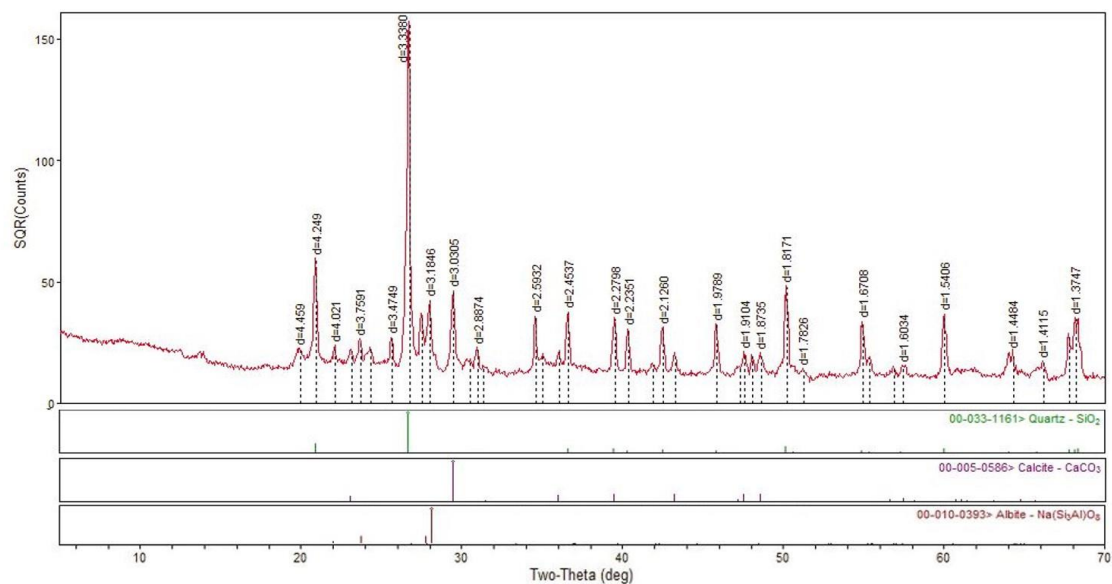

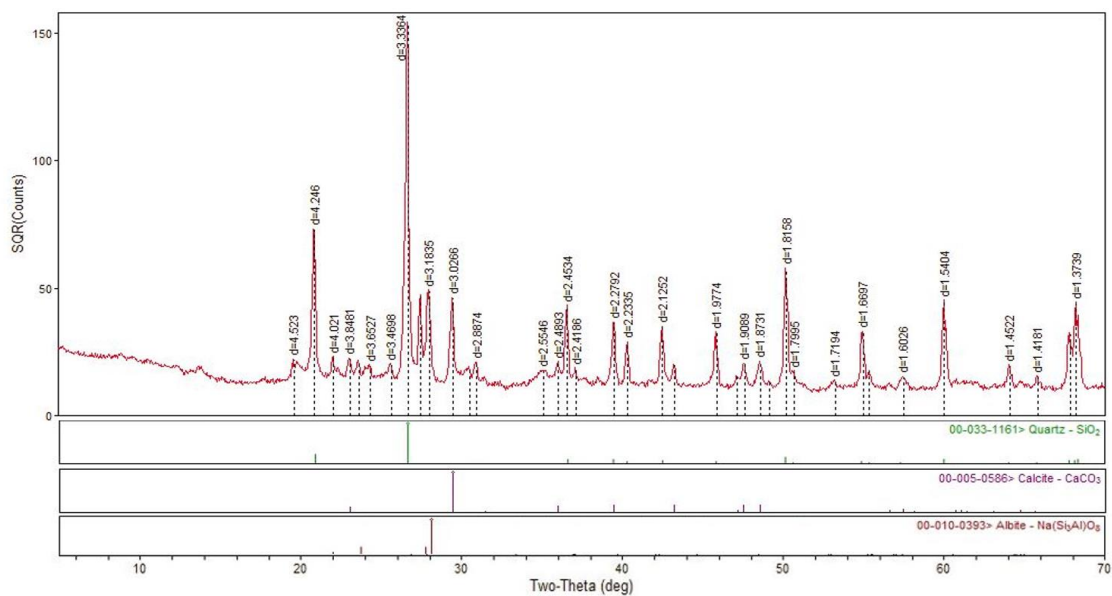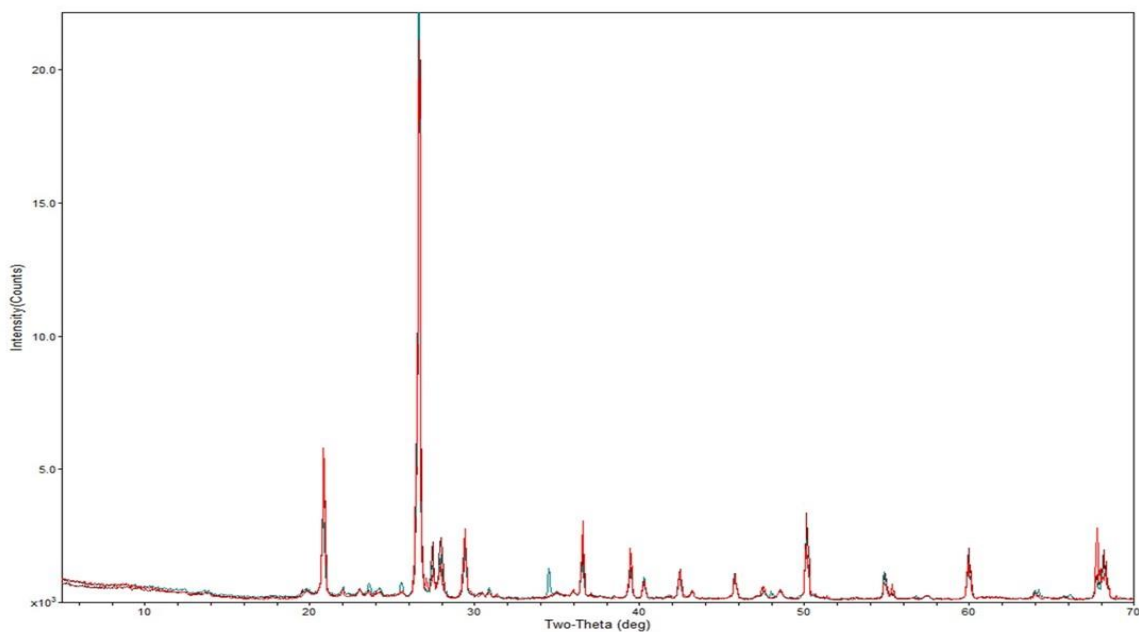**Figure G-14. XRD pattern for BCP A-treated Soil 4**

279

Figure G-15. XRD pattern for BCP B-treated Soil 4

Iowa State

Figure G-16. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 4 samples

Table G-1. Identified inorganic materials from XRD for Soil 1 set

	Chemical formula	Pure Soil 1	Soil 1+BCP A	Soil 1+BCP B
Albite	$NaAlSi_3O_8$	√	√	√
Calcite, syn	$CaCO_3$	√	√	√
Dolomite	$CaMg(CO_3)_2$	√	√	√
Muscovite-1M, syn	$KAl_2Si_3AlO_{10}(OH)_2$	√	√	√
Quartz, syn	SiO_2	√	√	√

Table G-2. Identified inorganic materials from XRD for Soil 2 set

	Chemical formula	Pure Soil 2	Soil 2+BCP A	Soil 2+BCP B
Albite	$NaAlSi_3O_8$	√	√	√
Dolomite	$CaMg(CO_3)_2$	√	√	√
Quartz, syn	SiO_2	√	√	√

Table G-3. Identified inorganic materials from XRD for Soil 3 set

	Chemical formula	Pure Soil 3	Soil 3+BCP A	Soil 3+BCP B
Calcite, syn	$CaCO_3$	√	√	√
Quartz, syn	SiO_2	√	√	√

Table G-4. Identified inorganic materials from XRD for Soil 4 set

	Chemical formula	Pure Soil 4	Soil 4+BCP A	Soil 4+BCP B
Albite, ordered	$NaAlSi_3O_8$	√	√	√
Calcite, syn	$CaCO_3$	√	√	√
Quartz, syn	SiO_2	√	√	√

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