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Performance of bio-based soil stabilizers in transportation earthworks-laboratory investigations

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Performance of bio-based soil stabilizers in transportation earthworks-laboratory investigations

by

Bo Yang

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
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Iowa State University

Ames, Iowa

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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. Three different types of co-products were tested: (1) a liquid type with medium lignin content (BCP A), (2) a powder type with the low lignin content (BCP B), and (3) another liquid type with high lignin content (BCP C). 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 for testing, and the results indicated that BCPs are 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. UCS and freeze-thaw durability of BCPs-treated soils were also compared to the same qualities of traditional stabilizer (cement)-treated soil. Scanning electron microscope (SEM) and X-ray diffraction (XRD) were also performed to identify mechanisms of BCP based soil stabilization. A microstructural analysis showed that BCP materials could coat and bind soil grains and thereby form a strong soil structure.

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. Only BCP A and BCP C tests were conducted in some of the testing activity due to lack of a sufficient quantity of these two BCPs. When a sufficient quantity of these BCPs becomes available, balanced tests and field investigation is recommended to verify the effects of BCP in soil stabilization practices.

CHAPTER 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 1983; 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 fossil energy shortage and the voice of environment protection has therefore motivated significant development of biofuel production (ethanol) derived from biomass to fulfill transportation needs. 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 environment benefits, including production of electrical energy and soil improvement.

Corn is a very common agricultural crop in the United States. The residual parts of corn after harvesting such as stalk and leaves are termed “corn stover”. 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, can also be used to produce biofuel and lignin, and the estimated annual yield of lignin could exceed 8.5 million tons (Fox, 2006). 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 1992; Sundstrom, et al., 1983). In pavement construction particularly, lignin derived from the paper industry has been proven to have positive effects with respect to road dust control, increase in 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.

The poor engineering properties of much natural soil can’t provide a desired platform for pavement construction, 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 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 of 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 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, et al., 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 other category of lignin, “sulfur-free lignin”, has gained little attention. Ceylan, et al., (2009) 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 geomaterial stabilization should be investigated because it is hypothesized that stronger geomaterial stabilization may be thereby achieved, possibly reducing the geomaterial need through this innovative approach.

Research Objective

The primary purpose of this research is to continue 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, a liquid-type BCP (oil type) produced at the Iowa State University (ISU) Bioeconomy Institute was evaluated. The specific objectives of the study were:

- To evaluate the performance of BCP in different soils with respect to engineering properties and strength properties
- To evaluate the performance of BCP in different soils with respect to freeze-thaw durability and moisture susceptibility
- To identify the mechanisms of BCP soil stabilization through using microstructural analysis

Research Approach

This research focused on investigating soil-BCP mixtures through laboratory testing. Four types of soil from Calhoun County, Sioux County, and Buchanan County in Iowa were mixed with BCPs. Three types of BCP were investigated, and Type I Portland cement was also used as a traditional stabilizer for comparison purpose. 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 engineering properties of soil can be achieved by BCP stabilization. X-ray diffraction (XRD) and scanning electron microscope (SEM) studies were also conducted to analyze microstructure of soil-BCPs mixture and identify potential mechanisms of BCP soil stabilization. BCP A and BCP C had not been previously available in sufficient quantities, so their performance with respect to UCS and freeze-thaw durability were considered high-priority activities.

Thesis Organization

This report is organized into five sections. Chapter 1 presents the background, motivation, objectives, and general approach of this study. A literature review of traditional stabilizers, nontraditional stabilizers, and BCP is summarized in Chapter 2. In Chapter 3, the soils and additives used, specimen preparation methods, and various laboratory testing methods are described in detail. Chapter 4 discusses the results from the laboratory test program. Finally, Chapter 5 concludes the thesis and states recommendations for future laboratory testing and field performance studies.

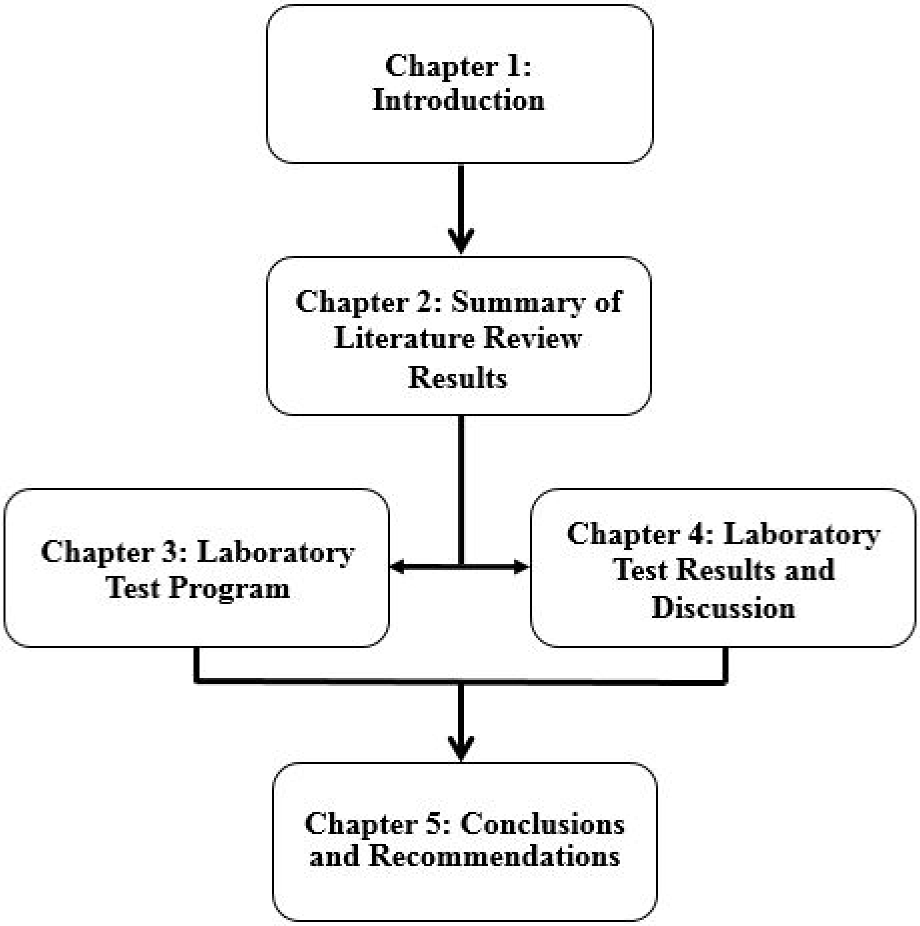


Figure 1. Report organization flow chart

CHAPTER 2

SUMMARY OF LITERATURE REVIEW RESULTS

Overview of Traditional Soil Stabilizers

A high-quality subgrade soil foundation can provide 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-colored fine powder comprised of calcium silicates, aluminum and iron compounds, and some other compounds (ASTM 150). 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 in (the abbreviation was given in Table 1). Water can react with these chemical compounds to form some 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 geomaterial 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 AASHTO soil classification system can use cement as a stabilizer, and the recommended amount of cement varies from 3% to 16% (PCA 1978). 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. It is important to know that this short-cut method can’t be applied to organic soil or soil containing more than 50% by weight of particles passing through a 0.05 mm sieve and/or less than 20% by weight of particles passing through a 0.005 mm sieve. If the soil materials don’t satisfy these criteria, the short-cut method cannot be used. For soil containing no particles retained on 4.75 mm sieve (No.4 sieve), short-cut method A can be used to estimate cement amount. Figures 2 through 4 below give the general design steps for method A. The first step is to perform 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 the 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 optimum moisture content (OMC) for strength measurement. After a 7-day moist-curing process, the average measured compressive strength values shown in Figure 4 should be close to the specimen strength of (PCA 1956). 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 in this way.

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 1991).

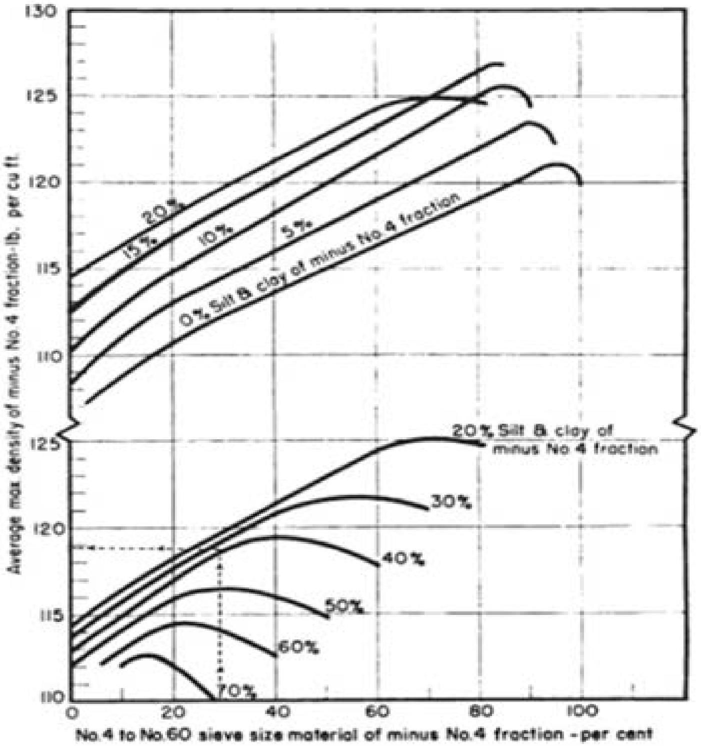


Figure 2. The estimated average maximum densities of soil-cement mixtures without materials retained on the No.4 sieve (adopted from PCA, 1956)

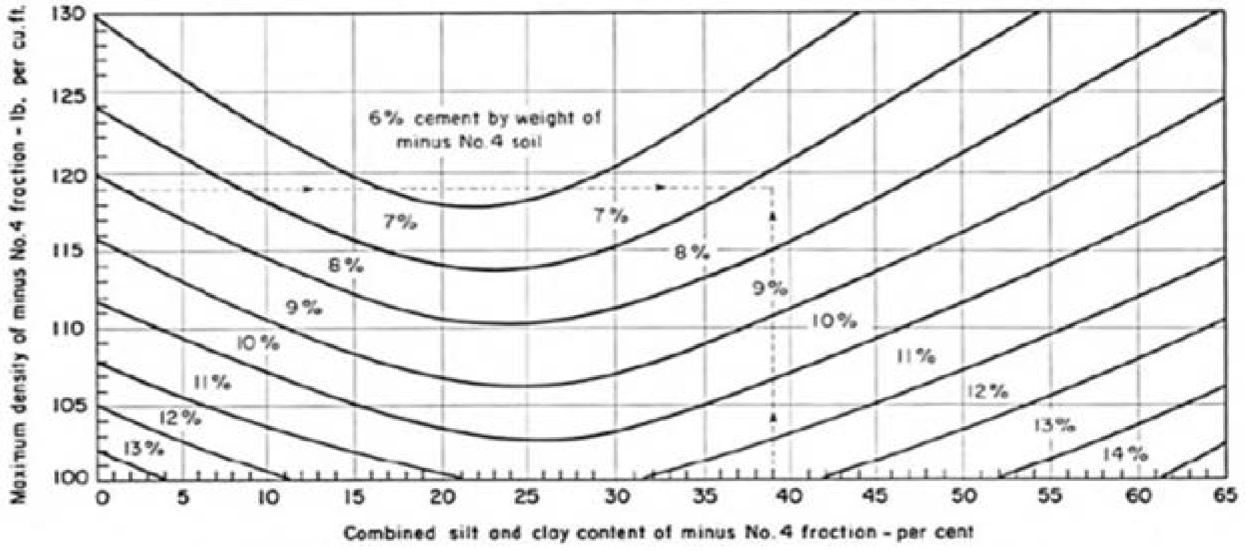


Figure 3. The required cement content for soil-cement mixtures without materials retained on the No.4 sieve (adopted from PCA, 1956)

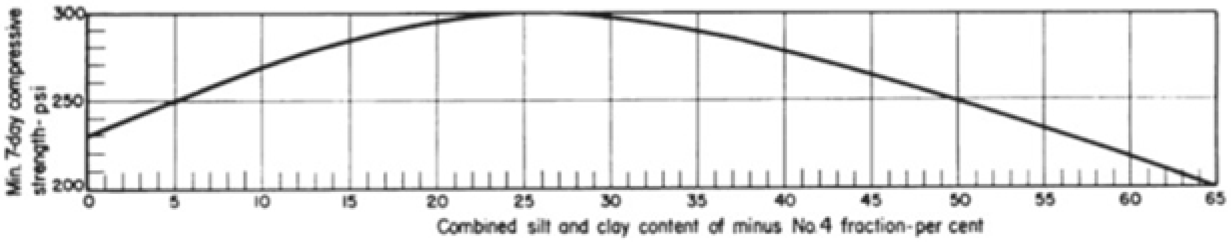


Figure 4. The required minimum 7-day compressive strength for soil-cement mixtures without materials retained on the No.4 sieve (adopted from PCA, 1956)

Table 1. Chemical composition of Portland cement (adopted from Fang, 1991)

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	

Lime

Lime is a white calcium-compound material. Generally, there are has 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 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 1991).

Lime-stabilized mixture design procedures are based on statistical analysis of laboratory tests. After much data analysis and validation activity, the National Lime Association (NLA) has developed an approach for estimating proper lime application rate in soil stabilization, as shown in Figure 5. It can be seen that this chart doesn't work for soil with less than 10 percent passing through a No.40 (0.42 mm) sieve and a 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 (determine plasticity, PI). The obtained value of plasticity is then entered at the top axis. Next, go down along the curved line and find the intersection with the percentage of soil binder. Finally, read the required percentage of lime from curves modified for aggregate top.

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.

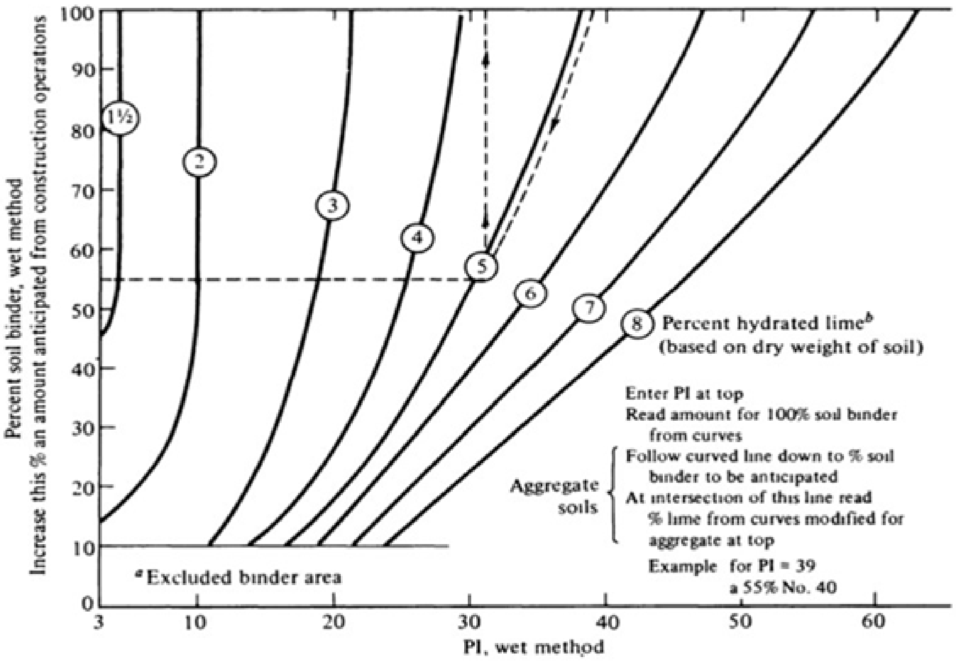


Figure 5. Recommended amounts of lime for stabilization of subgrades and bases (adopted from NLA 1972)

Fly-ash

Fly-ash is also widely used in the United States 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. Generally, the primary components of fly-ash are calcium oxide, aluminum oxide, ferric oxide, and silicon dioxide. Fly-ashes are 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 618. The burning of younger lignite or sub-bituminous coal typically produces Class F fly-ash containing less calcium oxide (ASTM 618). 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 some stable gel with the presence of water, but not nearly as effectively as Portland cement. Class F fly-ash is pure pozzlan and a not hydraulic stabilizer. One notable characteristic of this ash is that it must be used with lime to be effective (Winterkorn 1991); 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).

Table 2. Weight percentage of various components of fly-ash (adopted from Styron 1980)

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

Fly-ash mix design is based on trial-mix data. The great variability among fly-ashes 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 and Handy (1960) proposed a lime- to fly-ash ratio chart (Figure 6) that satisfies the strength requirement. In this chart, the required strength curve can be used to identify the appropriate lime and fly-ash content in 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 1991). To perform the UCS test (ASTM C 39) and thereby verify the trial mix lime-to-fly-ash selection, ASTM C 593 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 to make pavement 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 more and more global attention.

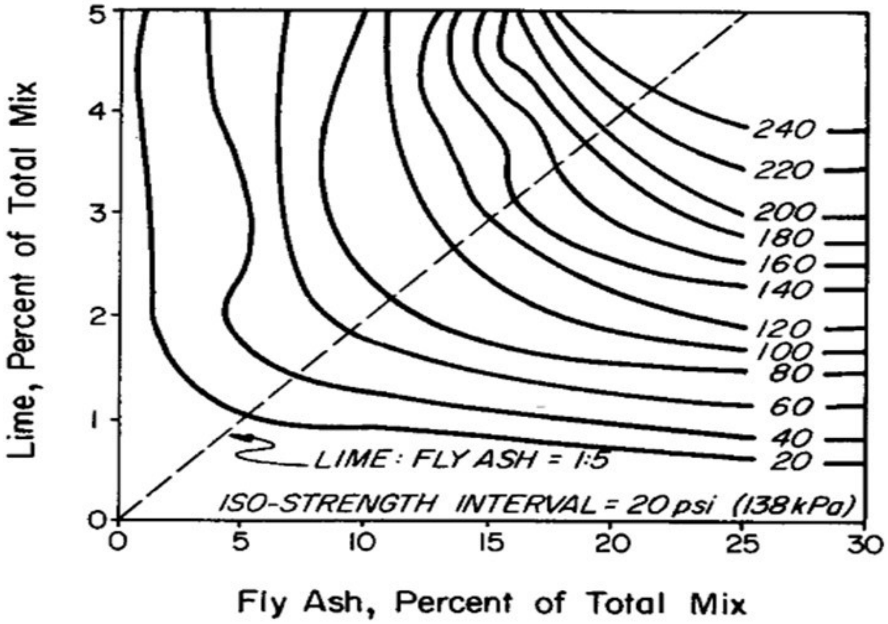


Figure 6. Trial mix selection for lime-fly ash-soil mixtures based on compressive strength requirement (Davidson and Handy 1960)

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 to traditional stabilizers. 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 have generally been more highly valued than understanding their interactions with geomaterials, much effort has been expended toward determining the mechanisms of nontraditional stabilizers. A comprehensive summary of an annotated bibliography of nontraditional stabilizer studies is listed in Appendix B.

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 very significant quality 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 close-packed and produce more flocculation, thereby improving soil strength. Most previous studies have already reported the benefits of 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 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 such 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 (Scullion 2002). 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 2010).

Enzyme stabilizers

Enzymes are biological molecules that catalyze chemical reactions. Enzymes, unlike traditional stabilizers, don't consume themselves in reactions, so 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 neutralized charge to reduce affinity for moisture. Similar to laboratory testing results of ionic stabilizer, Rauch, et al., (2002) found no significant changes in XRD and specific 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 2002). Lignosulfonates are regarded as cementing agents that form physical bonds between soil particles through minor chemical reactions (Landon, et al., 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. To investigate the effects of lignosulfonate stabilization, Tingle and Santoni (2003) cooperated to conduct laboratory testing on a CL soil. A significant increase in strength was obtained after twenty-eight 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 achievement of 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 area for bonding formation.

In Alabama, a lignin-based stabilizer was added for testing low-volume road subgrade soil (Rummer, et al., 2001). Compare to untreated road sections, a lignosulfonate-treated section showed a higher California Bearing Ratio (CBR), as defined in a penetration test guided by ASTM D 4429 and ASTM D 1883 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 mixture, 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 2002). The hypothesized underlying mechanisms of salt stabilizers therefore indicate that both granular and fine soil can be treated with these additives. Singh, et al., (1999) conducted a series of laboratory testing to investigate the use of sodium chloride in soil stabilization. He reported that the use of sodium chloride can greatly improve CBR value, UCS, indirect tensile strength (ASTM D 6931), and resilient modulus (ASTM STP 1437) for both gravel and clay soils. He also reported an increase in maximum dry unit weight compaction produced by a 1 percent salt content.

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 resulting potential 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 geomaterial pavement stabilization. The primary mechanism of bituminous stabilization is to coat soil particles and physically bind them together (Tingle 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 lower specific area. Particles in fine-grained soil with high specific area are more difficult to adequately bond than those in granular soil with asphalt emulsion.

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 ten-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 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 condition. 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 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 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 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, respectively. However, the same silty sand treated with polymer emulsion showed greater strength improvement than tree resin stabilization. Santoni and Tingle (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. The Federal Highway Administration (FHWA) evaluated field performance of several commercial resin productsand reported that tree resin products are desirable stabilizers in improving pavement strength and reducing dust (FHWA, 2002).

Table 3. The brief summaries of categories, laboratory performance and hypothesized mechanisms of nontraditional stabilizers (summarized from Tingle et al. 2007)

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

Summary of nontraditional stabilizers

The mechanisms underlying different stabilizers are summarized in Table 3. Stabilizers relying on physical bonds and cementations are suitable for granular soil due to high specific 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 John 2010). During future development the entire industry should cooperate with research organizations to conduct laboratory and field testing for additive evaluation. They also should embrace change and use databases to propose protocols for nontraditional stabilization mix design.

Biofuel Co-product (BCP)

The burning of fossil fuel (petroleum, coal, natural gas, etc.) has brought us energy for development of society, but it has also polluted the environment through emission of greenhouse gas. 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 waste food biomass. Its use has been strongly supported by the United States 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 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 Mcakkister 2010). Figure 7 depicts the process of biofuel and co-products production. Biomass processes of pyrolysis, gasification, combustion, biochemical, hydrolysis, transesterification, hydroprocessing and metathesis can produce ethanol, electricity, hydrogen, methanol, and transportation oils (Yue, et al., 2013). 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 Mcakkister 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., 2015). As a byproduct derived from biomass, lignin exhibits a variety of structures depending on 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 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 (SO3H, etc), but also have aliphatic thiol groups that may generate nasty smells, especially during heating (Lora and Glasser 2002).

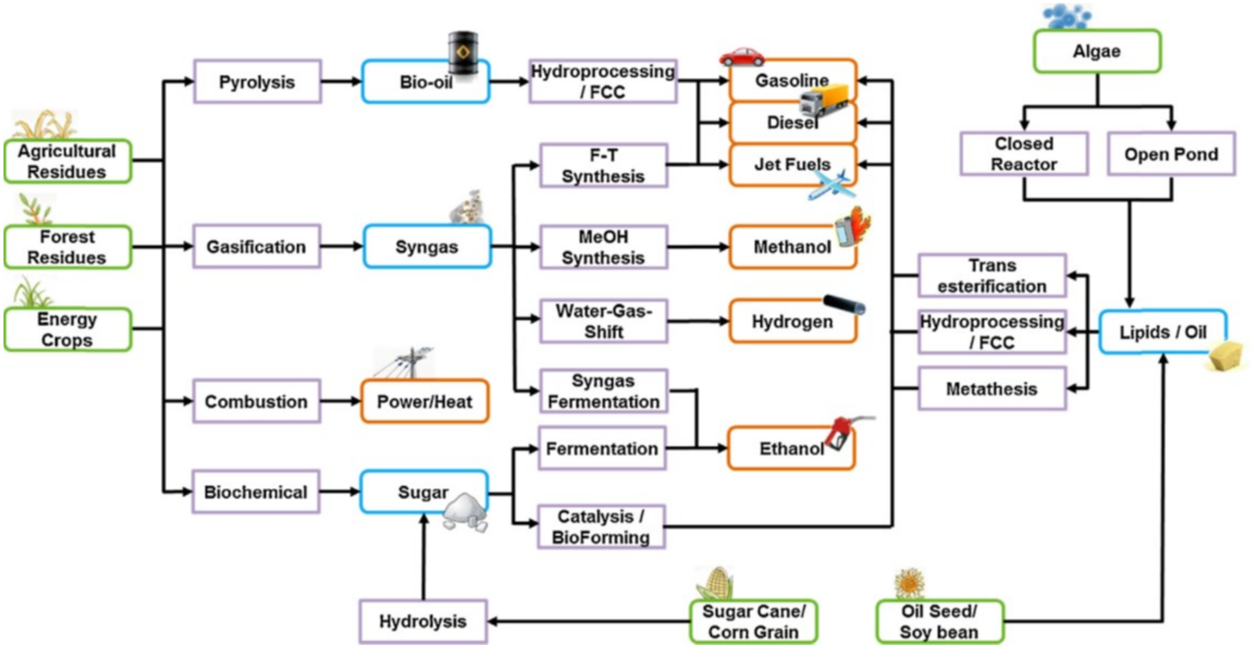


Figure 7. Generalized biomass to biofuel process diagram (adopted from Yue et al. 2013)

Lignin products derived from industry as byproducts or coproducts 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 commercialized as that from other industry, 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 Iowa State University (ISU) for deriving potential new economic benefits from lignocellulosic biorefineries (Ceylan, et al. 2009; 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 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 1-day and 7-day curing, they reported that maximum strength improvement (UCS) was achieved on both specimens containing 12% of the two BCPs (Figure 7). 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 liquid-type treatment. Puppala, et al., (2014) and Puppala, 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-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.

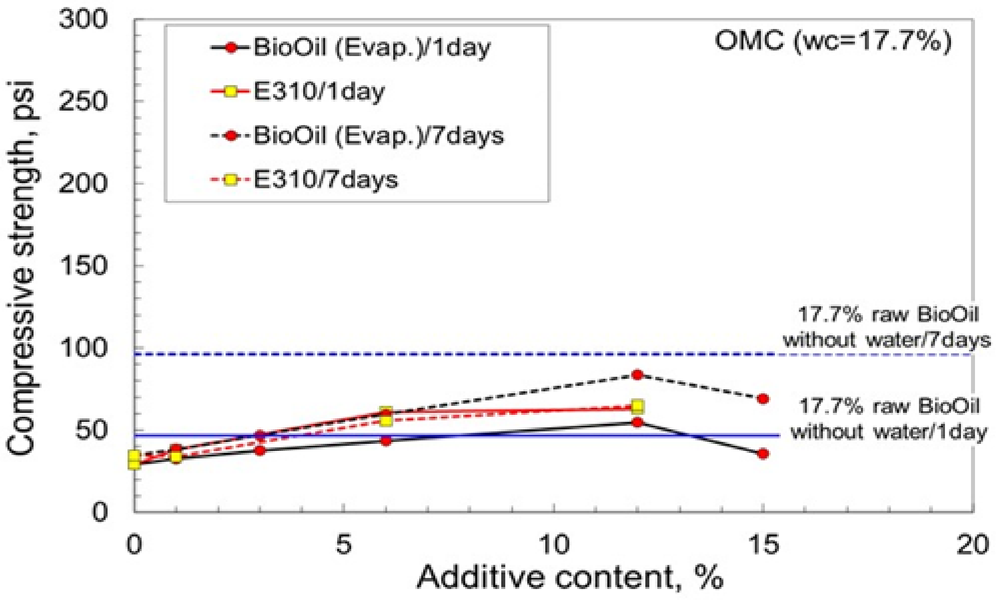


Figure 8. Unconfined compressive strength for soil treated with various contents of BCPs at optimum moisture content (adopted from the final report of Ceylan et al. 2010)

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 practices 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 whose promise is aligned with the massive 21st century development of the biofuel industry.

Ceylan, et al., (2010), Puppala, et al., (2014) and Puppala, et al., (2015) conducted UCS test for sulfur-free lignin treated silt and clay soils. In addition, Puppala, et al., (2014) and Puppala, 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 basically an extension of the study of Ceylan, et al., (2010); they developed this laboratory test program and the same BCP 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.

CHAPTER 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 9). In this research, four types of soil were collected from different counties; their characteristics and pictures are given in Table 4 and Figure 10, respectively. The American Association of State Highway and Transportation Officials (AASHTO) soil classification system and Unified Soil Classification System (USCS) are the two primary approaches used in classifying these soils by their gradation (Figures 11 through 14). 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 relatively "coarser" soil than the others, and Soil 2 is the finest soil with the highest clay content, 63%.

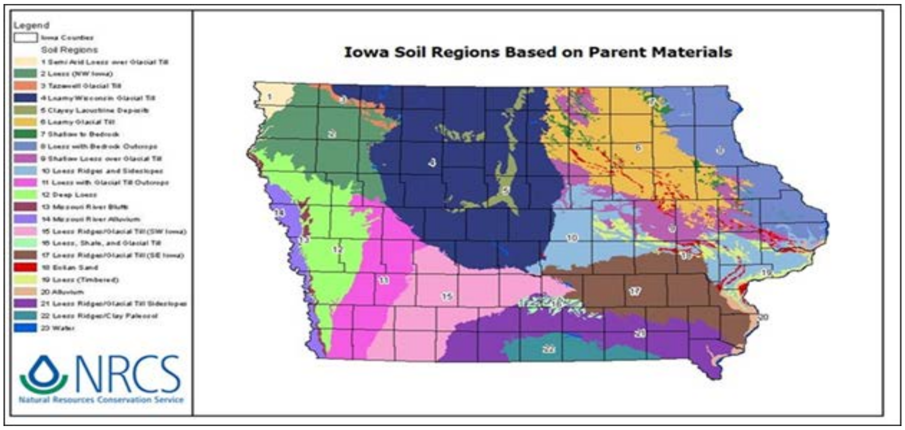


Figure 9. Iowa State soil map (adopted from Natural Resource Conservation Service)

Figure 10. Collected four types of soil in Iowa for research

Table 4. 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 (> 4.75 mm), %	7.1	0.1	5.2	3.8
Sand (0.075–4.75 mm), %	54.9	37.2	41.7	45.3
Silt and clay (< 0.075mm), %	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 ($\gamma_{d\ max}$), kg/m^3(pcf)	1,728 (107.9)	1,631 (101.8)	1,818 (113.5)	1,839 (114.8)

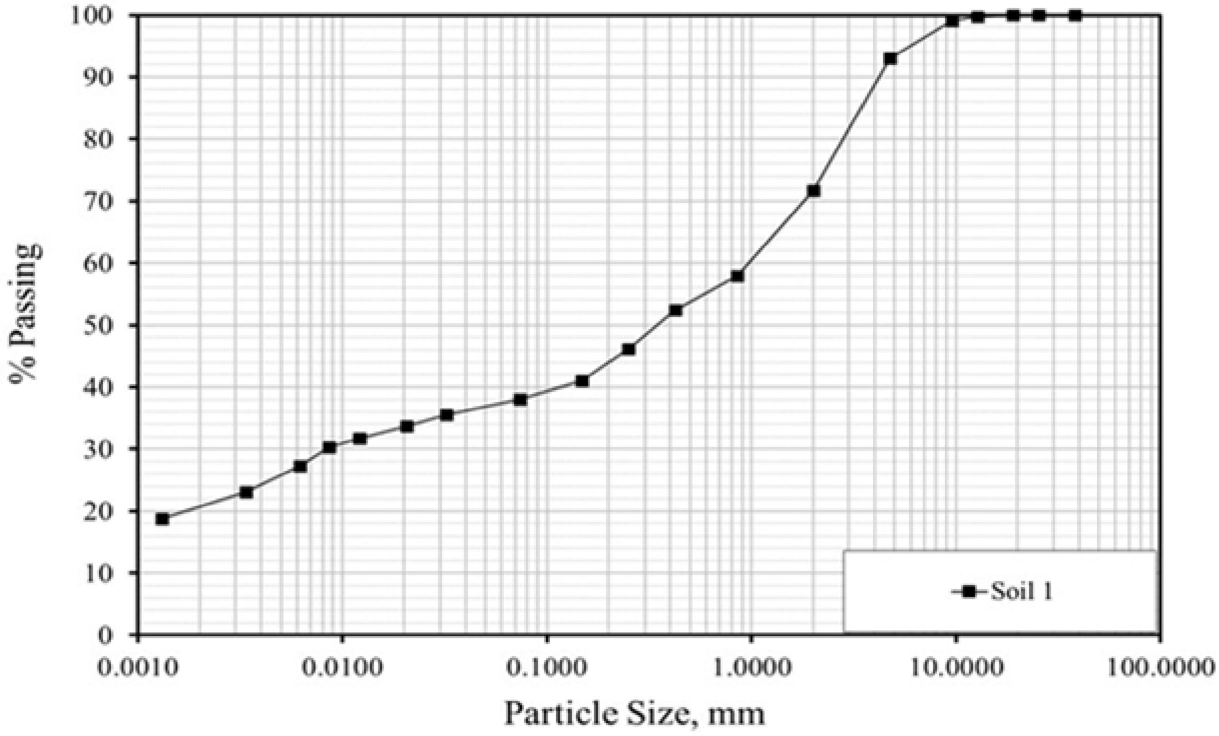


Figure 11. Particle size distribution curve of Soil 1 classified as A-6(2) and SC

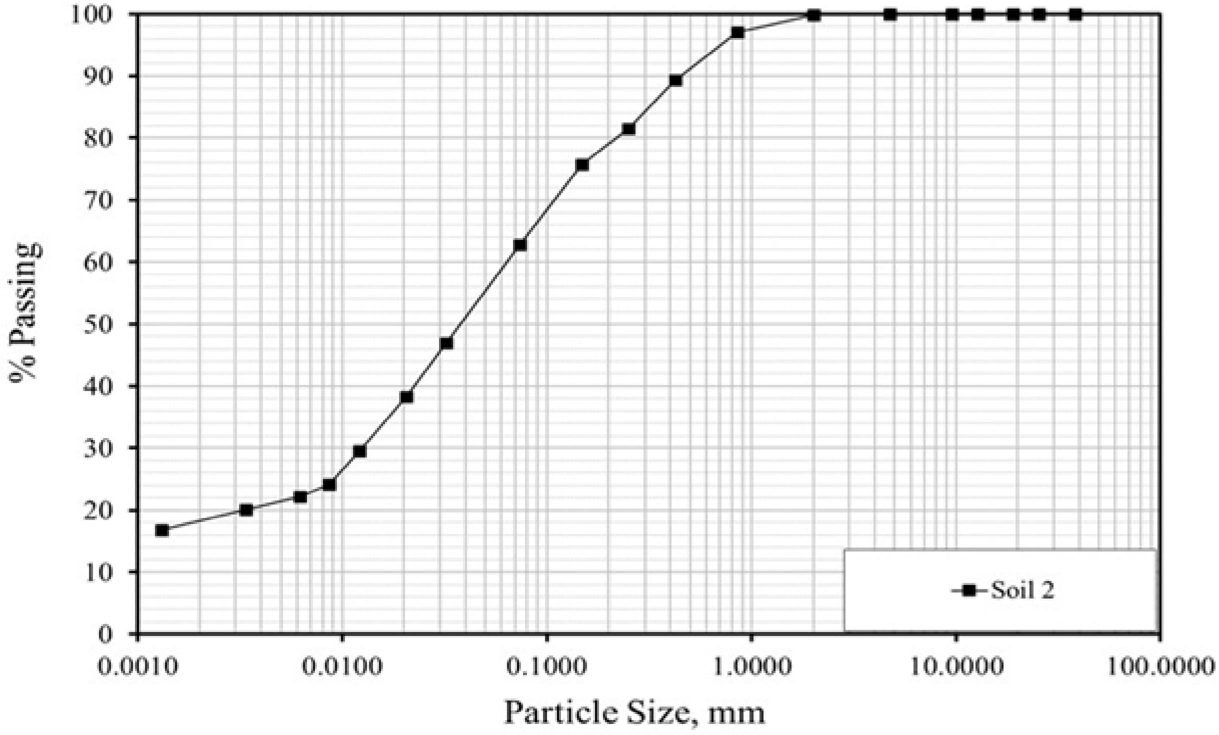


Figure 12. Particle size distribution curve of Soil 1 classified as A-4(2) and CL-ML

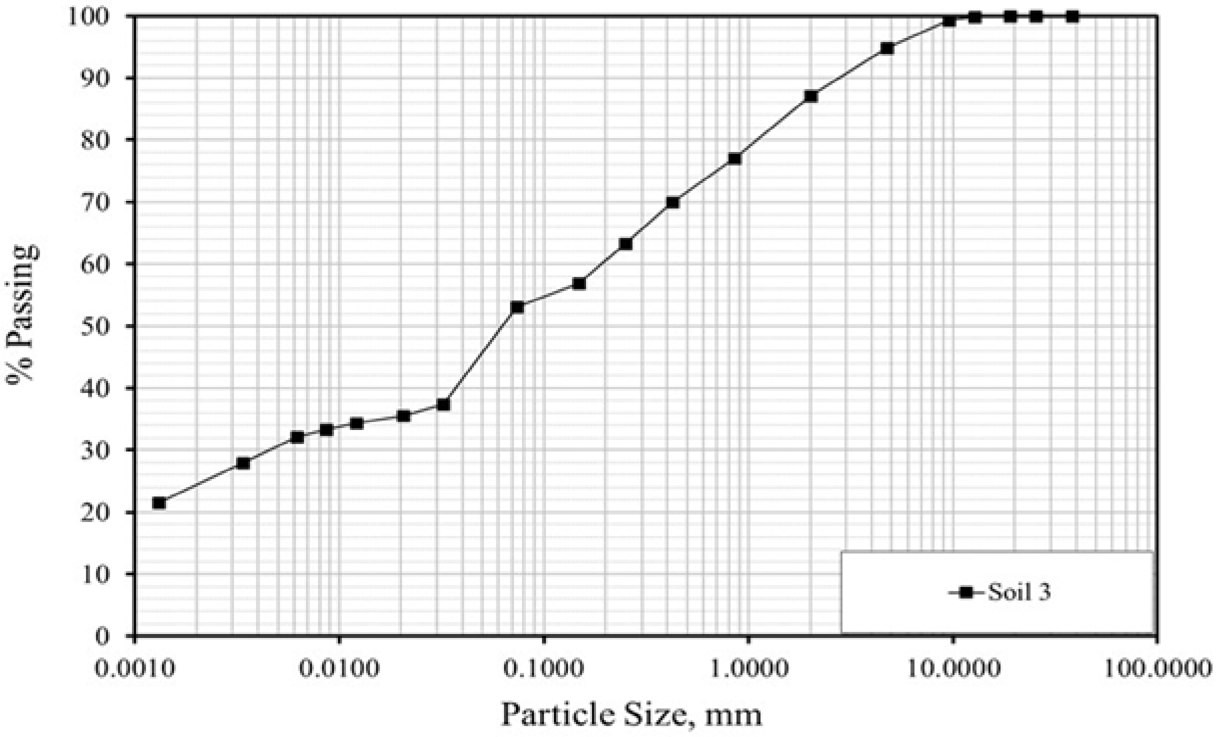


Figure 13. Particle size distribution curve of Soil 1 classified as A-4(1) and ML

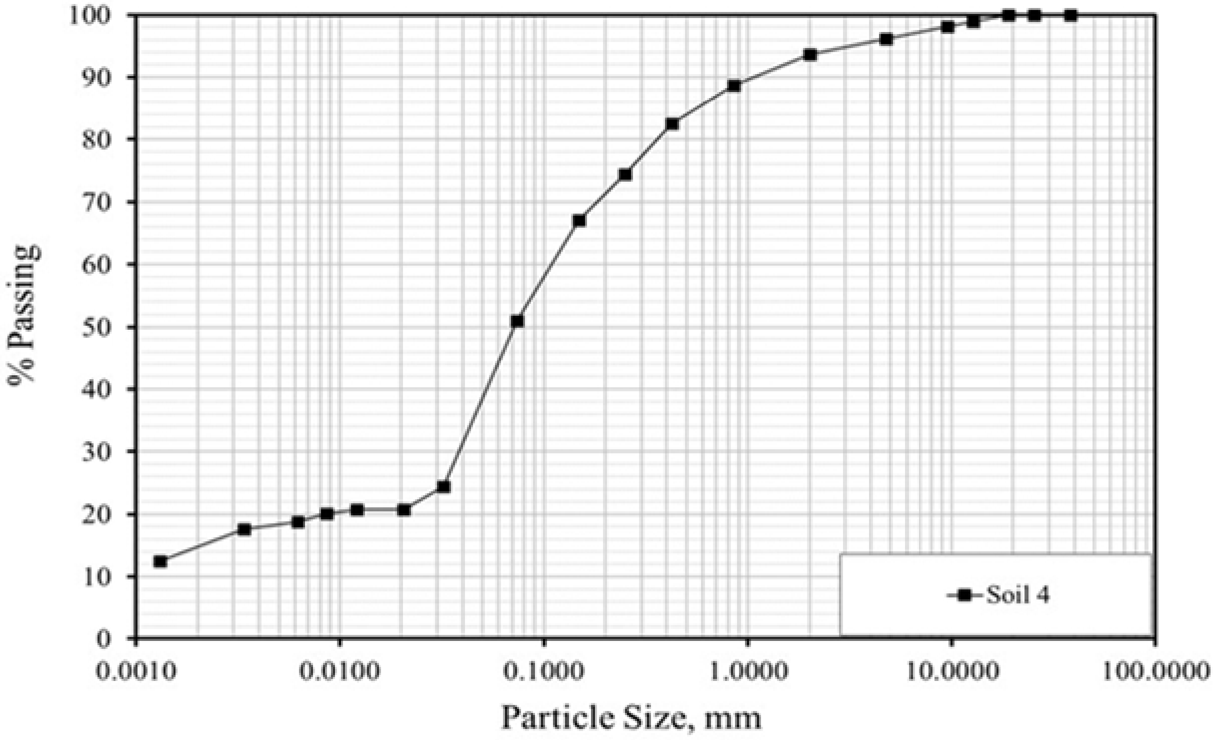


Figure 14. Particle size distribution curve of Soil 1 classified as A-4(0) and ML

Additives

This study investigated three different types of BCPs containing sulfur-free lignin as additives for soil stabilization; they were designated as BCP A, BCP B, and BCP C, respectively (Figure 15). In addition, Type I Portland cement, a traditional stabilizer, was also used for comparison purposes.

BCP A is a dark brown liquid obtained from Dynamotive Energy Systems Corporation who develop and commercialize energy solutions in Canada for conversion of biomass-to-liquid fuel based on its fast pyrolysis technology. This liquid is produced from fast pyrolysis of biomass (plant), a process that heats forest and agriculture residues at temperatures ranging from 400°C to 500°C in an oxygen-free environment (Dynamotive Energy Systems Corporation 2007). This liquid has a pungent smell, especially during heating. The primary component materials of BCP A are shown in Table 5. 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 liquid can be heated to remove some portion of moisture after which its behavior becomes more like asphalt binder. At high temperature it behaves as a liquid, while at low temperature 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 test and direct shear strength (DS) test 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 C shown in Table 6 are 50% hemicellulose, 20% cellulose, 5% lignin, and assorted others. This BCP is more like corn ash, and its unit weight is low due to its light molecular weight.

Co-product A (BCP A) | Co-product B (BCP B) | Co-product C (BCP C)

Figure 15. Three types of biofuel co-products used in this research

Table 5. Component materials in BCP A

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

Table 6. Component materials in BCP B

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

BCP C is also a dark brown 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 wash 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 laboratory testing. As for the other liquid types of BCP containing water, the addition of BCP A and BCP C in soil should consider their influence on moisture content of mixtures. This means that the required amount of water in soil-BCP A or soil-BCP C mixtures should be adjusted by water content in BCP A or BCP C. The mixing of liquid BCPs with soil also requires good liquid flowability; however, these liquid co-products are viscous and difficult to mix. To achieve uniform mixing, it is recommended that these liquid BCPs be heated for about twelve hours at 100°C before use, reducing their moisture content to approximately 18%.

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

Table 7. Component 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%

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 test; freeze-thaw durability test; microstructural characterization consisting of XRD and SEM. For the purposes of comparison, there were five different soil treatments in this experiment plan:

(1) pure soil without any treatment (control),

(2) BCP A-treated soil specimen,

(3) BCP B-treated soil specimen,

(4) BCP C-treated soil specimen, and

(5) Type I Portland cement 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. Puppala, et al., (2014) and Puppala, 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. 12% of BCP content may not be the optimum additive content for each soil type but seems close enough to provide strength improvement in practical use.

However, the lack of BCP A and BCP C materials meant that some laboratory tests couldn’t represent 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 8. In the UCS test, 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 test machine 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-day, and 28-day after sample preparation.

The treatment group combinations for freeze-thaw durability evaluation are listed in Table 9. Similarly 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; 1-day and 7-day curing periods were investigated.

Table 8. Treatment group combinations for strength property tests

Soil Types	Moisture content level	Curing period	Additives[a], %				
			Unconfined compressive strength				Direct shear strength
			BCP A	BCP B	BCP C	Cement	BCP B
Soil 1	OMC-4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC+4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
Soil 2	OMC-4%	1 day	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
	OMC	1 day	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
	OMC+4%	1 day	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0, 12	0, 3, 6, 12	0, 12
Soil 3	OMC-4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC+4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
Soil 4	OMC-4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
	OMC+4%	1 day	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12
		28 days	0, 12	0, 12	0	0, 3, 6, 12	0, 12

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

Table 9. Treatment group combinations for freeze-thaw durability tests

Soil Types	Moisture content level	Curing period	Additives[a], %			
			BCP A	BCP B	BCP C	Cement
Soil 1	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12
Soil 2	OMC	1 day	0, 12	0, 12	0, 12	0, 3, 6, 12
		7 days	0, 12	0, 12	0, 12	0, 3, 6, 12
Soil 3	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12
Soil 4	OMC	1 day	0, 12	0, 12	0	0, 3, 6, 12
		7 days	0, 12	0, 12	0	0, 3, 6, 12

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

Table 10. Treatment group combinations for moisture susceptibility, XRD and SEM tests

Soil Types	Moisture content level	Curing period	Additives[a], %	
			BCP A	BCP B
Soil 1	OMC	7 days	0, 12	0, 12
Soil 2	OMC	7 days	0, 12	0, 12
Soil 3	OMC	7 days	0, 12	0, 12
Soil 4	OMC	7 days	0, 12	0, 12

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

Table 10 lists the treatment group combinations for moisture susceptibility, XRD, and SEM 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., 2005) 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 7-day, respectively. Untreated soil specimens were also fabricated for comparison purposes.

Specimen Preparation

Different laboratory tests had different specimen requirements. Atterberg limits test, stand Proctor compaction test, XRD, and SEM need only loose soil-water-additive mixtures, but the other tests required compacted and cured specimens. In this study, two 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 other 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. To fabricate the two different types of specimens, mixing designs and procedures, compaction methods, and curing methods should be considered. Test specimen preparation required five steps:

1. First, the collected soil should be dried at a temperature between 100°C and 110°C for about twenty-four hours and at constant weight for removal of initial moisture. After drying, the soil could be broken down into smaller particles. The fraction of soil passing a No.4 (4.75 mm) sieve was used for specimen preparation. BCP A and BCP C were also heated to 100°C for about twelve hours to reduce their water content to about 18%. BCP B could be heated at a temperature below 60°C to reduce its water content to nearly 0°C.
2. Second, after materials preparation, the soil was mixed with stabilizers and water

uniformly to achieve target water and stabilizer values.

3. Then measure a quantity of loose mixture materials to achieve maximum dry unit weight of soil obtained from standard Proctor compaction test (shown in Table 4) for each 2 in. by 2 in. and 2.5 in. by 1 in. specimen. Assemble the parts of a specific mold and put measured material into it. Two types of mold were used to produce different sizes of specimens. The mixing proportions are listed in Appendix A.
4. The next step is to compact the specific mold with loose mixture to fabricate a specimen with 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 are wrapped in plastic film and cured using air-dried conditions at a 25°C room temperature to avoid loss of moisture. The curing time is 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. 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 D 698), 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 16. It has four parts: a 1 in. high spacer plug, a 4 in. high spacer plug, a mold, and a removable collar.

After adding the mold to the removable collar at the top and inserting the 1 in. high spacer plug, the measured amount of loose mixture was placed in the mold and a 4 in. high spacer plug was placed on the mixture in the mold. Static loading was then applied on the end of 4 in. high 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 the extruder used to remove the compacted specimen from the mold. The compacted specimens shown in Figure 17 were then wrapped in plastic film for curing.

Figure 16. Mold apparatus for 2 in. by 2 in specimen compaction

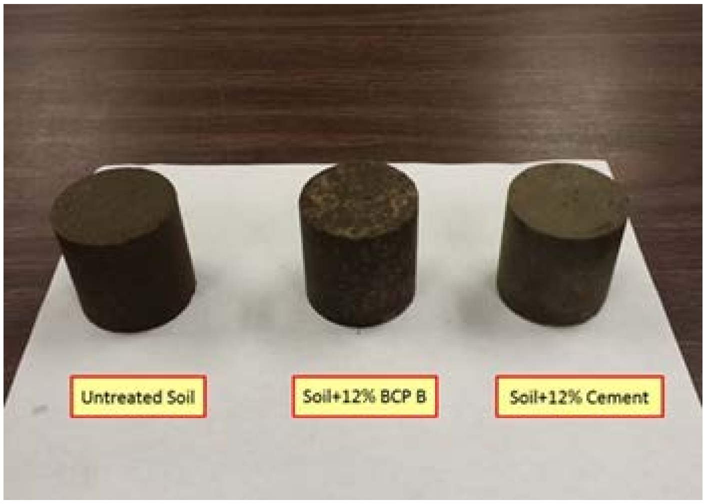


Figure 17. Prepared 2 in. by 2 in. samples

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. high metal rings of 2.5 in. inside diameter, a 1 in. high spacer plug of 2.5 in. diameter, and a 4 in. metal plate. Two 1 in. high metal rings were stacked up and assembled into a 2 in. high mold and placed on the metal plate. A measured amount of loose mixture was placed in this mold and a 1 in. high 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. high spacer plug, the compacted specimen could be exacted an extruder, as shown in Figure 19. This 2.5 in. by 1 in. specimen has the same density as a 2 in. by 2 in. specimen. Compared to traditional DS sampling methods introduced in ASTM D 3080, 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 one produced by a dynamic load; this might be important in reducing error due to contact surface fraction.

Figure 18. Mold apparatus for 2.5 in. by 1 in specimen compaction

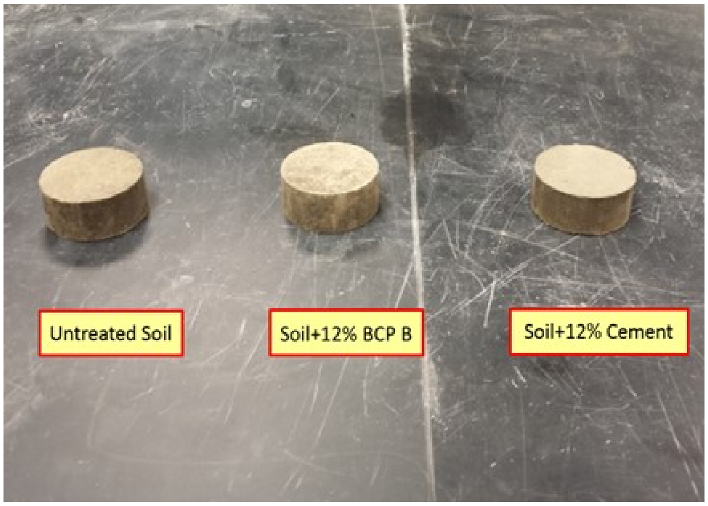


Figure 19. Prepared 2.5 in. by 1 in. samples

Atterberg Limits Testing

Fine-grained soil undergoes distinct changes in behavior and consistency with increase in water content, from solid to semi-solid, plastic, and 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 additive were subjected to Atterberg limits tests, basic measures of critical water contents of soil and their mixtures for finding plastic limit (PL) and 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 (425 μm) 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 20; it consists of a metal bowl that can be struck. 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 10 mm 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 D 4318 “Standard test method for liquid limit, plastic limit, and plasticity index of soils”. The plastic Index (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):

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \quad \textbf{(1)}$$

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.

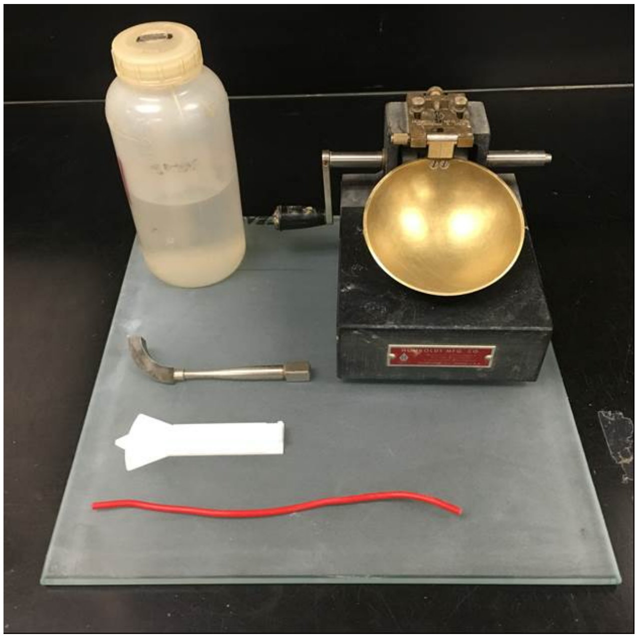


Figure 20. Atterberg limits test apparatus

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 21 shows moisture-density relationships for a cohesive soil with various compaction efforts. 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 increase in pore pressure.

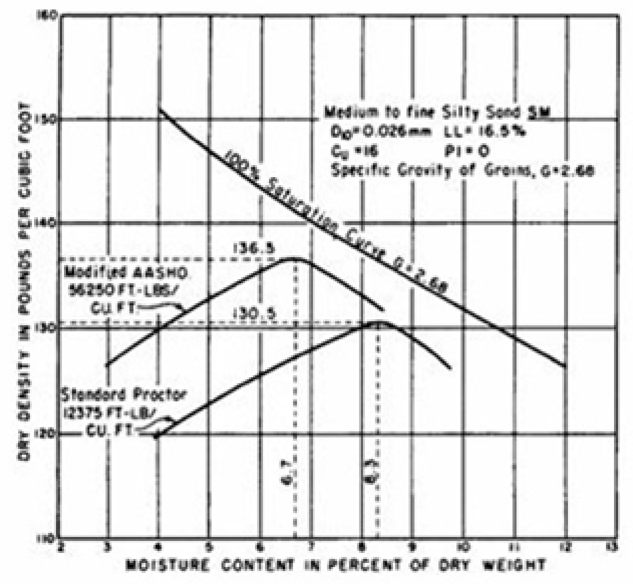


Figure 21. Moisture-density relationships of a soil for two compaction efforts (adopted from Hilf, 1956)

The moisture-density relationship of a cohesive soil is generally obtained by a standard Proctor compaction test in accordance with ASTM D 698 “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 D 698 was adopted due to a retaining of 20% or less mass of soil by the the No.4 (4.75 mm) screen. 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 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 22.

Figure 22. 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 D 2166 “Standard test method for UCS of cohesive soil”. Figure 23 depicts the automated computer control system used in this study for determining soil UCS. 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 D 2166 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 D 2166.

The prepared 2 in. by 2 in. 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 unit it reached a peak, then the stress went down due to sample crush. 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 D 2166 didn't provide an accepted reference value, the precision and bias for results depended on self-engineering judgement.

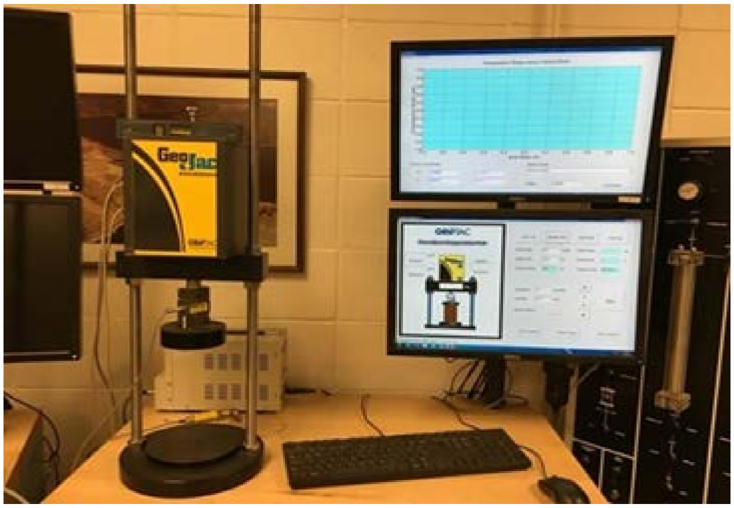


Figure 23. Automated Geotac system for unconfined compressive strength testing

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 soil properties in accordance with ASTM D 3080 “Standard test method for direct shear test of soils under consolidated drained conditions”. The consolidated drained shear test allowed the specimen under pore pressure to consolidate and adjust to the surrounding stresses. Figure 24 shows the automated computer control system used for the DS test. 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 25 depicts a shearing demonstration for a specimen in the shear box. Once the specimen had been properly held by 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.

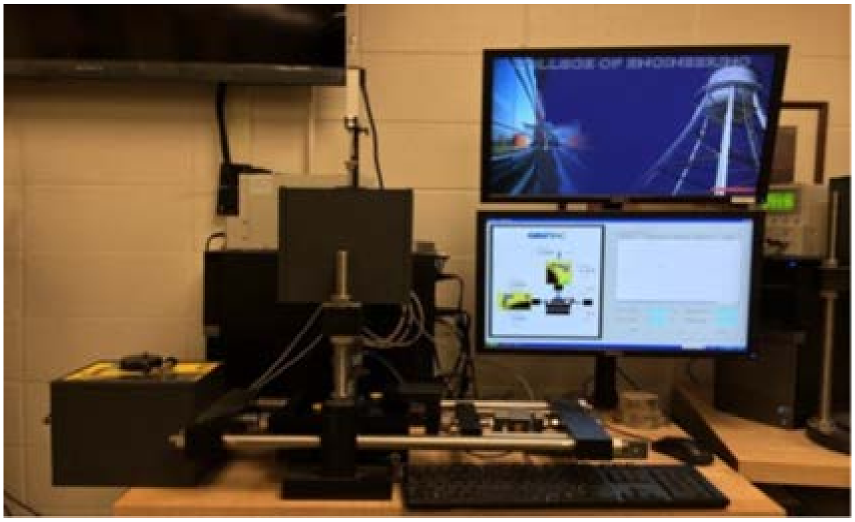


Figure 24. Automated Geotac system for direct shear strength testing

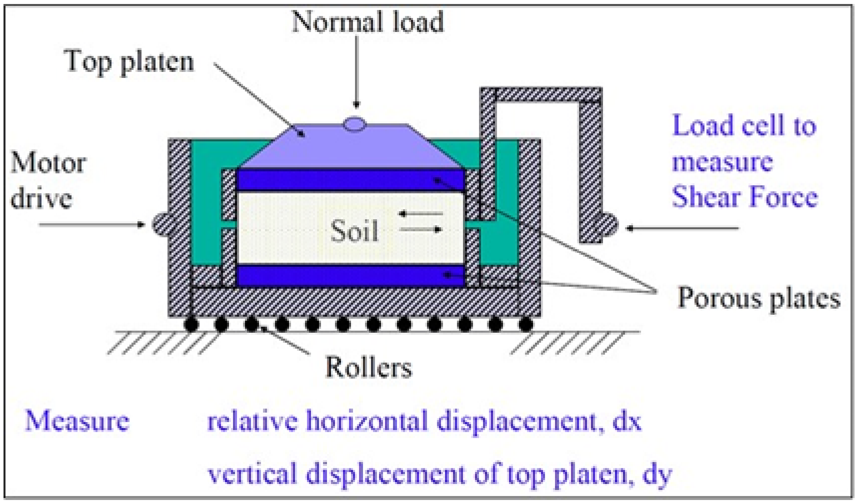


Figure 25. Demonstration of direct shear test.

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 26 and expressed in Equation (2). 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.

$$\tau = c + \sigma \tan \phi \tag{2}$$

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

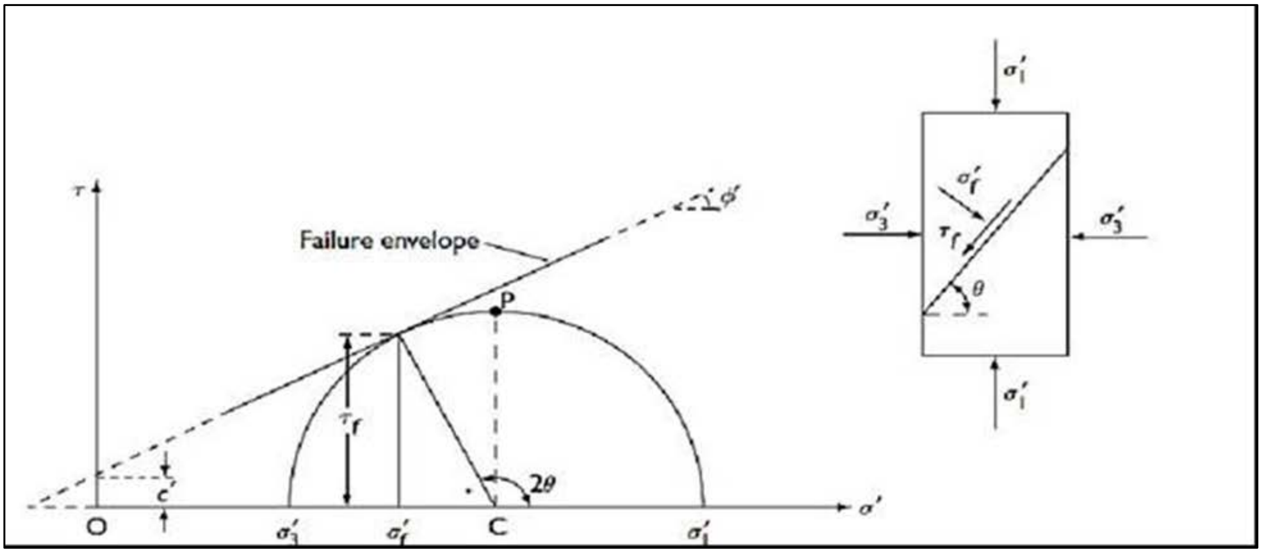


Figure 26. Mohr–Coulomb plot for determination of shear parameters (from Craig, 2005)

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. A free-thaw durability test was conducted in this study by imitating natural freeze-thaw cycles to evaluate the durability improvement for additive-modified soils in accordance with ASTM D 560 “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 twelve freeze-thaw cycles. Each cycle was scheduled as twenty-four hours in a freezing cabinet at -23˚C, followed by another twenty-three hours in a moist room at 21˚C 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; 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 D 560. 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 oven-dried weight for mass loss evaluation after only twelve cycles. Equation (3) shows the calculation of mass loss. Three repetitions were conducted to improve test reliability. It should be noticed that 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, six specimens were processed over twelve freeze-thaw cycles. At each 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 twelve cycles, the other three specimens were oven-dried at 110 ˚C to measure percentage mass loss.

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

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 causes 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 7-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.

Microstructural Characterization

Microstructural characterization of a stabilizer-treated soil can be used to understand the stabilization mechanism. SEM and XRD 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. 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 7-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.

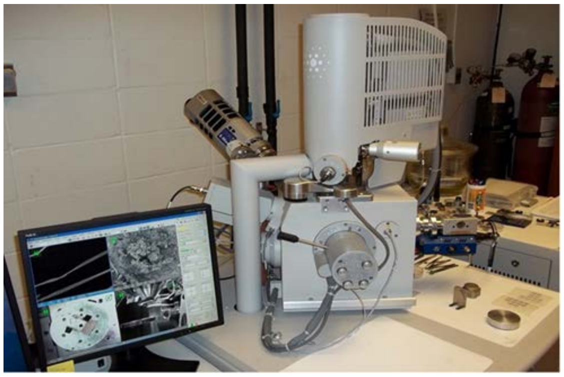


Figure 27. Scanning electron microscope equipment in Iowa State University

Figure 28. X-ray diffraction equipment in Iowa State University

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.

CHAPTER 4

LABORATORY TEST RESULTS AND DISCUSSIONS

Atterberg Limits Results

The effects of co-products and cement on Atterberg limits of different soils are shown in Figure 29 and Table 11. The selected application rate of additives was 12% because the highest increases of UCS that rate of co-products were reported in the final report of Ceylan, et al., (2010).

As shown in Figure 29, the four types of soil investigated in this research have different consistency limits. Soil 1 had the highest values of 32.8 for 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 oil-type BCP A decreased the plasticity for all soils. The 9%, 2%, and 6% decreases in plasticity of Soils 1, 2, and 3 were obtained with the addition of BCP A. Plasticity of Soil 4 was reduced by 19% with BCP A, a difference of 0.4. 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. 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 limit results indicate that BCP A is a more promising additive in terms of reduction in soil plasticity.

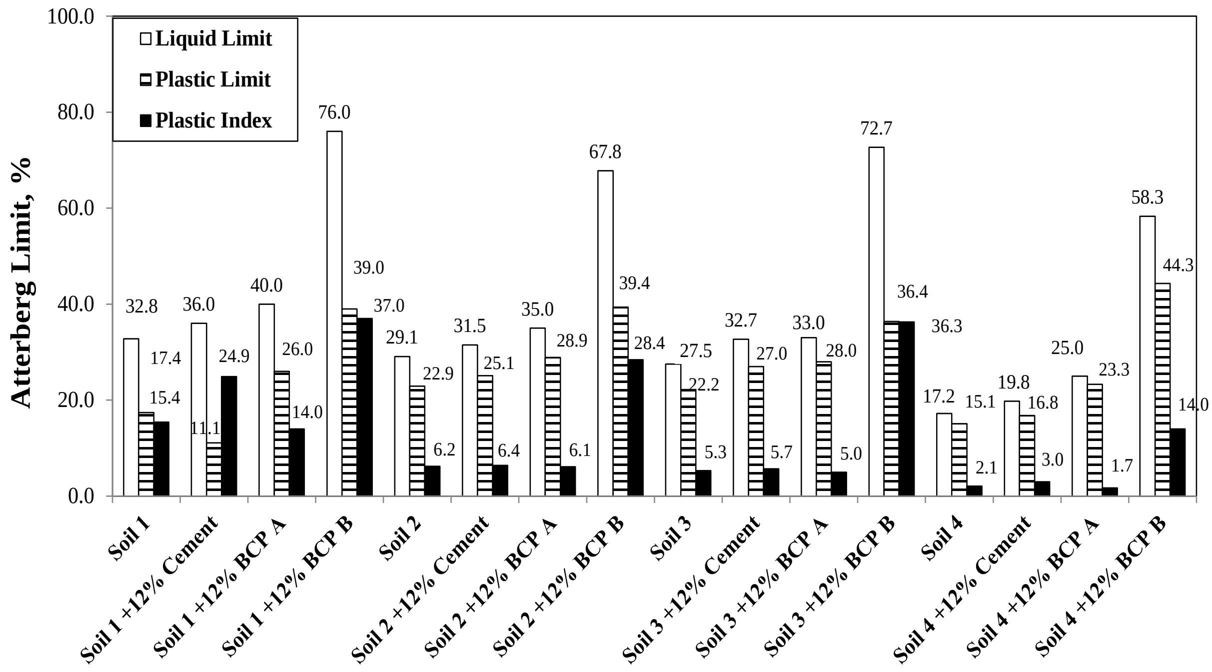


Figure 29. Effect of additives on consistency limits of soil

Table 11. Effect of additives on consistency limits of soil

	Value of increase			Percentage of increase[a]		
Mixture	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%

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

Moisture-Density Relationships Results

Figure 30 presents the effects of additives on compaction characteristics 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 1728 kg/m^3 with 14.4% of OMC. The maximum dry density and OMC for Soil 3 were 1818 kg/m^3 and 13.5%, respectively. Soil 2 had the lowest maximum dry density and the highest OMC, 1631 kg/m^3 and 18.2%, respectively. In contrast to the compaction properties of Soil 2, Soil 4 had the highest maximum dry density, 1839 kg/m^3, 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 37 kg/m^3. The powder type co-product BCP B produced a significant decrease in maximum dry density of soil, between 180 and 300 kg/m^3, 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.

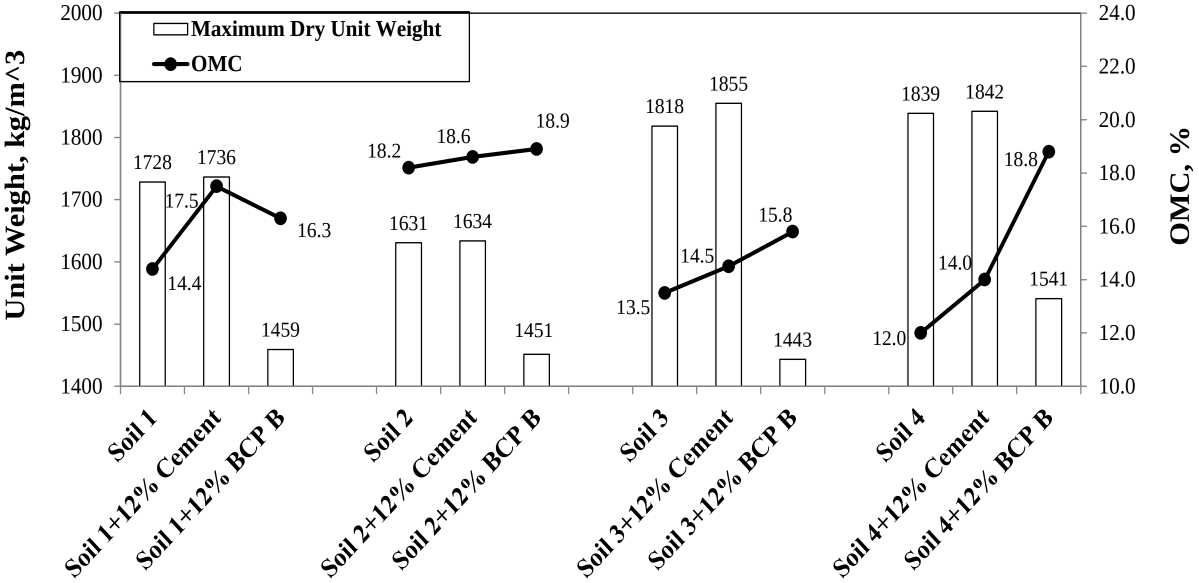


Figure 30. Effect of additives on compaction properties of soil

Unconfined Compressive Strength Results and Analysis

The effects of additives on compressive capacity of soil are shown in Figures 31 through 42. Figures 31 through 33 present the strength results for Soil 1, Figures 34 through 36 show the strength capacity of Soil 2, Figures 37 through 39 and Figures 40 through 42 present strengths of Soils 3 and 4, respectively. 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, OMC+4%) and different curing periods (1-day, 7-day, 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 content of cement varied from 3% to 12% only for comparison purpose.

Effects of soil types

Soil type (classification) based on fine content affects the compressive strength capacity of soil. Soil 1 classified as A-6(2) and SC with lowest fine 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 fine 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 fine 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 fine content of soil, i.e., the fine 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 (Thomas, et al., 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 fine 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 fine content generally has relatively low strength capacity.

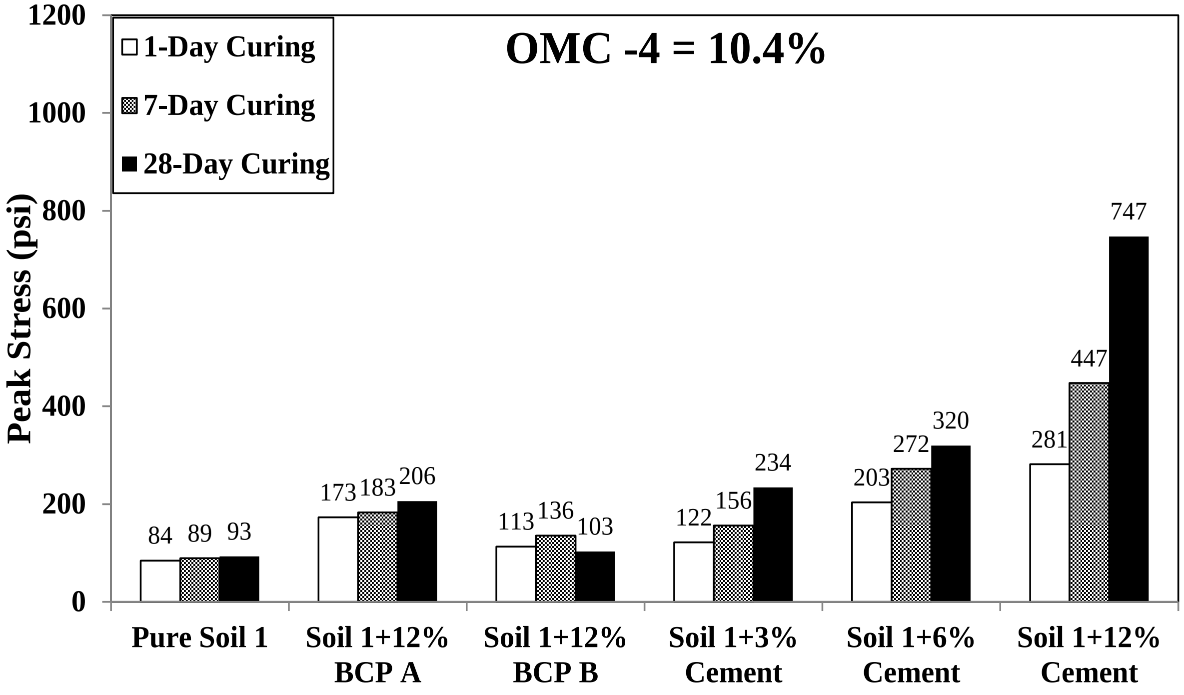


Figure 31. UCS test results for Soil 1 under OMC-4%

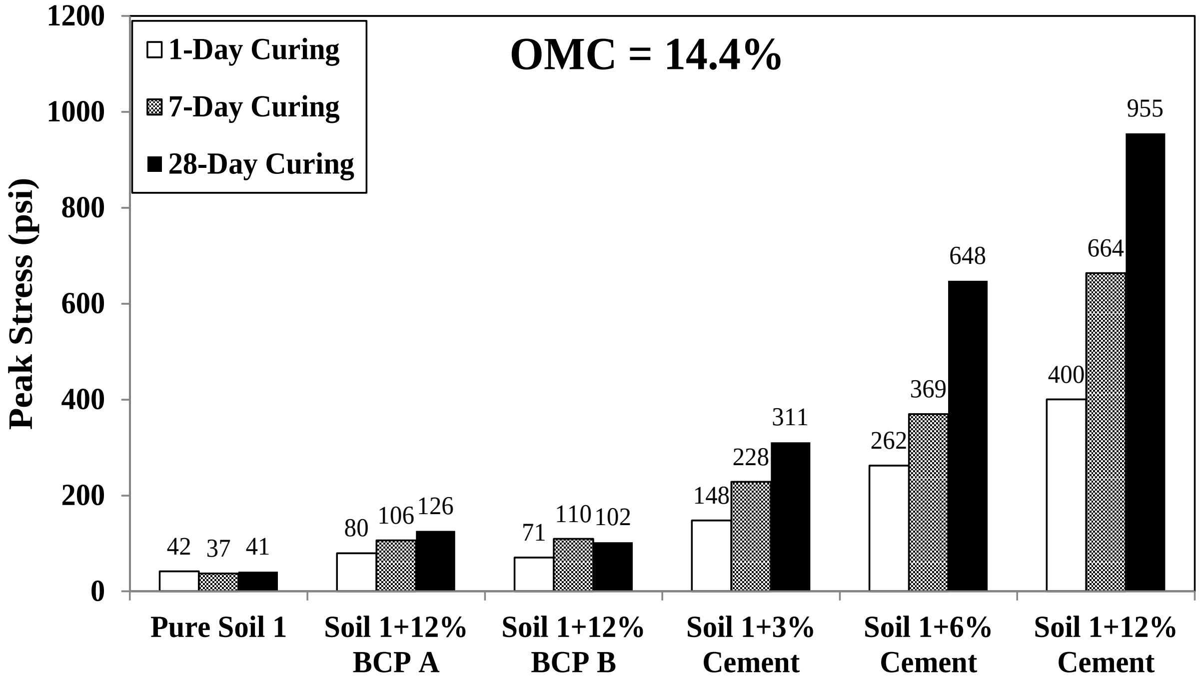


Figure 32. UCS test results for Soil 1 under OMC

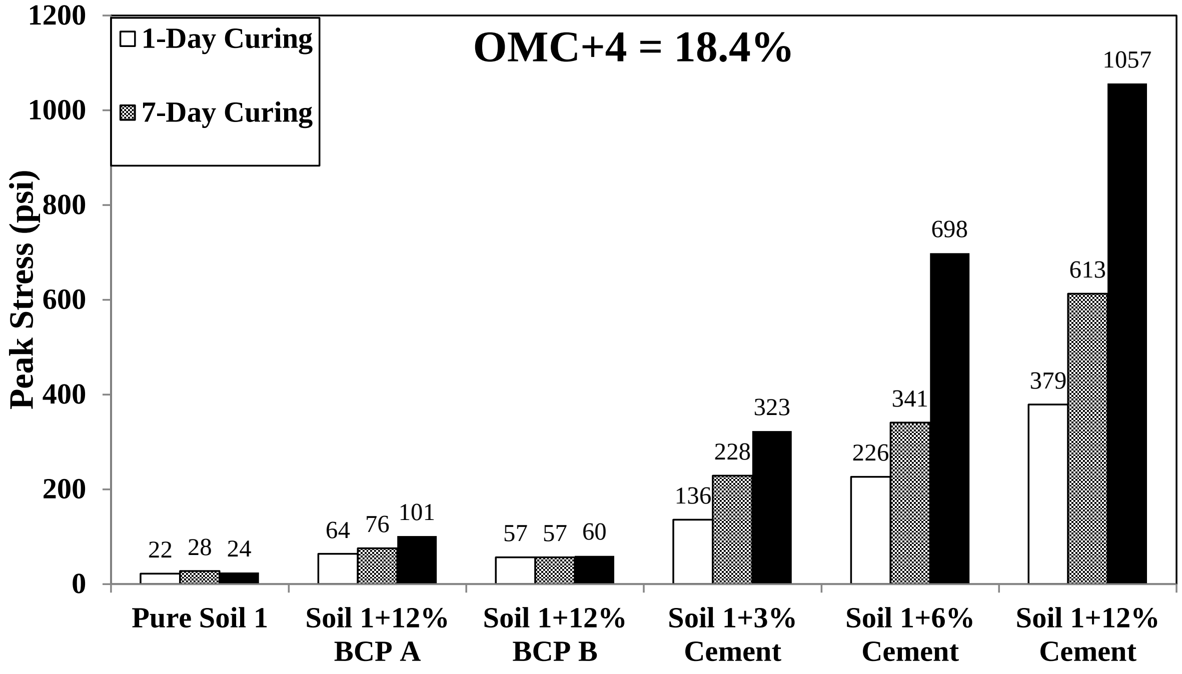


Figure 33. UCS test results for Soil 1 under OMC+4%

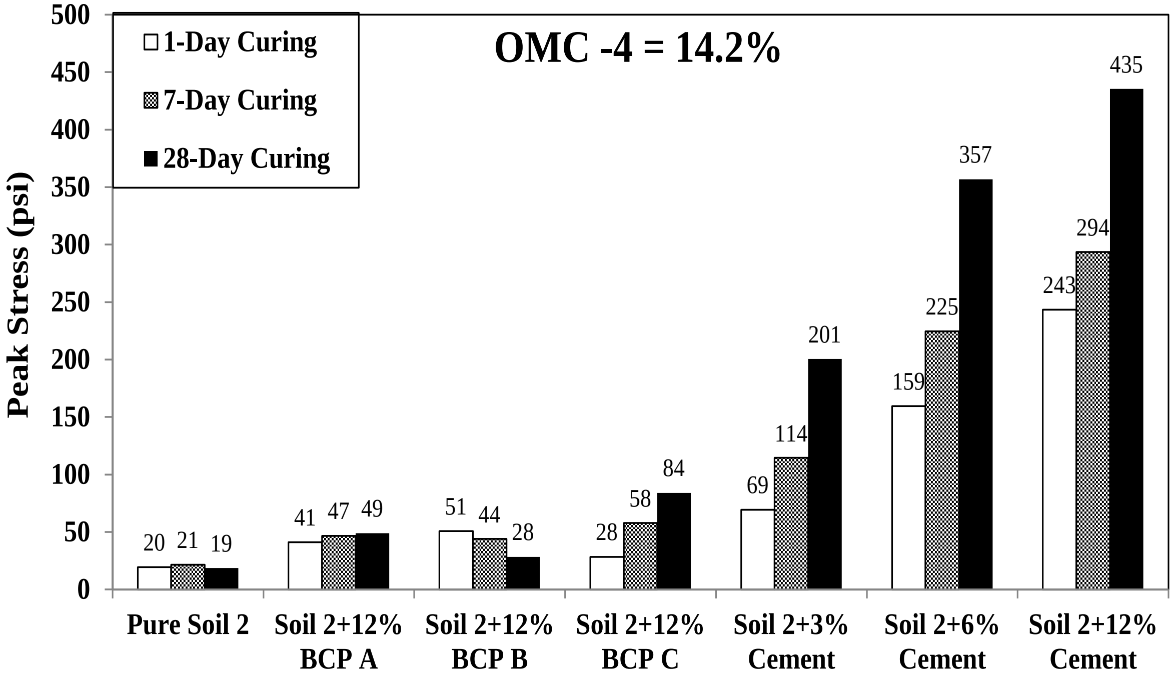


Figure 34. UCS test results for Soil 2 under OMC-4%

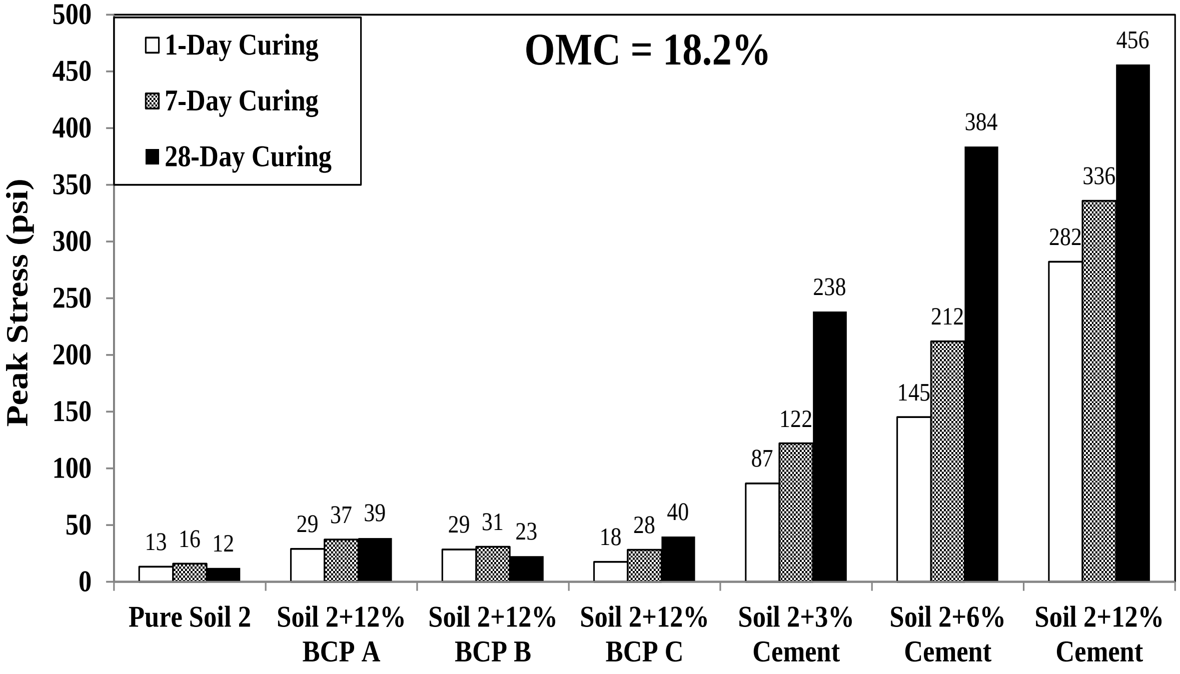


Figure 35. UCS test results for Soil 2 under OMC

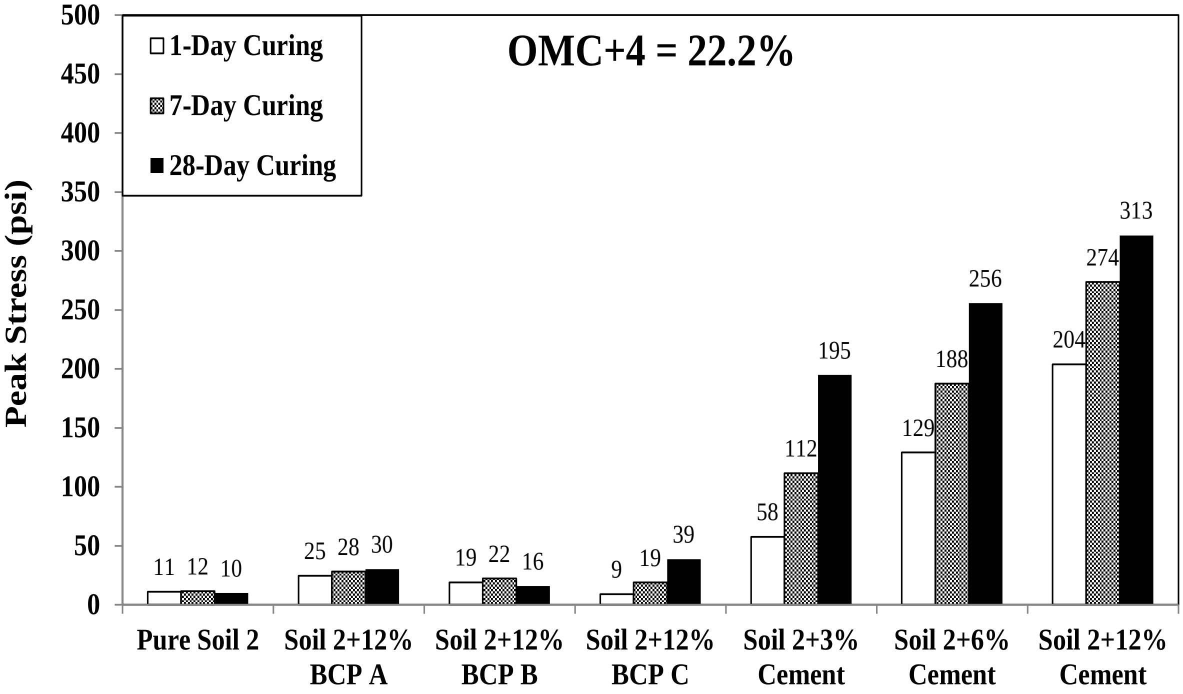


Figure 36. UCS test results for Soil 2 under OMC+4%

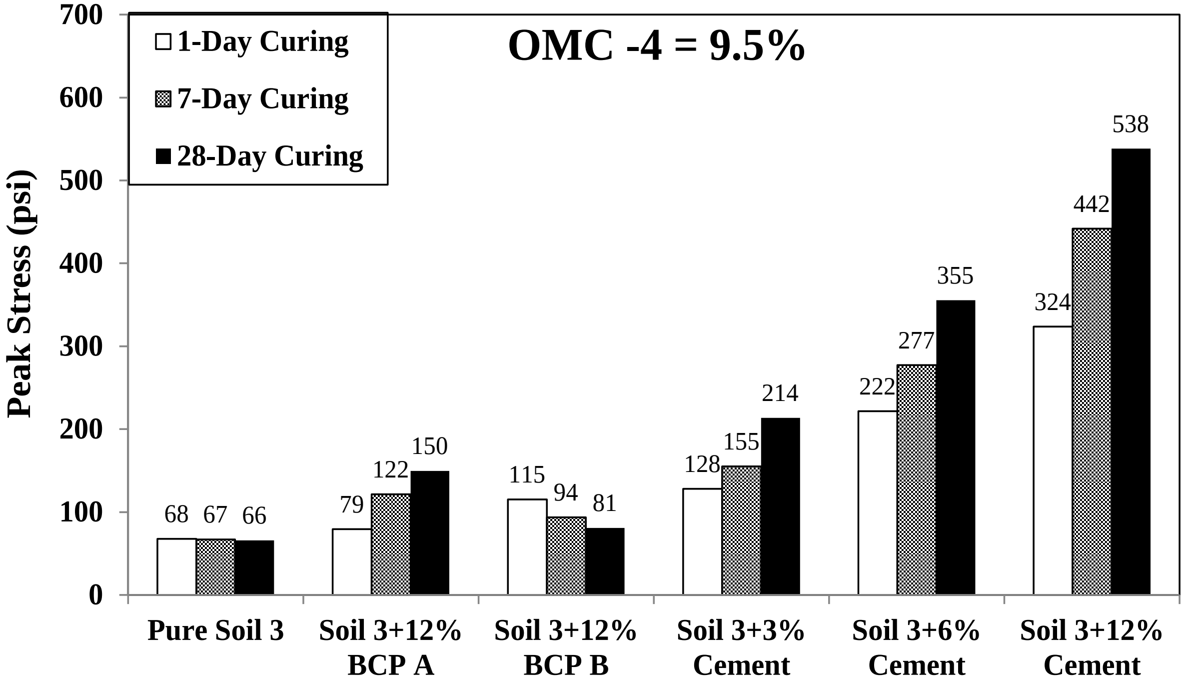


Figure 37. UCS test results for Soil 3 under OMC-4%

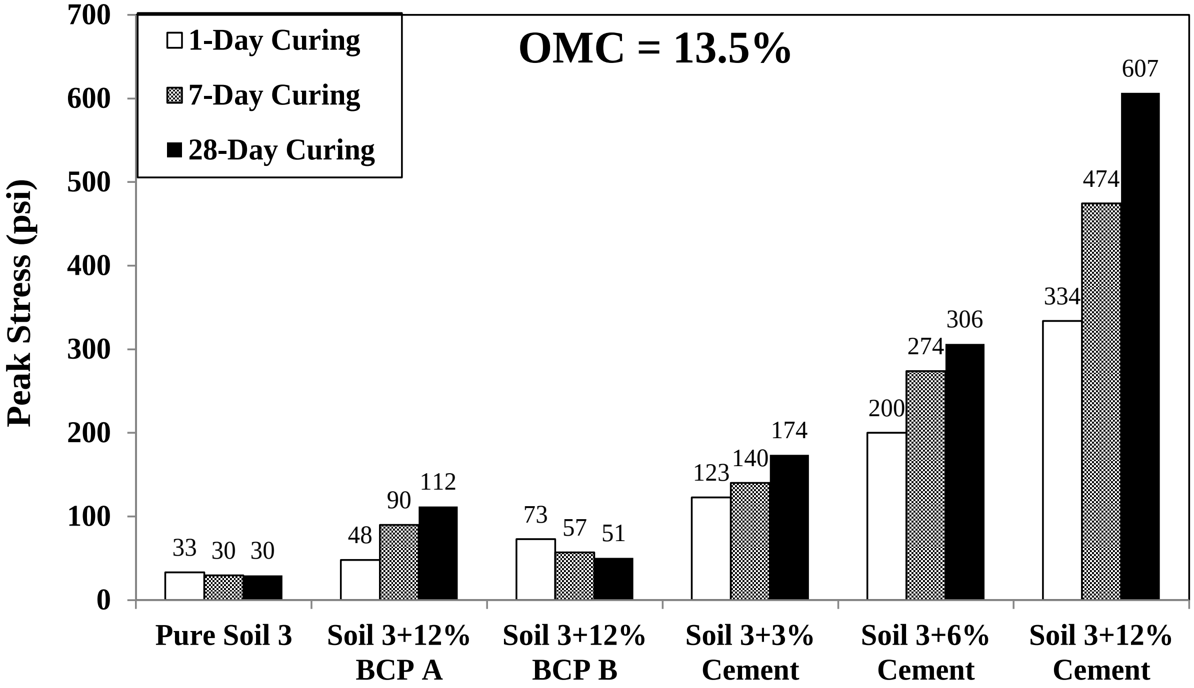


Figure 38. UCS test results for Soil 3 under OMC

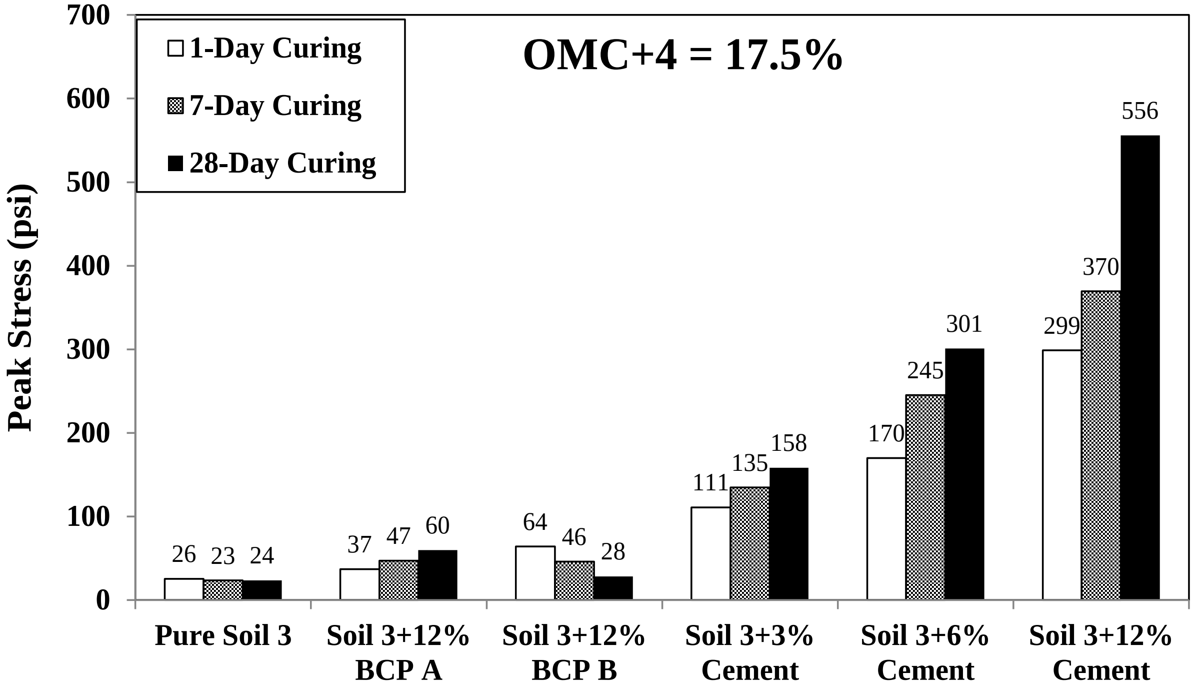


Figure 39. UCS test results for Soil 3 under OMC+4%

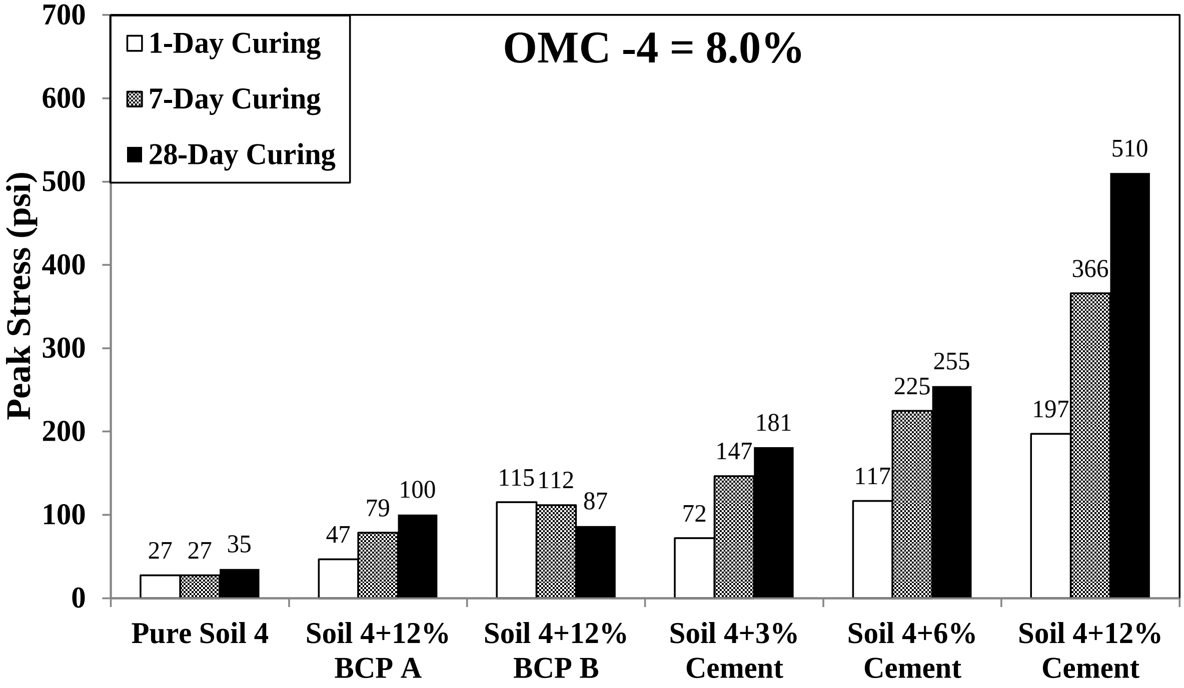


Figure 40. UCS test results for Soil 4 under OMC-4%

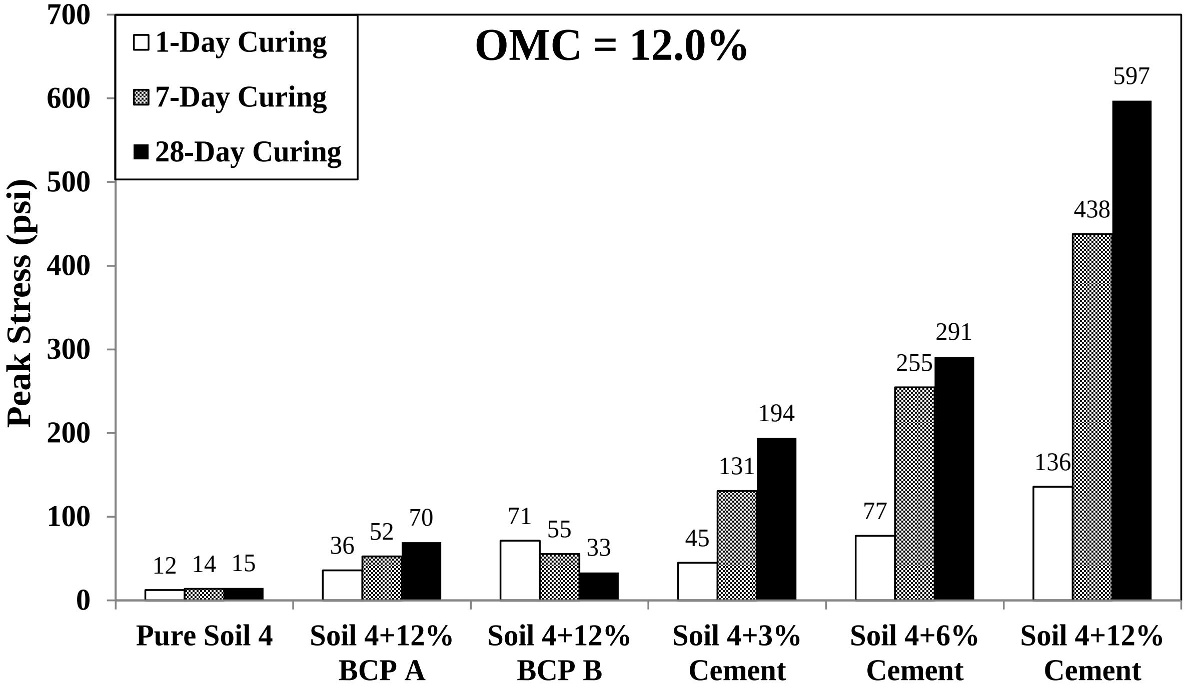


Figure 41. UCS test results for Soil 4 under OMC

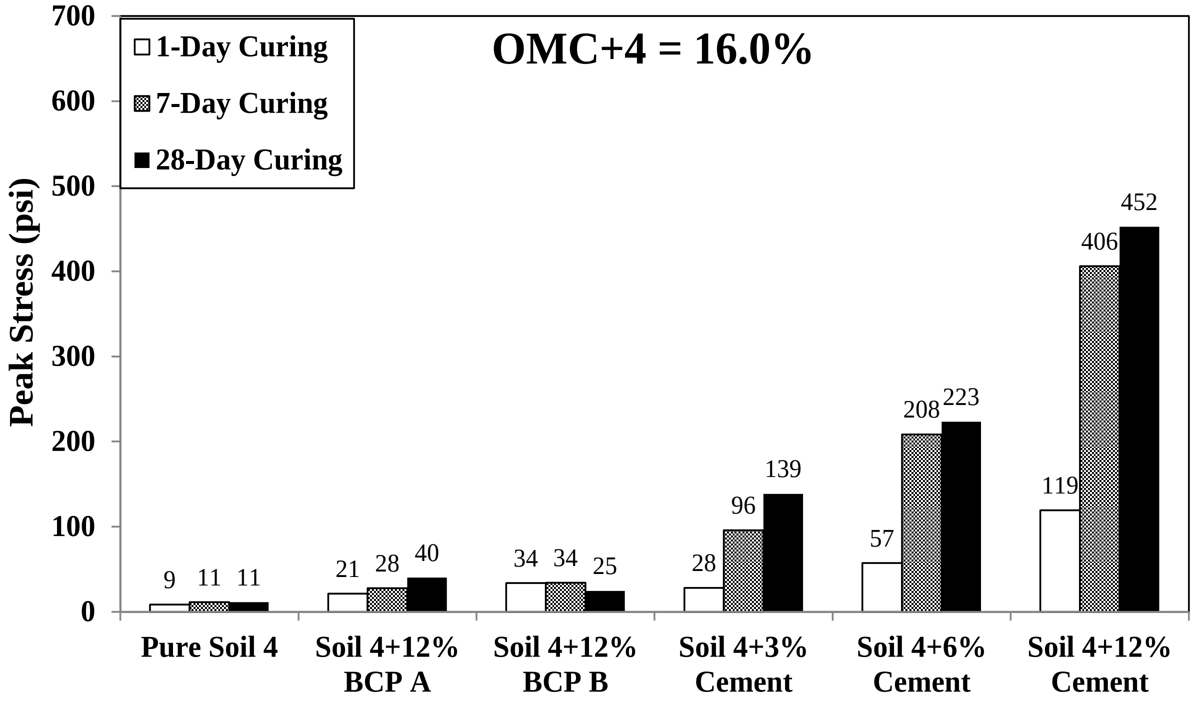


Figure 42. UCS test results for Soil 4 under OMC+4%

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 12, the percentage strength improvement (SI) obtained by Equation (4) and used for quantitative assessments of soil UCS was increased by use of additives.

$$\mathrm{SI}, \% = (\mathrm{SAD} - \mathrm{SCD})/\mathrm{SCD} \times 100 \qquad \textbf{(4)}$$

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 31. 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 strength of Soil 4 was improved by over 300% for 1-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 1900% 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 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 strength of untreated soil because of the presence of lignin. BCP A is more suitable for Soils 1 and 4, relatively coarse soils. BCP B is 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 oil co-product, BCP C was difficult to identify as the most suitable soil because only Soil 2 was evaluated using this additive. The UCS results for BCP C indicate that it is a more promising additive than BCP A or BCP B for Soil 2, Iowa loess, due to its highest lignin content.

Table 12. Percent strength improvement of additive-treated soils compared to pure soil

Soil Types	Sample Type	UCS Improvement (SI), %								
		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

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-4% represents the dry side of moisture level, OMC+4% represents the wet side of moisture level, and OMC is the moisture content at which soil reaches its maximum dry density. 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. Figures 31 through 42 and Table 12 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 oil-type co-product treated specimens, UCSs also decreased with rising moisture content, but SI values were increased below OMC and OMC+4% compared to OMC-4%. For example, the strength of Soil 1 at the dry side after 28-day curing could be increased by 121% with a 12% BCP A-treatment, but the strength of Soil 1 at 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 at the wet side when compared to their strengths at the dry side, Soils 1 and 3 with BCP C had higher SIs at the wet side in contrast to Soils 2 and 4 with BCP B which had higher SIs at 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 interfrictional 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 interfrictional 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 indicates that co-products don’t modify diffuse a double layer of solid particles to change the formation of dispersed structures with increase in soil water content, so co-products-treated specimens also exhibit 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 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 diffuse double layer theory. However, the addition of co-products in soil can reduce the loss of strength at 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

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 Figures 31 through 42. While 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, 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 Soil 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-curing. BCP C added in Soil 2 presented similar results to BCP A as shown in Figures 34 through 36, 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 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 7-day curing. 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 oil-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 oil 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 oil 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 43 is an image of a failed specimen with BCP B-treatment after long-term curing. The fractured surface of 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 growth of bacteria may negatively affect soil strength after long-term curing.

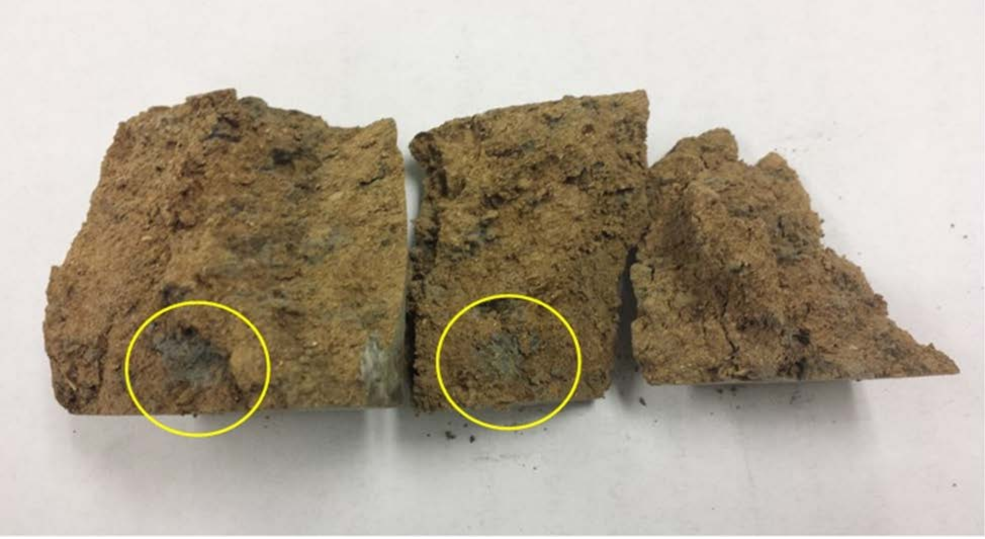


Figure 43. Bacterial colony in BCP B-treated specimen

In summary, oil-type co-products could provide an increase of up to 140% in UCS of treated soil after 28-day curing when compared to 1-day curing. This indicates that oil-type co-products can benefit the long-term UCS of soil through their setting behavior. Cement also dramatically increased 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, oil-type co-products A and 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., (2014). They investigated the effects of co-product contents on soil strength to identify the most suitable additive content. Figures 8, 44, and 45 show the strength capacities of soil treated with various co-product contents under OMC, OMC-4%, and OMC+4%, respectively. 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.

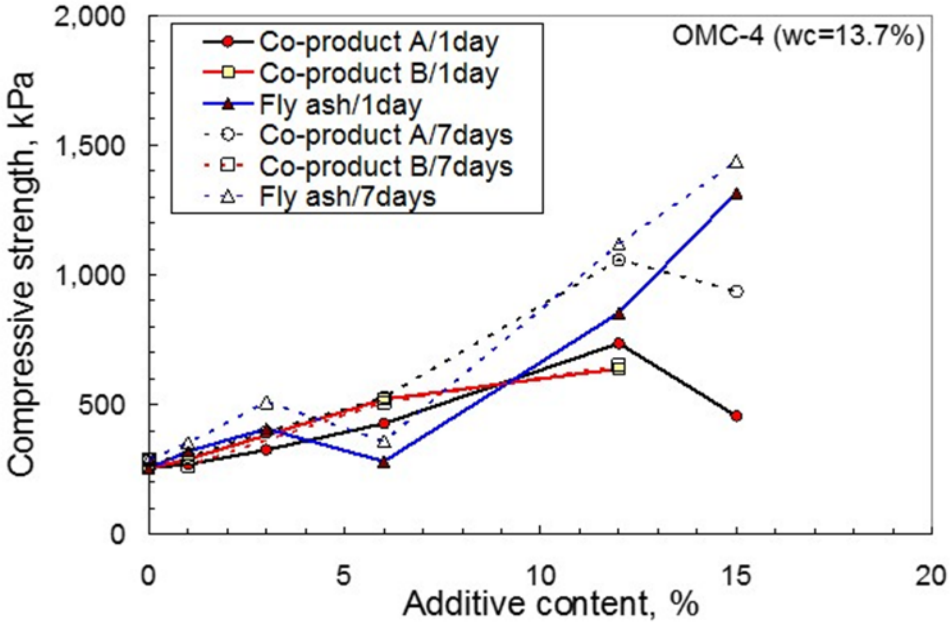


Figure 44. Unconfined compressive strength for soil treated with various contents of BCPs under OMC-4% (adopted from the final report of Ceylan et. al, 2010)

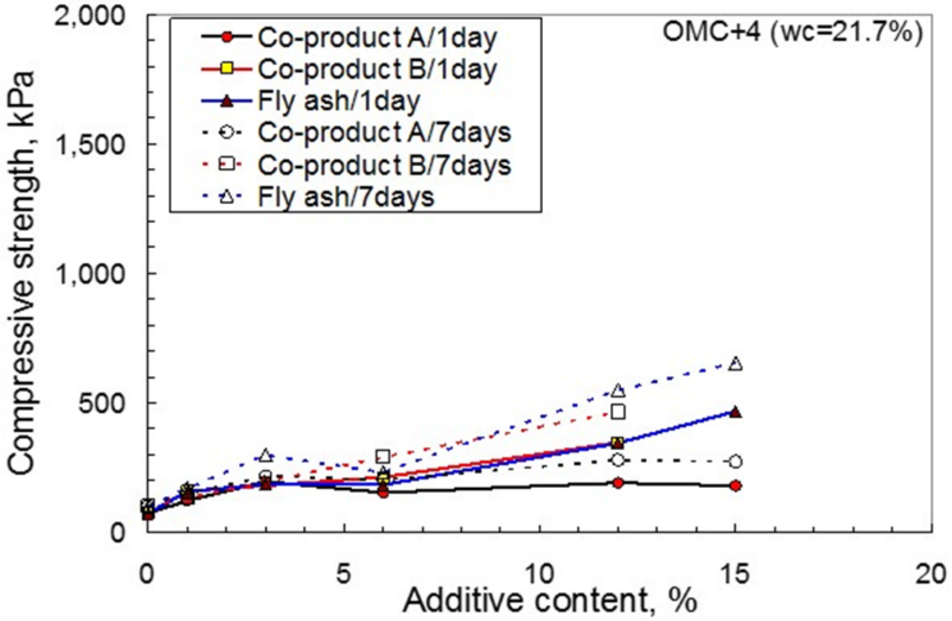


Figure 45. Unconfined compressive strength for soil treated with various contents of BCPs under OMC-4% (adopted from the final report of Ceylan et. al, 2010)

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 oil-type co-product treated soil. In addition, treatments using two oil-type co-products achieved a higher strength capacity than powder-type BCP B treatment at 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. The recommended co-product content was 12% based on a previous study. 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 oil-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, OMC+4%) and different curing periods (1-day, 7-day, 28-day) were measured by subjecting them to shear loads until they failed, with the results shown in Figures 46 through 57. Shear strength envelopes for each untreated and treated soil were fit using the Mohr–Coulomb plot shown in Figure 26 to identify corresponding shear strength parameters, cohesion (c) and friction angle (ϕ), listed in Table 13. 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 sear 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 Figures 46 through 57 and Table 13 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

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.

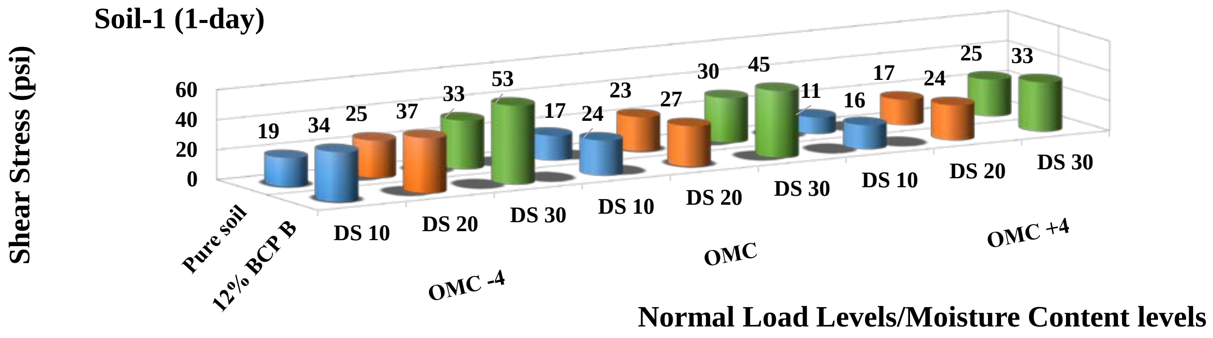


Figure 46. Shear strength for Soil 1 after 1-day curing

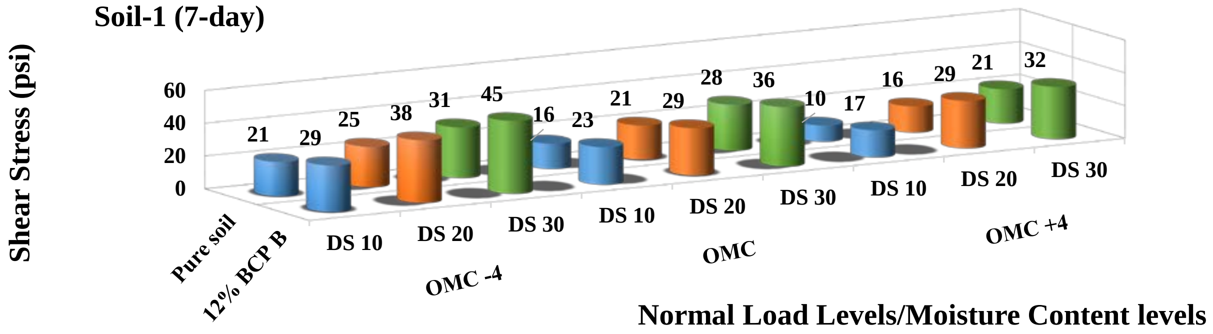


Figure 47. Shear strength for Soil 1 after 7-day curing

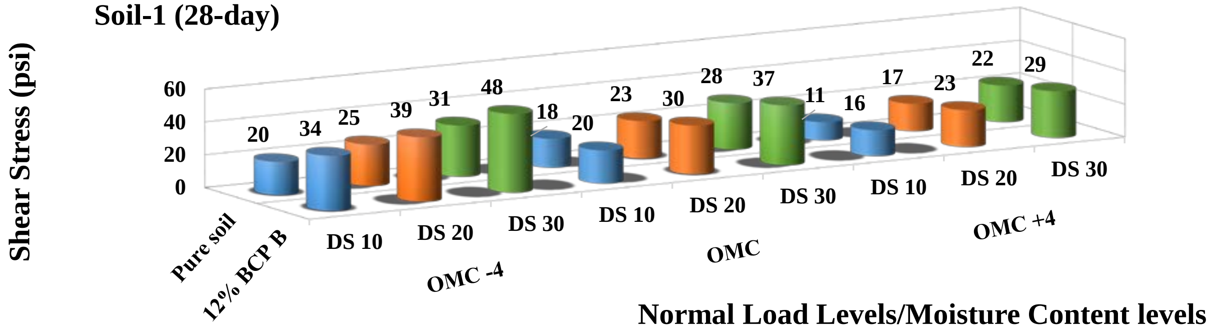


Figure 48. Shear strength for Soil 1 after 28-day curing

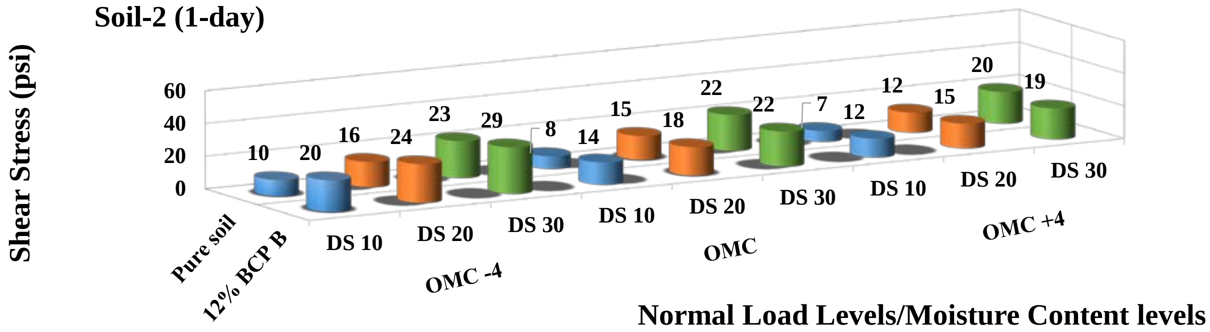


Figure 49. Shear strength for Soil 2 after 1-day curing

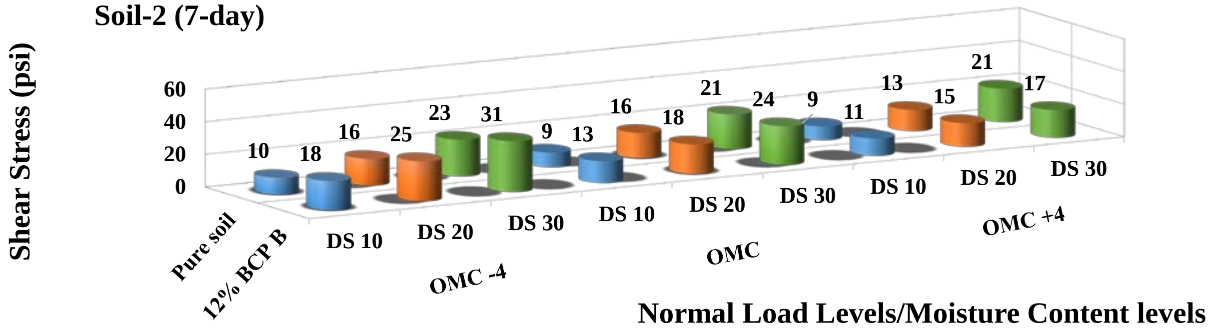


Figure 50. Shear strength for Soil 2 after 7-day curing

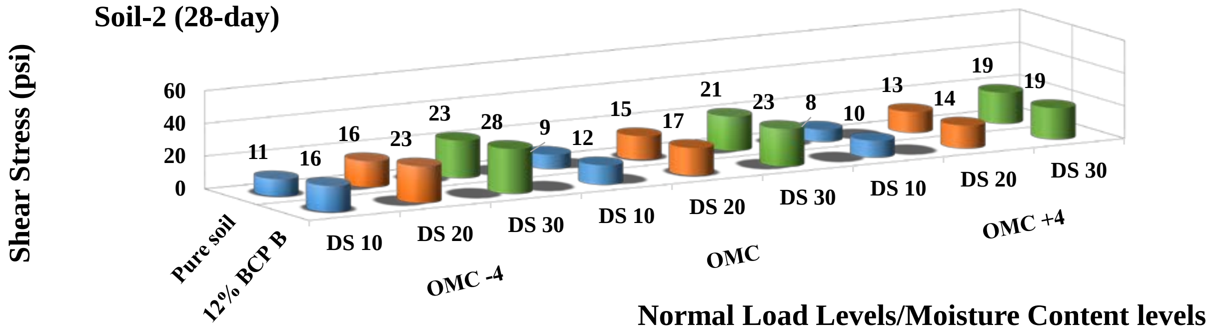


Figure 51. Shear strength for Soil 2 after 28-day curing

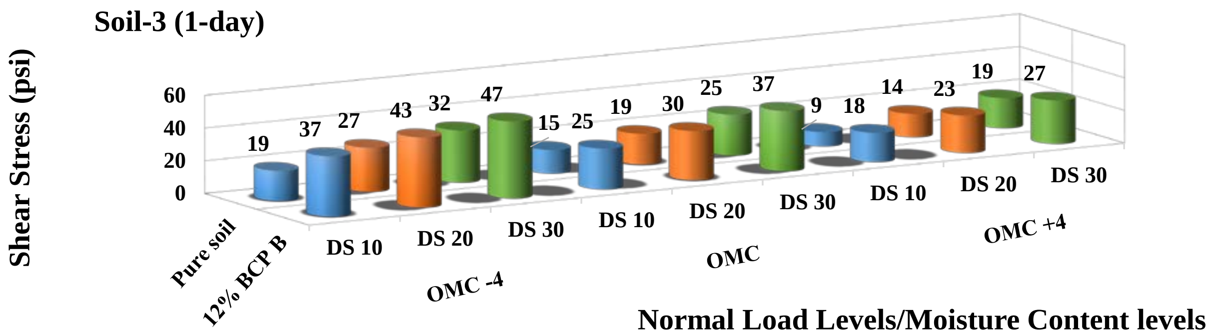


Figure 52. Shear strength for Soil 3 after 1-day curing

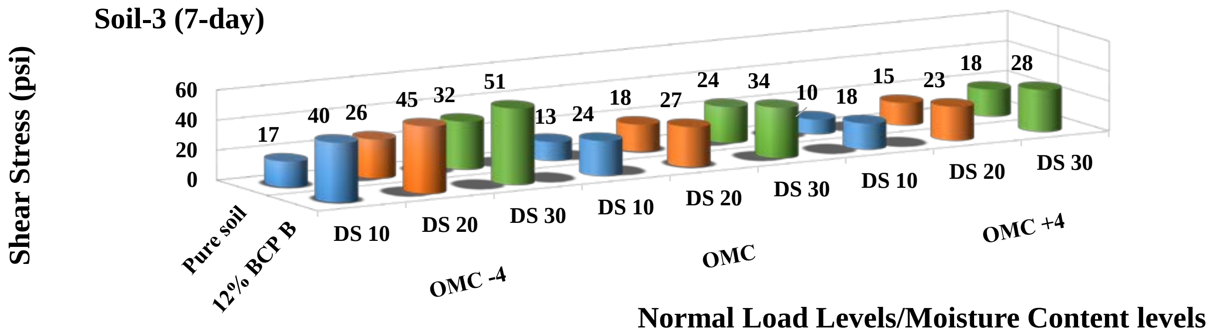


Figure 53. Shear strength for Soil 3 after 7-day curing

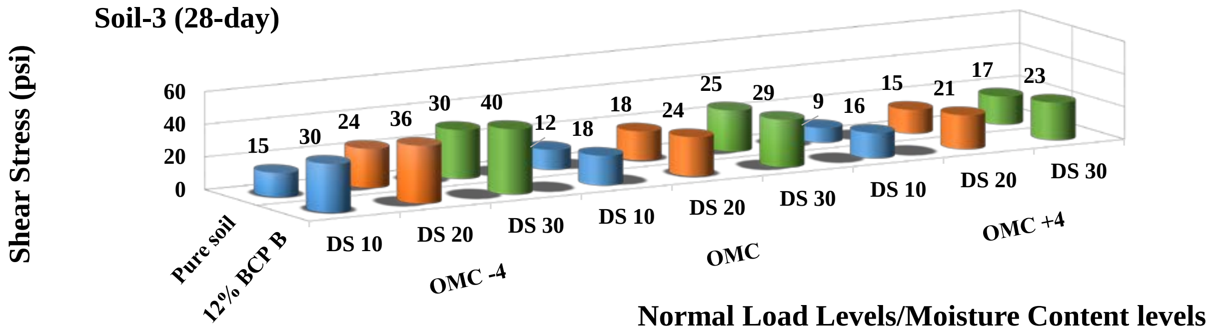


Figure 54. Shear strength for Soil 3 after 28-day curing

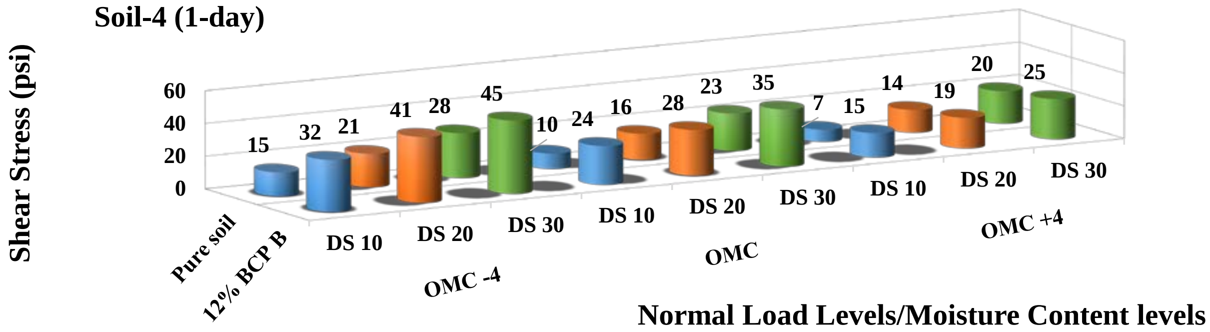


Figure 55. Shear strength for Soil 4 after 1-day curing

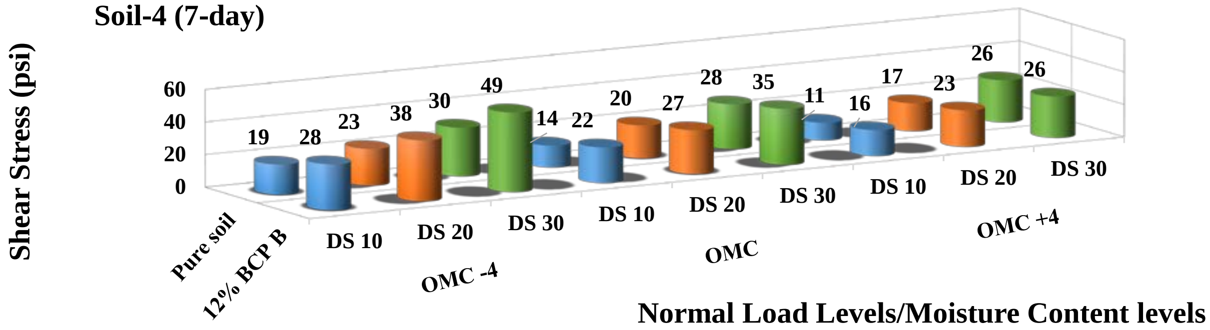


Figure 56. Shear strength for Soil 4 after 7-day curing

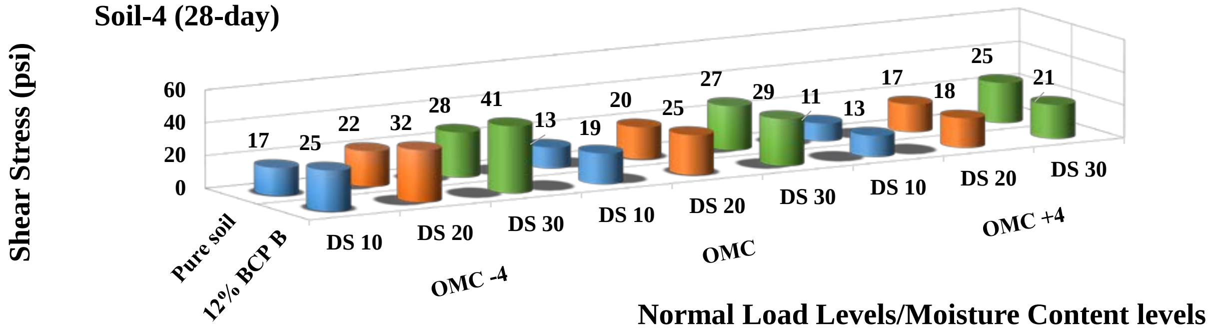


Figure 57. Shear strength for Soil 4 after 28-day curing

Table 13. Shear strength parameters for untreated and treated soil

Specimen Type		**Curing periods**	**Friction angle (ϕ), deg**			**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

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 in 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 conducted for DS test due to the unavailability of necessary quantities. However, the lignin in BCP A and BCP C appears to have 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 tests are presented in Appendix F and Figures 58 through 69. In this test, each set of treatment group combinations containing the six same 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 F 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 3 cycles. The untreated Soil 4 specimens began to fail after 2 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 9 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 8 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 7-day curing demonstrated better performance than specimens with 1-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 e in BCP B-treated specimens were also noticed in the images. The other oil-type co-product, BCP C, was used only for Soil 2. Both 1-day cured and 7-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. Actually, full failure occurred only at the end of tenth cycle in the 1-day cured Soil 2 specimens treated with 3% of 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 Figures 58 through 61. 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 by Soils 1, 3, and 4. BCP B performed best among these 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 control of mass loss. An increase in curing period also affected reduction of mass loss for co-products-treated specimens. For BCP A and BCP C-treatments, 7-day cured specimens slightly decreased mass loss, but the mass loss of BCP B-treated specimens with 7-day curing was only 50% that of BCP B-treated specimens with 1-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

Figures 62 through 69 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. 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 1-day curing. For all types of soils, BCP A-treated specimens with 7-day curing exhibited less than 10% volume expansion, much better than specimens with 1-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, 1-day cured specimens treated with BCP-B had 5% or more expansion than 7-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 1-day curing and 7-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.

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. 12% of BCP A-treated specimens had similar values of mass loss and higher volume expansion compared to 3% of cement-treated specimens Among the co-products, BCP B-treatment for soil presented the best capability for reducing mass loss and was similar in that regard to that for 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 12% cement, but they were better than 3% cement. The co-products tested are promising additives for improving durability under freeze-thaw conditions, and each type has specific advantages.

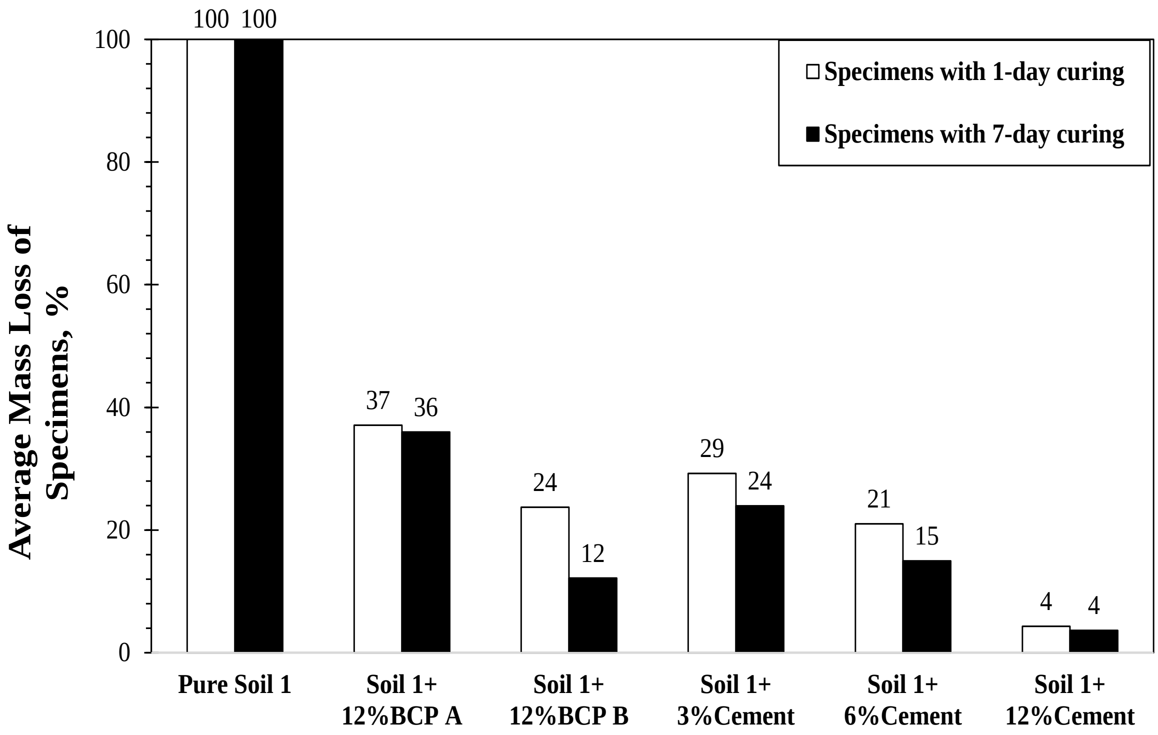


Figure 58. Average mass loss of specimens in Soil 1 sets.

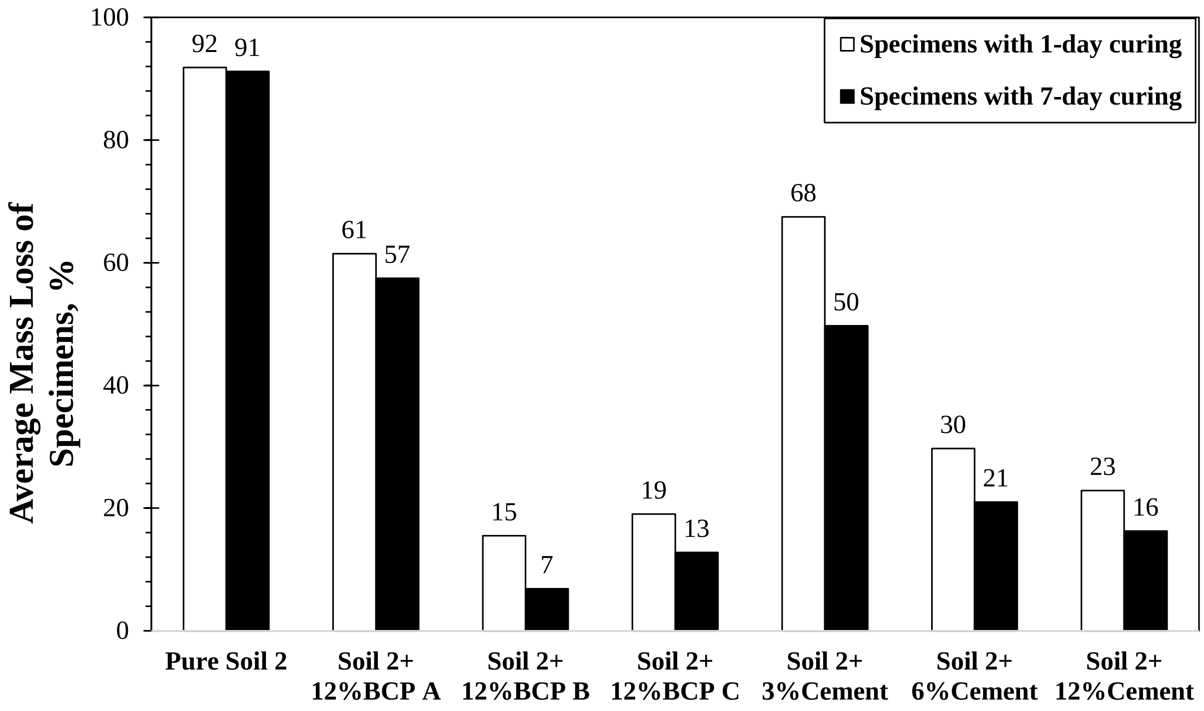


Figure 59. Average mass loss of specimens in Soil 2 sets

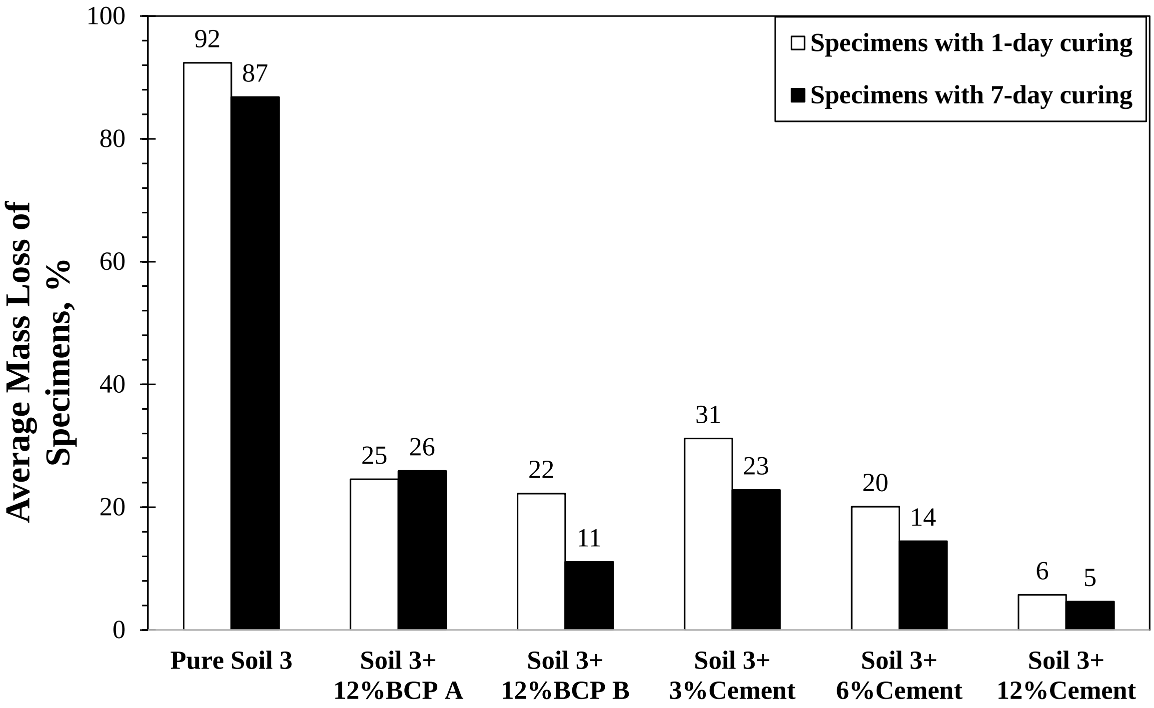


Figure 60. Average mass loss of specimens in Soil 3 sets

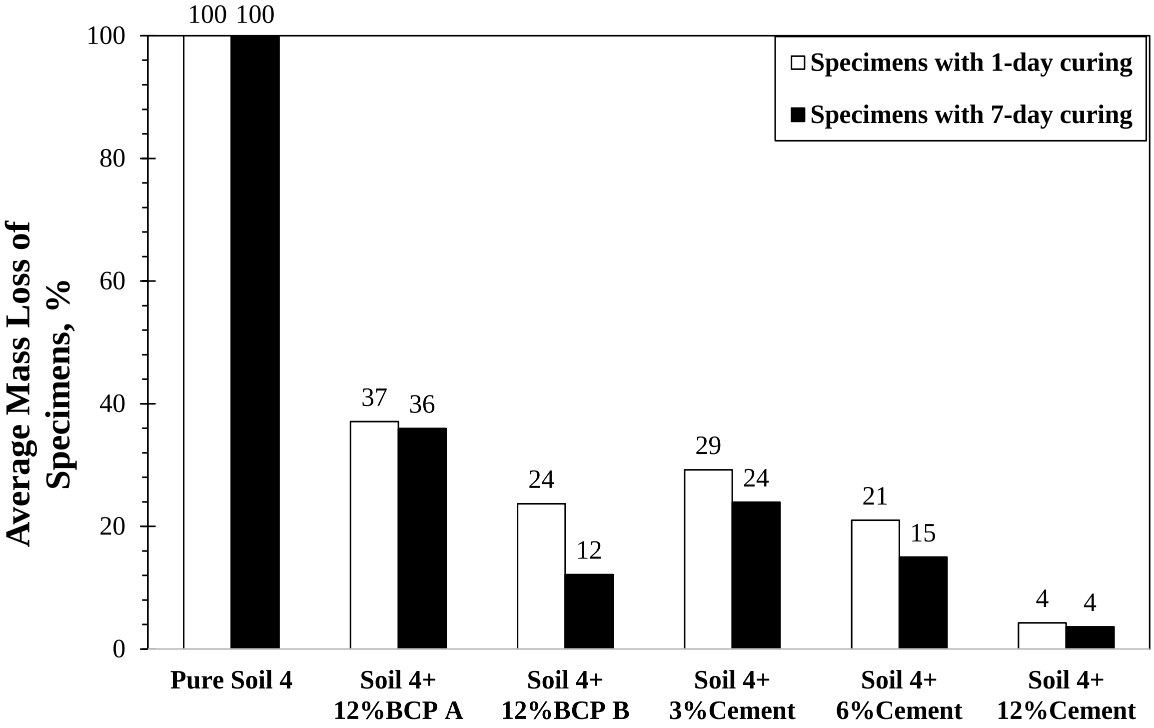


Figure 61. Average mass loss of specimens in Soil 4 sets

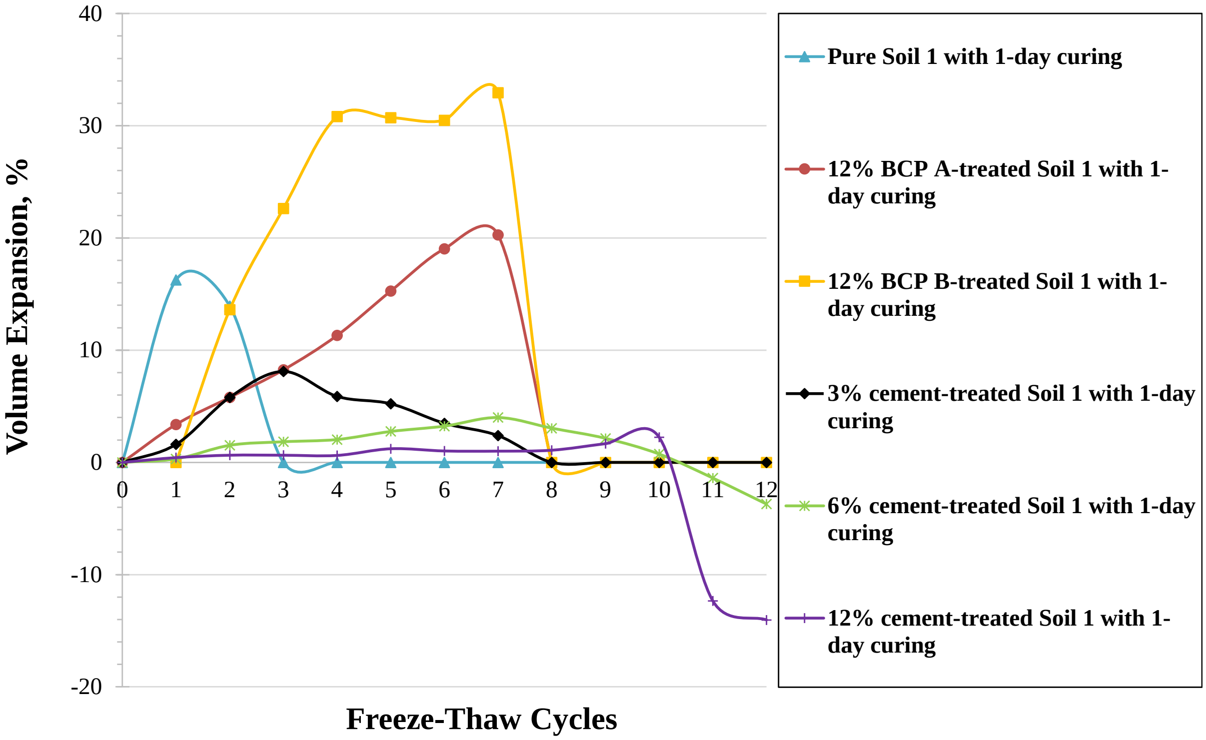


Figure 62. Average volume expansion of specimens in Soil 1 sets with 1-day curing

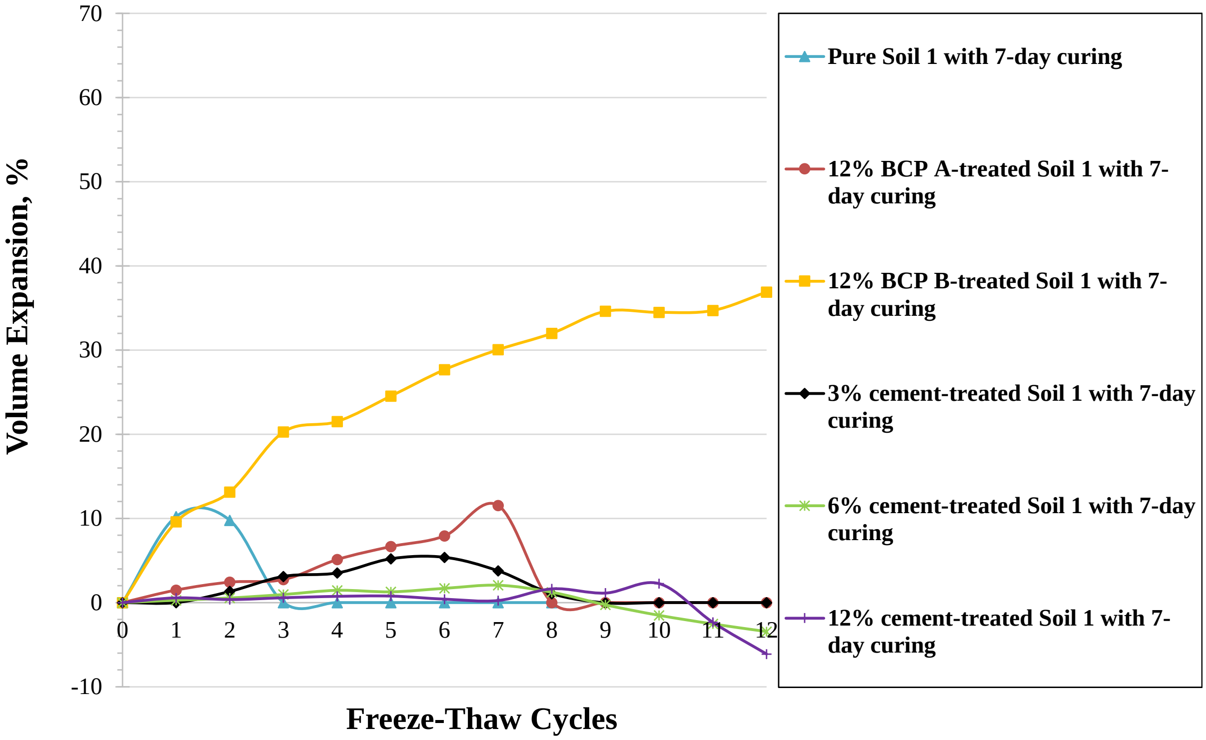


Figure 63. Average volume expansion of specimens in Soil 1 sets with 7-day curing

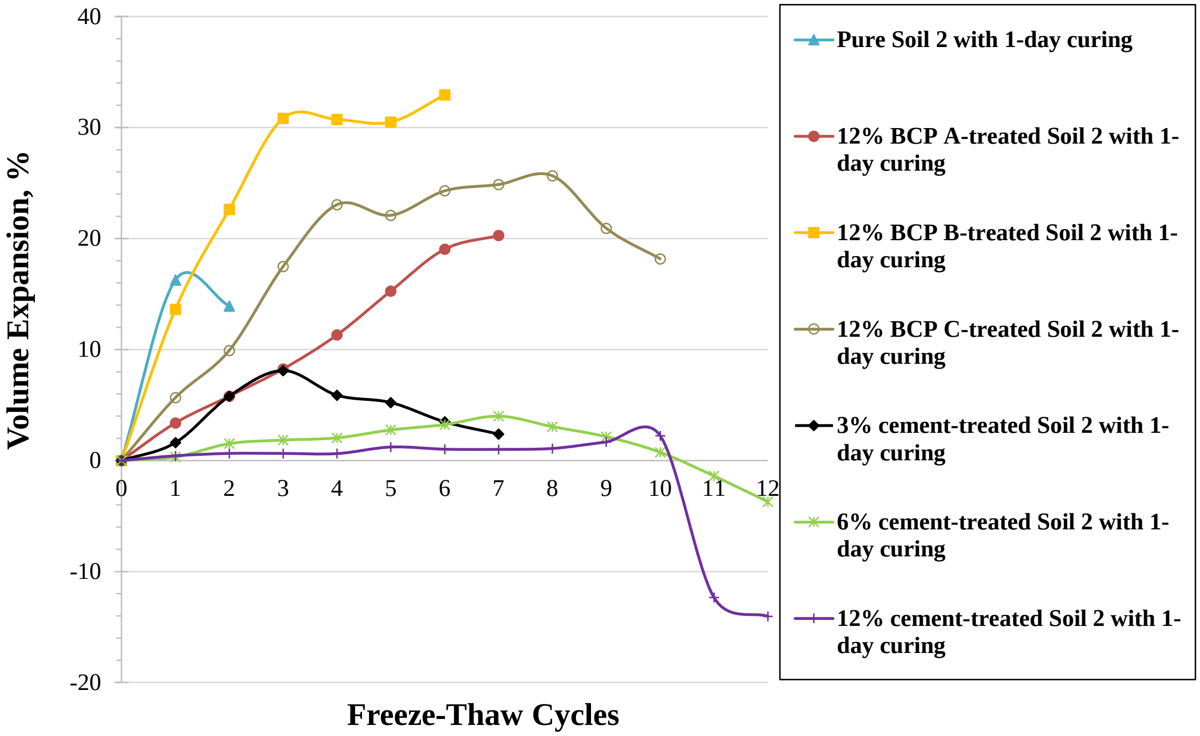


Figure 64. Average volume expansion of specimens in Soil 2 sets with 1-day curing

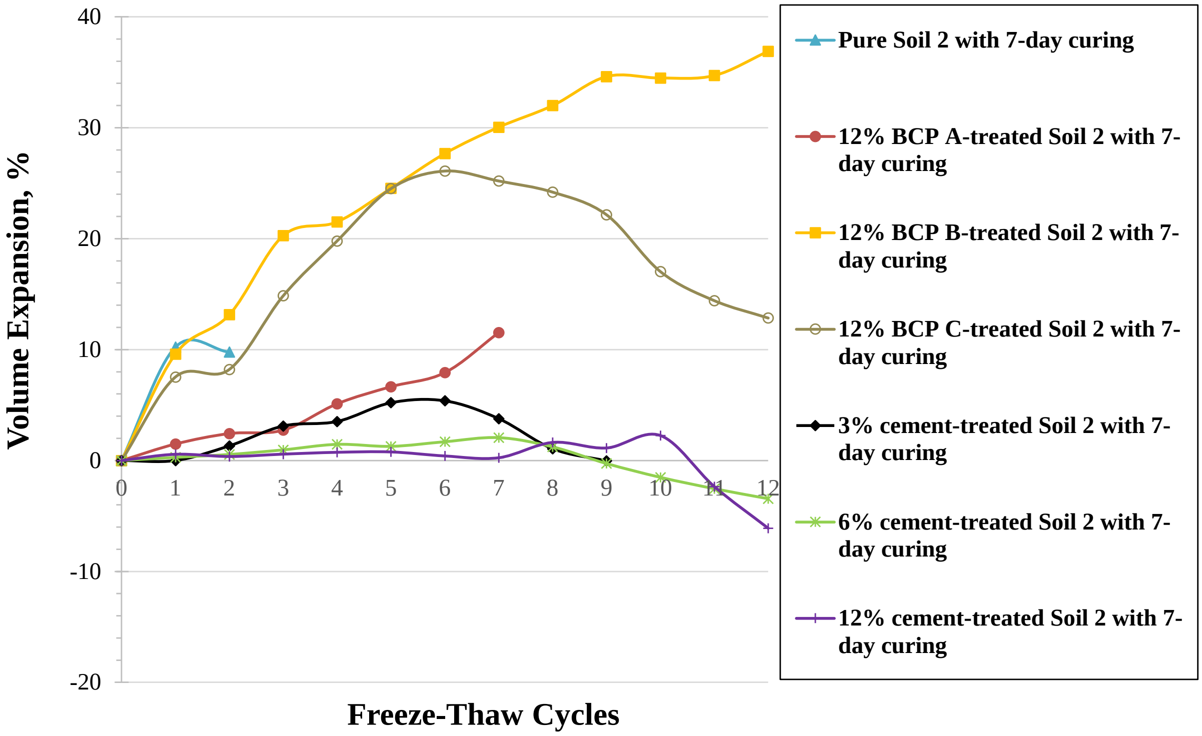


Figure 65. Average volume expansion of specimens in Soil 2 sets with 7-day curing

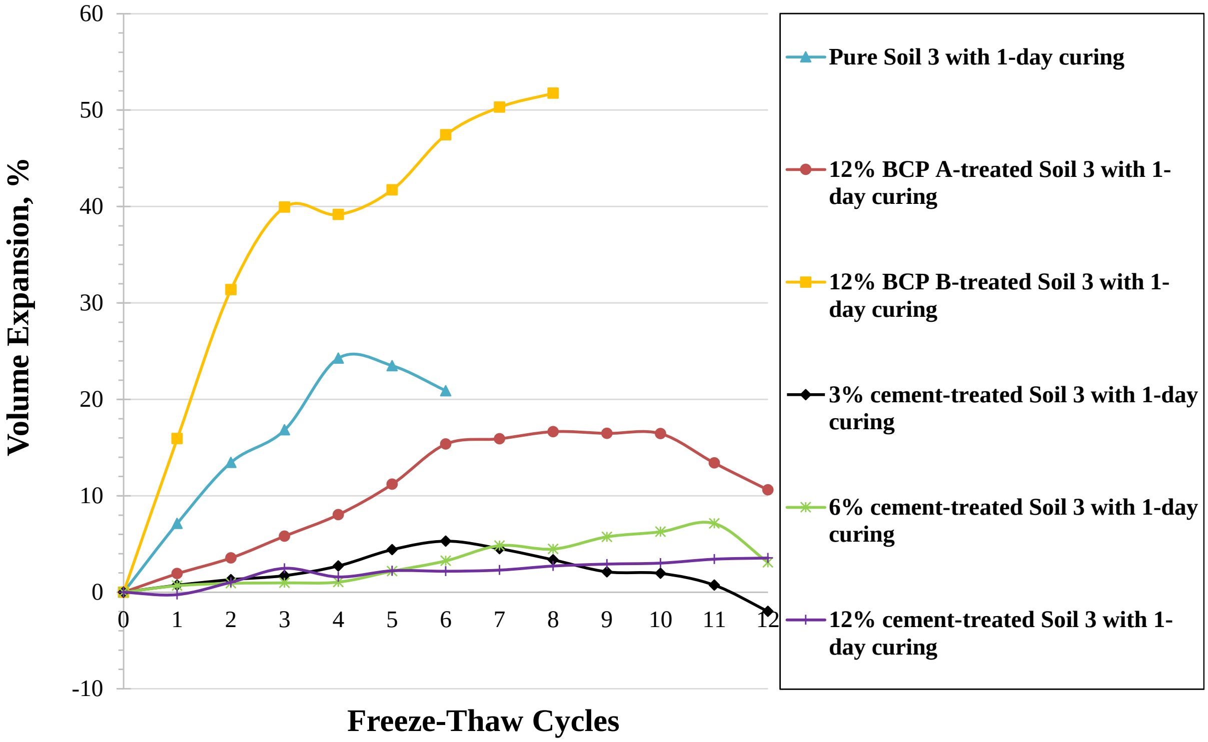


Figure 66. Average volume expansion of specimens in Soil 3 sets with 1-day curing

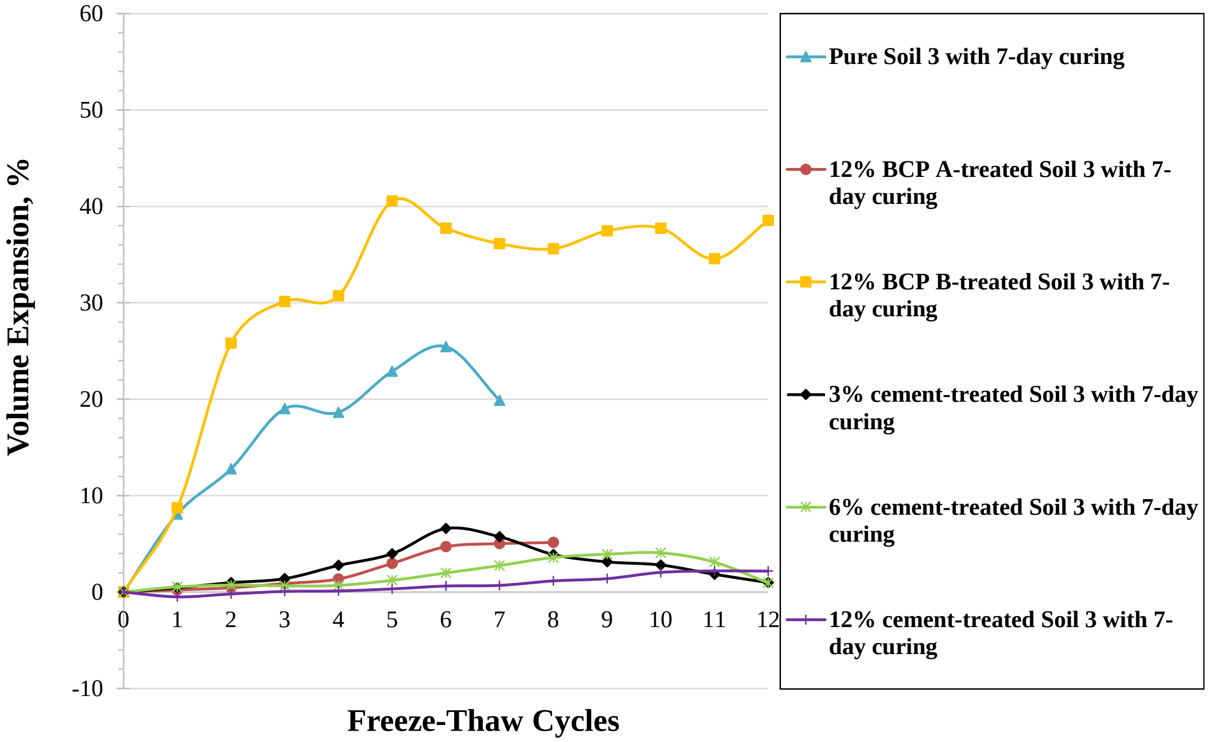


Figure 67. Average volume expansion of specimens in Soil 3 sets with 7-day curing

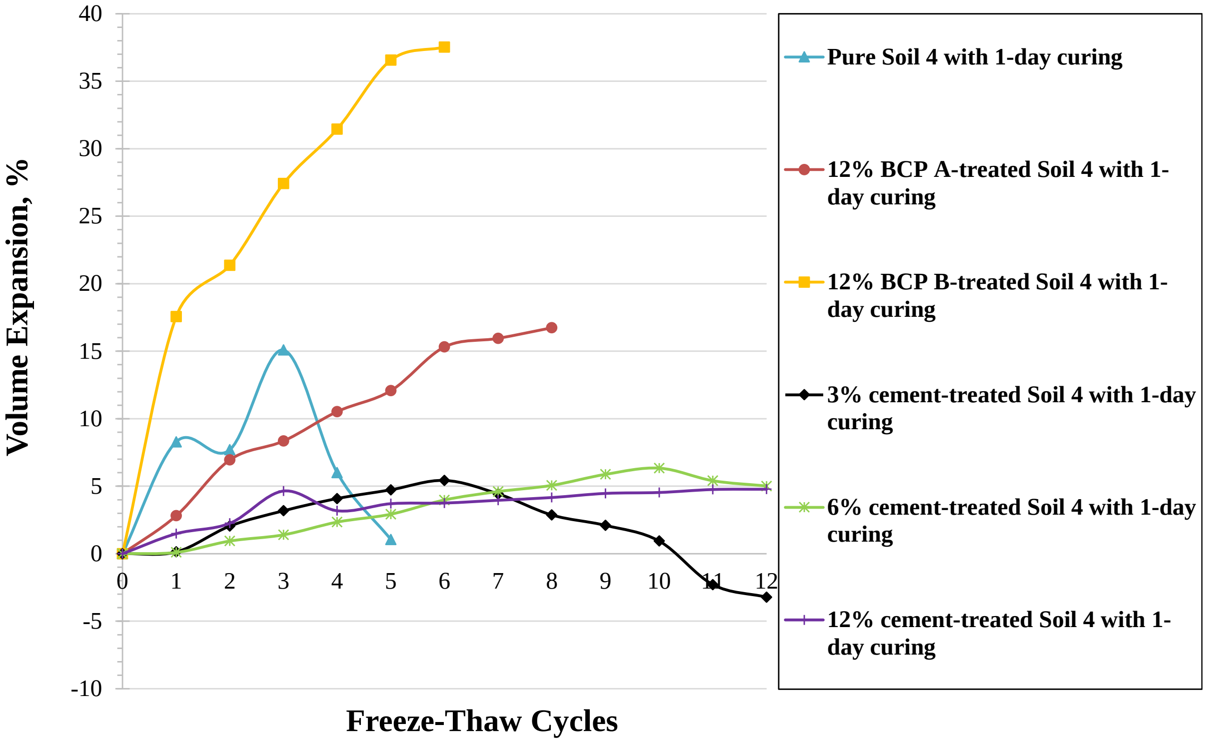


Figure 68. Average volume expansion of specimens in Soil 4 sets with 1-day curing

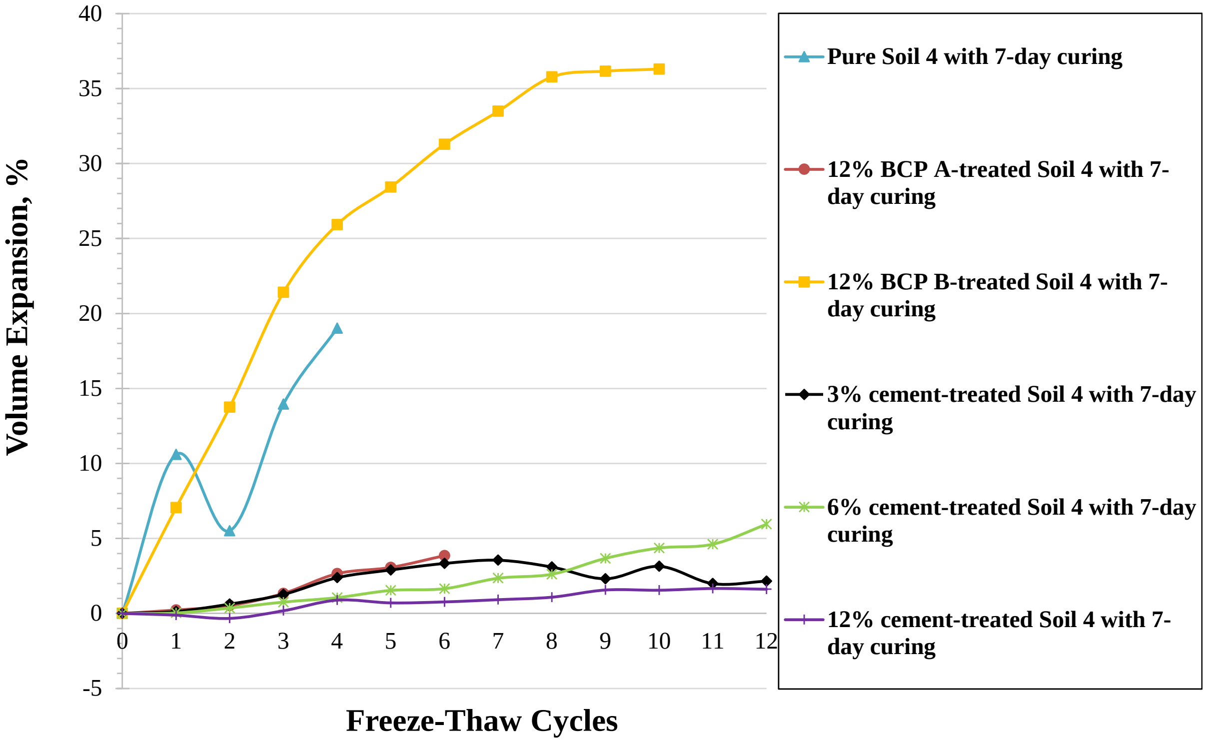


Figure 69. Average volume expansion of specimens in Soil 4 sets with 7-day curing

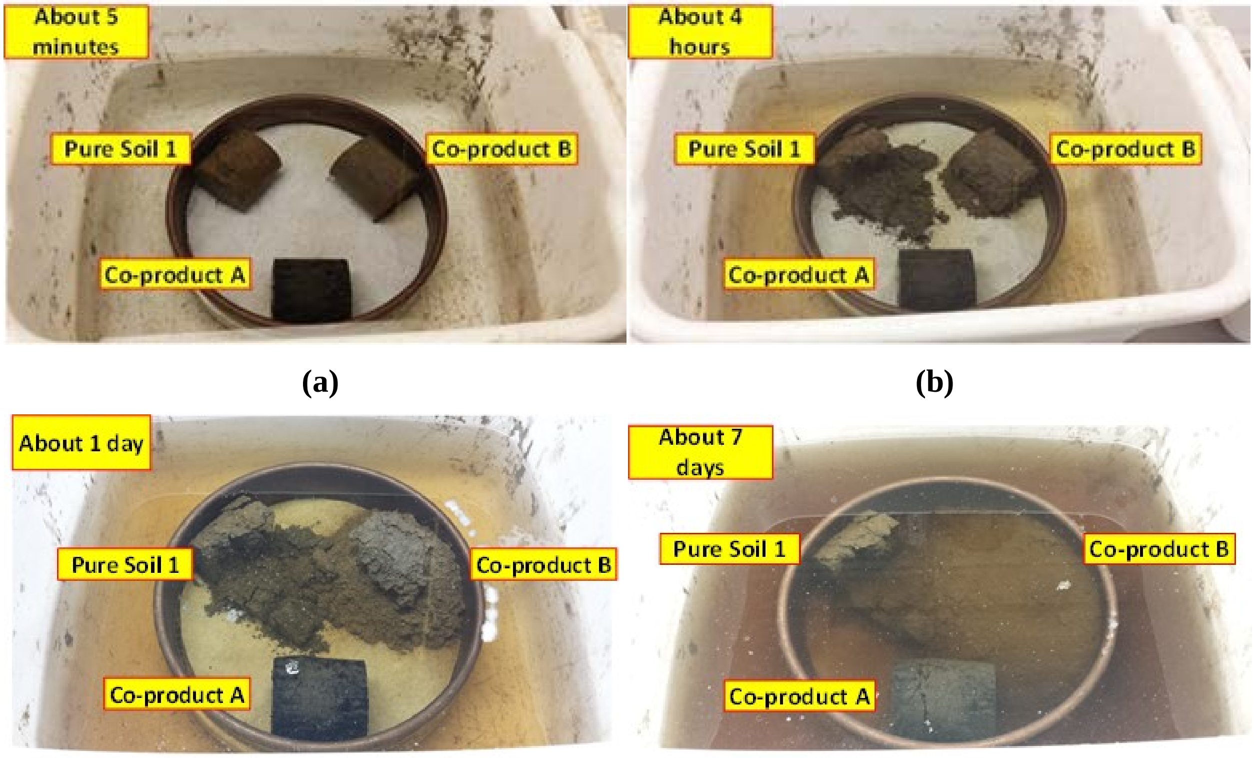
Moisture Susceptibility Test

The untreated, BCP A-treated, and BCP B-treated soil specimens with 7-day curing under OMC were soaked in water for seven days. The recorded images shown in Figures 70 through 73 present visual evidence for evaluating the effects of BCPs on moisture susceptibility of soil.

Figure 70 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 71 shows that the untreated Soil 2 specimen was fully disintegrated only after four hours of soaking and the BCP B Soil 2 treated specimen became partially disintegrated after one day of soaking and fully disintegrated before seven days of soaking. Figure 72 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 73, 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. Figures 70 through 73 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 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 similar to BCP A would strongly suggest good waterproofing capability.

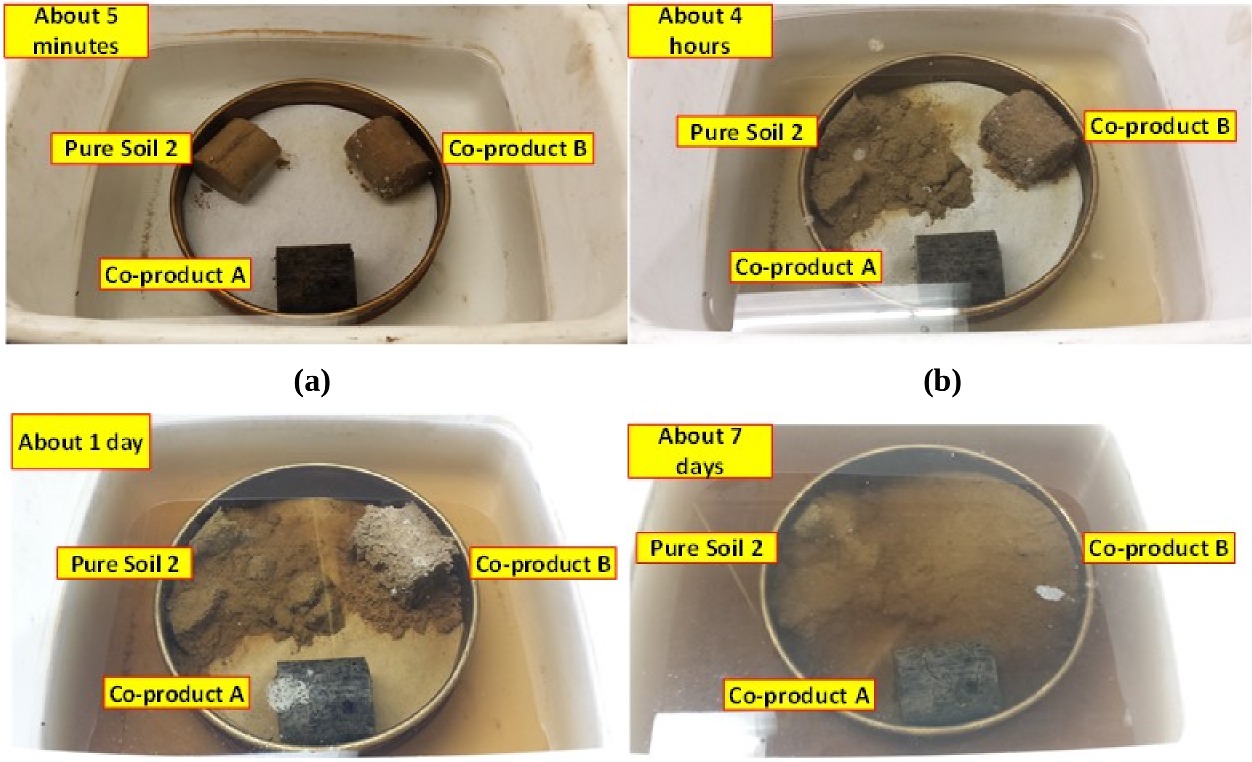
The soaking-test results demonstrate the benefits of using co-products to reduce moisture susceptibility of natural soil. Untreated soil specimens soaked in water bath exhibited rapid disintegration and had completely failed before only 1 day of soaking. BCP A-treated specimens in this test performed 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.



(a) **(b)**

(c) **(d)**

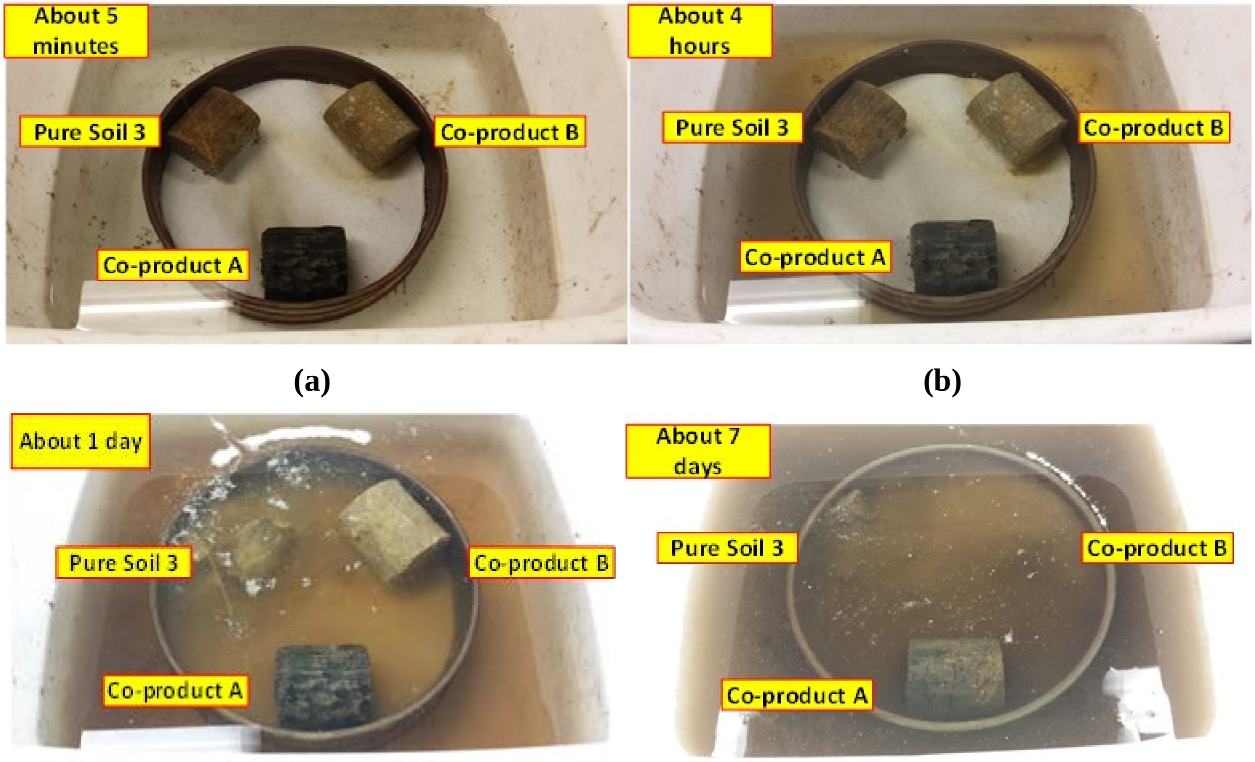
Figure 70. Soaking test results for specimens: (a) five minutes for Soil 1 set, (b) four hours for Soil 1 set (c) one day for Soil 1 set, (d) seven days for Soil 1 set



(a) (b)

(c) (d)

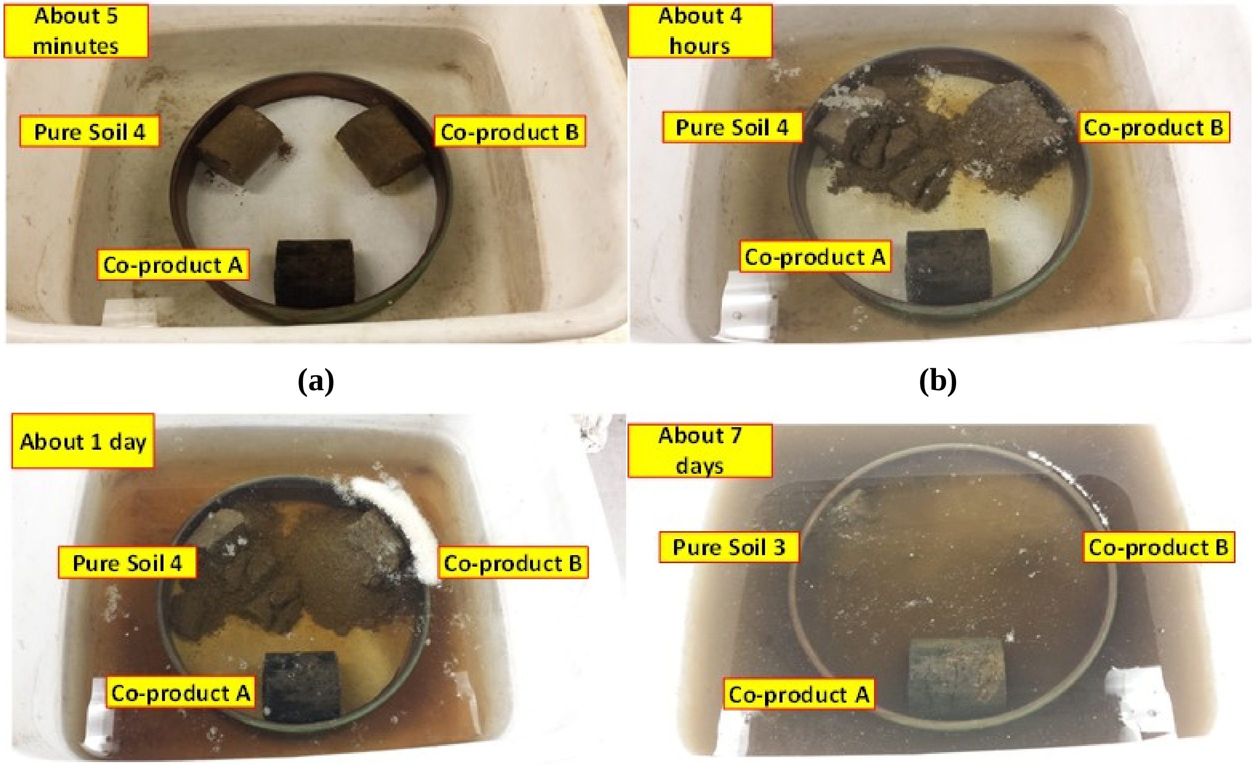
Figure 71. Soaking test results for specimens: (a) five minutes for Soil 2 set, (b) four hours for Soil 2 set. (c) one day for Soil 2 set, (d) seven days for Soil 2 set



(a) **(b)**

(c) **(d)**

Figure 72. 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, (d) seven days for Soil 3 set



(a) (b)

(c) (d)

Figure 73. 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, (d) seven days for Soil 4 set

Micro-Structural Characterization Results and Discussion

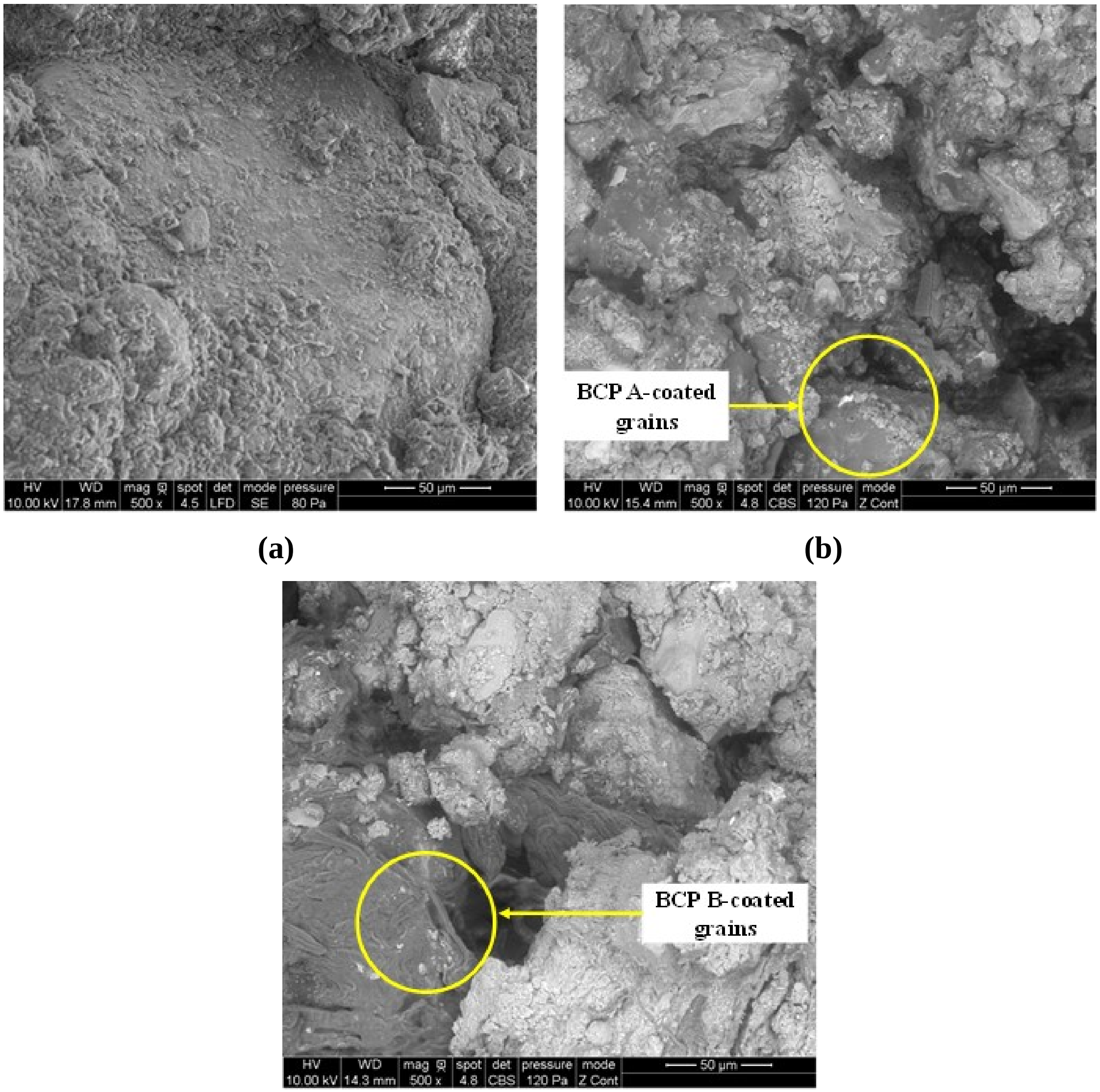
Scanning electron microscope (SEM)

A SEM can capture a large number of digital images for analyzing the mechanism of BCP stabilization at the particle level. Figures 74 through 77 show the morphologies of 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 7-day curing under OMC. The untreated soil images show clear particle surfaces and boundaries and porous structures under 500x magnification. As seen in the images of 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., 2005) 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 was conducted for the same specimens used in the SEM studies.

X-ray diffraction (XRD)

XRD patterns for untreated, BCP A-treated, and BCP B treated soils are shown in Figures 78 through 81 and Appendix E. The inorganic materials identified in samples are listed in Appendix E. 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. What’s more, less chemical reactions in soil treatment generally indicated the less 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., 2005). It can be concluded that the underlying mechanism of cement is hydration reaction.

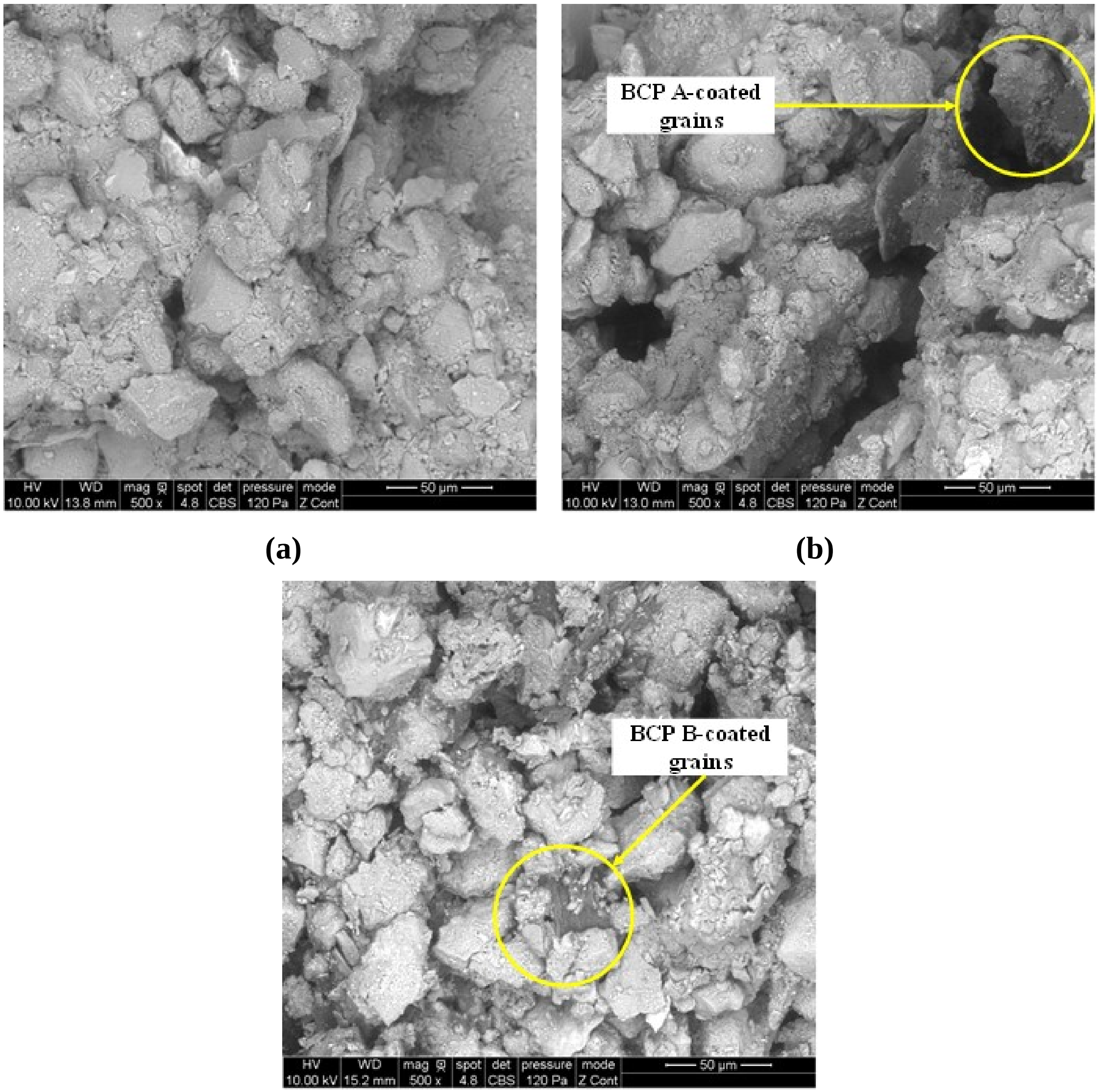
The combined SEM and XRD analyses can identify mechanisms of stabilization. In this test, the results of microstructural analysis indicate that the primary mechanisms of BCP A and BCP B for soil stabilization are coating and binding soil particles by adhesive film to form strong soil structures. Puppala, et.al, (2014) and Puppala, 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 mechanism may be similar to that of BCP A if their similar physical properties and chemical composition are considered.



(a) **(b)**

(c)

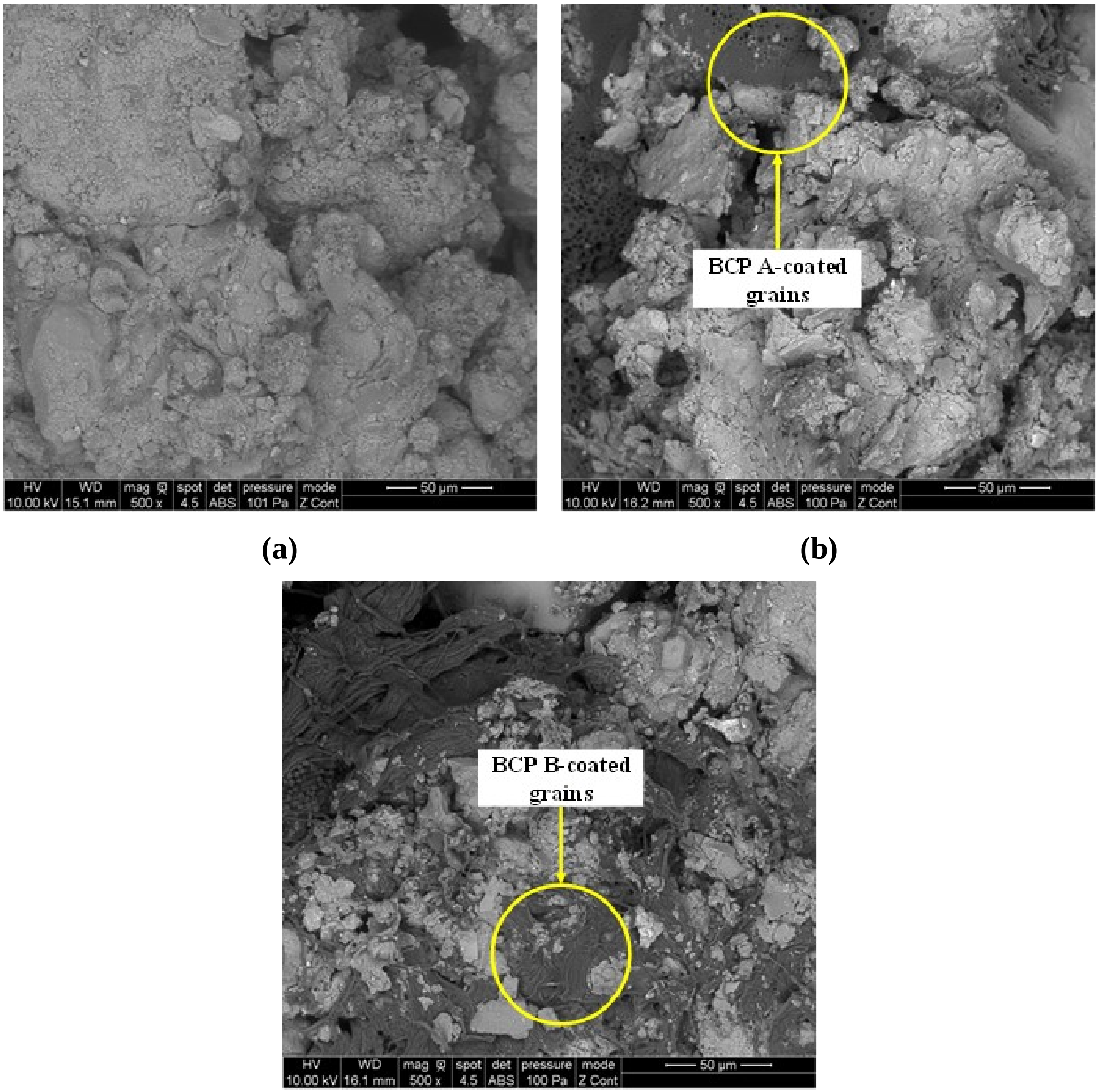
Figure 74. Images of SEM for Soil 1 set with 500x magnification: (a) untreated Soil 1, (b) 12% of BCP A-treated Soil 1, (c) 12% of BCP B-treated Soil 1



(a) **(b)**

(c)

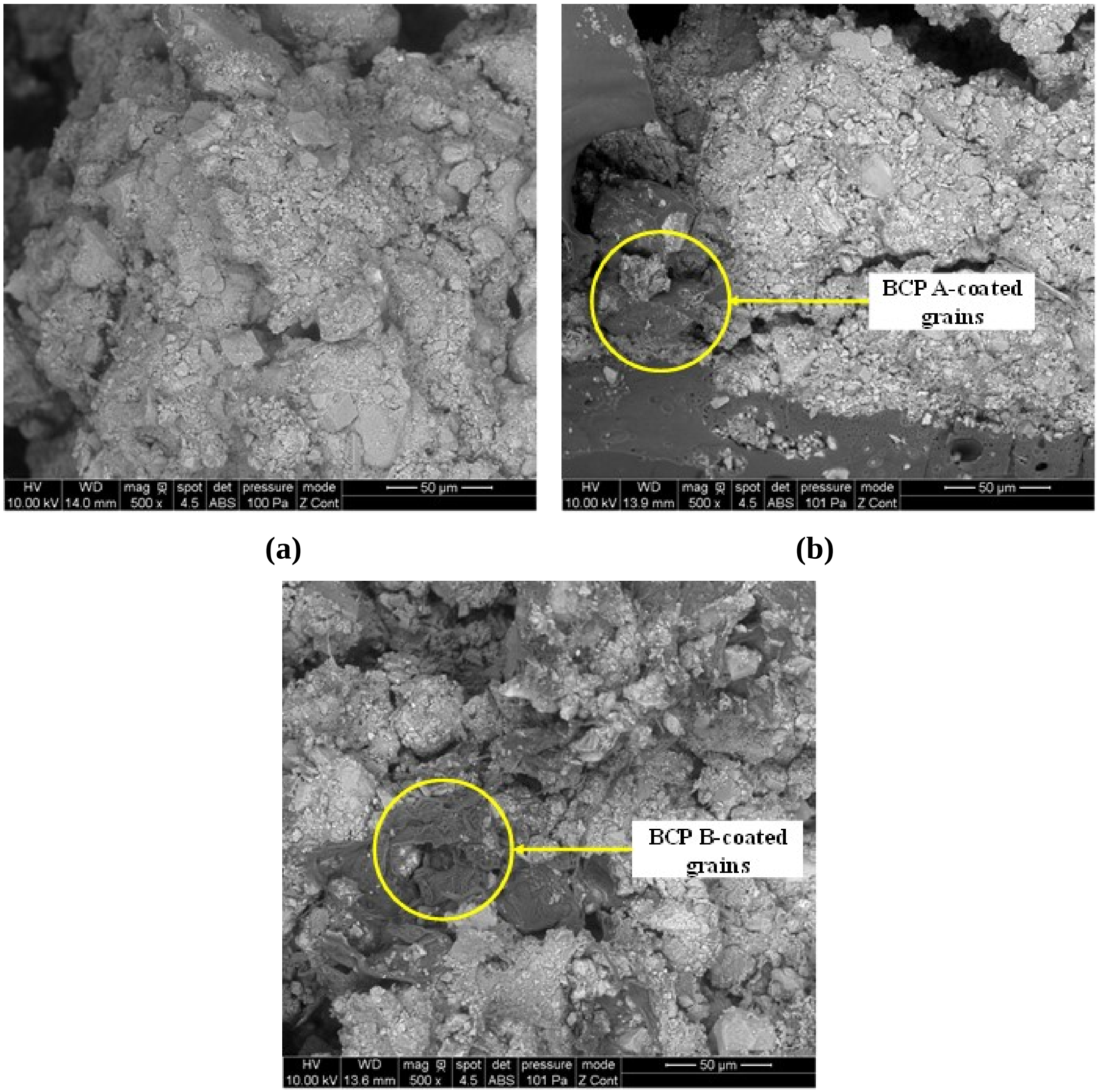
Figure 75. Images of SEM for Soil 1 set with 500x magnification: (a) untreated Soil 2, (b) 12% of BCP A-treated Soil 2, (c) 12% of BCP B-treated Soil 2



(a) **(b)**

(c)

Figure 76. Images of SEM for Soil 1 set with 500x magnification: (a) untreated Soil 3, (b) 12% of BCP A-treated Soil 3, (c) 12% of BCP B-treated Soil 3



(a) **(b)**

(c)

Figure 77. Images of SEM for Soil 1 set with 500x magnification: (a) untreated Soil 4, (b) 12% of BCP A-treated Soil 4, (c) 12% of BCP B-treated Soil 4

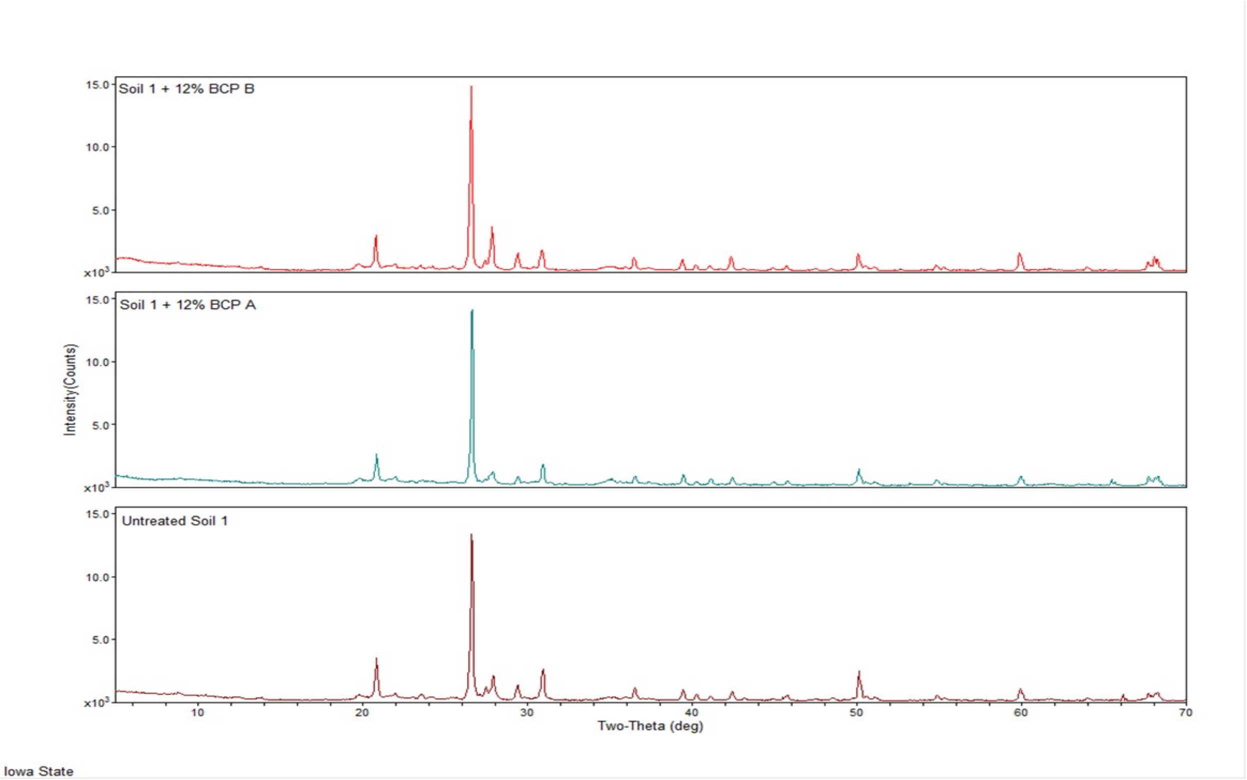


Figure 78. X-ray patterns for untreated, BCP A-treated and BCP B-treated Soil 1

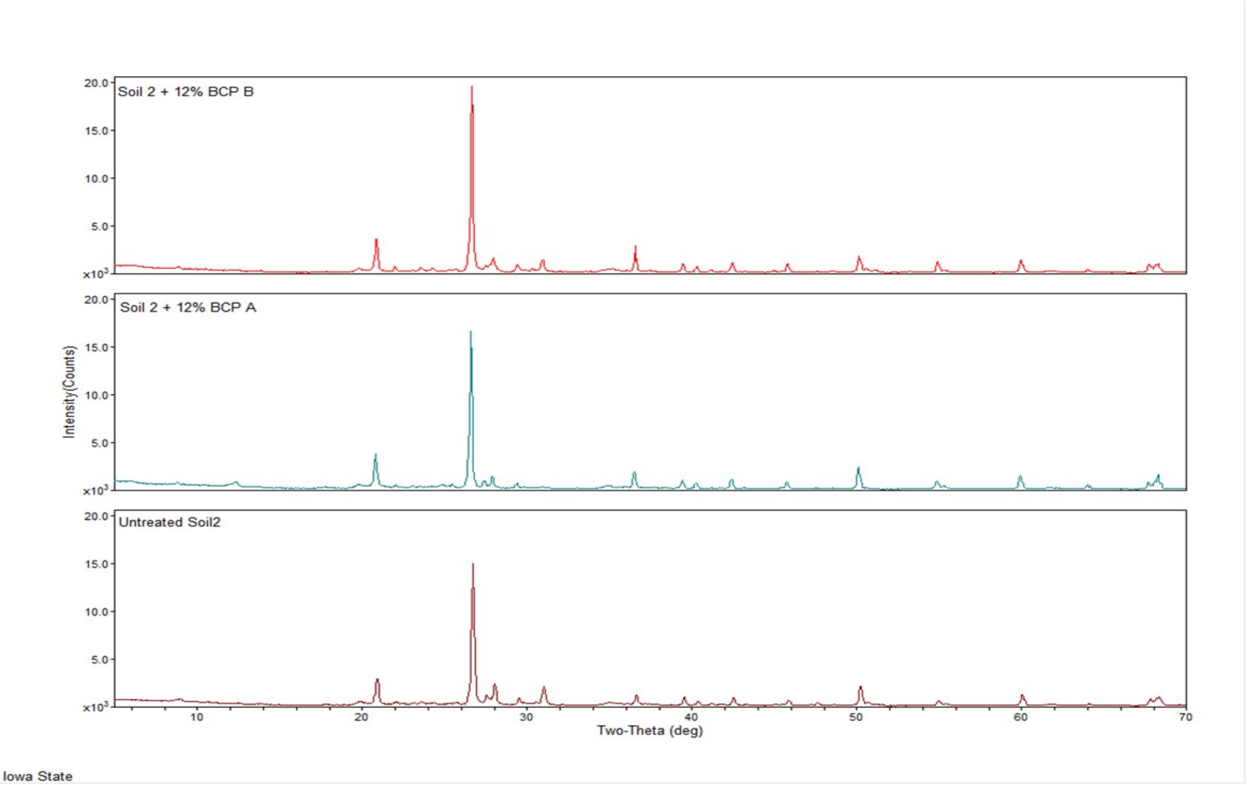


Figure 79. X-ray patterns for untreated, BCP A-treated and BCP B-treated Soil 2

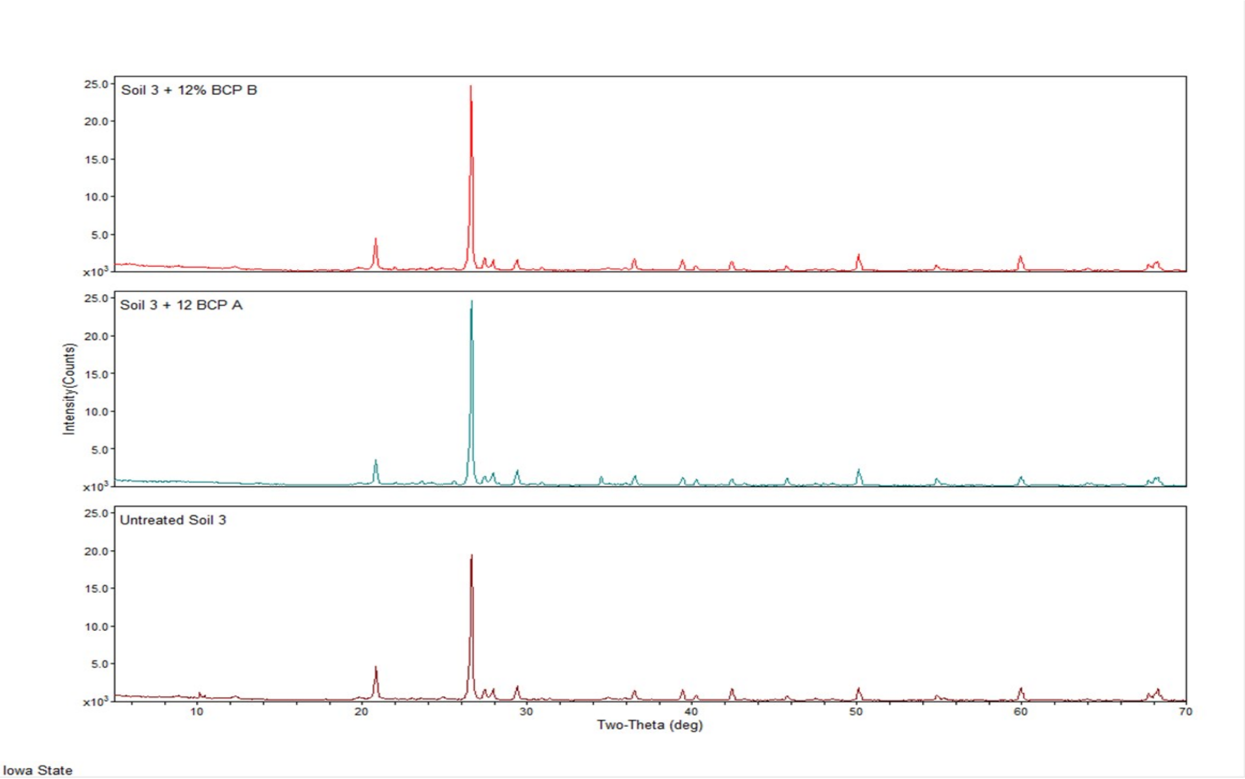


Figure 80. X-ray patterns for untreated, BCP A-treated and BCP B-treated Soil 3

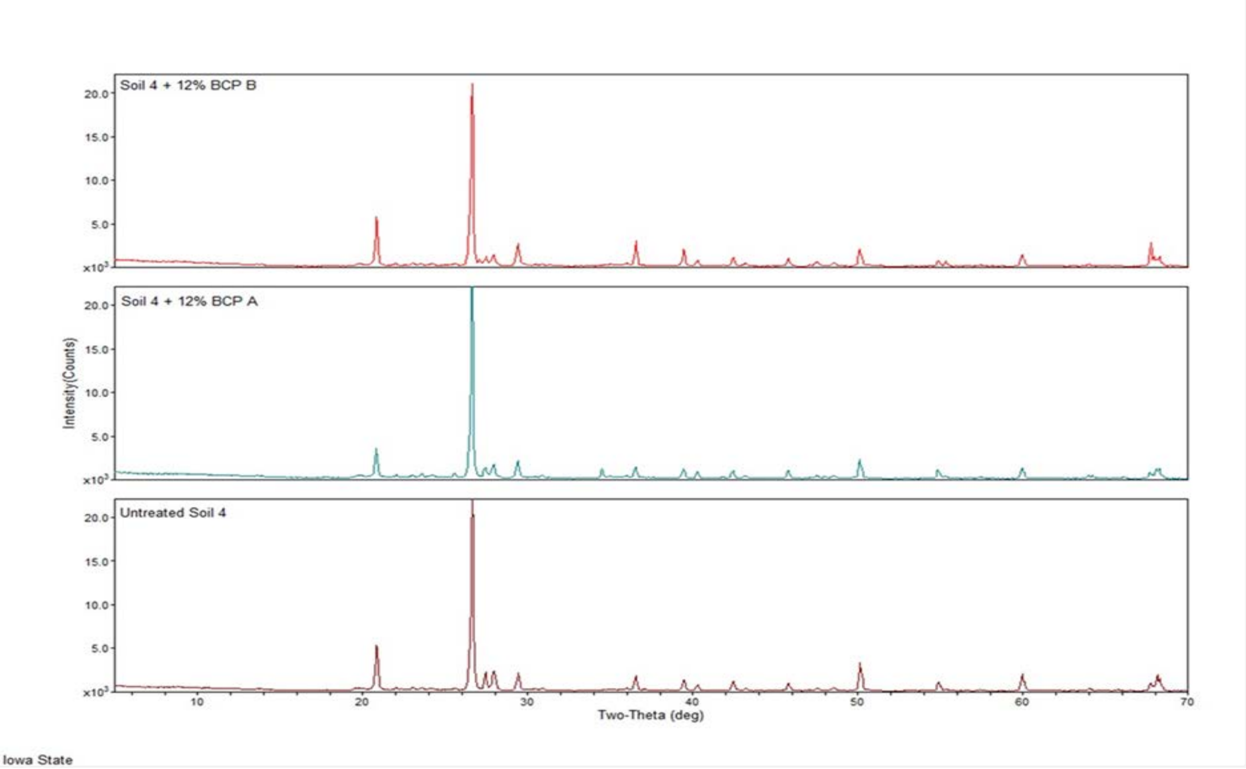


Figure 81. X-ray patterns for untreated, BCP A-treated and BCP B-treated Soil 4

CHAPTER 5

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. 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) a 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 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 test 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.

Specific Research Findings

The test results of utilization of BCPs 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 USC (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 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.

Although the results of laboratory tests in this research indicate that BCPs 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 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.

Recommendations and Future Research

BCPs can provide benefits in soil stabilization added to natural soil. 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 BCP-based strength improvements are less effective than cement-based soil treatment, co-products are primarily recommended for use in subgrade soil stabilization for unpaved, gravel paved, low-volume roads because their strength requirement is relatively less and durability is of greater concern. The BCP materials also offer the following remarkable advantages compared to traditional stabilizers (cement):

- Lignin products are renewable and sustainable materials derived from biomass.
- Lignin products are derived from widely-available source materials such as corn, trees, and other plants.
- The utilization of lignin 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 little commercialized, is potentially cost-effective if the large available quantity of inexpensive source material (food waste materials, corn residuals, etc) is considered.
- Cement as a soil stabilizer has some shortcomings such high cost, high alkalinity, potential shrinkage cracking, and potential damage from sulfate attacks; all these issues negatively influence roadway service life. (Winterkorn 1991).

While addition of water to liquid type BCP can increase its flowability and make BCP easily spreadable to produce a homogenous soil-additive mixture, the water in liquid co-products has a negative effect on soil binding. The recommendation for utilization of liquid co-products in field practice is therefore to first remove initial moisture by drying 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, field demonstrations would be valuable for evaluating the benefits of co-products compared to traditional stabilizers. The field demonstration recommendation would be to construct a test pavement comprised of both different BCP-treated subgrade soil sections and an untreated section. Field data should be collected and analyzed to verify the effects of BCP in soil stabilization practice.

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APPENDIX A: DRAFTS OF MIX DESIGN

Table A-1. Mix design of Soil 1 for 2” by 2” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	**OMC -4%**	10.4	18.5	178.0	196.5	0.0	196.5	9.4	**No Addtives**	0.0
	OMC	14.4	25.6	178.0	203.6	0.0	203.6	12.6		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	**OMC -4%**	10.4	13.8	178.0	191.8	26.0	217.8	6.3	**BCP A**	12.0
	OMC	14.4	20.9	178.0	198.9	26.0	224.9	9.3		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	**OMC -4%**	10.4	18.5	178.0	196.5	21.4	217.8	8.5	**BCP B**	12.0
	OMC	14.4	25.6	178.0	203.6	21.4	224.9	11.4		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	**OMC -4%**	10.4	18.5	178.0	196.5	5.3	201.8	9.2	**Type I Portland Cement**	3.0
	OMC	14.4	25.6	178.0	203.6	5.3	208.9	12.3		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	**OMC -4%**	10.4	18.5	178.0	196.5	10.7	207.1	8.9	**Type I Portland Cement**	6.0
	OMC	14.4	25.6	178.0	203.6	10.7	214.3	12.0		6.0
	OMC +4%	18.4	32.7	178.0	210.7	10.7	221.4	14.8		6.0

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

Note: water content of BCP A is 18%.

Table A-2. Mix design of Soil 2 for 2” by 2” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	23.8	167.9	191.7	0.0	191.7	12.4	**No Addtives**	0.0
	OMC	18.2	30.6	167.9	198.5	0.0	198.5	15.4		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	19.4	167.9	187.3	24.6	211.9	9.2	**BCP A or BCP C**	12.0
	OMC	18.2	26.1	167.9	194.0	24.6	218.6	12.0		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	23.8	167.9	191.7	20.1	211.9	11.3	**BCP B**	12.0
	OMC	18.2	30.6	167.9	198.5	20.1	218.6	14.0		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	23.8	167.9	191.7	5.0	196.8	12.1	**Type I Portland Cement**	3.0
	OMC	18.2	30.6	167.9	198.5	5.0	203.5	15.0		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	23.8	167.9	191.7	10.1	201.8	11.8	**Type I Portland Cement**	6.0
	OMC	18.2	30.6	167.9	198.5	10.1	208.5	14.7		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	**OMC -4%**	14.2	23.8	167.9	191.7	20.1	211.9	11.3	**Type I Portland Cement**	12.0
	OMC	18.2	30.6	167.9	198.5	20.1	218.6	14.0		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 A-3. Mix design of Soil 3 for 2” by 2” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	17.8	187.2	205.0	0.0	205.0	8.7	**No Addtives**	0.0
	OMC	13.5	25.3	187.2	212.5	0.0	212.5	11.9		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	12.9	187.2	200.0	27.4	227.4	5.7	**BCP A**	12.0
	OMC	13.5	20.3	187.2	207.5	27.4	234.9	8.7		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	17.8	187.2	205.0	22.5	227.4	7.8	**BCP B**	12.0
	OMC	13.5	25.3	187.2	212.5	22.5	234.9	10.8		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	17.8	187.2	205.0	5.6	210.6	8.4	**Type I Portland Cement**	3.0
	OMC	13.5	25.3	187.2	212.5	5.6	218.1	11.6		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	17.8	187.2	205.0	11.2	216.2	8.2	**Type I Portland Cement**	6.0
	OMC	13.5	25.3	187.2	212.5	11.2	223.7	11.3		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 3	**OMC -4%**	9.5	17.8	187.2	205.0	22.5	227.4	7.8	**Type I Portland Cement**	12.0
	OMC	13.5	25.3	187.2	212.5	22.5	234.9	10.8		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 A-4. Mix design of Soil 4 for 2” by 2” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	15.1	189.3	204.5	0.0	204.5	7.4	**No Addtives**	0.0
	OMC	12.0	22.7	189.3	212.1	0.0	212.1	10.7		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	10.2	189.3	199.5	27.7	227.2	4.5	**BCP A**	12.0
	OMC	12.0	17.7	189.3	207.1	27.7	234.8	7.6		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	15.1	189.3	204.5	22.7	227.2	6.7	**BCP B**	12.0
	OMC	12.0	22.7	189.3	212.1	22.7	234.8	9.7		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	15.1	189.3	204.5	5.7	210.2	7.2	**Type I Portland Cement**	3.0
	OMC	12.0	22.7	189.3	212.1	5.7	217.7	10.4		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	15.1	189.3	204.5	11.4	215.8	7.0	**Type I Portland Cement**	6.0
	OMC	12.0	22.7	189.3	212.1	11.4	223.4	10.2		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 4	**OMC -4%**	8.0	15.1	189.3	204.5	22.7	227.2	6.7	**BCP B**	12.0
	OMC	12.0	22.7	189.3	212.1	22.7	234.8	9.7		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 A-5. Mix design of Soil 1 for 2.5” by 1” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	OMC -4%	10.4	14.5	139.0	153.5	0.0	153.5	10.4	No Addtives	0.0
	OMC	14.4	20.0	139.0	159.1	0.0	159.1	14.4		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 1	OMC -4%	10.4	14.5	139.0	153.5	16.7	170.2	8.5	BCP B	12.0
	OMC	14.4	20.0	139.0	159.1	16.7	175.7	11.4		12.0
	OMC +4%	18.4	25.6	139.0	164.6	16.7	181.3	14.1		12.0

Table A-6. Mix design of Soil 2 for 2.5” by 1” specimen

		Target Moisture Content	Water Weight	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	OMC -4%	14.2	18.6	131.2	149.8	0.0	149.8	14.2	No Addtives	0.0
	OMC	18.2	23.9	131.2	155.0	0.0	155.0	18.2		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	Soil Weight	Soil + Water Weight	Additive Weight	Total Weight	Actual Water Content	Addtive Material	Addictive Content
		(%)	(g)	(g)	(g)	(g)	(g)	(%)		(%)
Soil 2	OMC -4%	14.2	18.6	131.2	149.8	15.7	165.5	11.3	BCP B	12.0
	OMC	18.2	23.9	131.2	155.0	15.7	170.8	14.0		12.0
	OMC +4%	22.2	29.1	131.2	160.3	15.7	176.0	16.5		12.0

Table A-7. Mix design of Soil 3 for 2.5” by 1” 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	Addictive Content (%)
Soil 3	**OMC -4%**	9.5	13.9	146.2	160.1	0.0	160.1	9.5	**No Addtives**	0.0
	OMC	13.5	19.7	146.2	166.0	0.0	166.0	13.5		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	Addictive Content (%)
Soil 3	**OMC -4%**	9.5	13.9	146.2	160.1	17.5	177.7	7.8	**BCP B**	12.0
	OMC	13.5	19.7	146.2	166.0	17.5	183.5	10.8		12.0
	OMC +4%	17.5	25.6	146.2	171.8	17.5	189.4	13.5		12.0

Table A-8. Mix design of Soil 4 for 2.5” by 1” 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	Addictive Content (%)
Soil 4	**OMC -4%**	8.0	11.8	147.9	159.8	0.0	159.8	8.0	**No Addtives**	0.0
	OMC	12.0	17.8	147.9	165.7	0.0	165.7	12.0		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	Addictive Content (%)
Soil 4	**OMC -4%**	8.0	11.8	147.9	159.8	17.8	177.5	6.7	**BCP B**	12.0
	OMC	12.0	17.8	147.9	165.7	17.8	183.4	9.7		12.0
	OMC +4%	16.0	23.7	147.9	171.6	17.8	189.3	12.5		12.0

APPENDIX B: ANNOTATED BIBLIOGRAPHY

This annotated bibliography includes key references related to the utilization of nontraditional additives in soil stabilization (including almost verbatim abstracts/conclusions from each reference) which have been summarized in the body of the report. The bibliography is organized by: (1) study levels (national or state) and (2) publication year.

TRB studies

Singh, G., and Das, B. M. 1999. Soil stabilization with sodium chloride. *Transportation Research Record* 1673: 99-0079.

This study investigated the performance of sodium chloride stabilization for soil by laboratory testing including: Atterberg limits tests, compaction tests, CBR tests, unconfined compression tests, indirect tensile strength tests (split tests), and cyclic triaxial tests. The significant conclusions identified are reproduced as follows:

- The 0.5% of salt content had no influence on consistency limits of soil. The plasticity index decreased slightly with increasing salt content.
- Compaction test showed that maximum dry unit weight increased with the increase in salt content because of lubrication effect of the salt solution.
- In CBR test, the CBR values were greatly reduced for all specimens which soaked in water bath for 4 days.
- In UCS test, the mixture with higher clay content had the more strength improvement with 1.5% of sodium chloride.
- In spilt test, the correlation between q_u and indirect tensile strength (σ_t) was obtained: $\sigma_t = 5.5 + 0.13\, q_u$, kN/m^2
- In Cyclic Triaxial Tests, the addition of sodium chloride as a stabilizer improved resilient modulus significantly.

Katz, L. E., Rauch, A. F., Liljestrand, H. M., Harmon, J. S., Shaw, K. S., and Albers, H. 2001. Mechanisms of soil stabilization with liquid ionic stabilizer. *Transportation Research Record* 1757: 50-67.

The study performed detailed physical-chemical studies (XRD, SEM, etc.) to identify the mechanisms associated with the ionic soil stabilizer and clay. In conclusion, the principal active constituents of this ionic stabilizer are limonene and sulfuric acid, which react to form a concentrated, low-pH solution of sulfonated limonene. It stabilizes a soil by altering the clay lattice, and sufficient high application rate can improve the engineering properties of soil.

Katz, L. E., Rauch, A. F., Liljestrand, H. M., Harmon, J. S. 2002. Measured effects of liquid soil stabilizers on engineering properties of clay. *Transportation Research Record* 1787: 33–41.

The study investigated the effects of liquid stabilizers (ionic, polymer and enzyme) on the change of engineering properties of clay soil. The significant conclusions identified are reproduced as follows:

- The ionic stabilizer caused a decrease in the PI for the mesquite and montmorillonite clays but caused an increase in the PI for the other soils. None of the stabilizers were observed to consistently increase or decrease the PI of the five types of soils.
- The swelling of Illite soil was decreased by all three liquid stabilizers, but Kaolinite had the opposite results. The swelling of Bryan soil was increased by ionic and polymer products but decreased by enzyme products. Mesquite and Montmorillonite didn’t have any swelling by the use of three liquid products.

Tingle, J. S., Santoni, R. L., and Webster, S. L. 2002. Stabilization of silty sand with nontraditional additives. *Transportation research record* 1787: 61-70.

Tingle, J. S., and Santoni, R. L. 2003. Stabilization of clay soils with nontraditional additives. *Transportation Research Record* 1819: 72-84.

The two studies investigated the effects of nontraditional stabilizers (acid, lignosulfonate, polymer, petroleum emulsion, tree resin and enzyme types) on the UCS of clay soil and silty sand under both wet and dry conditions. The significant conclusions identified are reproduced as follows:

- Acid didn’t show any significant improvement on UCS of both of two soils under wet and dry conditions compared to untreated soils.
- Lignosulfonate performed best on UCS under both dry and wet conditions in CL soil. Its UCS performance was only good for silty sand under wet side.
- Enzymes were not effective in these two soils under both wet and dry sides.
- Polymers were effective in these two soils under both dry and wet conditions.
- Petroleum emulsion was effective to resist moisture but ineffective in strength improvement.
- Tree resin was only effected on silty sand under wet condition.
- The nontraditional stabilizers gained strength faster than traditional stabilizers. It means that the utilization of these nontraditional stabilizers can minimize construction time and delays.

Tingle, J. S., Santoni, R. L., and Nieves, M. 2005. Accelerated strength improvement of silty sand with nontraditional additives. *Transportation Research Record 1936*: 34-42.

This research evaluated the effect of two accelerators (cement and polymer) on the stabilization process of chemical stabilizers and determined the potential engineering benefits of these products for stabilizing a silty sand (SM) subgrade material. The significant conclusions identified are reproduced as follows:

- Use cement as accelerator can get better strength performance than polymer.
- The combined use of polymer and cement produced higher pH and strength.
- From the results of dry and wet conditions, all the products showed the prevention of disintegration during wet trials. They can be used for waterproofing or dust control in pavement construction.
- The increased quantities for cement caused better strength performance, but for polymer 4 was not.
- Accelerators helped nontraditional stabilizers gain strength rapidly. Also, the required quantity was small.

Little, L., Carlson, R. F., Connor, B. G. 2007. Tests of stabilization products for sandy soils from the national petroleum reserve – Alaska. *Transportation Research Record* 2186: 120-129.
The research evaluated the effect of four commercial nontraditional stabilizers (EMC^2®, Enviroseal®, Soil-Sement® and Soiltac®) on Alaska native soil stabilization. Dry CBR and freeze-thaw CBR test was conducted in this research. For the four nontraditional stabilizers, the Soil-Sement provided the strongest and the most moisture-resistant soil-additive mixture. In addition, the other two polymer emulsions, Enviroseal and Soiltac, appeared to be good candidates for future stabilization applications in northern Alaska.

Newman, K., and Rushing, J. F. 2007. Field testing of silty sand stabilized using combinations of hydraulic cements, fibers, and polymer emulsions. Paper presented at 86th Transportation Research Annual Meeting. No. 07-2179. Washington, DC.
This study investigated the field performance of blends of soil-cement mixture with polymer emulsions or fibers. The significant conclusions identified are reproduced as follows:

- The cement stabilization provided the best resistance to rutting, but it needed high content. The combined use of 5.8% of polymer and 3% of cement for soil provided similar performance of soil with 6% of cement. This method achieved the target strength with less cement content in consideration to saving cost.
- The blend of 4% of cement and 0.4% of fibers provided excellent load support.
- The blend of 3% of cement and 3% of polymer emulsion increased greatly the required number of loadings for failure compared to the control section.
- It was hard to say the use of fiber was better than the use of polymer because the cement content was different. Anyway, the use of both polymer and fiber can provide similar results with less cement content.

Rafalko, S. D., Filz, G. M., Brandon, T. L., and Mitchell, J. K. 2007. Rapid chemical stabilization of soft clay soils. *Transportation Research Record* 2026: 39-46.
This research investigated the most effective stabilizer to increase the strength of two soft clay soils at early age (within three days) to support aircrafts. The effects of secondary stabilizer (sodium silicate, polymer, superplasticizer and accelerator) was also investigated. The traditional stabilizers, cement and lime, were most effective in the increase of UCS of the two clays tested in this study, while all of the secondary stabilizers failed to produce any significant increases in UCS. In this research, the combined use is not successful though the different secondary stabilizer dosages were used.
The reasons for why secondary stabilizer failed to improve soil strength were listed following:

- Sodium silicate, it was due to weak calcium silicate gel. The available Ca ion for exchange was fewer.
- Super absorbent polymer, it was not effective for calcium carbide because its properties were not good at hardening. It could reduce available calcium for ion exchange.

Surdahl, R. W., Woll, J. H., and Marquez, H. R. 2007. Stabilization and dust control at the Buenos Aires National Wildlife Refuge, Arizona. *Transportation Research Record* 1989 (1): 312-321.

This study evaluated road stabilizers and dust palliatives (different lignosulfonates, Caliber, Soil-Sement®, Permazyme and Terrazyme) on a pavement construction for long-term performance (CBR, soil modulus, loading, cost and overall score) and recommended products with acceptable performance for the use in other projects. The findings showed that Caliber was the best product in consideration to both performance and cost. Permazyme, Terrazyme and Soil-Sement® obtained the lowest scores. Lignosulfonates showed the medium performance compared to other stabilizers.

Visser, A. T. 2007. Procedure for evaluating stabilization of road material with nontraditional stabilizers. *Transportation Research Record* 1989 (2): 21-26.

This study evaluated the effects of nontraditional stabilizers (polymer, enzyme and sulfated oil) on field performance (CBR) of different soil. Control panels were set up for comparison purpose. The significant conclusions identified are reproduced as follows:

- The different soil types had significantly different performance with nontraditional additives. Pufontein and Quantam could be improved by all the stabilizers tested. For Daveyton B and Benoni, only sulfonated oil worked, but the improvement was not very good.
- Soak condition decreased CBR value significantly. The CBR for different soils could be improved by specific stabilizer in soaking condition.
- Sulfonate oil was the most effective stabilizer with in-situ condition, and polymer 1 was the most effective stabilizer with soaked condition.
- Sulfonated oils provided gain in strength particularly in materials that had the active clay, such as the Benoni weathered dolerite used in the Benoni experiment. It had no benefit when used on inert materials such as sands with low PI.
- Providing a sealing surface, as in the case of Polymer1, reduced the permeability, and thus moisture sensitivity, of the stabilized material. For low-volume roads, consideration should be given not only to stabilizing a soil but also to providing a seal to resist traffic abrasion and moisture ingress.

Ceylan, H., Gopalakrishnan, K., and Kim, S. 2010. Soil stabilization with bioenergy coproduct. *Transportation Research Record* 2186: 130-137.

This research investigated the effects of two types of BCPs containing lignin (a liquid oil, BCP A and a powder BCP B) on engineering properties, compaction properties, UCS under dry and wet conditions of Iowa Class 10 soil. The significant conclusions identified are reproduced as follows:

- BCP A had better performance than BCP B in consideration to the decrease in PI, OMC and the increase in maximum dry unit weight.
- The optimum BCP content was 12% after various contents were evaluated.
- The increase in UCS were observed by both of two BCPs. BCP A performed better in dry condition. It also performed better in wet condition because of its good ability of waterproofing. BCP A had higher lignin content.
- The increase in curing time and decrease in moisture content had positive effects on UCS of soil treated with both BCP A and BCP B.

Puppala, A, J., Zhang, T., Cai, G. J., and Liu, S. Y. 2014. Stabilization of silt using a lignin-based bioenergy coproduct. Paper presented at *93rd Transportation Research Board Annual Meeting*. No. 14-205. Washington, DC.

This research investigated the effects of two types of BCPs containing lignin (a liquid oil, BCP A and a powder BCP B) on silt soil. The mechanism of BCPs were investigated by SEM and XRD. The BCPs used in this research were different from the BCPs used by Ceylan et al. (2010), however, their chemical compositions were similar (lignin contents were different). The significant conclusions identified are reproduced as follows:

- The optimum BCP content was 12% to achieve the maximum UCS.
- Both of BCP A and BCP B increased soil pH from 8.2 to 9.5 or higher.
- They decreased electrical resistivity of soil with the increase in additive content.
- SEM and XRD results showed that BCPs bind soil particles together to form strong soil structures. They are cementing materials.

FHWA projects

Narsavage, P. 2012. *Evaluation of roadbond EN-1 for soil stabilization on LAK-2-7.76*. FHWA/OH-2012/9. Columbus: OHIO Department of Transportation, Office of Construction Administration.

The project tested the stabilization product called Roadbond EN1 to reduce the amount of cement required for subgrade soil stabilization on pavement construction. The primary findings were that Roadbond EN1 could't increase the soil compressive strength, and it could resulted in more soil expansion than cement. In conclusion, adding the Roadbond EN1 product to the subgrade soil would not allow us to significantly reduce the amount of cement, nor would it reduced the amount of expansion due to sulfates.

Kansas

Milburn, J. P., and Parsons, R. L. 2005. *Performance of soil stabilization agents*. Report No. K-TRAN: KU-01-8. Lawrence, KS: University of Kansas.

The study summarized the performance of lime, cement, fly ash and permazyme 11-X (Enzyme) used with a wide range of soils (CH, CL, ML, SM and SP) and monitored changes in modulus during the curing days.

- All the traditional stabilizers were effective to improve the plasticity on soils. Lime was the most effective one.
- All the traditional stabilizers were effective to control swelling for CL soil. For sulfate-bearing CH soils, they resulted in similar or higher swelling.
- Lime, fly ash and cement treated soil gained the significantly strength improvement. The enzyme treated soil gained the modest strength improvement.
- For freeze-thaw testing, cement got the best performance. The second best performance was fly ash and enzyme. Lime was the worst one.
- For wet-dry condition testing, lime performed well on fine-grained soil, cement performed well on coarse-grained soil and CH clays, fly ash only performed well on the SM soil and enzyme perform bad on all soils.

- After leaching, lime and cement treated soils got the higher strength and lower PI than fly-ash-treated soil.
- Less thorough mixing influenced soil stabilization effectiveness because of large soil lump size.
- The stiffness gauge and impact echo showed that the best stiffness was lime and cement treated soil, the next was fly ash treated soil and enzyme performed worst.

Minnesota

Marasteanu, M. O., Hozalski, R., Clyne, T. R., and Velasquez, R. 2005. *Preliminary laboratory investigation of enzyme solutions as a soil stabilizer*. Report No. MN/RC – 2005-25. Minneapolis, MN: University of Minnesota Department of Civil Engineering.
The study investigated the stabilization mechanisms of two of commercially available enzyme-based products to better understand their potential value for road construction. Two types of soils were evaluated for resilient modulus and shear with two enzyme stabilizations. The preliminary findings and conclusions are shown below:

- Both enzyme A and B reduced the compaction effort. They improved not only soil workability, also soil shear capacity.
- The results and observation suggested that enzyme A behaved like a surfactant, contrary to the behavior of enzyme B.
- Enzyme A did not affect the resilient modulus of soil I, however, it increased soil II resilient modulus in average by 54%. Enzyme B had remarkable influence on resilient modulus of soils I and II. It increased stiffness of soils I and II in average by 69% and 77%, respectively.
- Soil classification can influence the effectiveness of treatment.

Texas

Katz, L. E., Rauch, A. F., and Liljestrand, H. M. 2003. *An Analysis of the Mechanisms and Efficacy of Three Liquid Chemical Soil Stabilizers*. Research Report 1993-1. Austin, TX: Center for Transportation Research, University of Texas.
This study investigated the mechanisms of clay soils which were modified or altered by liquid chemical agents (ionic products, enzyme products, and polymer products). The microstructural analysis (EDX, XRD, SEM and BET) was used to identify the mechanisms of nontraditional stabilizers.

- In ionic stabilizer, the main ingredient was sulfonated limonene. The hypothesized mechanism was to alter the clay mineral lattice by cation exchange. This hypothesized theory believed that the Al from a clay mineral could be extracted sulfonated limonene.
- In enzyme stabilizer, the main ingredient was polyethylene glycol. For clay with nonexpanding property, the proposed mechanism hypothesized that the adsorbing surface could be formed on the boundaries of clay grains. The results of surface area measurements, pore size distributions, ESEM images, and EDX provided evidence to support this hypothesis. Additionally, it caused the largest decrease in surface areas of soil.

- In polymer stabilizer, the main ingredient was sodium silicate. The hypothesized mechanism was to form a strongly adhesive film to bind soil grains. It provided surface coating and aggregation for the soil particles.

Little, D. N., and Kim, Y. R. 2000. *Laboratory evaluation of PennzSuppress D as a soil stabilizer*. Project Number 404701. College Station: Texas Transportation Institute.
This study investigated the effect of stabilizer named PennzSuppress D (bituminous product) on physical and mechanical characteristics of soil. The preliminary findings and conclusions are shown below:

- PennzSuppress D showed a small strength improvement and very little effects on resilient modulus for soil.
- 6% of PennzSuppresss D increased cohesive resistance significantly.
- PennzSuppresss D was effective in decreasing moisture susceptibility. It was expected to reduce effectively permeability and swelling potential of soil.
- Suction test showed that more PennzSuppresss D mixed in specimen had higher suction value.
- Optical microscopy pictures validated mechanical and suction data. The void structure in untreated sample was continuous, and became disconnected after PennzSuppresss D stabilization.
- PennzSuppresss D was an environmentally safe material capable of replacing cutbacks asphalts

Virginia

Geiman, C. M., Filz, G. M., Brandon, T. L., and Plaut, R. H. 2005. *Stabilization of soft clay subgrade in Virginia phase I laboratory study*. VTRC Report 05-CR16. Charlottesville, VA: Virginia Transportation Research Council.
The research screened a suite of traditional and nontraditional stabilizers used for three native soils in Virginia that had poor properties and led to poor performance of paveemnt. The effects of traditional stabilizer (cement and lime) and nontraditional stabilizers (lignosulfonate, polymer, $MgCl_2$ and proprietary cementitious stabilizer) on 28-day of UCS was evaluated. The preliminary findings and conclusions are shown below:

- Dry stabilizers were more effective than the liquid type of nontraditional stabilizers to improve the strength of the soils.
- Different soil types also affected the stabilizer performance, and traditional stabilizers were influenced more.
- Cement stabilization was sensitive to water-cement ratio which could affect the UCS. Higher ratio led to lower strength. The UCS of lime stabilization was sensitive to PI and water amendment ratio. Higher PI and ratio led to higher strength, it was different from cement.
- The specimens treated with lime, lignosulfonate, synthetic polymer, and the proprietary cementitious stabilizer obtained their majority of strength increases after 7-day curing.
- Portland cement and proprietary cementitious stabilizer had better performance than others, but they also had higher cost.

Others

Tingle, J. S., and Newman, K. Emulsion polymers for soil stabilization. 2004. Paper presented at FAA Worldwide Airport Technology Transfer Conference, Atlantic City, NJ.

This study investigated the UCS improvement of a silty sand treated with six different emulsion polymers (P1 to P6) under dry and wet conditions. The significant conclusions identified are reproduced as follows:

- All the additives empolyed in this study increse sttrength for both dry and wet conditions after 28-day curing. P1, P2 and P4 with 2.75% of content had the similar performance to 9% of cement.
- The emulsion polymers showed the better ability to resist the moisture than cement. The strength difference between dry and wet was small.
- At the early curing time, cement exhibited higher strenth than other stabilizers. However, P1, P2 and P4 reached significantly higher 28-day strengths than P3, P5, and P6. It also appeared that P1, P2, and P4 might not have reached their ultimate strengths after 28-day of cure.
- The effects of the polymer’s native chemical type were not significant. Their effects on soil stabilization not worse than cement.

Marasteanu, M. O., Velasquez, R. A., and Hozalski. R. M. 2006. Investigation of the effectiveness and mechanisms of enzyme products for subgrade stabilization. *International Journal of Pavement Engineering*, Vol. 7. 3: 213-220.

In this study, soil stabilization effectiveness and mechanisms of two enzyme products (enzyme A and B) were investigated by using chemical analysis and resilient modulus testing. In conclusion of this study, the addition of enzyme A did not improve significantly the resilient modulus of Soil I, but increased the resilient modulus of Soil II by an average of 54%. On the other hand, the addition of enzyme B significantly increased the resilient modulus of both soils. The soil clay content and percent of fines appeared to play an important role in the effectiveness of enzyme-based stabilizer treatment. The limited effectiveness of enzyme A (for low clay content soil) appeared to be due to its surfactant-like characteristics while enzyme B, which was effective for both soils, exhibited no surfactant-like characteristics.

Hazirbaba, K., and Connor, B. 2009. *The use of geofiber and synthetic fluid for stabilizing marginal soils*. Paper presented at the *Bearing Capacity of Roads, Railways and Airfields. 8th International Conference*. Champaign, IL.

The study investigated how to use two nontraditional stabilizer agents, geofiber and synthetic fluid, to improve the bearing capacity of soil. CBR and undrained unconsolidated (UU) triaxial compression tests were conducted for evaluation of two stabilizers. The combined use of these two stabilizers was also investigated. The preliminary findings showed that the use of geofiber had a medium increase in CBR and dramatic increase in cohesion. The use of synthetic fluid decreased CBR. The combined use showed the significant increase in CBR and medium increase in cohesion and friction angle. In conclusion, the use of geofiber or combined with synthetic fluid are recommended for different project purposes.

Yilmaz, Y., Gungor, A. G., and Avsar, C. 2009. Stabilization of clays using liquid enzymes. Paper presented at the *Bearing Capacity of Roads, Railways and Airfields. 8th International Conference*. Champaign, IL.

This study presented the results of standard laboratory soil tests conducted to measure changes in the engineering properties such as Atterberg limits, maximum dry unit weight, optimum moisture content, CBR and swell characteristics of three clay soils (CL, CH and CL) when treated with three different commercially available liquid enzymes. They reported that liquid enzymes provided some beneficial effects in CBR values. However, due to their negative influence on the volume expansion they were unlikely to be a substitute for CH type of soils.

Zandieh, A. R., and Yasrobi, S. S. 2010. Study of factors affecting the compressive strength of sandy soil stabilized with polymer. *Geotechnical and Geological Engineering* 28. 2: 139-145.

This research investigated the effects of two different polymers (P1 and P2) of wide range of dosages on soil. UCS and SEM of polymer-treated soils were evaluated. The significant conclusions identified are reproduced as follows:

- Both P1 and P2 increased soil strength. The increases in both application rate and curing time could improve the UCS of soil treated with P1 or P2. P2 had better performance with higher content after long-term curing than P1.
- Under wet condition, P2 had higher strength than P1. P2 had better ability to resist moisture.
- SEM images showed that the polymer stabilization formed the integrated lattice to improve UCS.
- Higher curing temperature increased strength for both P1 and P2. P1 was better at 20 □C. P2 was better at 40 □C. At 70 □C, they had same UCS.
- The combined use of NaCl decreased UCS. P2 decreased less UCS than P1.

Manso, J. M., Lopez, V. O., Polanco, J. A., and Setien, J. 2013. The use of ladle furnace slag in soil Stabilization. *Construction and Building Materials*, Vol. 40 (2013): 126-134.

This research studied the effects of utilization of ladle furnace slag (LFS) on stabilization for several clayey soils. The combined use of lime and LFS was also investigated. In this research, XRD, TG-DSC, UCS, expansion and pH test were conducted. The significant conclusions identified are reproduced as follows:

- LFS showed the expansion after long-term curing in water at 70 □C which was primarily caused by lime hydration and magnesium oxide presented in LFS. The various hydrated and carbonated products also contributed to expansion of LFS.
- LFS stabilization improved natural soil bearing capacity. Its bearing capacity improvement was very close to lime stabilization.
- Both the soil- LFS and soil-lime mixtures reduced the PI and volume swelling. LFS and lime also significantly increased UCS and reduced the collapse slump of soil.
- Mixtures were immersed in water for curing to monitor and measure the pH values. The results showed that the LFS slag needs longer time for curing.
- The soil- LFS mixtures showed the higher durability index than the soil-lime mixtures.

Peric, D., Bartley, P. A., Davis, L., Uzer, A. U., and Gurer, C. 2014. Assessment of sand stabilization potential of a plant-derived biomass. *Science and Engineering of Composite Materials*, 2014-0061.

This research investigated the effects of calcium lignosulfonate (CaL) with various contents on shear behavior of sand at early age. The significant conclusions identified are reproduced as follows:

- CaL bonded soil particles together to provide a large load-bearing area.
- Shear results showed that 2% to 9% of CaL content provided good shear improvement. 6% of CaL performed the best result.
- The addition of CaL in dry sand had the smaller cohesion than the wet sand treated with CaL. The presence of water in sand-CaL mixture also improved tensile strength.
- Lignin is a “green” material to increase cohesion of sand. It was recommended to use in desert areas.

Puppala, A, J., Zhang, T., Cai, G. J., and Liu, S. Y. 2015. Experimental investigation of thermal and mechanical properties of lignin treated silt. *Engineering Geology*, Vol. 196: 1-11.

This study investigated the compaction properties, thermal resistivity, UCS, resilient modulus, pore-size distribution and mechanism of silt treated with various lignin content. The significant conclusions identified are reproduced as follows:

- The increase in lignin content to 8% showed the increase in maximum dry density without change in OMC. When the lignin content went up to 15%, the maximum dry density didn’t change but OMC increased.
- The lowest thermal resistivity for silt treated with 12% of lignin was under OMC. At wet side, resistivity increased. However, at dry side, the resistivity was the highest. The increase in curing days increased the resistivity, and the differences between three moisture contents were became small.
- 12% of lignin could obtain the highest UCS than other contents. The increase in curing time and decrease in moisture content contributed to the higher UCS.
- 12% of lignin could obtain the highest resilient modulus than other contents. The increase in curing time and decrease in moisture content contributed to the higher resilient modulus.
- The increase in lignin content decreased the pore volume at the same pore diameter.
- SEM images showed than lignin bonded soil grains together to form strong soil structures.

APPENDIX C: RAW DATA OF UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS

Table C-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 C-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	Soil-12% BCP B	OMC - 4	1	126	10.7	113	13.05	10.4	10.8	10.3
56		OMC - 4	1	95	11.2			10.4	9.9	
57		OMC - 4	1	119	10.7			10.4	10.1	
58	Soil-12% BCP B	OMC - 4	7	122	10.7	136	10.53	10.4	10.5	10.5
59		OMC - 4	7	147	10.5			10.4	10.2	
60		OMC - 4	7	138	10.7			10.4	10.8	
61	Soil-12% BCP B	OMC - 4	28	110	9.5	103	9.46	10.4	9.6	9.8
62		OMC - 4	28	90	13.7			10.4	9.9	
63		OMC - 4	28	110	11.3			10.4	9.8	
64	Soil-12% BCP B	OMC	1	71	11.7	71	2.57	14.4	13.9	14.1
65		OMC	1	74	11.2			14.4	13.8	
66		OMC	1	67	13.2			14.4	14.7	
67	Soil-12% BCP B	OMC	7	113	11.7	110	5.42	14.4	13.4	13.9
68		OMC	7	114	13.7			14.4	13.5	
69		OMC	7	102	10.1			14.4	14.7	
70	Soil-12% BCP B	OMC	28	101	12.2	102	1.67	14.4	13.5	14.4
71		OMC	28	102	11.7			14.4	14.7	
72		OMC	28	105	10.7			14.4	15.0	
73	Soil-12% BCP B	OMC + 4	1	51	11.2	57	8.11	18.4	17.7	17.7
74		OMC + 4	1	68	15.0			18.4	17.7	
75		OMC + 4	1	50	11.3			18.4	17.7	
76	Soil-12% BCP B	OMC + 4	7	61	14.2	57	5.90	18.4	18.0	17.9
77		OMC + 4	7	48	14.2			18.4	17.9	
78		OMC + 4	7	61	15.0			18.4	17.9	
79	Soil-12% BCP B	OMC + 4	28	54	12.2	60	4.73	18.4	17.9	18.1
80		OMC + 4	28	66	15.0			18.4	18.6	
81		OMC + 4	28	59	15.0			18.4	17.8	
82	Soil-3% Cement	OMC - 4	1	127	5.0	122	7.63	10.4	10.0	10.2
83		OMC - 4	1	128	3.4			10.4	9.8	
84		OMC - 4	1	111	4.3			10.4	10.7	
85	Soil-3% Cement	OMC - 4	7	170	2.7	156	10.26	10.4	9.5	10.0
86		OMC - 4	7	154	2.6			10.4	10.3	
87		OMC - 4	7	145	3.2			10.4	10.1	
88	Soil-3% Cement	OMC - 4	28	226	2.9	234	11.02	10.4	9.3	9.4
89		OMC - 4	28	227	3.0			10.4	9.4	
90		OMC - 4	28	250	3.5			10.4	9.5	
91	Soil-3% Cement	OMC	1	137	4.5	148	7.97	14.4	14.2	14.4
92		OMC	1	154	3.9			14.4	14.2	
93		OMC	1	153	3.6			14.4	14.8	
94	Soil-3% Cement	OMC	7	248	3.0	228	14.61	14.4	13.6	13.7
95		OMC	7	214	3.5			14.4	14.1	
96		OMC	7	223	3.7			14.4	13.5	
97	Soil-3% Cement	OMC	28	316	3.0	311	16.50	14.4	13.7	13.4
98		OMC	28	289	4.1			14.4	13.1	
99		OMC	28	329	4.3			14.4	13.6	
100	Soil-3% Cement	OMC + 4	1	135	3.1	136	1.88	18.4	18.6	18.4
101		OMC + 4	1	133	3.1			18.4	18.7	
102		OMC + 4	1	138	3.0			18.4	17.8	
103	Soil-3% Cement	OMC + 4	7	233	2.8	228	7.31	18.4	18.0	17.8
104		OMC + 4	7	218	3.2			18.4	17.7	
105		OMC + 4	7	235	3.2			18.4	17.7	
106	Soil-3% Cement	OMC + 4	28	339	3.5	323	12.11	18.4	17.3	17.2
107		OMC + 4	28	310	3.1			18.4	17.2	
108		OMC + 4	28	319	3.4			18.4	17.1	

Table C-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	Soil-6% Cement	OMC - 4	1	190	3.9	203	12.98	10.4	9.8	10.0
110		OMC - 4	1	199	3.7			10.4	10.2	
111		OMC - 4	1	221	3.2			10.4	9.9	
112	Soil-6% Cement	OMC - 4	7	292	3.9	272	13.96	10.4	10.8	10.3
113		OMC - 4	7	265	3.5			10.4	10.2	
114		OMC - 4	7	260	3.5			10.4	10.0	
115	Soil-6% Cement	OMC - 4	28	314	2.9	320	9.22	10.4	9.4	9.3
116		OMC - 4	28	313	3.8			10.4	9.3	
117		OMC - 4	28	333	3.5			10.4	9.3	
118	Soil-6% Cement	OMC	1	256	3.7	262	6.78	14.4	14.3	13.7
119		OMC	1	259	4.0			14.4	13.7	
120		OMC	1	272	2.9			14.4	13.2	
121	Soil-6% Cement	OMC	7	352	4.1	369	12.52	14.4	13.8	13.9
122		OMC	7	380	3.6			14.4	14.5	
123		OMC	7	376	3.7			14.4	13.6	
124	Soil-6% Cement	OMC	28	652	3.8	648	17.02	14.4	13.4	13.3
125		OMC	28	666	3.9			14.4	13.5	
126		OMC	28	625	4.2			14.4	12.9	
127	Soil-6% Cement	OMC + 4	1	230	3.2	226	5.79	18.4	17.9	18.0
128		OMC + 4	1	218	4.6			18.4	17.9	
129		OMC + 4	1	231	3.1			18.4	18.1	
130	Soil-6% Cement	OMC + 4	7	356	3.2	341	11.72	18.4	17.5	17.6
131		OMC + 4	7	328	3.1			18.4	17.3	
132		OMC + 4	7	337	3.1			18.4	18.0	
133	Soil-6% Cement	OMC + 4	28	670	3.6	698	20.95	18.4	17.2	17.4
134		OMC + 4	28	720	3.5			18.4	17.4	
135		OMC + 4	28	705	3.3			18.4	17.7	
136	Soil-12% Cement	OMC - 4	1	266	3.9	281	15.26	10.4	9.7	10.3
137		OMC - 4	1	302	4.6			10.4	10.9	
138		OMC - 4	1	276	5.5			10.4	10.4	
139	Soil-12% Cement	OMC - 4	7	451	4.4	447	12.00	10.4	9.8	10.0
140		OMC - 4	7	431	5.0			10.4	10.1	
141		OMC - 4	7	460	6.0			10.4	10.1	
142	Soil-12% Cement	OMC - 4	28	729	4.3	747	21.17	10.4	9.3	9.2
143		OMC - 4	28	777	4.6			10.4	9.1	
144		OMC - 4	28	736	4.7			10.4	9.0	
145	Soil-12% Cement	OMC	1	411	3.9	400	7.39	14.4	14.7	14.4
146		OMC	1	396	4.4			14.4	14.5	
147		OMC	1	394	3.8			14.4	14.1	
148	Soil-12% Cement	OMC	7	650	4.2	664	9.90	14.4	14.3	13.9
149		OMC	7	667	4.5			14.4	13.5	
150		OMC	7	674	4.6			14.4	13.8	
151	Soil-12% Cement	OMC	28	976	4.5	955	28.52	14.4	13.3	13.2
152		OMC	28	915	4.6			14.4	13.1	
153		OMC	28	975	4.6			14.4	13.1	
154	Soil-12% Cement	OMC + 4	1	392	4.2	379	11.11	18.4	18.8	18.2
155		OMC + 4	1	381	4.5			18.4	17.6	
156		OMC + 4	1	365	5.3			18.4	18.2	
157	Soil-12% Cement	OMC + 4	7	621	4.8	613	11.48	18.4	17.4	17.7
158		OMC + 4	7	621	5.2			18.4	17.3	
159		OMC + 4	7	597	4.8			18.4	18.2	
160	Soil-12% Cement	OMC + 4	28	1119	5.1	1057	44.75	18.4	17.4	17.5
161		OMC + 4	28	1016	4.9			18.4	17.6	
162		OMC + 4	28	1035	5.3			18.4	17.6	

Table C-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	

Table C-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 C-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	Soil-3% cement	OMC	28	251	3.6	238	9.11	18.2	17.7	17.5
287		OMC	28	235	3.4			18.2	17.8	
288		OMC	28	229	2.7			18.2	17.1	
289	Soil-3% cement	OMC + 4	1	50	4.0	58	5.44	22.2	21.6	21.5
290		OMC + 4	1	62	3.5			22.2	21.4	
291		OMC + 4	1	62	2.5			22.2	21.7	
292	Soil-3% cement	OMC + 4	7	119	3.2	112	5.08	22.2	20.6	20.7
293		OMC + 4	7	108	3.8			22.2	20.8	
294		OMC + 4	7	108	3.9			22.2	20.6	
295	Soil-3% cement	OMC + 4	28	198	3.8	195	5.28	22.2	20.7	20.9
296		OMC + 4	28	188	2.9			22.2	21.1	
297		OMC + 4	28	200	2.6			22.2	21.0	
298	Soil-6% cement	OMC - 4	1	151	4.2	159	6.15	14.2	13.1	13.4
299		OMC - 4	1	166	4.0			14.2	13.6	
300		OMC - 4	1	161	2.9			14.2	13.4	
301	Soil-6% cement	OMC - 4	7	224	4.7	225	20.42	14.2	13.4	13.8
302		OMC - 4	7	200	4.5			14.2	13.4	
303		OMC - 4	7	250	4.0			14.2	14.6	
304	Soil-6% cement	OMC - 4	28	358	2.3	357	9.60	14.2	13.5	13.5
305		OMC - 4	28	345	3.5			14.2	13.7	
306		OMC - 4	28	368	3.8			14.2	13.3	
307	Soil-6% cement	OMC	1	137	4.6	145	5.75	18.2	17.6	17.8
308		OMC	1	149	4.1			18.2	17.8	
309		OMC	1	150	4.8			18.2	18.0	
310	Soil-6% cement	OMC	7	215	4.6	212	8.88	18.2	17.3	17.7
311		OMC	7	221	4.0			18.2	17.3	
312		OMC	7	200	4.4			18.2	18.6	
313	Soil-6% cement	OMC	28	352	3.0	384	24.53	18.2	17.8	17.6
314		OMC	28	387	3.7			18.2	17.7	
315		OMC	28	412	3.1			18.2	17.2	
316	Soil-6% cement	OMC + 4	1	130	3.4	129	1.55	22.2	21.4	21.1
317		OMC + 4	1	131	4.1			22.2	20.9	
318		OMC + 4	1	127	3.5			22.2	21.0	
319	Soil-6% cement	OMC + 4	7	191	4.0	188	4.53	22.2	20.9	21.0
320		OMC + 4	7	191	4.4			22.2	21.4	
321		OMC + 4	7	181	5.2			22.2	20.8	
322	Soil-6% cement	OMC + 4	28	270	3.7	256	11.64	22.2	21.7	21.4
323		OMC + 4	28	241	2.6			22.2	21.3	
324		OMC + 4	28	256	3.0			22.2	21.2	
325	Soil-12 %Cement	OMC - 4	1	251	5.4	243	13.02	14.2	14.8	14.0
326		OMC - 4	1	254	4.2			14.2	13.7	
327		OMC - 4	1	225	5.8			14.2	13.4	
328	Soil-12 %Cement	OMC - 4	7	283	3.9	294	8.22	14.2	13.9	14.4
329		OMC - 4	7	303	2.8			14.2	14.6	
330		OMC - 4	7	295	3.3			14.2	14.7	
331	Soil-12 %Cement	OMC - 4	28	429	4.1	435	14.83	14.2	13.8	13.7
332		OMC - 4	28	456	5.1			14.2	13.6	
333		OMC - 4	28	421	3.5			14.2	13.6	
334	Soil-12 %Cement	OMC	1	291	3.9	282	13.95	18.2	17.5	17.6
335		OMC	1	293	5.6			18.2	17.7	
336		OMC	1	263	4.2			18.2	17.7	
337	Soil-12 %Cement	OMC	7	340	3.8	336	15.77	18.2	18.5	18.2
338		OMC	7	353	3.2			18.2	18.4	
339		OMC	7	315	4.2			18.2	17.8	
340	Soil-12 %Cement	OMC	28	451	4.2	456	8.95	18.2	16.8	17.3
341		OMC	28	449	5.3			18.2	17.5	
342		OMC	28	469	5.1			18.2	17.6	
343	Soil-12 %Cement	OMC + 4	1	199	3.5	204	8.61	22.2	20.7	21.4
344		OMC + 4	1	216	3.7			22.2	22.3	
345		OMC + 4	1	197	3.0			22.2	21.2	
346	Soil-12 %Cement	OMC + 4	7	278	3.0	274	6.53	22.2	22.0	21.7
347		OMC + 4	7	265	3.8			22.2	21.4	
348		OMC + 4	7	279	5.3			22.2	21.6	
349	Soil-12 %Cement	OMC + 4	28	302	2.1	313	9.55	22.2	22.1	21.5
350		OMC + 4	28	312	5.4			22.2	20.8	
351		OMC + 4	28	325	2.8			22.2	21.8	

Table C-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	**Natural Soil**	OMC - 4	1	73	3.6	68	7.92	9.5	9.7	9.6
317		OMC - 4	1	73	2.7			9.5	9.4	
318		OMC - 4	1	56	4.4			9.5	9.6	
319	**Natural Soil**	OMC - 4	7	63	4.5	67	5.66	9.5	9.7	9.5
320		OMC - 4	7	75	4.2			9.5	9.3	
321		OMC - 4	7	63	3.5			9.5	9.6	
322	**Natural Soil**	OMC - 4	28	74	3.2	66	8.78	9.5	9.2	9.0
323		OMC - 4	28	70	2.9			9.5	9.0	
324		OMC - 4	28	54	1.8			9.5	8.9	
325	**Natural Soil**	OMC	1	34	6.5	33	3.67	13.5	13.2	13.4
326		OMC	1	37	3.9			13.5	13.5	
327		OMC	1	28	4.8			13.5	13.6	
328	**Natural Soil**	OMC	7	34	5.5	30	3.09	13.5	13.7	13.4
329		OMC	7	27	6.5			13.5	13.1	
330		OMC	7	28	6.0			13.5	13.5	
331	**Natural Soil**	OMC	28	29	6.1	30	0.54	13.5	12.9	13.0
332		OMC	28	30	5.2			13.5	13.1	
333		OMC	28	29	7.2			13.5	13.1	
334	**Natural Soil**	OMC + 4	1	24	4.4	26	2.86	17.5	17.4	17.6
335		OMC + 4	1	23	4.0			17.5	17.7	
336		OMC + 4	1	30	4.2			17.5	17.8	
337	**Natural Soil**	OMC + 4	7	21	6.3	23	3.01	17.5	17.7	17.7
338		OMC + 4	7	28	5.4			17.5	17.9	
339		OMC + 4	7	22	5.6			17.5	17.4	
340	**Natural Soil**	OMC + 4	28	29	5.6	24	6.65	17.5	17.0	17.0
341		OMC + 4	28	28	5.6			17.5	16.8	
342		OMC + 4	28	14	8.7			17.5	17.1	
343	**Soil-12% BCP A**	OMC - 4	1	81	14.8	79	1.87	9.5	10.3	10.2
344		OMC - 4	1	80	13.4			9.5	10.4	
345		OMC - 4	1	77	14.0			9.5	10.0	
346	**Soil-12% BCP A**	OMC - 4	7	119	9.6	122	9.11	9.5	9.8	9.8
347		OMC - 4	7	112	9.9			9.5	10.1	
348		OMC - 4	7	134	9.0			9.5	9.5	
349	**Soil-12% BCP A**	OMC - 4	28	149	8.5	150	2.17	9.5	10.3	10.1
350		OMC - 4	28	152	7.9			9.5	9.9	
351		OMC - 4	28	147	7.9			9.5	10.1	
352	**Soil-12% BCP A**	OMC	1	45	15.0	48	3.61	13.5	13.9	14.0
353		OMC	1	53	14.4			13.5	13.8	
354		OMC	1	45	17.7			13.5	14.2	
355	**Soil-12% BCP A**	OMC	7	84	8.1	90	5.78	13.5	13.7	13.8
356		OMC	7	98	7.2			13.5	13.6	
357		OMC	7	88	8.0			13.5	14.2	
358	**Soil-12% BCP A**	OMC	28	111	7.8	112	3.42	13.5	13.2	13.5
359		OMC	28	108	7.9			13.5	13.8	
360		OMC	28	117	7.6			13.5	13.4	
361	**Soil-12% BCP A**	OMC + 4	1	39	10.9	37	1.59	17.5	17.6	18.0
362		OMC + 4	1	35	11.6			17.5	18.3	
363		OMC + 4	1	37	11.8			17.5	18.1	
364	**Soil-12% BCP A**	OMC + 4	7	46	11.4	47	2.17	17.5	17.3	17.4
365		OMC + 4	7	45	9.2			17.5	17.8	
366		OMC + 4	7	50	9.0			17.5	17.2	
367	**Soil-12% BCP A**	OMC + 4	28	60	8.8	60	1.31	17.5	17.2	17.8
368		OMC + 4	28	61	8.6			17.5	18.0	
369		OMC + 4	28	58	8.7			17.5	18.1	

Table C-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	Soil-12% BCP B	OMC - 4	1	116	5.3	115	5.24	9.5	9.3	9.4
371		OMC - 4	1	109	5.7			9.5	9.6	
372		OMC - 4	1	121	6.7			9.5	9.4	
373	Soil-12% BCP B	OMC - 4	7	95	8.4	94	13.44	9.5	9.2	9.3
374		OMC - 4	7	109	6.6			9.5	9.1	
375		OMC - 4	7	77	7.8			9.5	9.5	
376	Soil-12% BCP B	OMC - 4	28	75	9.5	81	8.01	9.5	8.8	9.0
377		OMC - 4	28	76	7.6			9.5	9.0	
378		OMC - 4	28	92	8.0			9.5	9.1	
379	Soil-12% BCP B	OMC	1	64	7.4	73	6.71	13.5	13.2	13.3
380		OMC	1	80	5.5			13.5	13.1	
381		OMC	1	75	5.8			13.5	13.5	
382	Soil-12% BCP B	OMC	7	72	9.6	57	10.85	13.5	13.6	13.4
383		OMC	7	48	8.5			13.5	13.4	
384		OMC	7	50	7.9			13.5	13.3	
385	Soil-12% BCP B	OMC	28	36	7.3	51	15.01	13.5	13.5	13.4
386		OMC	28	44	10.0			13.5	13.4	
387		OMC	28	71	8.8			13.5	13.3	
388	Soil-12% BCP B	OMC + 4	1	63	8.9	64	1.85	17.5	17.8	17.6
389		OMC + 4	1	63	6.1			17.5	17.7	
390		OMC + 4	1	67	6.5			17.5	17.4	
391	Soil-12% BCP B	OMC + 4	7	41	7.6	46	4.40	17.5	17.3	17.5
392		OMC + 4	7	52	7.2			17.5	17.6	
393		OMC + 4	7	45	8.1			17.5	17.6	
394	Soil-12% BCP B	OMC + 4	28	28	8.8	28	3.97	17.5	17.0	17.1
395		OMC + 4	28	34	9.2			17.5	17.1	
396		OMC + 4	28	24	9.7			17.5	17.2	
397	Soil-3 %Cement	OMC - 4	1	124	5.1	128	3.43	9.5	9.9	9.5
398		OMC - 4	1	132	3.4			9.5	9.5	
399		OMC - 4	1	128	4.3			9.5	9.1	
400	Soil-3 %Cement	OMC - 4	7	141	5.3	155	11.99	9.5	8.9	8.7
401		OMC - 4	7	170	3.5			9.5	8.7	
402		OMC - 4	7	153	3.9			9.5	8.7	
403	Soil-3 %Cement	OMC - 4	28	221	3.2	214	10.26	9.5	8.2	8.2
404		OMC - 4	28	199	3.0			9.5	8.0	
405		OMC - 4	28	221	2.7			9.5	8.5	
406	Soil-3 %Cement	OMC	1	123	4.2	123	0.33	13.5	12.9	13.0
407		OMC	1	122	3.7			13.5	13.0	
408		OMC	1	123	3.6			13.5	13.0	
409	Soil-3 %Cement	OMC	7	145	4.2	140	10.17	13.5	12.8	12.9
410		OMC	7	150	4.4			13.5	12.9	
411		OMC	7	126	4.7			13.5	12.9	
412	Soil-3 %Cement	OMC	28	169	3.0	174	5.99	13.5	12.9	12.6
413		OMC	28	182	3.0			13.5	12.4	
414		OMC	28	169	3.6			13.5	12.4	
415	Soil-3 %Cement	OMC + 4	1	107	4.5	111	3.14	17.5	17.4	17.3
416		OMC + 4	1	113	4.1			17.5	17.2	
417		OMC + 4	1	113	4.0			17.5	17.3	
418	Soil-3 %Cement	OMC + 4	7	130	4.7	135	4.64	17.5	17.0	16.8
419		OMC + 4	7	133	4.1			17.5	16.9	
420		OMC + 4	7	141	3.4			17.5	16.6	
421	Soil-3 %Cement	OMC + 4	28	154	3.3	158	3.18	17.5	16.9	16.9
422		OMC + 4	28	161	3.2			17.5	16.9	
423		OMC + 4	28	160	3.6			17.5	17.0	

Table C-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	Soil-6 %Cement	OMC - 4	1	213	4.6	222	11.63	9.5	9.2	9.1
425		OMC - 4	1	214	3.9			9.5	9.3	
426		OMC - 4	1	238	3.5			9.5	8.9	
427	Soil-6 %Cement	OMC - 4	7	270	4.0	277	6.11	9.5	9.0	9.2
428		OMC - 4	7	285	3.1			9.5	9.5	
429		OMC - 4	7	276	3.5			9.5	9.2	
430	Soil-6 %Cement	OMC - 4	28	348	3.5	355	13.95	9.5	8.9	8.9
431		OMC - 4	28	375	3.5			9.5	8.8	
432		OMC - 4	28	344	4.6			9.5	9.0	
433	Soil-6 %Cement	OMC	1	192	5.3	200	6.17	13.5	13.1	13.3
434		OMC	1	200	4.7			13.5	13.3	
435		OMC	1	207	3.4			13.5	13.5	
436	Soil-6 %Cement	OMC	7	288	3.7	274	11.06	13.5	12.6	12.8
437		OMC	7	261	5.2			13.5	12.8	
438		OMC	7	272	4.7			13.5	12.9	
439	Soil-6 %Cement	OMC	28	295	4.2	306	9.15	13.5	13.0	12.9
440		OMC	28	307	4.0			13.5	13.1	
441		OMC	28	318	4.5			13.5	12.7	
442	Soil-6 %Cement	OMC + 4	1	163	3.9	170	5.47	17.5	17.0	17.3
443		OMC + 4	1	170	4.3			17.5	17.3	
444		OMC + 4	1	177	3.6			17.5	17.7	
445	Soil-6 %Cement	OMC + 4	7	264	3.9	245	16.45	17.5	16.2	16.2
446		OMC + 4	7	224	5.2			17.5	16.3	
447		OMC + 4	7	247	4.4			17.5	16.1	
448	Soil-6 %Cement	OMC + 4	28	284	3.9	301	11.99	17.5	16.4	16.3
449		OMC + 4	28	307	4.1			17.5	16.3	
450		OMC + 4	28	312	4.2			17.5	16.3	
451	Soil-12 %Cement	OMC - 4	1	330	5.4	324	6.39	9.5	9.3	9.5
452		OMC - 4	1	315	3.7			9.5	9.4	
453		OMC - 4	1	326	4.8			9.5	9.7	
454	Soil-12 %Cement	OMC - 4	7	431	4.2	442	30.56	9.5	8.8	8.5
455		OMC - 4	7	483	4.2			9.5	8.0	
456		OMC - 4	7	411	3.8			9.5	8.5	
457	Soil-12 %Cement	OMC - 4	28	540	5.4	538	12.55	9.5	8.4	8.3
458		OMC - 4	28	553	5.2			9.5	8.2	
459		OMC - 4	28	522	4.5			9.5	8.3	
460	Soil-12 %Cement	OMC	1	313	4.4	334	17.33	13.5	13.1	13.3
461		OMC	1	333	4.9			13.5	13.5	
462		OMC	1	356	4.1			13.5	13.2	
463	Soil-12 %Cement	OMC	7	471	5.1	474	9.00	13.5	12.8	12.7
464		OMC	7	465	5.1			13.5	12.6	
465		OMC	7	486	4.6			13.5	12.6	
466	Soil-12 %Cement	OMC	28	589	5.6	607	12.95	13.5	12.4	12.5
467		OMC	28	610	4.8			13.5	12.6	
468		OMC	28	621	4.7			13.5	12.4	
469	Soil-12 %Cement	OMC + 4	1	279	3.7	299	18.71	17.5	17.1	16.7
470		OMC + 4	1	293	3.7			17.5	16.6	
471		OMC + 4	1	324	4.1			17.5	16.4	
472	Soil-12 %Cement	OMC + 4	7	359	4.7	370	8.73	17.5	16.5	16.4
473		OMC + 4	7	381	5.4			17.5	16.6	
474		OMC + 4	7	369	5.1			17.5	16.2	
475	Soil-12 %Cement	OMC + 4	28	520	3.5	556	26.03	17.5	15.8	15.8
476		OMC + 4	28	568	4.5			17.5	15.9	
477		OMC + 4	28	580	3.8			17.5	15.7	

Table C-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		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		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		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		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		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		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		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		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		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		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		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		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		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		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		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		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		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		OMC + 4	28	40	6.6			16.0	15.9	
531		OMC + 4	28	42	6.0			16.0	15.7	

Table C-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	Soil-12% BCP B	OMC - 4	1	117	6.6	115	5.59	8.0	7.7	7.8
533		OMC - 4	1	121	6.9			8.0	7.8	
534		OMC - 4	1	108	6.3			8.0	8.0	
535	Soil-12% BCP B	OMC - 4	7	105	6.4	112	7.41	8.0	8.2	8.0
536		OMC - 4	7	108	7.2			8.0	8.0	
537		OMC - 4	7	122	6.4			8.0	7.7	
538	Soil-12% BCP B	OMC - 4	28	97	6.2	87	7.41	8.0	7.8	7.7
539		OMC - 4	28	83	7.3			8.0	7.7	
540		OMC - 4	28	80	7.4			8.0	7.5	
541	Soil-12% BCP B	OMC	1	76	8.4	71	3.40	12.0	11.9	12.0
542		OMC	1	68	7.0			12.0	12.3	
543		OMC	1	70	7.2			12.0	11.9	
544	Soil-12% BCP B	OMC	7	55	8.2	55	3.68	12.0	11.5	11.8
545		OMC	7	51	7.9			12.0	11.9	
546		OMC	7	60	8.0			12.0	12.0	
547	Soil-12% BCP B	OMC	28	32	8.5	33	2.25	12.0	11.6	11.7
548		OMC	28	37	8.0			12.0	11.4	
549		OMC	28	32	8.6			12.0	12.2	
550	Soil-12% BCP B	OMC + 4	1	39	7.7	34	5.87	16.0	16.6	16.4
551		OMC + 4	1	37	8.5			16.0	16.4	
552		OMC + 4	1	26	7.9			16.0	16.1	
553	Soil-12% BCP B	OMC + 4	7	39	8.9	34	4.05	16.0	15.9	15.9
554		OMC + 4	7	35	9.2			16.0	16.1	
555		OMC + 4	7	29	7.5			16.0	15.7	
556	Soil-12% BCP B	OMC + 4	28	23	9.6	25	1.47	16.0	15.4	15.7
557		OMC + 4	28	26	9.6			16.0	15.8	
558		OMC + 4	28	25	9.4			16.0	16.0	
559	Soil-3 %Cement	OMC - 4	1	77	3.7	72	3.40	8.0	9.9	9.5
560		OMC - 4	1	71	4.5			8.0	9.5	
561		OMC - 4	1	69	3.9			8.0	9.1	
562	Soil-3 %Cement	OMC - 4	7	146	3.3	147	5.71	8.0	8.9	8.7
563		OMC - 4	7	154	3.6			8.0	8.7	
564		OMC - 4	7	140	4.4			8.0	8.7	
565	Soil-3 %Cement	OMC - 4	28	176	2.8	181	4.98	8.0	8.2	8.2
566		OMC - 4	28	179	3.7			8.0	8.0	
567		OMC - 4	28	188	3.7			8.0	8.5	
568	Soil-3 %Cement	OMC	1	45	3.4	45	1.48	12.0	12.9	13.0
569		OMC	1	47	3.9			12.0	13.0	
570		OMC	1	43	4.2			12.0	13.0	
571	Soil-3 %Cement	OMC	7	128	2.7	131	2.04	12.0	12.8	12.9
572		OMC	7	132	2.9			12.0	12.9	
573		OMC	7	132	3.3			12.0	12.9	
574	Soil-3 %Cement	OMC	28	198	4.1	194	6.19	12.0	12.9	12.6
575		OMC	28	185	3.6			12.0	12.4	
576		OMC	28	199	3.9			12.0	12.4	
577	Soil-3 %Cement	OMC + 4	1	29	4.3	28	0.62	16.0	17.4	17.3
578		OMC + 4	1	28	3.9			16.0	17.2	
579		OMC + 4	1	27	4.1			16.0	17.3	
580	Soil-3 %Cement	OMC + 4	7	95	3.5	96	3.64	16.0	17.0	16.8
581		OMC + 4	7	92	4.4			16.0	16.9	
582		OMC + 4	7	100	3.5			16.0	16.6	
583	Soil-3 %Cement	OMC + 4	28	133	3.1	139	4.05	16.0	16.9	16.9
584		OMC + 4	28	143	4.0			16.0	16.9	
585		OMC + 4	28	140	3.0			16.0	17.0	

Table C-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	Soil-6 %Cement	OMC - 4	1	116	4.7	117	2.72	8.0	9.2	9.1
587		OMC - 4	1	120	4.5			8.0	9.3	
588		OMC - 4	1	114	4.4			8.0	8.9	
589	Soil-6 %Cement	OMC - 4	7	234	4.3	225	10.40	8.0	9.0	9.2
590		OMC - 4	7	210	4.1			8.0	9.5	
591		OMC - 4	7	229	4.4			8.0	9.2	
592	Soil-6 %Cement	OMC - 4	28	260	3.3	255	5.12	8.0	8.9	8.9
593		OMC - 4	28	257	3.6			8.0	8.8	
594		OMC - 4	28	248	4.2			8.0	9.0	
595	Soil-6 %Cement	OMC	1	81	4.8	77	4.93	12.0	13.1	13.3
596		OMC	1	70	5.7			12.0	13.3	
597		OMC	1	80	5.3			12.0	13.5	
598	Soil-6 %Cement	OMC	7	238	3.8	255	16.49	12.0	12.6	12.8
599		OMC	7	277	3.3			12.0	12.8	
600		OMC	7	248	3.5			12.0	12.9	
601	Soil-6 %Cement	OMC	28	274	4.4	291	12.49	12.0	13.0	12.9
602		OMC	28	298	3.7			12.0	13.1	
603		OMC	28	302	3.6			12.0	12.7	
604	Soil-6 %Cement	OMC + 4	1	53	4.6	57	2.96	16.0	17.0	17.3
605		OMC + 4	1	61	6.3			16.0	17.3	
606		OMC + 4	1	57	5.2			16.0	17.7	
607	Soil-6 %Cement	OMC + 4	7	198	3.6	208	12.60	16.0	16.2	16.2
608		OMC + 4	7	201	4.0			16.0	16.3	
609		OMC + 4	7	226	4.1			16.0	16.1	
610	Soil-6 %Cement	OMC + 4	28	221	3.6	223	7.02	16.0	16.4	16.3
611		OMC + 4	28	216	2.8			16.0	16.3	
612		OMC + 4	28	233	6.1			16.0	16.3	
613	Soil-12 %Cement	OMC - 4	1	198	4.1	197	5.57	8.0	10.3	10.2
614		OMC - 4	1	204	3.7			8.0	10.4	
615		OMC - 4	1	190	3.8			8.0	10.0	
616	Soil-12 %Cement	OMC - 4	7	345	5.3	366	17.97	8.0	9.8	9.8
617		OMC - 4	7	389	4.5			8.0	10.1	
618		OMC - 4	7	364	3.8			8.0	9.5	
619	Soil-12 %Cement	OMC - 4	28	485	4.7	510	22.20	8.0	10.3	10.1
620		OMC - 4	28	507	4.6			8.0	9.9	
621		OMC - 4	28	539	5.0			8.0	10.1	
622	Soil-12 %Cement	OMC	1	136	4.4	136	1.03	12.0	13.9	14.0
623		OMC	1	135	3.9			12.0	13.8	
624		OMC	1	137	4.6			12.0	14.2	
625	Soil-12 %Cement	OMC	7	426	5.6	438	12.09	12.0	13.7	13.8
626		OMC	7	454	4.4			12.0	13.6	
627		OMC	7	434	4.5			12.0	14.2	
628	Soil-12 %Cement	OMC	28	600	4.5	597	11.72	12.0	13.2	13.5
629		OMC	28	610	4.5			12.0	13.8	
630		OMC	28	582	3.7			12.0	13.4	
631	Soil-12 %Cement	OMC + 4	1	124	4.5	119	3.24	16.0	17.6	18.0
632		OMC + 4	1	119	4.1			16.0	18.3	
633		OMC + 4	1	116	3.7			16.0	18.1	
634	Soil-12 %Cement	OMC + 4	7	420	5.2	406	12.63	16.0	17.3	17.4
635		OMC + 4	7	409	4.0			16.0	17.8	
636		OMC + 4	7	389	4.8			16.0	17.2	
637	Soil-12 %Cement	OMC + 4	28	451	5.1	452	2.87	16.0	17.2	17.8
638		OMC + 4	28	456	5.6			16.0	18.0	
639		OMC + 4	28	450	5.3			16.0	18.1	

APPENDIX D: RAW DATA OF FREEZE THAW DURABILITY TEST RESULTS

Table D-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 D-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%

Table D-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%

Table D-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 D-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 D-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 D-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 D-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 E: IMAGES AND DATA OF XRD PATTERNS

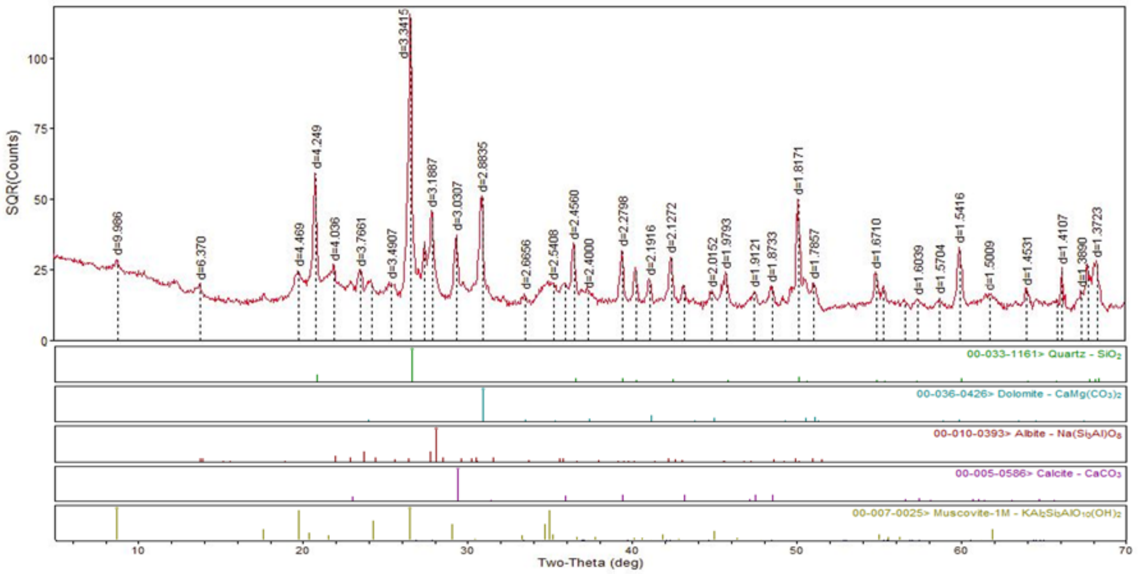


Figure E-1. XRD pattern for untreated Soil 1

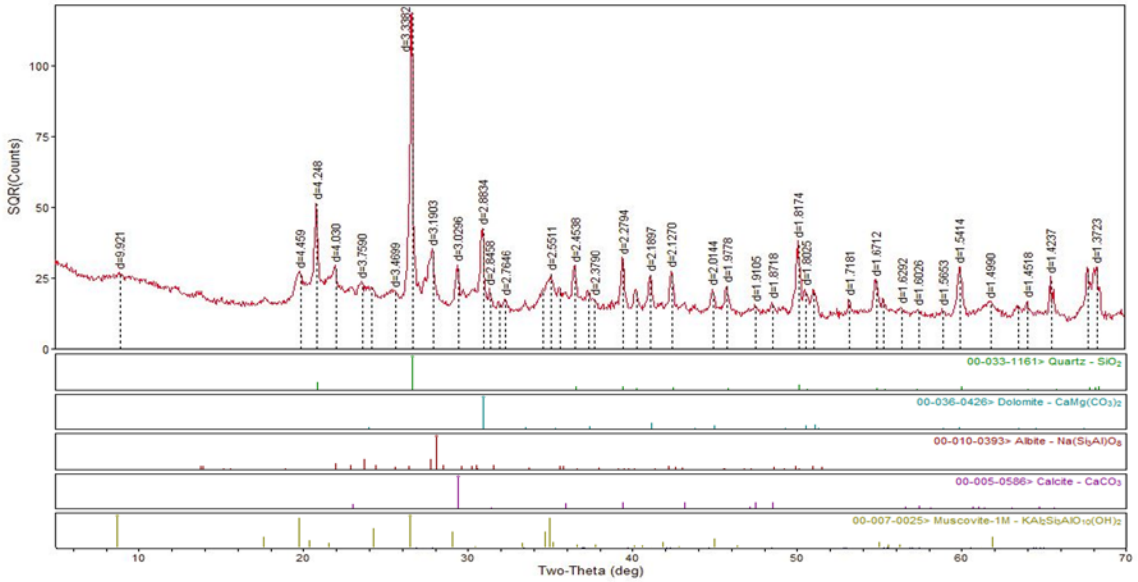


Figure E-2. XRD pattern for BCP A-treated Soil 1

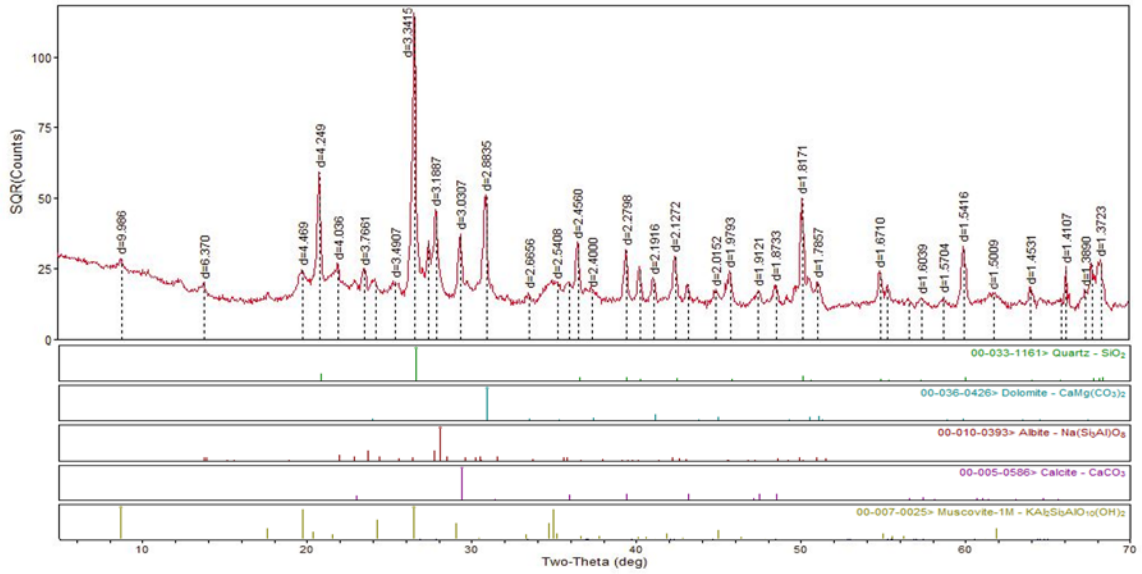


Figure E-3. XRD pattern for BCP B-treated Soil 1

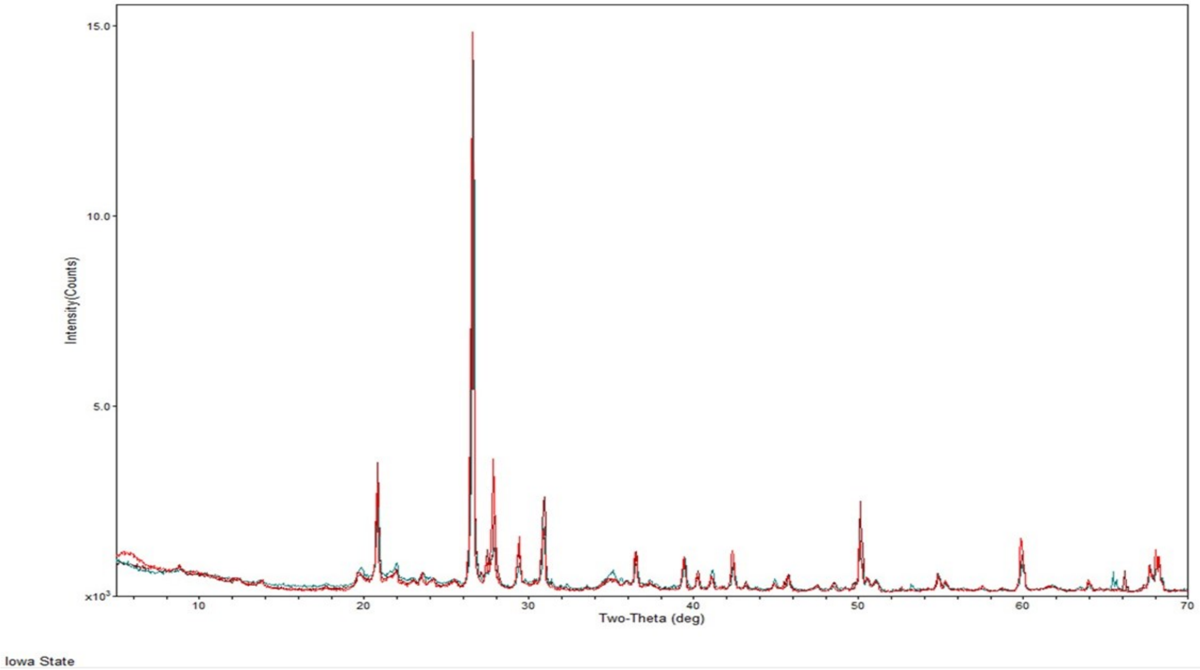


Figure E-4. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 1 samples

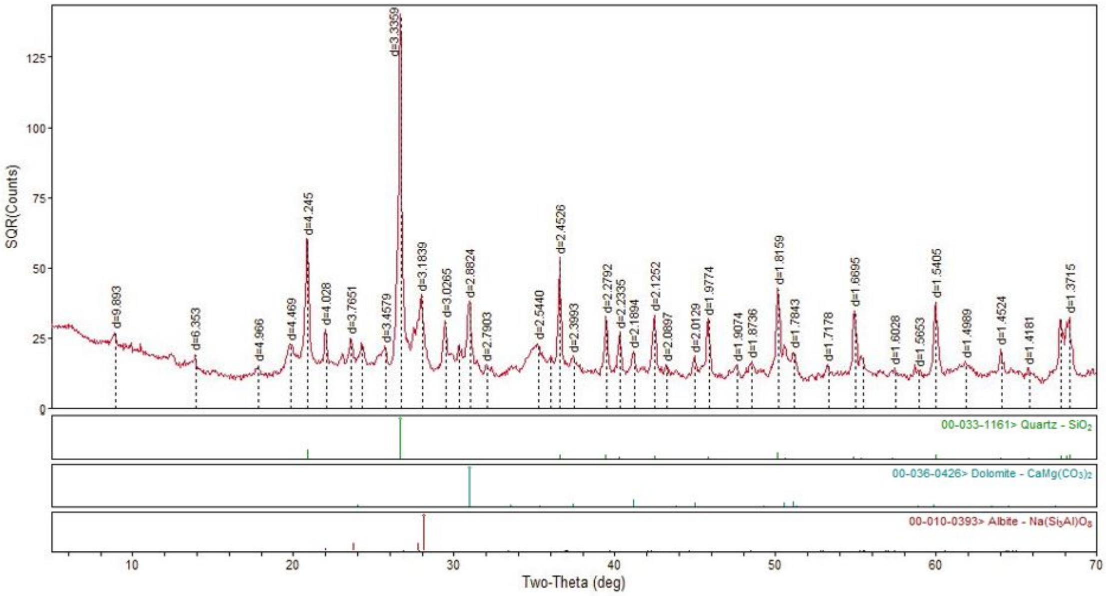


Figure E-5. XRD pattern for untreated Soil 2

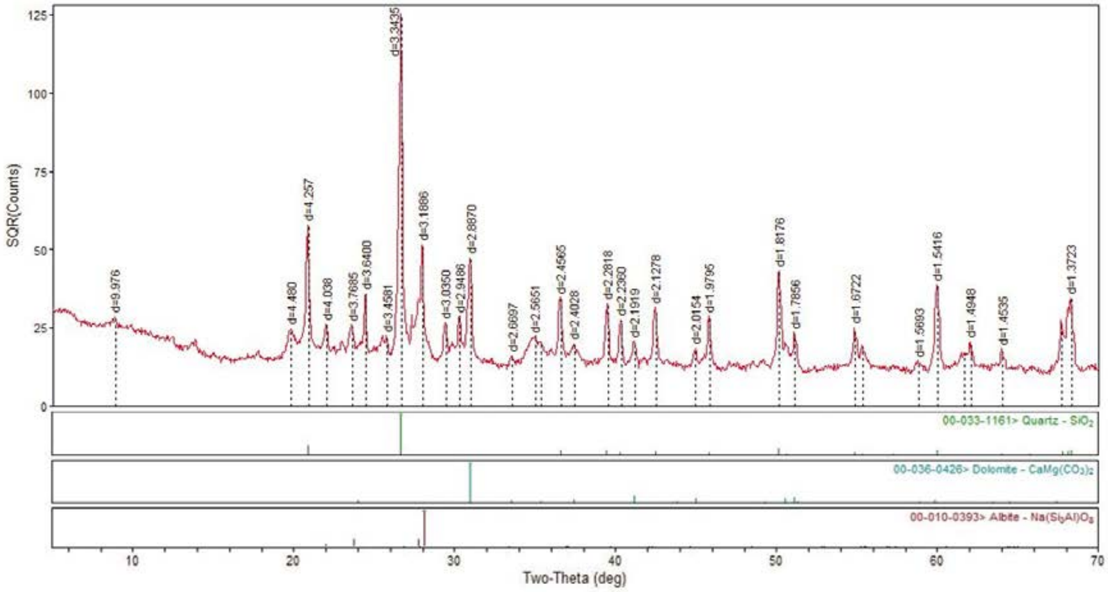


Figure E-6. XRD pattern for BCP A-treated Soil 2

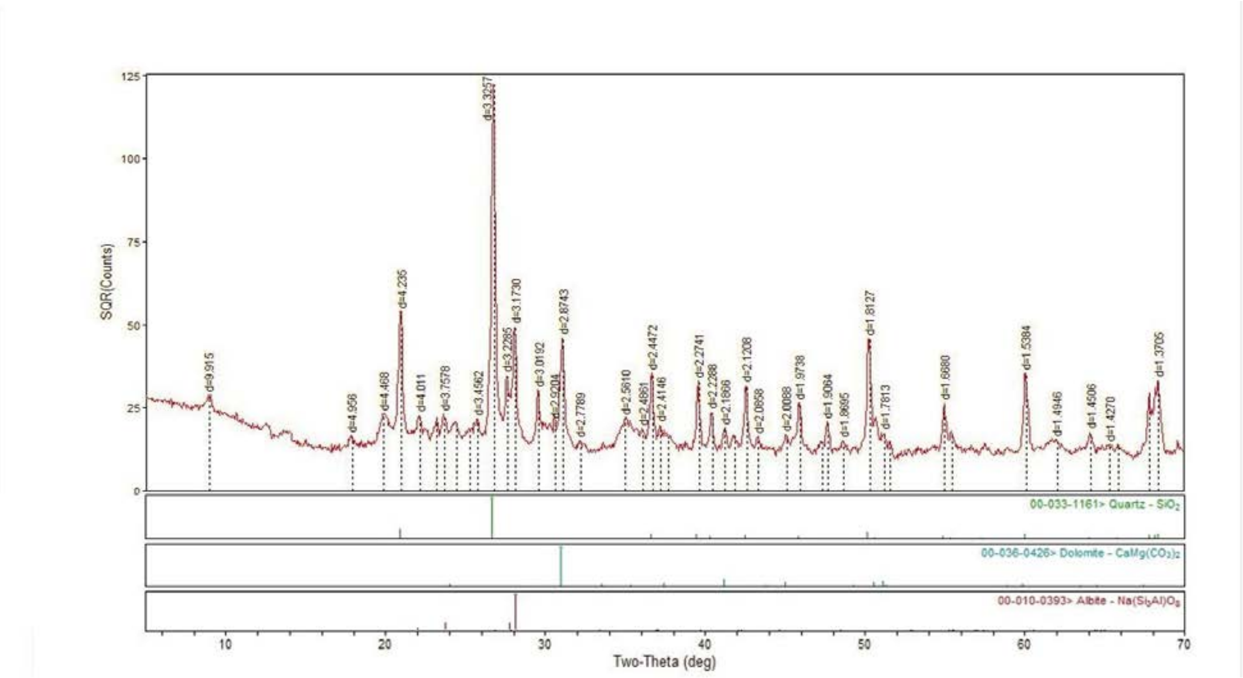


Figure E-7. XRD pattern for BCP B-treated Soil 2

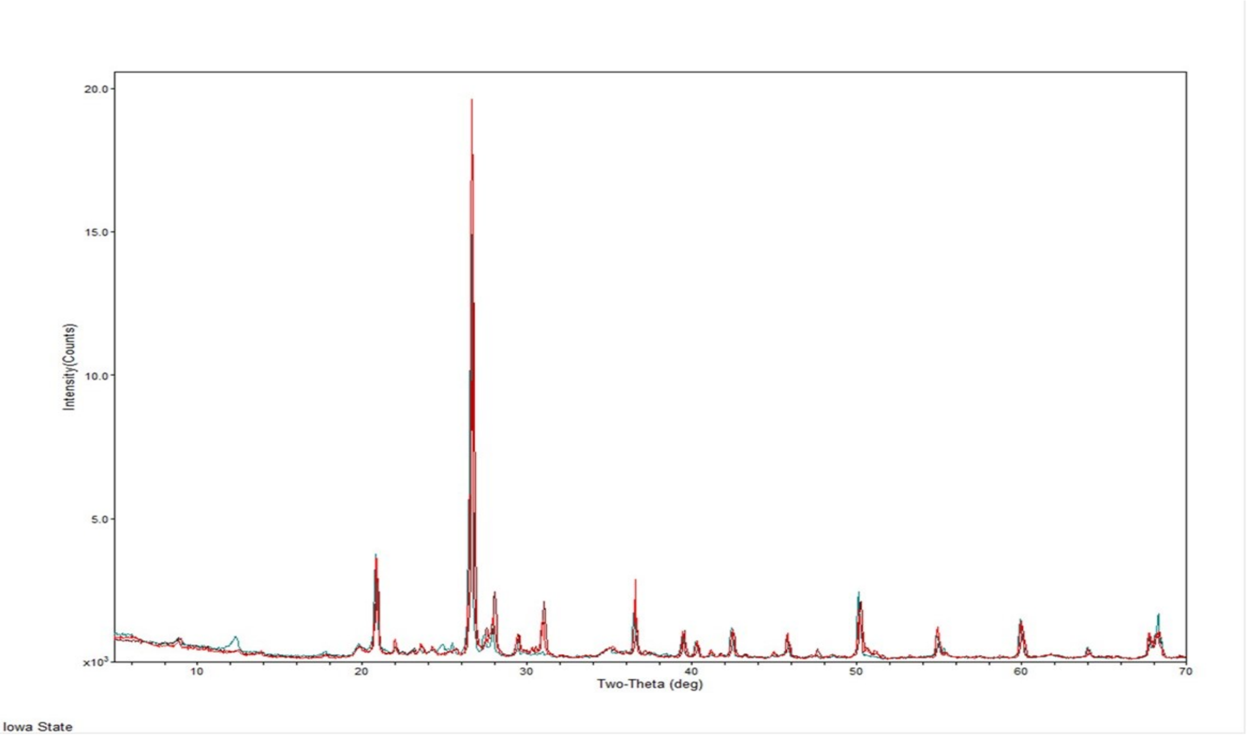


Figure E-8. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 2 samples

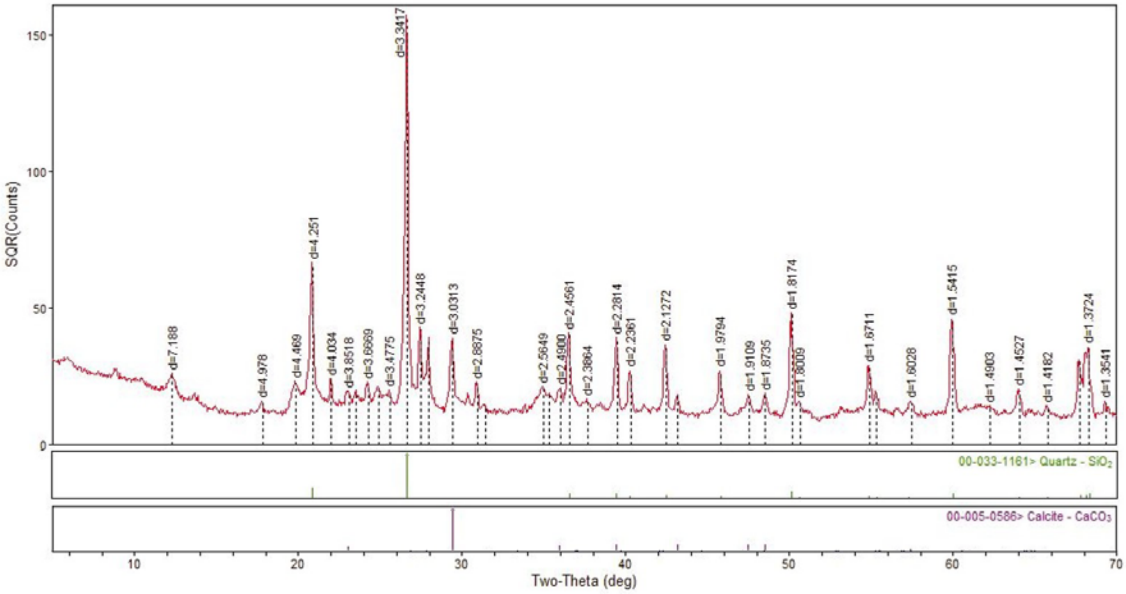


Figure E-9. XRD pattern for untreated Soil 3

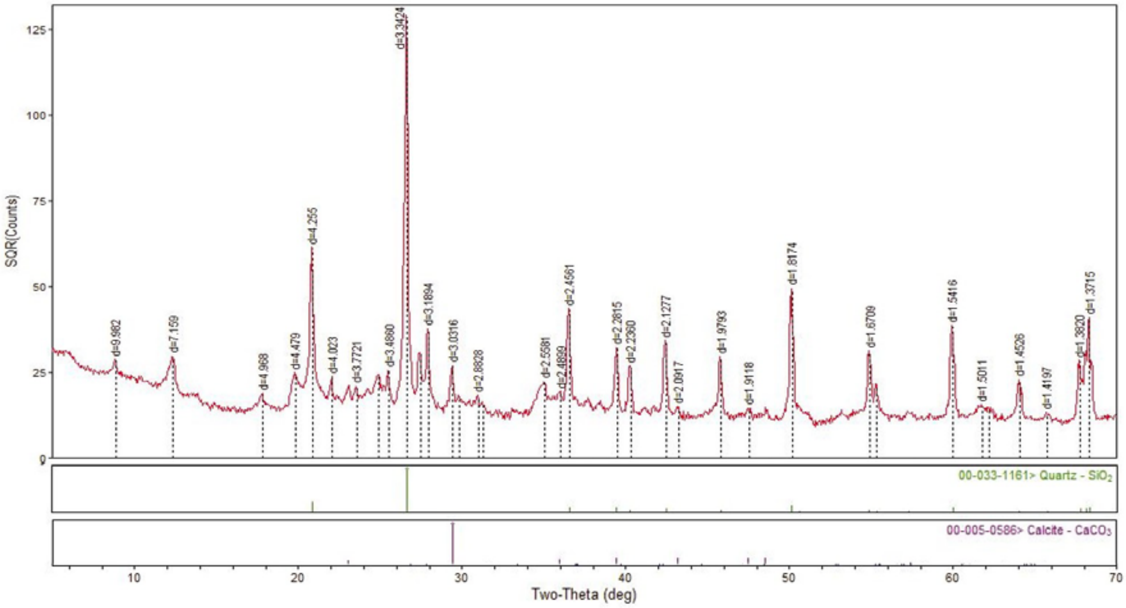


Figure E-10. XRD pattern for BCP A-treated Soil 3

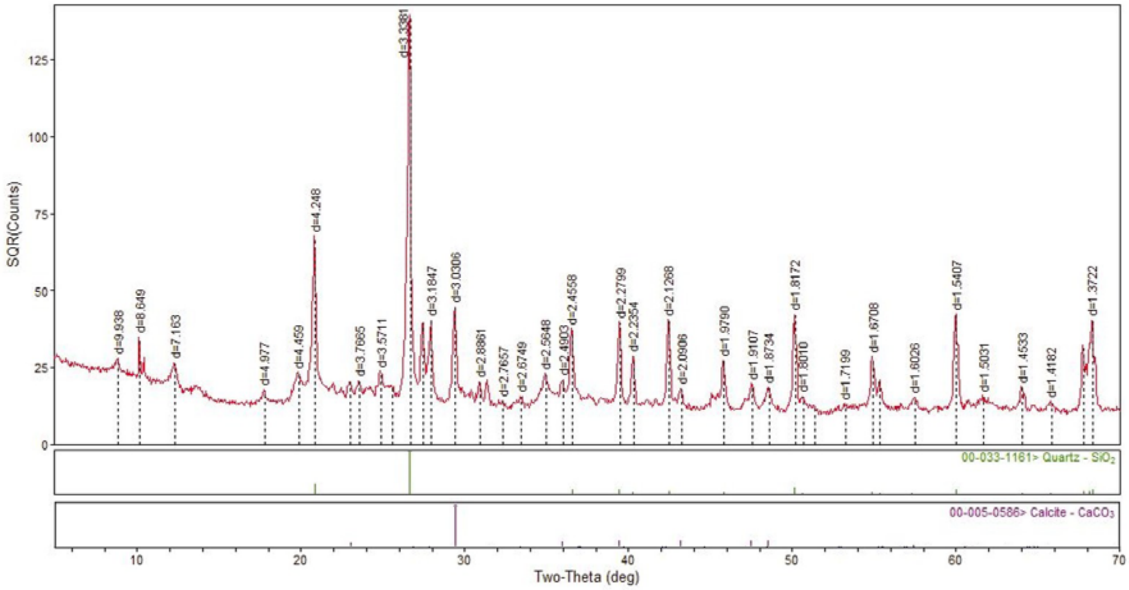


Figure E-11. XRD pattern for BCP B-treated Soil 3

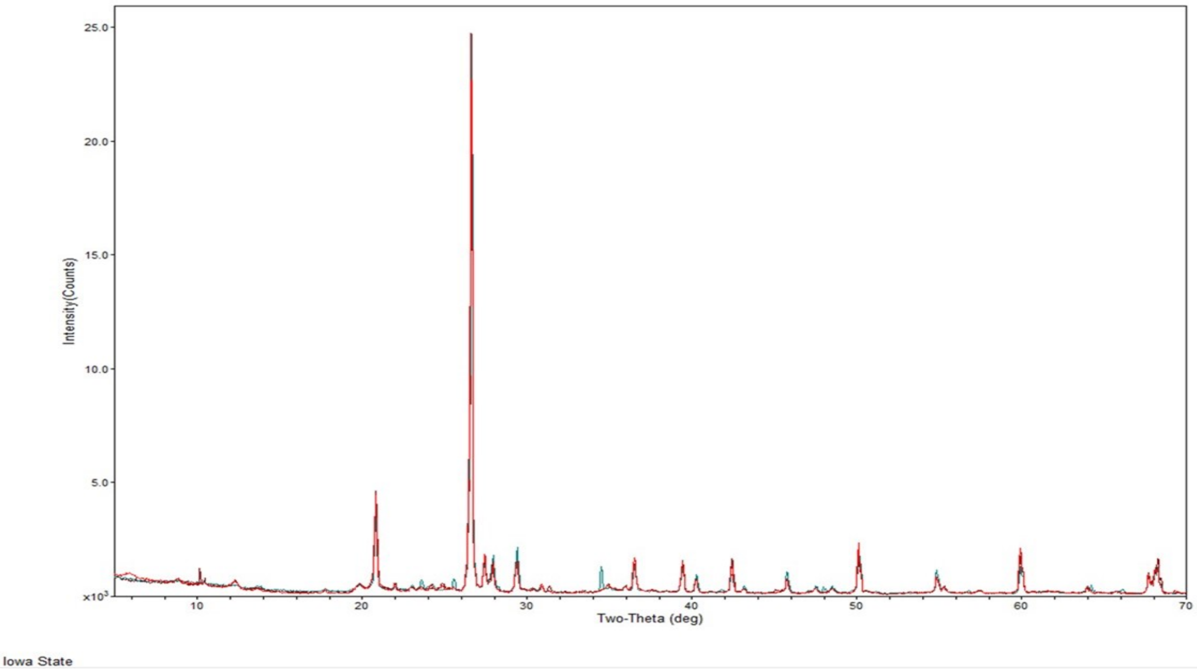


Figure E-12. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 3 samples

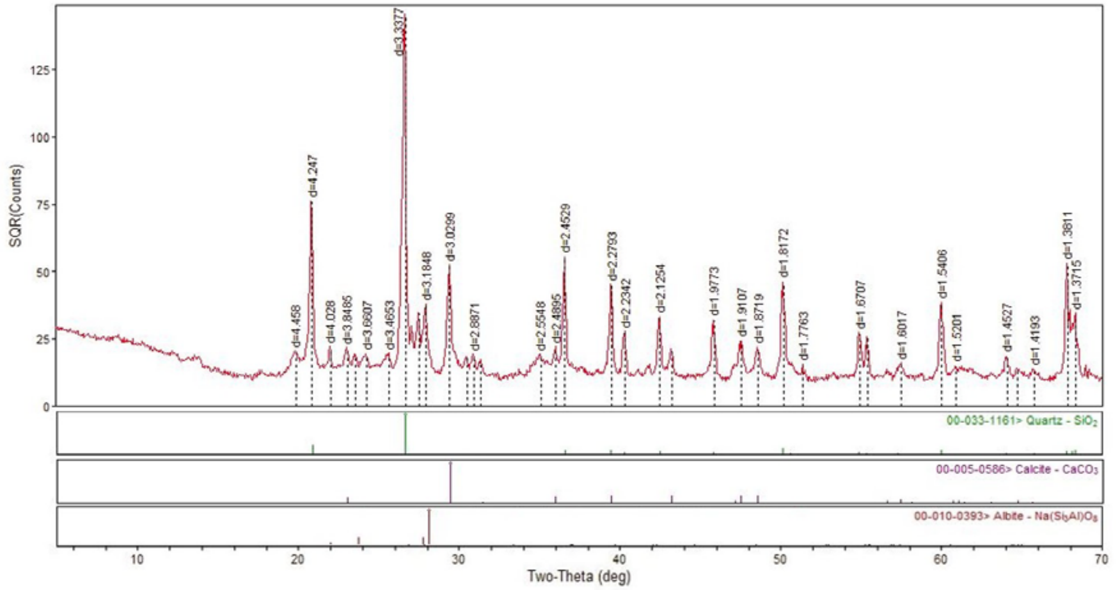


Figure E-13. XRD pattern for untreated Soil 4

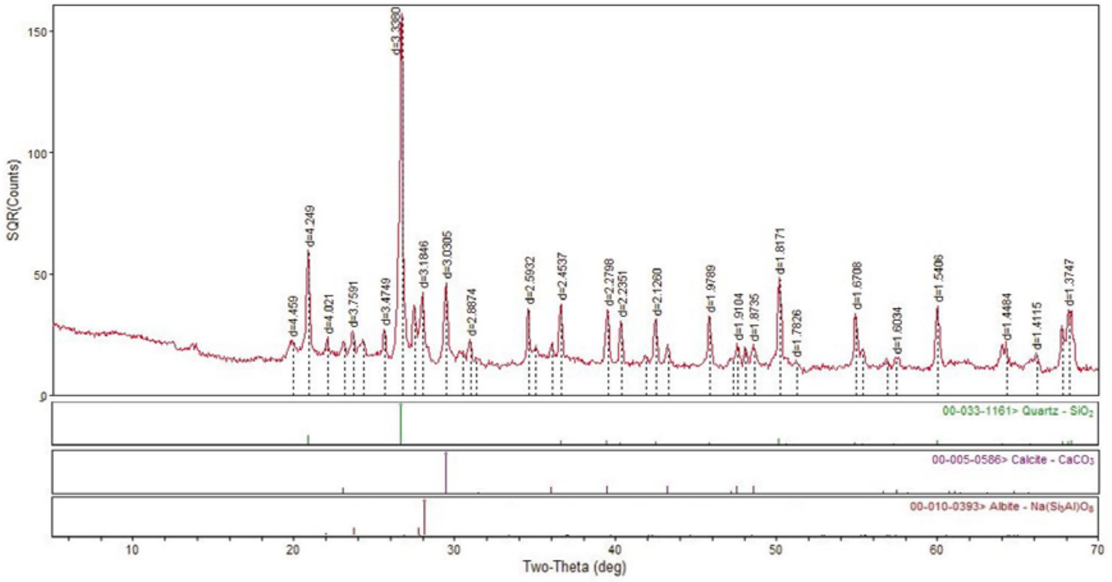


Figure E-14. XRD pattern for BCP A-treated Soil 4

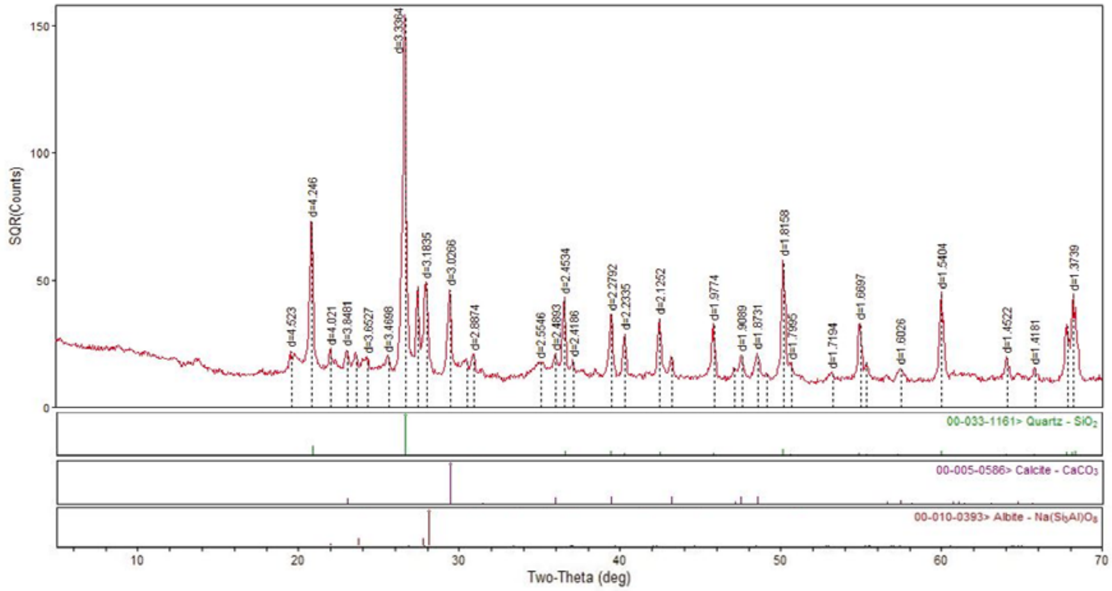


Figure E-15. XRD pattern for BCP B-treated Soil 4

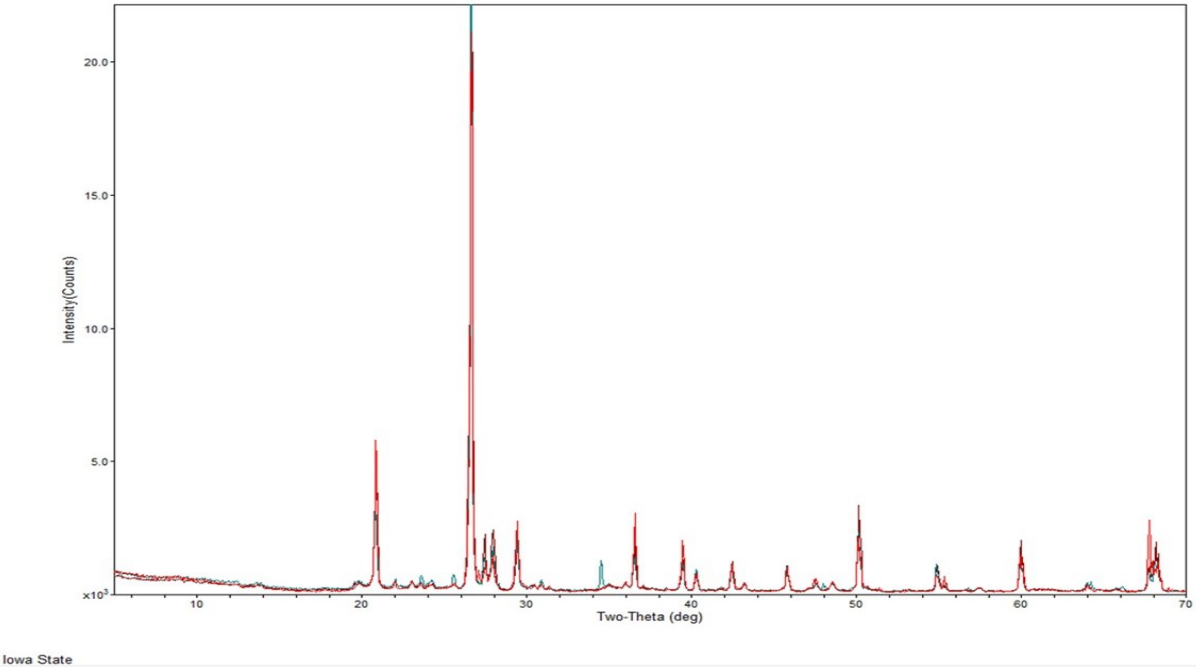


Figure E-16. Overlaid XRD patterns for untreated, BCP A and B treated-Soil 4 samples

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

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 E-2. Identified inorganic materials from XRD for Soil 2 set

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	√	√	√

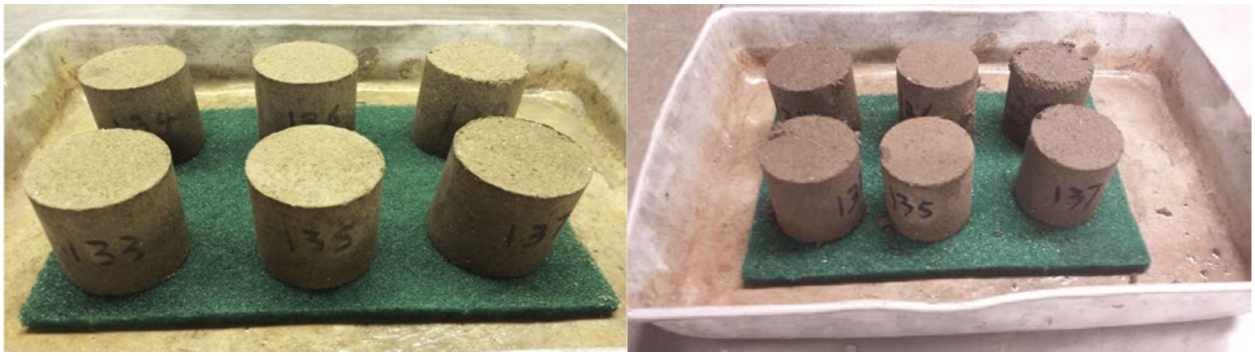
Table E-3. Identified inorganic materials from XRD for Soil 3 set

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 E-3. Identified inorganic materials from XRD for Soil 4 set

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	√	√	√

APPENDIX F: IMAGES OF FREEZE-THAW DURABILITY TEST



(a) 1st cycle

(b) 2nd cycle

(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

(f) 6th cycle

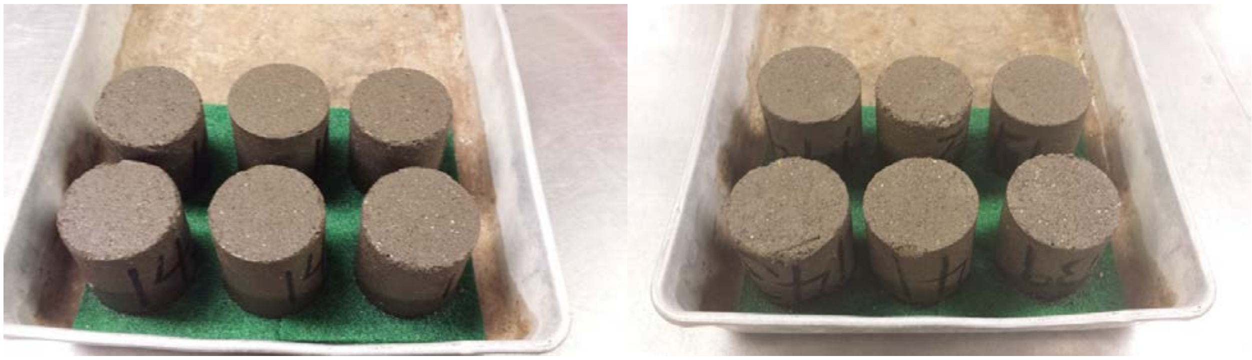
Figure F-1. Images of 1-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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

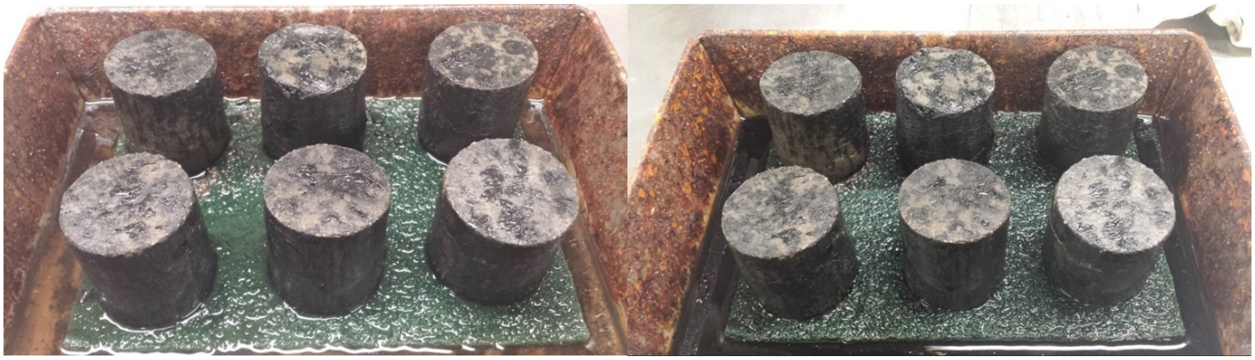
Figure F-2. Images of 7-day cured and untreated Soil 1 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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 F-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

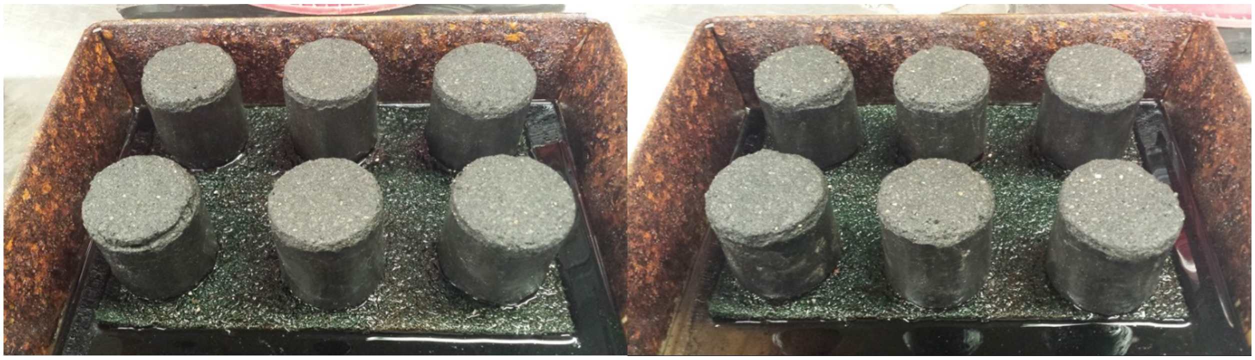
(k) 11th cycle

(l) 12th cycle

Figure F-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 F-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

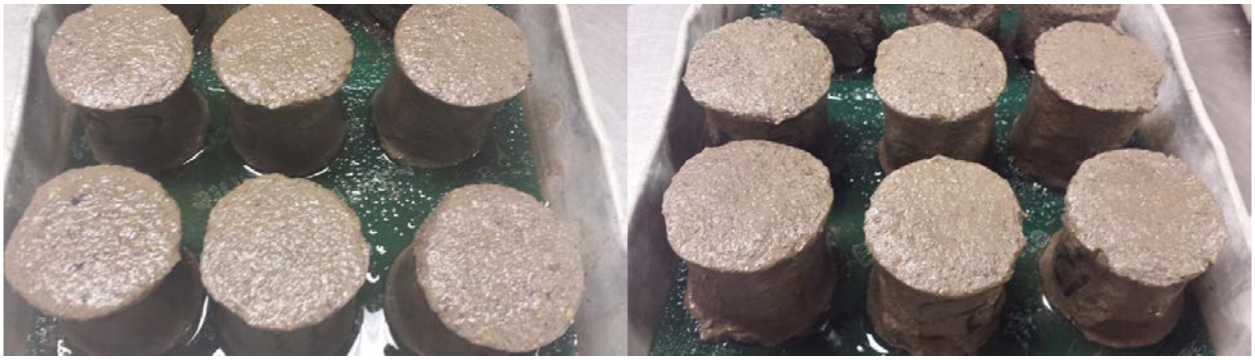
(i) 9th cycle (j) 10th cycle

(k) 11th cycle (l) 12th cycle

Figure F-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

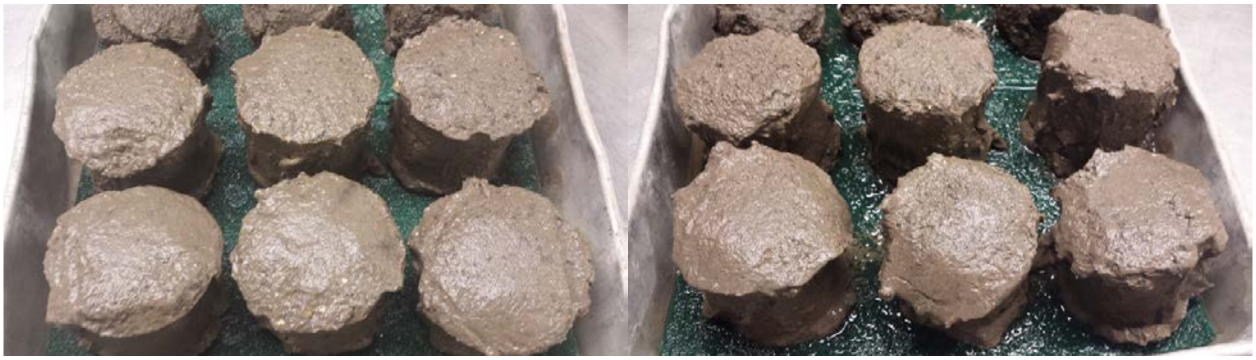
(c) 3rd cycle (d) 4th cycle



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

Figure F-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 F-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

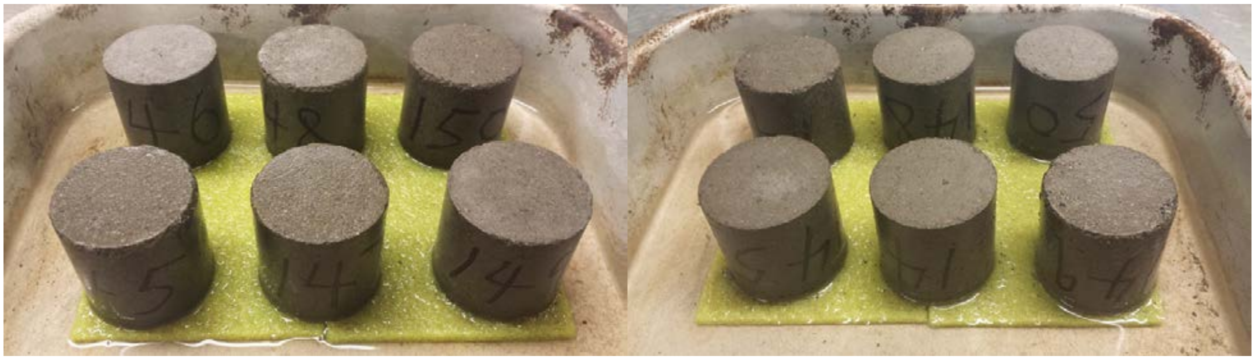
Figure F-6. Images of 7-day cured and 12% of BCP B-treated Soil 1 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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

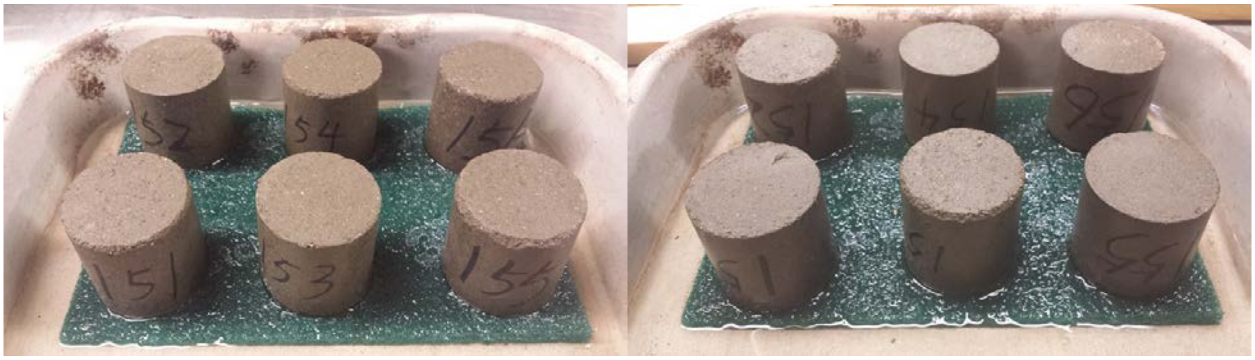
Figure F-7. Images of 1-day cured and 3% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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

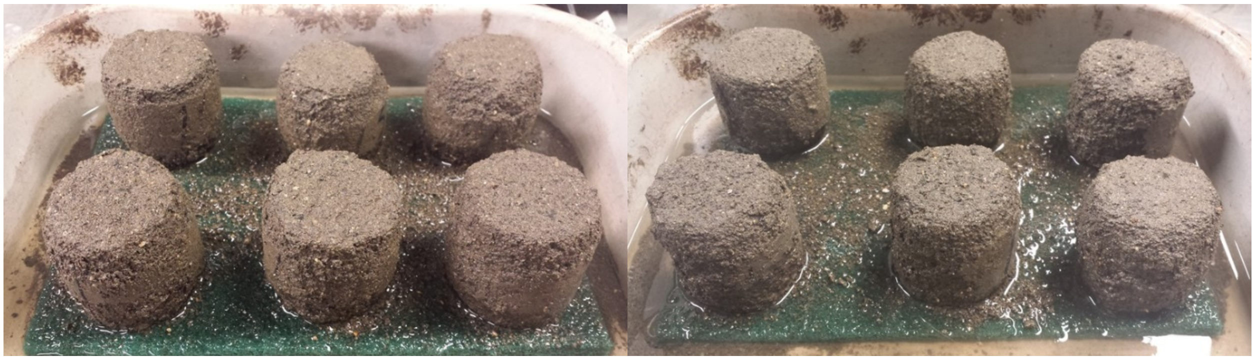
(c) 3rd cycle (d) 4th cycle

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

Figure F-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

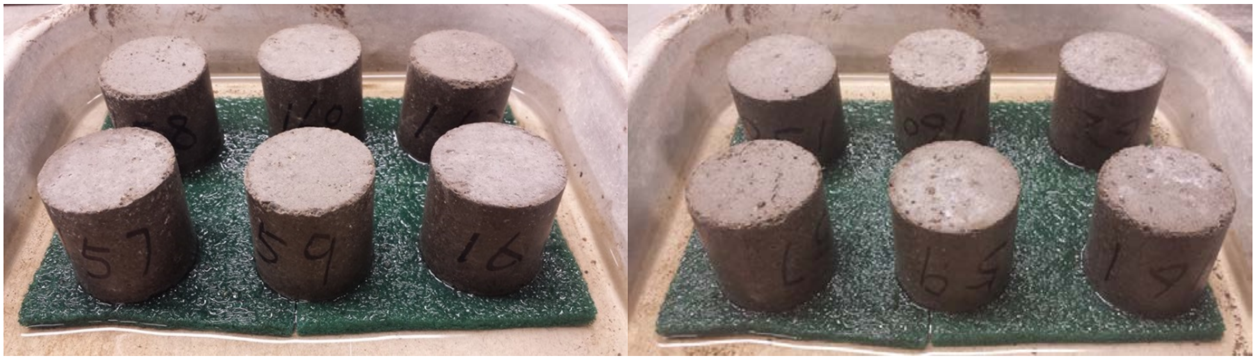
(i) 9th cycle (j) 10th cycle



(k) 11th cycle (l) 12th cycle

Figure F-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

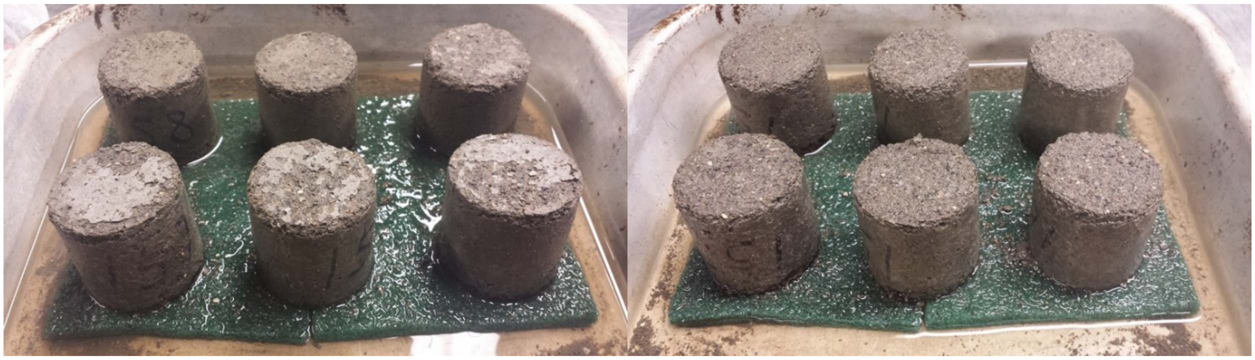
Figure F-9. Images of 1-day cured and 6% of cement-treated Soil 1 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

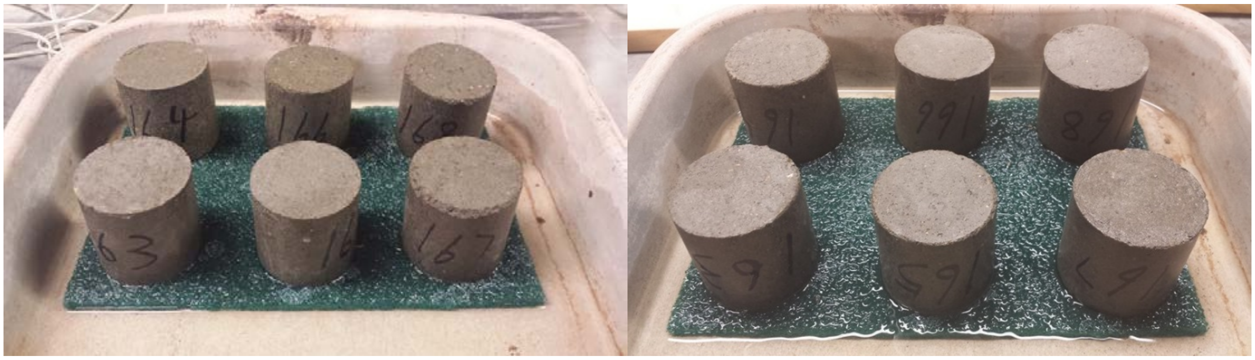
(j) 10th cycle



(k) 11th cycle

(l) 12th cycle

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

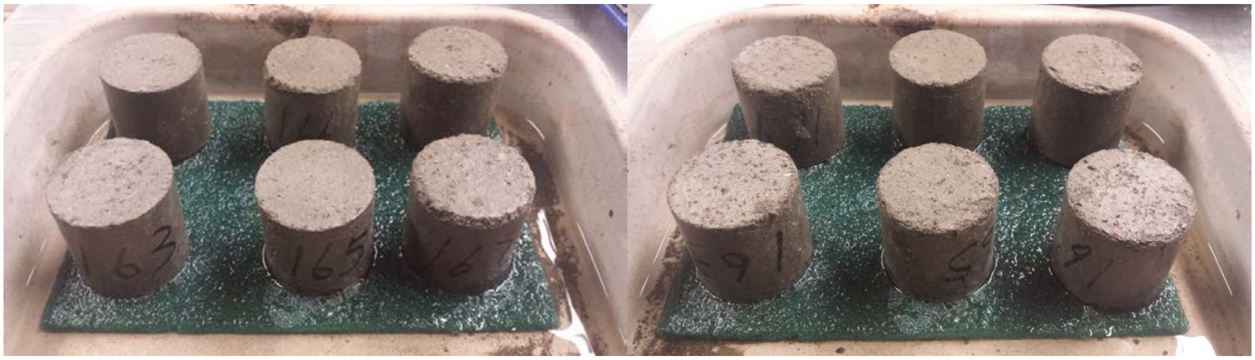


(a) 1st cycle (b) 2nd cycle

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

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

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

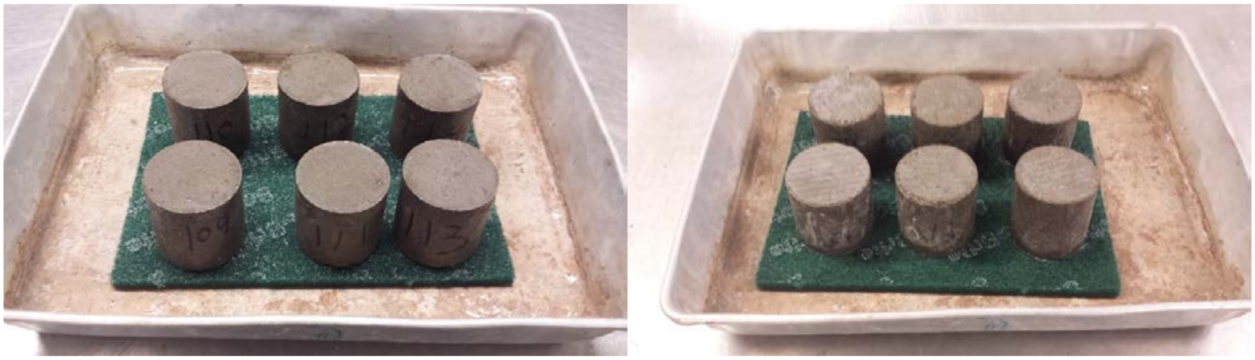


(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

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



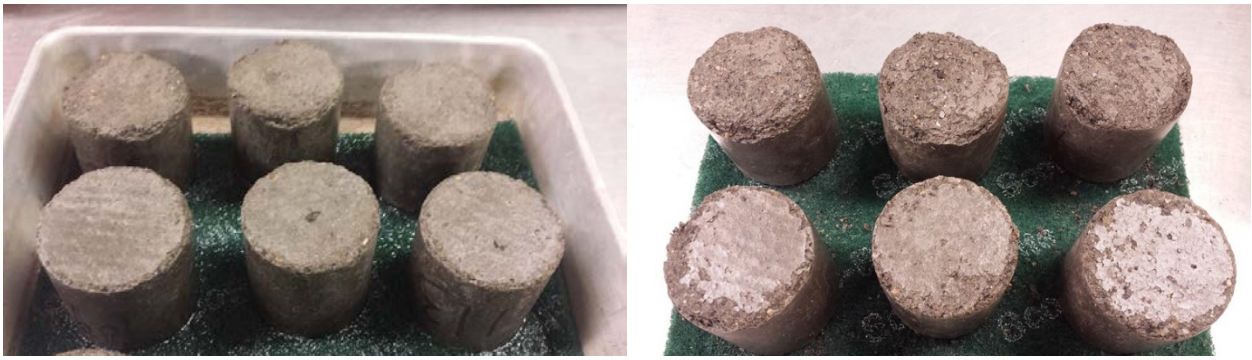
(a) 1st cycle (b) 2nd cycle

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

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

Figure F-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 F-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 F-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 F-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 F-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 F-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 F-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 F-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 F-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 F-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

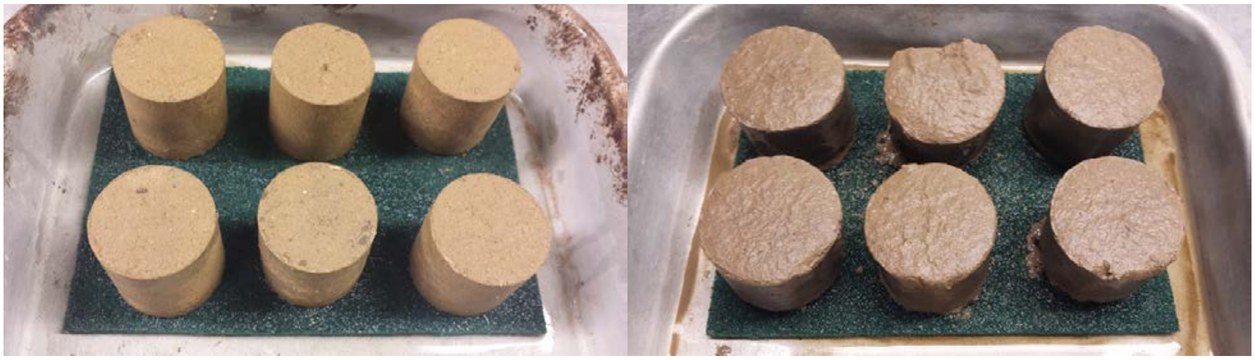
Figure F-16. Images of 7-day cured and 12% of BCP A-treated Soil 2 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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

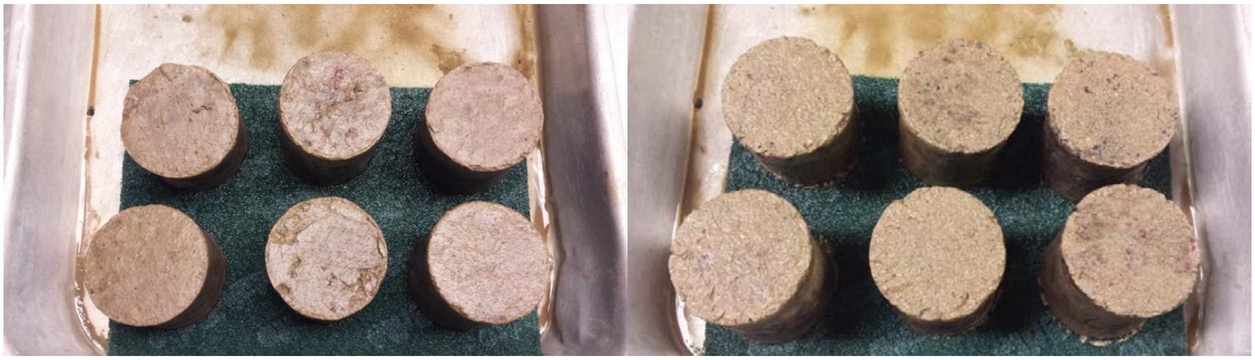
Figure F-17. Images of 1-day cured and 12% of BCP B-treated Soil 2 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

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

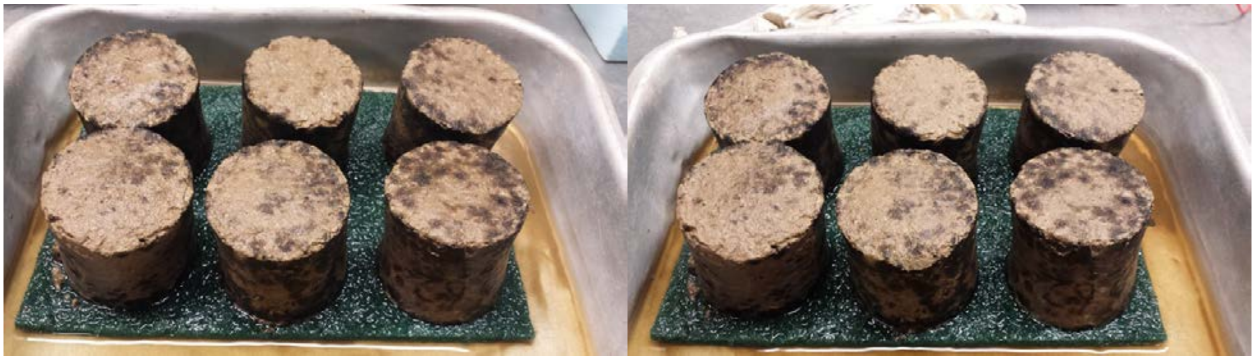


(a) 1st cycle (b) 2nd cycle

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

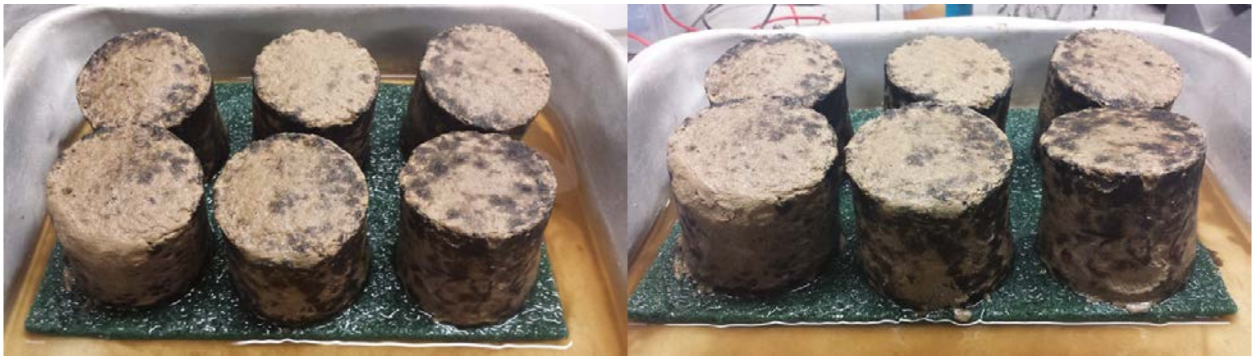
(e) 5th cycle (f) 6th cycle

Figure F-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 F-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 F-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

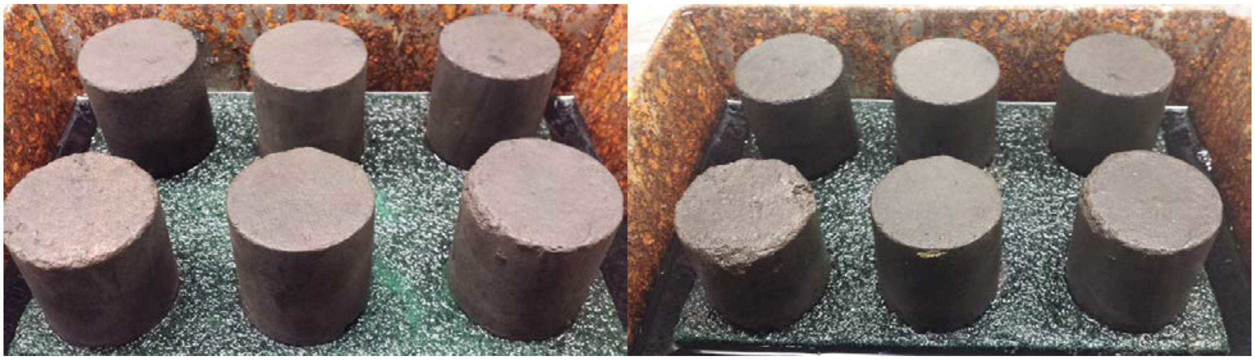
(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure F-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

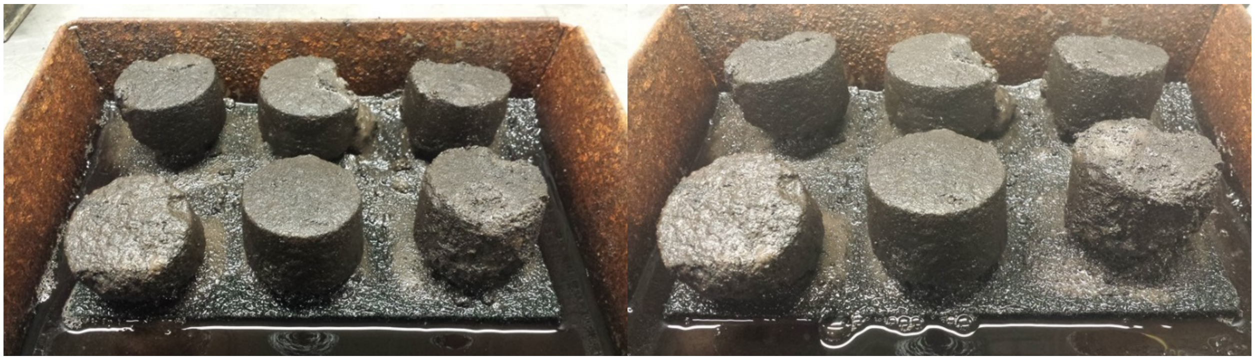
(c) 3rd cycle (d) 4th cycle

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

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

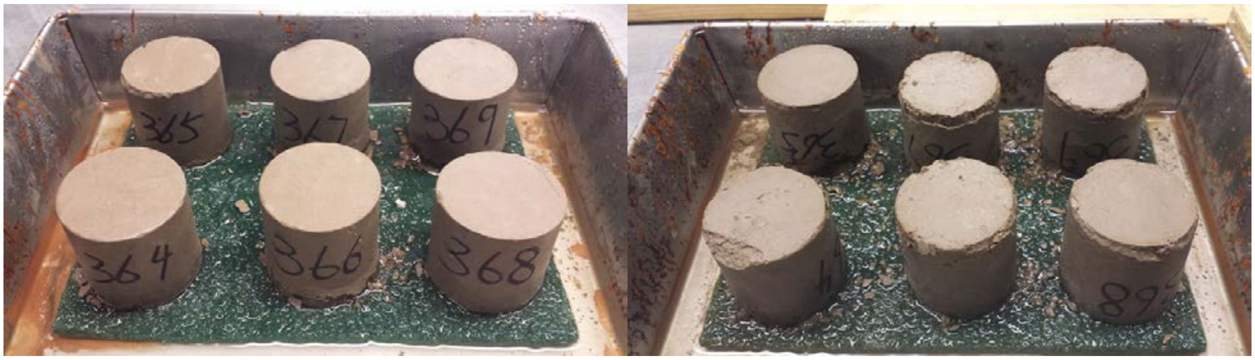
(g) 7th cycle (h) 8th cycle

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



(k) 11th cycle (l) 12th cycle

Figure F-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 F-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 F-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

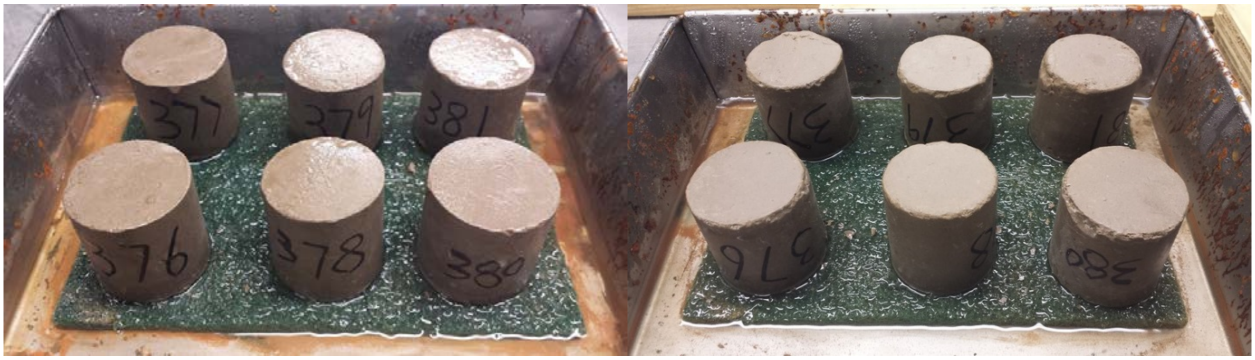
Figure F-22. Images of 7-day cured and 3% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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 F-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 F-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 F-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

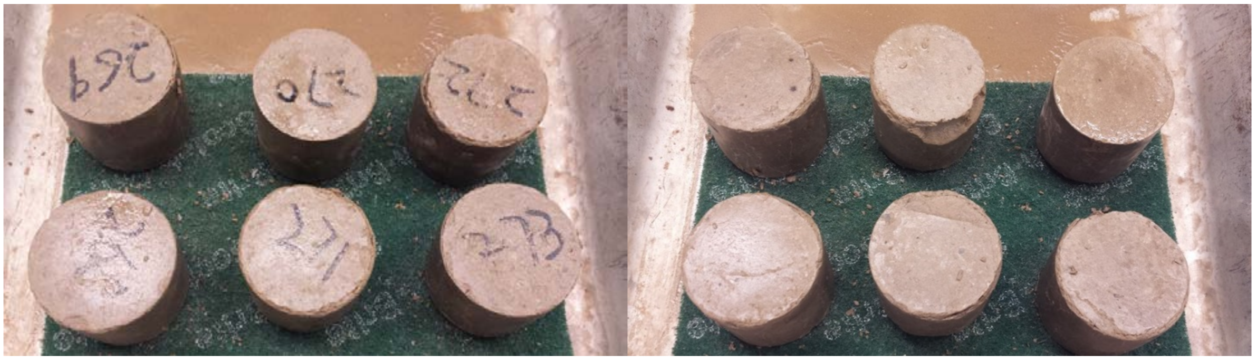
Figure F-24 (Continued). Images of 7-day cured and 6% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test.

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

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

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

Figure F-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 F-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

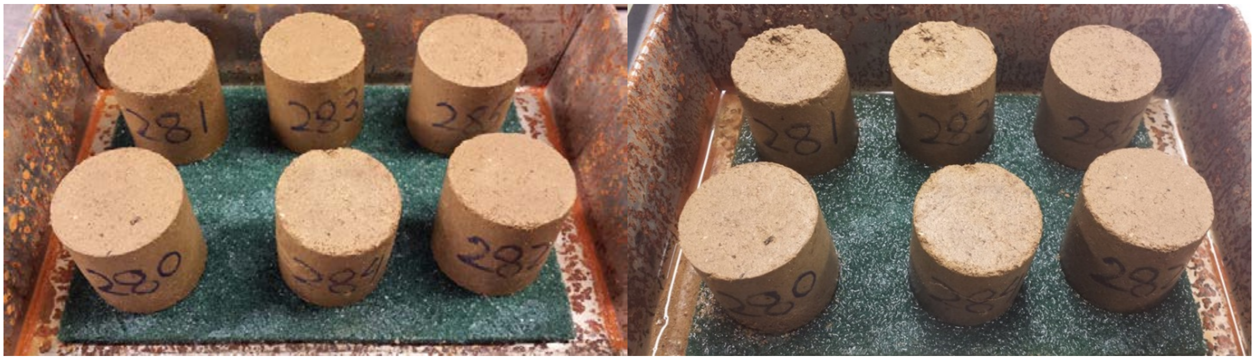
Figure F-26. Images of 7-day cured and 12% of cement-treated Soil 2 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

(k) 11th cycle (l) 12th cycle

Figure F-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 F-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

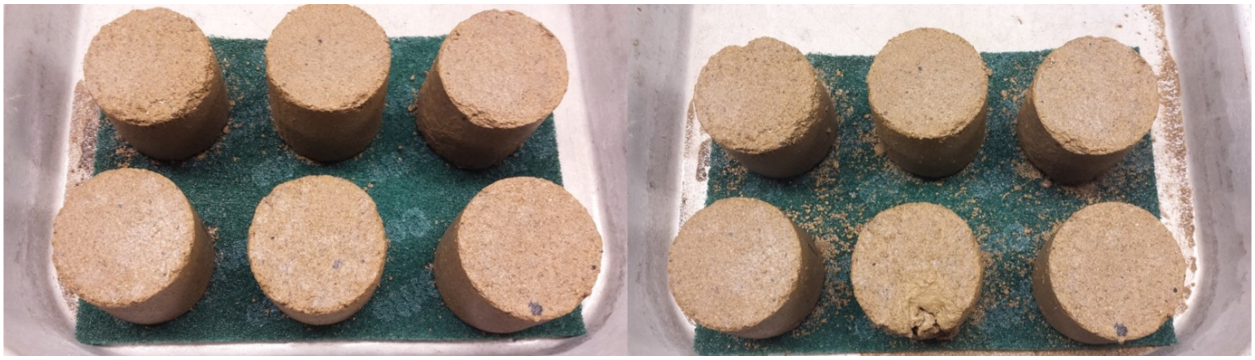
(j) 10th cycle

(k) 11th cycle

(l) 12th cycle

Figure F-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 F-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 F-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

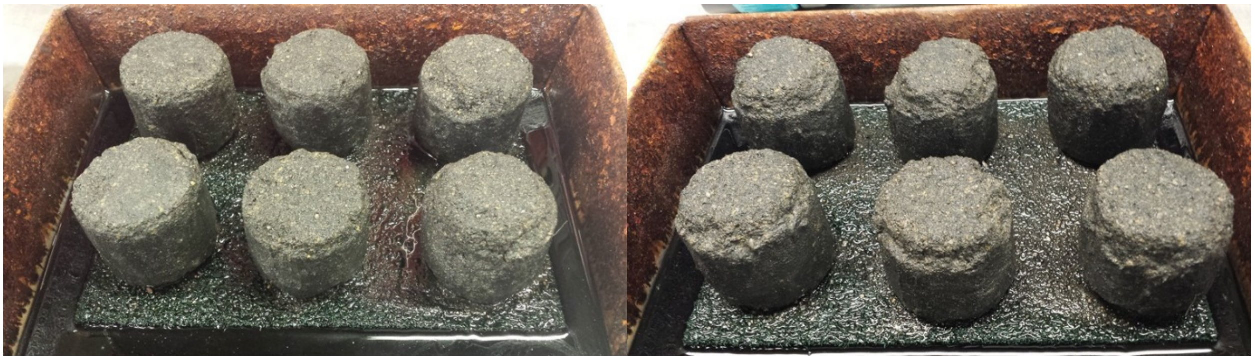
(c) 3rd cycle

(d) 4th cycle

(e) 5th cycle

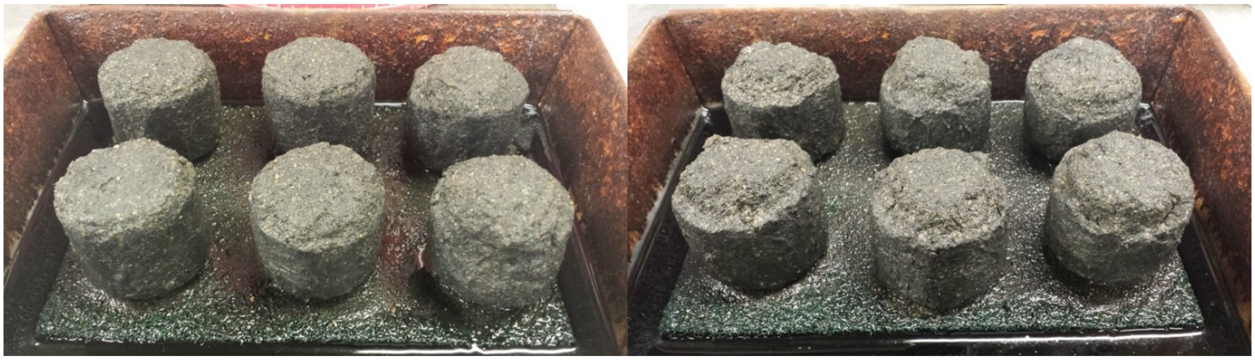
(f) 6th cycle

Figure F-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



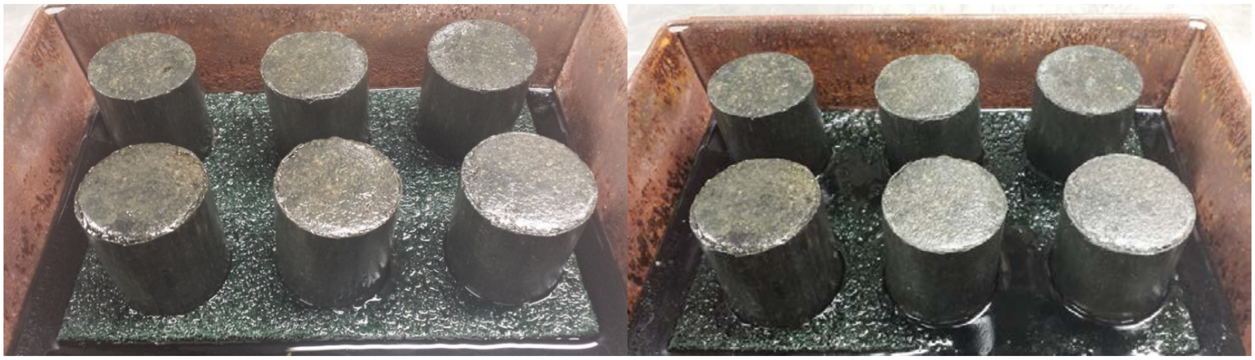
(i) 9th cycle

(j) 10th cycle

(k) 11th cycle

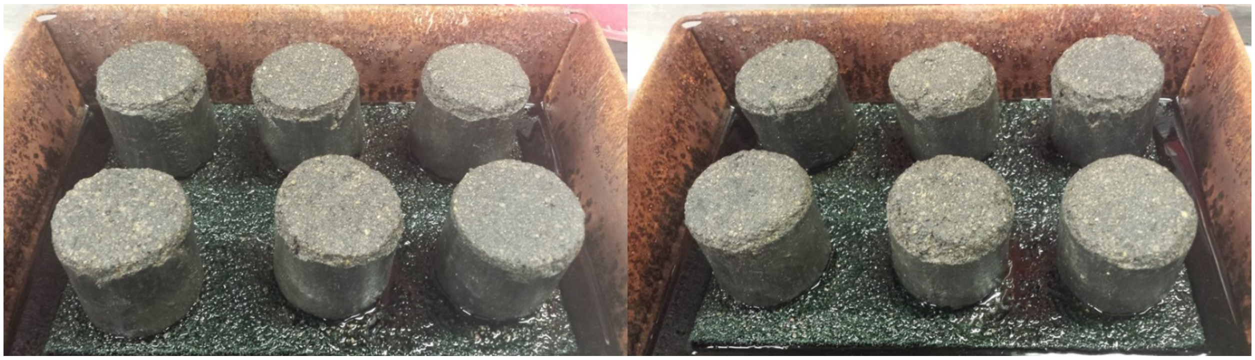
(l) 12th cycle

Figure F-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

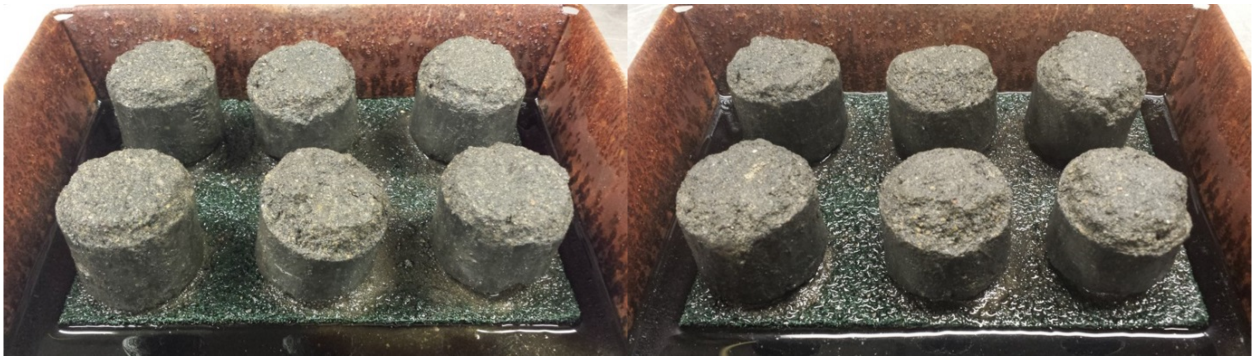
(c) 3rd cycle (d) 4th cycle



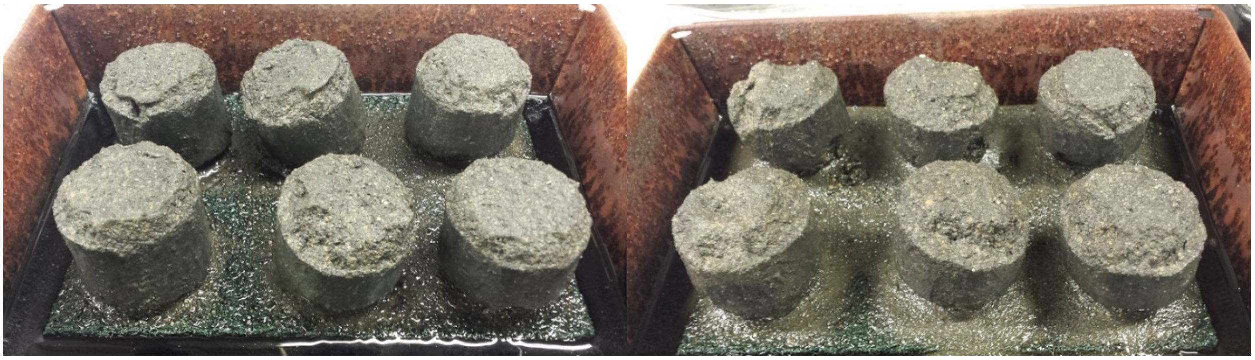
(e) 5th cycle (f) 6th cycle

Figure F-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

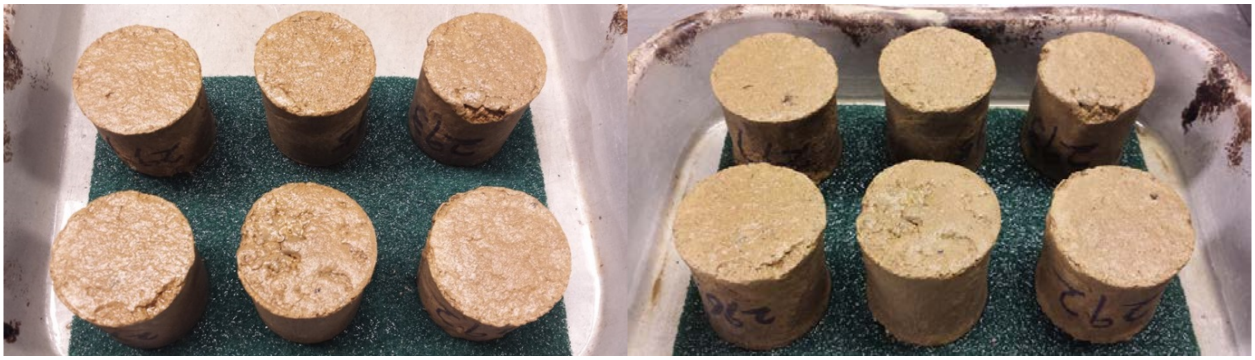


(i) 9th cycle (j) 10th cycle

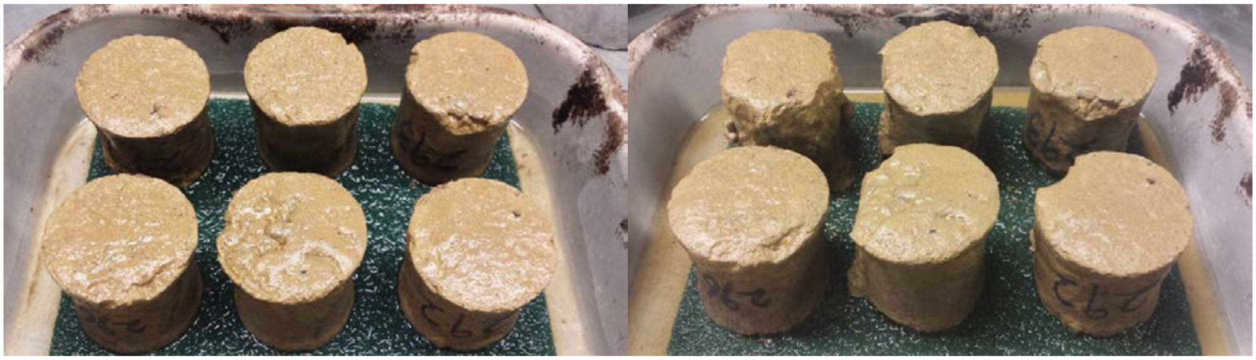


(k) 11th cycle (l) 12th cycle

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



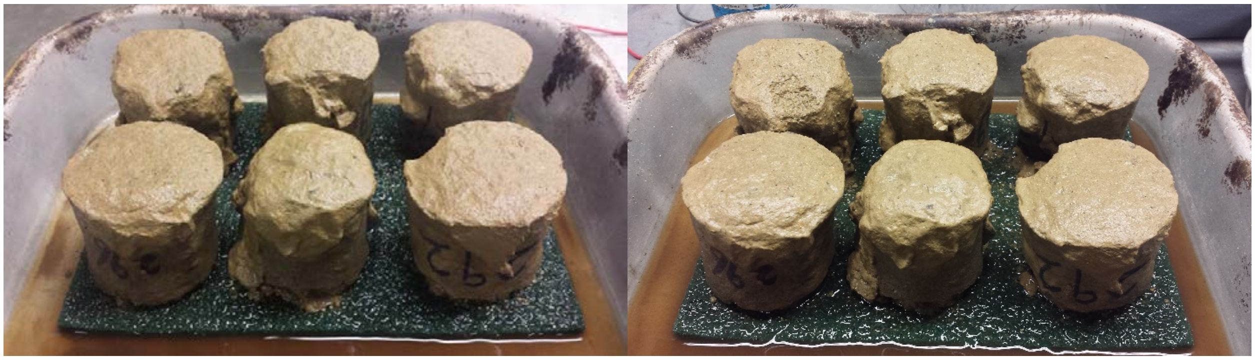
(a) 1st cycle (b) 2nd cycle



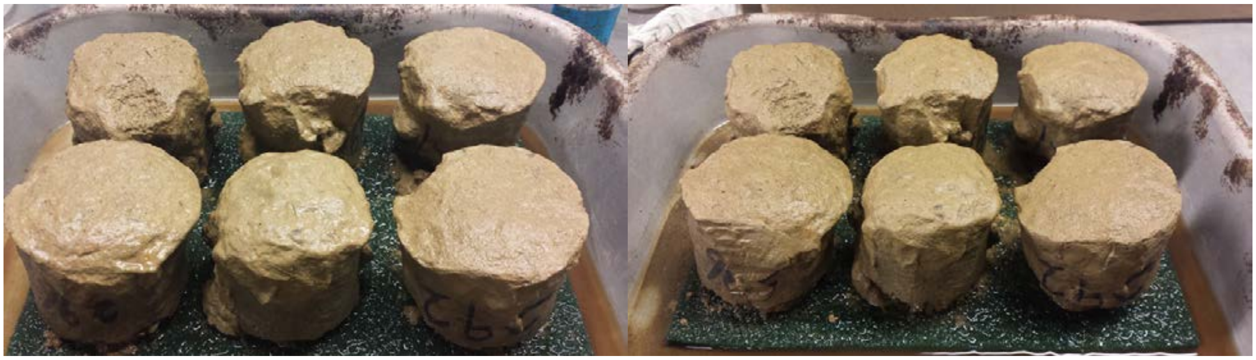
(c) 3rd cycle (d) 4th cycle

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

Figure F-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 F-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 F-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 F-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 F-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 F-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

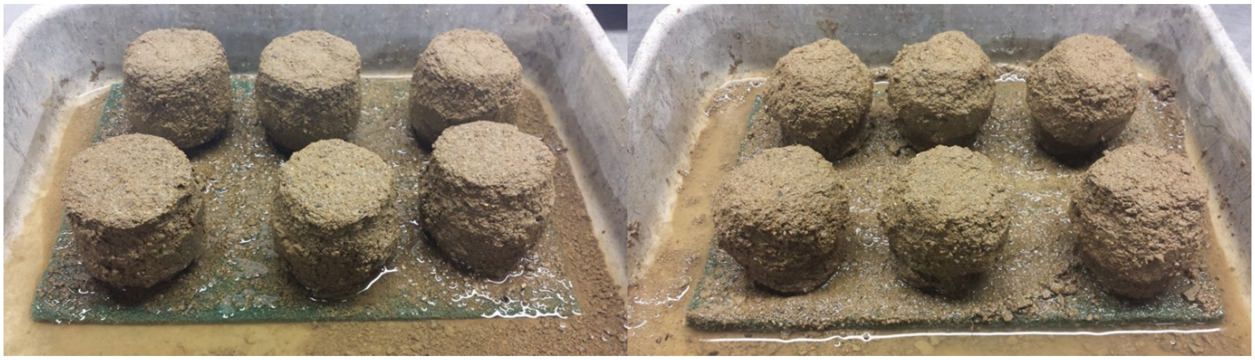
Figure F-34. Images of 7-day cured and 3% of cement-treated Soil 3 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle

(h) 8th cycle

(i) 9th cycle

(j) 10th cycle



(k) 11th cycle

(l) 12th cycle

Figure F-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 F-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 F-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 F-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 F-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

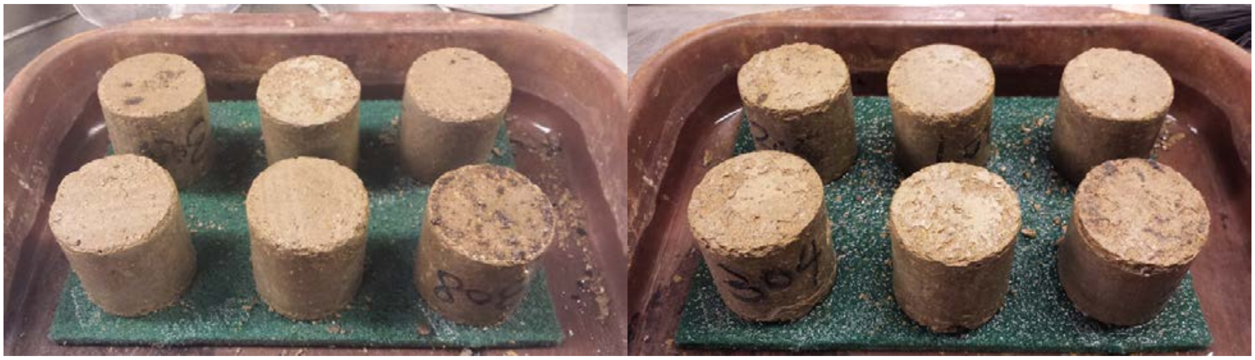
(c) 3rd cycle (d) 4th cycle

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

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

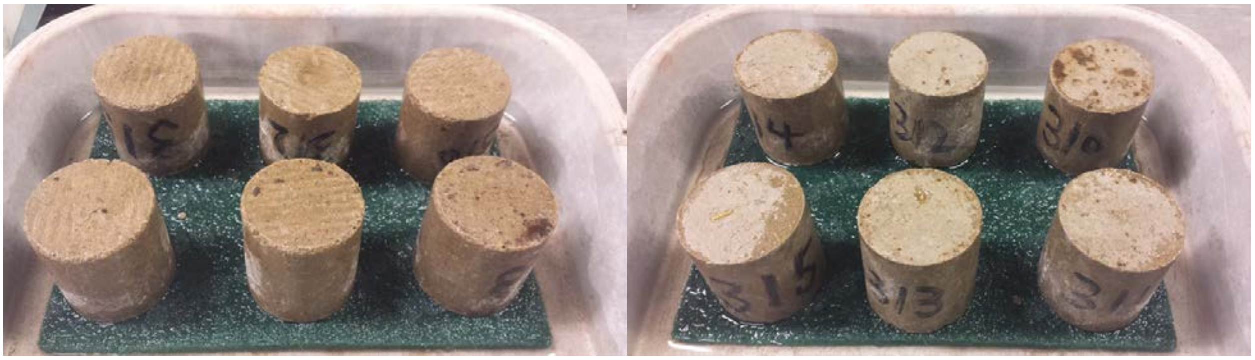
(g) 7th cycle (h) 8th cycle

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

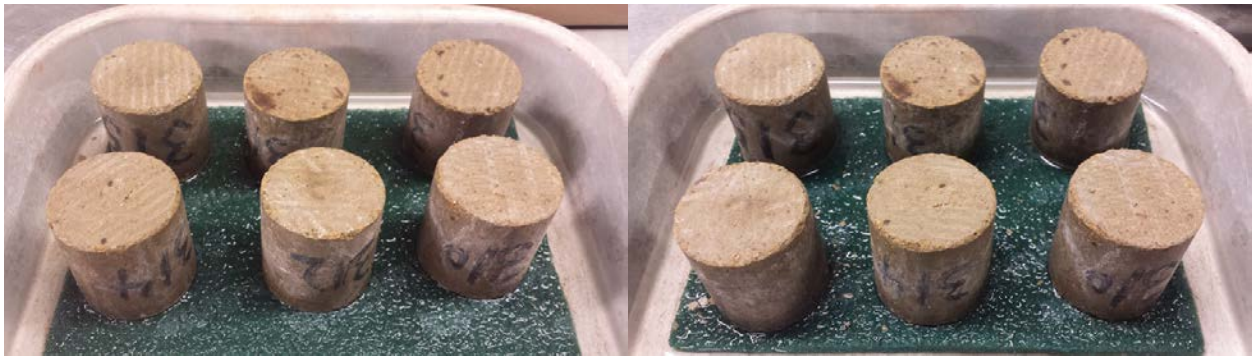


(k) 11th cycle (l) 12th cycle

Figure F-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

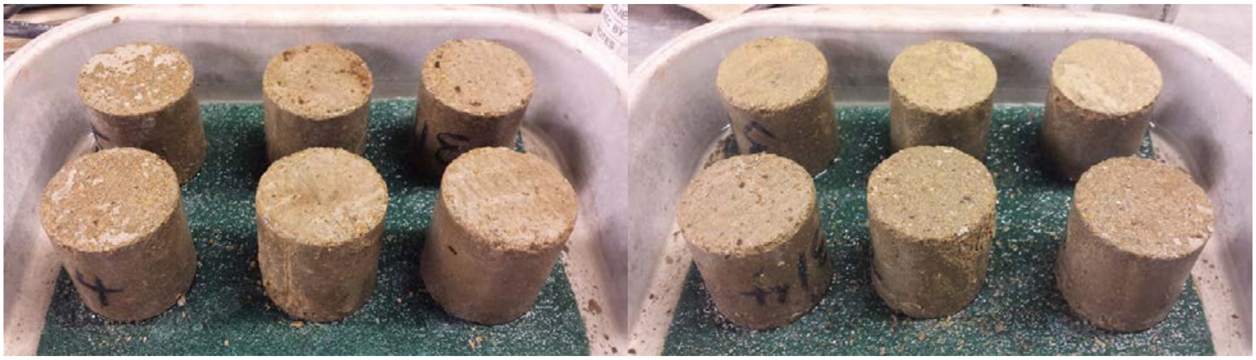


(c) 3rd cycle (d) 4th cycle

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

Figure F-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 F-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

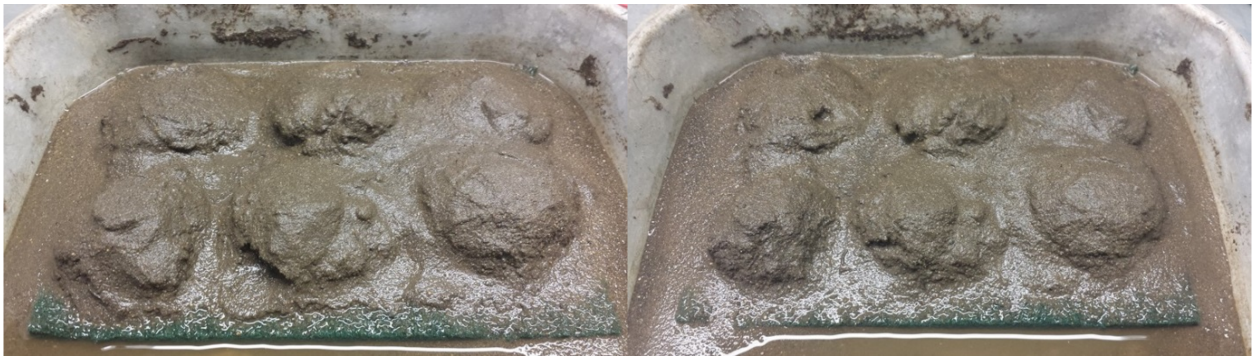
(e) 5th cycle

(f) 6th cycle

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

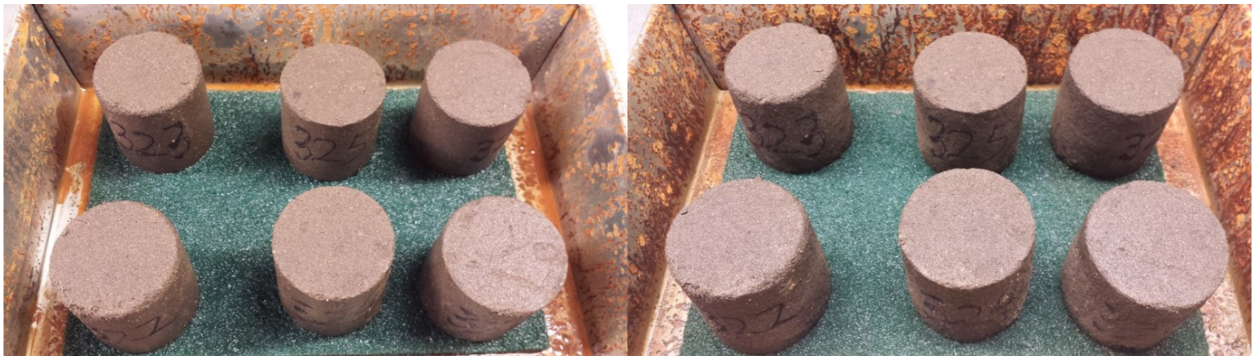
(g) 7th cycle (h) 8th cycle

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



(k) 11th cycle (l) 12th cycle

Figure F-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

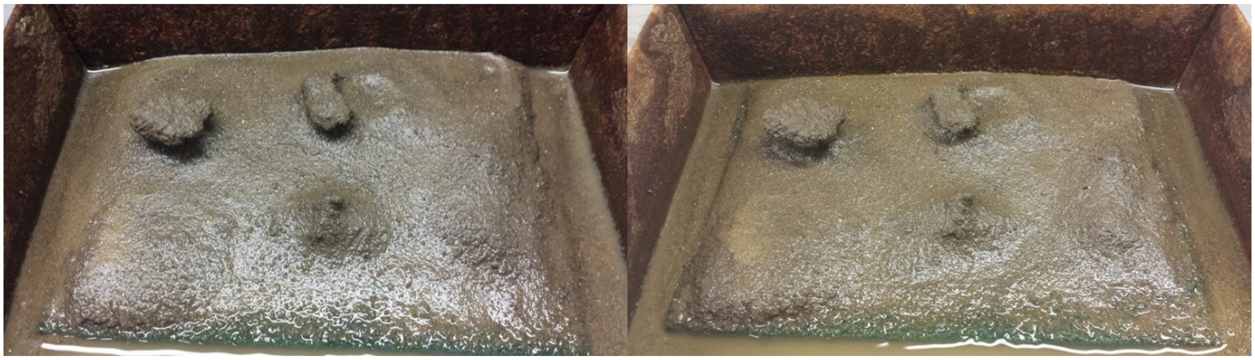
(c) 3rd cycle (d) 4th cycle

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

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

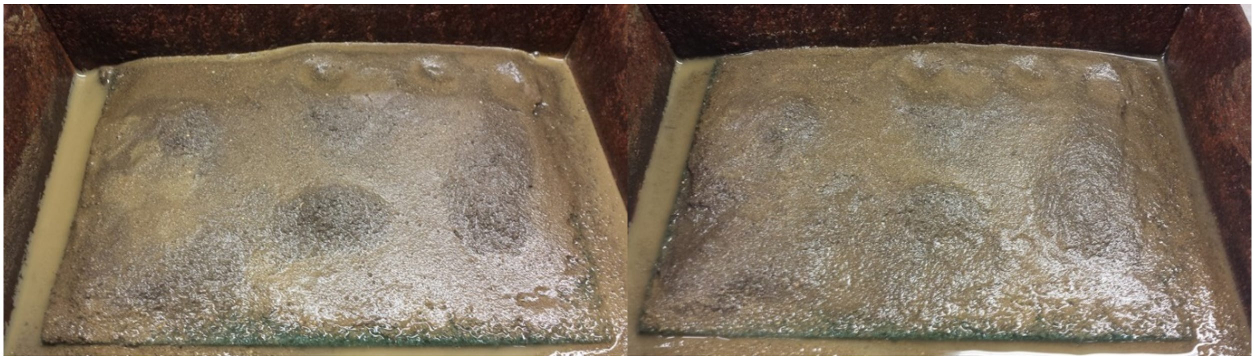
(g) 7th cycle

(h) 8th cycle



(i) 9th cycle

(j) 10th cycle

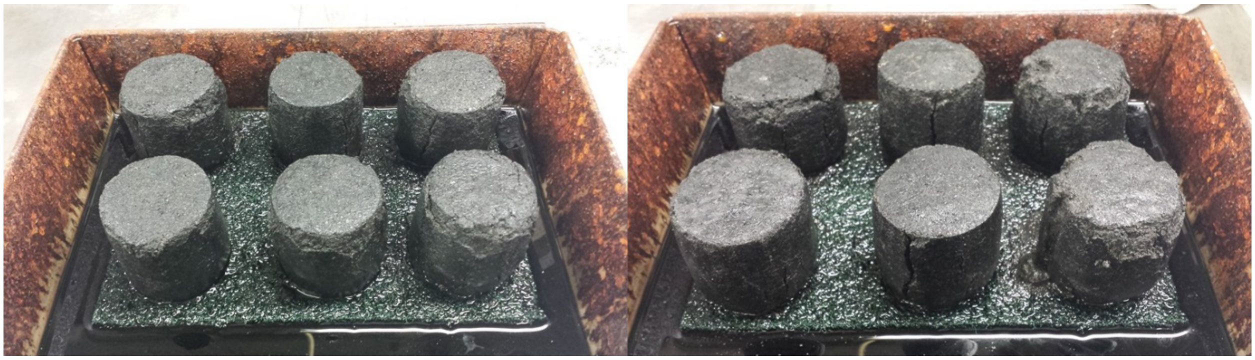


(k) 11th cycle

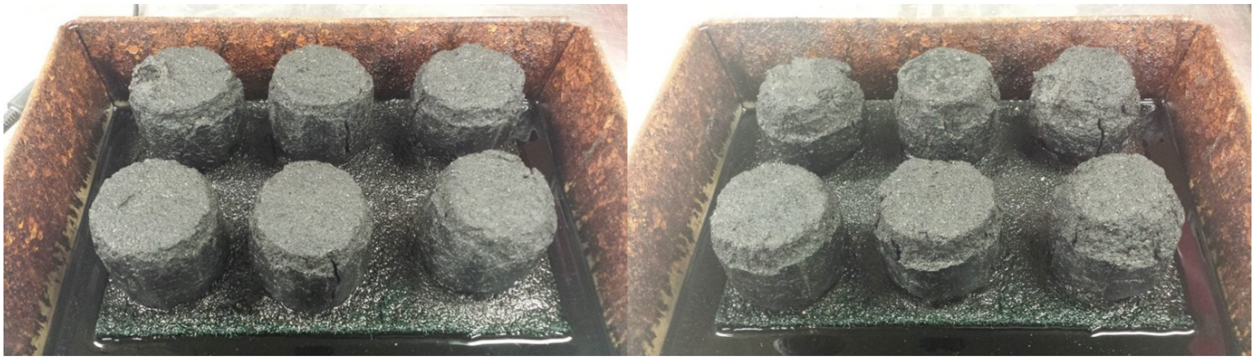
(l) 12th cycle

Figure F-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



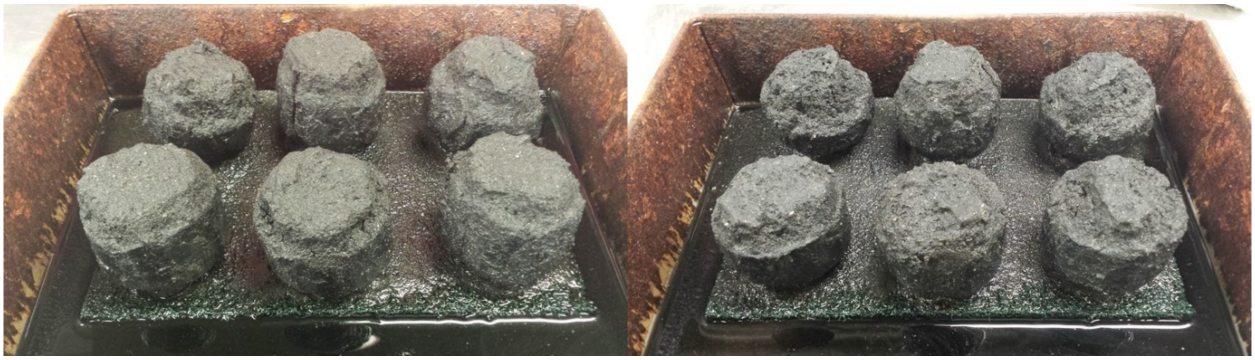
(c) 3rd cycle (d) 4th cycle



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

Figure F-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 F-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

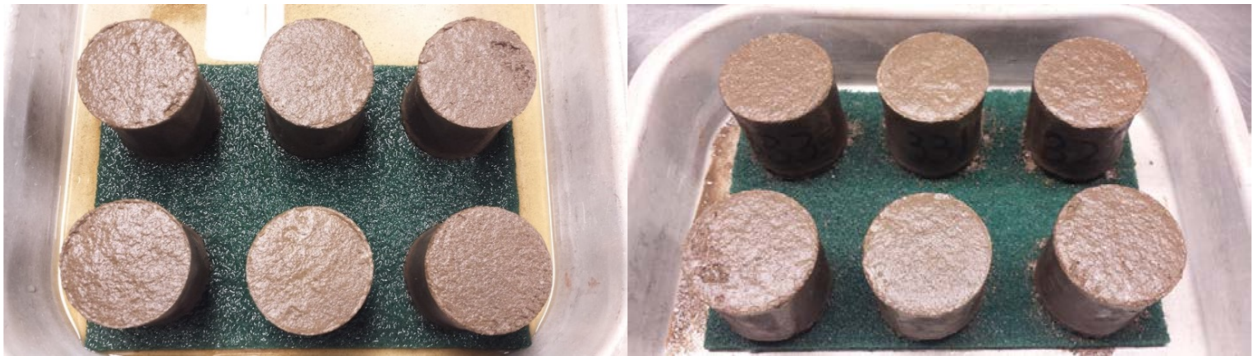
Figure F-42. Images of 7-day cured and 12% of BCP A-treated Soil 4 for 12 cycles of freeze-thaw durability test.

(g) 7th cycle (h) 8th cycle

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

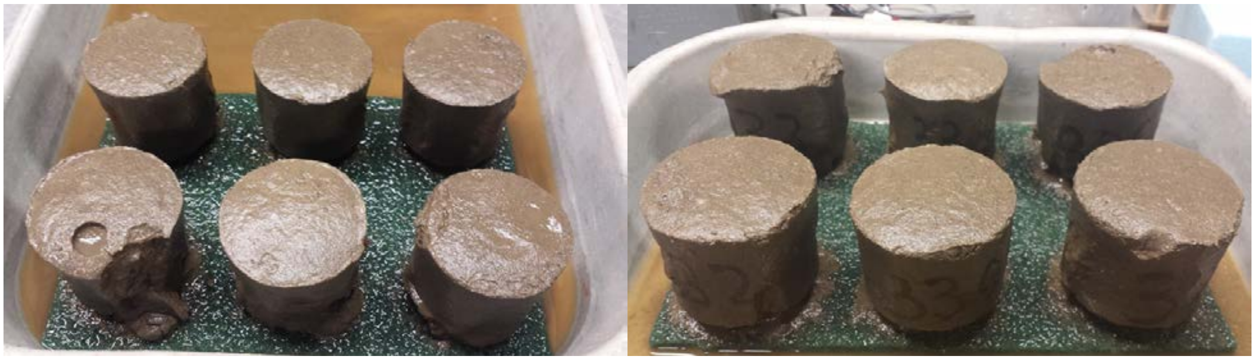
(k) 11th cycle (l) 12th cycle

Figure F-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 F-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

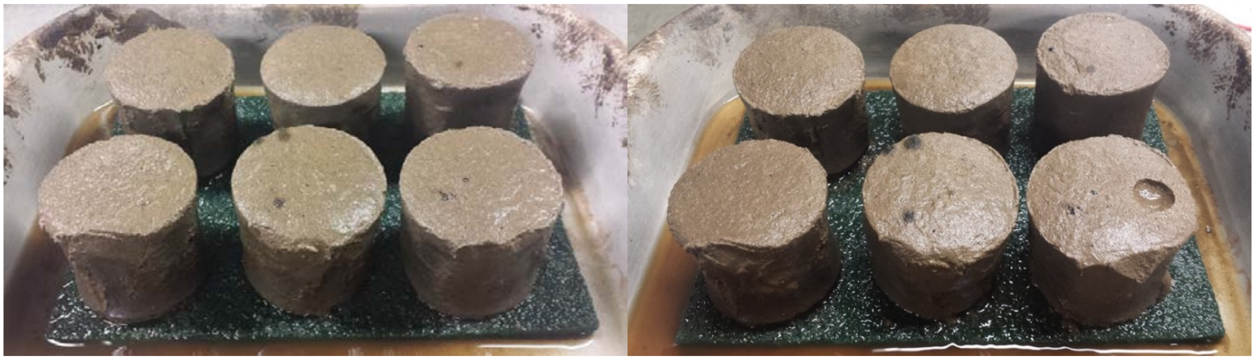
(i) 9th cycle (j) 10th cycle

(k) 11th cycle (l) 12th cycle

Figure F-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

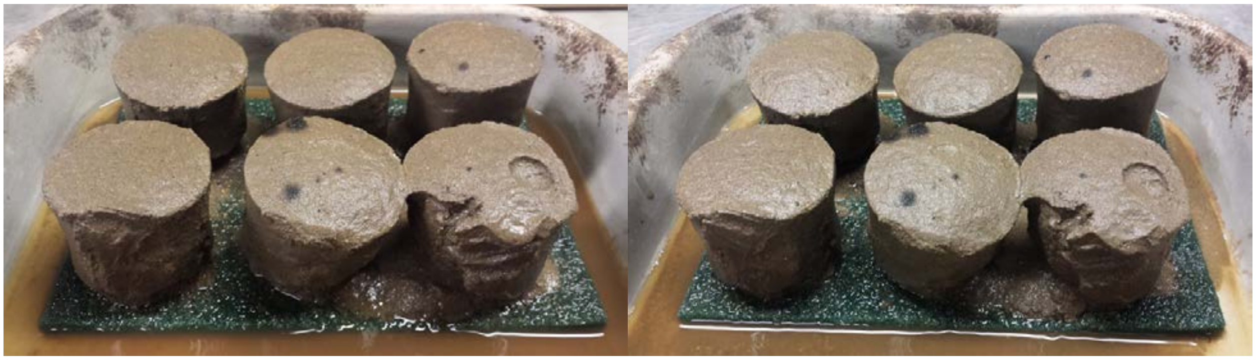
(c) 3rd cycle (d) 4th cycle



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

Figure F-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



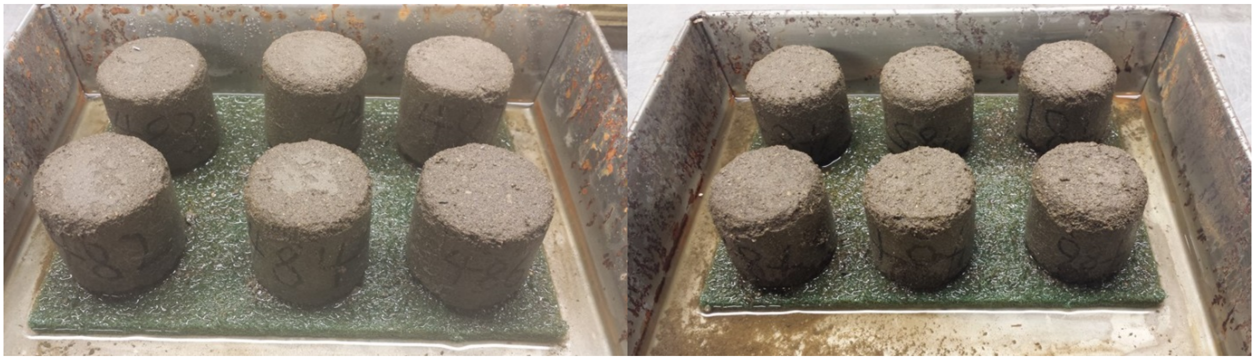
(i) 9th cycle (j) 10th cycle

(k) 11th cycle (l) 12th cycle

Figure F-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 F-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 F-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 F-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 F-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 F-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 F-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 F-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 F-48 (Continued). Images of 7-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 F-49. Images of 1-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

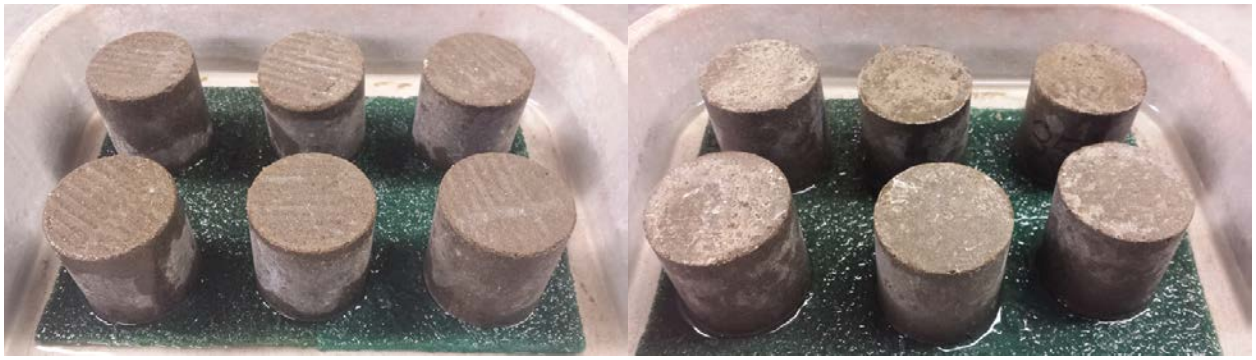
(j) 10th cycle

(k) 11th cycle

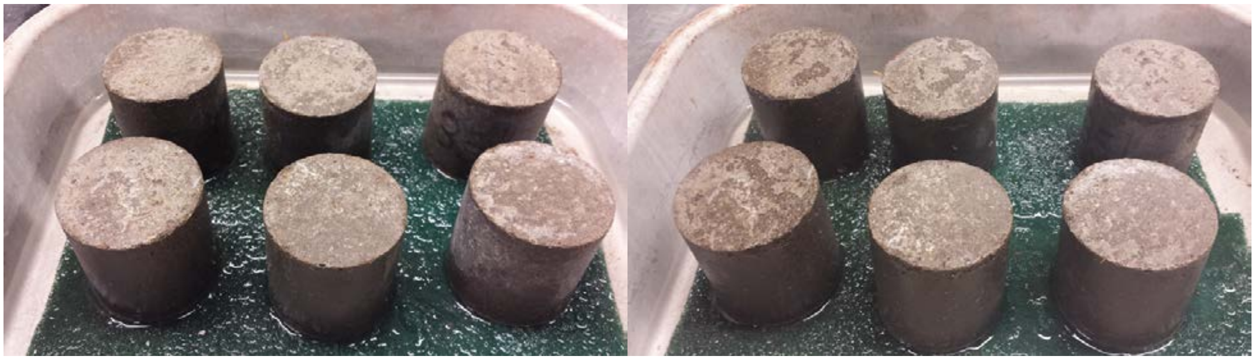
(l) 12th cycle

Figure F-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



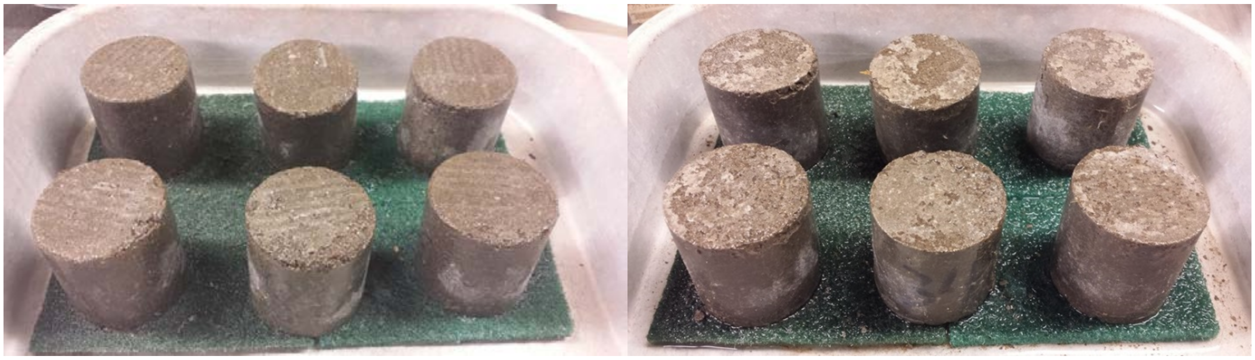
(c) 3rd cycle (d) 4th cycle



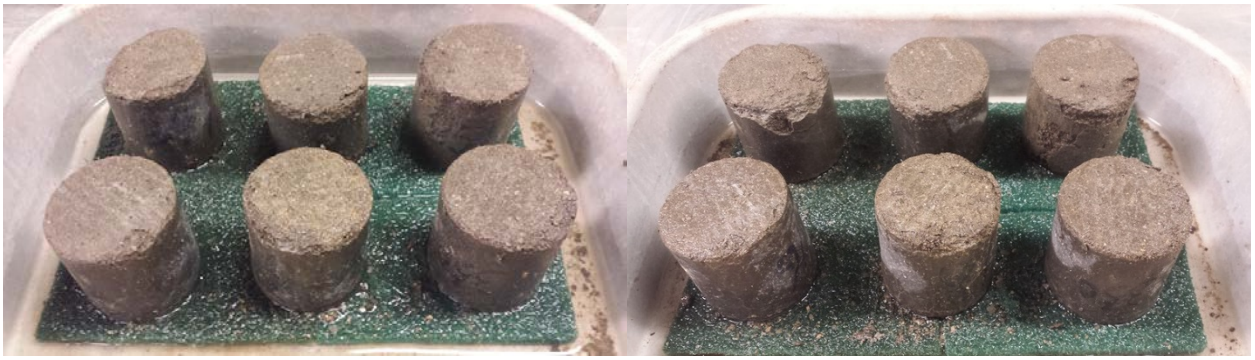
(e) 5th cycle (f) 6th cycle

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