LIME TREATMENT OF INTERIOR AND SOUTH-CENTRAL ALASKAN SOILS

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A

THESIS

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Abstract

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Lime treatment of soil is the practice of introducing lime to soil to improve subgrade conditions or to improve a soil's properties to meet construction aggregate qualifications. Lime treated soils commonly exhibit improvements in moisture-density, strength, and thaw performance. Although lime treatment has been practiced in many regions of the United States and Canada for several decades, it is not practiced in Alaska.

The purpose of this study was to determine potential of improving commonly encountered Alaskan soils with lime treatment. The two soils analyzed during this study were a silt from the Fairbanks area and a silty gravel from the Anchorage area. These soils were analyzed due to their similarity with soils encountered within regions of Alaska that are currently developed, and have potential for future development. Several laboratory tests were conducted to analyze the effect lime has on the engineering properties of both studied soils. The properties analyzed included moisture-density, strength, frost susceptibility, and thaw strength.

The results of this study show lime treatment has potential to improve the engineering properties of commonly encountered Alaskan soils. The results of this study also show potential to improve Alaskan soil with low concentrations of lime during cool and short construction seasons.

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I give special thanks to my beloved wife. If not for her patience and support, I would not have been able to complete this endeavor.

Chapter 1. Introduction

Lime-treatment of soil is the practice of introducing lime to soil in order to improve the soil's engineering properties. Improvements in lime-treated soil are due to either lime modification or lime stabilization. Both lime modification and lime stabilization have potential to improve a soil's engineering properties, however, as discussed in Section 2.3, lime modification generally results in more moderate improvements in soil properties than does lime stabilization. Lime treatment has been commonly practiced in highway construction within the continental United States for several decades (see Figure 1.1), and can be employed to improve both subgrade conditions and the quality of fine-grained construction materials. Other common applications of lime treatment include the construction of commercial buildings, residential housing, airport runways, and railroad embankments (NLA, 2004). Improvements in subgrade conditions as well as quality of construction materials due to lime treatment can potentially improve infrastructure performance, and reduce construction costs. There are many widely accepted improvements in soil engineering properties resulting from lime treatment including, improve moisture-density characteristics and workability, increased strength, improved durability, and improved thaw performance (Little, 1987, 1999; Parsons and Milburn, 2003; Mallela et al., 2004).

As shown in Figure 1.1, lime treatment is not practiced in all American States; particularly in the northern states. Lime treatment may not be practiced in Alaska due to Alaska's low air and ground temperatures and, particularly in interior Alaska, a lack of reactive soils. However, as discussed throughout this report, several studies have observed moderate improvements in less reactive soils in cooler climates. Moderate improvements due to lime modification and relatively low degrees of lime stabilization may have sufficient potential in infrastructure development.

In road construction, the combined thickness of the structural layers within a road section is largely dictated by the design traffic load and subgrade strength. For a given design traffic load, increasing the subgrade strength as commonly measured by the California bearing ratio

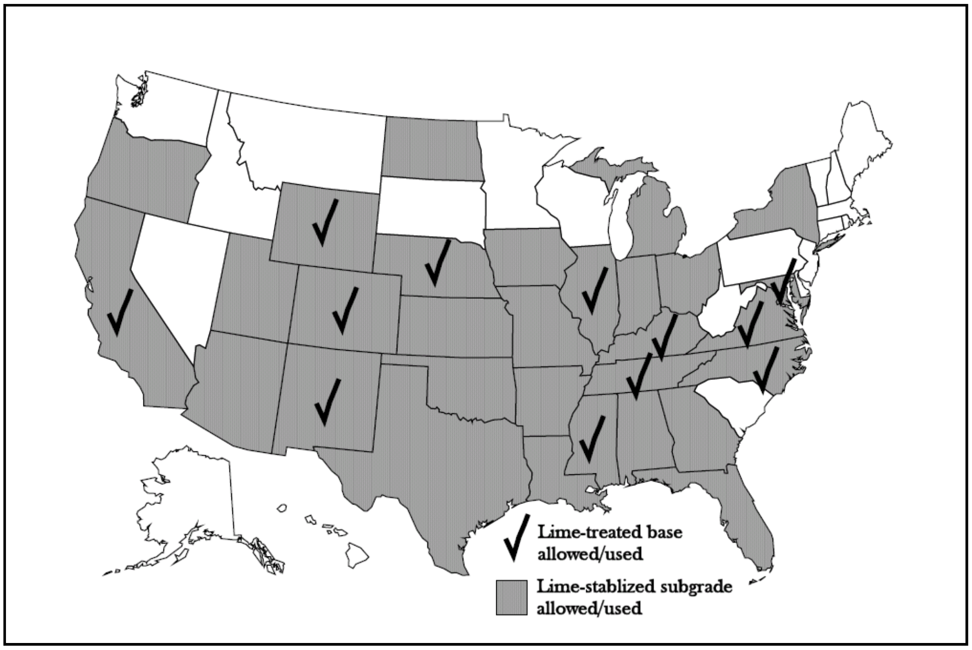

Figure 1.1: United States distribution of lime treatment practices.
Taken from Mallela et al. (2004).

(CBR) can significantly reduce the required thickness of the road section’s structural layers, thereby reducing the required volume of construction materials. This has significance in interior Alaska where quality construction materials are relatively sparse and difficult to acquire, particularly in remote regions.

For example, following road construction techniques as described by USACE (1984a), a flexible pavement road section assigned a design index of 3, constructed on a subgrade with a CBR of 4, will need to be approximately 16 inches thick. By modestly increasing the subgrade CBR to 10, the same road section thickness may be reduced to approximately 8 inches. This relatively modest improvement in subgrade CBR will reduce the amount of construction material needed by approximately one-half. Figure 1.2, taken from the USACE (1984a), shows the relationship between subgrade CBR and road section thickness.

Reductions in required road section thickness for a given design index may also be reduced with respect to thaw strength of soil. According to USACE (1984b), in areas where frost susceptible soils are subjected to seasonal frost, an assigned frost-area soil support index is used in the design curve in lieu of the CBR value. The frost-area soil support index accounts for sharp decreases in support strength when soils subjected to frost action thaw, and can be as low as 3.5 for silty soils. If moderate improvements in frost susceptibility and thaw strength of subgrade soils can be shown, however, there may be potential to base the design off of larger values, thereby decreasing the required road section thickness and construction costs in regions subjected to seasonal frost.

1.1. Objective and Scope

The objective of this study was to determine the potential to improve the engineering properties of soils commonly encountered in Alaska by treating these soils with lime. The engineering properties analyzed for potential improvements included moisture-density characteristics (including workability), strength, frost susceptibility, and thaw strength (strength upon thawing). The ability to improve these properties in commonly encountered Alaskan subgrade soil may result in reduced highway, railroad, and other infrastructure

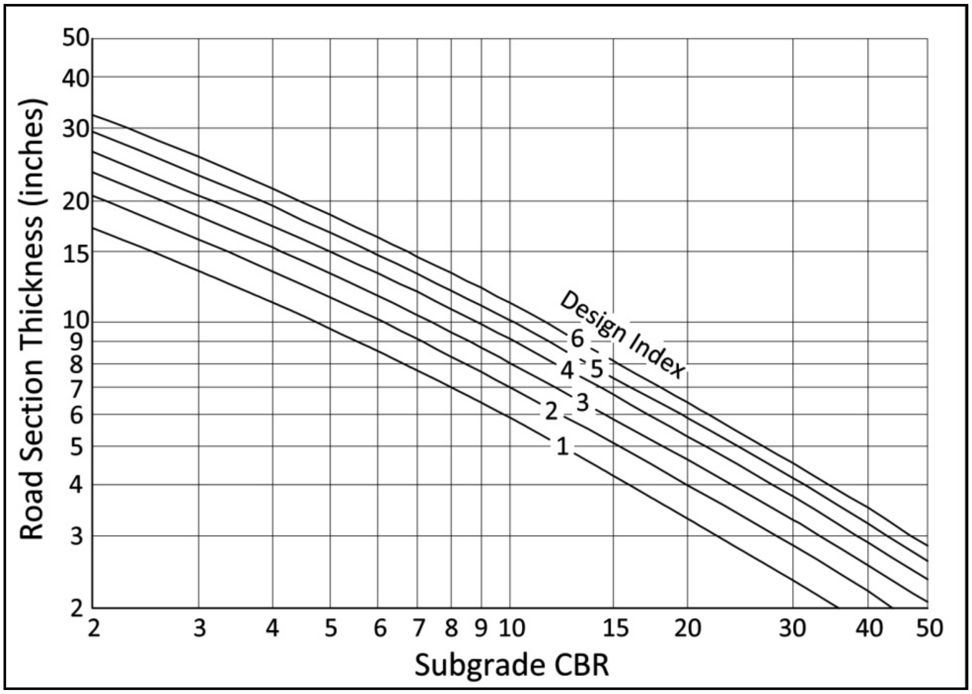

Figure 1.2: Road section thickness as a function of subgrade CBR and design index. Taken from USACE (1984a).

construction and maintenance costs within Alaska, possibly facilitating future development of Alaska’s mineral resources.

It should be noted that the scope of this study was limited to analyzing the potential to improve engineering properties of Alaskan soil with lime treatment. An economic analysis was beyond the scope of this study, but is recommended for future work. In addition, some of the limitations of this study include a lack of a quantitative determination of the clay mineralogy for both soils, and the lack of direct analysis of the extent of reaction between the studied soils and hydrated lime.

1.2. Studied Soil

The two studied soils were silt from the Fairbanks area, and silty gravel from the Anchorage area. These soils were chosen due to the large expanses of land within Alaska and northwestern Canada that are currently developed, have potential for future development, and are overlain by similar soils.

The studied silt was collected from an exposed mine cut within Goldstream valley, approximately 7.5 miles northeast of Fairbanks, Alaska (see Figure 1.3). This soil is part of an extensive deposit of retransported silt belonging to the Goldstream and Ready Bullion Formations. These deposits overlay many lower slopes and valley bottoms within central Alaska, are similar in composition to deposits that extend as far east as Canada, and as far west as the Seward Peninsula, and have been observed in locations such as Tofty, Livengood, Circle, Chicken, and Dawson City in the Yukon Territory of Canada (Péwé, 1975b). The soil in these deposits and the upland silts that overlie upper slopes and hilltops are grouped within Fairbanks Loess due to the soil originating and tracing down slope from the upland silt (Tuck, 1940; Péwé, 1955 and 1975b). According to Péwé (1975b), the silt within these formations is commonly perennially frozen at depth and organic-rich, consisting of small organic debris, sticks, peat lenses, etc. In addition, these silts are generally well-sorted, angular and are comprised of abundant quartz and muscovite (Péwé, 1955). Transport distances of the retransported silt are relatively small; therefore the particles have retained the uniform

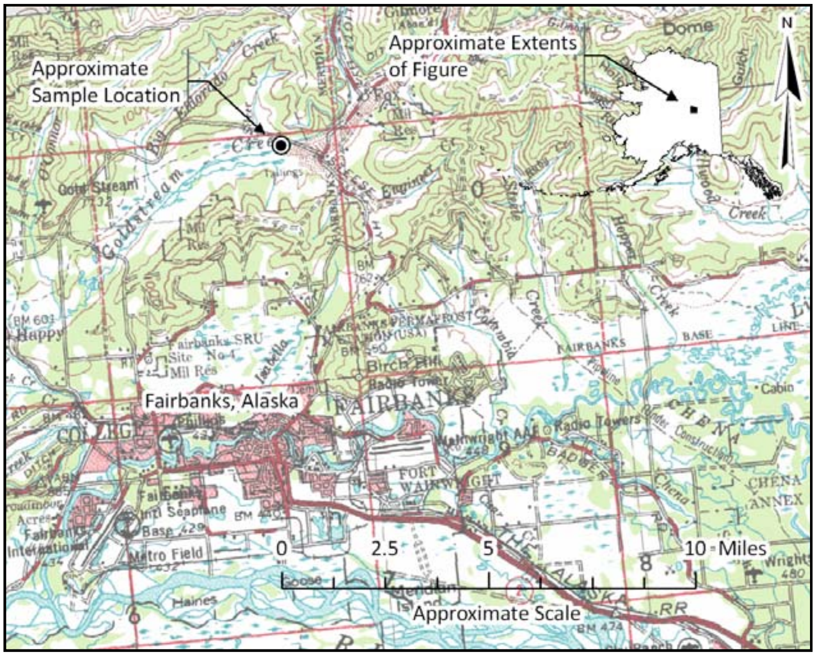

Figure 1.3: Approximate sample location for the studied silt.
Located approximately 7.5 miles northeast of Fairbanks, Alaska.

distribution and angularity derived from their eolian origin. As shown in Section 4.1, this soil was classified as ML, SILT according to the Unified Soil Classification System (USCS).

The studied silty gravel was collected from an exposed ground moraine within Point Mackenzie, approximately 13 miles north and across the Knik Arm from Anchorage, Alaska (see Figure 1.4). This ground moraine is part of an extensive deposit of glacial till formed during the Naptowne glaciation that covers areas extending north into the Susitna River Valley, east into the Matanuska River valley, and southeast across the Knik Arm into Elmendorf Air Force Base just north of Anchorage, Alaska (Péwé, 1975a; Clark and Kautz, 1998; Miller and Dobrovolny, 1959). As shown in Section 4.1, this soil was classified as GM, SILTY GRAVEL WITH SAND according to the USCS classification system. A U.S. Department of Agriculture (USDA) report developed by Clark and Kautz (1998) states that the gravel tills within this deposit commonly consist of cobbles, gravel, sand, silt, and clay, and commonly refers to these soils as loamy and matrix supported. A U.S. Geological Survey (USGS) report developed by Miller and Dobrovolny (1959) reported similar findings, stating that the till within a moraine deposit near Elmendorf Air Force base (the Elmendorf moraine) consists of boulders, cobbles, and pebbles that are supported within a silt and clay matrix. X-ray analysis data illustrated in their report shows that a soil sample taken from the east side of Knik Arm contains mixed-layered chlorite and montmorillonite.

Bulk samples of the two soils were collected via hand shovel and mattock and sealed with 5-gallon buckets for transport. Photographs of the exposures that the silt and silty gravel bulk samples were excavated from are shown in Figures 1.5 and 1.6, respectively.

1.3. Laboratory Analyses

Laboratory analyses conducted throughout this study include several tests to classify and characterize the studied soils, as well as several tests conducted to determine the engineering properties of untreated and lime-treated variants of both studied soils. The laboratory tests conducted to classify and characterize the studied soils include:

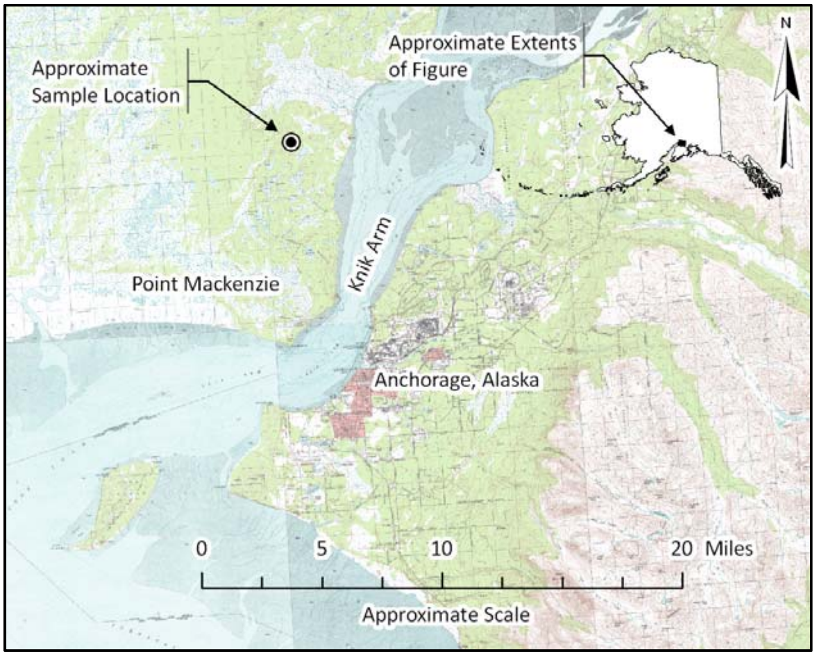

Figure 1.4: Approximate sample location for the studied silty gravel. Located approximately 13 miles north of Anchorage, Alaska.

Figure 1.5: Photograph of the studied silt sample location.

Figure 1.6: Photograph of the studied silty gravel sample location.

- Particle Size Distribution
- Atterberg Limits
- pH
- Permeability

The techniques used to conduct each of these tests are detailed in the respective subsections of Section 3.2.

The engineering properties of the soils analyzed throughout the study include moisture-density characteristics, bearing strength, frost susceptibility, and thaw strength. These engineering properties were analyzed due to their significance to infrastructure development. Furthermore, frost susceptibility and thaw strength of soil are of particular concern in regions such as interior and south-central Alaska, where frost heave and thaw-settlement are a prevalent cause of structural damage and maintenance costs.

A modified proctor analysis was conducted to characterize the moisture-density properties of untreated and selected lime-treated samples of both studied soils. The purpose of this analysis was to characterize the maximum density and optimum moisture content of the soil variants, and to determine which moisture content the soils were to be compacted molds during the following CBR tests. A detailed description of the moisture-density relationship analysis is provided in Section 3.3.2.

CBR tests were conducted on samples of the studied silt to characterize the bearing strength of the untreated and lime-treated soil. The CBR test was chosen due to its common usage in highway engineering, relative ease to conduct, and the fact that the CBR molds provided a convenient apparatus to perform subsequent freeze testing. Furthermore, the alternate Unconfined Compression Test is not appropriate for cohesionless soil such as the studied silt. A detailed description of the CBR test is provided in Section 3.3.3.

Originally, the CBR test was to be used to characterize the bearing strength of the studied silty gravel; however as detailed in Section 3.3.4, some of the analyzed samples of silty gravel were too strong to assign a CBR value. Therefore, the 5,000-pound test was developed because the majority of the samples of silty gravel were subjected to a minimum load of 5,000 pounds by the CBR press. This test is similar to the CBR test insomuch that it too employs the use of the CBR press and molds. A detailed description of the 5,000-pound test is provided in Section 3.3.4.

The relative frost susceptibility for untreated and lime-treated variants of both the silt and the silty gravel was analyzed via a modified freeze test. During the modified freeze test, samples of studied soil previously compacted in CBR molds, were subjected to freezing conditions, where daily measurements of frost-induced vertical strain were recorded. This test, which was modified from previous studies, allowed for the subsequent CBR/5,000-pound testing on the same soil samples in order to characterize each soil's thaw strength. A detailed description of the modified freeze tests used during this study is provided in Section 3.3.5.

The thaw strength of untreated and lime-treated variants for both studied soils was analyzed by subjecting samples of previously frozen soil to either a CBR test, or a 5,000-pound test. These tests were conducted to characterize the spring-time performance of both studied soils. A detailed description of the thaw strength analysis is provided in Section 3.3.6.

To characterize the effect post-thaw curing has on the engineering properties of the lime-treated variants of both studied soils, select lime-treated, previously frozen samples of the studied soils were allowed additional time to cure and then subjected to strength testing as described above. The purpose of this analysis was to characterize potential for these soils to regain engineering improvements potentially lost due to winter time freezing if allowed to cure throughout the following warm season. A detailed description of the post-thaw curing analysis is provided in Section 3.3.7.

To characterize the effect cure temperature may have on the engineering performance of both studied soils, selected samples of each lime-treated soil were cured at 50^{o}F (10^{o}C), and subjected to the various tests as described above. The resulting engineering performance was then compared with that of similarly treated soils that were cured at room temperature (approximately 70^{o}F (21^{o}C)). A detailed description of the cure temperature and engineering performance analysis is provided in Section 3.3.8. Figures 1.7 and 1.8 (see supplemental CD) are flowcharts that detail the laboratory work conducted throughout this study.

Chapter 2. Literature Review

As previously discussed, the objective of this study was to determine the potential for commonly encountered Alaskan soils to exhibit engineering improvements when treated with lime. Major focus of this study was placed on the moisture-density characteristics, strength, frost susceptibility, and thaw strength of the two studied soils. Due to the relatively low air and ground temperatures in Alaska, focus was also placed on the effect cure temperature has on the analyzed engineering properties of the lime-treated studied soils. Furthermore, due to the relatively short warm season in Alaska, and to characterize long-term, multi-seasonal performance, focus was placed on the effect post-seasonal curing has on the engineering properties of the studied soils.

Prior to development and testing of the hypothesis, a comprehensive review of relevant literature on lime treatment of soil was conducted. Works reviewed consisted of previous studies on lime treatment theory and practices, including studies of the reaction between soils and lime, engineering properties of lime-treated soil, correlations between laboratory testing results and predicted field reactivity and performance, as well as design guides outlining accepted lime treatment test methods and field applications.

For sake of organization, discussion of the literature reviewed is ordered in terms of relevant soil-lime reaction criteria, and the engineering properties that were analyzed during this study. A brief discussion of current lime treatment practices is also provided. The following subsections are categorized as follows:

- Reactions between Soil and Lime
- Soil Properties and Environmental Conditions that Facilitate Soil-Lime Reactivity
- Lime Modification and Lime Stabilization of Soil
- Engineering Properties of Lime-Treated Soil
- Current Lime Treatment Practices

2.1. Reactions between Soil and Lime

Engineering improvements observed in fine-grained soils that are treated with lime are attributed to two phases of reaction. The first reaction phase occurs almost immediately, and includes an exchange between the cations adsorbed on soil particle surfaces and the cations introduced to the soil-water system with the addition of lime. This results in a reduction of the water layer thickness surrounding soil particles, followed by flocculation and agglomeration of soil particles. The second reaction phase involves what is termed the pozzolanic reaction. The pozzolanic reaction occurs between calcium cations added to the system by lime, available water, and pozzolans. According to Little (1987), a pozzolan is a siliceous or aluminous material that reacts with calcium cations and water to form cementitious products. In most cases, available soluble silica and alumina provided by certain soil particles act as pozzolans. The pozzolanic reaction results in the formation of cementitious calcium-silicate-hydrates (CSH) and/or calcium-aluminate-hydrates (CAH), similar to those formed during the hydration of Portland cement (Little, 1987; Mallela et al., 2004; NLA, 2004).

Cation exchange occurs almost immediately within most fine-grained soils upon addition of lime (Little, 1987; Parsons and Milburn, 2003; Mallela et al., 2004); however, the pozzolanic reaction is confined to more reactive soils (i.e., soils that can act as, or provide pozzolans) within a sufficiently high pH environment, and requires a sufficient quantity of cations added to the system to fill adsorbed cation exchange sites on particle surfaces while leaving available cations to react with the water and the soluble silica and/or soluble alumina (Eades and Grim, 1966; Little, 1987).

The following subsections provide a more detailed description of cation exchange and flocculation and agglomeration of soil particles, and the pozzolanic reaction between soil and lime.

2.1.1. Cation Exchange, and Flocculation and Agglomeration of Soil Particles

Many soil particles, particularly clay particles, have a negatively charged surface. Positively charged cations, as well as dipolar water molecules, adsorb to the surface of the negatively charged soil particle, partially to fully neutralizing the soil-water system. Due to thermal agitation and ionic repulsion, the cations and dipolar water molecules form a relatively wide, diffused water layer surrounding the soil particle (Little, 1987; Mallela et al., 2004).

In fine-grained soil, ionic repulsion between the soil particles may result in the soil particles being separated by a relatively thick diffused water layer, the thickness of which is a function of the ionic charge in the soil-water system. A Soil-water system may be partially neutralized by monovalent cations such as such as sodium (Na^+) and potassium (K^+), or by low concentrations of divalent and trivalent cations (Parsons and Milburn, 2003); however, a negative charge and inter-soil particle ionic repulsion will persist. As an example, soil-water systems consisting of soil particles with a relatively strong negative charge, and adsorbed cation concentrations with a relatively weak positive charge, will have thicker surrounding water layers than systems consisting of soil particles with a relatively weak negative charge, and adsorbed cation concentrations with a relatively strong positive charge. Increased concentrations of ions and/or ions with larger charge potential (such as divalent or trivalent cations) will more effectively balance the negative charge of the soil particle resulting in a thinner water layer surrounding the soil particle (Little, 1987). The relatively thick water layer separating negatively charged soil particles results in a soil mass with relatively low shear strength, flexural modulus and CBR, and relatively high swell potential and plasticity (Little, 1987, 1999; Parsons and Milburn, 2003).

When soil is treated with lime, calcium ions are almost immediately released into the soil-water system. The Ca^{++} ion will concentrate in the diffused water layer surrounding the soil particle, and begin replacing any monovalent cations previously adsorbed on the soil particle. The ability of Ca^{++} to replace other ions in the system is described by the Lyotropic series:

$$\mathrm{Na}^{+} < \mathrm{K}^{+} << \mathrm{Mg}^{++} < \mathrm{Ca}^{++} \tag{2.1}$$

where Na^+ and K^+ are the monovalent sodium and potassium cations, respectively, and Mg^{++} and Ca^{++} are the divalent magnesium and calcium cations, respectively. The Lyotropic series states cations of higher valence will replace cations of lower valence, and among cations of same valency, larger cations will replace smaller ones (Little, 1987; Mallela et al., 2004).

The exchange of cations adsorbed on soil particles with cations of higher valency neutralizes the ionic repulsion between soil particles, reducing the thickness of the water layer separating the soil particles. The effect cation exchange has on inter-soil particle water layer thickness is shown in Figure 2.1.

The reduction of the diffused water layer due to the exchange of adsorbed monovalent cations with divalent calcium cations released from lime results in the flocculation and agglomeration of soil particles (Little, 1987; Mallela et al., 2004). Flocculation and agglomeration of soil particles results in a change in soil texture, where the soil particles agglomerate together into larger aggregates, and the soil becomes a more granular material (Parsons and Milburn, 2003). Figure 2.2 details flocculation and agglomeration of soil particles due to a reduction in water layer thickness resulting from cation exchange.

The new soil texture resulting from the flocculation and agglomeration of soil particles results in a soil mass with increased internal friction and shear strength (Little, 1987). Furthermore, other engineering benefits due to flocculation and agglomeration of particles include reduced plasticity, and improved workability (Little, 1987, 1999; Mallela et al., 2004; Parsons and Milburn, 2003).

2.1.2. Pozzolanic Reaction

As previously discussed, the pozzolanic reaction occurs when calcium cations released by lime react with available water and soluble silica and alumina to form either CSH or CAH. The pozzolanic reaction is defined by the following relationship described by Little (1987), and Mallela et al. (2004):

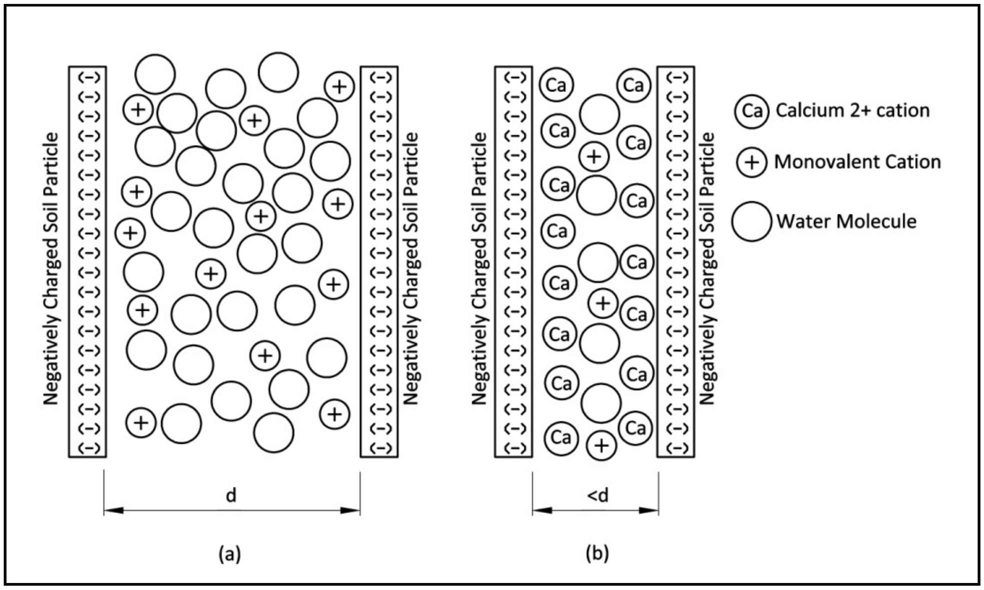

Figure 2.1: Cation exchange within diffused water layer.
Modified after Little (1987), and Mallela et al. (2004). Thick diffused water layer resulting from a negatively charged soil-water system (a); reduced diffused water layer due to cation exchange of monovalent cations with divalent Ca^{++} cations supplied by lime (b).

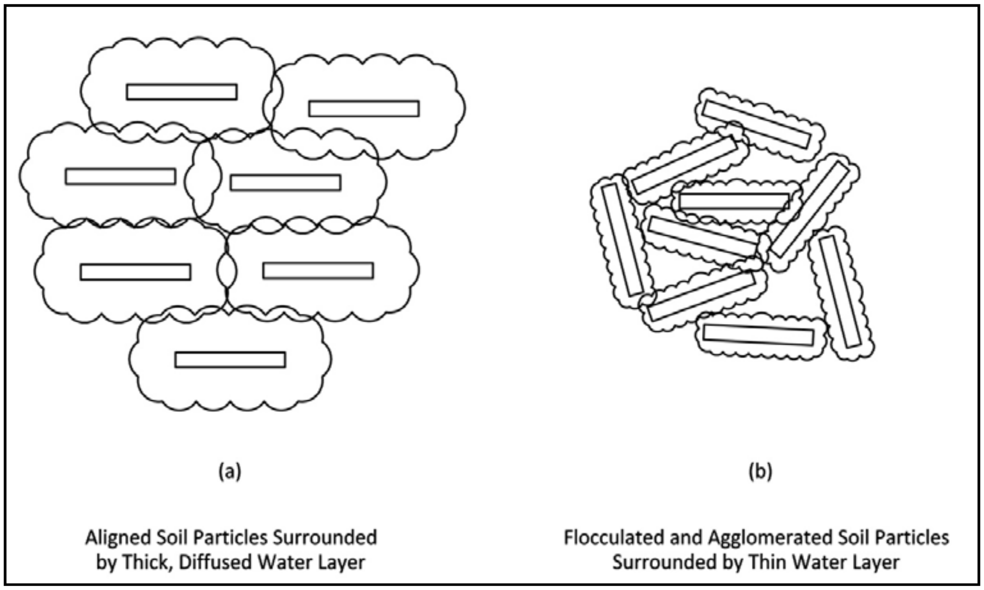

Figure 2.2: Flocculation and agglomeration of soil particles with addition of lime.
Modified after Little (1987); soil particles separated by relatively thick water layer resulting in low shear strength (a). Addition of divalent calcium cations reduces diffused water layer thickness between soil particles, resulting in flocculation/agglomeration of soil particles (b).

$$\mathrm{Ca^{++} + OH^{-} + SiO_2 \rightarrow CSH} \tag{2.2}$$
$$\mathrm{Ca^{++} + OH^{-} + Al_2O_3 \rightarrow CAH}$$

The Ca^{++} and OH^- are released from lime by the following reactions described by Mallela et al. (2004) and Hicks (2002):

$$\mathrm{Ca(OH)_2 \rightarrow Ca^{++} + 2(OH)^{-}};\text{for hydrated lime and slurry} \tag{2.3}$$
$$\mathrm{CaO + H_2O \rightarrow Ca(OH)_2 + Heat \rightarrow Ca^{++}\ 2(OH)^{-}};\ \text{for quicklime added to soil and water}$$

Potential sources of soluble silica and alumina that are commonly found in most fine-grained soils include quartz, feldspars, micas, and other silicate or alumino-silicate minerals (Mallela et al., 2004).

In order for the soluble silica and alumina to be available for reaction, the pH of the soil-water needs to be sufficiently high to dissolve these pozzolans. Some authors such as Hicks (2002) and Eades and Grim (1966) suggest the pH of the soil-water system must be as high as 12.3 to maintain dissolution of the soluble silica and alumina. However, according to Little (1999) and NLA (2004), the pH of the soil-water system may be as low as 10 to 10.5 to dissolve available soluble silica and alumina. In any case, the soil-water system must be relatively alkaline to facilitate the pozzolanic reaction. Furthermore, according to Eades and Grim (1966), Little (1987), Parsons and Milburn (2003), and Mallela et al. (2004), the pozzolanic reaction can only occur where sufficient quantities of lime have been introduced to the system to satisfy the exchange of adsorbed monovalent cations with divalent calcium cations and still provide sufficient quantities of calcium to react with soluble silica and alumina to form CSH and CAH. The quantity of lime needed to satisfy the exchange of adsorbed monovalent cations with divalent calcium cations is commonly referred to as the fixation point. According to Bell (1996), in relatively reactive soils, lime added in excess of the fixation point will be utilized in the formation of cementitious CSH and CAH.

2.2. Soil Properties and Environmental Conditions that Facilitate Soil-Lime Reactivity

Discussions of the reactivity of soil with lime are generally confined to the degree of which the pozzolanic reaction occurs. Soils that facilitate the pozzolanic reaction are commonly referred to as reactive soils, which generally have a combination of high clay content, high pH, and a high plasticity index (PI) (Hicks, 2002; Mallela et al., 2004). Because the pozzolanic reaction in a soil is generally confined to the soil's clay particles, the magnitude of reaction is partially dependent upon the quantity of clay particles within the soil. According to Mallela et al. (2004), the minimum clay content for a soil to be pozzolanically reactive is approximately 10%. According to Little and Nair (2009), however, previous research has shown that soil with clay content as low as 7% has reacted pozzolanically with lime. Furthermore, the mineralogy of a soil's clay particles partially dictates its reactivity. According to Little (1987) and Hicks (2002), montmorillonite clays are generally more reactive than kaolinite clays due to having a higher negative charge and more available soluble silica and alumina. Montmorillonite clays are also made of a three –layer (2:1) sheet structure while kaolinite clays are made of a two-layer (1:1) sheet structure. Three-layer (2:1) sheet structure clays (such as montmorillonite) generally have a high negative surface charge and a large surface area that provides numerous cation exchange sites.

The pH of a soil partially dictates the soil's overall reactivity with lime. As previously discussed, in order for soluble silica and alumina to be available for the pozzolanic reaction, the soil-water system must remain relatively alkaline (pH of 10 or more). Strongly alkaline soils require the addition of less lime than do lesser alkaline soils, to sufficiently raise the pH of the soil-water system to a level that facilitates a pozzolanic reaction. According to Thompson (1968), a soil having a pH of 7 or more is likely sufficiently reactive with lime.

The plasticity of a soil has been commonly used as an indicator of the soil's reactivity with lime. Many soil lime treatment design guides suggest using a soil's PI as this indicator. According to NLA (2004), soils having a PI greater than 10 are good candidates for lime stabilization. Hicks (2002) suggests that alternative soil stabilization techniques should be considered for soil with a PI less than 10.

Environmental conditions also contribute to the degree a soil will react with lime. In addition to being a function of combined soil properties, the pozzolanic reaction is also a function of both time and temperature. In a soil of given reactivity, the degree to which the pozzolanic reaction occurs within the soil increases with increased temperature and cure duration. Dempsey and Thompson (1973) showed that increasing cure temperature will result in further strength development within a relatively reactive lime-treated soil. According to Little (1987), Hicks (2002), Parsons and Milburn (2003), and Mallela et al. (2004), both air and ground temperatures affect the speed and extent of reaction within a lime-treated soil, where warmer temperatures result in a faster and more extensive reaction. According to Anday (1962) and USACE (1984c), the pozzolanic reaction will not occur to a significant degree at temperatures lower than 50^{o}F (10^{o}C). Furthermore, according to Bell (1996) and NLA (2004), temperature conditions should be a minimum of 40^{o}F (4^{o}C) and rising in order for the pozzolanic reaction to occur within a lime-treated soil. Assuming a pozzolanic reaction within lime-treated soil will not occur at temperatures below 50^{o}F (10^{o}C), and attempting to assure sufficient development of CSH and CAH, Anday (1962) suggested lime treatment of soil should not be conducted where a minimum accumulation of 750 degree-days above 50^{o}F (10^{o}C) is not anticipated during the first warm season.

Studies conducted by Thompson (1969) and Rosen and Marks (1974) suggested any portion of the pozzolanic reaction not completed before the first freezing season will be completed throughout subsequent warm seasons. Bell (1996) stated the pozzolanic reaction may remain dormant during periods with temperatures lower than 40^{o}F (4^{o}C) and continue again when temperatures increase. In other words, lime-stabilized soil will remain dormant during cool periods, and continue to cure to a higher degree when subjected to warmer climates throughout the following years. Furthermore, according to field data observed by Thompson (1968), lime-stabilized soil can continue to cure for up to ten years. This not only suggests that benefits of lime stabilization can occur in regions of relatively short and cool summers, but also reactive soils treated with lime may continue to gain strength over several years.

2.3. Lime Modification and Lime Stabilization of Soil

As discussed, treating soil with lime is commonly conducted in construction to either modify or stabilize subgrade soil and/or soil to be used as aggregate. Generally, the term “lime modification” describes soil improvements largely due to cation exchange and the flocculation and agglomeration of soil particles, whereas the term “lime stabilization” describes soil improvements due to the pozzolanic reaction. It should be noted, however, that the term, “lime modification” has been used relatively loosely by some authors. Authors such as Hicks (2002), Parsons and Milburn (2003), and Mallela et al. (2004) suggested that improvements in plasticity and workability in lime-modified soil are confined to improving the construction platform and expediting construction procedures. In contrast, Little (1987, 1999) suggests improvements in the engineering properties of lime-modified soil may be significant enough for engineering design. Furthermore, some authors suggest that lime modification of soil describes immediate improvements due to cation exchange in relatively reactive soils that will undergo stabilization with time.

For purposes of this study, lime modification describes improvements in the engineering properties of relatively non-reactive soil due to cation exchange and the flocculation and agglomeration of soil particles, and lime stabilization describes improvements in engineering properties of more reactive soil due to the formation of pozzolans within the soil mass.

2.4. Engineering Properties of Lime-Treated Soil

As previously discussed, lime stabilization generally results in larger improvements in the soil’s engineering properties than lime modification. Because of this, it appears that potential improvements in soil engineering properties due to lime modification are largely ignored. In addition, regions that consist of relatively non-reactive soil, as well as regions with cooler climates (such as Alaska) do not generally employ lime treatment of soil in infrastructure development. Several previous studies, however, have observed improvements in engineering properties exhibited in relatively non-reactive soils that were treated with lime. Furthermore, studies also have shown improvements in some engineering properties of both reactive and non-reactive soil within regions of cool climate.

2.4.1.1. Moisture-Density Characteristics of Lime-Modified and Lime-Stabilized Soil

Soils treated with lime generally display an increase in optimum moisture content and a decrease in maximum compaction density (Hicks, 2002; Mallela et al., 2004). This is generally observed within both lime-modified and lime-stabilized soil and is attributed to both the flocculation and agglomeration of soil particles due to cation exchange, and the fine-grained nature of hydrated lime (Hicks, 2002). According to Bell (1996), treating soil with lime allows the soil to be compacted to a sufficient density over a wider range and higher values of moisture content. Lime treatment of soil may facilitate construction during wetter conditions by reducing potential for muddy construction sites, and increasing potential for achieving acceptable compaction (Mallela et al., 2004).

2.4.2. Engineering Properties of Lime-Modified Soil

As previously discussed, lime modification of soil occurs due to cation exchange and flocculation and agglomeration of soil particles. Lime modification can occur within both reactive and non-reactive soils and commonly results in rapid changes of texture and plasticity (Little 1987). In addition to improvements in plasticity and workability, lime modification of soil may result in improved moisture-density characteristics, and marked increases in strength.

Due to the premise that many Alaskan soils may be non-reactive with lime and that Alaskan temperatures may not facilitate lime stabilization of soil, the discussion of engineering properties considered unique to lime-modified soil are sub-categorized as follows.

2.4.2.1. Relative Strength of Lime-Modified Soil

Although not of the same magnitude as observed in lime-stabilized soils, strength development is still observed in lime-modified soils. According to Thompson (1968, 1969), Little (1987, 1999), and Mallela et al. (2004), both non-reactive and uncured lime-modified soils can exhibit marked increases in both unconfined compressive strength (UCS) and CBR. Little (1999) reports CBR improvements on the order of 15% to 25% have been observed in lime-modified soils that were treated within relatively wet and cool European environments; however, these soils may not have been entirely cured, and may otherwise be relatively reactive with lime. Thompson (1969) observed CBR values as low as 2.6% and 4.3% increase to 9.9% and 39.0%, respectively, in samples of non-reactive soil treated with lime. Parsons and Milburn (2003) reports increases in the UCS of two lime-treated silty and sandy soils with low plasticity (PI of 3 and 7) from approximately 270 kPa and 310 kPa to approximately 1,200 kPa and 1,500 kPa, respectively.

Strength increases exhibited in lime-modified soil may be attributed to cation exchange, and flocculation and agglomeration of soil particles as well as the corresponding coarsening of soil fabric and increase in internal friction (Little, 1987; Mallela et al., 2004).

2.4.2.2. Permeability of Lime-Modified Soil

In general, lime-modified soils experience an increase in permeability. Increased permeability of lime-modified soil is commonly attributed to coarsening of soil fabric due to flocculation and agglomeration of soil particles, facilitating unimpeded water flow though interstitial spaces. Several authors, including Townsend and Klym (1966), and Arabi et al. (1989), noted increased permeability in some lime-treated soil, attributing the increased permeability to flocculation and agglomeration of soil particles.

2.4.2.3. Frost Susceptibility of Lime-Modified Soil

In general, lime-modified soils experience increased frost susceptibility due to increases in permeability that result from coarsening of soil fabric (see Section 2.4.2.2). Permeability increases within lime-treated soils can facilitate flow of unfrozen water and ice segregation (Townsend and Klym, 1966; Arabi et al., 1989). Arabi et al. (1989) observed increased frost heave in soil treated with low concentrations of lime, attributing the increased frost heave to the combined effect of increased permeability (due to flocculation and agglomeration), and insufficient development of impermeable cementitious products.

2.4.3. Engineering Properties of Lime-Stabilized Soil

As previously discussed, lime stabilization occurs within reactive soils treated with lime. Generally, lime stabilization of soil results in, among other improvements, significant long-term increases in strength and reduction in soil plasticity (Little, 1999; Parsons and Milburn, 2003). Lime stabilization of soil may also reduce the soil's frost susceptibility. In their studies, O'Flaherty and Andrews (1968) and Arabi et al. (1989) observed a reduction in the frost susceptibility of some of their reactive, lime-stabilized soil.

The following subsections detail the changes in a soil's relative strength, frost susceptibility, and permeability that may be anticipated in lime-stabilized soil. Each subsection also addresses the mechanisms involved (i.e. soil's reaction to lime) that result in the respective change in the soil's property.

2.4.3.1. Relative Strength of Lime-Stabilized Soil

It is commonly accepted by many authors that lime stabilization of soil may result in marked increases in the soil's shear strength and bearing capacity. According to Little (1987), reactive clay soils may experience a three-fold to four-fold, and in some cases a ten-fold or more, increase in strength when treated with lime. Thompson (1969) observed CBR values as low as 2.6% and 3.1% for samples of natural soil increase to 351% and 370%, respectively, when the soils were treated with lime. Little (2000) observed values of unconfined compressive strength as low as 145 kPa in a sample of natural soil increase to 2,765 kPa when the soil was treated with lime. Other authors who observed significant increases in the strength of natural soil stabilized with lime include Parsons and Milburn (2003), Thompson (1966), and Bell (1996).

The magnitude of strength increase within a lime-stabilized soil, or rather the degree to which the pozzolanic reaction occurs, is largely controlled by the soil's mineralogy (Mooney, 2010). Many authors discuss the reactivity of a soil with lime in terms of montmorillonite content vs. kaolinite content. Soils containing montmorillonite will generally display larger strength improvements when stabilized with lime than will similar soils containing kaolinite. The ability of montmorillonite to react with lime (both in terms of cation exchange and pozzolanic reaction) more readily than kaolinite is due to the mineral's higher surface charge, higher specific surface area, and increased ability to release soluble silica and alumina in the soil water system (see Section 2.2). Albeit to a lesser degree, other silicate minerals, as well as the degree of mineral crystallization, also play a role in a soil's reactivity with lime (Bell, 1996).

2.4.3.2. Permeability of Lime-Stabilized Soil

As with lime-modified soil, lime-stabilized soil too commonly experiences increased permeability as a result of soil fabric coarsening due to the flocculation and agglomeration of soil particles. However, development of relatively impermeable, cementitious CSH and CAH within lime-stabilized soil partially counters the permeability increasing effects of flocculation and agglomeration. This effect increases with an increased level of stabilization. Some authors, such as Parsons and Milburn (2003) and Arabi et al. (1989), have observed permeability of lime-stabilized soil decrease with increased cure duration and/or increased lime content, although the observed permeability remained greater than that of untreated soil. Both authors attributed the observed decreases in permeability to enhanced development of cementitious CSH, and CAH. Furthermore, according to NLA (2004), extensive formation of cementitious products produces a relatively impermeable soil matrix.

2.4.3.3. Frost Susceptibility of Lime-Stabilized Soil

Lime-stabilized soils generally experience reduced frost susceptibility, provided sufficient development of cementitious CSH and CAH has occurred. This has been observed in several studies, where the resistance to frost action was either measured directly via heave test, or indirectly via a durability test. Townsend and Klym (1966), O'Flaherty and Andrews (1968), and

Arabi et al. (1989) observed reductions in the frost susceptibility of various lime-stabilized soils.

Reduction in the frost susceptibility of lime-stabilized soil is largely attributed to the development of inter-particle bonding due to the formation of CSH and CAH. According to Townsend and Klym (1966) and Arabi et al. (1989), extensive formation of CSH and CAH within lime-treated soil may sufficiently increase the soil's tensile strength enough to counter frost heave forces, thereby reducing the soil's frost susceptibility. However, if the soil is not sufficiently reactive, or other conditions prevent sufficient strength development within the soil, the frost susceptibility of the soil may be increased due to increased permeability as discussed in Sections 2.4.2.2 and 2.4.2.3. O'Flaherty and Andrews (1968) observed less frost heave resistance in less reactive, kaolinite-rich soils, than in more reactive, montmorillonite-rich soils. Arabi et al. (1989) observed increased frost heave in soil treated with relatively low concentrations of lime, attributing the increased frost heave to the combination of increased permeability and insufficient development of tensile strength.

2.5. Current Lime Treatment Practices

With respect to lime treatment practices to date, the majority of focus has been towards soil improvements resulting from lime stabilization. Lime modification of soil is generally confined to improving the working platform of a construction site, and is not commonly practiced to structurally improve soils for engineering purposes. This is likely due to a belief that soil improvements resulting from lime modification are not sufficient for engineering design. As a result, there has not been significant focus on lime treatment (in the form of research and construction practices) of relatively non-reactive soil, or within regions of cooler climate.

Currently, lime treatment of soil is not practiced in Alaska (see Figure 1.1). This is likely attributed to Alaska's relatively cool air and ground temperatures, relatively short construction season, and limited extent of reactive soil. For example, according to Hicks (2002), lime has not been widely used in Alaska due to a lack of appropriate soil.

As discussed in Section 2.4.2, moderate improvements in strength may be realized in lime-modified soil. Increases in the strength of lime-modified soil on the order of magnitude observed by Thompson (1969) and Parsons and Milburn (2003) are relatively large and may be significant enough for engineering consideration. Furthermore, several authors including Little (1999) have noted marked increases in the strength of soil treated with lime in regions of relatively cool climate.

2.6. Discussion

As discussed in Section 1.1, the objective of this study was to determine the potential for lime treatment to improve the engineering properties of soils commonly encountered in Alaska. In addition to the environmental conditions in which a soil exists, the extent to which that soil will react with lime is dictated by the soil's clay mineralogy and content, pH, and plasticity (see Section 2.2). Although it may be believed that neither Alaskan soils nor the temperature conditions encountered in Alaska facilitate soil-lime reactions (see Section 2.5), the results of several studies indicate that moderate improvements in engineering properties of relatively non-reactive soil may occur when these soils are treated with lime. In addition, improvements in the engineering properties of lime-treated soil may also occur within relatively cool environments (see Section 2.4.2.1).

The hypothesis of this study is that the engineering properties of common interior and south-central Alaskan soils may be improved when these soils are treated with lime. The improvements include increased bearing and thaw strength, and reduced frost susceptibility. These improvements may be largely attributed to lime modification due to cation exchange and flocculation and agglomeration of soil particles. It is further hypothesized that improvements exhibited in lime-treated interior and south-central Alaskan soils may be due to some component of lime stabilization, resulting from varying degrees of pozzolanic reaction. The study also hypothesizes that, after the first warm season, any uncompleted portion of stabilization may be completed throughout the duration of several subsequent warm seasons (see Section 2.2).

Chapter 3. Study Methods

The laboratory testing conducted for this study included tests that classified and characterized the studied soils, as well as tests that determined the engineering properties analyzed for both untreated and lime-treated variants of the soils. Several standard test methods were employed while conducting the laboratory analyses; these methods are listed in Table 3.1. Flowcharts detailing the laboratory test methods used for this study are shown in Figures 1.5 and 1.6. It is recommended that these figures be followed throughout this discussion. The following sections detail the laboratory testing methods used throughout this study.

3.1. Sample Preparation

Oven drying was not practical while preparing the large volume of soil necessary for laboratory testing. Therefore, the studied soils were air dried following techniques described in ASTM D421 and AASHTO T87. The collected soil was placed on a tarp and stirred daily with a shovel until the soil appeared sufficiently dry for gradation and CBR analysis. Figure 3.1 displays both the soils air drying in an open environment. Upon appearing sufficiently dried, the soils were sealed in 5-gallon plastic buckets until needed for laboratory analyses.

3.2. Classification and Characterization of the Studied Soils

Several laboratory tests first were conducted to classify the soils and to characterize their reactivity with lime. The studied soils were classified in general accordance with ASTM D2487, utilizing information gained from particle size distribution and the Atterberg limits analyses. The lime reactivity potential for the studied soils was characterized from information acquired through the Atterberg limits and pH analyses. The permeability of the soils was determined to characterize their general properties. The following sections detail the methods used in these analyses.

Table 3.1: Standard test methods used for laboratory analyses

Test	Test Title
AASHTO T87	Standard Method of Test for Dry Preparation of Disturbed Soil and Soil and Soil Aggregate Samples for Test
AASHTO T88	Standard Method of Test for Particle Size Analysis of Soils
AASHTO T89	Standard Method of Test for Determining the Liquid Limit of Soils
AASHTO T90	Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
AASHTO T180	Standard Method of Test for Moisture-Density Relationship of Soils Using a 10-lb Rammer and an 18-in Drop.
AASHTO T193	Standard Method of Test for the California Bearing Ratio
ASTM D421	Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants
ASTM D2487	Standard Practice for Classification of Soil for Engineering Purposes (Unified Soil Classification System)
ASTM D5856	Standard Method of Test for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter
ASTM D5918	Standard Test Method for Frost Heave and Thaw Weakening Susceptibility of Soils
ASTM D6276	Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization
ATM 206	pH of Topsoil

Figure 3.1: Photographs of the air-dried soils.
Studied silt (left), and studied silty gravel (right).

3.2.1. Particle Size Distribution of the Studied Soils

A particle size distribution analysis was conducted on representative samples of the silt and silty gravel. This analysis was conducted in general accordance with AASHTO T88, and included a sieve analysis for particles exceeding 2.00 mm (No. 10 sieve), as well as a hydrometer analysis for particles finer than 2.00 mm. Due to inherent differences in their gradations, there was variation in the techniques used to analyze the particle size distributions of the two soils, as summarized in the following subsections.

3.2.1.1. Particle Size Distribution of the Silt

The studied silt is fine-grained, with the majority of the soil particles finer than the No. 200 (0.075 mm) sieve. Because of this, a large portion of the representative sample was confined to the hydrometer analysis. Approximately 100 grams of a representative sample of the silt was sieved through a 12-inch diameter No. 10 sieve. The approximate 98-gram sample then was subjected to a hydrometer analysis conducted in general accordance with the techniques described in AASHTO T88.

3.2.1.2. Particle Size Distribution of the Silty Gravel

Large diameter particles within the silty gravel were hand-sieved using a double stack of round 12-inch diameter sieves. This stack consisted of a 3 inch and a 2 inch mesh sieve (see Figure 3.2). The 3 inch-plus particles were removed from further analysis due to their scattered distribution, and to prevent their excessive weight skewing the gradation. A representative 2 inch-minus portion of the silty gravel, previously hand-sieved, then was sieved for 20 minutes through a Gilson test screen apparatus consisting of 1.5 inch, 1.0 inch, 0.75 inch, 0.5 inch, 0.25 inch, and No. 4 (4.75 mm) sieves; all sieves had dimensions of 14.75 inches by 22.75 inches (see Figure 3.3). A representative portion of the material passing the No. 4 (4.75 mm) sieve then was sieved through a 12-inch diameter No. 10 (2.00 mm) sieve. The weight distribution for portions of the silty gravel exceeding the No. 10 sieve was recorded. A hydrometer analysis then was conducted in general accordance with AASHTO T88 on a representative portion of

Figure 3.2: Round 12-inch diameter sieves used during gradation analysis of the silty gravel.

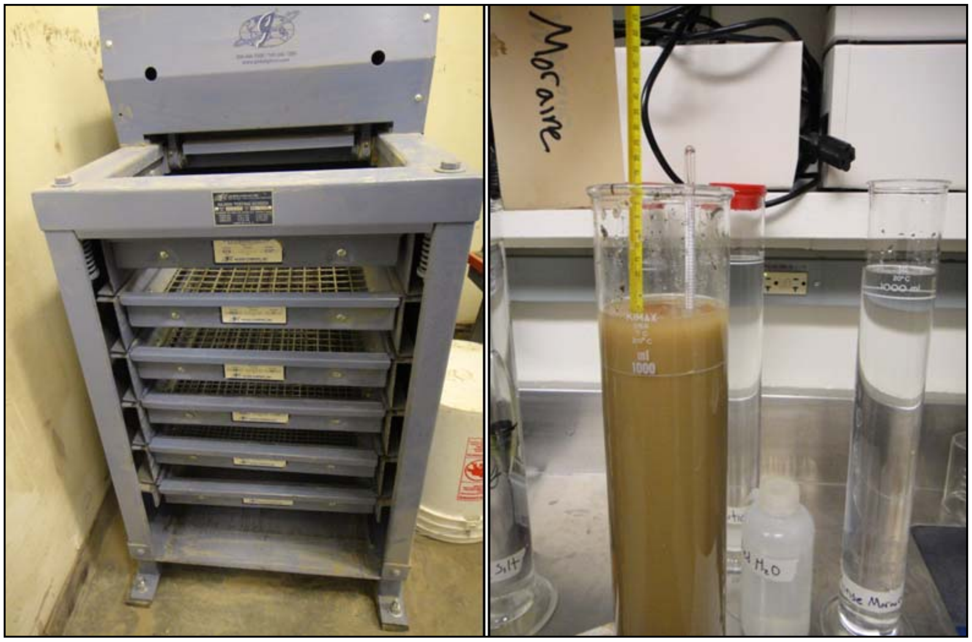

Figure 3.3: Equipment used for the particle size distribution analysis.
Gilson 14.75 inch by 22.75 inch screen apparatus (left), and a hydrometer reading for fine-grained portion of the silty gravel (right).

the minus No. 10 material (see Figure 3.3). The results of the particle size analyses of the studied soils then were used in conjunction with the results of the Atterberg limits (see Section 3.2.2) to classify each of the studied soils in accordance with ASTM D2487.

3.2.2. Atterberg Limits of the Studied Soils

The Atterberg limits, i.e. the plastic limit (PL) and the liquid limit (LL) (as well as the plasticity index (PI)), for both studied soils were determined, generally following the techniques described by AASHTO T89*,* and AASHTO T90. This analysis was used to classify the soils in accordance to ASTM D2487, as well as to characterize the soil's reactivity with hydrated lime. Figure 3.4 illustrates a sample within the liquid limit device and as threads on the plastic limit plate.

3.2.3. pH of the Studied Soils

The pH of untreated samples of both soils was determined in general accordance to ATM 206 and ASTM D6276. This analysis was conducted to characterize the soils, and determine variability between their pH and minimum pH requirements for soil-lime reactivity (see Section 2.2). The optimum soil-lime content for each soil (as determined from procedures in ASTM D6276) was not determined due to a belief that potential for pozzolans formation within these soils is low, even at high concentrations of lime.

A representative sample of studied soil was sieved through the No. 10 sieve until approximately 350 grams of sieved material was obtained (Figure 3.5). Three, approximate 25-gram samples of both soils were placed within separate, sealed plastic containers with approximately 100 mL of reagent water. The soil-water mixture was shaken for 30 seconds at ten-minute intervals for one hour. A pH measurement for each prepared sample was taken with a digital pH meter, a simple pill-type soil pH test kit, and pH test strips (see Figure 3.6).

Figure 3.4: Conducting Atterberg limits testing on studied soil.
Sample of soil within liquid limit device (left) and on plastic limit plate (right).

Figure 3.5: Preparing sample of soil for pH measurements.
Sieving a 350 gram sample (left) and weighing a 25 gram sample (right).

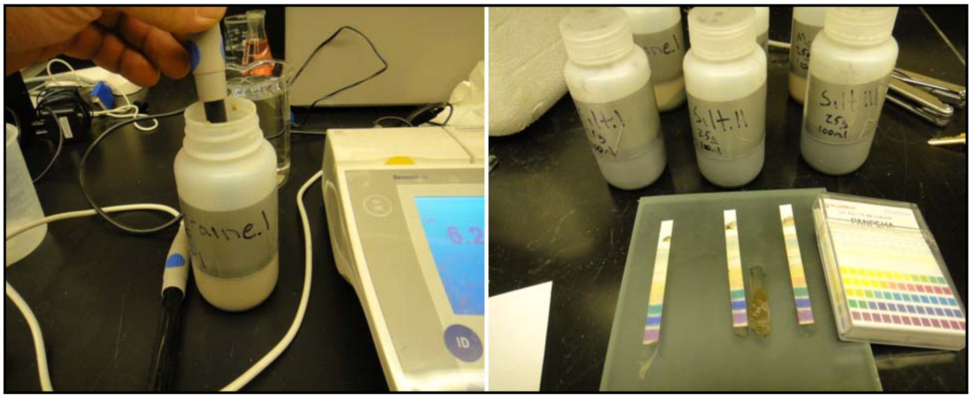

Figure 3.6: Measuring pH of studied silt.
pH meter (left) and pH test strips (right).

3.2.4. Permeability of the Studied Soils

The permeability of both untreated soils as well as all the analyzed lime-treated variants was determined by conducting falling head permeability analyses in general accordance with ASTM D5856. The purpose of these analyses was to determine the variation in permeability between the untreated and lime-treated soils.

Two samples from each of the untreated and lime-treated soil variants were compacted at the predetermined optimum moisture content (see Section 3.3.2.) in a rigid-wall compaction permeameter, with one sample of each variant compacted within a 4-inch diameter mold, and the other sample compacted within a 6-inch diameter mold. The falling head permeability apparatus consisted of rigid-wall compaction molds containing the compacted specimens, with the pressure head provided by water within a 100 ml graduated burette, and the tail head provided by a funnel, placed at a height lower than the graduated burette. Figure 3.7 illustrates both the 4-inch and 6-inch diameter rigid-wall falling head apparatuses.

Permeability was determined by the following equation:

$$\kappa = \frac{V_W \times L}{(h_1 - h_2) \times \tau \times A} \times ln\left(\frac{h_1}{h_2}\right) \tag{3.1}$$

where *k* is the permeability of the soil specimen in cm/s, V_w is volume of water, in cm^3, that flowed through soil specimen over measured time duration, L is the length of the soil specimen in cm, h_1 - h_2, in cm, is the measured head loss across the specimen over elapsed time, τ is the time duration in seconds, and A is the cross sectional area of the soil specimen in cm^2. The permeability assigned to each analyzed soil sample was determined by taking the average value from four consecutive measurements that fell within ±25% of the mean of the four measurements.

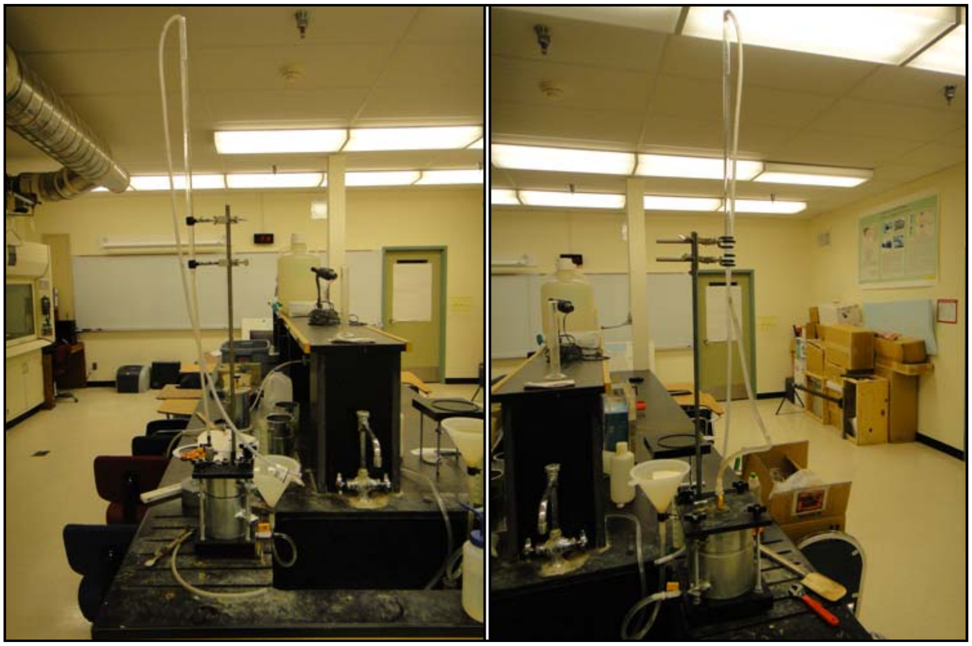

Figure 3.7: Falling head apparatuses used to estimate permeability of the soils. 4-inch diameter mold (left), and 6-inch diameter mold (right).

3.3. Engineering Properties of the Studied Soils

Several laboratory tests were performed to determine the engineering properties of the untreated and lime-treated soils. These tests were conducted to characterize potential performance increases in the lime-treated soils. These laboratory tests included:

- Determining Moisture-Density Relationship
- Determining the California Bearing Ratio of the Silt
- 5,000-pound Test Analysis for the Silty Gravel
- Modified Freeze Test
- Thaw Strength
- Post-Freeze Curing and Relative Strength Analysis
- Cure Temperature and Performance Analysis

The following sections detail the methods used in these analyses.

3.3.1. Preparing the Silty Gravel for Moisture-Density and 5,000-pound Analyses

Since the silty gravel consisted of particles exceeding 3 inches (as well as ¾ inches) in diameter, it was necessary to modify this soil’s gradation prior to conducting the moisture-density and 5,000-pound analyses. The 3 inch-plus particles were removed from further analysis so the tested soil would have a gradation similar to that determined from the gradation analysis. The remaining ¾ inch-plus material was removed and then replaced with an equal weight of material passing the ¾ inch sieve and retained on the No. 4 (4.75 mm) sieve according to methods described in AASHTO T193. Portions of the silty gravel with this modified gradation then were suitable for use in the subsequent moisture-density and 5,000-pound test analyses, as detailed in Sections 3.3.2 and 3.3.4. Figure 3.8 displays the process of scalping the 3 inch-plus material while obtaining the weight percent passing the 3 inch sieve and retained on the ¾ inch sieve, and preparation of material passing the ¾ inch sieve and retained on the No. 4 sieve. This process described was not necessary for the silt due to its lack of ¾ inch-plus particles.

Figure 3.8: Preparation of the silty gravel for moisture-density and 5,000-pound analyses. Obtaining 3 inch-minus/ ¾ inch-plus material (left) and obtaining ¾ inch-minus/No. 4-plus material (right).

3.3.2. Determining Moisture-Density Relationship

A moisture-density relationship analysis was conducted on prepared samples of each of the untreated and lime-treated soil variants. The testing was conducted in general accordance with AASHTO T180. The purpose of this analysis was to determine the optimum moisture content used in preparing the soils for future CBR testing and 5,000-pound testing, as well as to characterize the effect lime treatment may have on the compaction density of the soils. An example of a modified Proctor hammer and a 4 inch Proctor mold are shown in Figure 3.9. The optimum moisture of each soil-lime-content variant as determined from the moisture-density relationship analysis then was applied while filling CBR molds with studied soil during the respective CBR or 5,000-pound testing (see Sections 3.3.3 and 3.3.4).

3.3.3. Determining the California Bearing Ratio of the Silt

A CBR test conducted in general accordance to AASHTO T193 was performed on each of the untreated and lime-treated variants of the silt. The purpose of this testing was to characterize the effect lime treatment may have on the relative strength and bearing capacity of the studied silt. The CBR test was chosen to measure the relative strength of the silt because of the ease in conducting this test, as well as the test's common use in highway engineering. As will be discussed in Section 3.3.4, the CBR test was not conducted on the silty gravel, however. Figure 3.10 illustrates a sample of silt compacted within a 6-inch diameter CBR mold, and a molded sample of silt within the CBR press. The relative strength of both untreated and lime-treated silt was measured by the CBR value of the soil as determined by the CBR test.

3.3.4. 5,000-pound Test Analysis for the Silty Gravel

Some of the lime-treated silty gravel did not display the necessary minimum 0.1 inches of penetration under the CBR press's maximum 10,000-pound load to be assigned an actual CBR value. It was observed, however, that nearly all (excluding two) samples of the tested silty gravel were affected by at least a 5,000-pound load by the CBR press. Therefore, a modified analysis was developed, where the penetration for each sample of untreated and lime-treated

Figure 3.9: Equipment used during moisture-density relationship analysis.
Modified compaction hammer and 4 inch Proctor mold (left). Preparation of sample within 4 inch Proctor mold (right).

Figure 3.10: Equipment used to measure CBR of the silt.
Sample of silt compacted within a 6 inch CBR mold (left). Molded sample within CBR press (right).

silty gravel measured at a 5,000-pound load was used to characterize the relative strength of each sample. Figure 3.11 contains two theoretical curves, one curve representing soils sufficiently weak to be assigned a CBR value, and the other curve representing soils too strong to be assigned a CBR value. As shown in Figure 3.11, the curve extending to the right displays a minimum 0.1 inches of penetration at a load of 10,000 pounds or less, while the curve on the left reaches the maximum 10,000-pound load at a penetration less than the minimum required 0.1 inches. Both curves show a measurable penetration value at a 5,000-pound load, however. The penetration observed at a 5,000-pound load was compared to characterize the relative strength of the untreated and lime-treated silty gravel. This analysis otherwise used the same equipment (i.e., 6-inch diameter CBR molds and a 10,000-pound CBR press) as used in the CBR analysis of the silt.

3.3.5. Modified Freeze Test

The relative frost susceptibility of each untreated and lime-treated soil variant was determined via a modified freeze test that was developed partially from ASTM D5918, and the methods used in previous similar studies such as those by Arabi et al. (1989) and Jessberger and Carbee (1970). The modified freeze test was developed to accommodate the use of CBR molds and to provide means for subsequent testing of previously frozen soil as described in Sections 3.3.6, 3.3.7, and 3.3.8.

A modified freezing apparatus was developed for this study. The apparatus had to accommodate frost heave of soil samples compacted in CBR molds. These samples then would be subjected to further testing upon thawing as described in Sections 3.3.6 and 3.3.7.

The freezing apparatus held an approximately 8-inch deep water bath insulated against heat loss by an envelope of polystyrene insulation placed along the bottom, walls, and lid. The temperature of the water bath was maintained at above-freezing temperatures via a series of ¾-inch diameter polyethylene hoses (PEX tubing) containing ethylene glycol that was heated and circulated by an Endocal RTE-4 bath circulator. Figure 3.12 shows the Endocal heater used

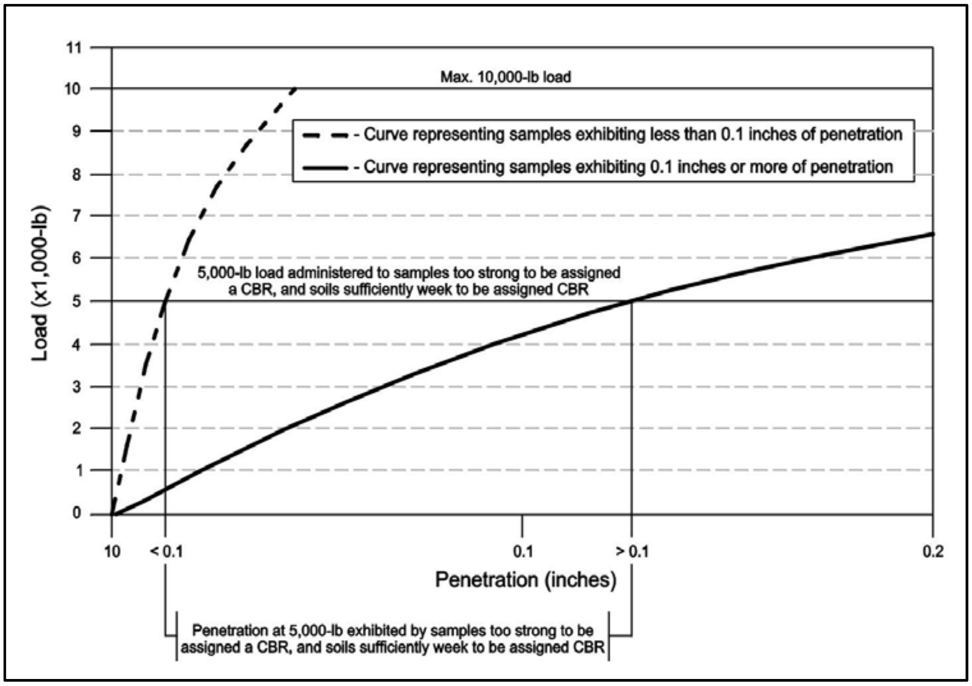

Figure 3.11: Chart illustrating conditions appropriate for CBR vs. 5,000-pound test.

Figure 3.12: Equipment used during the freeze tests.
Endocal circulating heater (left). Plumbed PEX lines extending into freezing apparatus (right).

to circulate heated glycol through the PEX lines, and the PEX lines extending into the freezing apparatus.

An isolated water supply was provided to each sample by a 10-inch square by 3.5-inch tall plastic container held at an elevation at which the container was partially submerged within the water bath by a 6-inch tall stand. Each sample was placed within one of these plastic containers and held at an elevation at which just their bases were submerged in isolated water by an approximate 2.5-inch tall spacer. The above-water portions of the samples extended through the 4-inch-thick polystyrene lid into below-freezing air cooled by the freezing chamber. Figure 3.13 is a simple schematic of the freezing apparatus and Figure 3.14 is a photograph of several samples embedded within the freezing apparatus.

Two duplicate samples of each analyzed soil-lime-content variant were compacted into CBR molds with the CBR swell plate placed on top, and loaded with two CBR surcharge weights - as per methods described in AASHTO T193 – and placed within the freezing apparatus (see Figures 3.13 and 3.14).

Two freeze tests were conducted, and each test varied from the other with respect to temperature and test duration. Freezing chamber temperature was recorded at a minimum of once a day to the nearest tenth of a degree Celsius with a HOBO temperature logger that had an accuracy of ±0.5 degrees Celsius. Each recorded temperature was verified via a mercury thermometer with 0.5 degree Celsius divisions. The temperature of the water bath within the freezing apparatus was measured at a minimum of once a day with a laboratory dial thermometer consisting of 0.5 degree Celsius divisions. Frost-induced strain of the soil samples was measured and recorded at a minimum of once a day via a CBR swell plate and tripod dial indicator, accurate to 0.001 inch (providing a 0.02% resolution for measured strain).

3.3.5.1. Conditions Simulated by the First Freeze test

During the first freeze test, the temperature of the freezing chamber was maintained at approximately 14^{o}F (-10^{o}C), while the water bath within the freezing apparatus varied

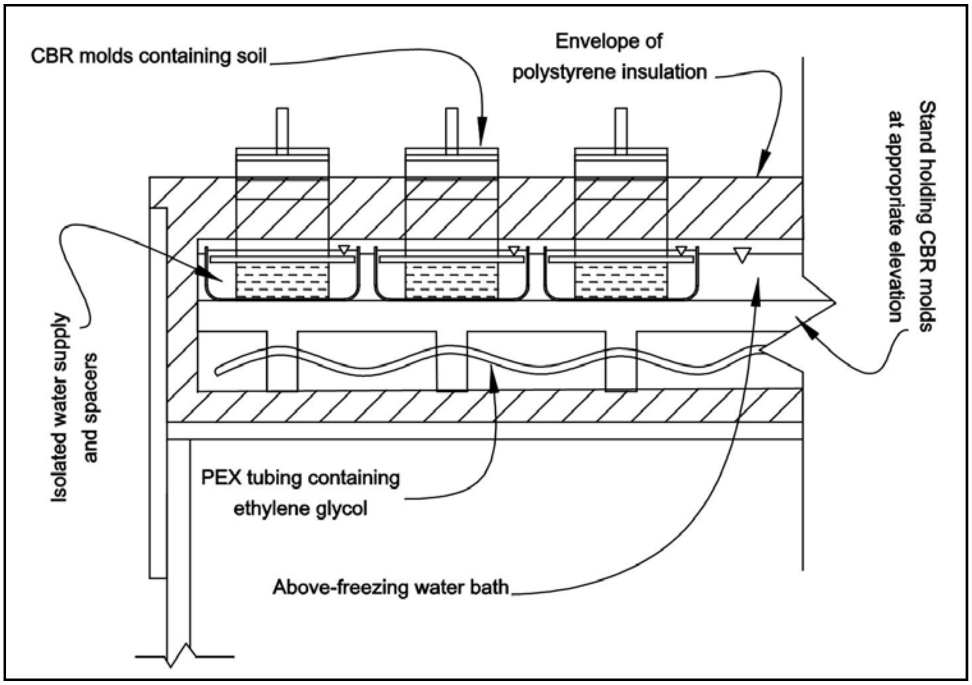

Figure 3.13: Simplified schematic of freezing apparatus.
The schematic shows the water bath, insulated envelope and lid, PEX tubing containing heated, circulating ethylene glycol, the stand, spacers, water isolating plastic containers, and the soil samples within the freezing apparatus.

Figure 3.14: Molded soil samples within the freezing apparatus.

between 34°F (1°C) to 37°F (3°C). The test was conducted for 10 days, at which point no further strain was observed within any of the soil samples.

3.3.5.2. Conditions Simulated by the Second Freeze test

The second freeze test was conducted for 20 days, at which point no further strain was observed within any of the soil samples for several consecutive days. The temperature of the freezing chamber was initially set at 32.9°F (0.5°C), and lowered 1.8°F (1°C) daily to -4°F (-20°C) upon completion of the test. The water bath temperature ranged between 33.8°F (1°C) and 46.4°F (8°C).

3.3.6. Thaw Strength Analysis

The thaw strength analysis was developed to characterize spring-time strength performance of both untreated and lime-treated variants of the studied soils. This analysis employed both the freeze tests, followed by either a CBR test or a 5,000-pound test (see Sections 3.3.3 through 3.3.5).

The thaw strength of each soil was characterized by analyzing the relative strength of soil samples that were previously frozen. This was done by subjecting selected untreated and lime-treated samples of each soil to either a CBR test (for the silt) or 5,000-pound test (for the silty gravel), after the soils had been subjected to one of the two freeze tests.

3.3.7. Post-Freeze Curing and Relative Strength Analysis

The post-freeze curing and relative strength analysis was developed to characterize the ability for each studied soil, given additional time to cure after thawing, not only to regain strength lost due to freezing but also to develop strength in excess of similarly treated and cured soil that was not subjected to freezing. This analysis may characterize long-term seasonal strength performance of lime-treated soil similar to the studied soil. The analysis was conducted by subjecting selected soil samples to one of the two freeze tests (see Section 3.3.5), allowing the soils to cure for additional time after thawing, and then subjecting the samples to either the CBR analysis (see Section 3.3.3), or the 5,000-pound test (see Section 3.3.4).

3.3.8. Cure Temperature and Performance Analysis

The cure temperature and performance analysis was conducted on selected soil samples that were cured at either 50^{o}F (10^{o}C) or 70^{o}F (21^{o}C). The purpose of this analysis was to characterize the effect varying cure temperature has on the engineering performance of lime-treated soil. The engineering properties analyzed included relative strength, relative frost susceptibility, and thaw strength, which were analyzed by employing either the CBR or 5,000-pound tests, and the freeze tests (see Sections 3.3.3 through 3.3.5).

The cure temperature and relative strength analysis was conducted by comparing the CBR or 5,000-pound results of selected samples of lime-treated soil that were cured at approximately 50^{o}F (10^{o}C) and 70^{o}F (21^{o}C), respectively. The cure temperature and relative frost susceptibility analysis was conducted by comparing the strain observed within selected samples of lime-treated soil that were cured at either 50^{o}F (10^{o}C) or 70^{o}F (21^{o}C), and then subjected to a freeze test. Finally, the cure temperature and thaw strength analysis was conducted by comparing the thaw strength observed within selected samples of lime-treated soil that were cured at both 50^{o}F (10^{o}C) and 70^{o}F (21^{o}C).

Chapter 4. Results

As discussed in Chapter 3, several laboratory tests were conducted on the studied soils either to classify and characterize or to determine the engineering properties of the soils. The results of each analysis are presented as separate sections within this chapter, and because similar laboratory tests and analyses were conducted on both the silt and the silty gravel, the respective results of each soil are presented separately within each section of this chapter. It is recommended that the flow charts illustrating laboratory work (see Figures 1.5 and 1.6) be used as visual aids throughout this discussion.

4.1. Soil Classification and Characterization

The following tests were conducted to classify and characterize the two studied soils:

- Atterberg Limits
- Particle Size Distribution
- pH
- Falling Head Permeability

The liquid limit (LL) and plastic limit (PL) were the two Atterberg Limits analyzed for both soils. The resulting LL and PL values provided information necessary to classify the soils according to the USCS classification system. The LL of each soil is illustrated in Figure 4.1 and 4.2, while the PL of both soils are summarized in Table 4.1. Calculations from these data determined the LL of the silt occurs at a moisture content of 30.6% and the LL of the silty gravel occurs at a moisture content of 14.0%. The data summarized in Table 4.1 indicates the PL of the silt occurs at a moisture content of 36.5% and the PL of the silty gravel occurs at a moisture content of 15.1%. As the PL for both soils occur at a higher moisture content than their LL, calculating their plasticity index (PI) is not possible, suggesting both soils are non-plastic (NP).

A particle size distribution analysis was conducted on representative, untreated samples of the studied soils. This analysis also provided information necessary to classify both soils according

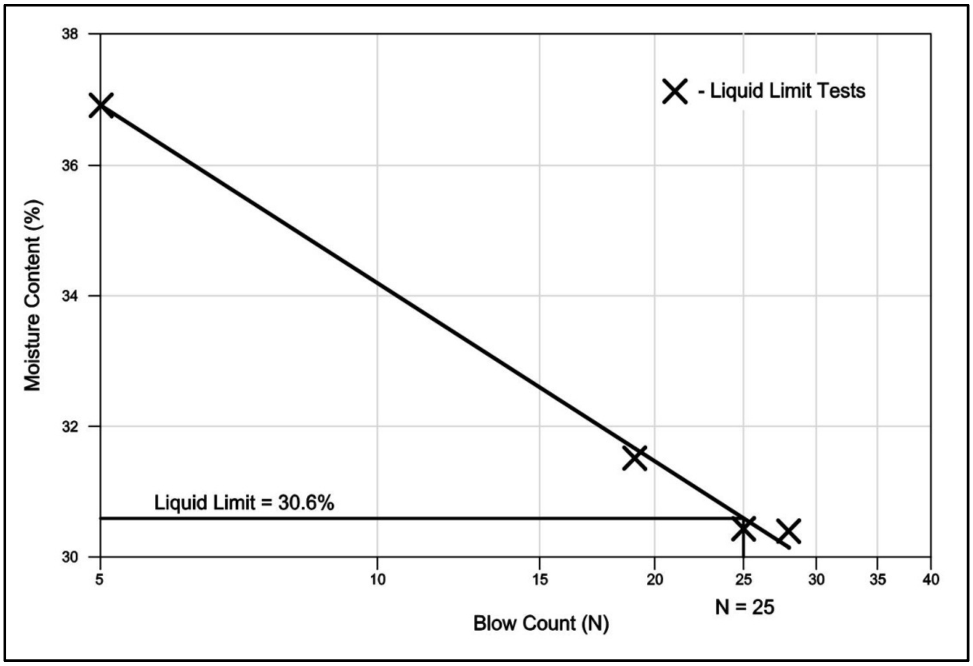

Figure 4.1: Liquid limit of the untreated studied silt.

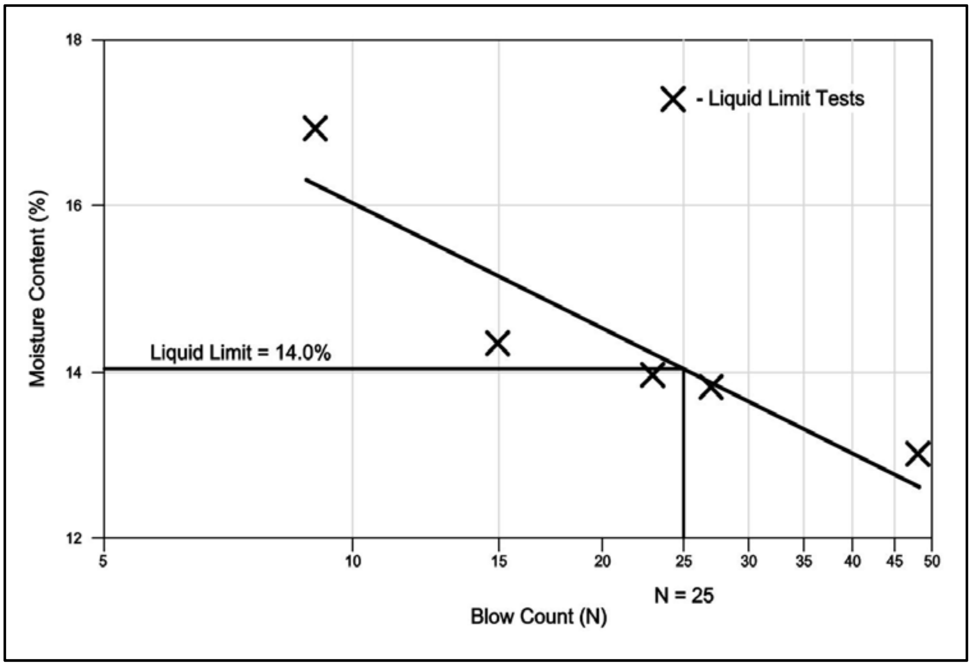

Figure 4.2: Liquid limit of the untreated studied silty gravel.

Table 4.1: Plastic limit of the untreated studied soils.

Plastic limit data	Silt	Silty Gravel
Mass of Can (g)	38.4	38.0
Mass of can + moist soil (g)	72.9	82.8
Mass of can + dry soi (g)	63.7	76.9
Plastic Limit (PL), ω%	36.5	15.1

to USCS. The results of the particle size distribution analysis for the two soils are illustrated in Figure 4.3. Based upon these results, approximately 85% (by weight) of the silt particles are smaller than 0.075 mm in diameter. According to the particle size distribution analysis, the silty gravel has the following properties:

- More than 50% (by weight)of particles exceed 0.075 mm in diameter
- More than 50% (by weight) of particles exceeding 0.075 mm in diameter exceed 4.75 mm in diameter
- More than 12% (by weight) of particles are less than 0.075 mm in diameter
- More than 15% (by weight) of particles exceed 0.075 mm in diameter and are less than 4.75 mm in diameter

Using the Atterberg Limits, particle size distribution, and USCS, the group symbol and group name for the silt is ML and SILT, respectively, and the group symbol and group name for the silty gravel is GM and SILTY GRAVEL WITH SAND, respectively. Due to its non-plastic nature as indicated by the Atterberg Limits analysis, the USCS classification for the studied silty gravel suggests low clay content in this soil. Assuming clay particles range in size from 0.002 mm to 0.004 mm, the silty gravel has a clay content somewhere between 6.4% and 10.5%. The percentage of particles finer than 0.075 mm in diameter that are also finer than 0.002 mm and 0.004 mm in diameter ranges from roughly 15% to 24%. For purposes of this study and simplicity, the two studied soils are referred to as silt and silty gravel.

Table 4.2 summarizes the results from the three tests used to measure the pH of both soils. For each soil, the three pH tests measured similar pH values. Steady calibration of the digital pH meter proved difficult, however, and the digital pH meter appeared to mis-measure pH solutions linearly. Therefore, it was assumed that subtracting the repeated error from actual measurements may be valid; these corrected values are summarized in Table 4.2. Considering the similarity between the adjusted digital pH meter measurements and the values of pH measured by both the pH indicator strips and the pill-type soil pH test kit, pH of 5.5 and 6.5 were assigned to the untreated silt and silty gravel, respectively.

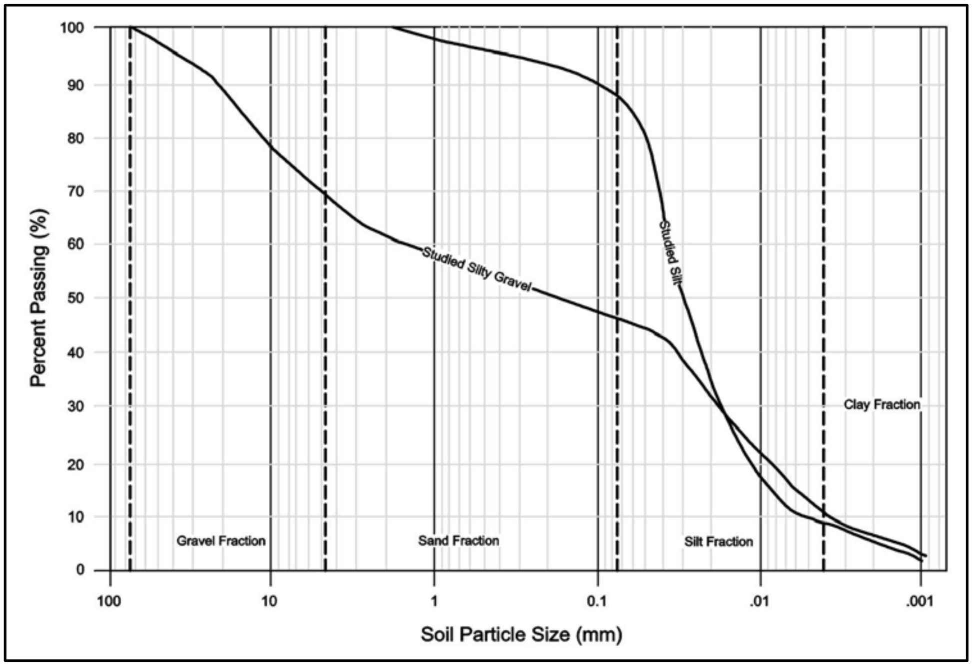

Figure 4.3: Particle size distribution of the studied soils.

Table 4.2: pH of the untreated studied soils.

Soil	Sample #	pH Test			Assigned pH
		Digital pH Meter (Corrected)	pH Indicator Strips	Pill-Type Soil pH Test	
Silt	Sample 1	5.1	5 - 6	5 - 6	5.5
	Sample 2	5.2	5 - 6	5 - 6	
	Sample 3	5.2	5 - 6	5 - 6	
Silty Gravel	Sample 1	6.4	6 - 7	6 - 7	6.5
	Sample 2	6.3	6 - 7	6 - 7	
	Sample 3	6.1	6 - 7	6 - 7	

An assigned pH of 5.5 suggests the studied silt is moderately acidic and does not meet the commonly accepted minimum pH of 7 or more (see Section 2.2) for an untreated soil to be reactive with lime. As discussed in Section 2.6, however, the silt was tested as if it is susceptible to modification when treated with lime. An assigned pH of 6.5 suggests the silty gravel is slightly acidic and does not meet the commonly accepted minimum pH of 7 or more for an untreated soil to be reactive with lime, and form cementitious CSH and CAH. Because the silty gravel's pH is relatively close to 7, it was assumed the soil may be slightly reactive with lime.

The permeability values observed within samples of the untreated, and 3% and 6% lime-treated silt, compacted in both the 4 inch and 6 inch molds, are illustrated in Figure 4.4. As illustrated in Figure 4.4, for each untreated and lime-treated variant, permeability was lower in the samples that were molded in the 4 inch molds, particularly within the untreated and 3% lime-treated samples. Generally, a soil is more densely compacted within 4 inch molds than within 6 inch molds; thus, the discrepancies in permeability within the untreated and 3% lime-treated soils are attributed to varying compaction densities.

In general, treating the silt with 3% lime resulted in a slight reduction of the soil's permeability, whereas, treating the silt with 6% lime appeared to result in an increase in permeability. As discussed in Section 2.4.2.2, several authors, including Townsend and Klym (1966) and Arabi et al. (1989), noted increased permeability in some lime-treated soil, attributing the increased permeability to flocculation and agglomeration of soil particles. These results suggest the silt's permeability will decrease when the soil is treated with low concentrations of lime and increase when the soil is treated with higher concentrations of lime. The reduced permeability observed within the samples of 3% lime-treated silt suggests flocculation and agglomeration of soil particles is not occurring at this lime content.

The permeability observed within samples of untreated, 3%, 6%, and 12% lime-treated silty gravel compacted in both the 4 inch and 6 inch molds are illustrated in Figure 4.5. The permeability observed within the samples of untreated and lime-treated silty gravel ranged

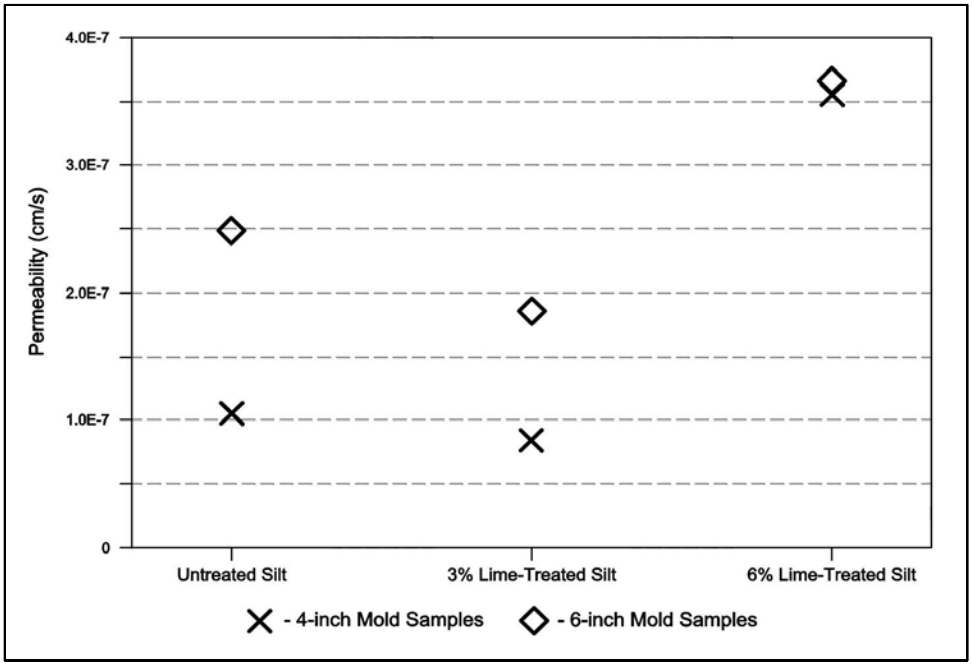

Figure 4.4: Permeability of the studied silt.

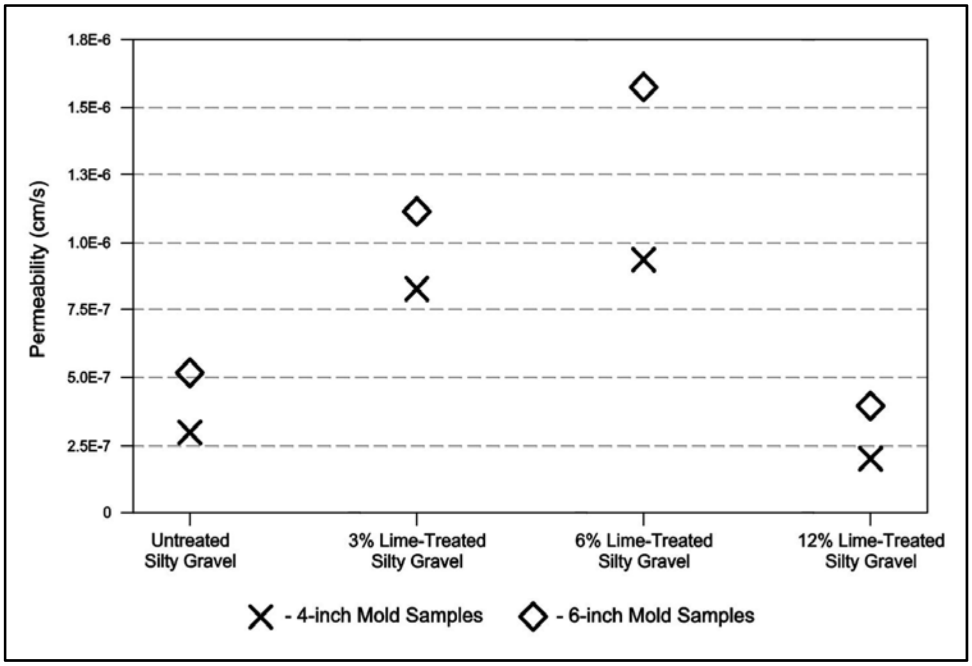

Figure 4.5: Permeability of the studied silty gravel.

from $2.0X10^{-7}$ cm/s to $1.6X10^{-6}$ cm/s. As with the silt samples, the discrepancies in permeability observed between the 4 inch and 6 inch molded samples is attributed to varying compaction densities.

Treating the silty gravel with up to 6% lime resulted in an increase in the soil's permeability, whereas the 12% lime treatment appeared to decrease the soil's permeability. The initial increase in permeability suggests flocculation and agglomeration and changes in soil fabric occurs at the 3% and 6% lime concentrations; however, the sharp decrease in permeability observed within the 12% lime-treated silty gravel suggests more extensive formation of impervious, cementitious CSH and CAH. These results suggest the silty gravel may be pozzolanically reactive with lime. In addition, the sharp permeability decrease observed in the 12% lime-treated samples that were cured for a relatively short time (less than 24 hours) suggests that the silty gravel may react pozzolanically when treated with lower concentrations of lime and allowed to cure for longer durations of time. This is further supported by the increases in relative strength observed within both the 3% and 6% lime-treated samples of the silty gravel (see Section 4.3).

4.2. Maximum Density and Optimum Moisture Content of the Studied Soils

Both the maximum density and optimum moisture content of untreated and lime-treated samples of the studied soils were determined by conducting moisture density relationship tests. Table 4.3 summarizes the samples analyzed and the maximum dry unit weight and optimum moisture content of each sample. Figures 4.6 and 4.7 illustrate the moisture density relationships for the analyzed untreated and lime treated variants of studied silt and silty gravel, respectively. The data illustrated in Figure 4.6 suggest that increasing the lime content of the silt will result in a reduction of the soil's maximum density and an increase in the soil's optimum moisture content. These results correlate with changes in the moisture-density relationship claimed to be common in lime-treated soils by Hicks (2002) and Mallela et al. (2004).

Table 4.3: Maximum dry unit weight and optimum moisture content for studied soils.

Soil	Lime Content	Max. Dry Unit Weight (lb/ft^3)	Optimum Moisture Content (%)
Silt	Untreated	92.7	19.5
	3% Lime-Treated	92.1	23.5
	6% Lime-Treated	88.4	22.3
Silty Gravel	Untreated	143.9	5.3
	6% Lime-Treated	137.2	5.7
	12% Lime-Treated	131.9	7.6

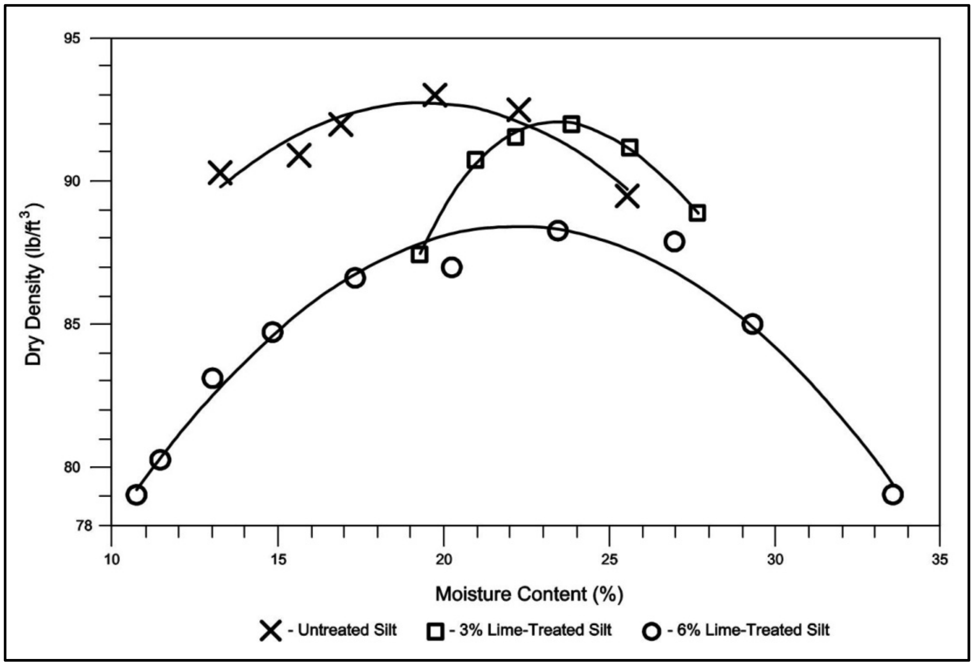

Figure 4.6: Moisture-density relationship for the studied silt.

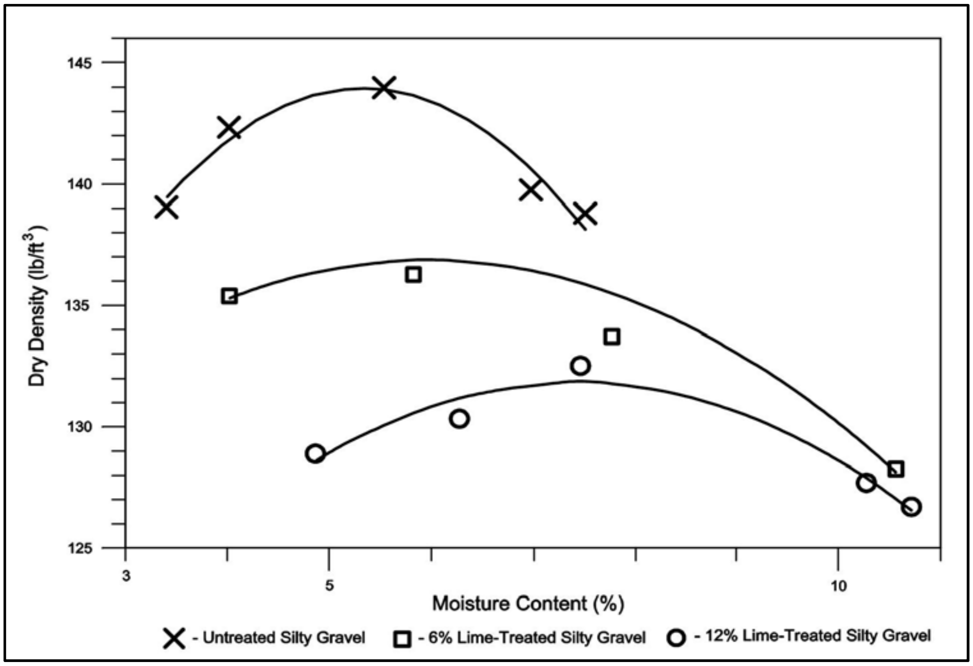

Figure 4.7: Moisture-density relationship for the studied silty gravel.

As with the silt, the data illustrated in Figure 4.7 suggests increasing the lime content of the silty gravel results in a reduction of the soil's maximum density and an increase in the soil's optimum moisture content. In addition, the widening of the lime-treated silty gravel's moisture-density curves suggests that the lime-treated soil is less sensitive to moisture content, allowing acceptable compaction densities over wider ranges of moisture content. According to Bell (1996), lime treatment of soil results in the soil being capable of obtaining sufficient density over a wider range and higher values of moisture content.

4.3. Relative Strength of the Studied Soils

The relative strength of each studied soil was analyzed by subjecting selected untreated and lime-treated samples to either the CBR test (for the silt), or the 5,000-pound test (for the silty gravel). Table 4.4 summarizes the lime content, cure duration, and CBR of the analyzed samples of silt, while the CBR of each of these samples is illustrated in Figure 4.8.

The data in Table 4.4 and Figure 4.8 illustrate an overall increase in CBR with increased lime content, but show no correlation between cure duration and CBR. These data suggest that an increase in the relative strength of the silt is a function of lime content rather than cure duration. The data also suggest the relative strength of the silt increases almost immediately upon treatment with lime, and that the relative strength of untreated silt increases when allowed to age (as shown in Sections 4.4 and 4.5, however, aged samples of the untreated silt demonstrated poor thaw performance, particularly amongst samples subjected to the second freeze test). The almost immediate increase in CBR observed within the lime-treated silt suggest that increases in strength may be due to flocculation and agglomeration of soil particles rather than a time-dependent pozzolanic reaction; however, the observed increases in strength are relatively large and correlate with observations of lime-modified soil previously made by several authors (see Section 2.4.2.1).

Table 4.5 summarizes the lime content, cure duration, and 5,000-pound penetration of the analyzed samples of silty gravel, while the 5,000-pound penetration of these samples is illustrated in Figure 4.9. The increased strength with cure duration demonstrated by these

Table 4.4: CBR of studied silt.

Soil	Lime Content	Cure/Age Duration (days)	Sample #	CBR (%)
Silt	Untreated	N/A	Sample 1	13
			Sample 2	16
		14	Sample 1	27
	3% Lime-Treated	1	Sample 1	38
			Sample 2	42
		14	Sample 1	31
			Sample 2	37
		28	Sample 1	38
			Sample 2	40
	6% Lime-Treated	1	Sample 1	50
			Sample 2	53
		14	Sample 1	47
			Sample 2	51
		28	Sample 1	53
			Sample 2	53

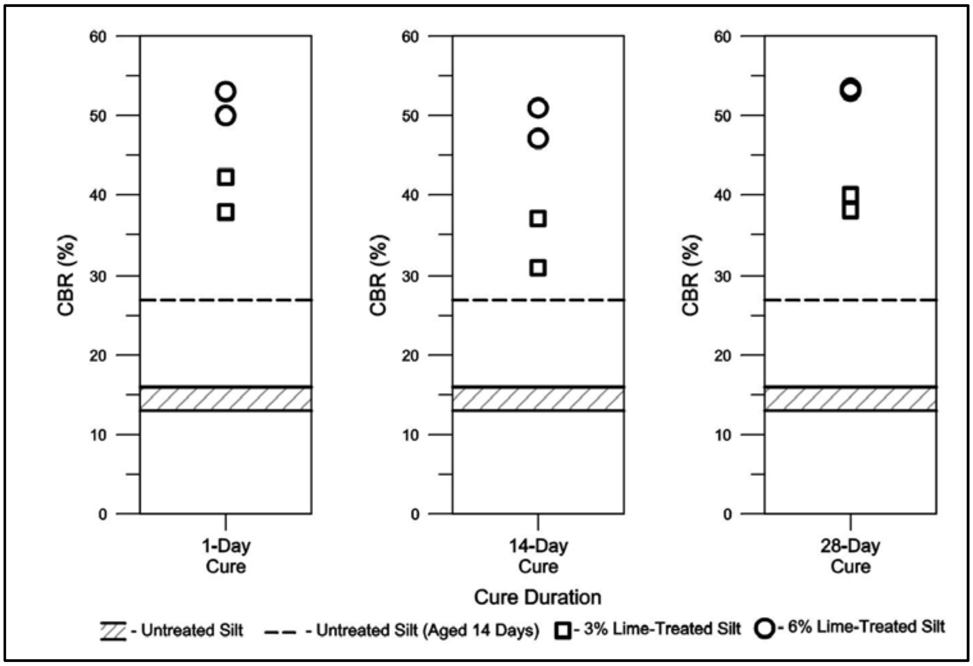

Figure 4.8: CBR of the studied silt.

Table 4.5: 5,000-pound penetration of silty gravel.

Soil	Lime Content	Cure/Age Duration (days)	Sample #	5,000-Pound Penetration (1/1000 in.)
Silty Gravel	Untreated	N/A	Sample 1	89
			Sample 2	111
		14	Sample 1	321
	3% Lime-Treated	14	Sample 1	25
			Sample 2	26
	6% Lime-Treated	14	Sample 1	26
			Sample 2	29
		28	Sample 1	14
			Sample 2	17
	12% Lime-Treated	1	Sample 1	34
			Sample 2	43
		14	Sample 1	30
			Sample 2	48
		28	Sample 1	21
			Sample 2	22

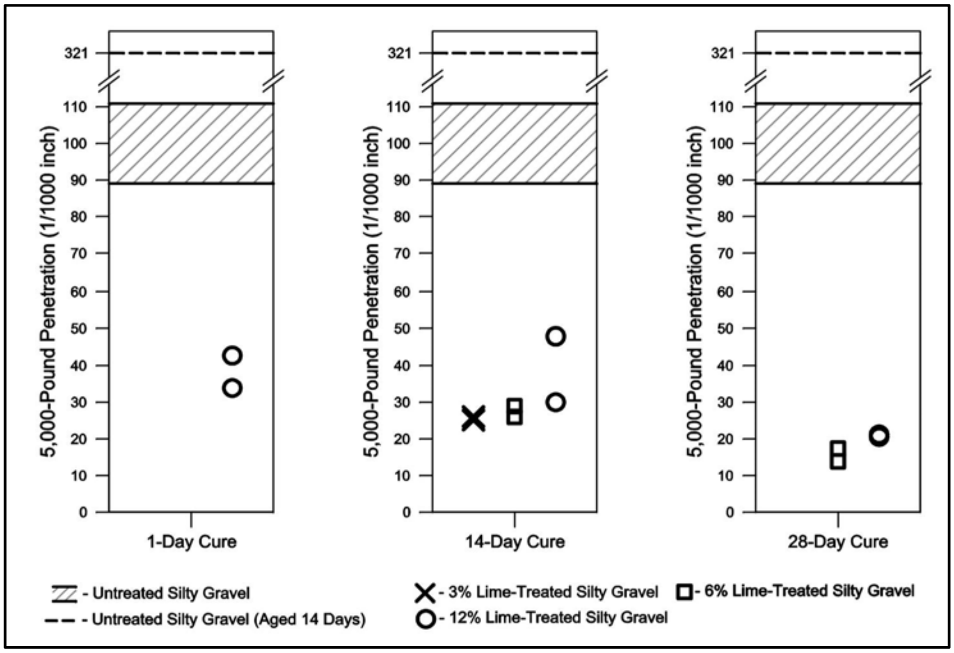

Figure 4.9: 5,000-pound penetration of silty gravel.

data suggests some degree of a pozzolanic reaction and formation of cementitious CSH and CAH may be occurring within the silty gravel when treated with lime. Furthermore, lower penetration observed within the 3% and 6% lime-treated samples suggest the optimum lime content for the silty gravel is closer to 3% to 6% than 12%.

4.4. Relative Frost Susceptibility of the Studied Soils

The relative frost susceptibility of each studied soil was analyzed by subjecting selected untreated and lime-treated samples to one of the two freeze tests and measuring frost-induced strain (see Section 3.3.5). Table 4.6 summarizes the lime content, cure duration and temperature, and frost-induced strain of each analyzed sample of silt subjected to the first freeze test, while the resulting strain for these samples is illustrated in Figure 4.10.

In general, during the first freeze test, the lime- treated samples of silt demonstrated less strain than the untreated samples, and amongst the lime-treated samples, the samples cured at 70°F (21°C) demonstrated less strain than the samples cured at 50°F (10°C). The data in Table 4.6 and Figure 4.10 indicate the frost susceptibility of the silt is reduced when the soil is treated with lime. In addition, the data suggest that further reductions in frost susceptibility will occur when the lime-treated silt is allowed to cure at warmer temperature.

Table 4.7 summarizes the lime content, cure duration, and frost-induced strain of each analyzed sample of silt subjected to the second freeze test, while the resulting strain is illustrated in Figure 4.11. During the second freeze test, the majority of the lime-treated samples demonstrated less strain then the untreated samples. The 3% lime-treated silt demonstrated a general trend of reduced strain with cure duration, with lower strain than the 6% lime-treated silt after a 28-day cure duration. As with the data from the first freeze test, these data also indicate that the silt’s frost susceptibility is reduced when the soil is treated with lime. In addition, these data indicate reductions in the soil’s frost susceptibility are larger when the soil is treated with 3% lime rather than 6% lime, and further reductions occur when the 3% lime-treated silt is allowed to cure for longer durations of time.

Table 4.6: Frost-induced strain of silt samples subjected to first freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Cure Temperature	Sample #	Frost-Induced Strain (%)
Silt	Untreated	N/A	N/A	Sample 1	0.97
				Sample 2	1.89
	6% Lime-Treated	14	50°F	Sample 1	0.27
				Sample 2	0.35
			70°F	Sample 1	0.03
				Sample 2	0.07

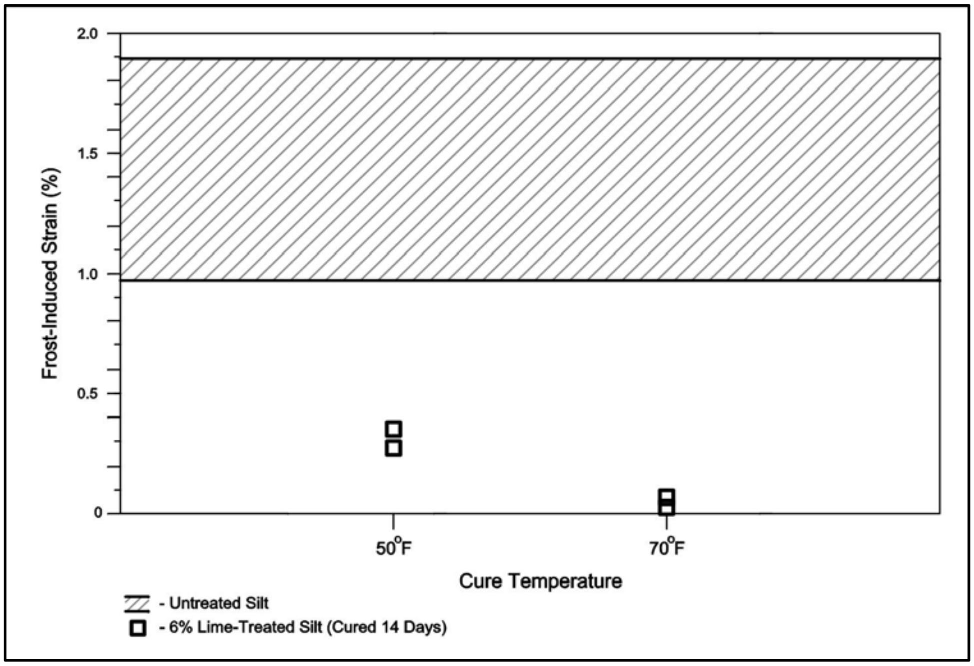

Figure 4.10: Frost-induced strain of silt samples subjected to first freeze test.

Table 4.7: Frost-induced strain of silt samples subjected to second freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Sample #	Frost-Induced Strain (%)
Silt	Untreated	N/A	Sample 1	7.88
			Sample 2	9.14
		7	Sample 1	7.16
	3% Lime-Treated	1	Sample 1	4.96
			Sample 2	8.89
		14	Sample 1	1.32
			Sample 2	2.72
			Sample 3	4.58
			Sample 4	5.06
			Sample 5	5.54
			Sample 6	5.69
		28	Sample 1	1.13
			Sample 2	1.20
	6% Lime-Treated	1	Sample 1	4.83
			Sample 2	4.94
		28	Sample 1	3.95
			Sample 2	6.27

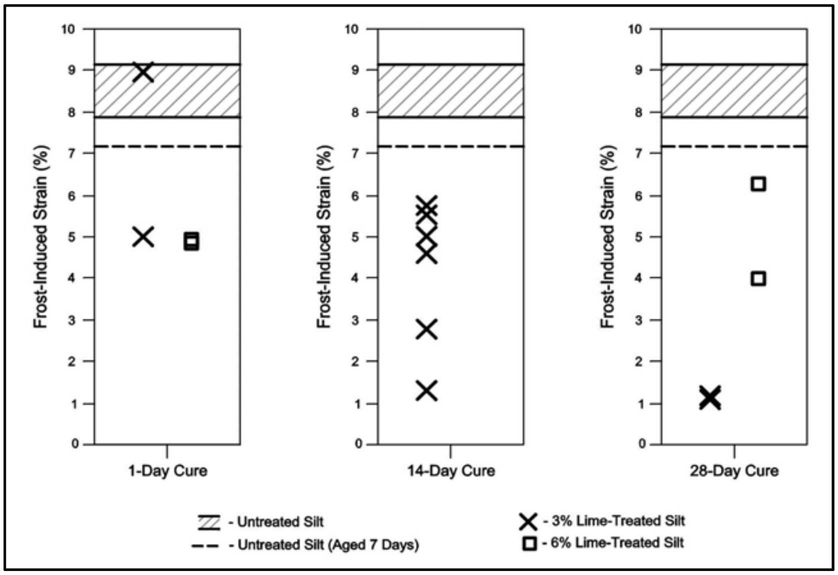

Figure 4.11: Frost-induced strain of silt samples subjected to the second freeze test.

Table 4.8 summarizes the lime content, cure duration and temperature, and frost-induced strain of each analyzed sample of silty gravel subjected to the first freeze test, while the resulting strain for these samples is illustrated in Figure 4.12. During this test, the 12% lime-treated samples demonstrated both wide variability and increases in strain, whereas the 6% lime-treated samples demonstrated no marked changes in strain. These data suggest the relative frost susceptibility of the silty gravel increases when the soil is treated with 12% lime, and generally does not change when the soil is treated with 6% lime. In addition, the data indicates that cooler cure temperature has no adverse effect on the frost susceptibility of the silty gravel treated with 12% lime (the effect cure temperature has on the frost susceptibility of the silty gravel is discussed more thoroughly in Section 4.8).

Table 4.9 summarizes the lime content, cure duration, and frost-induced strain of each analyzed sample of silty gravel subjected to the second freeze test, while the resulting strain for these samples is illustrated in Figure 4.13. These data show the strain demonstrated by all of the silty gravel is comparable, and the maximum and minimum strain observed within the samples of 3% lime-treated silty gravel fully encompass the strain observed within the untreated samples. As with the data from the first freeze test, these data suggest treating the silty gravel with concentrations of lime of 3% does not affect the soil's frost susceptibility.

4.5. Thaw Strength of the Studied Soils

The thaw strength of the studied soils was analyzed by conducting CBR tests on selected untreated and lime-treated samples that were previously subjected to one of the two freeze tests, and comparing the CBR results to those of similarly treated and cured samples of silt not subjected to freezing. Table 4.10 summarizes the lime content, cure duration and temperature, and CBR of each analyzed sample of silt, while the CBR for these samples is illustrated in Figure 4.14.

As shown by the data in Table 4.10 and Figure 4.14, the CBR values observed within both the untreated and lime-treated silt samples that were subjected to the first freeze test did not vary significantly from the values observed within the similarly treated silt samples that were not

Table 4.8: Frost-induced strain of silty gravel samples subjected to first freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Cure Temperature	Sample #	Frost-Induced Strain (%)
Silty Gravel	Untreated	N/A	N/A	Sample 1	0.24
				Sample 2	0.45
	6% Lime-Treated	14	70°F	Sample 1	0.34
				Sample 2	0.34
		28	70°F	Sample 1	0.37
				Sample 2	0.45
	12% Lime-Treated	1	70°F	Sample 1	0.70
				Sample 2	0.79
		14	70°F	Sample1	0.35
				Sample 2	0.41
				Sample 3	0.44
				Sample 4	0.49
				Sample 5	1.17
				Sample 6	1.73
		28	50°F	Sample 1	0.49
				Sample 2	0.94
			70°F	Sample 1	0.65
				Sample 2	1.57

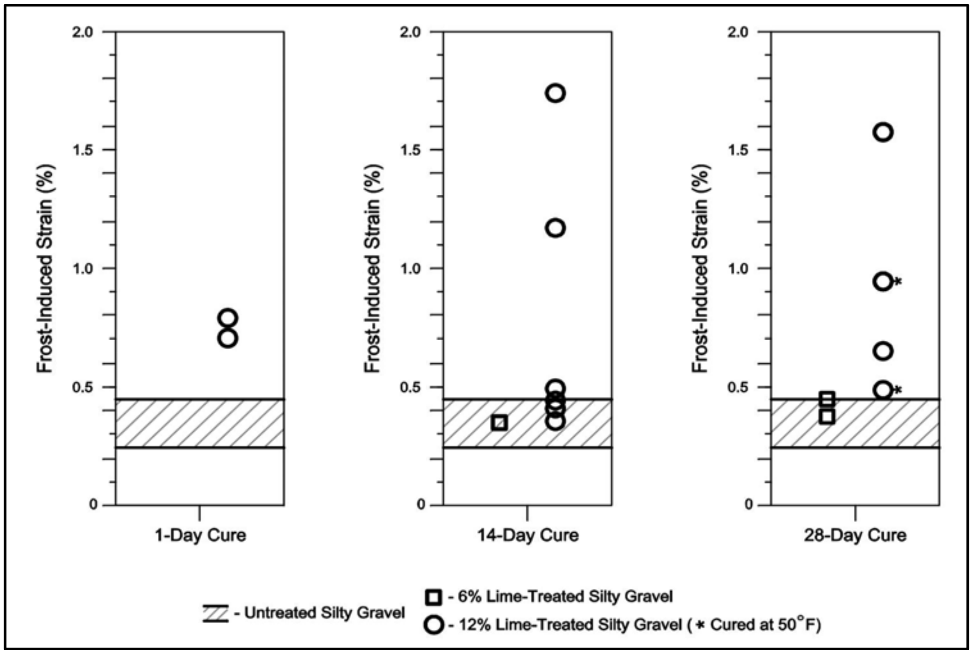

Figure 4.12: Frost-induced strain of silty gravel samples subjected to first freeze test.

Table 4.9: Frost-induced strain of silty gravel samples subjected to second freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Sample #	Frost-Induced Strain (%)
Silty Gravel	Untreated	N/A	Sample 1	3.95
			Sample 2	4.65
	3% Lime-Treated	10	Sample 1	3.13
			Sample 2	5.04

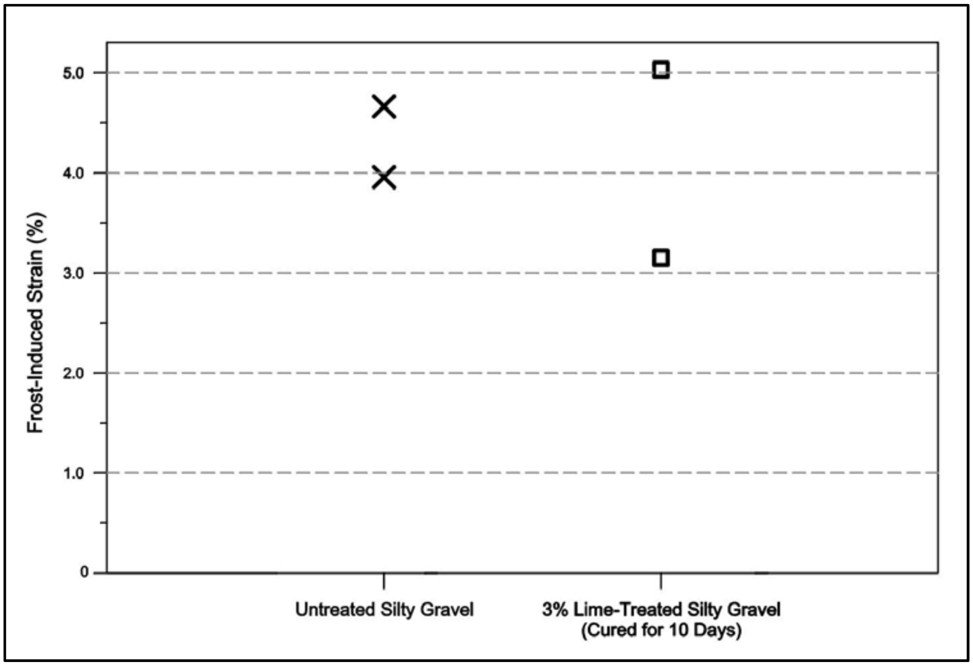

Figure 4.13: Frost-induced strain of silty gravel samples subjected to second freeze test.

Table 4.10: CBR of silt samples subjected to first freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Cure Temperature	Freeze Test	Sample #	CBR (%)
Silt	Untreated	N/A	N/A	N/A	Sample 1	13
					Sample 2	16
				First	Sample 1	11
					Sample 2	16
	6% Lime-Treated	14	50°F	N/A	Sample 1	46
					Sample 2	49
				First	Sample 1	53
					Sample 2	54
			70°F	N/A	Sample 1	47
					Sample 2	51
				First	Sample 1	44
					Sample 2	46

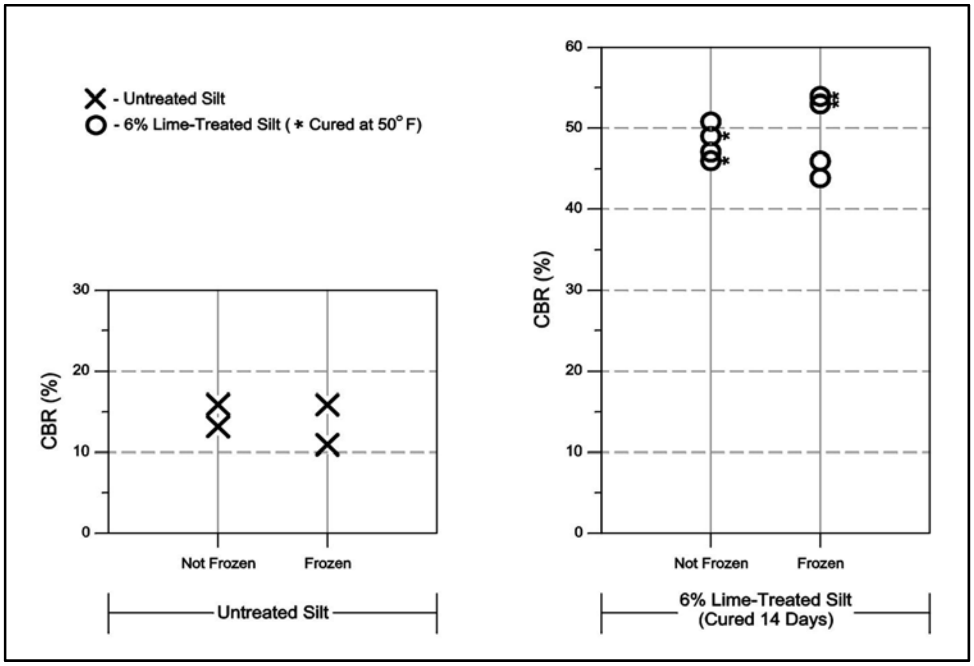

Figure 4.14: CBR of silt samples subjected to first freeze test.

frozen. These results suggest freezing conditions similar to those simulated by the first freeze test do not have an adverse effect on the thaw strength of the silt. This may be attributed to the lack of strain demonstrated by these samples during the first freeze test.

Table 4.11 summarizes the lime content, cure duration, and CBR of each analyzed sample of silt, while the resulting strain for these samples is illustrated in Figure 4.15. In addition, Table 4.11 lists the loss of CBR demonstrated by the samples of silt that were frozen, while Figure 4.16 illustrates CBR loss as a function of strain demonstrated by these samples. CBR loss is reported in percent and is defined by the following equation:

$$\text{CBR Loss (\%)}=\left(\frac{(\text{CBR}_{\text{AVE1}})\text{-}(\text{CBR}_{\text{AVE2}})}{(\text{CBR}_{\text{AVE1}})}\right)\times 100 \tag{4.1}$$

where CBR_{AVE1} and CBR_{AVE2} are the average CBR of samples not subjected to, and subjected to freezing, respectively.

As shown by these data, the samples of lime-treated silt demonstrated more thaw strength, and less CBR loss than did the untreated samples. Although the samples of 6% lime-treated silt generally displayed more thaw strength than did the 3% lime-treated samples, the samples of 3% lime-treated silt that were cured for 28 days displayed less CBR loss than did the similarly cured 6% lime-treated samples. These results suggest lime treatment may result in increased thaw strength and reduced CBR loss within the silt. The results also suggest that the silt may exhibit increased thaw strength when treated with higher concentrations of lime (within the limits of analyzed lime concentrations). The variance in thaw strength between the 3% and 6% lime-treated silt appears minimal, however, particularly compared to the increased thaw strength observed between the untreated and lime-treated silt. In addition the general increase in CBR loss with increased strain illustrated in Figure 4.16 suggests that lime treatment can serve to not only reduce the frost susceptibility of the studied silt, but to also increase the soil’s thaw strength and reduce its thaw strain.

Table 4.12 summarizes the lime content, cure duration, penetration observed within each analyzed sample of silty gravel either subjected to the first freeze test or not frozen, while the

Table 4.11: CBR of silt samples subjected to second freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Freeze Test	Sample #	CBR (%)	Average CBR Loss (%)
Silt	Untreated	N/A	N/A	Sample 1	13	N/A
				Sample 2	16	
			Second	Sample 1	6	55
				Sample 2	7	
		14	N/A	Sample 1	27	N/A
		7	Second	Sample 1	7	74
	3% Lime-Treated	1	N/A	Sample 1	38	N/A
				Sample 2	42	
			Second	Sample 1	23	38
				Sample 2	27	
		14	N/A	Sample 1	31	N/A
				Sample 2	37	
			Second	Sample 1	19	39
				Sample 2	23	
		28	N/A	Sample 1	38	N/A
				Sample 2	40	
			Second	Sample 1	28	28
				Sample 2	28	
	6% Lime-Treated	1	N/A	Sample 1	50	N/A
				Sample 2	53	
			Second	Sample 1	35	30
				Sample 2	37	
		14	N/A	Sample 1	47	N/A
				Sample 2	51	
		28	N/A	Sample 1	53	N/A
				Sample 2	53	
			Second	Sample 1	32	40
				Sample 2	32	

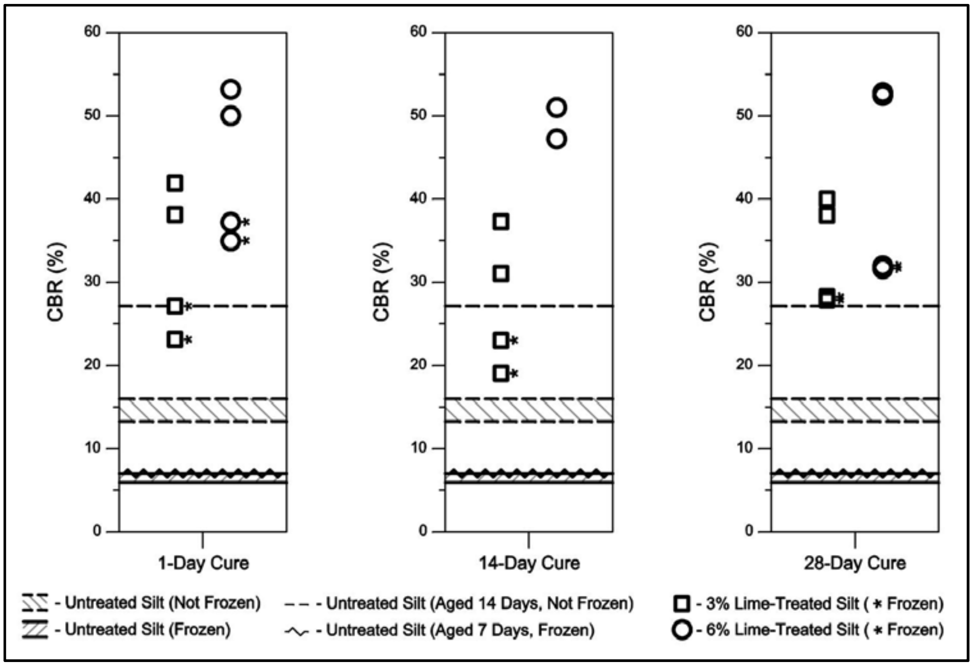

Figure 4.15: CBR of silt samples subjected to second freeze test.

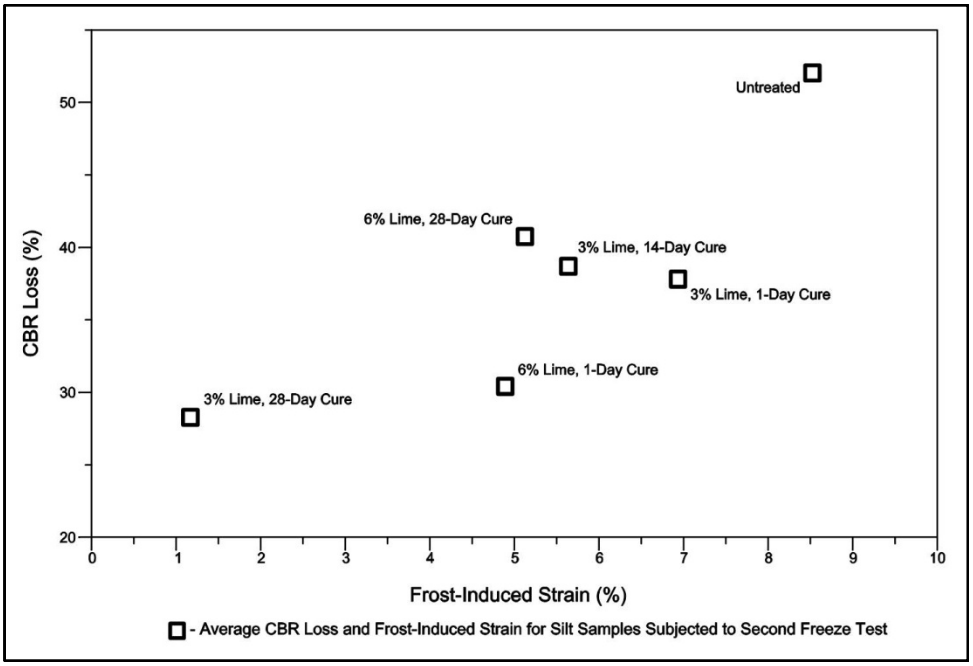

Figure 4.16: CBR loss as a function of strain for samples of silt subjected to second freeze test.

Table 4.12: 5,000-pound penetration of silty gravel samples subjected to first freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Freeze Test	Sample #	5,000-Pound Penetration (1/1000 in.)	Average Increase in 5,000-pound Penetration (1/1000 in.)
Silty Gravel	Untreated	N/A	N/A	Sample 1	89	N/A
				Sample 2	111	
			First	Sample 1	225	152
				Sample 2	280	
	6% Lime-Treated	14	N/A	Sample 1	26	N/A
				Sample 2	29	
			First	Sample 1	29	11
				Sample 2	50	
		28	N/A	Sample 1	14	N/A
				Sample 2	17	
			First	Sample 1	39	27
				Sample 2	46	
	12% Lime-Treated	1	N/A	Sample 1	34	N/A
				Sample 2	43	
			First	Sample 1	60	26
				Sample 2	70	
		14	N/A	Sample 1	30	N/A
				Sample 2	48	
			First	Sample 1	14	0
				Sample 2	63	
		28	N/A	Sample 1	21	N/A
				Sample 2	22	
			First	Sample 1	20	-9
				Sample 2	6	

resulting penetration for these samples is illustrated in Figure 4.17. These data illustrate that the samples of lime-treated silty gravel demonstrated less penetration than the untreated samples. In addition, variance in penetration between unfrozen and similarly treated and cured frozen samples was smaller in the lime-treated samples than the untreated samples. These data also show that the samples of 12% lime-treated silty gravel that were both cured for 14 days or 28 days and then frozen did not demonstrate an average increase in penetration over the similarly treated and cured samples that were not frozen. Rather, amongst these samples, the samples cured for 28 days demonstrated a slight reduction in penetration.

The lack of reduction in thaw strength (penetration under the 5,000-pound load) demonstrated by the silt samples subjected to the first freeze test is attributed to the minor frost heave these samples exhibited while frozen. The silty gravel, however, does not appear to have the same relationship. While demonstrating as much or more frost heave during both freeze tests, the lime-treated silty gravel demonstrated more thaw strength than the untreated samples. These data suggest that in spite of being more frost susceptible (albeit a small and possibly insignificant amount), an increase in thaw strength may be exhibited by the silty gravel when treated with lime. These data also suggest further increases in thaw strength of the silty gravel may be exhibited when this soil is treated with lime and allowed to cure for increased durations of time. Increases in this soil’s thaw strength with increased cure duration, however, may be minimal, particularly when compared to increases in thaw strength for any cure duration.

Table 4.13 summarizes the lime content, cure duration, and penetration observed within each analyzed sample of silty gravel. Because the analyzed suite of 3% lime-treated samples of silty gravel were cured at varying duration, it was not possible to make a direct comparison. The data in Table 4.13, however, may provide some insight on the effect treating the silt with 3% lime has on the soil’s thaw strength. Similar to the results from the first freeze test, these data illustrate that the samples of 3% lime-treated silty gravel demonstrated less penetration than the untreated samples. In addition, variance in penetration between unfrozen and frozen samples was smaller in the 3% lime-treated samples than the untreated samples.

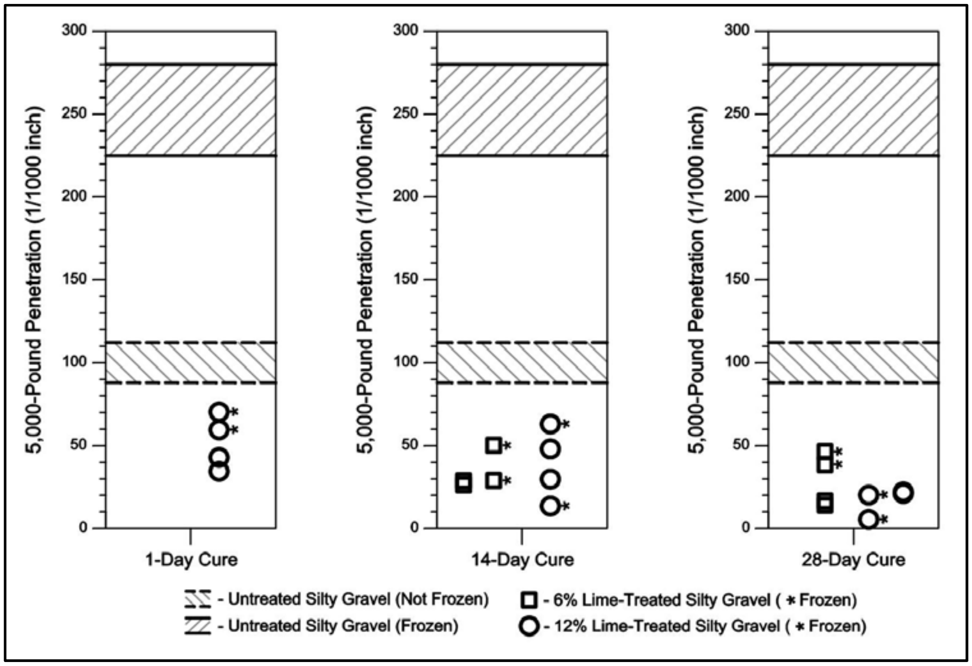

Figure 4.17: 5,000-pound penetration of silty gravel samples subjected to the first freeze test.

Table 4.13: 5,000-pound penetration of silty gravel samples subjected to second freeze test.

Soil	Lime Content	Cure/Age Duration (days)	Freeze Test	Sample #	5,000-Pound Penetration (1/1000 in.)	Average Increase in 5,000-pound Penetration (1/1000 in.)
Silty Gravel	Untreated	N/A	N/A	Sample 1	89	N/A
				Sample 2	111	
			Second	Sample 1	633	617
				Sample 2	801	
	3% Lime-Treated	14	N/A	Sample 1	25	N/A
				Sample 2	26	
		10 (+14)	Second	Sample 1	26	2.5
				Sample 2	30	

As with the first freeze test, during the second freeze test, the lime-treated samples demonstrated frost heave similar in magnitude to the untreated samples; however, as shown in Table 4.13 the samples of 3% lime-treated silty gravel demonstrated less thaw strain than the untreated samples. These results suggest that in spite of having similar frost heave characteristics as the untreated silty gravel, an increase in thaw strength may be exhibited in the silty gravel when treated with 3% lime, particularly when allowed to cure for an additional 14 days after thawing.

4.6. Post-Thaw Strength of the Studied Soils

The post-thaw strength analysis involved subjecting selected samples of lime-treated silt and silty gravel, that were previously frozen and allowed to cure for additional time, to either the CBR test (for silt) or the 5,000-pound test (for silty gravel). Table 4.14 summarizes the lime content, initial and additional cure time, and CBR of each analyzed sample of 3% lime-treated silt that were initially cured for 14 days, while the CBR for these samples is illustrated in Figure 4.18.

All samples of 3% lime-treated silt that were frozen demonstrated lower CBR values than the samples of 3% lime-treated silt that were not frozen. Amongst the samples that were frozen, the samples that were allowed to cure for an additional 7 days demonstrated CBR values similar to those demonstrated by the samples that were not allowed to cure for additional time, while the samples that were allowed to cure for an additional 14 days demonstrated higher CBR values. In addition, the CBR values demonstrated by the frozen lime-treated silt samples that were allowed to cure for an additional 14 days approached those demonstrated by the samples that were not frozen. These results indicate that an increase in post-thaw strength may be realized in the silt when treated with lime and allowed to cure for durations of time exceeding 14 days upon thawing. These results also suggest that when allowed to cure for moderate durations of time after thawing, the strength of the lime-treated and previously-frozen silt may approach that of similarly treated silt that was not frozen. The

Table 4.14: CBR of silt samples subjected to the post-thaw curing and strength analysis.

Soil	Initial Cure Duration (days)	Additional Cure Duration (days)	Freeze Test	Sample #	CBR (%)
3% Lime-Treated Silt	14	N/A	N/A	Sample 1	31
				Sample 2	37
			Second	Sample 1	19
				Sample 2	23
		7	Second	Sample 1	21
				Sample 2	23
		14	Second	Sample 1	24
				Sample 2	30

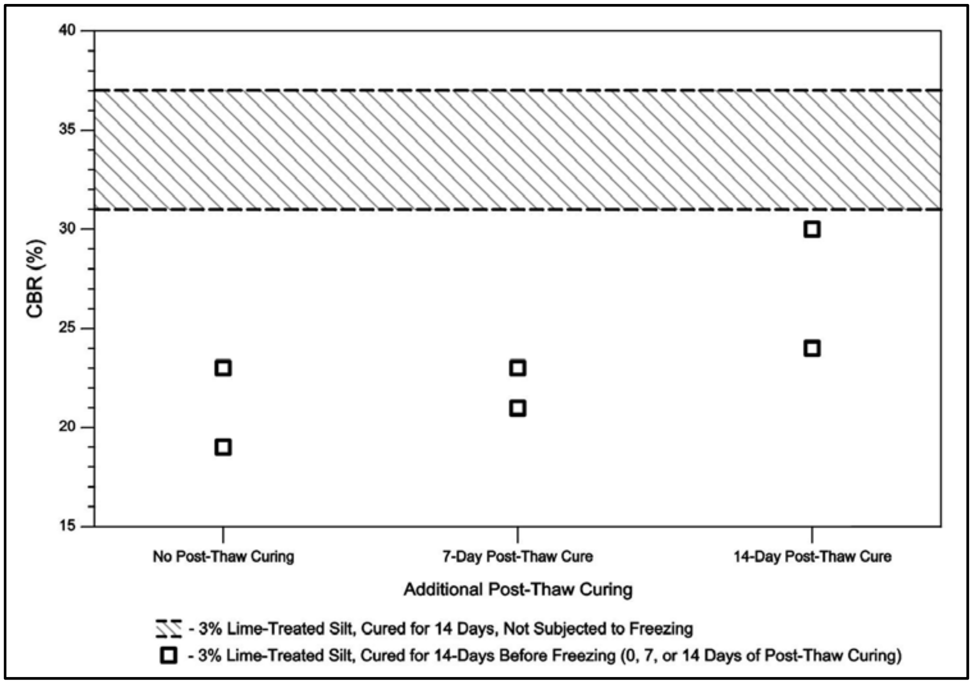

Figure 4.18: CBR of silt samples subjected to the post-thaw curing and strength analysis.

recovery of strength over time demonstrated by these lime-treated samples may be attributed to a pozzolanic reaction, suggesting the silt may be slightly reactive to lime.

Table 4.15 summarizes the lime content, initial and additional cure time, and penetration of each analyzed sample of silty gravel. Amongst these samples, the penetration demonstrated by 12% lime-treated samples subjected to the first freeze test are illustrated in Figure 4.19. A figure for the analyzed samples of 3% lime-treated silty gravel that were subjected to the second freeze test was not developed due to these samples having varying initial cure durations.

The two previously frozen samples of 12% lime-treated silty gravel that were not cured for additional time exhibited a wide range of penetration (141 and 632 thousandths of an inch). If the lower of these two values was treated as an outlier, the data would demonstrate a general decrease in penetration with increased post-thaw cure duration amongst the samples of previously frozen lime-treated silt. The lower penetration value, however, cannot be conclusively determined as an outlier due the limited data. Figure 4.19 does, however, illustrate a penetration decrease between the samples of previously frozen 12% lime-treated samples that were cured for an additional 14 days and 28 days, respectively. Furthermore, amongst the samples of previously frozen 12% lime-treated silty gravel, the average penetration for the two samples that were cured for an additional 14 days was less than the average penetration value for the two samples that were not frozen, while the penetration demonstrated by both samples that were cured for an additional 28 days was less than that demonstrated by both samples that were not frozen.

Because the initial cure duration for the previously frozen samples of 3% lime-treated silty gravel differed from the samples that were not frozen, a direct analysis of the effect that 3% lime treatment has on the post-thaw strength of the silty gravel could not be made. Due to the small variance in the initial cure duration of these samples, however, it was believed this analysis would too provide some insight on the effect that additional cure time after thawing has on the soil’s strength. As shown in Table 4.15 the penetration demonstrated among all of

Table 4.15: 5,000-pound penetration of silty gravel samples subjected to the post-thaw strength analysis.

Soil	Lime Content	Initial Cure Duration (days)	Additional Cure Duration (days)	Freeze Test	Sample #	5,000-Pound Penetration (1/1000 in.)
Silty Gravel	3% Lime	14	N/A	N/A	Sample 1	25
					Sample 2	26
		10	14	Second	Sample 1	26
					Sample 2	30
	12% Lime	14	N/A	N/A	Sample 1	297
					Sample 2	477
				First	Sample 1	141
					Sample 2	632
			14	First	Sample 1	222
					Sample 2	376
			28	First	Sample 1	184
					Sample 2	191

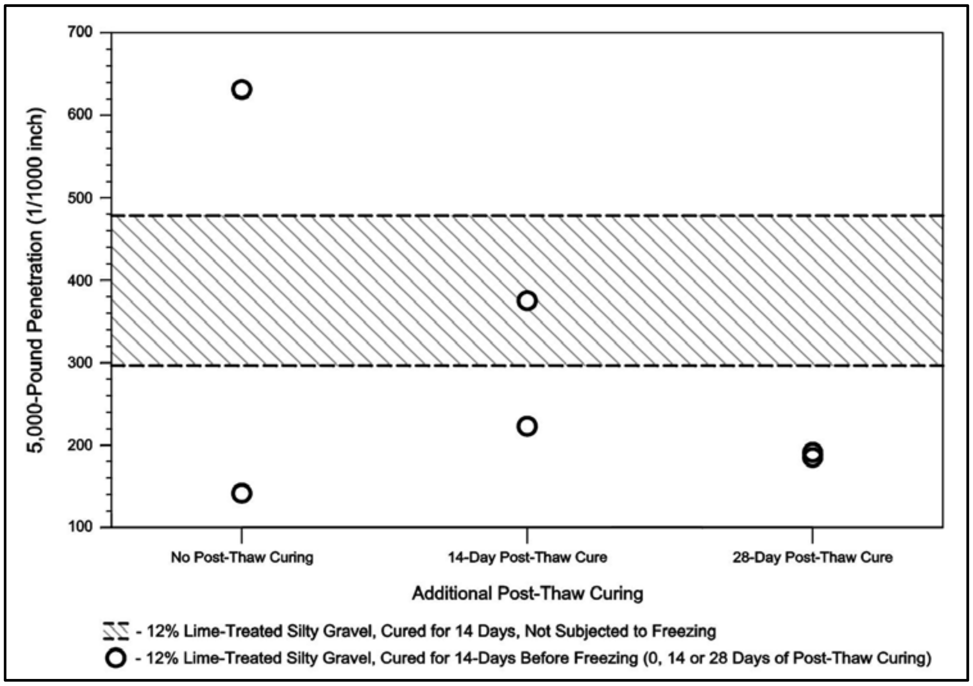

Figure 4.19: 5,000-pound penetration of 12% lime-treated silty gravel samples subjected to the post-thaw strength analysis.

the samples of 3% lime-treated silty gravel was similar in magnitude, and there was only approximately 2.5 thousandths of an inch average increase in penetration between the unfrozen and frozen samples.

These results suggest portions of any loss in strength of the lime-treated silty gravel due to freezing may be recovered when the soil is allowed to cure after thawing. In addition, these results suggest when allowed sufficient post-thaw curing, the strength of the lime-treated silty gravel may exceed that of the similarly treated silty gravel that was not subjected to freezing. The continued strength increases over time demonstrated by the previously frozen lime-treated silty gravel suggests this soil maybe pozzolanically reactive to lime.

4.7. Cure Temperature and Relative Strength of the Studied Soils

To characterize the effect cure temperature has on the strength of the studied soils, a comparison was made between either the CBR (for the silt) or 5,000-pound penetration (for the silty gravel) of selected untreated, and lime-treated samples that were cured at 50°F (10°C) and 70°F (21°C), respectively. Table 4.16 illustrates the lime content, cure duration and temperature, and CBR of the analyzed samples of silt, while Figure 4.20 illustrates the resulting CBR of these samples.

As illustrated in Figure 4.20, the CBR values for the lime-treated silt are significantly higher than the CBR values of the untreated silt. There is no significant variation between the CBR values demonstrated by the samples of 6% lime-treated silt that were cured at 50°F (10°C), and 70°F (21°C). These results indicate that cure temperatures within the analyzed temperature range do not have a significant effect on the strength of the lime-treated silt. This lack of temperature dependency, suggests strength increases observed within the lime-treated silt are due to cation exchange and flocculation and agglomeration of soil particles more than the formation of cementitious CSH and CAH (which are more temperature dependent).

Table 4.17 illustrates the lime content, cure duration and temperature, and 5,000-pound penetration of the analyzed samples of silty gravel, while Figure 4.21 illustrates the resulting

Table 4.16: CBR of lime-treated silt cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	CBR (%)
Silt	Untreated	N/A	N/A	Sample 1	13
				Sample 2	16
	6% Lime	14	50°F	Sample 1	46
				Sample 2	49
			70°F	Sample 1	47
				Sample 2	51

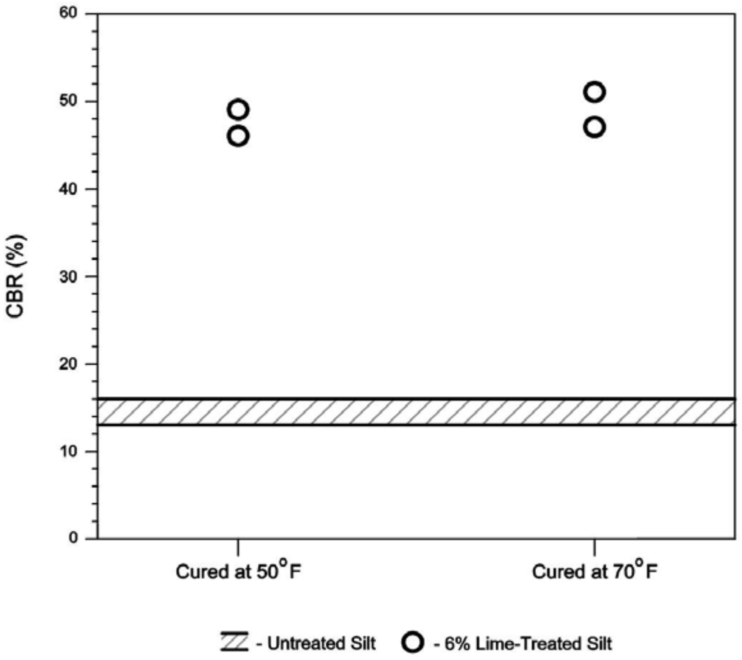

Figure 4.20: CBR of lime-treated silt cured at 50°F and 70°F.

Table 4.17: 5,000-pound penetration of lime-treated silty gravel cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	5,000-Pound Penetration (1/1000 in.)
Silty Gravel	Untreated	N/A	N/A	Sample 1	89
				Sample 2	111
	6% Lime	14	50°F	Sample 1	28
				Sample 2	41
			70°F	Sample 1	21
				Sample 2	22

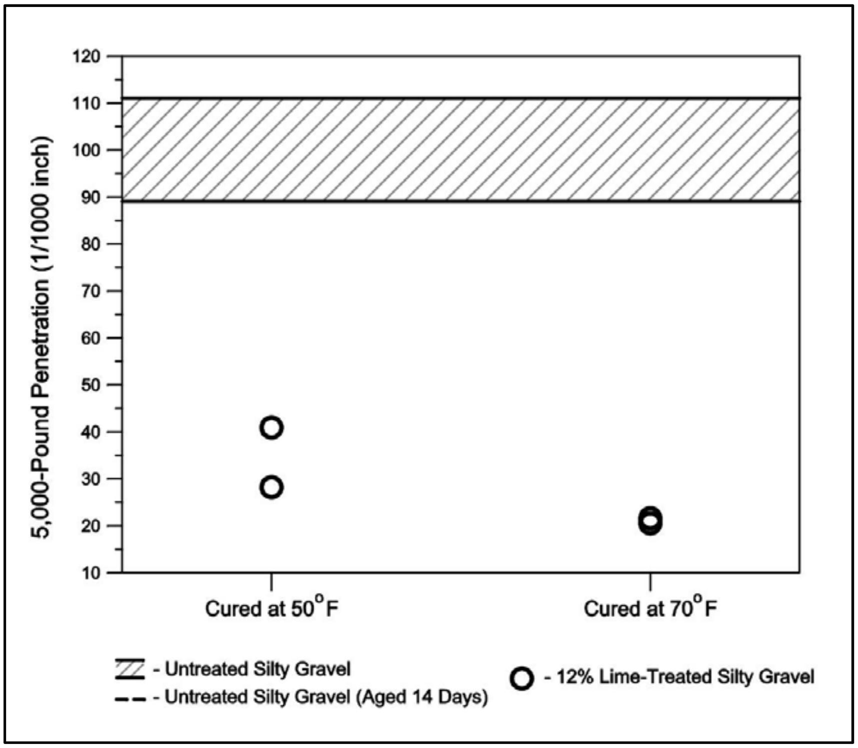

Figure 4.21: 5,000-pound penetration of lime-treated silty gravel cured at 50°F and 70°F.

5,000-pound penetration of these samples. The penetration observed within the samples of lime-treated silty gravel was significantly lower than the penetration observed within the untreated samples. Amongst the lime-treated samples of silty gravel, the penetration observed within the samples that were cured at 70°F (21°C) was lower than the penetration observed within the samples that were cured at 50°F. (10°C) These results suggest a small increase in the strength of the lime-treated silty gravel may occur when the soil is cured at warmer temperatures within the analyzed temperature range. The temperature induced variation in the strength of the lime-treated silty gravel, however, is small compared to the general increase in strength between the untreated and lime-treated silty gravel. These data suggest that the largest improvement in strength may be due to flocculation and agglomeration of soil particles. The slightly lower penetration observed within the lime-treated silty gravel cured at 70°F (21°C), however, suggests a small component of strength increase may be due to a pozzolanic reaction.

4.8. Cure Temperature and Relative Frost Susceptibility of the Studied Soils

To characterize the effect cure temperature has on the frost susceptibility of the studied soils, a comparison was made between the frost-induced strain exhibited by selected untreated, and lime-treated samples that were cured at 50°F (10°C) and 70°F (21°C), respectively. Table 4.18 illustrates the lime content, cure duration and temperature, and frost-induced strain of the analyzed samples of silt, while Figure 4.22 illustrates the resulting frost-induced strain of these samples.

As illustrated in Figure 4.22, the strain demonstrated by the samples of lime-treated silt was lower than that of the untreated samples. Amongst the lime-treated samples of silt, the strain demonstrated by the samples that were cured at 70°F (21°C) was lower than that of the samples that were cured at 50°F (10°C). These results suggest a slight reduction in the frost susceptibility of the lime-treated silt may occur when the soil is cured at warmer temperatures within the analyzed temperature range. The temperature induced reduction of the lime-treated silt's frost susceptibility, however, is small compared to the general frost

Table 4.18: Frost-induced strain of lime-treated silt cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	Frost-Induced Strain (%)
Silt	Untreated	N/A	N/A	Sample 1	0.97
				Sample 2	1.89
	6% Lime	14	50°F	Sample 1	0.27
				Sample 2	0.35
			70°F	Sample 1	0.03
				Sample 2	0.07

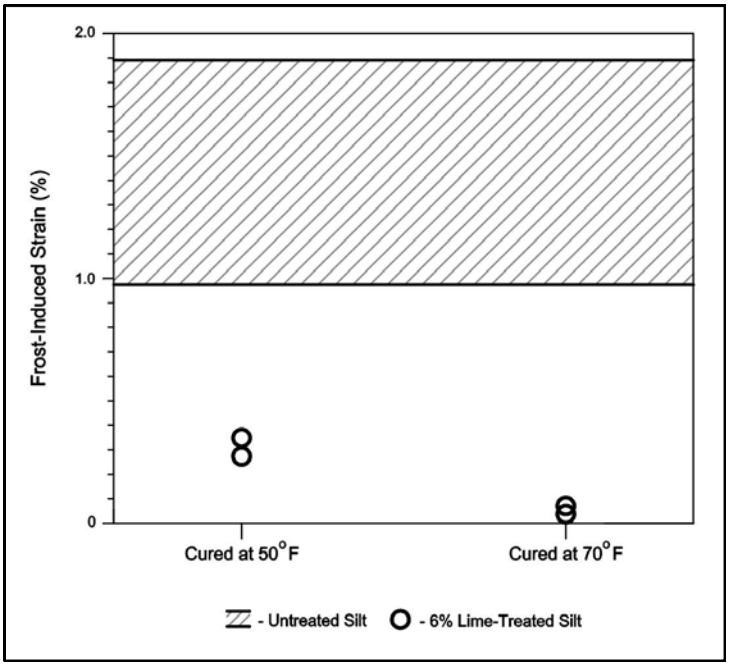

Figure 4.22: Frost-induced strain of lime-treated silt cured at 50°F and 70°F.

susceptibility reductions between the untreated and lime-treated silt. Albeit relatively small, the temperature induced reductions in frost susceptibility between the lime-treated samples of silt subjected to this analysis suggest a slight level of interparticle bonding may have occurred; particularly within the samples that were cured at approximately 70^{o}F (21^{o}C).

Table 4.19 illustrates the lime content, cure duration and temperature, and frost-induced strain of the analyzed samples of silty gravel, while Figure 4.23 illustrates the resulting frost-induced strain of thesesamples.

As illustrated in Figure 4.23, the strain demonstrated by the samples of lime-treated silty gravel was higher than that of the untreated samples. Amongst the lime-treated samples of silty gravel, the strain demonstrated by the samples that were cured at 70^{o}F (21^{o}C) was higher than that of the samples that were cured at 50^{o}F (10^{o}C). These results suggest a slight increase in the frost susceptibility of the lime-treated silty gravel may occur when this soil is treated with lime, particularly when cured at warmer temperatures within the analyzed temperature range. These results are counter to what was expected; however, as previously noted, soils subjected to the first freeze test generally exhibited relatively low strain and frost heave on the order of 2% or less is minor.

4.9. Cure Temperature and Thaw Strength of the Studied Soils

To characterize the effect cure temperature has on the thaw strength of both studied lime-treated soils, a comparison was made between the CBR (for the silt) and 5,000-pound penetration (for the silty gravel) exhibited by selected, previously frozen, untreated and lime-treated samples of these soils. The lime-treated samples analyzed included samples that were cured at 50^{o}F (10^{o}C) and 70^{o}F (21^{o}C).

Table 4.20 illustrates the lime content, cure duration and temperature, and CBR of the analyzed samples of silt, while Figure 4.24 illustrates the CBR of these samples. The post-thaw CBR demonstrated by the samples of lime-treated silt was higher than that of the untreated samples. Amongst the lime-treated samples of silt, the CBR demonstrated by the samples that

Table 4.19: Frost-induced strain of lime-treated silty gravel cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	Frost-Induced Strain (%)
Silty Gravel	Untreated	N/A	N/A	Sample 1	0.24
				Sample 2	0.45
	12% Lime	28	50°F	Sample 1	0.49
				Sample 2	0.94
			70°F	Sample 1	0.65
				Sample 2	1.57

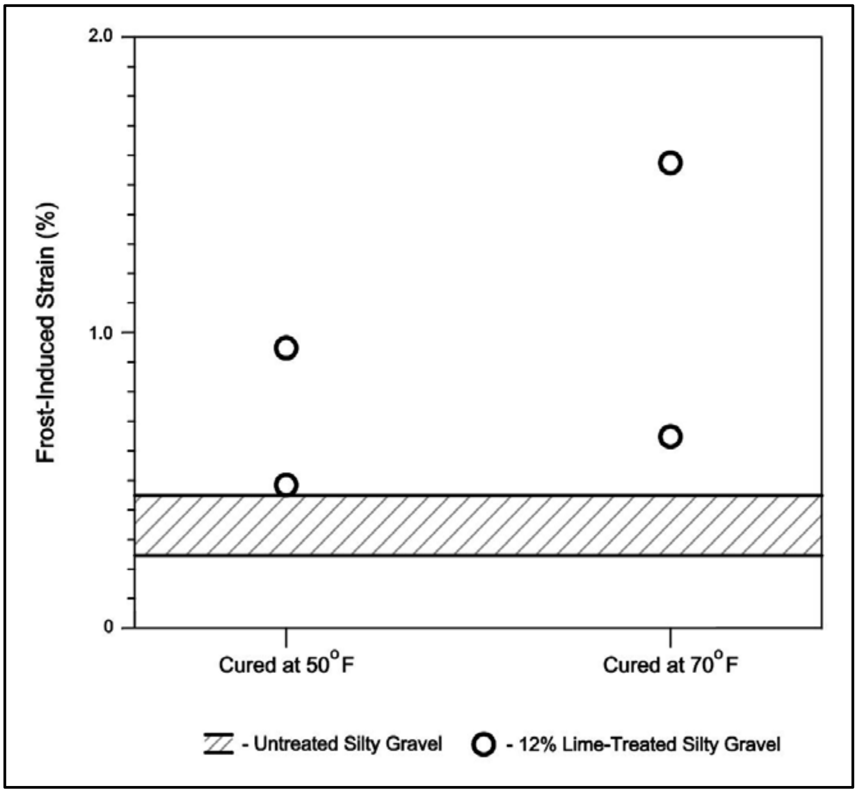

Figure 4.23: Frost-induced strain of lime-treated silty gravel cured at 50°F and 70°F.

Table 4.20: CBR of previously frozen lime-treated silt cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	CBR (%)
Silt	Untreated	N/A	N/A	Sample 1	11
				Sample 2	16
	6% Lime	14	50°F	Sample 1	53
				Sample 2	54
			70°F	Sample 1	44
				Sample 2	46

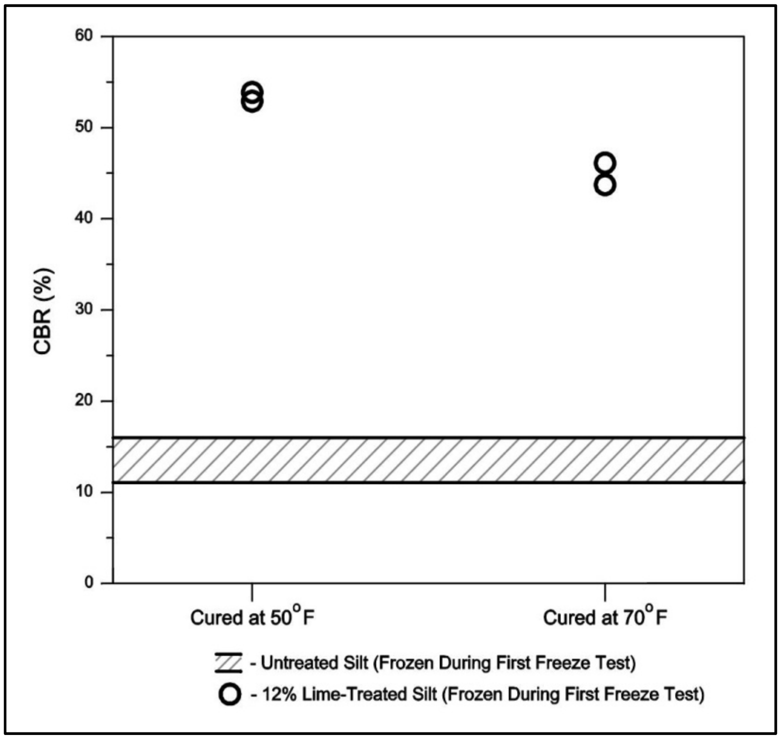

Figure 4.24: CBR of previously frozen lime-treated silt cured at 50°F and 70°F.

were cured at 70°F (21°C) was lower than that of the samples that were cured at 50°F (10°C). These results suggest an increase in the silt's thaw strength will occur when the soil is treated with lime. These results also suggest, however, that increases in the lime-treated silt's thaw strength are larger when the soil is cured at lower temperatures (within analyzed temperature range), which is counter to what was expected. The temperature induced variability of the lime-treated silt's thaw strength, however, is small compared to the general increases in the silt's thaw strength when treated with lime.

Table 4.21 illustrates the lime content, cure duration and temperature, and penetration of the analyzed samples of silty gravel, while Figure 4.25 illustrates the resulting penetration of these samples. The penetration observed within the samples of lime-treated silty gravel was lower than that of the untreated samples. In addition, amongst the lime-treated samples of silty gravel, the penetration observed within the samples that were cured at 70°F (21°C) was lower than that observed within the samples that were cured at 50°F (10°C). This is in spite of these samples displaying more frost heave on average than the samples that were cured at 50°F (10°C) (see Section 4.4). These results suggest an increase in the silty gravel's thaw strength will occur when the soil is treated with lime. These results also suggest that increases in the lime-treated silty gravel's thaw strength are larger when the soil is cured at warmer temperatures (within analyzed temperature range). Finally, these results suggest, in spite of being non-plastic, and having a low pH, in addition to flocculation and agglomeration of soil particles, a portion of the increases in the lime-treated silty gravel's thaw strength may be due to a pozzolanic reaction and development of cementitious CSH and CAH.

Table 4.21: 5,000-pound penetration of previously frozen lime-treated silty gravel cured at 50°F and 70°F.

Soil	Lime Content	Cure Duration (days)	Cure Temperature (°F)	Sample #	5,000-Pound Penetration (1/1000 in.)
Silty Gravel	Untreated	N/A	N/A	Sample 1	225
				Sample 2	280
	6% Lime	14	50°F	Sample 1	28
				Sample 2	32
			70°F	Sample 1	6
				Sample 2	20

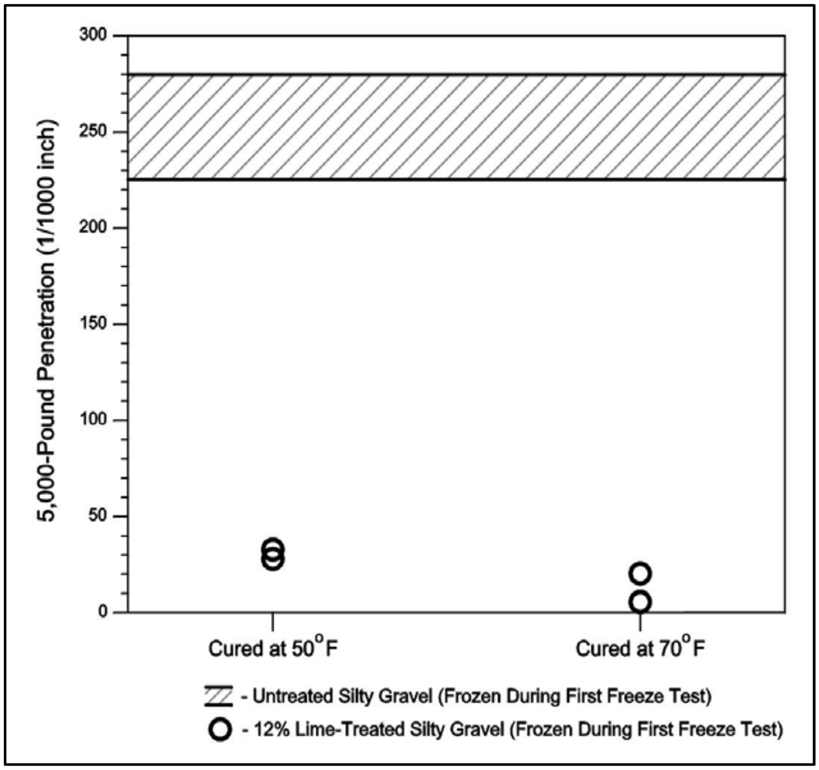

Figure 4.25: 5,000-pound penetration of previously frozen lime-treated silty gravel cured at 50°F and 70°F.

Chapter 5. Discussion, Summary and Conclusions

A discussion of the results for each studied soil is presented in the following subsections. It was felt these discussions should be separate due to the varying nature of each soil, as well as variations in each soil's reaction to the hydrated lime. These discussions are followed by subsections that outline summaries of the results for each soil. These summaries present bullet points felt to be the important implications of the results of this study, and include lists of general conclusions with respect to soils similar to the studied soils.

5.1. Discussion of Results for Studied Silt

During this study, improvements in the moisture-density, strength, frost susceptibility, and thaw-strength of the studied silt were observed with lime treatment. Improvements of these properties were observed within silt samples cured at both 50°F (10°C) and 70°F (21°C). These results suggest that lime treatment of the silt will result in improvements of the soil's engineering properties, even during relatively cool and short warm seasons. The results of this study also suggest the majority of silt's engineering improvements are due to flocculation and agglomeration of soil particles (lime modification). Slight temperature induced improvements in frost susceptibility and strength, however, suggest some component of these improvements may be due to pozzolanic reaction (lime stabilization). As discussed, however, these temperature induced improvements were minor compared to overall improvements due to lime treatment, and the laboratory methods used were not capable of determining the mechanisms of reaction.

The permeability of the silt increased when treated with 6% lime, and decreased when treated with 3% lime. Several authors, including Townsend and Klym (1966), and Arabi et al. (1989) noted increased permeability in some lime-treated soil, attributing this to coarsening of soil fabric due to flocculation and agglomeration of soil particles. This suggests flocculation and agglomeration of soil particles occurs within the silt when treated with 6% lime, but does not occur when the soil is treated with lime concentrations as low as 3%. The reduced permeability of the 3% lime-treated silt may be a combined result of the fine-grained nature of hydrated lime, and a lack of soil-fabric coarsening. The laboratory methods used during this study, however, were not capable of quantifying this. While improvements in strength and frost susceptibility were observed within the lime-treated silt, marked reductions in permeability were not. Therefore, no correlation between increased performance and reduced permeability was made.

The results of the moisture-density testing suggest treating the studied silt with lime will lower the soil's maximum density and increase its optimum moisture content. According to Hicks (2002) and Mallela et al. (2004), these are commonly observed reactions in the moisture-density relationship of lime-treated soils. Increasing the optimum moisture content of the silt may expedite construction by facilitating acceptable compaction densities during wetter conditions, as well as reducing potential for mud-prone construction platforms, which according to Mallela et al.(2004) is a benefit realized in lime-treated soils.

During this study, marked increases in the strength (as measured by CBR) of lime-treated samples of the studied silt were observed. These increases in strength were observed within both the 3% and 6% lime-treated samples, with larger increases in strength observed within the 6% lime-treated samples. These increases in strength were relatively instantaneous and did not significantly change with increased cure duration. In addition, similar increases in strength were observed between samples that were cured at 50^{o}F (10^{o}C) and 70^{o}F (21^{o}C), with the samples cured at 70^{o}F (21^{o}C) displaying slightly more strength than the samples cured at 50^{o}F (10^{o}C). This suggests strength increases in the lime-treated silt are largely due to cation exchange and the flocculation and agglomeration of soil particles, or rather, lime modification. As discussed In Section 2.4.2.1, several authors including Thompson (1968, 1969), Little (1987, 1999), and Mallela et al. (2004) have observed significant strength improvements in lime-modified soils. The slight temperature induced strength increases observed within the silt, however, suggests some component of strength development within this soil may be due to a pozzolanic reaction (lime stabilization). As previously discussed, however, the laboratory methods used during this study were not capable of quantifying extent of reaction between the soil and lime. These results suggest lime treatment of the soil similar in nature to the studied silt may result in marked strength increases, moderate strength increases may be observed when the soil is treated with relatively low concentrations of lime, and these strength increases are largely attributed to lime modification. These results also suggest that strength increases in soil similar to the silt may even occur when the soil is treated with lime and cured in a relatively cool environment.

In general, the samples of studied silt subjected to the second freeze test displayed more frost-induced strain than the samples subjected to the first freeze test. It is believed that conditions simulated by the first freeze test did not produce a temperature gradient that would facilitate ice segregation. Furthermore, with the exception of one untreated sample, the samples of silt subjected to either freeze test did not demonstrate frost heave equal to- or exceeding 9% (which generally is the amount of heave in a soil due to pore water expansion). Mechanisms which account for the lack of heave demonstrated by these samples is unknown but may include expulsion of water from the soil, increase in soil-water alkalinity with the addition of lime, and friction between the soil and the walls of the CBR molds (despite the application of a silicon-base lubricant). Water expulsion resulting in lack of frost heave in soils has either been observed or theorized as a mechanism by several authors including Darrow et al. (2008), Townsend and Klym (1966), Arabi et al. (1989), and Hoekstra (1969). Townsend and Klym (1966) also described increased alkalinity and depression of freezing point in lime-treated soils as a mechanism for reduced frost heave. The laboratory methods used during this study, however, did not allow for measuring water expulsion, monitoring soil-water chemistry, or quantifying potential friction between the soil and CBR mold.

Although the frost heave demonstrated by the samples subjected to both freeze tests was relatively small, evidence of ice segregation in the form of lenticular and microlenticular ice lenses was observed in the untreated samples and 3% lime-treated samples that were cured for 1 day (see Figure 5.1). The thickness and distribution of the ice lenses in these samples should warrant more than 9% heave, particularly if lensing occurred throughout the entire soil sample, and water expulsion was minimal. The laboratory methods used, however, did not

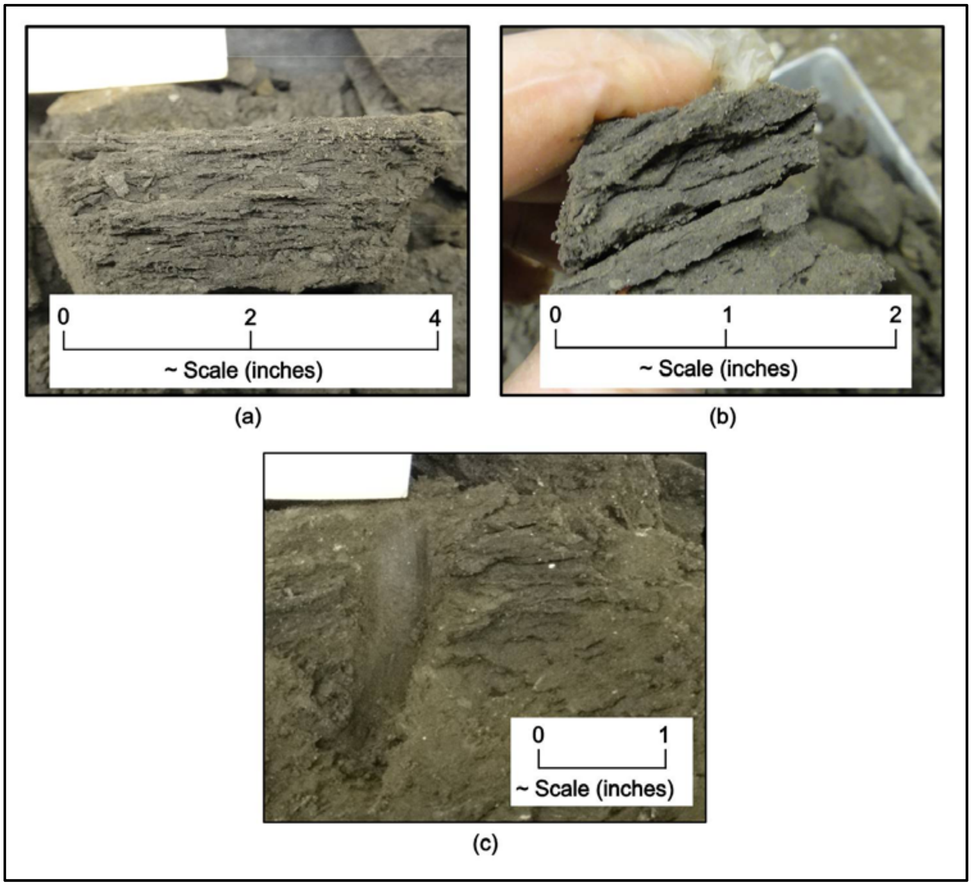

Figure 5.1: Photographs of ice lenses observed in untreated and 3% lime-treated silt. Lenticular ice lenses observed within untreated samples (a) and (b). Microlenticular lenses observed in 3% lime-treated samples (c). Scales are approximate.

allow accurate measurement of the portion of the sample demonstrating ice segregation, or the portion of heave due to either ice segregation or *in situ* pore water expansion. The increased frost heave (as compared to the majority of the lime-treated samples of silt (see Table 4.7 and Figure 4.11)) and evidence of ice segregation observed within these samples suggest some component of interparticle bonding may be occurring within the lime-treated samples that were allowed to cure for longer duration of time. This is further supported by the slight temperature induced frost heave reduction observed within the 6% lime-treated samples that were subjected to the first freeze test (see Table 4.18.and Figure 4.22). The higher heave demonstrated by the 6% lime-treated samples that were cured for 28 days and subjected to the second freeze test, however, is counter to what is expected if interparticle bonding is occurring.

Although the mechanism and extent of reaction within the silt is unknown, these results suggest lime treatment of soil similar to the studied silt may result in an overall decrease in the soil's frost susceptibility. These results also suggest larger reductions in frost susceptibility may be observed when the soil is treated with relatively low concentrations of lime and allowed to cure for approximately 28 days. Finally, these results suggest reductions in the frost susceptibility (although not as large) of soils similar to the studied silt may occur when treated with lime and cured in cooler climates.

Comparing the results of the thaw strength and the frost susceptibility analyses suggest that the magnitude of frost heave and corresponding reduction in density is the most significant contributor to the thaw strength of the studied silt. Generally, samples of the silt that demonstrated less frost-induced strain demonstrated more thaw strength than samples that demonstrated more frost-induced strain. The correlation between frost heave and CBR loss demonstrated by the samples of silt subjected to the second freeze test is illustrated in Figure 4.16. Jessberger and Carbee (1970) also observed a correlation between CBR loss and frost action demonstrated by soil. This emphasizes the significance of controlling frost heave within a soil to not only mitigate frost damage during winter months but to also prevent excessive settlements and deformation during the spring thaw. In addition, the results of the cure temperature and thaw strength not only indicated that the silt's thaw strength is increased when treated with lime, but further increases in strength may be realized when the soil is cured at 50°F (10°C) rather than 70°F (21°C), which was counter to what was expected. These results suggest that increased thaw strength may be realized in soil similar to the studied silt when treated with lime. These results also suggest increases in thaw strength may be realized even when the soil is allowed to cure in a relatively cool climate.

The increase in post-thaw CBR with additional curing demonstrated by the samples of 3% lime-treated silt indicates some development of CSH and CAH may have been occurring within the soil. It is believed, however, the silt is only slightly pozzolanically reactive with lime and the largest component of increased strength within this soil is due to flocculation and agglomerations of soil particles (i.e. lime modification). Furthermore, the laboratory methods used did not allow for determination of extent and nature of the soil's reaction with lime. Increased strength with additional post-thaw curing has been observed in lime-treated soil by Thompson (1968) and Rosen and Marks (1974). The results of this study suggest the strength of previously frozen, lime-treated soil similar to the studied silt may approach that of the same lime-treated soil not subjected to freezing, provided the lime-treated soil is allowed to cure for a moderate duration of time after thawing. Furthermore, the increased post-thaw strength observed within samples treated with relatively low concentrations of lime (3%) suggest strength increases may be observed within previously frozen soil similar to the studied silt when treated with relatively low concentrations of lime, and allowed to cure.

5.2. Discussion of Results for the Silty Gravel

During this study, improvements in the moisture-density, strength, and thaw strength were observed in the studied silty gravel with lime treatment. Improvements of these properties were observed within the lime-treated silty gravel cured at both 50°F (10°C) and 70°F (21°C), although these improvements were generally larger in samples cured at 70°F (21°C). It does not appear that treating the silty gravel with lime will reduce the soil's frost susceptibility. Increases in frost susceptibility of the lime-treated silty gravel, however, are believed to be trivial due to their small magnitude and the improvements in thaw strength demonstrated by the same soil. Both cure duration and temperature induced improvements in strength and thaw strength suggest this soil is pozzolanically reactive with lime and susceptible to lime stabilization. As previously mentioned, however, laboratory methods used did were not capable of determining extent and nature of this soil's reaction with lime. In general this study suggests that treating soil similar in nature to the studied silty gravel with lime may result in an overall increase in the soil's engineering performance. The results of this study also suggest that improvements in this soil's engineering properties may even occur during relatively cool and short warm seasons.

The permeability of the silty gravel increased when treated with 3% and 6% lime, and decreased when treated with 12% lime to a value slightly lower than that of the untreated soil. Increases in permeability of the soil when treated with up to 6% lime suggest reactions between this soil and these concentrations of lime are limited to flocculation and agglomeration of soil particles. The decrease in permeability demonstrated by the 12% lime-treated silty gravel, however, suggests that this soil may pozzolanically react with this concentration of lime. In addition, the samples of silty gravel subjected to the permeability analysis were cured for less than 24 hours. Parsons and Milburn (2003) observed decreases in the permeability of lime-treated soils when allowed to cure for up to 28 days, attributing this to the continued formation of interparticle bonds. As previously mentioned, however, this study's methods did not allow for determining extent and nature of reaction between the studied soils and lime. While increased strength and reduced frost susceptibility were observed within the lime-treated silty gravel there was no correlation between increased performance, and reduced permeability.

As with the studied silt, the results of the moisture-density testing indicate treating soils similar to the studied silty gravel with lime will lower the soil's maximum density and increase its optimum moisture content. In addition the widened moisture-density curves for the lime-treated samples indicate sufficient compaction densities can be reached over a wider range of moisture contents. As previously discussed, lime treatment of soil commonly increases the soil's optimum moisture content, and widens the soil's moisture-density curve. This results in a soil that can be compacted to sufficient density at both a higher, and a wider range of moisture contents (Bell, 1996). The results of the moisture density testing suggest that treating soil similar in nature to the studied silty gravel may expedite construction by reducing the potential of encountering muddy construction platforms, and allowing acceptable compaction at a wider range of moisture content.

Strength increases (as measured by the 5,000-pound test) were observed within the lime-treated silty gravel at all lime concentrations. Smaller strength increases, however, were observed within the samples that were treated with 12% lime, suggesting the optimum lime content for this soil may be closer to 3% or 6% than 12%. It is believed the slight reduction in strength associated with higher lime concentrations are attributed to the relatively weak physical properties of hydrated lime. At concentrations of hydrated lime exceeding that necessary to cause beneficial reactions, the physical properties of lime-treated soil may begin to approach that of the added lime. Although many studies have observed upward increases in the strength of lime-treated soil with increased lime content, several authors have observed decreases in strength when soils are treated with lime above a certain concentration. Bell (1996), Liu et al. (2010), and Farooq et al. (2011) observed decreases in the strength of several lime-treated soils when their lime content exceeded a certain concentration, attributing this to the low internal friction, cohesion and compressive strength of hydrated lime. The optimum lime content that results in maximum strength of a lime-treated soil varies amongst different soils; however, Liu et al. (2010) believes the optimum lime content ranges between 3% and 9% for most lime reactive soils.

Strength increases with cure duration and temperature demonstrated by the silty gravel when treated with lime suggest the soil is pozzolanically reactive with lime and susceptible to lime stabilization. It is believed, however, a large component of increased strength is due to flocculation and agglomeration of soil particles, although this study’s methods did not provide means of quantifying nature of reaction between the studied soils and lime. The results of this study suggest soil similar to the studied silty gravel may demonstrate relatively large strength increases when treated with lime. The optimum lime content for this soil may be closer to 3% or 6% than 12%, and strength increases may be due to some component of lime stabilization.

In addition, the results of this study suggest improvements in the silty gravel's strength may occur even when the lime-treated soil is cured in regions of cooler climate such as Alaska.

Similar to what was observed within the studied silt, samples of the studied silty gravel subjected to the second freeze test generally displayed more frost heave than the samples subjected to the first freeze test. Also similar to the silt, all the samples of silty gravel subjected to freezing demonstrated relatively low frost heave, and the mechanism attributing to this lack of heave is unknown. Several potential causes of the lack of frost heave, however, were previously discussed in Section 5.1. Despite this, it is believed this analysis provided some insight on the effect lime treatment and cure duration have on the relative frost susceptibility of the studied silty gravel.

The results of the first freeze test indicate that treating the silty gravel with 6% lime may not affect the soil's frost susceptibility, while treating the soil with 12% lime will increase the soil's frost susceptibility. Amongst the 12% lime-treated samples subjected to the first freeze test, the samples cured at 50^{o}F (10^{o}C) demonstrated less heave on average than the samples cured at 70^{o}F (21^{o}C). These values, however, were still higher than the untreated samples. Similar to the results of the 6% lime-treated samples subjected to the first freeze test, the results of the second freeze test indicate treating the silty gravel with 3% lime does not affect the soil's frost susceptibility. These results suggest treating soil similar to the studied silty gravel with relatively high concentrations of lime may increase the soil's frost susceptibility, while treating the soil with relatively low concentrations of lime may generally not affect the soil's frost susceptibility. In addition, these results suggest that cure temperatures provided by relatively cool regions will not significantly change the effect lime treatment has on the soil's frost susceptibility.

Unlike the silt, there does not appear to be a correlation between frost-induced density reductions and thaw strength for the studied silty gravel. In spite of demonstrating increased frost heave, the lime-treated samples of silty gravel demonstrated more thaw strength than the untreated samples. The lime-treated samples that were cured at 70^{o}F (21^{o}C) demonstrated lower penetration than those that were cured at 50°F (10°C). This temperature induced variation in thaw strength, however, is relatively small. These results suggest increased strength is partially due to both flocculation and agglomeration of soil particles and a pozzolanic reaction. Again, as previously mentioned, the laboratory methods were not capable of determining nature of the reaction between the studied soils and lime. The results of this study suggest that the thaw strength of soil similar to the studied silt will be increased when this soil is treated with lime. In addition, these results suggest that increases in the thaw strength of this lime-treated soil will be realized even when the soil is cured in relatively cool climates such as Alaska.

With exception of one data point, the lime-treated silty gravel demonstrated a general trend of increased post-thaw strength with increased cure duration. This increased post-thaw strength was demonstrated by both the 12% and 3% lime-treated samples that were subjected to the first and second freeze tests, respectively. In addition, the post-thaw strength demonstrated by the 3% lime-treated samples was similar to that of the similarly treated samples not subjected to freezing, while the post-thaw strength demonstrated by the 12% lime-treated samples that were cured for an additional 28 days exceeded that of the similarly treated samples that were not subjected to freezing. Although the nature of reaction was not determined nor is fully understood, this suggests the silty gravel is somewhat pozzolanically reactive with lime, and any portion of CSH and CAH development not completed prior to freezing may continue when temperatures that facilitate the pozzolanic reaction are again reached. This phenomenon has been observed by several authors including Thompson (1968) and Rosen and Marks (1974). The results of this study suggest the strength of previously frozen lime-treated soil similar to the silty gravel may increase with increased cure duration after thawing. The results further suggest, given moderate duration of post-thaw cure time, the strength of this lime-treated soil may exceed that of the same soil that was not subjected to freezing. Finally, the higher post-thaw strength demonstrated by the 3% lime-treated silty gravel suggests the optimum lime content for this soil may be closer to 3% than 12%.

5.3. Summary of Conclusions for the Studied Silt

- Lime treatment of soil similar to the studied silt may improve the soil’s moisture-density characteristics, increasing the optimum moisture content, facilitating compaction during wetter conditions, and reducing problems due to mud-prone construction platforms.
- Treating soil similar to the studied silt with lime may result in increases in the soil’s strength. More moderate but relatively large improvements in strength may be observed within the silt when treated with relatively low concentrations of lime. These strength improvements are likely due to lime modification and may occur within relatively cool regions such as Alaska.
- Although the mechanisms are not fully understood, lime treatment of soil similar to the studied silt may result in overall reductions in the soil’s frost susceptibility, and these reductions may be more significant when the soil is treated with relatively low concentrations of lime. Frost susceptibility reductions of the lime-treated soil may occur, even if cured during a relatively cool and short warm season.
- Lime treatment of soil similar in nature to the studied silt may result in increased thaw strength. Thaw strength demonstrated by soil similar to the studied silt may be a function of the soil’s frost heave and corresponding density reduction, which is reduced when the soil is treated with lime. Thaw strength of soil similar to the studied silt may be improved upon where the soil is treated with lime – even in regions of cool climate such as Alaska.
- Within a lime-treated soil similar to the studied silt, portions of lost strength due to being previously frozen may be recovered when the soil is allowed to cure for a moderate duration of time after thawing. When cured for more extensive duration of time after thawing, the strength of a lime-treated soil similar to the studied silt may exceed that of the same soil that was not subjected to freezing, provided the two soils were treated with same concentration of lime and cured for same duration of time prior to being frozen.

In general, the following conclusions have been developed for interior Alaska soil similar in nature to the studied silt:

- Soils similar to the studied silt within interior Alaska may be susceptible to lime modification; however a slight component of stabilization may occur particularly at relatively high concentrations of lime and longer cure durations.
- Improvements of lime-treated interior Alaska soil similar to the studied silt may include improved moisture-density characteristics and workability, increased strength, reduced frost susceptibility, and increased thaw strength.
- Improvements of lime-treated interior Alaska soils similar to the studied silt may occur when treated with relatively low concentrations of lime.
- Improvements in lime-treated interior Alaska soil similar to the studied silt may occur during relatively cool and short summers, and continue seasonally to some degree for several years

5.4. Summary of Conclusions for the Studied Silty Gravel

- Lime treatment of soil similar to the studied silty gravel may improve the soil's moisture-density characteristics by increasing the optimum moisture content and widening the range of moisture at which acceptable compaction can be achieved. Therefore, treating soil similar to the studied silty gravel with lime may facilitate construction during wetter conditions by reducing the potential of encountering muddy construction platforms, and allowing acceptable compaction at a wider range of moisture content.
- Lime treatment of soil similar in nature to the studied silty gravel may result in increases in the soil's strength. Strength increases of lime-treated soil similar to the studied silty gravel may be realized in cooler climates such as Alaska. The optimum lime content for soil similar to the studied silty gravel may be closer to 3% or 6% than 12%. Increases in the strength of lime treated soil similar to the studied silty gravel may be due to some component of lime stabilization.

- Treating soil similar to the studied silty gravel with relatively high concentrations of lime may increase the soil’s frost susceptibility, while relatively low concentrations may not affect the soil’s frost susceptibility. Cure temperatures similar to those of cooler regions may not significantly change the effect lime treatment has on the frost susceptibility of lime-treated soil similar to the studied silty gravel.
- Lime treatment of soil similar in nature to the studied silty gravel may result in an increase of the soil’s thaw strength. Even in regions of cool climate such as Alaska, the thaw strength of soil similar to the studied silty gravel may be improved upon when the soil is treated with lime. Although a large portion of improved thaw strength may be due to lime modification, it is believed a component may be due to lime stabilization.
- Within a lime-treated soil similar to the studied silty gravel, a portion of lost strength due to freezing may be recovered if the soil is allowed to cure for a relatively short duration of time after thawing. If allowed to cure for a moderate duration of time after thawing, the strength of a lime-treated soil similar to the studied silty gravel may exceed that of the same soil that was not subjected to freezing, provided the two soils were treated with same concentration of lime and cured for same duration of time prior to being frozen. The optimum lime content for this soil similar to the studied silty gravel may be closer to 3% or 6% rather than 12%.

The following generalized conclusions have been developed for south-central Alaskan soil similar in nature to the studied silty gravel:

- Soils similar to the studied silty gravel within south-central Alaska may demonstrate improvements in engineering properties due to a combination of lime modification and lime stabilization. The degree to which lime stabilization attributes to the engineering improvements of such soil is unknown but may largely be controlled by cure duration.
- Potential improvements of lime-treated south-central Alaskan soil similar to the studied silty gravel include improved moisture-density characteristics and workability, increased strength, and increased thaw strength.

- Treating south-central Alaskan soils similar to the studied silty gravel with lime may increase the soil's frost susceptibility. Limitations of the freeze testing, however, make it difficult to determine the magnitude of this increased frost susceptibility.
- Improvements of lime-treated south-central Alaskan soils similar to the studied silty gravel may occur with relatively low concentrations of lime, and the optimum lime content for such soil may be closer to 3% or 6% rather than 12%.
- Improvements in lime-treated south-central Alaskan soil similar to the studied silty gravel may occur during relatively cool and short summers, and continue seasonally for several years.

5.5. Recommended Future Work

For similar studies on lime treatment of soil, a laboratory analysis should consider the following:

Conduct tests to determine the soil's clay mineralogy and properties. The results from such analyses may aid in characterizing the nature of the soil's reaction with lime. Such tests may include:

- X-ray diffraction (XRD) or X-ray fluorescence (XRF) to analyze clay constituents.
- Ammonium-acetate method to determine cation exchange capacity (CEC).

Conduct tests to analyze and quantify extent of soil reaction with lime. The results from such analyses may quantify extent of reaction, and allow observed engineering improvements to be attributed to these reactions. Such tests may include:

- pH tests that determine change in pH over time in lime-soil-water slurries.
- Examination with an electron microscope to identify changes in soil particle texture and formation of secondary products.

Engineer freeze testing that simulates local freezing conditions and allows for the monitoring of water expulsion, extent of ice-segregation, and extent of *in situ* pore water expansion, so these mechanisms can be directly attributed to their respective portion of frost heave.

- Simulating local freezing conditions may provide results that are pertinent to particular regions.
- Monitoring water expulsion and extents of ice segregation and pore water expansion will facilitate the researcher in understanding the mechanisms that resulted in measured heave.

Conduct freeze-thaw tests to characterize long-term seasonal durability of untreated and lime-treated variants of soil.

Conduct analysis on an increased number of lime concentrations to narrow down the optimum lime content for studied soil, and increase number of redundant samples for testing to analyze repeatability of results.

The researcher should determine what laboratory methods are applicable and appropriate for a particular study. In general, it is recommended that long term field testing be conducted to check results of laboratory analysis. The field tests could include relatively small, discontinuous, and localized highway and rail-line test strips.

An economic feasibility analysis should be conducted, comparing costs of treating soil with pre-determined concentrations of lime against potential benefits estimated from both laboratory and field performance increases. The cost-benefit analysis should include characterizing the economic sensitivity of potential construction and maintenance costs against the predicted engineering benefits for several lime concentrations for the studied soil.

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Appendices

Appendix A:
Definitions

- Adsorption: attraction and adhesion of dissolved ions to negatively charged soil surface.
- Diffusion: spread of cations and water molecules from regions of higher concentration to regions of lower concentration.
- Flocculation and agglomeration: the process of soil particles combining together in randomly oriented arrangements, forming larger aggregated masses.
- Frost heave: Increased volume observed within soil due to freezing of pore-water and/or development of segregated ice..
- Lime modification of soil: Improvements in a soil's engineering properties that are attributed to cation exchange and flocculation and agglomeration of soil particles.
- Lime stabilization: Improvements in a soil's engineering properties that are attributed to the development of cementitious calcium-silicate-hydrates and/or calcium-aluminate-hydrates.
- Pozzolan: a siliceous or aluminous material that reacts with the calcium cation and water to form cementitious calcium-silicate-hydrates and calcium-aluminate-hydrates.
- Thaw-strength: A term used throughout this report to describe a soils strength upon thawing.

Appendix B:
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