STABILIZATION OF MARGINAL SOILS USING GEOFIBERS AND NONTRADITIONAL ADDITIVES

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A

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Abstract

Western Alaska lacks gravel suitable for construction of roads and airports. As a result, gravel is imported, at a cost of between $200 and $600 per cubic yard, to fill transportation construction needs. In an effort to reduce these costs, the Alaska University Transportation Center (AUTC) began searching for methods to use local materials in lieu of imported gravel. The approach discussed in this thesis uses geofibers and chemical additives to achieve soil stabilization. Geofibers and chemical additives are commercially available products. The goal of the research presented in this thesis is to test the impact of addition of two geofiber types, six chemical additives, and combinations of geofibers with chemical additives on a wide variety of soil types. California Bearing Ratio (CBR) testing was used to measure the effectiveness of the treatments. Soils ranging from poorly graded sand (SP) to low plasticity silt (ML) were all effectively stabilized using geofibers, chemical additives, or a combination of the two. Through the research conducted a new method of soil stabilization was developed which makes use of curing accelerators in combination with chemical additives. This method produced CBR values above 300 for poorly graded sand after a seven day cure.

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Chapter 1 Introduction

1.1 The Problem

Many soils encountered in many areas of Alaska do not meet engineering properties required for use in construction. Soil with desirable engineering properties must be transported using either ice roads in the winter or brought by barge in the summer. The transportation of large quantities of building material has negative impact on the environment and is not a sustainable practice. The cost of importing quality soils can reach $200-$600 per cubic yard. As a result, roads and runways in rural Alaska are expensive to construct and maintain. The Alaska Department of Transportation and Public Facilities is looking for alternative methods for design and construction of rural roads. The goal of this research is to use combinations of geofibers and nontraditional additives to economically stabilize soils of marginal quality for use on roads, runways, and other similar applications.

1.2 Background

The addition of geofibers and/or chemical additives show an ability to strengthen fine grained soils. Geofibers and chemical additives combine two existing technologies. Geofibers add mechanical stabilization to soil in the same way fiberglass fibers add tensile strength to concrete. The chemical additives have binders that add cohesion to soils. When combined, geofibers and chemical additives increase tensile strength, cohesion, shear strength and compressive strength.

To date, two applications of geofibers and chemical additives for soil stabilization purposes have been reported. The first took place at Cape Simpson, Alaska (Hazirbaba et al., 2007). This application used a combination of two inch long tape geofibers and EnviroKleen. In the second case, a 500 foot section of road in Wasilla, Alaska was treated with 0.75 inch fibrillated geofibers with Soil-Sement. Both of these applications were successful at the time of application in stabilizing poorly graded sand material.

1.3 Scope of Work

The successful applications of geofibers and chemical additives spurred a laboratory investigation using several soil types. The study began with Ottawa and Monterey sands which are poorly graded and have low bearing strength. Naturally occurring soils typically contain fines which aids in bearing capacity. The lack of fines in Ottawa and Monterey sands makes stabilization more difficult. Geofibers and Chemical Additives (synthetic fluids) were added to the sands to determine optimum contents. The optimum fiber and fluid contents were used to mutually provide reinforcement to Monterey and Ottawa sands.

To predict fiber content based only on the fines content Monterey and Ottawa sand were mixed with several dosages of fines. A range of geofiber contents were used to measure any change in optimum fiber content based on fines available in the soil. Ottawa sand was mixed with three dosages of Fairbanks silt (low plasticity silt), while Monterey sand was mixed with five dosages of Mabel Creek silt (low plasticity silt).

Fairbanks silt was the first naturally occurring soil tested. Geofibers and chemical additives (synthetic fluid and polymer emulsions) were added to Fairbanks silt to determine optimum fluid and fiber contents. Fairbanks silt was conditioned in several ways to evaluate the effects of factors such as a freeze and thaw cycle, soaked conditions, and curing on CBR value.

Horseshoe lake sand was initially tested to determine optimum geofiber and fluid contents for usage in a small section of road. In the initial testing phase three chemical additives were evaluated. The best of these was subjected to freeze and thaw and curing tests to ensure the samples would survive an Alaskan winter. The second phase of testing evaluated the performance of several chemical additives against each other.

In the second phase of testing Horseshoe lake sand polymer emulsion was mixed with a curing additive causing a large increase in bearing capacity. The polymer emulsion used in the second phase of the Horseshoe lake sand testing was one of three available. When the other polymers were mixed with the curing additive the bearing capacity increased. Further tests with combinations of polymers and curing additives were conducted using unconfined compressive strength testing. A challenging soil, Kwigillingok silt, was successfully stabilized using a combination of polymer emulsion and curing additive.

Chapter 2 Literature Review

2.1 Subject Overview

The use of fibers for soil stabilization dates back to biblical times when straw was mixed with clay (Freitag, 1986). Modern literature regarding the use of fiber stabilization starts in Gray and Ohashi (1983) study of fiber reinforcement of beach sand. They concluded that fibers improve shear strength characteristics of clean beach sand and recommended further research that continues to the present. Literature published after 1983 includes testing on compressive, tensile and shear strength of soil reinforced with fibers, as well as, resistance to factors such as freezing and thawing and soaking and drying.

Chemical additives for soil stabilization include products produced by the commercial sector which includes polymer emulsions, synthetic fluids and others. The use of chemical additives for soil stabilization is a new area of research. Most of applications relate to military rapid construction of roads and runways.

The combination of fiber and chemical soil stabilization was not introduced in the literature until Hazirbaba et al. (2007) published findings on mixing silty sand with geofibers and synthetic fluids. These results showed improvement in bearing capacity of the sand using Earth Armor (Synthetic Fluid) and two inch tape geofibers.

2.2 Geofiber Stabilization of Sands

The benefits of adding geofibers to sands are provided in the literature. One of the main benefits described is an increase in shear strength and ductility of sand. Several authors noted gains in shear strength and ductility in sand. Gray and Ohashi (1983) indicated the fibers increase the peak shear strength and limit the post-peak shear strength reduction. The shear characteristics of sands treated with geofibers were also evaluated by Gray and Al-Refeai (1986) who were the first to look at randomly distributed fibers in sand. The results indicated that increasing the fiber content increased peak shear strength, as well as, making the sand more ductile. This behavior is similar to what is observed by Gray and Ohashi (1983); the main differences come from fibers being oriented in the early study and randomly distributed in the latter. In the oriented tests the reinforcement area is increased which leads to the increase in shear strength. The first study that showed that increasing fiber content above a certain point may have a detrimental effect on shear strength was presented by Maher and Gray (1990). Triaxial testing was used to evaluate the effects of fiber reinforcement on a total of nine sands. All sands tested showed shear strength increased linearly with increasing amounts of fiber. For fiberglass fibers in dune sand at low confining pressure shear strength approaches an asymptotic upper limit at 6% fiber content. Al-Refeai (1991) showed an increase in shear strength of fine and medium sands using geofibers. This focused mainly on fiber length and type and it was concluded that different fiber characteristics can improve various aspects of the shear strength of soil.

The main objective of all of these studies was to evaluate sand and fiber characteristics in order to predict the shear strength with fiber reinforcement. Variables such as soil characteristics (particle size, shape, and gradation) and fiber properties (angle of orientation, shape, finish, length, and modulus) were used to predict shear strength.

Another common theme in fiber reinforcement of sands is a change in the shape of the failure envelope. Several authors describe a change in the failure envelope from the typical linear failure envelope to either a bilinear or curved linear shape. A minimum confining pressure is described as the point where failure envelopes transition to become parallel with untreated sand. The critical confining stress is governed by the modulus of the fibers used for reinforcement. Fig. 2-1 presents an illustration of failure envelopes after reinforcing with geofibers.

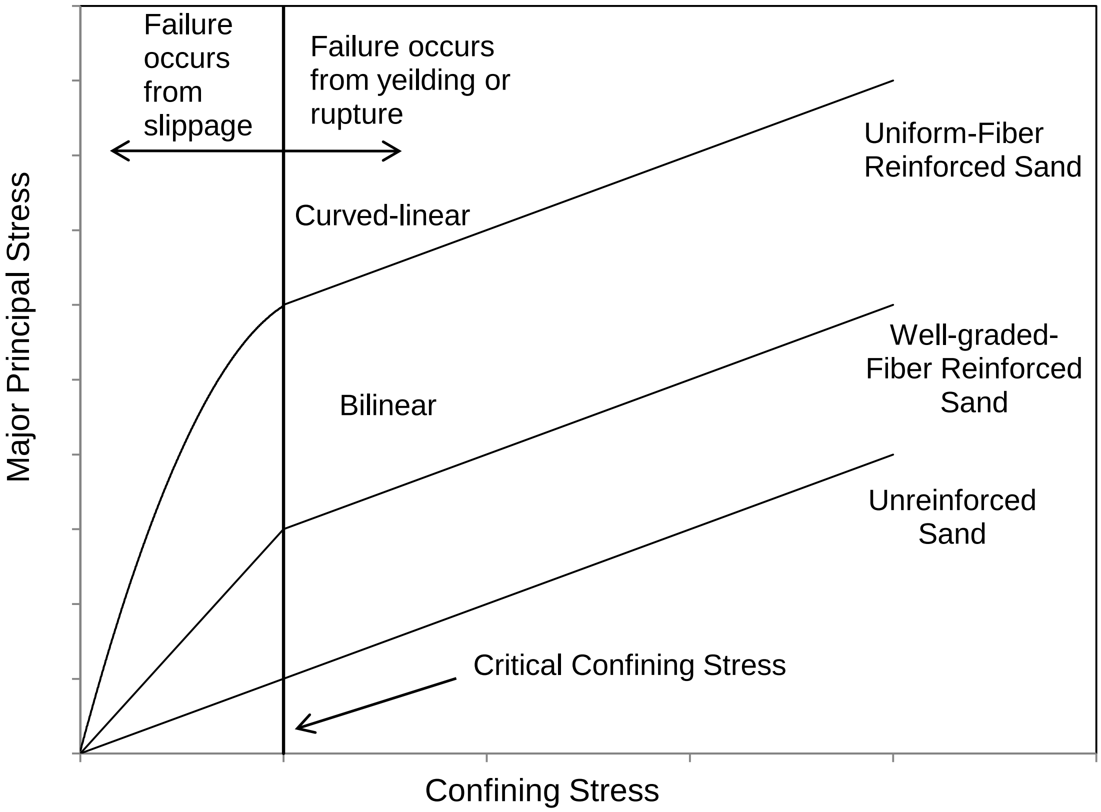

Figure 2- 1: Failure Envelopes with Fiber Reinforcement

Several authors including Gray and Ohashi (1983) describe a critical confining stress where fibers slip or pull out below and rupture or yield above. Gray and Al-Refeai (1986) found that the critical confining stress is greater if the surface roughness or interface friction between the sand and fiber is greater. Maher and Gray (1990) discovered the behavior of the failure envelope before the critical confining stress was found to behave in either a linear or curved-linear manner depending on whether the soil was well-graded or uniform, respectively. Al-Refeai (1991) confirmed the critical confining stress is depended on the modulus of the fibers used for stabilization. Yetimoglu and Salbas (2003) and Ibraim and Fourmount (2006) did not observed linear failure envelopes in direct shear tests on clean sand mixed with fibers.

Some authors conclude that geofibers increase the internal friction angle of sand while others conclude there is either a decrease or no change. In oriented fiber arrays Gray and Ohashi (1983) concluded that fibers have no effect on internal friction angle because above the critical confining stress the failure envelopes were parallel.

Direct shear tests performed on sand mixed with fibers and cement by Craig et al. (1987) showed fibers positively affect internal angle of friction. The fiber content and material affect the angle of internal friction and cohesion of sand. When the soil-cement mixture was mixed with straight steel fibers the friction angle decreased, with fiberglass fibers the opposite occurred. Al-Refeai (1991) describes improvement using friction angle ratio to describe sands treated with geofibers. Mesh fibers were found to improve the friction angle ratio better than fiberglass or pulp fibers. Another example of fibers improving the friction angle of sand is presented by Consoli et al. (1998). Triaxial testing of silty sand mixed with fibers caused the internal friction angle of sand to increase. Triaxial testing sand with polypropylene fiber reinforcement by Consoli et al. (2007) showed an increase in internal friction of sand. Ibraim and Fourmount (2006) conducted direct shear testing on sand treated with crimped polypropylene fibers which increased internal friction angle.

Yetimoglu and Salbas (2003) used direct shearing tests on clean uniform sands treated with fibers. The results of this testing showed increasing fiber content decreased the internal friction angle of sand. These results are counter to what is found in other literature. The decrease in internal friction angle could be attributed to the size of the shear box (2.4 inches x 2.4 inches by 1 inch deep) used in the study relative to the size of the fibers (0.8 inches long, 0.002 inches in diameter). It is possible that the fibers could not achieve a development length necessary to provide added benefit. Another explanation for the decrease in internal friction angle is a reduction in the fiber/soil interface. When fiber to fiber contact is greater than fiber to soil contact the result could be a decrease in the internal angle of friction.

A small portion of available literature describes dosage rates and types of fibers to meet a particular need. The first study where a particular sand was evaluated using a range of fiber types was conducted by Ahlrich and Tidwell (1994). A combination of gyratory shear and CBR testing was used to determine an optimum fiber content, fiber length, and fiber type for beach sand. A 2 inch monofilament fiber at a 1% by dry weight dosage rate was found to provide a 6% increase in CBR in the unsoaked condition. In the soaked condition all fiber contents and configurations decreased the CBR value below the untreated sample. Dutta and Sarda (2007) overlaid saturated sand with stone dust mixed with waste plastic strips. The combination of stone dust with 4% waste plastic strips (1.4 inches long, 0.5 inches wide) provided a 189% improvement in CBR value. Marandi et al. (2008) concluded 1.6 inch palm fibers at a dosage of 2.5% by dry weight provide the best Unconfined Compressive Strength (UCS) for silty sand.

2.3 Geofiber Stabilization of Fine-Grained Soils

Literature shows that the addition of geofibers to silts and clays can have positive effects. Low and high plasticity clays as well as silts improve significantly with the addition of geofibers. The earliest study involving geofiber stabilization of low plasticity clay comes from Freitag (1986). Three fiber types including spun nylon string, polypropylene rope fiber, and fibermesh commonly used in concrete were mixed with clay and tested using UCS. All fibers improved the UCS although the difference between the strength results was negligible. The fiber type did not have an effect on the strength of low plasticity clay. A study by Fletcher and Humphries (1991) on silt indicated that monofilament and fibrillated fibers increase the bearing capacity of silt. The improvement for silt treated with 0.75 inch long monofilament fibers at a content of 0.09% is 65%. Fibrillated fibers of the same length and fiber content provide a 91% improvement. Jadhao and Nagarnaik (2008) stabilized a sandy silt- fly ash mixture using 0.5 inch polypropylene fibers at a1% fiber content.

2.4 Soil Stabilization Using Nontraditional Additives

Santoni et al. (2003) stabilized silty sand with several nontraditional stabilizers, including acids, enzymes, lignosulfonates, petroleum emulsions, polymers, and tree resins. UC tests were used as an index performance test for all samples. Samples were prepared in moist and dry test conditions. A total of six control samples, twelve nontraditional samples, and three traditional stabilizer samples were tested. The results indicated three polymers have the potential to increase the strength of silty sand in wet and dry conditions. For the traditional stabilizers, only cement provided significant strength improvement. Both the traditional and nontraditional stabilizers lost strength under wet conditions. The optimum additive dosage for the polymer emulsion ranged from 2.5% to 5% by weight of dry soil.

Tingle et al. (2003) looked at the stabilization of clay soils using several nontraditional additives including several polymer emulsions. The purpose of this study was to develop a compare effectiveness of several different liquid stabilizers. Low- and high-plasticity clays were used in this study. Samples were subjected to wet and dry test conditions and were tested using unconfined compression. The nontraditional stabilizers were compared to more traditional ones, such as cement and lime. The unconfined compression results showed the polymer emulsions to have variable improvements in the dry condition with minimal loss of unconfined compressive strength in the wet conditions with both soil types. The optimum amount of fluid for polymer emulsions was in the range of 2-5% by dry soil weight. Overall, the products used in this study proved to be promising for use in low-volume roads.

Newman and Tingle (2004) investigated the use of four polymer emulsions on silty sand specifically manufactured for their study. The level of 2.75% polymer emulsion by dry mass of the soil was chosen as a basis of comparison for all of the polymer emulsions. This was compared to Portland cement used at concentrations of 2.75%, 6%, and 9%. All samples were subjected to unconfined compression testing. The toughness was used as an index property to measure the effectiveness of the mix designs. The toughness is a measure of the energy absorbed by the system per unit volume to the yield point. Three separate cure periods were investigated: 24 hours, 7 days, and 28 days. Samples showed similar strength in the 24-hour time period compared to the 7-day cure time, with the Portland cement samples seeing the greatest increase in strength. Samples treated with polymer emulsions showed marked improvement in Unconfined Compressive Strength (UCS) and toughness after a 28-day curing period, with polymers showing significantly higher toughness values than the soil-cement mixtures.

Chapter 3 Testing Methodology

3.1 Introduction

California Bearing Ratio and Unconfined Compressive Strength testing are two very common methods of measuring strength of materials for construction purposes. California Bearing Ratio (CBR) (ASTM D1883) is a standard test used to measure bearing capacity. Unconfined Compression (UC) (ASTM D2166) testing is used for measuring the strength of soils mixed with polymer emulsions and curing additives. Testing was performed in accordance with all applicable American Society for Testing and Materials (ASTM). Samples were prepared in a similar manner for all testing presented. Nomenclature was adopted for naming samples treated with combinations of geofibers and chemical additives.

3.2 California Bearing Ratio Testing

CBR samples were prepared according to ASTM D1883-07. Samples were compacted using a mechanical compactor, designed with a moving hammer in order to compact samples in accordance with modified proctor compaction (ASTM D1557-09). Moisture content samples were collected before and after compaction. The CBR was performed on a mechanical press manufactured by Soiltest, which is shown in Fig. 3-1. A 10 kip digital load cell was used to measure force. A linear variable differential transformer (LVDT) was used to measure vertical deflection into the sample.

CBR samples were performed at a strain rate of 0.05 inches per minute. Stress measurements are recorded every 0.025 inches of penetration to a total depth of 0.5 inches. CBR values are recorded at each 0.1 inch interval by taking the stress at each interval and dividing that by the stress of a standard gravel material. The design CBR is taken as the higher value at either 0.1 or 0.2 inches of penetration into the sample. The design CBR value is used as the index measurement of soil strength. Table 3-1 presents the general soil ratings for roads and runways corresponding to ranges of CBR Value **(**Bowles, 1978**)**

Table 3- 1: General soil ratings for roads and runways corresponding to ranges of CBR Value (Bowles, 1978)

CBR%	General Rating	Uses	Classification System	
			Unified	AASHTO
0-3	Very poor	Subgrade	OH, CH, MH, OL	A5, A6, A7
3- 7	Poor to fair	Subgrade	OH, CH, MH, OL	A4, A5, A6, A7
7- 20	Fair	Subbase	OL, CL, ML, SC, SM, SP	A2, A4, A6, A7
20-50	Good	Base, subbase	GM, GC, SW, SM, SP, GP	A1b, A2-5, A3, A2-6
>50	Excellent	Base	GW, GM	A1a, A2-4, A3

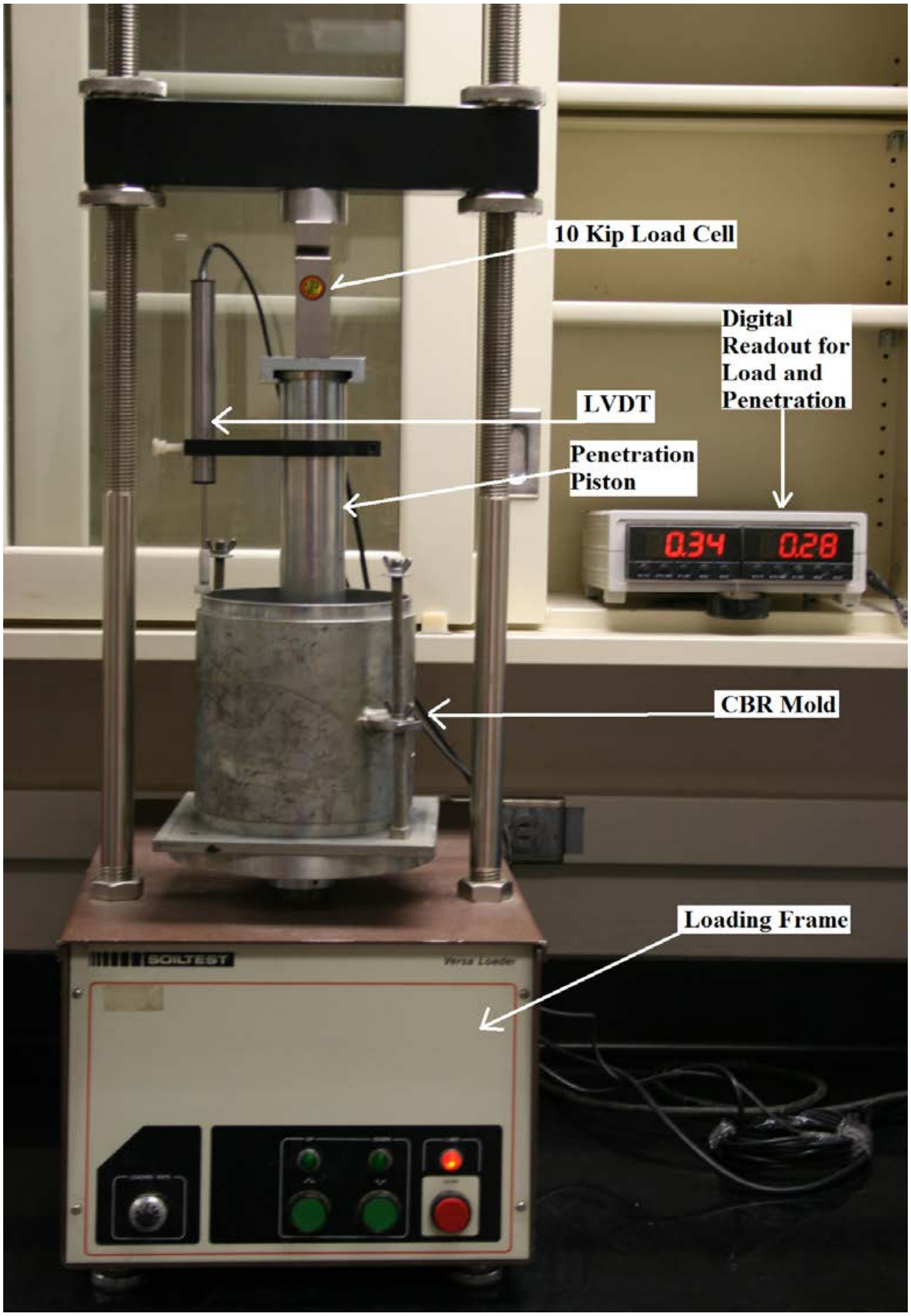

Figure 3- 1: CBR Apparatus used for testing

3.3 Unconfined Compression Testing

Unconfined Compression (UC) testing was used for sand and fine-grained material treated with polymer emulsion and curing additive. The Soiltest loading frame used in CBR testing was modified by exchanging the penetration piston with a 4 inch plate. Figure 3-2 provides an illustration of the Unconfined Compression apparatus. Samples were compacted in a 4 inch by 8 inch mold using modified proctor compaction. After compaction samples were extruded from the mold and wrapped in a rubber membrane to prevent excess air from curing the samples. A strain rate of 0.6 inches per minute was used with measurements taken every 0.01 inches to a total strain of 15% (up to 1.23 inches). Table 3-2 presents the consistency classification for fine-grained soils (Terzaghi et al., 1996).

Table 3- 2: Consistency classification for fine grained soils

Classification	Description	Unconfined Compressive Strength, q_u (lb/in^2)
Very soft	Thumb penetrates easily; extrudes between fingers when squeezed	<3.5
Soft	Thumb will penetrate soil about 1 inch; molds with light finger pressure	3.7-6.9
Medium	Thumb will penetrate about 0.25 inches with moderate effort; molds with strong finger pressure	6.9-13.9
Stiff	Thumb indents easily, and will penetrate 0.5 inches with great effort	13.9-27.8
Hard	Thumb will not indent soil, but thumbnail readily indents it	27.8-55.5
Very hard	Thumbnail will not indent soil or will indent it only with difficulty	>55.5

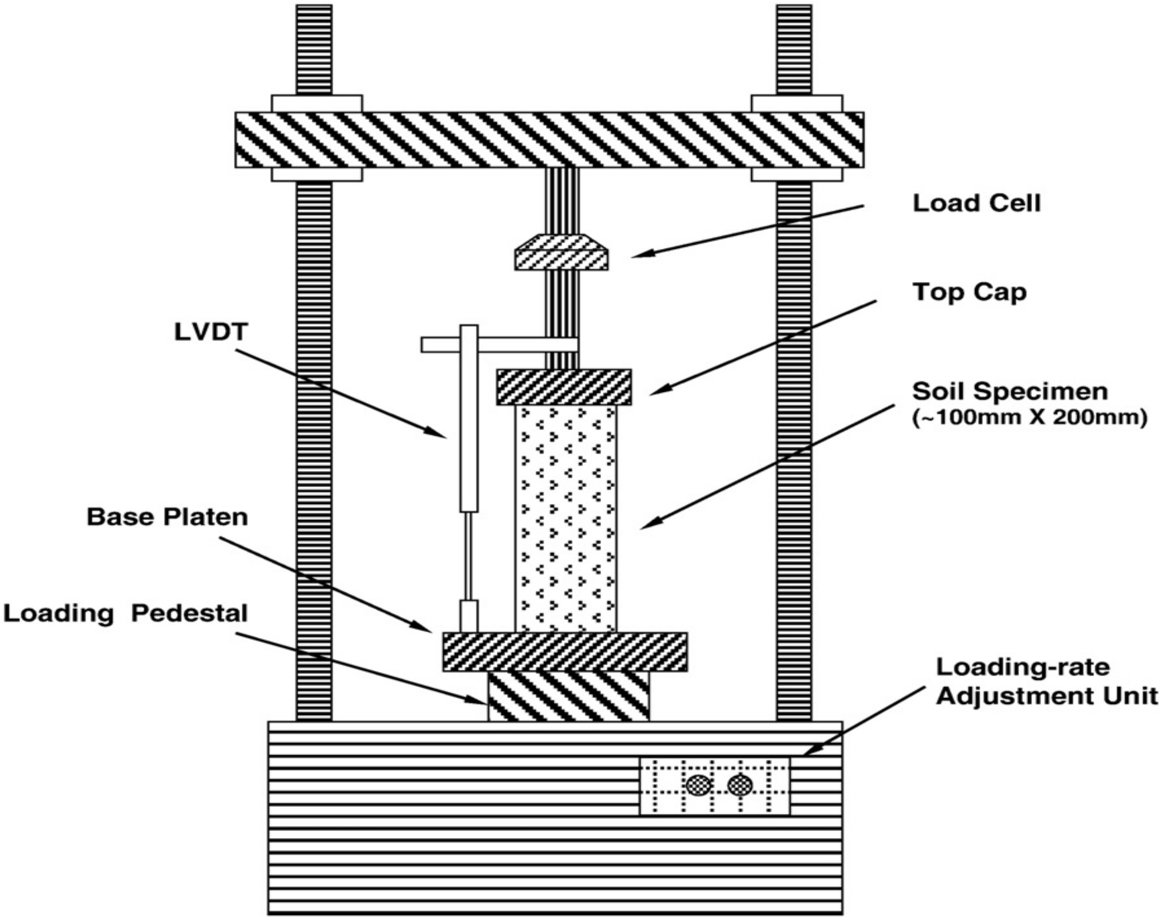

Figure 3- 2: Unconfined Compression Apparatus used for Testing (From Hazirbaba and Gullu, 2010)

3.4 Soils Used

A total of six soils were used in this research. These included Ottawa sand, Monterey sand, Fairbanks silt, Horseshoe lake sand, Kwigillingok silt, and Mabel Creek silt. Ottawa and Monterey sand are clean uniform materials purchased specifically for the project; the remaining soils were collected from natural sources.

3.4.1 Ottawa Sand

Ottawa sand is typically used for Sand Cone Density testing (ASTM D1556-07). Soil index properties such as maximum dry unit weight, optimum moisture content, and specific gravity were used to classify soils further. These tests were performed in accordance with their respective ASTM standards. Results of soil index property testing are presented in Table 3-3.

Table 3- 3: Index Properties of Ottawa Sand

Property	Ottawa Sand
G_s	2.66
C_u	1.8
C_c	1.15
γ_d (lb/ft^3)	104
OMC	13%
Classification	SP

For most soils, finding the optimum moisture content and maximum dry density follows a straightforward testing procedure. Ottawa sand has extremely high permeability; water drains directly through the soil. This makes completion of modified proctor compaction testing extremely difficult.

The results of the optimum moisture contents test were inconclusive. At several moisture content levels, the variation between the dry density values was deemed unacceptable. In an effort to find the optimum moisture content, a new approach was taken. This consisted preparing the Ottawa sand samples for CBR testing at a range of moisture contents. The design CBR was plotted versus the moisture content of the samples. This made it clear that the optimum moisture content is 13%. The small variation in dry density indicates that any moisture content used would be acceptable, however, the lack of apparent cohesion in the samples made testing at low moisture contents impossible. The optimum moisture curve for Ottawa sand is presented as Fig. 3-3. Soil Particle size analysis was performed using mechanical sieving in accordance with ASTM C136. Ottawa sand is classified as poorly-graded sand (SP) according to USCS (United Soil Classification System). The gradation for the Ottawa sand is presented as Fig. 3-4.

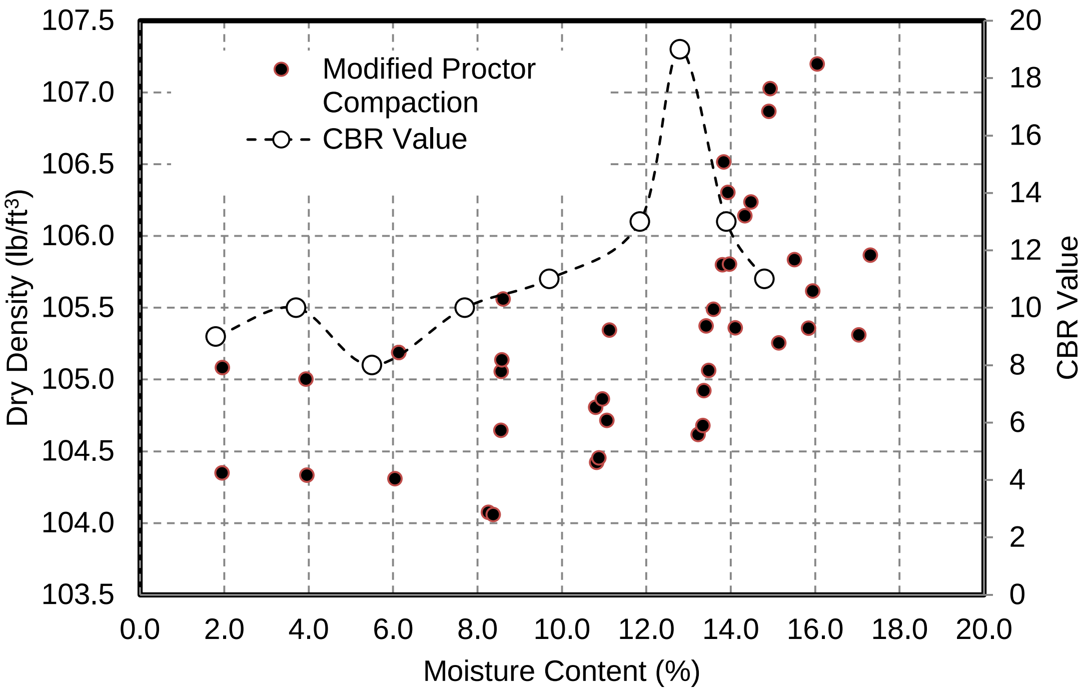

Figure 3- 3: Moisture Density Curve and CBR Values for Ottawa sand

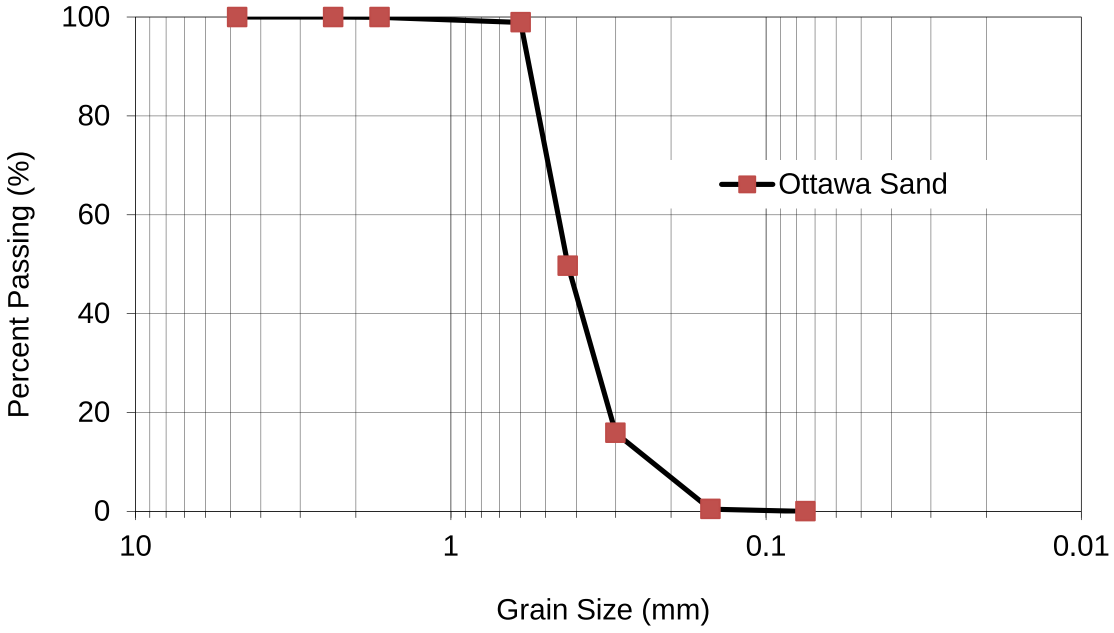

Figure 3- 4: Gradation for Ottawa Sand

3.4.2 Monterey Sand

Monterey sand is commonly used in water filters and sand blasting applications. The Monterey sand used in this study is identified as #0/30. The sand was obtained from Kleenblast located in Tacoma, Washington.

Soil index properties, including specific gravity, dry-unit weight, and optimum moisture content, were tested following their respective ASTM Standards. The summary of index soil properties is found in Table 3-4.

The maximum dry density and optimum moisture curves were prepared using moisture contents ranging from 2% to 14%. The samples showed extremely high permeability and resistance to compaction. The dry density does not show much variation. At moisture contents higher than 14% bleeding occurred. Results for samples at 16% are unreliable due to the escaped water. The data indicates an optimum moisture content of 9% with a maximum dry density of 100.5 lb/ft^3. The moisture density curve is presented as Fig. 3-5.

The particle size analysis of Monterey sand was performed for classification purposes. The test was performed in accordance with ASTM C136. Monterey sand is classified as poorly-graded sand (SP) by the United Soil Classification System (USCS). The gradation of Monterey sand is presented as Fig. 3-6 (Ottawa sand is included for comparison purposes).

Table 3- 4: Soil Index Properties of Monterey Sand

Property	Monterey Sand
G_s	2.66
C_u	0.9
C_c	2
γ_d (lb/ft^3)	100
OMC	9%
Classification	SP

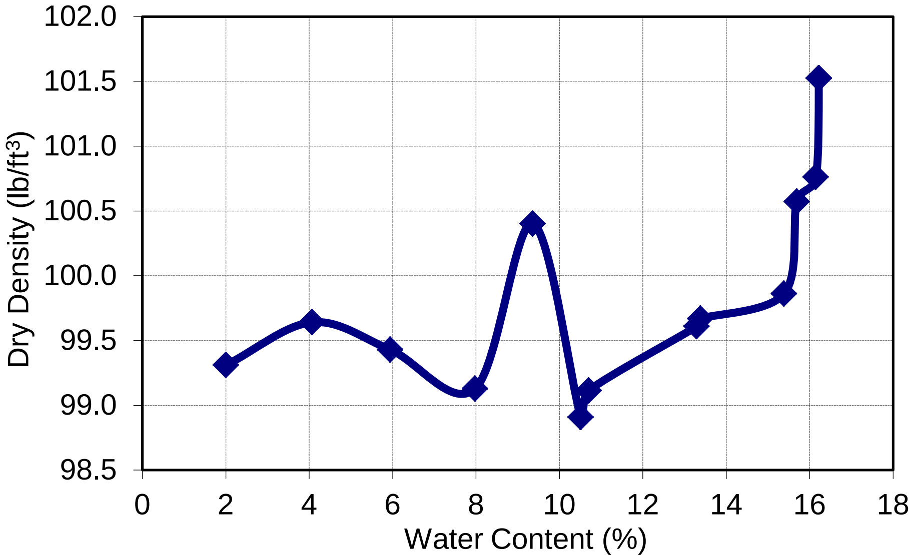

Figure 3- 5: Moisture Density Curve for Monterey Sand

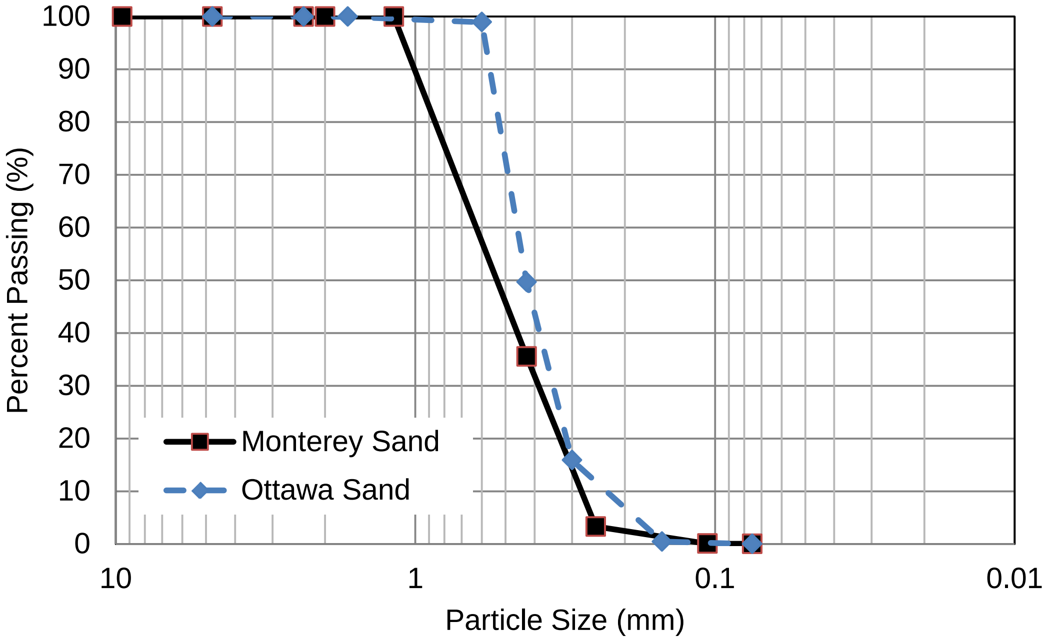

Figure 3- 6**:** Grain Size Distribution of Monterey Sand with Ottawa Sand for Comparison

3.4.3 Fairbanks Silt

Fairbanks silt was collected from a large deposit on Brown’s Hill in Fairbanks, Alaska. The soil index properties for Fairbanks silt are presented in Table 3-5. The soil is classified as low plasticity silt (ML) according to USCS. The optimum moisture content is 12%. This has a corresponding maximum dry unit weight of 108 lb/ft^3. The moisture density curve is presented as Fig. 3-7.

The particle size distribution for Fairbanks silt requires the use of hydrometer testing. The gradation of Fairbanks silt is presented in Fig. 3-8. Fairbanks silt is extremely fine-grained, as 95% of the particles pass a #200 mesh sieve.

Table 3- 5: Soil Index Properties for Fairbanks Silt

Property	Fairbanks Silt
G_s	2.73
C_u	12.3
C_c	1.91
LL	25.6
PL	24.3
PI	1.3
γ_d (lb/ft^3)	108
OMC	12%
Classification	ML

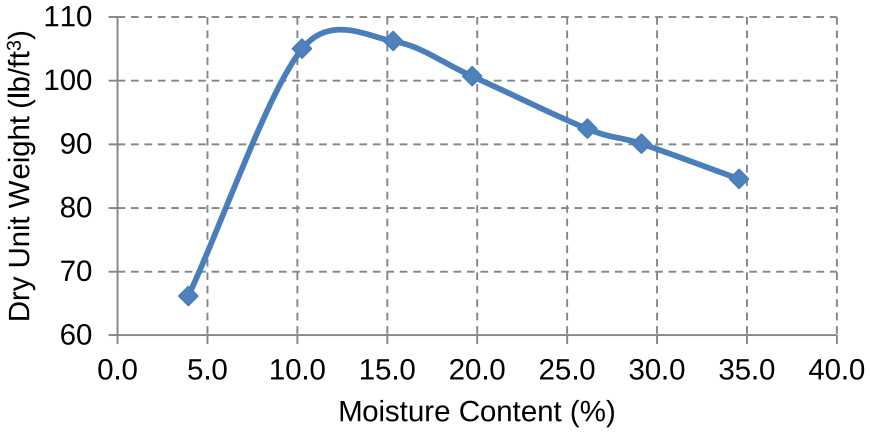

Figure 3- 7: Moisture Density Curve for Fairbanks Silt

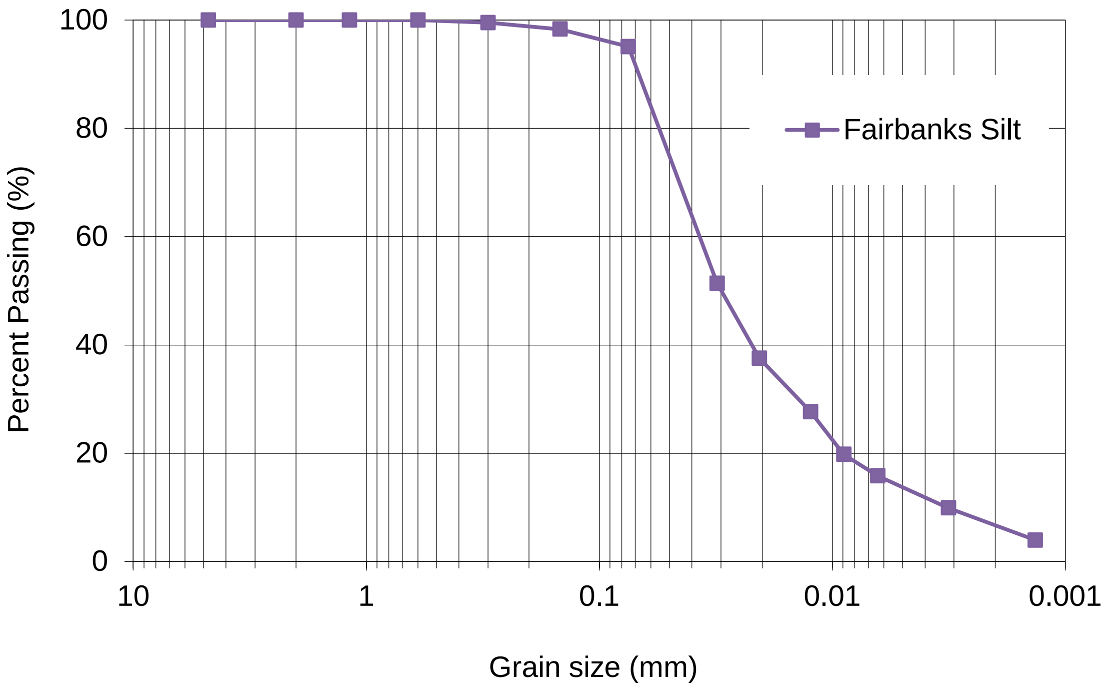

Figure 3- 8: Grain Size Distribution of Fairbanks Silt

3.4.4 Mabel Creek Silt

Mabel Creek silt was collected in Tok, Alaska near the Mabel Creek and Slana River bridges on the Tok Cutoff Highway. The soil index properties for Mabel Creek silt are presented in Table 3-6. The index properties for Mabel Creek Silt come from Zhang (2010). Hydrometer testing was necessary for the Mabel Creek silt as the majority of the sample passed the #200 sieve mesh. Hydrometer testing was performed in accordance with ASTM D422 by Zhang (2010). The particle size analysis is presented as Fig. 3-9.

Table 3- 6: Soil Index Properties of Mabel Creek Silt

Property	Mabel Creek Silt
G_s	2.78
C_u	7.5
C_c	1.48
LL	34.5
PL	29.2
PI	5.3
γ_d (lb/ft^3)	98
OMC	20.2
Classification	ML

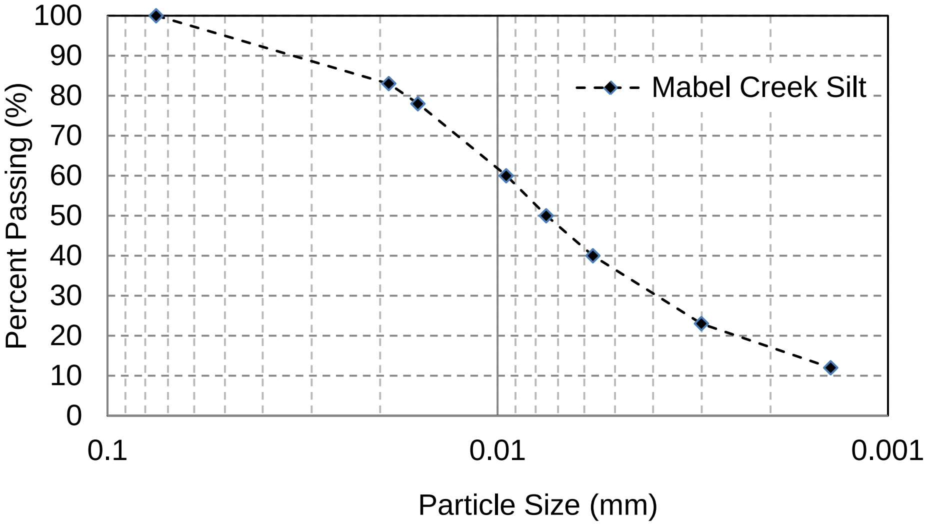

Figure 3- 9: Particle Size Analysis for Mabel Creek Silt

3.4.5 Horseshoe Lake Sand

Horseshoe Lake sand for this testing regime was collected on Horseshoe Lake Road near Wasilla, Alaska. The section of road this material was collected from is a notoriously unstable area. Previous actions to address this stability issue included adding gravel to the sand. When the material was collected and brought to the laboratory, all material was dried and sieved through a #4 mesh sieve to remove gravel. The basic soil index properties of Horseshoe Lake sand are presented in Table 3-7. These include the optimum moisture content, maximum dry unit weight, and specific gravity.

The optimum moisture content and maximum dry unit weight were determined according to ASTM D1557. A mechanical compactor was used. The moisture density curve is presented as Fig. 3-10. Moisture contents of 4%, 8%, and 12% are all acceptable choices due to the small variation in dry-unit weight.

Table 3- 7: Soil Index Properties for Horseshoe Lake Sand

Property	Horseshoe Lake Sand
G_s	2.65
C_u	1.5
C_c	1.7
LL	-
PL	-
PI	-
γ_d (lb/ft^3)	110
OMC	4%
Classification	SP

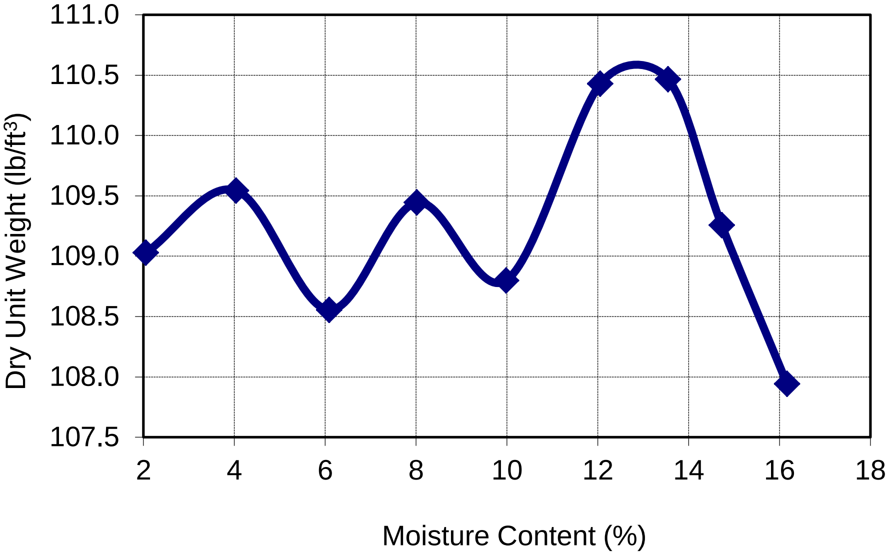

Figure 3- 10: Moisture Density Curve for Horseshoe Lake Sand

3.4.6 Kwigillingok Silt

Kwigillingok silt was collected from Kwigillingok, Alaska. The basic soil index properties of Kwigillingok silt are presented in Table 3-8. All testing was performed in accordance with its respective ASTM standard. Kwigillingok silt was found with an in-situ moisture content of 55%. The particle size analysis for Kwigillingok silt was determined using hydrometer analysis and is presented as Fig. 3-11.

Table 3- 8: Soil Index Properties for Kwigillingok Silt

Property	Kwigillingok Silt
G_s	2.64
C_u	9.7
C_c	1.3
LL	41
PL	34
PI	7
γ_d (lb/ft^3)	97.4
OMC	18%
Classification	ML

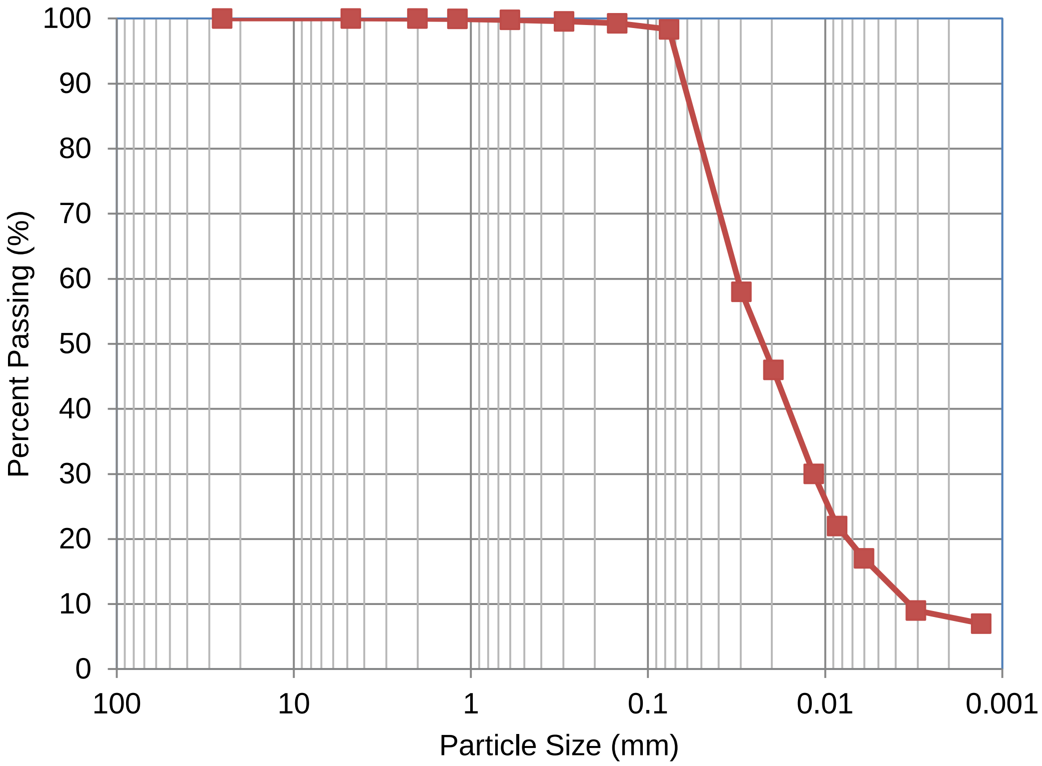

Figure 3- 11: Grain Size Distribution of Kwigillingok Silt

3.5 Geofibers

Geofibers used in the study were donated from Fibersoils. Two types of 2-inch long polypropylene geofibers were used in this study; a tape-type geofiber and a fibrillated geofiber. The index properties of the fibers are provided as Table 3-9. The two types of geofibers have different mechanisms for improvement of soil. Tape-type fibers are a flat and rectangular in shape with a large surface area. This provides greater friction between the soil particles and polypropylene. Fibrillated fibers are similar to tape-type fibers except that they are comprised of webs and stems, resembling a lattice-work when stretched (Fletcher and Humphries, 1991). A picture contrasting the two fibers is provided in Fig. 3-12.

Table 3- 9: Index Properties of Geofibers

Property	**Test Method**	**Requirement**
Polypropylene	ASTM D4101 Group 1/Class 1/ Grade 2	99% Minimum
Moisture Absorption	-----	Nil
Fiber Length	Measured	1-3”
Color	-----	Black
Specific Gravity	ASTM D792	0.91 gm/cm^3
Carbon Black Content	ASTM D1603	0.5%, minimum
Tensile Strength	ASTM D2256	30,000 psi, minimum
Tensile Elongation	ASTM 2256	20%, maximum
Young’s Modulus	ASTM D2101	500,000 psi, minimum

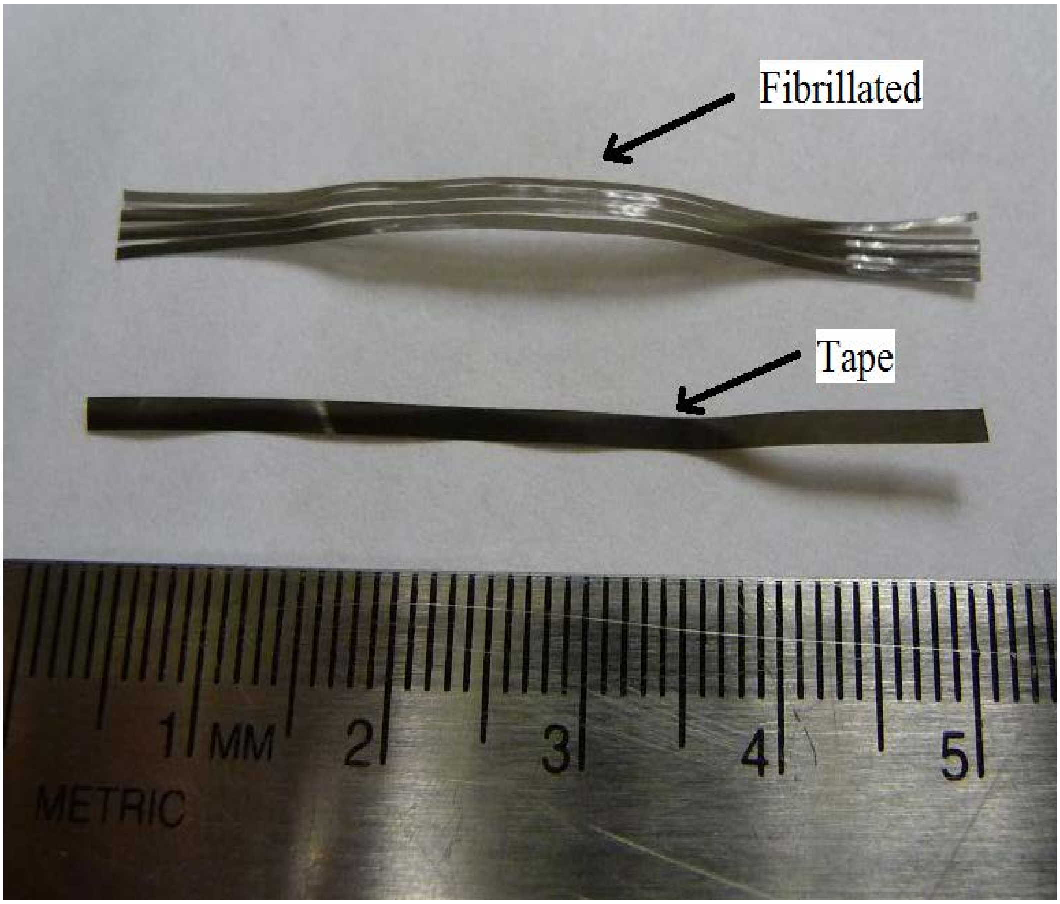

Figure 3- 12: Fibrillated and Tape Type Polypropylene Geofibers (from Omorov, 2010)

3.6 Chemical Additives

The chemical additives used in this study are considered Nontraditional additives. There are many types of chemical additives however only the following were tested in this study: synthetic fluids, polymer emulsions, and isoalkanes. All of the products used in the study were donated by their respective producer. Table 3-10 contains all the chemical additives used including a description of the product type and function. Sections 3.6.1-3.6.7 contains a brief overview of each product.

Table 3- 10: Chemical additives Used in Study

Product	Manufacturer	Product type	Function
Earth Armor	Midwest Industries	Synthetic Fluid	Increase density of treated soil
Soil-Sement	Midwest Industries	Polymer Emulsion	Increase cohesion of treated soil
EnviroKleen	Midwest Industries	Synthetic Fluid	Increase density and cohesion of treated soil
EK35 (B Formula)	Midwest Industries	Synthetic Fluid	Increase density and cohesion of treated soil
Soiltac	Soilworks	Polymer Emulsion	Increase cohesion of treated soil
DirtGlue	DirtGlue	Polymer Emulsion	Increase cohesion of treated soil
PolyCure	DirtGlue	Curing Additive	Cures Polymer Emulsions

3.6.1 Earth Armor

Earth Armor is a synthetic fluid soil stabilizer produced by Midwest Industries. The arctic type formulation was used for all testing. The fluid is designed to coat and lubricate soil particles to improve compaction, and cohesion. Earth armor also acts as a dust palliative by weighing down soil particles. Earth armor was used in a previous laboratory investigation by Hazirbaba and Connor (2008), as well as papers published by Hazirbaba and Gullu (2010) and Gullu and Hazirbaba (2010). Material safety data of Earth Armor is available the product MSDS.

3.6.2 Soil-Sement

Soil-Sement is a polymer emulsion (aqueous acrylic vinyl acetate) soil stabilizer produced by Midwest Industries. Polymer emulsions are used for many things including applications in the food industry to paints and cosmetics. Polymers are especially useful because they do not require a solvent, are easy to clean up, and most are environmentally friendly. The use of polymer emulsions for soil stabilization is a fairly new application. Further data regarding Soil-Sement is available in the product MSDS from Midwest Industries.

3.6.3 EnviroKleen

EnviroKleen is a synthetic organic dust control agent produced by Midwest Industries. The main application of EnviroKleen is related to dust control however it possesses a binder which when blended with soil increases cohesion and compaction. Earth armor is similar in nature to EnviroKleen however it does not possess a binder. Further data about EnviroKleen is available in the product MSDS from Midwest Industries.

3.6.4 EK35

EK35 (B formulation) is a synthetic organic dust control agent produced by Midwest Industries. A naturally occurring pitch/rosin blend binder system adds cohesion to soil when mixed. EK35 was the first commercially available synthetic organic dust control palliative available on the market. Further data on EK35 can be found in the product MSDS from Midwest Industries.

3.6.5 Soiltac

Soiltac is a polymer emulsion (vinyl copolymer) soil stabilization fluid and dust suppressant produced by Soilworks. Soiltac is available in a liquid and powdered version. Both types were used for testing. The product MSDS available from Soilworks provides further data.

3.6.6 DirtGlue

DirtGlue is a polymer emulsion (aqueous acrylate polymer emulsion) soil stabilization fluid and dust suppressant produced by DirtGlue Enterprises. The product MSDS available from DirtGlue provides further data.

3.6.7 PolyCure

PolyCure is curing additive for polymer emulsions produced by DirtGlue. Information regarding PolyCure can be found in the MSDS from DirtGlue Enterprises.

3.7 Sample Preparation

All CBR samples are prepared by first measuring the necessary amount of soil to fill a standard CBR mold into a 2 gallon plastic bag. The amount of water required to bring the soil to optimum moisture content is added and blended until homogenously distributed. If chemical additives are used they are added at the desired content to the moist soil mixture. The chemical added is then blended with the soil-water mixture. Geofibers and moist soil are placed in small alternating layers in a large bowl and blended by hand until the mixture is homogenous. Samples are compacted according to ASTM D1557-09, after samples are prepared.

3.8 Sample Conditioning

A total of four types of sample conditioning were used. These conditions were placed on the samples prior to testing.

3.8.1 Unsoaked

The unsoaked condition is the fastest conditioning method used. Unsoaked samples are soil samples that are subjected to CBR testing immediately after compaction.

3.8.2 Soaked

The soaked condition is CBR samples that have been submerged in water for 96 hours. Swell measurements are recorded before and after submerging the sample in water. The soaked condition typically causes CBR values to decrease compared to unsoaked samples.

3.8.3 Cured

Cured CBR samples were placed on a shelf in the laboratory at 70°F. Curing times are indicated in their respective chapters. The perforated plate and surcharge mass used for soaking CBR samples was left on all samples subjected to curing.

3.8.4 Freeze and Thaw

Samples were subjected to one freeze and thaw cycle in accordance with ASTM D560-03. This includes a freeze cycle where CBR samples were placed in a freezer at -20°F for 24 hours in closed system conditions. To achieve closed system conditions CBR molds were wrapped in fiberglass insulation and placed on top of polystyrene. Details of the freezing environment are presented in the following figures. Figure 3-13 is a profile view of the CBR mold as placed in the freezer. Figure 3-14 is a plan view of CBR samples in the freezer. Figure 3-15 is a profile view of CBR samples in the freezer. The curing cycle used occurred in an insulated box at 70°F at 100% relative humidity for 24 hours. After thawing CBR samples were subjected to CBR testing.

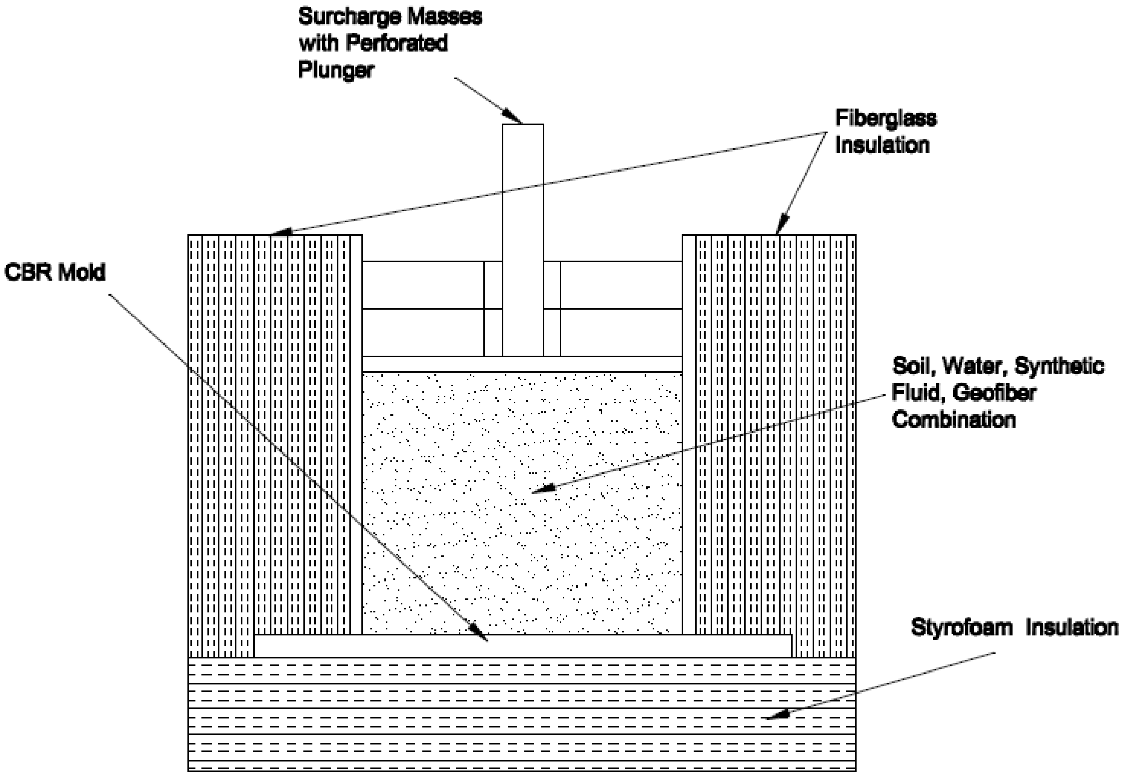

Figure 3- 13: Profile View of CBR Sample Wrapped in Insulation

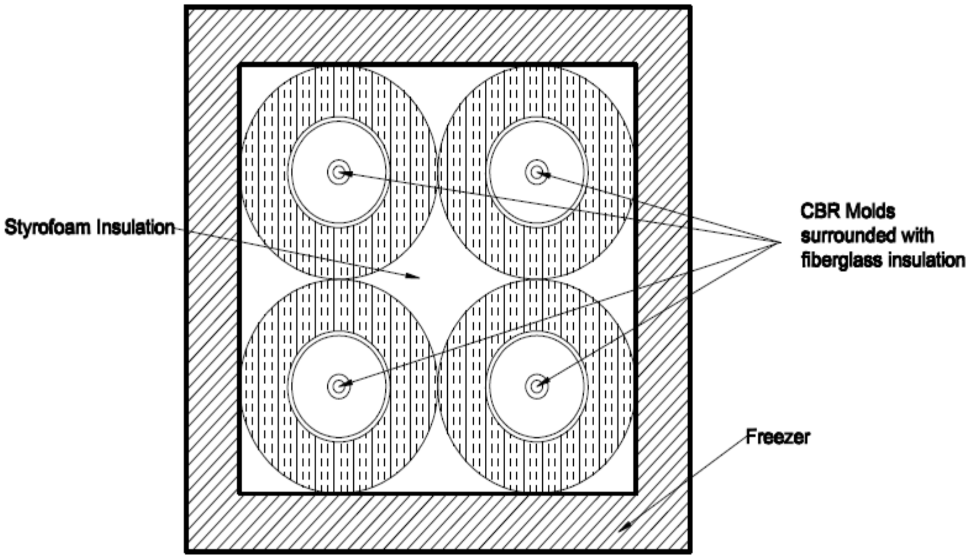

Figure 3- 14: Plan View of CBR Samples in Freezer

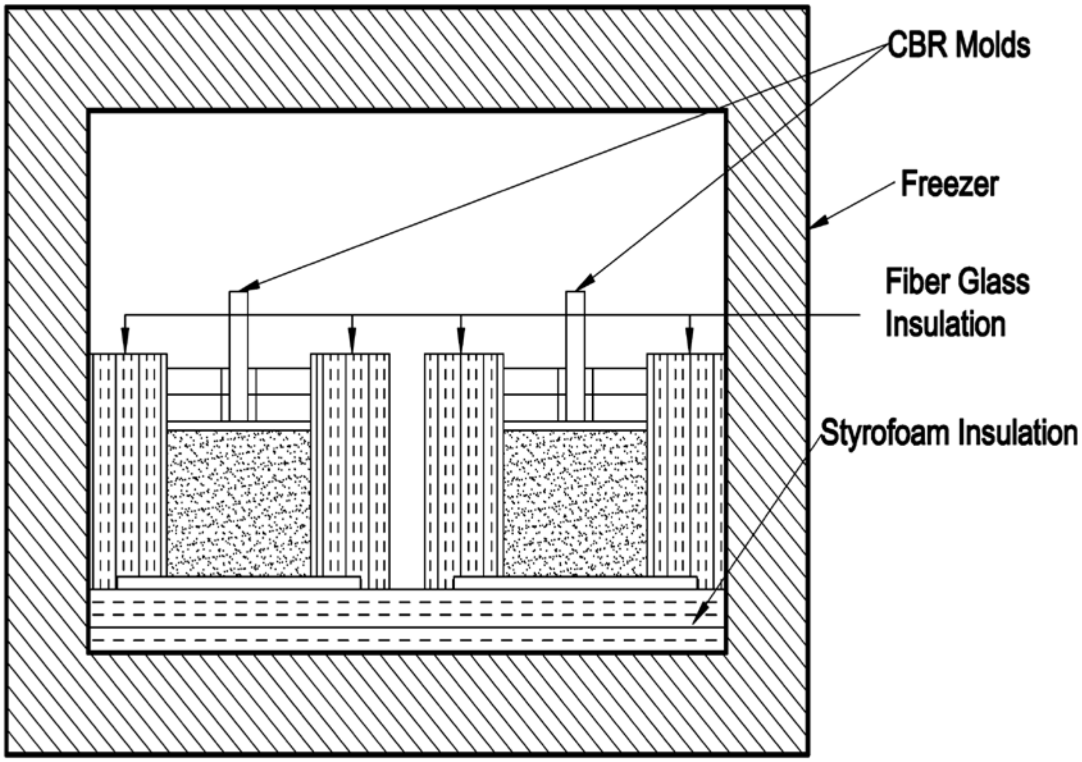

Figure 3- 15: Profile View of CBR Sample in Freezer

3.9 Sample Nomenclature

The sample composition nomenclature will be used throughout this thesis in the form XX%GF+XX%SF+XX%W. The XX%GF corresponds to fiber content taken by the dry weight of soil. GF will change depending on fiber type. If fibrillated fibers are used GF will display F, if tape is used GF will display T. XX%SF corresponds to the chemical dosage used in the mixture, also taken by the dry soil weight, the letters will change depending on the type of chemical used. For Earth Armor the abbreviation SF is used to indicate synthetic fluid, other fluids are usually abbreviated based on the product name. The final part of the nomenclature is XX%W which will represent the moisture content of the sample. An example of the nomenclature would be 0.5%T+3.3%DG+5%PC+8%W, which would mean the samples has 0.5% tape geofibers, 3.3% DirtGlue, 5% PolyCure, and 8% water. Another would be 0.2%F+4%EK+12%W, which is 0.2% fibrillated geofibers, 4% EnviroKleen, and 12% water.

Chapter 4 Stabilization of Ottawa Sand

4.1 Introduction

Poorly-graded sands possess characteristics that often make them undesirable as construction materials. The lack of fine material in poorly-graded sands gives little cohesion, and makes compaction nearly impossible. This chapter will focus on the improvement of Ottawa sand, which is unlike most soils encountered in field situations because all particles are of uniform size and there are no fines. Ottawa sand is a good soil to stabilize because it is one of the most difficult construction materials available. If Ottawa sand can be stabilized there is hope for other soils that have more favorable soil characteristics. Improvement will involve the use of both fibrillated and tape-type geofiber improvement. Synthetic fluid will be used in conjunction with geofibers to stabilize Ottawa sand. All Ottawa sand samples were prepared in the unsoaked condition.

4.2 Ottawa Sand Treated with Tape and Fibrillated Geofibers

The design CBR results for Ottawa sand treated with tape and fibrillated geofibers is presented in Table 4-1. Tape fibers contribute increased strength with increasing fiber contents. The largest improvement came from the 0.8% tape fiber content. Tape fibers provide significantly better improvement than fibrillated fibers at all fiber contents. The tape geofiber is large in comparison to the particle size, which likely provides more frictional resistance between the fiber and the sand particles resulting in increased bearing capacity.

Table 4- 1: Design CBR Values of Ottawa Sand Treated with Tape and Fibrillated Geofibers

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0.2F%+0%SF+13%W	22	13.2
0.5F%+0%SF+13%W	35	84.2
0.8F%+0%SF+13%W	30	55.3
0.2T%+0%SF+13%W	31	60.5
0.5T%+0%SF+13%W	38	100.0
0.8T%+0%SF+13%W	58	205.3

4.3 Ottawa Sand Treated with Earth Armor

Ottawa sand was treated with Earth Armor in several combinations in an attempt to isolate the optimum fluid content. Fluid Contents were chosen to provide total liquid contents near optimum. One advertised benefit of using synthetic fluid is an increase in densification. To this extent, three samples were prepared well below optimum moisture content. In total, four samples were prepared at a total liquid content of 13%. Synthetic fluid was added in 1% increments until reaching 4%. For every 1% increase in synthetic fluid there was a 1% decrease in moisture content of the sample.

The results of stabilization of Ottawa sand using synthetic fluid are presented in Table 4-2. Design CBR values indicate that samples treated with Earth Armor see a reduction in bearing capacity. For all mixtures of Earth Armor, the design CBR is lower than the untreated control sample. Earth Armor seems to provide lubrication between the soil particles resulting in decreased bearing capacity, which indicates it should not be used with Ottawa sand.

Table 4- 2: Design CBR Values of Ottawa Sand Treated with Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0GF%+1%SF+12%W	10	-47.4
0GF%+2%SF+11%W	12	-36.8
0GF%+3%SF+10%W	12	-36.8
0GF%+4%SF+9%W	12	-36.8
0GF%+1%SF+3%W	10	-47.4
0GF%+2%SF+2%W	7	-63.2
0GF%+2%SF+6%W	9	-52.6
0GF%+4%SF+4%W	4	-78.9

4.4 Ottawa Sand Treated with Earth Armor and Geofibers

Ottawa sand was treated with an Earth Armor fluid content of 2% and 11% moisture. Tape and fibrillated fibers were added at 0.5% fiber content. Table 4-3 presents the design CBR results of Ottawa sand stabilized with geofibers and Earth Armor. The results of the samples treated with only Earth Armor, and only geofibers are also included for comparison purposes. The CBR results indicate that stabilization using a combination of geofibers and Earth Armor is not as effective as using only geofibers. The use of Earth Armor decreases the design CBR of all mixtures likely due to the lubrication of soil particles. Therefore, Earth Armor should not be used in Ottawa sand with geofibers.

Table 4- 3: Design CBR Values of Ottawa Sand Treated with Geofibers and Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0GF%+2%SF+11%W	12	-38.6
0.5F%+0%SF+13%W	35	84.2
0.5T%+0%SF+13%W	38	100.0
0.5F%+2%SF+11%W	32	68.4
0.5T%+2%SF+11%W	33	71.1

4.5 Summary and Conclusions

Ottawa sand was mixed with tape and fibrillated geofibers, as well as Earth Armor to provide increased bearing capacity. Three fiber contents of tape and fibrillated geofibers were used to find the optimum fiber content. Earth Armor was added to Ottawa sand to evaluate any benefits to the natural qualities of Ottawa sand. Four fluid contents of Earth Armor were used and none of them improved the bearing capacity of Ottawa sand. Earth armor decreased the bearing capacity of Ottawa sand treated with geofibers.

The decrease in bearing capacity after the addition of Earth Armor is likely due to the liquid acting as a lubricant effectively reducing friction between soil particles and geofibers.

The results of testing indicate that the best method for stabilization of Ottawa sand is simply by using 0.8% tape-type geofibers. A combination of geofibers and Earth Armor provides no advantage over using only geofibers.

Chapter 5 Effects of Geofiber Improvement on Ottawa Sand at Varying Fines Contents

5.1 Introduction

This chapter describes testing of varying fiber contents on laboratory-manufactured sand. The laboratory manufactured soil consisted of Ottawa sand mixed with 10%, 20%, and 30% Fairbanks silt (by dry weight of Ottawa sand). The fines content of the laboratory-manufactured sand was manipulated to study the effect of fiber reinforcement as a function of fines content. Tape and fibrillated geofibers at fiber contents of 0.2%, 0.5%, and 0.8% were used. The results of this testing will help practicing engineers to select a geofiber dosage based on the fines content of silty sand material.

5.2 CBR Results for Ottawa Sand with 10%, 20%, and 30% Fines

The design CBR values of Ottawa sand treated with 10% fines and both types of geofibers are presented Table 5-1. The native Ottawa sand design CBR results are included for comparison. Ottawa sand treated with 10% fines show increased bearing capacity with all geofiber contents and types. The tape fibers provide greater reinforcement than fibrillated fibers. The design CBR increases with increasing fiber dosages for both fiber types. With 0.8% tape geofibers providing the greatest increase in design CBR value. In a similar manner to Ottawa sand with no fines tape geofibers perform better than fibrillated. The enhanced performance of the tape geofiber is attributed to large size of the fiber in relation to the particle size of the soil. The larger fiber creates better frictional contact between the sand particle and the tape fiber.

Table 5- 1: Design CBR Results of Ottawa Sand Mixed with 10% Fines and Geofibers

Sample composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0GF%+10%fines+10%W	22	15.8
0.2%F+10%fines+10%W	26	36.8
0.5%F+10%fines+10%W	37	94.7
0.8%F+10%fines+10%W	63	228.9
0.2%T+10%fines+10%W	31	60.5
0.5%T+10%fines+10%W	52	173.7
0.8%T+10%fines+10%W	80	321.1

The design CBR results for Ottawa sand mixed with 20% fines and geofibers are presented in Table 5-2. The most noticeable result demonstrated is an increase in performance of 0.2% and 0.5% fibrillated fiber contents compared to results obtained with 10% fines. CBR values are nearly equal with fiber contents of 0.2% and 0.5% for both fiber types. The performance increase of fibrillated geofibers is likely due to the fines providing adequate frictional contact with the fibrillated fibers. The CBR value is greatest with 0.8% tape fiber content because the Ottawa sand is still the predominate soil in the mixture and the particle size of the soil is still quite small compared with the fiber.

Table 5- 2: Design CBR Results of Ottawa Sand Mixed with 20% Fines and Geofibers

Sample composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0GF%+20%fines+8%W	19	0.0
0.2%F+20%fines+8%W	42	121.1
0.5%F+20%fines+8%W	70	268.4
0.8%F+20%fines+8%W	81	323.7
0.2%T+20%fines+8%W	42	121.1
0.5%T+20%fines+8%W	74	286.8
0.8%T+20%fines+8%W	107	463.2

The design CBR values of Ottawa sand mixed with 30% fines and treated with geofibers are presented in Table 5-3. The CBR values obtained show behavior significantly different from that observed for Ottawa sand mixed with 10% and 20% fines. The most noticeable aspect is 30% fines alone stabilize Ottawa sand. The addition of both tape and fibrillated fibers at all dosage rates decreases the design CBR value. This behavior indicates that the addition of geofibers to stabilized soil could cause bearing capacity to decrease. The fibrillated and tape type geofibers perform in a nearly identical manner with all geofiber dosages due to fine particles filling spaces between individual fibrillations which allows for good frictional contact and results in nearly identical design CBR values.

Table 5- 3: Design CBR Results of Ottawa Sand Mixed 30% Fines and Geofibers

Sample composition	Design CBR	% Improvement
0GF%+0%SF+13%W	19	-
0%GF+30%fines+6%W	85	347.4
0.2%F+30%fines+6%W	77	305.3
0.5%F+30%fines+6%W	73	286.0
0.8%F+30%fines+6%W	72	276.3
0.2%T+30%fines+6%W	70	268.4
0.5%T+30%fines+6%W	71	271.1
0.8%T+30%fines+6%W	78	310.5

5.3 Summary and Conclusions

In laboratory testing, Fairbanks silt was mixed with Ottawa sand in contents of 10%, 20%, and 30% by dry weight of the sand. Two types of geofiber reinforcement were mixed in with the manufactured soil at three separate fiber contents including 0.2%, 0.5%, and 0.8%.

Samples treated with 10% and 20% fines show the best improvement with 0.8% tape geofibers because the soil mixture contains primarily Ottawa sand. Above 30% fines geofibers have a detrimental effect on the bearing capacity because the soil mixture is stabilized. The addition of geofibers to the stabilized soil matrix results in a loss of bearing capacity. At 30% fines tape and fibrillated geofibers begin to behave in a similar manner which is likely due to fines filling the spaces between fibrillations and increasing frictional contact.

Chapter 6 Stabilization of Monterey Sand with Geofibers and Earth Armor

6.1 Introduction

Monterey sand is clean uniform sand that is difficult to compact and has low unconfined bearing strength. The combination of geofibers and Earth Armor were used to improve the natural qualities of Monterey sand. All tests with Monterey sand were tested in the unsoaked condition.

6.2 Monterey Sand Treated with Tape and Fibrillated Geofibers

Monterey sand was treated with fibrillated and tape geofibers using three fiber contents including 0.2%, 0.5%, and 0.8% by the dry weight of the soil. The design CBR values of Monterey sand treated with geofibers are presented in Table 6-1. Both fiber types provided an increase in the bearing capacity of Monterey sand. The design CBR value increased in magnitude with increasing fiber contents. The optimum fiber content for Monterey sand is 0.8%, using either tape or fibrillated geofibers. The most likely reason tape and fibrillated geofibers perform in such a similar manner is due to the particle size of the Monterey sand, which causes the fibrillations to have little effect on bearing capacity.

Table 6- 1: Design CBR Values of Monterey Sand Treated with Geofibers

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	18	-
0.2%F+0%SF+12%W	34	91.4
0.5%F+0%SF+12%W	41	134.3
0.8%F+0%SF+12%W	50	185.7
0.2%T+0%SF+12%W	33	88.6
0.5%T+0%SF+12%W	39	120.0
0.8%T+0%SF+12%W	49	177.1

6.3 Monterey Sand Treated with Earth Armor

Earth Armor was added to Monterey sand in fluid contents of 2% and 4%. Both of these fluid contents were mixed with water to bring the total liquid content to 12%. The design CBR results of Monterey sand treated with Earth Armor are presented as Table 6-2. The results indicate that 2% Earth Armor is more effective in improving the bearing capacity of Monterey sand than 4% fluid content. The larger fluid dosage provides an excess amount of lubrication between the soil particles which decreases the frictional contact and results in a lower design CBR.

Table 6- 2: Design CBR Results of Monterey Sand Treated with Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	18	-
0%GF+2%SF+10%W	25	42.9
0%GF+4%SF+8%W	15	-14.3

6.4 Monterey Sand Treated with Geofibers and Earth Armor

The 0.5% geofiber dosage was chosen for testing with Earth Armor, because of the potential for increase in bearing capacity with the addition of Earth Armor. The design CBR results for

Monterey sand treated with geofibers and Earth Armor is presented as Table 6-3. For comparison purposes the design CBR results of Monterey sand treated with 0.5% fiber content alone, and 2% Earth Armor alone are also included. The mixture of geofibers and Earth Armor causes the design CBR to decrease compared to the sample with geofibers alone. This behavior is attributed to a loss of frictional contact between the soil particles and the fibers due to the addition of Earth Armor.

Table 6- 3: Design CBR Results of Monterey Sand Treated with Earth Armor and Geofibers

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	18	-
0%GF+2%SF+10%W	25	42.9
0.5%F+0%SF+12%W	41	134.3
0.5%T+0%SF+12%W	39	120.0
0.5%F+2%SF+10%W	31	74.3
0.5%T+2%SF+10%W	29	62.9

6.5 Summary and Conclusions

Monterey sand was treated with tape and fibrillated geofibers at 0.2%, 0.5% and 0.8% fiber contents. Earth Armor was used as an additive to further improve the natural qualities of Monterey sand. The results indicate that Monterey sand can be effectively improved using geofibers, synthetic fluid, and a combination of geofibers and synthetic fluid. The 0.8% tape or fibrillated geofiber content provided the best stabilization method for Monterey sand. Earth Armor alone increases the natural bearing capacity characteristics of Monterey sand. When Earth Armor is mixed with geofibers, the result is a decrease in effectiveness of the geofibers. This could be attributed to a decrease in friction between the soil particles and the geofibers. In general, Earth Armor does not provide sufficient improvement to bearing capacity of Monterey sand to warrant widespread use.

Chapter 7 Geofiber Improvement of Monterey Sand with Varying Fines Content

7.1 Introduction

Monterey sand was mixed with Mabel Creek silt to evaluate the effect of various fines contents on geofibers. The fines contents used included 10%, 20%, 30%, 50%, and 70% by dry weight of Monterey sand. Fibrillated geofibers were added to each mixture in fiber contents of 0.2%, 0.5%, and 0.8%. The goal was to find the optimum geofiber treatment for each percentage of fines.

7.2 CBR Results for Monterey Sand with 10% Fines

The addition of geofibers to Monterey sand containing 10% fines provides stabilization. The design CBR of soil improves as the fiber content increases as show in Table 7-1. The results indicate that 0.8% fibrillated geofibers provides maximum improvement over the untreated sample of 487%. All geofiber contents successfully provided an increase in bearing capacity over the untreated control sample. The dry density increases with geofiber contents up to 0.8%, where the density is lowest. This decrease in density does not affect the design CBR value. This is likely because the large amount of geofibers in combination with the low fines content provides enough frictional resistance to increase bearing capacity and negate any losses that occur from the loss in density.

Table 7- 1: Design CBR Values for Monterey Sand Mixed with 10% Fines Treated with Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+10%W- 10% Fines	12	-	106.1
0.2GF%+0%SF+10%W- 10% Fines	38	226.1	105.7
0.5GF%+0%SF+10%W- 10% Fines	47	308.7	106.6
0.8GF%+0%SF+10%W- 10% Fines	68	487.0	104.8

7.3 CBR Results for Monterey Sand with 20% Fines

The design CBR results for Monterey sand treated with 20% fines are presented in Table 7-2. The addition of 20% fines to Monterey sand causes a bearing capacity increase. The efficiency of geofibers decreases. The largest CBR improvement comes from the 0.5% geofiber sample. The improvement for this dosage is 129%. The 0.8% fiber content shows a lower CBR because there is a decrease in dry density which is not overcome by the frictional resistance provided by geofibers.

Table 7- 2: Design CBR Values for Monterey Sand Mixed with 20% Fines Treated with Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+9%W- 20% Fines	38	-	116.9
0.2GF%+0%SF+9%W- 20% Fines	55	43.4	116.9
0.5GF%+0%SF+9%W- 20% Fines	87	128.9	116.8
0.8GF%+0%SF+9%W- 20% Fines	79	107.9	114.0

7.4 CBR Results for Monterey Sand with 30% Fines

The Monterey sand treated with 30% fines provides a high design CBR value. The addition of 0.2% geofibers increases the bearing capacity. Additional fiber dosages of 0.5% and 0.8% do not provide any significant increase to the untreated design CBR value. In the case of the sample treated with 0.8% geofibers there is a decrease in design CBR value compared to the sample without geofibers. This is due to a loss in densification through the addition of geofibers. The design CBR results are provided in Table 7-3.

Table 7- 3: Design CBR Values for Monterey Sand Mixed with 30% Fines Treated with Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+8%W- 30% Fines	68	-	124.8
0.2GF%+0%SF+8%W- 30% Fines	87	27.2	122.8
0.5GF%+0%SF+8%W- 30% Fines	70	2.2	118.9
0.8GF%+0%SF+8%W- 30% Fines	65	-4.4	116.7

7.5 CBR Results for Monterey Sand with 50% Fines

The addition of 50% fines to Monterey sand is the first soil configuration where all dosages of geofibers decrease the design CBR value. The CBR value decreases with the addition of geofibers because with 50% fines the soil is stabilized. Addition of geofibers results in a loss in densification. The design CBR values for Monterey sand mixed with 50% fines are presented in Table 7-4. Based on these results the use of fibers is not recommended.

Table 7- 4: Design CBR Values for Monterey Sand Mixed with 50% Fines Treated with Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+8%W- 50% Fines	95	-	126.5
0.2GF%+0%SF+8%W- 50% Fines	73	-23.7	124.6
0.5GF%+0%SF+8%W- 50% Fines	58	-39.5	121.4
0.8GF%+0%SF+8%W- 50% Fines	60	-36.8	120.0

7.6 CBR Results for Monterey Sand with 70% Fines

The final mixture of Monterey sand and Mabel creek silt consists of 30% Monterey sand and 70% Mabel Creek Silt. The results show that geofibers decrease the bearing capacity of the mixture in a similar manner to Monterey sand mixed with 50% fines. This again is attributed to a loss in densification with the addition of geofibers. The Monterey sand mixed with 70% fines has a lower magnitude loss in improvement compared to the 50% fines mixture. It is possible that at higher fines contents geofibers would begin to show further improvement. The design CBR values for Monterey sand mixed with 70% fines and treated with geofibers are presented in Table 7-5.

Table 7- 5: Design CBR Values for Monterey Sand Mixed with 70% Fines Treated with Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+8%W- 70% Fines	69	-	124.6
0.2GF%+0%SF+8%W- 70% Fines	64	-8.0	122.7
0.5GF%+0%SF+8%W- 70% Fines	47	-31.9	119.0
0.8GF%+0%SF+8%W- 70% Fines	43	-37.7	118.1

7.7 Summary and Conclusions

This chapter provides the CBR testing results of adding geofibers to Monterey sand with controlled fines contents. Mabel Creek silt was used for fines content. Dosages of Mabel Creek silt were 10%, 20%, 30%, 50%, and 70%. The geofibers used in this study were two-inch-long fibrillated type. These were added in dosages of 0.2%, 0.5%, and 0.8%. The results of this testing indicates geofibers can increase bearing capacity in primarily sandy soils. When silt and sand are at equal levels, geofibers cause a decrease in strength capacity.

In samples containing 10% fines, the 0.8% fiber content provides the best reinforcement. This is because the Monterey sand alone has very poor bearing capacity. The addition of only 10% fines is not enough to provide adequate stabilization to Monterey sand. Therefore, the addition of increasing amounts of geofibers provides reinforcement between soil particles. This provides the noticeable increase in bearing capacity.

An increase in fines content to 20% causes larger geofiber dosages to lose effectiveness. The optimum fiber content for Monterey sand mixed with 20% fines is 0.5%. The sample treated with 30% fines has a peak design CBR value with 0.2% geofiber dosage. Geofibers have a negative effect on design CBR value on samples containing 50% and 70% fines. The loss in strength associated with the addition of geofibers at high fines contents is related to a decrease in the density of the samples.

There is a transition point where soil transitions from a silty-sand to a sandy-silt where geofibers are not effective. At low fines contents geofibers improved the bearing capacity of silty sand. As the mixture of silt and sand approaches an equal point geofibers decrease bearing capacity. The addition of fines to 70% caused geofibers to improve in effectiveness. Further testing should be conducted at larger fines contents to see if the addition of geofibers increases bearing capacity.

Chapter 8 Stabilization of Fairbanks Silt Using Geofibers and Chemical Additives

8.1 Introduction

CBR testing of Fairbanks silt treated with geofibers and two types of chemical additives are described in this chapter. Fairbanks silt is frost-susceptible and often unusable in traditional engineering applications such as embankments. Two types of chemical soil stabilization aids are used in this study; Earth Armor Arctic and Soil-Sement. The Fairbanks silt testing regime is divided into four sections. The first section presents CBR results for soaked and unsoaked sample conditions. The second presents CBR results from Fairbanks silt samples subjected to a freeze and thaw cycle. The third section presents CBR results after Fairbanks silt was subjected to curing as well a freeze and thaw cycle. The final section regards Fairbanks silt treated with Soil-Sement.

8.2 Fairbanks Silt Treated with Geofibers

Tape and fibrillated geofibers were both mixed with Fairbanks silt at fiber contents of 0.2%, 0.375%, 0.5%, 0.625%, 0.8%, and 1% by dry weight of the soil to find the optimum geofiber content. The tests were conducted in unsoaked conditions. Geofiber contents including 0.2%, 0.5%, and 0.8% were repeated in the soaked condition. The fiber content that showed adequate performance in unsoaked conditions was submitted to a 96-hour soaking period to further evaluate performance.

The design CBR results for Fairbanks silt treated with fibrillated geofibers are provided in Table 8-1. The design CBR results indicate that the 0.2% geofiber content is the optimum geofiber content. While other fiber contents provide adequate stabilization, 0.2% causes the largest overall improvement. All geofiber contents provide an increase in the design CBR value, however, with 1% geofibers, the increase is negligible. The decrease in CBR value with increased fiber contents is likely attributed to an increase in fiber on fiber contact and a decrease in densification.

Table 8- 1: Design CBR Values of Fairbanks Silt Treated with Fibrillated Geofibers

Sample Composition	Design CBR	% Improvement	Dry Density (pcf)
0GF%+0%SF+12%W	34	-	104.9
0.2%F+0%SF+12%W	64	86.8	106.6
0.375%F+0%SF+12%W	44	27.9	103.8
0.5%F+0%SF+12%W	42	23.5	102.7
0.625%F+0%SF+12%W	44	27.9	102.6
0.8%F+0%SF+12%W	39	14.7	103.6
1%F+0%SF+12%W	35	2.9	103.6

Fairbanks silt was treated with tape geofibers at the same dosage rates used with fibrillated geofiber testing. The design CBR values for Fairbanks silt treated with geofibers are presented in Table 8-2. Tape geofibers provided improvement in design CBR using several dosages. Samples treated with 0.8% and 1% tape-type geofibers both saw a reduction in design CBR compared with the untreated sample. The design CBR value peaked using the 0.5% geofiber content.

Table 8- 2: Design CBR Values of Fairbanks Silt Treated with Tape Geofibers

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	34	-
0.2%T+0%SF+12%W	50	47.1
0.375%T+0%SF+12%W	40	17.6
0.5%T+0%SF+12%W	52	52.9
0.625%T+0%SF+12%W	44	29.4
0.8%T+0%SF+12%W	32	-5.9
1%T+0%SF+12%W	27	-20.6

Samples treated with 0.2%, 0.5%, and 0.8% fibrillated and tape geofibers were subjected to a 96-hour soak and then tested using CBR. The design CBR of soaked Fairbanks silt treated with fibrillated geofibers is presented as Table 8-3. In soaked samples treated with fibrillated geofibers, the 0.5% fiber content is optimum. This is a shift from the previous unsoaked results, which indicated that 0.2% geofibers was the optimum fiber content. The optimum fiber content with tape fibers in the soaked condition remains 0.2%. The 0.5% fibrillated fiber dosage may be more effective due to the way the fibrillated fibers separate throughout the soil matrix providing more frictional contact space between geofibers and soil particles. The tape geofibers have a smooth finish which reduces friction and decreases bearing capacity.

Table 8- 3: Design CBR Values of Soaked Fairbanks Silt Treated with Tape and Fibrillated Geofibers

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	7	-
0.2%F+0%SF+12%W	32	357.1
0.5%F+0%SF+12%W	46	557.1
0.8%F+0%SF+12%W	38	442.9
0.2%T+0%SF+12%W	39	457.1
0.5%T+0%SF+12%W	33	371.4
0.8%T+0%SF+12%W	22	214.3

8.3 Fairbanks Silt Treated with Earth Armor and Geofibers

Fairbanks silt treated with 2%, 4%, and 6% Earth Armor was mixed with 0.2% and 0.5% fibrillated and tape geofibers. The design CBR results of Fairbanks silt treated with 2% Earth Armor and geofibers are presented in Table 8-4. The results show that Fairbanks silt treated with fibrillated geofibers and Earth Armor has improved bearing capacity. The tape geofibers cause an increase in bearing capacity with the 0.5% tape fiber content. The Fairbanks silt seems to benefit from the addition of fibrillated geofibers most, which is likely due to the way fibrillated geofibers spread out in a soil matrix providing a large amount of small fibers that enhance frictional resistance.

Table 8- 4: Design CBR Results of Fairbanks Silt Treated with Geofibers and 2% Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	34	-
0%GF+2%SF+6%W	43	26.5
0.2%F+2%SF+6%W	43	26.5
0.5%F+2%SF+6%W	38	11.8
0.2%T+2%SF+6%W	31	-8.8
0.5%T+2%SF+6%W	43	26.5

The design CBR results for samples treated with 4% Earth Armor are presented as Table 8-5. The 0.5% fibrillated fiber content with 4% fluid content causes the largest increase in bearing capacity. The large increase in design CBR observed with 0.5% fibrillated fibers and 4% Earth armor is likely the result of extremely good frictional contact between the geofibers and the Fairbanks silt particles. The earth armor likely contributes to more effective compaction which also results in the large design CBR value.

Table 8- 5: Design CBR Results of Fairbanks Silt Treated with Geofibers and 4% Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	34	-
0%GF+4%SF+6%W	52	52.9
0.2%F+4%SF+6%W	49	44.1
0.5%F+4%SF+6%W	71	107.4
0.2%T+4%SF+6%W	49	42.6
0.5%T+4%SF+6%W	48	41.2

The design CBR values for samples treated with 6% Earth Armor are presented as Table 8-6. The trend observed with 4% Earth Armor continues; samples treated with fibrillated fibers see an increase in bearing capacity with 0.5% geofibers, tape geofibers cause nearly equal CBR values for both fiber contents. The 0.5% fibrillated geofiber content in combination with 6% Earth Armor provides the largest improvement in bearing capacity. The decrease in design CBR compared to results with 6% Earth Armor is likely the cause of increased lubrication with the larger Earth Armor content.

Table 8- 6: Design CBR Results of Fairbanks Silt Treated with Geofibers and 6% Earth Armor

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	34	-
0%GF+6%SF+6%W	50	47.1
0.2%F+6%SF+6%W	40	17.6
0.5%F+6%SF+6%W	63	85.3
0.2%T+6%SF+6%W	38	11.8
0.5%T+6%SF+6%W	36	5.9

Unsoaked CBR results indicated that 4% Earth Armor in combination with 0.5% fibrillated geofibers is the best combination of the two materials for improving the bearing capacity of Fairbanks silt. Fairbanks silt was treated with 4% Earth Armor as well as 0.2% and 0.5% dosages of fibrillated- and tape-type geofibers in the soaked condition. During the soaking period, significant amounts of Earth Armor leached from the samples and pooled on top of the water. Further testing with other dosages of Earth Armor was abandoned due to the loss of Earth Armor during soaked periods. The leaching indicates that Earth Armor should not be used in areas where heavy precipitation or excess moisture is expected.

The design CBR results for soaked Fairbanks silt treated with geofibers and 4% Earth Armor are presented in Table 8-7. These results show that geofiber contents improve the design CBR over the untreated samples and the sample treated only with Earth Armor. The 0.5% geofiber dosages for both types of geofiber offer the highest design CBR values. The difference between the design CBR results for tape and fibrillated geofibers with 4% Earth Armor at the 0.5% fiber content is negligible.

Table 8- 7: Design CBR Values of Soaked Fairbanks Silt Treated with 4% Earth Armor and Geofibers

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+12%W	7	-
0%GF+4%SF+6%W	12	64.3
0.2%F+4%SF+6%W	21	200.0
0.5%F+4%SF+6%W	23	228.6
0.2%T+4%SF+6%W	13	85.7
0.5%T+4%SF+6%W	25	257.1

Fairbanks silt was treated with three fluid contents including 2%, 4%, and 6%. CBR testing showed that 4% Earth Armor in combination with 0.5% fibrillated geofibers is the optimum treatment configuration. In soaked Fairbanks silt samples treated with Earth Armor and geofibers there was significant leaching of the synthetic fluid into the water. This behavior indicates that the Earth Armor and geofibers should be used only in conditions where heavy precipitation and excess moisture are concerns.

8.4 Fairbanks Silt Treated with Geofibers and Earth Armor Subjected to a Freeze and Thaw Cycle

Fairbanks silt was treated with 4% Earth Armor and 6% moisture and subjected to a freeze-thaw cycle. Fibrillated and tape geofibers were used in dosages of 0.2% and 0.5%. Samples were subjected to soaked and unsoaked conditions.

The design CBR values for unsoaked Fairbanks silt treated with geofibers and Earth Armor subjected to freeze and thaw are presented in Table 8-8. The results of the CBR testing indicate samples treated with fibrillated geofibers perform better than samples treated with tape fibers after a freeze-thaw cycle. The 0.2% fibrillated geofiber content in combination with 4% Earth Armor is the most effective treatment method.

Table 8- 8: Design CBR Results of Unsoaked Fairbanks Silt Treated with Geofibers and 4% Earth Armor Subjected to a Freeze and Thaw Cycle

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	26	-
0%GF+4%SF+6%W	35	32.7
0.2%F+4%SF+6%W	46	76.9
0.5%F+4%SF+6%W	48	84.6
0.2%T+4%SF+6%W	38	44.2
0.5%T+4%SF+6%W	36	38.5

The design CBR tests results for soaked Fairbanks silt treated with geofibers and Earth Armor and subjected to a freeze and thaw cycle are presented in Table 8-9. These results show that fibrillated type geofibers in combination with Earth Armor provide the highest design CBR values in soaked samples subjected to freeze-thaw. The low design CBR values make all treatment methods ineffective.

Table 8- 9: Design CBR Results of Soaked Fairbanks Silt Treated with Geofibers and 4% Earth Armor Subjected to a Freeze and Thaw Cycle

Sample Composition	Design CBR	% Improvement
0GF%+0%SF+12%W	4	-
0%GF+4%SF+6%W	5	42.9
0.2%F+4%SF+6%W	12	242.9
0.5%F+4%SF+6%W	11	214.3
0.2%T+4%SF+6%W	3	-14.3
0.5%T+4%SF+6%W	7	100.0

The effects of curing on Earth Armor were investigated. Two types of samples were prepared. The first contained only Earth Armor and water, in dosages of 4% and 6% respectively. The second contained tape-type geofibers at a 0.5% dosage in combination with Earth Armor and water. The samples were conditioned immediately after compaction using two methods. The first method consisted of a 28-day curing period followed by a 96-hour soak. The second started with a 96-hour soak followed by a 28-day cure. After the conditioning periods, samples were subjected to a 24-hour freeze in closed-system freezing conditions and then a 24-hour thaw. After the thawing period, samples were subjected to CBR testing.

The design CBR results for samples conditioned with a curing period are presented in Table 8-10. Fairbanks silt CBR samples cured for 28 days and frozen immediately after a soak did not perform as well as samples that had been soaked prior to a 28-day curing period. For both conditioning types, samples treated with 0.5% tape geofibers performed better than the samples treated only with Earth Armor. The design CBR values of samples without any curing period are included in the figure for comparison purposes. The results indicate Earth Armor does not gain strength with cure time

Table 8- 10: Fairbanks Silt Treated with Geofibers and Earth Armor Cured and Subjected to a Freeze and Thaw Cycle

Sample Composition	Curing Conditions	Design CBR	% Improvement
0%GF+4%SF+6%W	No Cure	5	-
0.5%T+4%SF+6%W	No Cure	7	-
0%GF+4%SF+6%W	28DayCure-Soaked	2	-60.0
0.5%T+4%SF+6%W	28DayCure-Soaked	4	-100.0
0%GF+4%SF+6%W	Soaked-28DayCure	6	10.0
0.5%T+4%SF+6%W	Soaked-28DayCure	9	22.2

8.5 Fairbanks Silt Treated with Geofibers and Soil-Sement

Fairbanks silt was treated with Soil-Sement in two liquid contents including 1.5% and 2%. Tape and fibrillated geofibers were used in combination with Soil-Sement at dosages of 0.2% and 0.5%. The length of the tape-type geofiber was increased from 2 inches in previous testing to 2.75 inches. The change in length comes from a discontinuation of 2-inch tape-type geofibers by the manufacturer. Samples were placed on a shelf in the laboratory for 14 days to allow curing to take place. After curing, samples were soaked for 96 hours. CBR testing was performed immediately after soaking.

The design CBR results for samples treated with 2% Soil-Sement are presented as Table 8-11. These results show Soil-Sement provide an increase in CBR value over untreated samples. The addition of geofibers increased the design CBR value further, compared to treatment with only Soil-Sement. For both geofiber dosages, the tape-type provides slightly larger design CBR value. The difference in design CBR value between tape and fibrillated geofibers is effectively negligible.

Table 8- 11: Design CBR of Fairbanks Silt Treated with 2% Soil-Sement and Geofibers

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+12%W	7	-
0.2%F+0%SF+12%W	32	357.1
0.5%F+0%SF+12%W	46	557.1
0.2%T+0%SF+12%W	39	457.1
0.5%T+0%SF+12%W	33	371.4
0%GF+2%SS+10%W	21	200.0
0.2%F+2%SS+10%W	22	207.1
0.5%F+2%SS+10%W	29	307.1
0.2%T+2%SS+10%W	25	257.1
0.5%T+2%SS+10%W	33	371.4

The design CBR values for Fairbanks silt treated with 1.5% Soil-Sement and geofibers are presented in Table 8-12. Samples treated with tape-type geofibers produced lower design CBR values than samples treated with fibrillated geofibers. The addition of 0.2% tape geofibers reduced the design CBR value below that of the sample treated only with Soil-Sement.

Table 8- 12: Design CBR of Fairbanks Silt Treated with 1.5% Soil-Sement and Geofibers

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+12%W	7	-
0.2%F+0%SF+12%W	32	357.1
0.5%F+0%SF+12%W	46	557.1
0.2%T+0%SF+12%W	39	457.1
0.5%T+0%SF+12%W	33	371.4
0%GF+1.5%SS+10%W	29	307.1
0.2%F+1.5%SS+10%W	31	342.9
0.5%F+1.5%SS+10%W	34	378.6
0.2%T+1.5%SS+10%W	23	228.6
0.5%T+1.5%SS+10%W	29	307.1

8.6 Summary and Conclusions

The natural bearing capacity characteristics of Fairbanks silt were improved using combinations of geofibers and synthetic fluid. Unsoaked CBR samples with 0.2% fibrillated and 0.5% tape geofibers provide 86.8% and 52.9% improvements in CBR value respectively. Fibrillated-type geofibers show greater improvement than the tape type. In soaked CBR samples, 0.5% fibrillated geofibers provide the largest increase in design CBR value with a 557.1% improvement over the untreated sample. Fairbanks silt has more resistance to a freeze-and-thaw cycle with treatment of fibrillated geofibers in soaked and unsoaked conditions. The 0.5% fibrillated geofiber dosage in combination with 4% Earth Armor provides 84.6% and 214% improvement in the soaked and unsoaked conditions, respectively. Based on test results after a freeze and thaw cycle, 0.5% fibrillated fiber content in combination with 4% Earth Armor is the recommended treatment for Fairbanks silt in cold weather conditions.

Earth Armor leached into water when soaked. This behavior indicates that Earth Armor should not be selected for use in areas subject to large amounts of precipitation or excess moisture. Curing Earth Armor for 28 days does not improve its natural characteristics.

Fairbanks silt is more effectively treated with Soil-Sement and geofibers rather than Earth Armor and geofibers. In the soaked condition Fairbanks silt treated with 0.5% fibrillated geofibers and 1.5% Soil-Sement has a design CBR of 34 for a total improvement of 378.6%.

Chapter 9 Stabilization of Horseshoe Lake Sand Using Geofibers and Chemical Additives

9.1 Introduction

Horseshoe Lake, Alaska is the first known construction site in the world using a combination of 0.75 inch fibrillated geofibers and Soil-Sement. A 500 foot section of Horseshoe lake road that required yearly maintenance was chosen for the stabilization project. A map of Horseshoe Lake road including the area stabilized is presented as Fig. 9-1. This chapter will detail the improvements made on Horseshoe Lake sand using a combination of geofibers and synthetic fluid. Samples were treated with fibrillated-type geofibers. Three dosages of geofibers were used. Early testing was done to evaluate the performance of Soil-Sement for use in a field test site. This early testing used several amounts of Soil-Sement to find the optimum treatment content, other tests involved testing samples after a freeze and thaw cycle. Horseshoe lake sand was then used to measure the bearing capacity improvements of several fluids against each other using a seven day cure and four day soak.

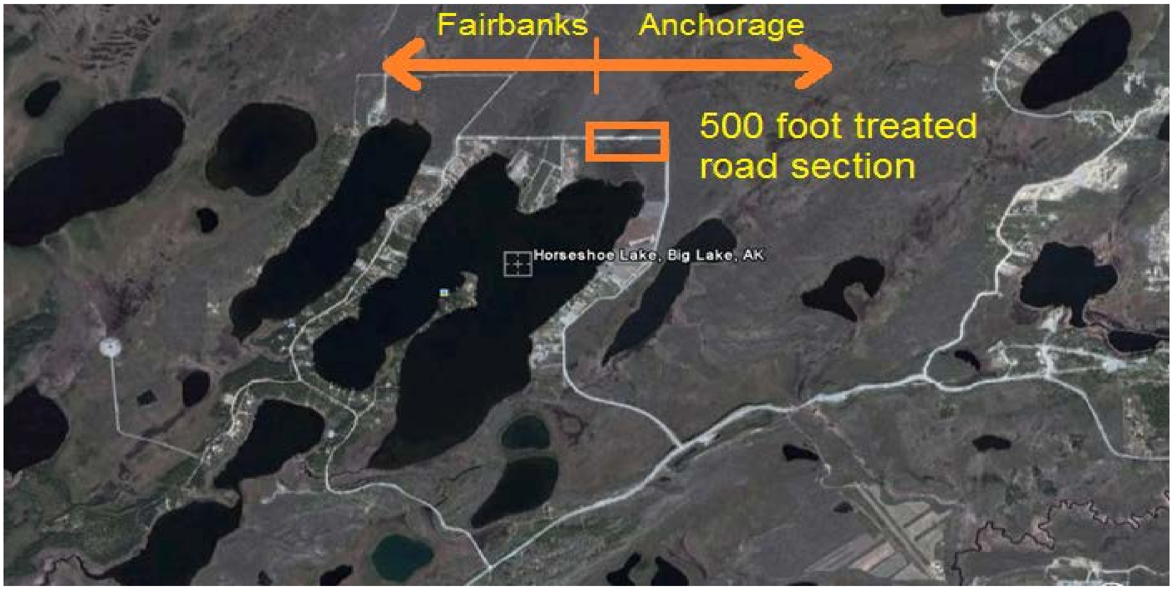

Figure 9- 1: Aerial view of Horseshoe Lake Road Including Treated Area

9.2 Horseshoe Lake Sand Treated with Geofibers

Horseshoe Lake sand was treated with 0.2%, 0.5%, and 0.8% geofibers to find the optimum fiber content. Unsoaked samples were first prepared to determine the optimum geofiber dosage. Soaked samples were prepared for an untreated control test, as well as one prepared at the optimum geofiber dosage.

The design CBR results for samples treated only with geofibers are presented as Fig. 9-1. The unsoaked results show that the 0.5% dosage is the optimum geofiber content. In all unsoaked samples, the addition of geofibers increased the design CBR values over the untreated control sample. The soaked sample showed a reduction in magnitude of CBR value compared to the unsoaked sample. The 0.5% fibrillated dosage for the soaked sample provided a large increase in design CBR value compared to the untreated control.

Table 9- 1: Design CBR Results of Horseshoe Lake Sand Treated with Geofibers

Sample Condition	Sample Composition	Design CBR	% Improvement
Soaked	0%GF+0%SF+8%W	14	-
	0.5%F+0%SF+8%W	34	142.9
Unsoaked	0%GF+0%SF+8%W	25	-
	0.2%F+0%SF+8%W	36	46.9
	0.5%F+0%SF+8%W	46	87.8
	0.8%F+0%SF+8%W	41	65.3

9.3 Unsoaked Horseshoe Lake Sand Treated with EnviroKleen and Earth Armor

EnviroKleen and Earth Armor were used to improve the bearing capacity characteristics of Horseshoe Lake sand. The liquid content of Earth Armor is based on the results from testing with Fairbanks silt. A 4% Earth Armor content was used in conjunction with 4% water to bring the sample to 8% total liquid content.

EnviroKleen had not been used in any other study, so experimentation was necessary to determine an optimum fluid content. Samples treated with EnviroKleen were prepared at 4% and 8% total liquid contents. The 4% liquid content samples consisted of two mixtures. The first contained 3% water and 1% EnviroKleen. The second contained 2% water and 2% EnviroKleen. The 8% global moisture content samples contained 2% EnviroKleen with 6% water, and 4% EnviroKleen and 4% water.

The design CBR results of samples treated with EnviroKleen and Earth Armor Arctic are presented as Table 9-2. The results showed that samples treated with EnviroKleen at 4% total liquid content actually performed worse than the untreated control sample. The sample treated with 2% EnviroKleen performed better than the sample treated with 1%. At 8% global moisture content, the addition of all synthetic fluids improved the CBR performance of Horseshoe Lake sand. A 37% improvement in design CBR value was gained from treatment with 4% EnviroKleen and 4% water.

Table 9- 2: Design CBR Values of Horseshoe Lake Sand Treated with Earth Armor and EnviroKleen

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+4%W	27	-
0%GF+1%EK+3%W	10	-63.0
0%GF+2%EK+2%W	24	-11.1
0%GF+0%SF+8%W	25	-
0%GF+4%SF+4%W	30	20.0
0%GF+2%EK+6%W	25	0.0
0%GF+4%EK+4%W	37	48.0

9.4 Horseshoe Lake Sand Treated with Soil-Sement

Horseshoe Lake sand was treated with Soil-Sement using a 1% dosage rate. Samples were prepared in soaked and unsoaked conditions. The Horseshoe Lake sand treated with 1% Soil-Sement was subjected to a 14-day cure. Resistance to freeze and thaw was investigated.

The design CBR results for Horseshoe Lake sand treated with Soil-Sement in the unsoaked condition are presented as Table 9-3. No loss of strength noted after freeze-thaw cycle, which is significant for cold regions such as Alaska.

The amount of Soil-Sement was increased to identify any potential gain that could be achieved. The initial 1% dosage was increased to 1.5% and 2%. Geofibers were also added at a 0.5% dosage rate. Samples were allowed to cure for a period of 14 days after compaction. After curing, samples were soaked for 96 hours. Design CBR results are presented as Table 9-4. These results show very little benefit through the increase in Soil-Sement dosage.

Table 9- 3: Design CBR Results of Horseshoe Lake Sand Treated with Soil-Sement

Sample Condition	Sample composition	Design CBR	% Improvement
Unsoaked	0%GF+0%SF+8%W	25	-
Unsoaked	0.5%F+0%SF+8%W	46	84.0
14 Day Cure	0.5%F+1%SS+8%W	44	74.0
14 Day Cure + Freeze and Thaw	0.5%F+1%SS+8%W	49	94.0
Soaked	0%GF+0%SF+8%W	14	-
Soaked	0.5%F+0%SF+8%W	34	142.9
14 Day Cure- Soaked	0.5%F+1%SS+8%W	47	232.1
14 Day Cure + Freeze and Thaw- soaked	0.5%F+1%SS+8%W	48	239.3

Table 9- 4: Design CBR Values of Horseshoe Lake with Increased Soil-Sement

Sample Composition	Design CBR	% Improvement
0.5%F+1%SS+8%W	47	-
0.5%F+1.5%SS+8%W	49	3.2
0.5%F+2%SS+8%W	44	-7.4

The Soil-Sement content was increased to 4% and samples were cured for seven days followed by a soak. The design CBR results are presented as Table 9-5. The results show that there is very little benefit in increasing the Soil-Sement content to 4%. This is most likely due to Soil-Sement curing inadequately due to the large liquid content.

Table 9- 5: Design CBR Results of Horseshoe Lake Sand Treated with 4% Soil-Sement

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0%GF+4%SS+8%W	30	110.7
0.5%F+4%SS+8%W	45	217.9

Horseshoe lake sand treated with 1% Soil-Sement produced a design CBR value that is very close to being classified as “excellent” according to Table 3-1. The combination of 1% Soil-Sement with 0.5% fibrillated geofibers produced design CBR value above 45 which is classified as “good”. The Horseshoe lake sand treated with Soil-Sement showed resistance to a freeze and thaw cycle, which was not, tested using other additives with Horseshoe lake sand.

9.5 Evaluation of Soil Stabilization Liquids on Horseshoe Lake Sand

A series of tests was conducted using Horseshoe Lake sand to measure various soil stabilization liquids against each other. All samples cured for seven days in the laboratory at 21°C. After the curing period, the samples were moved to a soaking tank for 96 hours. Samples were then subjected to CBR testing. Soil-Sement was included in this testing at an increased dosage rate.

The design CBR results of Horseshoe Lake sand treated with Soiltac are presented as Table 9-6. The results show that samples treated with Soiltac provided greater CBR values than untreated samples. The addition of geofibers increased the design CBR further. The sample treated with 1.1% Soiltac performed better than the sample treated with 4%. These results were unexpected because it was assumed that a larger dosage would result in a stronger sample. Polymer emulsions cure through the evaporation of water. Therefore, the sample treated with the higher dosage of Soiltac had too much moisture to allow for full evaporation.

Powdered Soiltac is another polymer-based soil stabilization aid, with the same formulation as the liquid Soiltac, however water is added prior to use. The powdered Soiltac contents included 0.6%, 1.2%, and 4%. The smaller dosages are recommended by the manufacturer. The larger dosage was selected in attempt to provide greater stabilization to Horseshoe Lake sand.

Table 9- 6: Design CBR Results of Horseshoe Lake Sand Treated with Soiltac

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0%GF+1.1%ST+8%W	33	132.1
0.5%F+1.1%ST+8%W	54	285.7
0%GF+4%ST+8%W	21	46.4
0.5%F+4%ST+8%W	32	125.0

The design CBR results for Horseshoe Lake sand mixed with powdered Soiltac are presented as Table 9-7. These results show that the samples treated with lower dosages of powdered Soiltac perform better than the sample with the higher dosage. These results are similar to the results found with liquid Soiltac. It is likely that higher amounts of polymers do not cure adequately under the imposed sample conditions. In all cases, samples treated with Soiltac and geofibers performed better than samples treated only with geofibers. The sample treated with 0.6% powder content performed better than any other amount of powdered Soiltac.

Table 9- 7: Design CBR Results of Horseshoe Lake Sand Treated with Powdered Soiltac

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0%GF+0.6%PST+8%W	27	89.3
0.5%F+0.6%PST+8%W	54	285.7
0%GF+1.2%PST+8%W	17	21.4
0.5%F+1.2%PST+8%W	55	292.9
0%GF+4%PST+8%W	23	60.7
0.5%F+4%PST+8%W	34	142.9

Design CBR results for Horseshoe Lake sand mixed with DirtGlue, PolyCure, and geofibers are presented as Table 9-8. The design CBR results indicate that the combination of DirtGlue and

PolyCure are extremely useful for stabilizing Horseshoe Lake sand. The addition of geofibers further improves the design CBR value of Horseshoe Lake sand treated with DirtGlue and PolyCure. When the dosage of PolyCure is reduced to 5%, the CBR values decrease by nearly 50%. When PolyCure is removed from the mixture, the CBR values decrease below untreated sample levels. This indicates the inclusion of PolyCure with DirtGlue is necessary in order to provide adequate stabilization to soils.

Table 9- 8: Design CBR Results of Horseshoe Lake Sand Treated with DirtGlue, PolyCure, and Geofibers

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0.%GF+3.3%DG+10%POLY+8%W	75	435.7
0.5%F+3.3%DG+10%POLY+8%W	95	578.6
0%GF+3.3%DG+5%POLY+8%W	39	178.6
0.5%F+3.3%DG+5%POLY+8%W	60	325.0
0.%GF+3.3%DG+8%W	6	-57.1
0.5%F+3.3%DG+8%W	32	125.0

The final soil stabilization liquid tested is EK 35 (B formulation). A dosage of 3% EK 35 was used based on manufacturer recommendation. The design CBR results for Horseshoe Lake sand treated with EK 35 are presented as Table 9-9. These results show that a mixture of geofibers and EK 35 can significantly increase the design CBR. The addition of EK 35 without geofibers results in a slight decrease in CBR value. The decrease in CBR value without geofibers is unexpected, but is likely attributed to a lubrication of soil particles through the addition of EK35.

Table 9- 9: Design CBR Values of Horseshoe Lake Sand Treated with EK35

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0.%GF+3%EK35+8%W	12	-14.3
0.5%GF+3%EK35+8%W	66	371.4

Other combinations of geofibers and nontraditional additives increased the bearing capacity of Horseshoe lake sand to a rating of “excellent” (any CBR value (>) 50 is excellent) according to the rating scale shown in Table 3-1.

The stabilization methods that improved the bearing capacity of Horseshoe Lake sand to “excellent” were as follows:

- 1.1% Soiltac in combination with 0.5% fibrillated geofibers
- 0.6% powdered Soiltac in combination with 0.5% fibrillated geofibers
- 3.3% DirtGlue with 5% PolyCure and 0.5% fibrillated geofibers, increasing the PolyCure content to 10% increases the CBR value by 35, (60 for 5% PolyCure and 95 for 10% PolyCure)
- 3% dosage of EK35 with 0.5% fibrillated geofibers

9.6 Summary and Conclusions

Horseshoe Lake sand was treated using combinations of several types of soil stabilization fluid as well as geofibers. The results indicate that the addition of these materials can provide stabilization. The optimum fibrillated geofiber content is 0.5% by dry weight of the soil which applies to Horseshoe Lake sand in both the soaked and unsoaked condition. A 4% dosage of EnviroKleen can provide a 48% improvement in CBR value compared to Horseshoe Lake sand at

8% moisture. The same dosage of Earth Armor Arctic provides a 20% increase in CBR value. When Earth Armor Arctic is added in conjunction with geofibers, the overall improvement is 100%. Horseshoe Lake sand treated with 1% Soil-Sement shows no bearing capacity loss after a freeze-thaw cycle which is beneficial for use in Alaska. Increasing the Soil-Sement dosage from 1% to 1.5% or 2% does not provide much increase in CBR value for samples subjected to 14-day cure and 96-hour soak.

Table 9-10 presents the stabilizing liquids tested in order of effectiveness. The clear cut most effective stabilization additive was a combination of 0.5% fibrillated geofibers with DirtGlue and PolyCure. The combination of DirtGlue and PolyCure with geofibers would be the recommended treatment for Horseshoe Lake sand. The addition of geofibers in combination with the stabilization liquid in all cases increased the design CBR. EK35 was the only stabilization additive to decrease the design CBR value without geofibers; however the addition of geofibers to Horseshoe lake sand with geofibers cased the second highest overall improvement for all liquid stabilizers tested. Soiltac provides nearly equal design CBR values for the powdered and liquid types; addition of geofibers causes increase in design CBR for both types. The 4% Soil-Sement content provides the lowest design CBR value when combined with geofibers. In lower liquid contents and other curing conditions Soil-Sement performed more effectively including proving resistant to freeze-thaw conditions.

Table 9- 10: Comparative Analysis of Stabilizing Liquids in Order of Best Design CBR

Sample Composition	Design CBR	% Improvement
0%GF+0%SF+8%W	14	-
0.5%F+0%SF+8%W	34	142.9
0.%GF+3.3%DG+10%POLY+8%W	75	435.7
0.5%F+3.3%DG+10%POLY+8%W	95	578.6
0.%GF+3%EK35+8%W	12	-14.3
0.5%GF+3%EK35+8%W	66	371.4
0%GF+1.1%ST+8%W	33	132.1
0.5%F+1.1%ST+8%W	54	285.7
0%GF+0.6%PST+8%W	27	89.3
0.5%F+0.6%PST+8%W	54	285.7
0%GF+4%SS+8%W	30	110.7
0.5%F+4%SS+8%W	45	217.9

Chapter 10: PolyCure in Combination with Polymer Emulsions for Soil Stabilization

10.1 Introduction

The combination of DirtGlue (polymer emulsion) and PolyCure (cuing additive) provided the largest increase in bearing capacity of Horseshoe lake sand in the initial testing. Soil-Sement and Soiltac are two other polymer emulsion type soil stabilizers that provide CBR values of 30 and 33 respectively without the addition of PolyCure. The design CBR of Horseshoe lake sand treated with Dirtglue without additional PolyCure is 6. It was hypothesized that if PolyCure was mixed with Soil-Sement and Soiltac the bearing capacity may yield similar results. To this measure, samples were prepared with combinations of PolyCure with Soil-Sement and Soiltac to evaluate performance. CBR testing was initially used to measure bearing capacity improvement however it was abandoned due to strength of samples exceeding the capacity of the testing equipment. Unconfined compression was used for subsequent testing which involved creating curing curves for Horseshoe lake sand and Fairbanks silt treated with Soil-Sement and PolyCure, as well as, strength measurements of Kwigillingok silt.

10.2 Unconfined Compression Testing of Soils Treated with PolyCure and Soil-Sement

A series of curing curves was developed for Horseshoe Lake sand and Fairbanks silt. These samples were prepared at their respective optimum moisture contents and mixed with 4% Soil-Sement and 10% PolyCure. The curing periods selected for the samples were: 24 hours, 4 days, 7 days, and 28 days. Two samples were prepared using Kwigillingok silt and cured for 7 days. For these samples, the moisture content was elevated to 30% to reflect field moisture conditions. Samples were prepared with 15% and 20% PolyCure in conjunction with 4% Soil-Sement.

The curing curves obtained from UC testing are presented as Fig. 10-1. These results show that the greatest initial strength gain in samples treated with PolyCure and Soil-Sement comes in the first seven days of curing. After seven days, the rate of increase in strength decreases. The samples tested at 28 days may not represent the full strength of the samples because the loads exceeded the capacity of the loading cells.

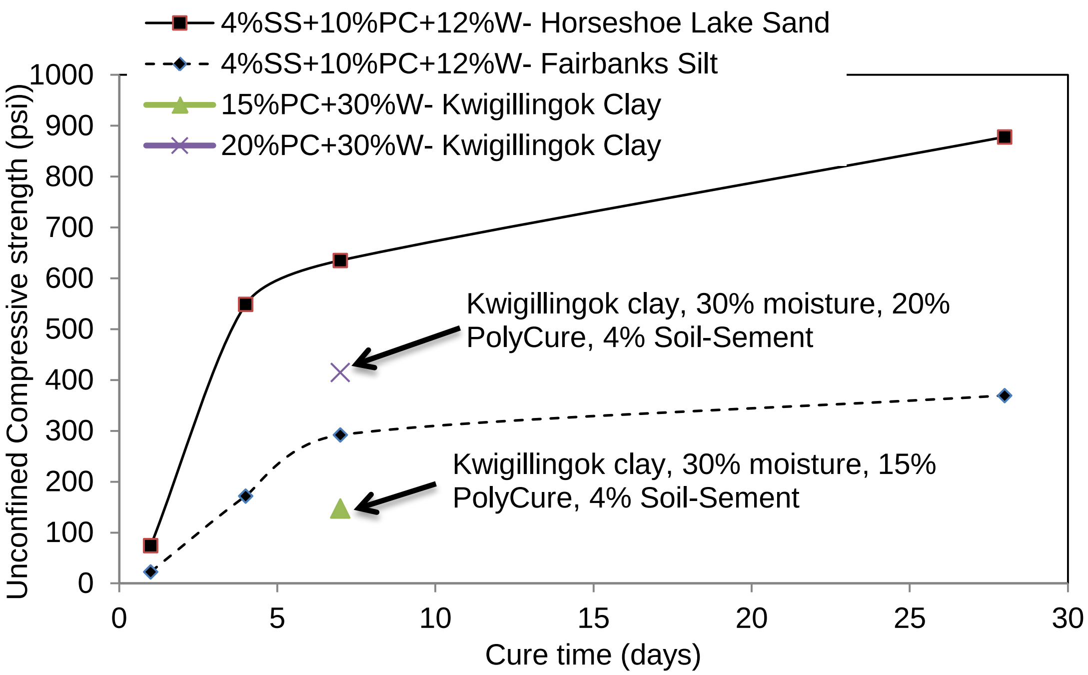

Figure 10- 1: Curing Curves for Soils Treated with PolyCure and Polymer Emulsions

10.3 Conclusions

Samples treated with PolyCure and polymer emulsion show increased strength capacity. CBR and UC testing both indicate that a mixture of PolyCure and polymer emulsions can be used to effectively stabilize poorly-graded sand, low-plasticity silt, and clay. Unconfined compression results indicate that samples treated with PolyCure and Soil-Sement show increased strength with longer curing durations.

Further testing should evaluate optimal mixtures of PolyCure and polymer emulsions for different soil types. The results presented only describe one combination of polymer emulsion and curing additive, other combinations of materials could produce more economical mix designs.

Chapter 11 Summary, Conclusions and Recommendations for Future Research

11.1 Summary

CBR testing was conducted on a total of four soils and two laboratory created soils. The combination of geofibers and nontraditional additives has shown an ability to improve the bearing capacity of marginal soils. For most soils tested the addition of nontraditional additives improved the bearing capacity. Nontraditional additives in combination with geofibers improved bearing capacity further. The new method of soil stabilization involved using polymer emulsions and curing additives. This method of stabilization has potential to revolutionize current construction practices in areas of the world without adequate sources of gravel.

11.2 Stabilization of Sands with Geofibers and Nontraditional Additives

A total of three sands were used in testing with geofibers and nontraditional liquid additives. These included Ottawa sand, Monterey sand, and Horseshoe lake sand. The Ottawa and Monterey sand are clean uniform sands, Horseshoe lake sand is locally collected material containing some fines. Fines were added to Ottawa and Monterey sand to evaluate the effect of fines on geofiber stabilization. Nontraditional additives in combination with geofibers were evaluated on all sand types with mixed results.

Ottawa sand was treated with Earth Armor and geofibers. Earth Armor decreases the natural bearing capacity of Ottawa sand by adding excess lubrication between soil particles. Geofibers alone increased the bearing capacity of Ottawa sand. When Earth Armor was added to Ottawa sand samples containing geofibers the design CBR value decreased below the value obtained for samples containing only geofibers. The optimum treatment for Ottawa sand is simply a 0.8% dosage of tape type geofibers or confinement.

The design CBR value of Monterey sand was not significantly affected by geofiber type. Tape and fibrillated geofibers can be used to stabilize Monterey sand with equal success. In a similar manner to Ottawa sand the optimum treatment for Monterey sand is a 0.8% tape or fibrillated geofiber content. The addition of Earth Armor to Monterey Sand mixtures containing geofibers causes the design CBR to decrease below the sample treated only with geofibers.

Horseshoe lake sand is most effectively treated with 4% Soil-Sement in combination with 10% PolyCure. Unconfined compression testing indicated that the mixture of Soil-Sement and PolyCure reaches nearly 70% of its 28 day strength in the first 7 days of curing. The rapid curing that takes place will allow roads and runways to be constructed quickly and with minimal effort. Unconfined compression tests with geofibers in combination with PolyCure and Soil-Sement were not conducted. The addition of geofibers to other mixtures of Horseshoe lake sand and nontraditional additives caused an increase in strength compared to using only nontraditional additives.

The stabilization methods that improved the bearing capacity of Horseshoe Lake sand to “excellent” were as follows:

- 1.1% Soiltac in combination with 0.5% fibrillated geofibers
- 0.6% powdered Soiltac in combination with 0.5% fibrillated geofibers
- 3.3% DirtGlue with 5% PolyCure and 0.5% fibrillated geofibers, increasing the PolyCure content to 10% increases the CBR value by 35, (60 for 5% PolyCure and 95 for 10% PolyCure)
- 3% dosage of EK35 with 0.5% fibrillated geofibers

Horseshoe lake sand treated with 1% Soil-Sement produced a design CBR value that is very close to being classified as “excellent”. The combination of 1% Soil-Sement with 0.5% fibrillated geofibers produced design CBR value above 45 which is classified as “good”. The Horseshoe lake sand treated with Soil-Sement showed resistance to a freeze and thaw cycle, which was not, tested using other additives with Horseshoe lake sand.

The CBR testing conducted on Monterey and Ottawa sand with various fines contents indicated that at low fines contents a 0.8% fiber content increases bearing capacity most efficiently. In Ottawa sand increasing the fines content to 30% raised the design CBR to the “excellent” range; geofibers decreased the design CBR. A similar trend was observed with Monterey Sand, however at 70% fines geofibers started to improve in effectively increasing bearing capacity. The point where the soil transfers from silty-sand to sandy-silt has a definite effect on geofiber stabilization.

11.3 Stabilization of Fine Grained Soils with Geofibers and Nontraditional Additives

Fairbanks and Kwigillingok silt were the only fine grained soils evaluated with geofibers and nontraditional additives. Earth Armor and Soil-Sement and PolyCure in combination with geofibers were used to stabilize Fairbanks silt. Kwigillingok silt was mixed with Soil-Sement and PolyCure and tested using unconfined compression. The result of testing both soils with different additives indicates stabilization is possible.

Several sample conditions were used to evaluate the performance of Fairbanks silt treated with geofibers and nontraditional additives. The most successful method for treated Fairbanks silt in the soaked condition is using 0.5% fibrillated geofibers. Both Earth Armor and Soil-Sement decrease the design CBR value below samples treated only with geofibers. After a freeze and thaw cycle Earth Armor and fibrillated geofibers provide a slight advantage over untreated soil, however the increase in design CBR value is so low it does not warrant use.

Fairbanks silt when mixed with 4% Soil-Sement and 10% PolyCure provides the best stabilization of all materials tested. In a similar manner to Horseshoe lake sand treated with Soil-Sement and PolyCure, 70% of the strength gained in a 28 day cure is obtained after a seven day cure. This makes using PolyCure and Soil-Sement a reasonable treatment method for Fairbanks silt in road and runway applications.

Kwigillingok silt is a fine-grained material that was extremely difficult to stabilize based on its high in-situ moisture conditions. Additional PolyCure was needed above the typical 10% content to react with the excess moisture in the silt. A 20% PolyCure content in combination with 4% Soil-Sement was more successful in improving UCS than the 15% content

11.4 Recommendations for Practical Use

Table 11-1 provides a usage recommendation for each soil type. The method of stabilization the best improvement in bearing strength is the recommended treatment. In some cases no treatment is recommended, these are instances where the addition of geofibers of synthetic fluid reduced bearing capacity below the untreated control sample. The CBR and UCS values are taken from test results. Soil-Sement and PolyCure are recommended based on their improvement in bearing capacity with the soils tested. There were no studies regarding the behavior after a freeze and thaw cycle.

Table 11- 1: Recommended Treatment by Soil Type

Soil Type	Fines Content	Recommended Treatment	Estimated CBR	Estimated UCS (psi)	Comments
Ottawa Sand	0	0.8% Tape Geofibers	58	-	Earth Armor reduced bearing capacity
	10%	0.8% Tape Geofibers	80	-	-
	20%	0.8% Tape Geofibers	107	-	-
	30%	No treatment	85	-	-
Monterey Sand	0	0.8% Tape or Fibrillated Geofibers	50	-	Earth Armor reduced CBR of soil treated with geofibers
	10%	0.8% Fibrillated Geofibers	68	-	-
	20%	0.5% Fibrillated Geofibers	87	-	-
	30%	0.2% Fibrillated Geofiber	87	-	-
	50%	No treatment	95	-	-
	70%	No treatment	69	-	Effectiveness of geofibers improves slightly
Fairbanks Silt		4% Soil-Sement, 10% PolyCure	-	292	0.5% fibrillated geofibers in combination with 4% Earth Armor showed best resistance to a freeze-thaw cycle
Horseshoe Lake Sand		4% Soil-Sement, 10% PolyCure	-	635	Soil-Sement with geofibers showed resistance to a freeze and thaw cycle
Kwigillingok Silt		4% Soil-Sement, 20% PolyCure, at 30% moisture content	-	415	-

11.5 Recommendations for Future Research

Further testing should be conducted on soils using combinations of PolyCure and polymer emulsions in combination with geofibers. A new curing additive produced by Midwest Industries should be evaluated with all existing polymer emulsions for soil stabilization.

Resilient Modulus testing should be considered for future testing because resilient properties of samples are not measured during CBR testing. Other testing that will measure behavior of samples treated with geofibers and nontraditional additives in dynamic load conditions such as earthquakes should be evaluated.

Durability of stabilized soil samples subjected to lab freeze-thaw conditions should be evaluated for samples treated with geofibers, polymer emulsion, and curing additives. Full scale testing environments should be constructed to monitor the effectiveness of using polymer emulsions and Polycure.

An in-depth analysis on the economical implications of using geofibers and nontraditional on marginal soils should be evaluated.

Finally, the full transition from silty-sand to sandy-silt should be evaluated. The effectiveness of geofiber behavior has been shown to vary at different fines contents. Completing the transition from silty-sand to sandy-silt will provide more information about geofiber behavior in sands and silts.

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Appendix

Table A. 1: Ottawa Sand Testing Summary

Sample Composition	**Treatment Condition**	**F&T System**	**Curing Time**	**w%**	**Chemical %**	**Chemical Type**	**Geofiber %**	**Geofiber Type**	**Design CBR**
0GF%+0%SF+2%W	Unsoaked	NA	NA	2	0	NA	0	NA	9
0GF%+0%SF+4%W	Unsoaked	NA	NA	4	0	NA	0	NA	10
0GF%+0%SF+6%W	Unsoaked	NA	NA	6	0	NA	0	NA	8
0GF%+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0	NA	10
0GF%+0%SF+10%W	Unsoaked	NA	NA	10	0	NA	0	NA	11
0GF%+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0	NA	13
0GF%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0	NA	19
0GF%+0%SF+14%W	Unsoaked	NA	NA	14	0	NA	0	NA	15
0GF%+0%SF+16%W	Unsoaked	NA	NA	16	0	NA	0	NA	11
0.2F%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.2	Fibrillated	22
0.5F%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.5	Fibrillated	35
0.8F%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.8	Fibrillated	30
0.2T%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.2	Tape	31
0.5T%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.5	Tape	38
0.8T%+0%SF+13%W	Unsoaked	NA	NA	13	0	NA	0.8	Tape	58
0GF%+1%SF+12%W	Unsoaked	NA	NA	12	1	Earth Armor	0	NA	10
0GF%+2%SF+11%W	Unsoaked	NA	NA	11	2	Earth Armor	0	NA	12
0GF%+3%SF+10%W	Unsoaked	NA	NA	10	3	Earth Armor	0	NA	12
0GF%+4%SF+9%W	Unsoaked	NA	NA	9	4	Earth Armor	0	NA	12
0GF%+1%SF+3%W	Unsoaked	NA	NA	3	1	Earth Armor	0	NA	10
0GF%+2%SF+2%W	Unsoaked	NA	NA	2	2	Earth Armor	0	NA	7
0GF%+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0	NA	9
0GF%+4%SF+4%W	Unsoaked	NA	NA	4	4	Earth Armor	0	NA	4
0.5F%+2%SF+11%W	Unsoaked	NA	NA	11	2	Earth Armor	0.5	Fibrillated	32
0.5T%+2%SF+11%W	Unsoaked	NA	NA	11	2	Earth Armor	0.5	Tape	33

Table A. 2: Ottawa Sand at Varying Fines Content Testing Summary

Sample Composition	Treatment Condition	Fines Content (%)	F&T System	Curing Time	w%	Chemical %	Chemical Type	Geofiber %	Geofiber Type	Design CBR
0GF%+10%W	Unsoaked	10	NA	NA	10	NA	NA	0	NA	22
0.2%F+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.2	Fibrillated	26
0.5%F+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.5	Fibrillated	37
0.8%F+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.8	Fibrillated	63
0.2%T+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.2	Tape	31
0.5%T+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.5	Tape	52
0.8%T+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.8	Tape	80
0GF%+8%W	Unsoaked	20	NA	NA	8	NA	NA	0	NA	19
0.2%F+8%W	Unsoaked	20	NA	NA'	8	NA	NA	0.2	Fibrillated	42
0.5%F+8%W	Unsoaked	20	NA	NA	8	NA	NA	0.5	Fibrillated	70
0.8%F+8%W	Unsoaked	20	NA	NA	8	NA	NA	0.8	Fibrillated	81
0.2%T+8%W	Unsoaked	20	NA	NA	8	NA	NA	0.2	Tape	42
0.5%T+8%W	Unsoaked	20	NA	NA	8	NA	NA	0.5	Tape	74
0.8%T+8%W	Unsoaked	20	NA	NA	8	NA	NA	0.8	Tape	107
0%GF+6%W	Unsoaked	30	NA	NA	6	NA	NA	0	NA	85
0.2%F+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.2	Fibrillated	77
0.5%F+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.5	Fibrillated	73
0.8%F+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.8	Fibrillated	72
0.2%T+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.2	Tape	70
0.5%T+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.5	Tape	71
0.8%T+6%W	Unsoaked	30	NA	NA	6	NA	NA	0.8	Tape	78

Table A. 3: Monterey Sand Testing Summary

Sample Composition	Treatment Condition	F&T System	Curing Time	w%	Chemical %	Chemical Type	Geofiber %	Geofiber Type	Design CBR
0GF%+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0	NA	18
0.2%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.2	Fibrillated	34
0.5%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.5	Fibrillated	41
0.8%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.8	Fibrillated	50
0.2%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.2	Tape	33
0.5%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.5	Tape	39
0.8%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.8	Tape	49
0%GF+2%SF+10%W	Unsoaked	NA	NA	10	2	Earth Armor	0	NA	25
0%GF+4%SF+8%W	Unsoaked	NA	NA	8	4	Earth Armor	0	NA	15
0.5%F+2%SF+10%W	Unsoaked	NA	NA	10	2	Earth Armor	0.5	Fibrillated	31
0.5%T+2%SF+10%W	Unsoaked	NA	NA	10	2	Earth Armor	0.5	Tape	29

Table A. 4: Monterey Sand with Varying Fines Content Summary

Sample Composition	Treatment Condition	Fines Content (%)	F&T System	Curing Time	w%	Chemical %	Chemical Type	Geofiber %	Geofiber Type	Design CBR
0GF%+10%W	Unsoaked	10	NA	NA	10	NA	NA	0	Fibrillated	12
0.2GF%+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.2	Fibrillated	38
0.5GF%+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.5	Fibrillated	47
0.8GF%+10%W	Unsoaked	10	NA	NA	10	NA	NA	0.8	Fibrillated	68
0GF%+9%W	Unsoaked	20	NA	NA	9	NA	NA	0	Fibrillated	38
0.2GF%+9%W	Unsoaked	20	NA	NA	9	NA	NA	0.2	Fibrillated	55
0.5GF%+9%W	Unsoaked	20	NA	NA	9	NA	NA	0.5	Fibrillated	87
0.8GF%+9%W	Unsoaked	20	NA	NA	9	NA	NA	0.8	Fibrillated	79
0GF%+8%W	Unsoaked	30	NA	NA'	8	NA	NA	0	Fibrillated	68
0.2GF%+8%W	Unsoaked	30	NA	NA	8	NA	NA	0.2	Fibrillated	87
0.5GF%+8%W	Unsoaked	30	NA	NA	8	NA	NA	0.5	Fibrillated	70
0.8GF%+8%W	Unsoaked	30	NA	NA	8	NA	NA	0.8	Fibrillated	65
0GF%+8%W	Unsoaked	50	NA	NA	8	NA	NA	0	Fibrillated	95
0.2GF%+8%W	Unsoaked	50	NA	NA	8	NA	NA	0.2	Fibrillated	73
0.5GF%+8%W	Unsoaked	50	NA	NA	8	NA	NA	0.5	Fibrillated	58
0.8GF%+8%W	Unsoaked	50	NA	NA	8	NA	NA	0.8	Fibrillated	60
0GF%+8%W	Unsoaked	70	NA	NA	8	NA	NA	0	Fibrillated	69
0.2GF%+8%W	Unsoaked	70	NA	NA	8	NA	NA	0.2	Fibrillated	64
0.5GF%+8%W	Unsoaked	70	NA	NA	8	NA	NA	0.5	Fibrillated	47
0.8GF%+8%W	Unsoaked	70	NA	NA	8	NA	NA	0.8	Fibrillated	43

Table A. 5: Fairbanks Silt Testing Summary

Sample Composition	Treatment Condition	F&T System	Curing Time (Days)	w%	Chemical %	Chemical Type	Geofiber %	Geofiber Type	Design CBR
0GF%+0%SF+6%W	Unsoaked	NA	NA	6	0	NA	0	NA	17
0GF%+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0	NA	19
0GF%+0%SF+10%W	Unsoaked	NA	NA	10	0	NA	0	NA	23
0GF%+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0	NA	35
0GF%+0%SF+14%W	Unsoaked	NA	NA	14	0	NA	0	NA	21
0.2%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.2	Fibrillated	64
0.375%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.375	Fibrillated	44
0.5%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.5	Fibrillated	42
0.625%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.625	Fibrillated	44
0.8%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.8	Fibrillated	39
1%F+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	1	Fibrillated	35
0.2%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.2	Tape	50
0.375%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.375	Tape	40
0.5%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.5	Tape	52
0.625%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.625	Tape	44
0.8%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	0.8	Tape	32
1%T+0%SF+12%W	Unsoaked	NA	NA	12	0	NA	1	Tape	27
0%GF+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0	NA	43
0%GF+4%SF+6%W	Unsoaked	NA	NA	6	4	Earth Armor	0	NA	52
0%GF+6%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0	NA	50
0%GF+8%SF+6%W	Unsoaked	NA	NA	6	8	Earth Armor	0	NA	52
0%GF+10%SF+6%W	Unsoaked	NA	NA	6	10	Earth Armor	0	NA	23
0.2%F+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0.2	Fibrillated	43
0.5%F+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0.5	Fibrillated	38
0.2%T+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0.2	Tape	31
0.5%T+2%SF+6%W	Unsoaked	NA	NA	6	2	Earth Armor	0.5	Tape	43
0.2%F+4%SF+6%W	Unsoaked	NA	NA	6	4	Earth Armor	0.2	Fibrillated	49
0.5%F+4%SF+6%W	Unsoaked	NA	NA	6	4	Earth Armor	0.5	Fibrillated	71
0.2%T+4%SF+6%W	Unsoaked	NA	NA	6	4	Earth Armor	0.2	Tape	49
0.5%T+4%SF+6%W	Unsoaked	NA	NA	6	4	Earth Armor	0.5	Tape	48
0.2%F+6%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.2	Fibrillated	40
0.5%F+6%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.5	Fibrillated	63
0.2%T+6%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.2	Tape	38
0.5%T+6%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.5	Tape	36
0.2%F+8%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.2	Fibrillated	40
0.5%F+8%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.5	Fibrillated	38
0.2%T+8%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.2	Tape	40
0.5%T+8%SF+6%W	Unsoaked	NA	NA	6	6	Earth Armor	0.5	Tape	45
0GF%+0%SF+6%W	Soaked	NA	NA	6	0	NA	0	NA	4
0GF%+0%SF+12%W	Soaked	NA	NA	12	0	NA	0	NA	7
0.2%F+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.2	Fibrillated	32
0.5%F+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.5	Fibrillated	46
0.8%F+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.8	Fibrillated	38
0.2%T+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.2	Tape	39
0.5%T+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.5	Tape	33
0.8%T+0%SF+12%W	Soaked	NA	NA	12	0	NA	0.8	Tape	22

0%GF+4%SF+6%W	Soaked	NA	NA	6	4	Earth Armor	0	NA	12
0.2%F+4%SF+6%W	Soaked	NA	NA	6	4	Earth Armor	0.2	Fibrillated	21
0.5%F+4%SF+6%W	Soaked	NA	NA	6	4	Earth Armor	0.5	Fibrillated	23
0.2%T+4%SF+6%W	Soaked	NA	NA	6	4	Earth Armor	0.2	Tape	13
0.5%T+4%SF+6%W	Soaked	NA	NA	6	4	Earth Armor	0.5	Tape	25
0%GF+4%SF+6%W	28DayCure-Soaked	Closed	28	6	4	Earth Armor	0	NA	2
0.5%T+4%SF+6%W	28DayCure-Soaked	Closed	28	6	4	Earth Armor	0.5	Tape	4
0%GF+4%SF+6%W	Soaked-28DayCure	Closed	28	6	4	Earth Armor	0	NA	6
0.5%T+4%SF+6%W	Soaked-28DayCure	Closed	28	6	4	Earth Armor	0.5	Tape	9
0GF%+0%SF+6%W	Unsoaked	Closed	NA	6	0	NA	0	NA	15
0GF%+0%SF+12%W	Unsoaked	Closed	NA	12	0	NA	0	NA	26
0%GF+4%SF+6%W	Unsoaked	Closed	NA	6	4	NA	0	NA	35
0.2%F+4%SF+6%W	Unsoaked	Closed	NA	6	4	Earth Armor	0.2	Fibrillated	46
0.5%F+4%SF+6%W	Unsoaked	Closed	NA	6	4	Earth Armor	0.5	Fibrillated	48
0.2%T+4%SF+6%W	Unsoaked	Closed	NA	6	4	Earth Armor	0.2	Tape	38
0.5%T+4%SF+6%W	Unsoaked	Closed	NA	6	4	Earth Armor	0.5	Tape	36
0GF%+0%SF+6%W	Soaked	Closed	NA	6	0	NA	0	NA	2
0GF%+0%SF+12%W	Soaked	Closed	NA	12	0	NA	0	NA	4
0.2%F+4%SF+6%W	Soaked	Closed	NA	6	4	Earth Armor	0.2	Fibrillated	12
0.5%F+4%SF+6%W	Soaked	Closed	NA	6	4	Earth Armor	0.5	Fibrillated	11
0.2%T+4%SF+6%W	Soaked	Closed	NA	6	4	Earth Armor	0.2	Tape	3
0.5%T+4%SF+6%W	Soaked	Closed	NA	6	4	Earth Armor	0.5	Tape	7
0%GF+2%SS+10%W	Soaked	NA	14	10	2	Soil-Sement	0	NA	21
0.2%F+2%SS+10%W	Soaked	NA	14	10	2	Soil-Sement	0.2	Fibrillated	22
0.5%F+2%SS+10%W	Soaked	NA	14	10	2	Soil-Sement	0.5	Fibrillated	29
0.2%T+2%SS+10%W	Soaked	NA	14	10	2	Soil-Sement	0.2	Tape (2.75 inch)	25
0.5%T+2%SS+10%W	Soaked	NA	14	10	2	Soil-Sement	0.5	Tape (2.75 inch)	33
0%GF+1.5%SS+10%W	Soaked	NA	14	10	1.5	Soil-Sement	0	NA	29
0.2%F+1.5%SS+10%W	Soaked	NA	14	10	1.5	Soil-Sement	0.2	Fibrillated	31
0.5%F+1.5%SS+10%W	Soaked	NA	14	10	1.5	Soil-Sement	0.5	Fibrillated	34
0.2%T+1.5%SS+10%W	Soaked	NA	14	10	1.5	Soil-Sement	0.2	Tape (2.75 inch)	23
0.5%T+1.5%SS+10%W	Soaked	NA	14	10	1.5	Soil-Sement	0.5	Tape (2.75 inch)	29

Table A. 6: Horseshoe Lake Sand Testing Summary

Sample Composition	Treatment Condition	F&T System	Curing Time (Days)	w %	Chemical %	Chemical Type	Geofiber %	Geofiber Type	Design CBR
0%GF+0%SF+8%W	Soaked	NA	NA	8	0	NA	0	NA	14
0.5%F+0%SF+8%W	Soaked	NA	NA	8	0	NA	0.5	F	34
0%GF+0%SF+4%W	Unsoaked	NA	NA	4	0	NA	0	NA	27
0%GF+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0	NA	25
0.2%F+0%SF+4%W	Unsoaked	NA	NA	4	0	NA	0.2	F	38
0.5%F+0%SF+4%W	Unsoaked	NA	NA	4	0	NA	0.5	F	57
0.8%F+0%SF+4%W	Unsoaked	NA	NA	4	0	NA	0.8	F	38
0.2%F+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0.2	F	36
0.5%F+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0.5	F	46
0.8%F+0%SF+8%W	Unsoaked	NA	NA	8	0	NA	0.8	F	41
0%GF+4%SF+4%W	Unsoaked	NA	NA	4	4	Earth Armor	0	NA	30
0%GF+1%EK+3%W	Unsoaked	NA	NA	3	1	EnviroKleen	0	NA	10
0%GF+2%EK+2%W	Unsoaked	NA	NA	2	2	EnviroKleen	0	NA	24
0%GF+2%EK+6%W	Unsoaked	NA	NA	6	2	EnviroKleen	0	NA	25
0%GF+4%EK+4%W	Unsoaked	NA	NA	4	4	EnviroKleen	0	NA	37
0.5%F+4%SF+4%W	Unsoaked	NA	Na	4	4	Earth Armor	0.5	F	50
0.5%F+1%SS+12%W	Unsoaked	NA	14 days	12	1	Soil-Sement	0.5	F	43
0.5%F+1%SS+8%W	Unsoaked	NA	14 days	8	1	Soil-Sement	0.5	F	44
0.5%F+1%SS+4%W	Unsoaked	NA	14 days	4	1	Soil-Sement	0.5	F	42
0.5%F+1%SS+4%W	Soaked	NA	14 days	12	1	Soil-Sement	0.5	F	46
0.5%F+1%SS+8%W	Soaked	NA	14 days	8	1	Soil-Sement	0.5	F	47
0.5%F+1%SS+12%W	Soaked	NA	14 days	4	1	Soil-Sement	0.5	F	43
0.5%F+1%SS+8%W	Soaked	closed	14 days	8	1	Soil-Sement	0.5	F	48
0.5%F+1%SS+4%W	Soaked	closed	14 days	4	1	Soil-Sement	0.5	F	43

0.5%F+1%SS+8%W	Unsoaked	closed	14 days	8	1	Soil-Sement	0.5	F	49
0.5%F+1%SS+4%W	Unsoaked	closed	14 days	4	1	Soil-Sement	0.5	F	44
0.5%F+1.5%SS+8%W	Soaked	NA	14 days	8	1.5	Soil-Sement	0.5	F	48
0.5%F+1.5%SS+4%W	Soaked	NA	14 days	4	1.5	Soil-Sement	0.5	F	41
0.5%F+2%SS+8%W	Soaked	NA	14 days	8	2	Soil-Sement	0.5	F	49
0.5%F+2%SS+4%W	Soaked	NA	14 days	4	2	Soil-Sement	0.5	F	63
0%GF+1.1%ST+8%W	Soaked	NA	7 days	8	1.1	Soiltac	0	NA	33
0.5%F+1.1%ST+8%W	Soaked	NA	7 days	8	1.1	Soiltac	0.5	F	54
0%GF+4%ST+8%W	Soaked	NA	7 days	8	4	Soiltac	0	NA	21
0.5%GF+4%ST+8%W	Soaked	NA	7 days	8	4	Soiltac	0.5	F	32
0%GF+0.6%PST+8%W	Soaked	NA	7 days	8	0.6	Powdered Soiltac	0	NA	27
0.5%F+0.6%PST+8%W	Soaked	NA	7 days	8	0.6	Powdered Soiltac	0.5	F	54
0%GF+1.2%PST+8%W	Soaked	NA	7 days	8	1.2	Powdered Soiltac	0	NA	17
0.5%GF+1.2%PST+8%W	Soaked	NA	7 days	8	1.2	Powdered Soiltac	0.5	F	55
0%GF+4%PST+8%W	Soaked	NA	7 days	8	4	Powdered Soiltac	0	NA	23
0.5%F+4%PST+8%W	Soaked	NA	7 days	8	4	Powdered Soiltac	0.5	F	34
0%GF+4%SS+8%W	Soaked	NA	7 days	8	4	Soil-Sement	0	NA	30
0.5%F+4%SS+8%W	Soaked	NA	7 days	8	4	Soil-Sement	0	F	45
0.%GF+3.3%DG+10%POLY+8%W	Soaked	NA	7 days	8	3.3%DG+10%POLY	DirtGlue + PolyCure	0	NA	75
0.5%F+3.3%DG+10%POLY+8%W	Soaked	NA	7 days	8	3.3%DG+10%POLY	DirtGlue + PolyCure	0	F	95
0%GF+3.3%DG+5%POLY+8%W	Soaked	NA	7 days	8	3.3%DG+5%POLY	DirtGlue + PolyCure	0	NA	39
0.5%F+3.3%DG+5%POLY+8%W	Soaked	NA	7 days	8	3.3%DG+5%POLY	DirtGlue + PolyCure	0	F	60
0.%GF+3.3%DG+8%W	Soaked	NA	7 days	8	3.3	DirtGlue	0	NA	6
0.5%F+3.3%DG+8%W	Soaked	NA	7 days	8	3.3	DirtGlue	0.5	F	32
0.%GF+3%EK35+8%W	Soaked	NA	7 days	8	3	EK35	0	NA	12

0.5%GF+3%EK35+8%W	Soaked	NA	7 days	8	3	EK35	0.5	F	66